Solid-State Lighting: An Integrated Human Factors, Technology and Economic Perspective

Quantifying past and potential-future trajectories

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ABSTRACT | Solid-state lighting is a rapidly evolving technology, now virtually certain to someday displace traditional lighting in applications ranging from the lowest-power spot illuminator to the highest-power area illuminator. Moreover, it has considerable headroom for continued evolution even after this initial displacement. In this article, we present a high-level overview of solid-state lighting, with an emphasis on white lighting suitable for general illumination. We characterize in detail solid-state lighting's past and potential-future evolution using various performance and cost metrics, with special attention paid to inter-relationships between these metrics imposed by human factors, technology and economic considerations.

KEYWORDS | Light-emitting diodes; lighting; color; luminescent devices; luminescence; costs; economics; human factors; technology forecasting.

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I. INTRODUCTION

Solid-state lighting (SSL) is an evolving technology [3-7] now virtually certain to displace all traditional lighting technologies, including incandescent, fluorescent and high-intensity discharge lighting in the developed world on grid electricity [9], and kerosene lighting in the undeveloped world not on grid electricity [12-13]. In this article, we present an overview of solid-state lighting, and of its past and potential-future evolution relative to traditional lighting. We characterize this evolution using various performance and cost metrics, with special attention paid to inter-relationships between these metrics imposed by human factors, technology and economic considerations.

We also quantify the impact that various research advances can have on potential SSL futures. Advances that can already be foreseen are projected to enable, sometime in 2012, commercial solid-state lamps with an effective lamp efficiency ~30%, and with a performance and cost superior to that of traditional fluorescent and HID lamps. Advances of a much more challenging nature are necessary to enable solid-state lamps to achieve effective total efficiencies much higher than this, particularly "ultra-high-efficiencies" [14] of 70% and beyond.

We organize the main body of this article into four sections. Section II discusses human factors: how the human visual response, combined with typical objects whose colors it is desirable to distinguish between, imposes constraints between luminous efficacy, color temperature and color rendering, and on the wavelengths, linewidths and power fractions of the light that must be mixed to create white. Sections III and IV discuss technology: past, present and potential future luminous efficacies corresponding to various assumptions about the serial and multiplicative chain of efficiencies beginning with DC electrical power and ending in white light matched to the human visual system. Section V discusses the economics of SSL: how an "equivalent" cost of light can be defined and used as a figure-of-merit to compare light sources with different luminous efficacies, lamp costs, color rendering indices, and correlated color temperatures.

Throughout, our focus is on the lamp, or the fully packaged component that emits light. For incandescent lighting, this is the bulb; for fluorescent lighting, the tube; and for SSL, the packaged light-emitting diode (LED) or light engine. Although important to lighting systems, we do not discuss except in passing either the drivers and control circuitry that power the lamp or the luminaires or fixtures that house the lamp.

Also throughout, we make reference to a number of different past and potential-future traditional and solid-state lamps. For convenient cross-referencing, we collect the characteristics of all of these lamps in Table 2 at the end of this paper.

Finally, to minimize ambiguity, we use throughout the following notation: ε's for dimensionless conversion efficiencies such as Watts out per Watt in or lumens out per lumen in; K's for luminous efficacies of radiation with units lumens per Watt of optical power; and η's for luminous efficacies of source with units lumens per Watt of electrical power.

II. HUMAN FACTORS: PERFECT RYGB SSL

Interaction with the human visual system is the ultimate end goal of artificial lighting, so we begin by asking: what are the characteristics of light that is "perfectly matched" to that visual system? In addressing this question, we exclude some considerations which are of great future interest, but are too open-ended for our current purpose.

For example, we do not consider the imaging aspect of the human visual system: the important but complex interplay between lighting systems and intentional spatially inhomogenous illumination of environments [15]. This is likely to be an area of great future interest: although it applies to all light sources, it applies *especially* to solid-state lighting, with its small source size, inherent directionality, and enhanced potential for adroit manipulation of light.

And, for example, we do not consider the human visual system under dim illumination for which rod rather than cone receptors are dominant, colors are no longer perceived, and the so-called blue-shifted scotopic or mesopic (mixed scotopic and photopic) visual sensitivity applies. Again, this is an area of great future interest: cost-effective evening illumination of large outdoor spaces could have significant benefits to human daily life and productivity.

With these exclusions, we consider here the three key performance metrics associated with the desirability of white light for illumination purposes: luminous efficacy of radiation (K, with the units lm/W, or lumens per optical Watt); the "standard" color rendering index R_a [16]; and correlated color temperature (CCT, with the units degrees K). Importantly, these performance metrics are not independent of each other. For example, all other things being equal, as R_a or CCT increase, K decreases. In the remainder of this Section II, we consider two trade-offs: that between K and R_a; and that between K and CCT. We do not consider the trade-off between R_a and CCT as these are independent within the current framework of color rendering quality. However, this independence is largely a limition of the current framework -- R_a values at different $CCTs$ should not be considered the same [17].

Throughout, we calculate K_{max} vs R_a and K_{max} vs CCT trade-offs – that is, trade-offs for light having the maximal (highest possible) luminous efficacies of radiation. As has been discussed recently [14], the highest such luminous efficacies are obtained for light composed of discrete colors with narrow linewidths. Four is the minimum number of discrete narrow-linewidth colors that can produce very high (up to 97) R_a's, with little benefit provided by using more than this number of colors [18]. Narrow-linewidth sources enable the highest luminous efficacies of radiation, by minimizing spillover of light to wavelengths – particularly in the deep blue and deep red – at which the human eye is less sensitive.[1]

Thus, we take the maximal (highest potential) luminous efficacy of radiation, K_{max}, possible for *any* light source, solid-state or otherwise, to be that obtainable from a narrow (~1 nm) linewidth RYGB (Red/Yellow/Green/Blue) source. To determine these luminous efficacies, we use a white-light simulator [19] that first adjusts the power fractions of RYGB light of specified wavelengths and linewidths so as to produce a particular CCT, then calculates the resulting luminous efficacy of radiation and R_a. By wrapping an iterative solver around this simulator, those wavelengths that maximize luminous efficacy of radiation for particular R_a's and $CCTs$ are obtained.

Finally, we note that, although for color rendering index we use exclusively the "standard" index R_a, color rendering in general is based on a complex interaction between the human visual system, the environment that system is embedded in, and the illumination source. There is much ongoing work aimed at improved metrics for color rendering [20-22], and indeed it is already clear from preliminary work that R_9, the color rendering index associated with the ninth, deep-red Munsell color sample, is an important additional metric [23]. For example, a light source might have a very high R_a value (85-90) but an unacceptably low (0 or even negative) R_9. To take this into account, in all of our simulations we require R_9 to be 1/4 of R_a. Thus, the higher R_a the higher R_9, and an R_a of 85, generally considered acceptable, will be associated with an R_9 of 21, also considered acceptable.[2]

A. K_{max} versus R_a

We begin with the relationship between maximal luminous efficacy of radiation, K_{max}, and R_a. This is an inverse relationship, as illustrated in Figure 1(c): K_{max} is highest at low R_a and lowest at high R_a. The reason is that these two metrics compete with one another. On the one hand, human eye sensitivity to light peaks at 555 nm, with a FWHM of about 100 nm, so maximizing luminous efficacy means concentrating as much optical power near 555 nm as possible. On the other hand, the reflectances of objects in the world around us span the visible spectrum, so maximizing the rendering of those colors requires optical power to be dispersed more broadly away (shorter and longer) from this 555 nm peak.

The result is that, as shown in Figure 1(a), to increase R_a, the yellow and green wavelengths become more widely spaced away from 555 nm and consequently K_{max} decreases. Effectively, the white light is becoming less RGB like (with the Y and G merged into one wavelength), and more RYGB like (with the Y and G clearly separated).

Note that, as R_a increases, the power fractions among the individual colors also change, as illustrated in Figure 1(b). As R_a increases (at fixed CCT), and as the red and green wavelengths move away from 555 nm (where the human eye is most sensitive), power shifts away from the red and

[1] Indeed, the detrimental effects of such "spillovers" are a pervading consideration for the improvements to SSL discussed in Section IV.

[2] M.R. Krames, private communication.

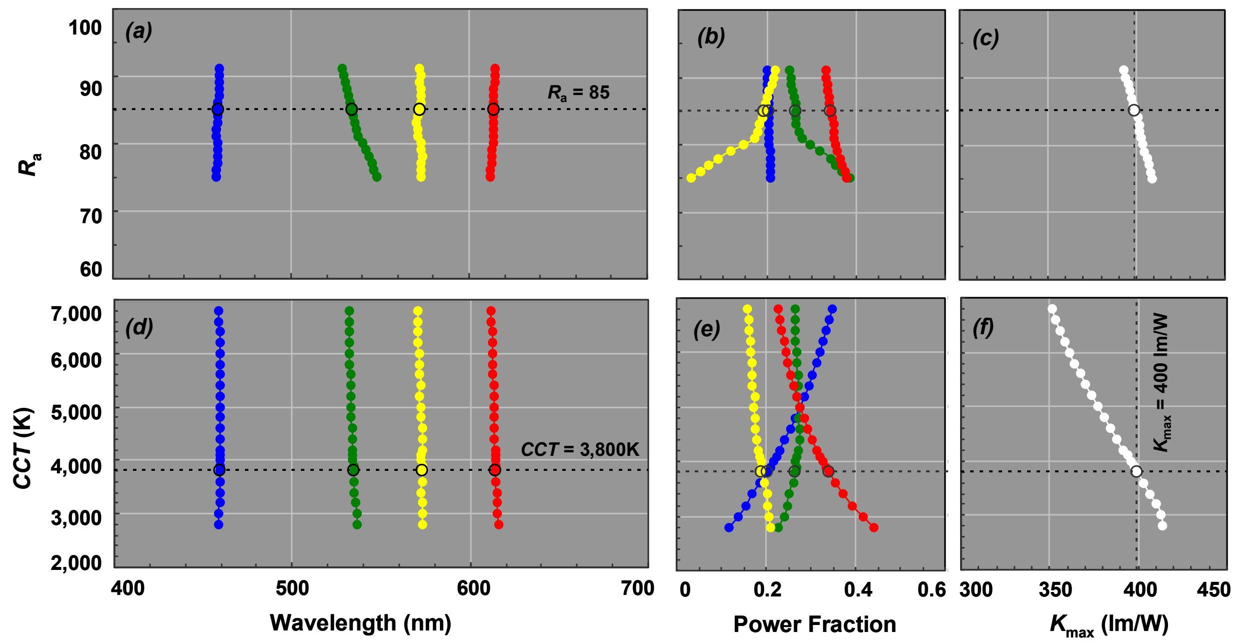

Figure 1. Characteristics of narrow (1 nm) linewidth RYGB white light having maximal luminous efficacies of radiation. The panels in the top row vary R_a for a fixed CCT = 3,800K; those in the bottom row vary CCT for a fixed R_a = 85 and R_9 = 85/4. The panels in the left column show the optimal center wavelengths, those in the center column show the optimal power fractions, and those in the right column show the resulting maximal luminous efficacies of radiation K_{max}.

green and into the yellow so as to minimize the reduction in luminous efficacy.

For our later purpose of projecting potential-futures for SSL, it is useful to identify an R_a that is compatible with human preference in most lighting applications. To that end, we show in Figure 2(a) the cumulative market sizes of traditional lamps used in the U.S. in 2001 as a function of the R_a's of those lamps [2]. As indicated in Figure 2(a), the "90%-R_a," the R_a that accounts for 90% of the market, is roughly 85. We consider this 90%-R_a for traditional lighting to be a reasonable estimate for what the 90%-R's might be for SSL.[3] It is consistent with qualitative notions that: R_a's in the range of 70, although common for many SSL white light sources (such as those found in flashlights), are not adequate for general illumination; R_a's of 80 to 85 are considered adequate for most general illumination applications; and R_a's of 90 and above are considered adequate for even the most demanding (e.g., surgical and museum art) illumination applications [24].

At R_a = 85 (and, as discussed in the next Section II.B, CCT = 3,800K), the maximum possibile luminous efficacy of radiation is K_{max} ~ 400 lm/W, in reasonable agreement with previous Monte Carlo simulations [25]. This luminous efficacy of radiation is thus our working definition in this paper of "100%" efficiency – the maximum obtainable (and highest potential) luminous efficacy of a 100%-efficient white light source at R_a = 85, R_9 = 21.1, and, as discussed below, CCT = 3,800K.

B. K_{max} versus CCT

We turn now to the trade-off between K_{max} and CCT. This relationship can be seen in Figure 1(f): luminous efficacy is highest at low CCT and lowest at high CCT. The reason is that, as CCT increases, the Planckian white point moves away from the green-yellow-red edge to the green-blue edge of the standard CIE chromaticity diagram [26]. Thus, as can be seen in Figure 1(e), the power fraction of the red component decreases and the power fraction of the blue component increases. Because the blue component is further out into the wing of the photopic human eye sensitivity than the red component is, the net luminous efficacy of radiation decreases [23].

Note that this inverse relationship is opposite to that for incandescent lamps. For incandescent lamps, luminous efficacy of radiation increases with CCT as a larger and larger fraction of blackbody power moves from the infrared into the visible, until at 6,300K (at which temperature luminous efficacy of radiation is 93 lm/W) more blackbody power moves from the visible into the ultraviolet [27].

It is also counter to recent experience in commercial SSL lamps, for which luminous efficacies are lower for warm-white than for cool-white lamps. In these cases, however, the reason is not fundamental, but is due to the particulars of current SSL lamp technology. Because, as discussed in

[3] Note that arguments can be made that it is either an underestimate or an overestimate. It might be an underestimate if people someday consumed more high-R_a light were its cost of light not as high as it currently is for incandescent lamps. It might be an overestimate if people someday consumed less high-R_a light were, e.g., R_a = 90 lamps nearly indistinguishable from the current R_a = 100 incandescent lamps to become available.

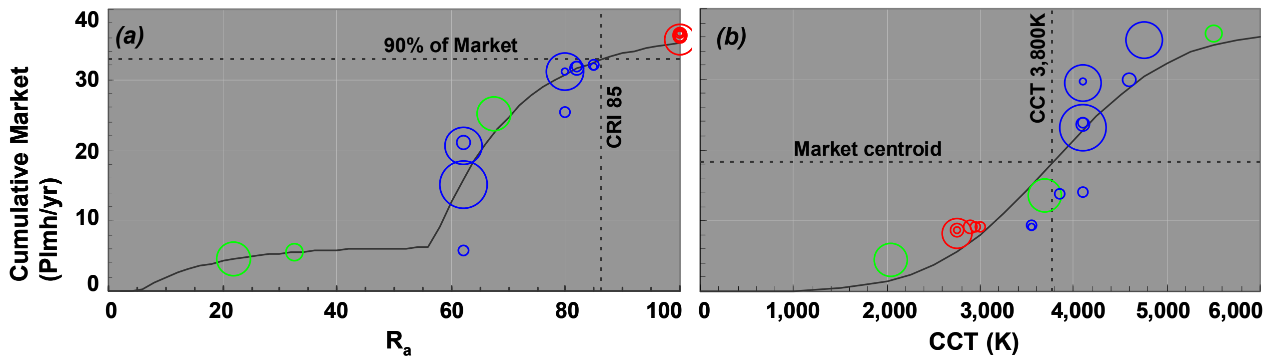

Figure 2. Cumulative sizes of the markets (in petalumen-hours per year, Plmh/yr, of light consumed) for the 20 most commonly used lamps in Navigant's comprehensive survey [2] of the U.S. lighting market in 2001, augmented with data from Philips Lighting,[2] as functions of their estimated (a) R_a's and (b) *CCTs*. The open circles represent the 6 incandescent (in red), 11 fluorescent (in blue) and 3 high-intensity-discharge (HID, in green) lamps surveyed, drawn so that their areas are roughly proportional to their 2001 market usage (in Plmh/yr). The horizontal position of each lamp type is its R_a or *CCT*; the vertical position of each lamp type is the cumulative market size of all lamp types with R_a's or *CCT*'s equal to or less than that lamp type. The solid black curve in (a) is a best fit to the integral of the sum of two exponential distributions; the black curve in (b) is a best fit (centroid *CCT* = 3,800K and FWHM 2,000K) to the integral (an error function) of a Gaussian distribution. Note that the Navigant data shown is for lighting consumption in the past, and does not incorporate forward-looking assumptions on market penetration or government regulations that might be necessary to estimate lighting consumption in the future.

Section III, the red phosphors that are currently used to produce warm white have a relatively broad (~95 nm) linewidth, there is significant spillover into the deep red, where the human eye is less sensitive. Thus, just as with incandescent lamps, lower *CCTs* give lower luminous efficacies. As discussed in Section IV, red phosphors with narrow linewidths would *reverse* the relationship, i.e., luminous efficacies of radiation would be higher for warm-white than for cool-white lamps [3].

Again, for our later purpose of projecting potential-futures for SSL, it is useful to identify a particular *CCT* that represents an average over human preferences in a broad range of lighting applications. To this end, we show in Figure 2(b) the cumulative market sizes of traditional lamps used in the U.S. in 2001 as a function of the *CCT*'s of those lamps. As indicated in Figure 2(b), the centroid-*CCT*, the *CCT* at which just as many lumen-hours are consumed from higher as from lower *CCT* lamps, is roughly 3,800K. We consider this centroid-*CCT* for traditional lighting to be a reasonable estimate for what the centroid-*CCT* might be for SSL.[4] It is roughly halfway between the 2,800K of the incandescent lamps used in many residential applications, and the 4,000-6,000K of the fluorescent and HID lamps used in many commercial and industrial applications.

At a *CCT* of 3,800K, denoted by the dashed line in Figures 1(d)-(f) (and, as discussed in Section II.A, R_a = 85 and R_9 = 21.1), the maximal luminous efficacy of radiation is K_{max} ~ 400 lm/W. The detailed characteristics of this RYGB source are: center wavelengths B 459, G 535, Y 573 and R 614 nm; and power fractions B 0.18, G 0.25, Y 0.22 and R 0.36. Because the *CCT* = 3,800K white point lies so much closer to the green-yellow-red edge than to the green-blue edge of the chromaticity diagram, the three component colors along that edge account for most (0.82) of the power, with only a small contribution (0.18) from the blue. Also, because the *CCT* = 3,800K white point lies about midway between the green/yellow and red, the power fractions are nearly half weighted to each, with the green and yellow contributing slightly more than 4/10, and the red contributing slightly less than 4/10, of the optical power.

C. Spectral Efficiency: ε_S

As discussed above in Sections II.A and II.B, we consider a white light source with R_a = 85, R_9 = 21.1 and *CCT* = 3,800K to be well matched to a wide range of applications, and hence to be a representative benchmark light source for evaluating the overall progress of solid-state lighting technology. In practice, one can anticipate that, just as for traditional lighting, there will be a wide range of applications for solid-state lighting, each of which may be served best by a different R_a and *CCT* combination. To assess the relative progress of solid-state lighting technology with these different R_a's and *CCTs*, it would be useful to be able to compare their luminous efficacies of radiation with the maximal luminous efficacies of radiation shown in Figure 1.

To this end, we have found (from the simulations in Figure 1) that the maximal luminous efficacies of radiation at various R_a's and *CCT*s is described reasonably well by the

[4] Note that here too arguments can be made that it is either an underestimate or an overestimate. It might be an underestimate: the sodium lamps used currently in outdoor evening applications are popular mainly because of their very low cost of light, not because of their low *CCT*; and the incandescent lamps that dominate indoor residential applications are popular in part because of their high R_a, not because of their low *CCT*. It might also be an overestimate: at lower *CCTs*, SSL luminous efficacies can be higher and, as discussed in Section V, cost of light lower, and this may drive a shift towards lower *CCTs*.

following polynomial expansion around R_a = 85 and CCT = 3,800K:

$$K_{\max}(R_a, CCT) = 400\,\text{lm/W} \\ -0.876\,(R_a - 85) \\ -0.0179\,(CCT - 3{,}800K) + 2.08\cdot 10^{-7}\,(CCT - 3{,}800K)^2 \qquad (1)$$

A light source at a given R_a and CCT having a luminous efficacy of radiation K lower than the K_{max} given in Equation (1) can be said to have a *spectral* efficiency of

$$\varepsilon_S = \frac{K}{K_{\max}(R_a, CCT)}. \qquad (2)$$

For example, the 2009.7 state-of-the-art warm-white SSL lamp discussed in the next Section III, from simulations similar to those just discussed, has a luminous efficacy of radiation K ~ 323 lm/W. The maximal luminous efficacy of radiation for light of the same R_a = 85 and CCT = 3,045K is, from Equation (1), K_{max} = 413 lm/W. The spectral efficiency of that warm-white SSL lamp is thus ε_S = 323/412 = 78%.

Or, for example, the luminous efficacy of radiation of a typical incandescent lamp is K ~ 14 lm/W. The maximum luminous efficacy of radiation for light of the same R_a = 100 and CCT = 2,760K is, from Equation (1), K_{max} = 361 lm/W. The spectral efficiency of that incandescent lamp is thus ε_S = 14/361 ~ 4%.

In this manner, the effective spectral efficiencies of white light sources of differing R_a's and *CCTs* can be deduced and self-consistently compared. We note that this concept of spectral efficiency is similar to a figure-of-merit developed in connection with the envelope of K_{max}'s and R_a's for fluorescent lamps [28].

III. TECHNOLOGY: MID-2009 SSL LAMP

In Section II, we discussed the maximal luminous efficacies of radiation for white light of various R_a's and *CCTs.* We also developed a procedure for estimating the effective spectral efficiency of a light source, a crucial element of the overall efficiency of a light source.

In this Section III, we discuss the mid-2009 state-of-the-art in white SSL lamps. Since their introduction in 1999 [29], white SSL lamps have had ten years to evolve and are now quite sophisticated. Their evolution is far from finished, and there are a number of variant architectures that might currently be denoted state-of-the-art. Here, we discuss one, the so-called thin-film flip-chip (TFFC) architecture [30-31]. This architecture has been discussed in some detail in the literature [32], and we base our analysis in this Section III on a state-of-the-art, commercially available version of this architecture: a 2009.7 Philips Lumileds Rebel warm-white lamp [1].[5]

We show at the bottom right of Figure 3 a schematic of this lamp. It is an example of a so-called R_BG_BB lamp – a blue light-emitting diode (LED) capped with green and red phosphors. Some of the blue light leaks through the phosphors, and some is absorbed by the phosphors and re-emitted as green and red light. The combination of blue, green and red light gives a warm-white light that has relatively high R_a = 85, relatively low CCT = 3,045K, and is pleasing to the human eye.

At the lower left of Figure 4, we show an approximate power spectrum of this lamp: it has a ~24-nm-wide peak centered at ~440 nm associated with the blue LED, a ~75-nm-wide peak centered at ~538 nm associated with the green phosphor, and a ~95-nm-wide peak centered at ~615 nm associated with the red phosphor. The wavelength widths and peaks are approximately consistent with those of the 2009.7 Philips Lumileds Rebel warm-white lamp [1], and of the phosphors considered [33-37] for these warm-white lamps.

The blue LED consists of a thin-film InGaN heterostructure grown epitaxially on sapphire, beginning with a low-temperature buffer, followed by n-type layers, intrinsic quantum-well recombination layers, and p-type layers. The heterostructure is metalized, then flipped over and bonded to a metalized semiconductor or ceramic heat-sink sub-mount [38]. The flip-chip p-layer-fully-metalized design simultaneously solves three problems [39].

First, because the heterostructure is relatively inefficient at converting DC input power into blue light, much of that DC input power generates heat rather than light. To efficiently extract this heat, the metalized side of the LED is attached directly to a ceramic heat sink in close proximity to the p-n junction where much of the heat is generated.

Second, because of well-known difficulties in p-type doping (of wide-bandgap semiconductors generally), the p-type layers are relatively poorly conducting. Therefore, current must be spread laterally in the p-contact before injection into the p-type layers, and can be done with a thick metal layer covering the entire p-type surface.

Third, because light is emitted from the intrinsic recombination layers both downwards and upwards, half of the light is potentially wasted. This can be circumvented by the metalization on the p-type layer, which provides not only current spreading but presents a high-reflectance interface to the light emitted downwards.

After the metalized heterostructure has been flipped and bonded, two more processes are applied. The sapphire substrate is removed [40] through a laser lift-off process, and the exposed GaN surface is roughened [41]. Removing the sapphire substrate eliminates a (GaN/sapphire) interface at which light could be internally reflected and trapped inside the structure. Roughening the exposed GaN surface randomizes the incidence angles of light striking the remaining (GaN/air) interface [42], reducing the number of internal reflections required for light to escape from the high-index heterostructure.

As advanced as the current state-of-the-art white SSL lamp is, it is still not very efficient at converting electrical

[5] We intentionally analyze here a commercially available lamp whose retail cost is known and hence that can be used in the economic analysis in Section V. Research laboratory results are better than these by 1-2 years.

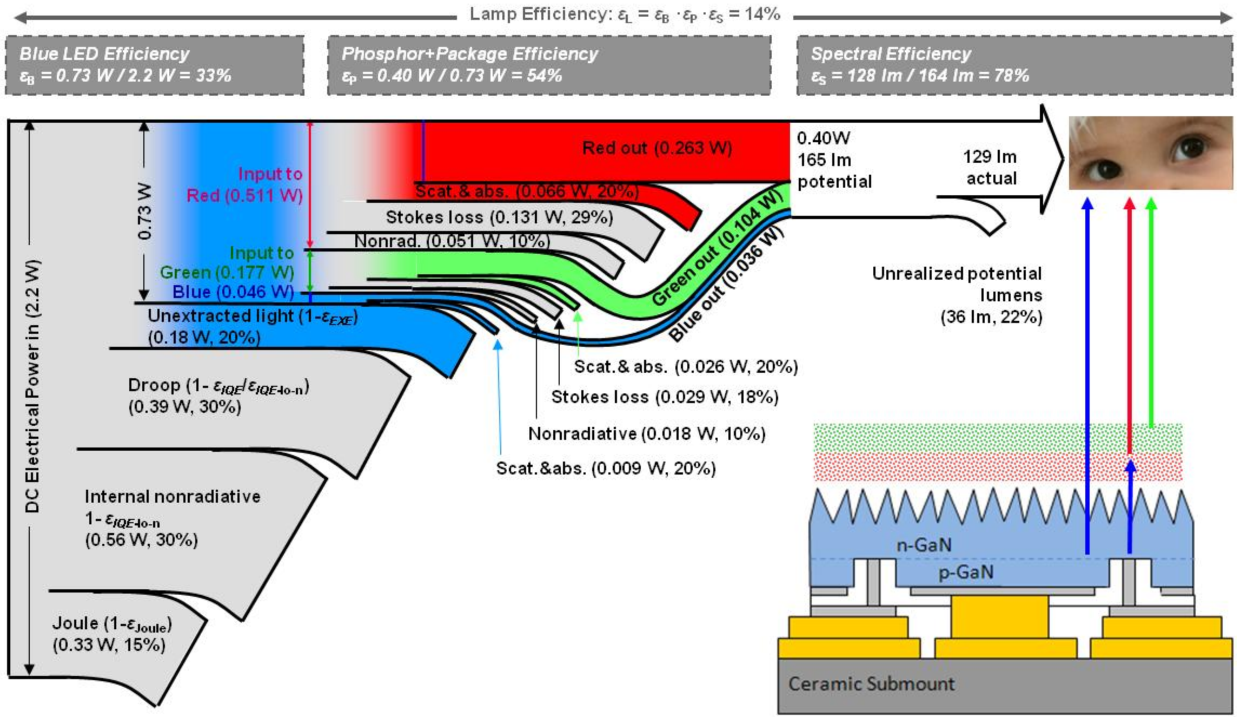

Figure 3. Electricity-to-light power-flow diagram for mid-2009 (August 2009, or 2009.7) state-of-the-art warm-white SSL. The white SSL lamp is modeled after a Philips Lumileds thin-film flip-chip (TFFC) Luxeon Rebel lamp [1]. The diagram indicates how 2.2W = 0.7A·3.2V of DC power is distributed into various useful and non-useful (loss) streams as it is converted into white light. The colors of the various streams indicate the type of power they contain: grey for electronic excitations, colored for light at various RGB wavelengths, and white for white light formed from a combination of colors. For the loss streams we indicate both its absolute power as well as the percentage it represents of its immediately preceding parent stream. The TFFC schematic is courtesy of Jonathan Wierer (Sandia National Laboratories); the human eye photo is courtesy of Bobby Mercer (http://bobbymercerbooks.com). The various elements of this Figure are discussed in detail in Section III.

power to visible light on an absolute scale. At the high injected current densities (roughly 700mA/1mm^2) desirable for low ownership cost of light (as discussed in Section V), its luminous efficacy is about η_L = 58 lm/W. From Equation (1), the maximum luminous efficacy of radiation at such an R_a and CCT is K_{max} = 413 lm/W, so the efficiency of this lamp relative to this maximal luminous efficacy is only ε_L = 14%.

Interestingly, this low efficiency is not the result of any single dominant loss channel, but rather the result of many loss channels contributing serially and cumulatively. To see this, we draw on the left side of Figure 3 an electricity-to-light power-flow diagram for this 2009.7 state-of-the-art white SSL lamp. Below, we discuss in turn the losses associated with: the blue LED pump (ε_B), the phosphor+package combination (ε_P), and the spectral match of the light to the human visual system (ε_S). Lamp efficiency is the product of these efficiencies: $\varepsilon_L = \varepsilon_B \cdot \varepsilon_P \cdot \varepsilon_S$.[6]

[6] Note that, in the limit where the blue LED pump and phosphor+package efficiencies are 100%, lamp efficiency would just be the spectral efficiency, as discussed in Section III.C and defined by Equation (2).

A. Blue LED Pump: ε_B

We begin with the injection of a hypothetical 2.2W of DC electrical power into the blue LED at the left of the power-flow diagram. For this blue (440 nm) LED, there are four loss channels removing, respectively, 15%, 30%, 30%, and 20% of the power present just before each loss channel. Each channel's loss is one minus one of the associated efficiencies defined in Table 1, and the product of the various associated efficiencies is the overall blue LED efficiency:

$$\begin{aligned} \varepsilon_B &= \varepsilon_{Joule} \cdot [\varepsilon_{EQE}] \\ &= \varepsilon_{Joule} \cdot [(\varepsilon_{IQE}) \cdot \varepsilon_{EXT}] \\ &= \varepsilon_{Joule} \cdot [(\varepsilon_{IQE-lo-n} \cdot \frac{\varepsilon_{IQE}}{\varepsilon_{IQE-lo-n}}) \cdot \varepsilon_{EXT}] \end{aligned} \quad (3)$$

The first loss channel, 1-ε_{Joule}, is due to the voltage drop as electron-hole pairs: are injected into the device; traverse the various semiconductor layers between the ohmic contacts and the intrinsic recombination layers; and thermalize within the recombination layers to the bottom and top of the conduction and valence bands, respectively. The efficiency of this channel is thus the ratio between the photon energy (divided by the electron charge) and the energy of an injected electron-hole pair (or the drive voltage). Using V_{photon} = 2.8V for photons of wavelength

Symbol	Meaning	Definition
ε_B	Power conversion efficiency	Blue optical power / Input electrical power
ε_{Joule}	Joule (voltage) efficiency	Energy of output photon / Energy of injected electron-hole pair
ε_{EQE}	External quantum efficiency	# photons out / # electron-hole pairs in
ε_{EXT}	Extraction efficiency	# photons out / # photons created
ε_{IQE}	Internal quantum efficiency	# photons created / # electron-hole pairs in
$\varepsilon_{IQE\text{-}lo\text{-}n}$	Internal quantum efficiency at low carrier density	# photons created / # electron-hole pairs in

Table 1. Definitions and symbols for efficiencies associated with the blue LED. As discussed in Section V, we are especially interested in efficiencies under the high injected carrier densities desirable for low ownership cost of light. Therefore, except for $\varepsilon_{IQE\text{-}lo\text{-}p}$, these efficiencies are assumed to be those under high-injected-carrier-density conditions.

440nm, and a forward voltage of 3.23V at I = 0.7A, we can deduce:

$$\varepsilon_{Joule} = \frac{V_{photon}}{V_f} = \frac{2.8V}{3.23V} \sim 0.85 \tag{4}$$

Note that the difference between the forward voltage and the photon energy (divided by the electron charge) is essentially a resistive IR loss, which we can calculate to be $IR = V_f - V_{photon}$ = 0.43V. Since the forward current is 0.7A, the magnitude of the effective resistance associated with this loss is $R = V/I$ = 0.43V/0.7A ~ 0.61Ω. Also note that the Joule efficiency is 100% at low currents (because the IR loss vanishes) and decreases with increasing current.

The second and third loss channels are physically the same and in principle should be combined; we have separated them here solely for the purpose of calling attention to (and quantifying) the importance of high injected carrier densities and droop.

The second loss channel, 1-$\varepsilon_{IQE\text{-}lo\text{-}n}$, is due to all processes by which carriers do not recombine radiatively at *low* injected carrier densities. These include processes by which carriers overshoot or escape from the recombination layers. They also include processes by which carriers, after injection into the recombination layers, recombine non-radiatively as catalyzed by crystallographic defects such as dislocations and V-defects, or by compositional defects such as single or clustered point defects. We estimate these losses to be ~30%: between those of similar research-lab 425-nm and 520-nm devices [32].

The third loss channel, 1-($\varepsilon_{IQE}/\varepsilon_{IQE\text{-}lo\text{-}n}$), is the so-called "droop" loss [43]: the decrease in the internal quantum efficiency when injected carrier densities are increased to those desirable, as discussed in Section V, for low capital and ownership costs of light. We estimate these losses to be ~30%: between those of similar research-lab 425-nm and 520-nm devices [32].

The fourth loss channel, 1-ε_{EXE}, is due to unextracted-light, as some of the generated blue light is internally reflected and trapped in the LED, and is ultimately absorbed by a metal or low-bandgap material. These losses are estimated to be on the order of 20%: 100% minus the extraction efficiency of a TFFC (ε_{EXE}~80%) [32].

All together, these four losses in series give an estimated overall efficiency for the 440-nm blue LED pump of ε_B = (1-0.15)·(1-0.30)·(1-0.30)·(1-0.20) = 33%. As a consistency check, the power conversion efficiency of a slightly longer wavelength (447.5 nm) 2009.7 Philips Lumileds Rebel royal-blue LED [44] at 700 mA input current is 31% = 0.74W /(0.7A·3.4V). These two efficiencies are reasonably consistent with each other, after adjusting for the higher efficiencies typical of shorter wavelengths.

B. Phosphor+Package: ε_P

Exiting the blue LED is 440 nm light representing 33% of the initial 2.2W of DC input power, or roughly 0.73W of optical power. From here, one can think of the blue light as being split into three streams, one that will leak through the phosphors and exit the lamp as blue light, and two others that will be absorbed by the adjacent phosphors and re-emitted as green and red light. The splitting ratios of the blue light must be such that, after all subsequent losses in the three streams (discussed next), the proportions of blue, green and red light produce white of the designed-for R_a and CCT. For the lamp shown, these splitting fractions can be deduced from our white light simulator to be: B 0.06, G 0.24, R 0.70.

Note that the blue fraction is small compared to the green and especially the red fractions, for two reasons. First, less final blue power is needed, as the CCT = 3,045K white point is much nearer the red-green than the blue-green edge of the chromaticity diagram. Second, the blue stream incurs only scattering and absorption losses as it passes through the phosphor grains, while the green and red streams incur not only scattering and absorption losses (as the re-emitted green and red light pass through the phosphor grains), but also internal non-radiative losses (as blue pump light is absorbed, converted into electron-hole pairs which occasionally recombine non-radiatively) and Stokes-deficit losses (as higher energy blue photons are converted to lower energy green or red photons).

The internal non-radiative loss for the yellow $YAG:Ce^{3+}$ phosphors used in cool-white SSL lamps is very low (5% or less) [37, 45-46]. The internal non-radiative losses for the green and red phosphors used in warm-white lamps (such as that considered here) are larger, but are still thought to be ~15% or lower [46]. Here, we use an estimate of 10% for both phosphors.

The Stokes-deficit loss is the easiest to determine – 100% minus the ratio of the blue to green, or blue to red, center wavelengths. These losses are 18% for the green and 29% for the red phosphors.

Finally, the scattering and absorption loss we estimate to be roughly 20% [8] for the blue, green and red, although these losses may well be different for each wavelength (according to their radiating geometry and their absorptivity by various materials).

As a consistency check, with the assumed center wavelengths and widths and the assumed blue LED pump and phosphor+package efficiencies, the simulated luminous efficacy is η_L = 58 lm/W, very close to that of the actual 2009.7 Philips Lumileds Rebel warm-white LED [1]. Note that the luminous efficacy is essentially the product of the blue LED efficiency, the phosphor+package efficiency, and the luminous efficacy of radiation: $\eta_L = \varepsilon_B \cdot \varepsilon_P \cdot K$. Since the blue LED pump efficiency is ε_B = 33%, and, as discussed at the end of Section II, the luminous efficacy of radiation of this warm-white LED is K = 323 lm/W, we can infer a phosphor+package efficiency of ε_P = 54%, consistent with the serial multiplication of the efficiencies associated with the three loss channels just discussed: 52% = (1-0.10)·(1-0.25)·(1-0.20).

C. Spectral Match to Human Visual System: ε_S

Finally, even after blue, green and red light has been created and combined, the white light produced is not necessarily as perfect a match to the human visual system as those from the "perfect" RYGB sources discussed in Section II. In particular, for the state-of-the-art lamp discussed here, the red phosphor emission has a broad (~95 nm) linewidth and hence emits significantly in the deep red where the human eye is not as sensitive. In addition, the green and red phosphors both absorb more efficiently in the deep blue, so the "dual purpose" blue LED is designed to emit at a wavelength (~440 nm) that is too far in the deep blue, again where the human eye is not as sensitive.

To calculate the spectral efficiency, we repeat the procedure discussed at the end of Section II.C. We use Equation (1) to determine $K_{max}(85,3045)$ = 413 lm/W, the maximal luminous efficacy of radiation at R_a = 85 and CCT = 3,045. As indicated in Figure 3, 0.4 W of optical power, if optimally distributed into four narrow-linewidth RYGB wavelengths, would then yield a potential 165 lm of white light. Because the 0.4 W of optical power is not optimally distributed, it yields an actual 129 lm of white light, for an actual luminous efficacy of radiation of K = 323 lm/W. The spectral inefficiency is thus 22%: 100% minus the ratio between the actual luminous efficacy of radiation (K = 323 lm/W) and the maximal luminous efficacy of radiation (K_{max} = 413 lm/W). Conversely, the spectral efficiency is 100% minus this, or ε_S = 323/413 = 78%.

D. Cumulative White Lamp Efficiency: ε_L

As discussed above, none of the individual loss channels are overwhelmingly dominant, although clearly the net efficiency of the blue LED pump (33%) is lower than those of the phosphor+package (54%) and the spectral match to the human visual system (78%). But because these losses are cumulative, and the efficiencies multiplicative, their product, the cumulative efficiency of the white lamp is relatively low: $\varepsilon_L = \varepsilon_B \cdot \varepsilon_P \cdot \varepsilon_S = 0.33 \cdot 0.54 \cdot 0.78$ = 14%.

IV. TECHNOLOGY: POTENTIAL-FUTURE SSL LIGHTING

We have just discussed, in Section III, the characteristics of an early-2009 state-of-the-art SSL warm-white lamp. Its total efficiency is only 14%, so clearly there is much room for improvement. In this Section, we discuss various "classes" of improvements that could be made to this mid-2009 state-of-the-art, and quantify the efficiencies that would be achieved.

Importantly, we do not limit our discussion to those improvements that would be sufficient to achieve efficiencies greater than those of traditional (incandescent, fluorescent, HID) light sources. Such improvements are of course of great interest to the SSL lamp industry, which would benefit from a massive transition to SSL from traditional lamps. Instead, we consider improvements that would enable performance approaching 100% efficiency. Such improvements, going well beyond those necessary to compete with traditional lamps, are of great import to humanity, as they would enable a reduction in global energy consumption while maintaining or even enhancing human productivity [47].

To illustrate the various classes of potential improvements, in Figure 4 we draw a lamp-efficiency progress line. The progress scale is logarithmic, so equal horizontal distances correspond to equal percentage changes.

At the far right of the plot is the 100%-efficient performance frontier. At the far left of the plot are the efficiencies of state-of-the-art solid-state white lamps achieved in the past four years (2006-2009). As discussed in somewhat more detail in the next Section V, we have deliberately chosen data points for solid-state white lamps that correspond to commercial products, have a high R_a and, most importantly, are driven fairly hard (operated at high power) so as to have lower capital and ownership costs of light.

Also shown on the lamp efficiency progress line are potential-future lamps corresponding to three classes of

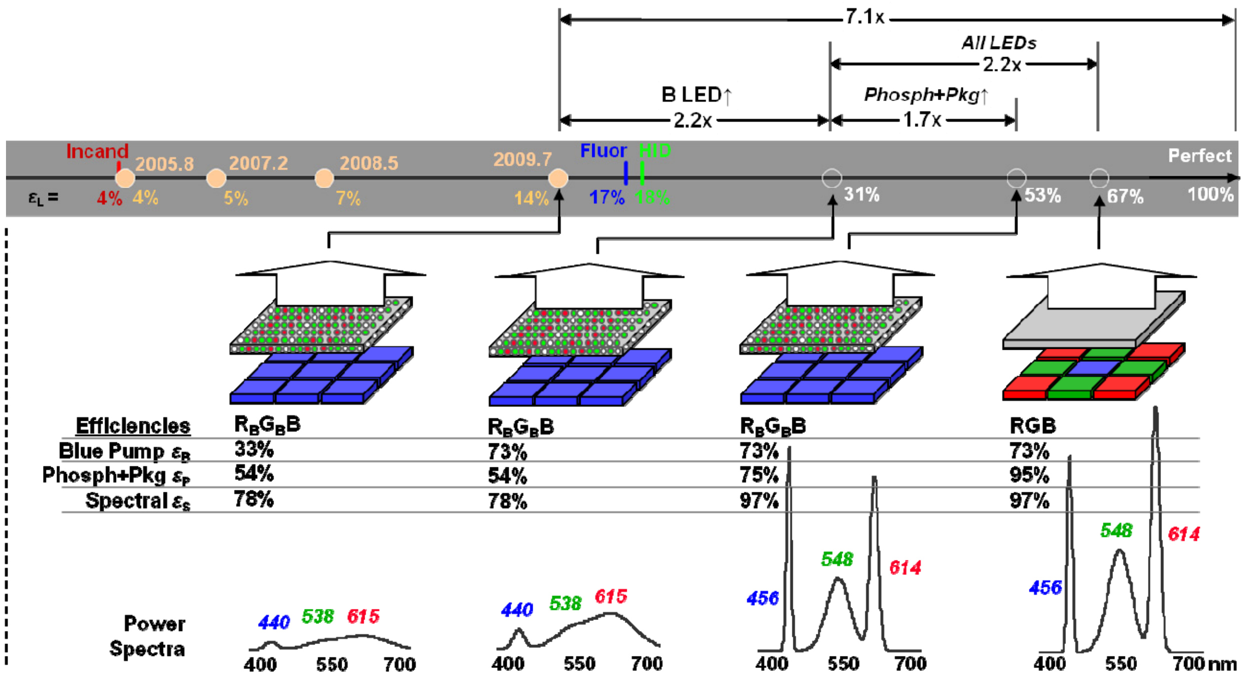

Figure 4. Efficiencies ($\varepsilon_L = \varepsilon_B \cdot \varepsilon_P \cdot \varepsilon_S$) of various past and potential-future traditional and solid-state lamps. Top: Logarithmic efficiency progress line. Middle: Schematics of SSL lamp architectures along with nominal blue pump, phosphor+package and spectral efficiencies. Bottom: Power spectra with center wavelengths labeled. Details of all lamps are given in Table 2.

improvements which we discuss below. The first two of these classes are associated with the current R_BG_BB approach to SSL: improvements to the blue LED pump source, and improvements to the phosphor and lamp package. The last of these classes is associated with non-phosphor approaches to SSL: the possible development of high-efficiency RGB sources, i.e., an "all-LED solution."

A. R_BG_BB: Blue LED Improvements

The first class of improvements is associated with the blue LED pump, but within the current R_BG_BB paradigm of blue plus blue-pumped green and red phosphors. Here, the challenge is mainly to decrease the magnitude of all the blue LED loss channels, each in the range 15-30%, that were discussed in Section III.A. Importantly, research laboratory results already indicate substantive improvements in all four of these channels [32, 46].

Joule losses are now 15% or lower, with an expectation of achieving 10% or lower in the future [46]. Low-current-density internal non-radiative losses are still 30% or so, but expectations are that these may decrease to 10% or lower in the future [46]. Droop at high-current density, particularly for the shorter-wavelength blue, has made significant improvement, and might be expected to decrease to nearly zero in the future [39]. Unextracted light is now 20% or less, with an expectation of achieving 10% or less in the future.

Taken together, it is quite reasonable to anticipate blue LED efficiency to improve from 33% to 73% or so. As indicated in Figure 4, these improvements would increase power output and overall efficiency by a factor 2.2 = (0.73/0.33), to 31%. This is in important efficiency milestone, as it surpasses that of traditional lighting. As shown on the progress line, the market-weighted aggregate efficiencies of traditional lighting are: incandescent (4%), fluorescent (17%) and HID (18%). Hence, due to anticipated improvements *in the blue LED alone*, the efficiency of SSL will almost assuredly exceed those of traditional lighting.

B. R_BG_BB: Phosphor and Package Improvements

The second class of improvements are those associated with the phosphors and packaging, again within the current R_BG_BB paradigm of blue from an LED and green+red from blue-pumped phosphors. The challenge here is twofold. First, it is to decrease the magnitude of the phosphor+package loss channels discussed in Section III.B. Second, through tailoring of the excitation and emission wavelengths of the phosphors, it is to decrease the magnitude of the spectral loss channel – that is, the decrease in luminous efficacy due to a mismatch between the emitted wavelengths and the human eye sensitivity.

First, consider the phosphor+package loss channels. The internal non-radiative losses are already relatively low: 10% or so. These may in principle be reduced to the 5% or less that characterize the yellow garnet phosphors. However, in the green and red this may require discovery of new phosphors. Scattering and absorption, now at levels of 20% or so, may also in principle be reduced to 5% or less, though doing so may require novel geometries that place the phosphor remotely so as to minimize the fraction of light scattered or emitted by the phosphors that intersect the blue LED chip [48-50]. The Stokes deficit, averaged over the green and red phosphors, is roughly 25%, which is a fundamental quantum loss unlikely to be alterable. Taken together, the phosphor+package loss channels could potentially be halved, from 46% to ~25%, although, due to the irreducible Stokes loss, they are unlikely to be reduced much further. Indeed, even a reduction to ~25% will be challenging, likely requiring new phosphors and new phosphor-placement geometries.

Second, consider the tailoring of excitation and emission wavelengths of the phosphors, to decrease the magnitude of the spectral loss channel. Here, the most significant opportunities are twofold. A first opportunity is in narrowing the linewidth of the green and red phosphors (from, say, 75 and 95 nm in the green and red to 50 nm in the green and $1.8kT$ = 17.6 nm in the red[7]), so that there is less spillover into sub-optimal wavelengths, especially into the deep red. A second opportunity is in shifting the emission wavelength of the green phosphor and the (blue) absorption wavelength of the green and red phosphors to longer wavelengths (from, say, 538 nm and 440 nm to 548 nm and 456 nm) to better match the human eye sensitivity. Doing all of these, as indicated in Table 2, would decrease the spectral waste from 22% to 3%. But doing so would again be challenging, likely requiring new phosphors.

We note in passing that there are two very different routes to improving the mismatch between the longer-wavelength blue that is best, when color-mixed with green and red, for producing white light, and the shorter-wavelength blue that is currently better-matched to excitation of the phosphors. A first route is to continue the "dual-purpose" use of one blue LED for color-mixing into white and for phosphor excitation. Then, if one uses a longer wavelength blue LED (456 nm instead of 440 nm) to better match the human eye sensitivity, one would need to tailor the green and red phosphors so that they can be excited efficiently by this longer wavelength [51]. A second route is to use separate blue LEDs for color-mixing into white and for phosphor excitation. This would allow the wavelengths of the two "blues" to be chosen independently, albeit with the complication of the optics associated with combining and mixing the colors. Indeed, one might imagine using blue pumps whose wavelengths are the same as those (405 nm) used for the increasingly efficient blue/purple lasers used in Blu-Ray optical discs, albeit with a small penalty in a slightly increased Stokes deficit.

Taken together, improvements in the phosphors and packaging could increase the phosphor+packaging efficiency from 54% to ~75%, and the spectral efficiency from 78% to ~97%. As indicated in Figure 4, doing so would shift and narrow the power spectrum, and increase the overall efficiency by a factor of 1.7 = (0.75/0.54)·(0.97/0.78), to 53%. Unlike for the potential-future improvements in the blue LED envisioned in Section IV.A, however, here it is less obvious from research laboratory results whether such substantive improvements will be possible, although progress continues to be made [36, 51-54]. On the one hand, we may be at a stage similar to that of fluorescent lamps in the early 1970's, just before the discovery of a new generation of phosphors enabling high luminous efficacy and color rendering [55-56]. On the other hand, the competing constraints imposed on the phosphors [57-58] could prove to be insurmountable.

C. RGB: Phosphor-free white

The third class of improvements are those associated with the development of high-efficiency green and red LEDs, enabling an RGB approach that eliminates phosphors entirely.[8] The reasons this is beneficial are two-fold: one eliminates the phosphor and package losses almost entirely, including the fundamental Stokes deficit loss; and, because of the typically narrower linewidths associated with LEDs than with phosphors, one reduces spectral spillover of light, especially into the deep red, where the human eye is not very sensitive.

The blue LED can be considered well on its way to the necessary high-efficiency performance. However, red and green LEDs are presently quite far from high-efficiency operation. For the red LED, the principal difficulty is that its optimal wavelength, determined from simulations similar to those outlined in Section II, is ~614 nm. This wavelength is, with the current state of technology, too long to be produced efficiently in the InGaN materials system, and too short to be produced efficiently in the AlInGaP materials system (particularly at the high drive currents necessary for low cost of light). For the green LED, the principal difficulty is that its optimal wavelength, ~548 nm, is also, with the current state of technology, too long to be produced efficiently in the InGaN materials system. It is not as long a wavelength as the 614 nm needed for the red source, however, and much progress has been made and more can be anticipated [59-60].

Note that, of the two colors, developing a red LED is more significant: as in the current R_BG_BB solution, the red phosphor has the larger irreducible Stokes deficit loss and the larger spillover into wavelengths of reduced human visual sensitivity. Interestingly, however, the green LED has garnered greater interest and effort from the research community. This is perhaps partly due to additional uses for semiconductor green LEDs and lasers apart from solid-state white lighting. For projection displays, e.g., green

[7] Emission linewidths from phosphors can in principle be much narrower than $1.8kT$. However, linewidths much less than this give only modest improvements in spectral efficiency, and $1.8kT$ is convenient for the purpose of comparing with the RGB all-LED improvements discussed in Section IV.C.

[8] We think of these improvements as the logical next step enroute to the "perfect" narrow-linewidth RYGB source discussed in Section II.

LEDs or lasers are a critical missing piece [61], while red LEDs and lasers at 650 nm already exist.[9]

From simulations similar to those outlined in Section II, the optimal wavelengths for an RGB solution based on red, green and blue LEDs are 456, 548 and 614 nm, where we have assumed double-heterostructure-like 1.8*kT* FWHM's [62] of 9.7 and 17.6 nm for the blue and red LEDs, but a wider FWHM of 50 nm (necessary for a high $R_a = 85$) for the green LED. With LED efficiencies of 73%, and allowing for 5% color-mixing losses, this approach would improve efficiencies beyond that by simply improving the blue LED (as discussed in Section IV.A) by a factor of 2.2 = (0.95/0.54)·(0.97/0.78), to 67%. This is a much higher efficiency than that discussed in Section IV.B for the phosphor+package improvements within the R_BG_BB paradigm. Just as with those improvements, however, here it is less obvious from research laboratory results whether such substantive improvements will prove possible. The benefits of developing green and especially red LEDs are clearly high, but the challenges are also exceedingly difficult.

We note that, although this factor of 2.2 improvement is large, and larger than that associated with the phosphor+package improvements discussed in Section IV.B, it would be reduced to a factor of 1.3 if the phosphor and package improvements outlined in Section IV.B were attained. While still significant, of course, this illustrates the important gains that can be achieved from improvements to the phosphors alone.

Nevertheless, the all-LED RGB solution has more headroom for improvement than the R_BG_BB solution. Indeed, the 97% spectral efficiency of the all-LED RGB solution is only slightly inferior to the assumed 100% spectral efficiency of the ultra-narrow-linewidth RYGB solution discussed in Section II. Thus, one should regard ultra-narrow linewidths, such as those considered in Section II, as beneficial, but not necessary, except to achieve the absolute highest spectral efficiencies.

V. ECONOMICS

In the previous Section IV, we outlined the performance of past and potential-future SSL technology with respect to total efficiency. Combined with the maximal luminous efficacy of radiation, total efficiency determines lamp luminous efficacy,

$$\eta_L = \varepsilon_L \cdot K_{\max}(R_a, CCT) \cdot \quad (5)$$

Combined with other quanitites such as lamp life and cost, lamp luminous efficacy then determines the cost of light (*CoL*). Cost of light, in turn, can be viewed as a natural economic figure-of-merit which measures relative progress of various lighting technologies.

Cost of light, however, is not the only important figure-of-merit – other aspects of light, such as R_a and *CCT*, are important. Here, we seek a way in which *CoL*, R_a and *CCT* can be combined into an over-arching figure-of-merit that can be used to assess technological progress.

To that end, we note that the primary reason luminous efficacy is not by itself a good measure of technological progress is that a lamp can easily achieve high luminous efficacies by sacrificing R_a. However, the degree to which it can do this is captured to a large extent by the dependence, described by Equation (1), of the maximal luminous efficacy of radiation on R_a. Thus, we might consider the ratio of luminous efficacy and maximal luminous efficacy, which is just the effective lamp efficiency, to be an improved (though still imperfect) measure of technological progress:

$$\varepsilon_L = \frac{\eta_L}{K_{\max}(R_a, CCT)} \quad (6)$$

If we wish now to compare a lamp's technological progress with the benchmark lamp discussed in Section II, we can define an "equivalent" luminous efficacy. This is the luminous efficacy that a lamp with the same efficiency would have at our benchmark lamp's *R*, = 85 and CCT = 3,800K:

$$\underline{\eta}_L = \varepsilon_L \cdot K_{\max}(85{,}3800) = \eta_L \cdot \frac{K_{\max}(85{,}3800)}{K_{\max}(R_a, CCT)} . \quad (7)$$

The equivalent luminous efficacy $\underline{\eta}_L$ of a low-R_a lamp will thus be lower than its actual luminous efficacy η_L, reflecting the natural inverse trade-off between luminous efficacy of radiation and R_a discussed in Section II.

A. Equivalent Cost of Light: $\underline{C}oL$

Using the above definition for equivalent luminous efficacy $\underline{\eta}_L$, we can now define an equivalent cost of light, $\underline{C}oL$. For a lamp with an R_a = 85 and *CCT* = 3,800K, this is the actual cost of light to the consumer. For a lamp with a different R_a and *CCT*, this is not the actual cost of light to the consumer. Instead, it is an over-arching figure-of-merit that allows its state of development to be compared to that of a lamp whose R_a = 85 would be sufficient to capture 90% of the current lighting market, and whose CCT = 3,800K is the market-weighted average of all current lighting applications (as discussed in the text associated with Figure 2) .

For this equivalent cost of light, we use the standard [26, 63-64] break-out:

$$\underline{C}oL = \underline{C}oL_{ope} + \underline{C}oL_{cap} , \quad (8)$$

where $\underline{C}oL_{ope}$ and $\underline{C}oL_{cap}$ are the equivalent operating and capital costs of light.

Equivalent Operating Cost of Light: $\underline{C}oL_{ope}$

The equivalent operating cost of light (in units of $/Mlmh),

$$\underline{C}oL_{ope} = CoE / \underline{\eta}_L , \quad (9)$$

is the cost of electricity, *CoE* (in $/MWh), divided by the equivalent luminous efficacy, $\underline{\eta}_L$ (in lm/W). Note that the

[9] Electrical power consumption is a lower fraction of the ownership cost for projection displays than for lighting, so electrical-to-visible-light conversion efficiency and overlap of the red wavelength with the human eye sensitivity are less important.

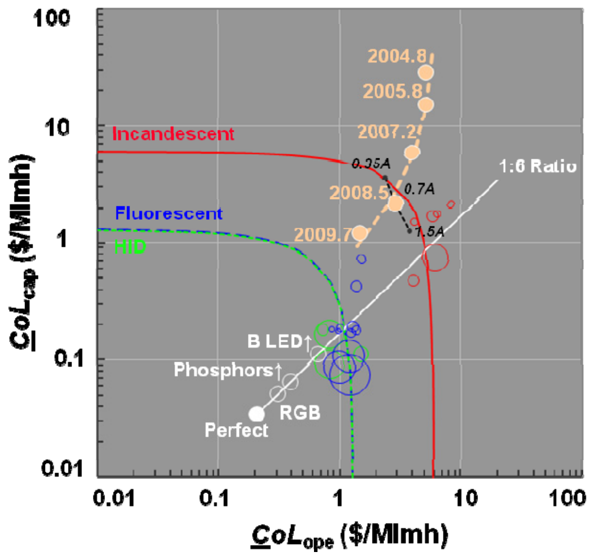

Figure 5. Equivalent capital and operating costs of light for various past and potential-future traditional and SSL lighting technologies. Open colored circles represent traditional lamps (red = incandescent, blue = fluorescent, green = HID), drawn so that their areas are proportional to their 2001 U.S. market size in lumen hours per year produced by that lamp [2]. The red, blue and green lines represent contours of constant market-weighted aggregate ownership costs of light for incandescent, fluorescent and HID lighting. Filled tan circles represent past and present SSL (with a dashed tan line to guide the eye); open white circles represent potential-future SSL. The black data points connected by the dashed line represent the 2008 SSL state-of-the-art driven at various currents (as drive current increases, capital cost decreases but, because of droop, operating cost also increases, so ownership cost of light is minimum at an intermediate current drive). The white line represents a lamp capital to operating cost ratio of 1/6.

cost of electricity is complicated by two potential refinements, both related to the fact that this cost is paid out over the lifetime of the lamp. On the one hand, the present value of that cost stream is slightly lower due to the annual interest rate of money. On the other hand, the present value could also be higher, depending on how the cost of electricity evolves in the future. Since these two refinements are in opposite directions and are higher-order effects, we ignore them for our current purpose.

Equivalent Capital Cost of Light: $\underline{C}oL_{cap}$

The equivalent capital cost of light (also in units of $/Mlmh),

$$\underline{C}oL_{cap} = \frac{\$_\Phi}{Min\{20,\tau\}} + \frac{1\$/klm}{\tau} = \frac{\$_W \cdot 10^3 W/kW}{\underline{\eta}_L \cdot Min\{20,\tau\}} + \frac{1\$/klm}{\tau}, \qquad (10)$$

is the cost to purchase the lamp ($\$_\Phi$, in units of $ per klm that the lamp supplies), plus the labor cost[10] to replace the bulb or lamp when it burns out (1$/klm), both amortized over lamp lifetime[11] (τ, in units of kh).

For the cost to purchase the lamp, we note that, by using the standard normalization of cost by the lumens the lamp supplies ($\$_\Phi$), this cost has embedded in it a luminous efficacy: the higher the luminous efficacy the more lumens the lamp produces for a given input power, and the lower the cost per lumen. Because one of our purposes here is to deconvolve improvements in performance (luminous efficacy) from improvements in cost, it is natural to rewrite the cost to purchase the lamp as $\$_\Phi = \$_W/\underline{\eta}_L$. Here, we have introduced a cost to purchase the lamp ($\$_W$, in units of $/W) that is normalized *by the input power the lamp is rated to sink*. Though this cost may appear somewhat non-intuitive, it has the great advantage that it does not have embedded in it a luminous efficacy. Moreover, since a major determinant of the cost of a lamp is the input power that it is rated to sink, one can think of $\$_W$ as a "power-sinking cost," or the cost of a lamp per unit power that it is able to sink.

Equivalent Ownership Cost of Light: $\underline{C}oL$

The sum of the equivalent operating and capital costs of light is the equivalent ownership cost of light, or simply the equivalent cost of light ($\underline{C}oL$). Importantly, $\underline{C}oL$ depends symmetrically on $\underline{C}oL_{ope}$ and $\underline{C}oL_{cap}$, but $\underline{C}oL_{ope}$ and $\underline{C}oL_{cap}$ themselves depend asymmetrically on lamp performance and cost.

This can be seen graphically in Figure 5, which plots $\underline{C}oL_{cap}$ vs $\underline{C}oL_{ope}$ for various traditional and solid-state lighting technologies. From Equations (9) and (10), we see that increases in luminous efficacy (increases in performance), cause both to decrease, and so cause movement approximately diagonally down and to the left in Figure 5. But decreases in lamp cost ($\$_W$, normalized to input power to the lamp) cause only $\underline{C}oL_{cap}$ to decrease, and so cause movement vertically down in Figure 5.

B. Traditional Lighting: 2001

Traditional lighting is dominated by three technologies: incandescent, fluorescent and HID. These technologies, in turn, are composed of a number of lamp types, each with its own luminous efficacy (hence operating cost of light), as well as purchase cost and lifetime (hence capital cost of light). To provide an orientation to the costs of these various lamp types, Figure 5 plots their 2001 values as the red, blue and green circles, respectively.

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[10] We use the standard rule-of-thumb that a typical 1 klm lamp (equivalent to a 60W incandescent bulb) takes 4 minutes to change at a labor rate of $15/hr.

[11] Note that we assume a cut-off lifetime of 20 kh for amortizing the purchase (but not the labor) cost. The reason is that we wish to define a performance metric that can be used to compare consumer preferences for SSL and traditional lamps. A lifetime of 20 kh, assuming a relatively intensive use of 12 hrs/day, is equivalent to requiring economic payback in ~4.5 years, somewhat longer than the 2-3 year time horizon of many consumers, but much shorter than the ~11 years associated with the full 50 kh lifetime of current SSL lamps.

Consider incandescent lighting, represented by the red circles. Its market-weighted equivalent luminous efficacy is quite low (16 lm/W), so its operating cost is relatively high. Delivering power to light bulbs is relatively cheap (a lamp cost of about 2¢ per input Watt), but because a light bulb's luminous efficacy is so low and its lifetime so short (~2.5 kh), its capital cost amortized over the life of the lamp ends up being rather high.

To enable a comparison of incandescents to other technologies, the red curve drawn through the largest red circle represents a curve of constant ownership cost of light. Points on the red curve, but toward the upper left, have higher capital cost but lower operating cost. Points on the curve, but toward the bottom right, have higher operating cost but lower capital cost. But all points on the curve have the same ownership cost of light as that of the dominant incandescent lamp.

Now consider fluorescent and HID lighting, represented by the blue and green circles, respectively. Their equivalent luminous efficacies are higher (69 and 72 lm/W, respectively), so they are lower in operating cost (further to the left in Figure 5) than incandescents. However, delivering power to fluorescent and HID lamps is more expensive (about 6-10¢ per input Watt), in part because these lamps are much more sophisticated. But, because their luminous efficacies are so much greater and their lifetimes so much longer (17-19 kh), they are lower in capital cost, amortized over the life of the lamp, compared to incandescents.

Just as for incandescents, to enable a comparison of fluorescents and HID to other technologies, the blue and green curves represent, respectively, their constant ownership costs of light.

Interestingly, note that for traditional lighting, the capital cost of light is more than a factor of 6 lower than the operating cost of light – most of the data points lie below a line offset downwards on the log-log plot of Figure 5 by a factor of 6. In essence, this means, consistent with intuition, that lighting is a true "energy service," for which the dominant ownership cost is due to consumption of energy: the capital cost of the light is only a small part (<1/6) of the ownership cost of light.

C. SSL: Past and Possible-Future Trajectories

Let us now consider how SSL compares to these traditional lighting sources. Figure 5 also shows data for SSL lamps for the last five years, drawn from state-of-the-art commercial devices driven fairly hard so that capital and ownership costs are low.

One can see that much of the progress from 2004 to 2009 has been vertically downward. That is, much of the progress has been in reducing power-sinking cost (7.1x) rather than in increasing luminous efficacy (3.4x). In fact, that progress enabled the capital cost in 2008.5 to be, for the first time, lower than the operating cost, and for the ownership cost to dip below that of incandescents.

If the economics of SSL is ultimately similar to that of traditional lighting, power-sinking cost has about a factor of 5.8x further to go before the capital cost reaches 1/6 of the operating cost; at that point the ratio is so low there is not much incentive to to decrease it further. Moreover, as indicated by the small black 2008.5 data point corresponding to a 1mm^2 device operating at 1.5A, power-sinking cost is actually within a factor 2.3x of achieving a capital-to-operating-cost ratio of 1/6, albeit at a reduced luminous efficacy.

In contrast, luminous efficacy has a much larger factor of 4.6x further to go before it reaches the potential-future η_L = 268 lm/W associated with the RGB approach discussed in Section IV.C. Moreover, for the black 2008.5 data point corresponding to a 1mm^2 device operating at 1.5A, luminous efficacy has, because of droop, a factor 12.2x further to go.

Thus, much of the remaining progress for SSL to reach and surpass the performance of fluorescent and HID lamps must mainly be diagonally down and to the left in Figure 5 – in other words, *to increase luminous efficacy (while maintaining low power-sinking cost) rather than to decrease power-sinking cost (while maintaining high luminous efficacy)*. These are the potential-future improvements in luminous efficacy discussed in Section IV. Indeed, for the potential-future SSL points plotted in Figure 5, we have simply assumed power-sinking costs that enable the ratio of SSL's operating to capital costs to be exactly 6.

We note that the 2.3x remaining improvement in power-sinking cost, though non-trivial, can come both from reduced manufacturing cost as SSL lamps become more mature, as well as from increased power that the lamp can sink (albeit with the challenge of maintaining luminous efficacy). Moreover, as has been noted [32], lowering lamp manufacturing cost while increasing current delivery will be greatly facilitated as power-to-light conversion efficiency improves: as the fraction of input power that becomes heat diminishes, thermal management and lamp design may become simpler and easier, and chip sizes may become smaller [65].

Indeed, there appears to be, in the long-term, much headroom for decreases in power-sinking cost beyond those required to achieve a capital-to-operating cost ratio of 1/6. One might thus envision a future in which additional functionality, such as those which would make lighting "smart" [66], are added even while maintaining a capital to operating cost ratio of 1/6 or less.

D. SSL: Roadmap Report Card

From the previous discussion in Sections V.A to V.C, equivalent cost of light can be thought of as a figure-of-merit for comparing lamp technologies. To make these comparisons, between SSL and traditional lamp technologies but also between SSL lamp technologies over time, we show, in Figure 6, the evolution of SSL lamp equivalent cost of light.

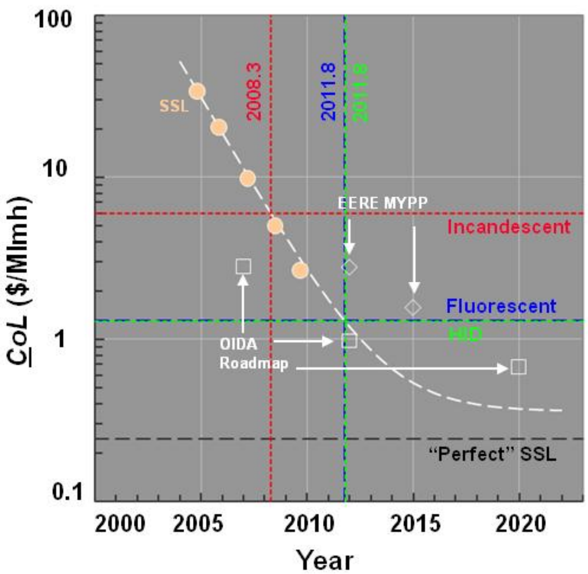

Figure 6. Evolution of SSL Equivalent Cost of Light. Solid tan-colored data points are from the 2004-2009 state-of—the-art commercial devices listed in Table 2, with *CoL* calculated assuming equivalent R_a = 85 and *CCT* = 3,800K luminous efficacies. The white curved line through the data points is an exponential fit with a 1.95-year time constant and a saturation *CoL* corresponding to the RGB improvements of Section IV.C. The colored horizontal lines represent the 6.0 and 1.3 \$/Mlmh equivalent costs of light for incandescent and fluorescent/HID lamps in 2001. The colored vertical dashed lines represent the years at which SSL lamps achieved, or might be projected to achieve, parity with traditional lamps. The white squares are from the OIDA 2002 roadmap [3]; the white diamonds are from the EERE multi-year program plan [8].

From this evolution, one sees that in ~2008 the SSL lamp equivalent cost of light became less than that of incandescent lamps. That was the year, in principle, in which a transition from incandescent lamps to SSL lamps might have begun. Although this transition has started, it will likely be slowed by three factors.

First, there has been the parallel development of compact fluorescent lamps with low enough *CCT* and high enough R_a to be competitive with incandescent lamps. Because the cost of light of these compact fluorescent lamps is lower even than that of SSL lamps, we are seeing now a transition from incandescent to compact fluorescent lamps that is bypassing what otherwise might have been an early transition from incandescent to SSL lamps.

Second, retrofitting lamps of one technology into luminaires and systems designed for another technology entails additional costs. Compact fluorescent lamps, designed for retrofit into incandescent lamp (bulb) sockets, have a roughly 3x higher capital cost of light than that of standard linear fluorescent tube lamps. One anticipates a similarly higher cost for SSL lamp retrofits, even with significant manufacturing volumes.

Third, we have, throughout this paper, neglected luminaires and systems, which also enter into the capital cost of light. For traditional lighting, this capital cost is commonly estimated to be comparable to the capital cost associated with the lamps themselves. For SSL, these luminaire and system costs are currently much higher, although one can anticipate they will decrease rapidly in the coming years.

Also from this evolution, one sees that ~2012 is the year in which SSL lamp cost of light, if it continues to decrease at its past-several-year rate, will reach parity with that of fluoresescent and HID lamps. This is the year, in principle, in which a transition from fluorescent and HID lamps to SSL lamps becomes economical. In the absence of any other competitors, one can anticipate that this will indeed happen, although, as discussed above for incandescents, it will depend heavily on the co-development of, and decreased capital cost associated with, luminaires and systems.

Note that the SSL lamp progress plotted in Figure 6 is significant and presents a sense of inevitability for the eventual displacement of traditional lighting by SSL. This is particularly so in light of the rough alignment between the curved white line, which projects future progress as an exponential fit to past progress, with targets from various roadmaps.

On the one hand, that progress is somewhat slower than was outlined in the relatively aggressive 2002 Optoelectronics Industry Association roadmap [3], which assumed large (and earlier) national and international investments [67] in basic and applied SSL research and development. On the other hand, that progress is somewhat faster than outlined in the more conservative U.S. Department of Energy multi-year program plan (EERE MYPP) [8].

In view of the improvements to SSL technology that have already been demonstrated in research laboratories, and that will be incorporated into coming generations of commercial devices, we share this optimistic sense of inevitability. We are much less certain, however, about the continued improvement of SSL technology beyond that necessary to compete with traditional lighting. The challenges outlined in Sections IV.B and IV.C, associated with achieving luminous efficacies and costs of light approaching their maximal potential, are daunting.

VI. SUMMARY OF KEY POINTS

We close by summarizing our key points.

First, within the current framework for calculating R_a, a "perfect" 100%-efficient SSL with a R_a of 85 and *CCT* of 3,800K would have a luminous efficacy of 400 lm/W. The characteristics of this ideal SSL light source are: center wavelengths at B 459, G 535, Y 573 and R 614 nm, with power fractions of B 0.18, G 0.25, Y 0.22 and R 0.36. Within the current framework for measuring color-rendering quality, the narrower the spectral emission the better. This is particularly the case in the red, so as to avoid spillover of power into the deep red, where the human visual system is less sensitive. Indeed, the optimum red is far from the deep red, and could more accurately be termed orange-red.

Second, a simple polynomial expansion can be used to estimate the luminous efficacy of radiation of "perfect" 100%-efficient SSL at other R_a's and *CCT*s. The ratio between the actual and this maximal luminous efficacy of radiation can be thought of as an effective lamp efficiency that can be used to compare light sources having different R_a's and *CCT*s.

Third, the mid-2009 state-of-the-art in commercial warm-white solid-state lighting, driven at the high currents that minimize the ownership cost of light, has a lamp luminous efficacy of roughly η_L = 58 lm/W. Relative to the K_{max} = 413 lm/W maximal luminous efficacy of radiation at its R_a (85) and *CCT* (3045K), it is thus only about 14% efficient. That efficiency is consistent with multiplicative efficiencies of: blue pump ε_B = 33%, phosphor+package ε_P = 54%, and spectral match to the human visual system ε_S = 78%.

Fourth, one can estimate the headroom available for various kinds of improvements to the current state-of-the-art. Improving the blue LED can give a factor of 2.2x; such improvements are challenging, but appear within reach. Improving the phosphors and package can give an additional improvement of 1.7x or, alternatively, replacing the green and red phosphors with green and red LEDs can give 2.2x. Such improvements are challenging and will require much more research. Of particular importance is the development of a high-efficiency narrow-linewidth phosphor or LED centered around 614 nm.

Fifth, most of SSL's progress the past five years (about a factor of 7.1x) has been in reducing lamp cost (when expressed in units of $ per unit input power to the lamp). There is still more progress to be made here, but soon SSL will reach a capital to operating cost ratio of 1/6, and there will be less incentive to decrease that ratio further. In contrast, less of SSL's progress these past three years (about a factor of 3.4x) has been in luminous efficacy. So there is more progress to be made here.

Six, 2012 is a key year, as this is when, extrapolating from current rates of technology improvement, SSL will surpass traditional fluorescent and HID lighting in terms of equivalent cost of light. This is the year when the transition from traditional to solid-state lighting can be envisioned to begin. The transition is sure to be gradual, however, as other costs not considered here, particularly those associated with luminaires and systems, must also evolve.

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				Traditional			R_BG_BB							RGB	RYGB
				Past			Past and Present SSL					Future		Future	Perfect
			Units	2001 Incandescents	2001 Fluorescents	2001 HID	2004.8	2005.8	2007.2	2008.5	2009.7	Improved Blue LED	Improved Phosphors + Packaging	Phosphors replaced by LEDs	"Perfect" RYGB
Blue	LED efficiencies after loss channels	Blue LED									0.33	0.73	0.73	0.73	1.00
		Joule									0.85	0.90	0.90	0.90	1.00
		Internal non-radiative at low power									0.70	0.90	0.90	0.90	1.00
		Droop at high power									0.70	1.00	1.00	1.00	1.00
		Unextracted light									0.80	0.90	0.90	0.90	1.00
		Phosphor and Package									0.80	0.80	0.95	0.95	
		Scattering & absorption									0.80	0.80	0.95	0.95	
	Source properties	Power fraction of white									0.09	0.09	0.21	0.21	0.18
		Luminous efficacy of radiation	lm/W_o								19	19	35	35	41
		Lumen fraction of white									0.0052	0.0052	0.0200	0.0200	0.0180
		Wavelength	nm								440	440	456	456	459
		Wavelength FWHM	nm								24.0	24.0	9.7	9.7	1.0
Green	LED efficiencies after loss channels	Green LED												0.729	0.000
		Joule												0.900	
		Internal non-radiative low power												0.900	
		Droop at high power												1.000	
		Unextracted light												0.900	
	Phosphor and package efficiencies after loss channels	Phosphor and Package									0.59	0.59	0.75	0.95	1.00
		Internal non-radiative									0.90	0.90	0.95		
		Stokes deficit									0.82	0.82	0.83		
		Scattering & absorption									0.80	0.80	0.95	0.95	
	Source properties	Power fraction of white									0.26	0.26	0.46	0.46	0.25
		Luminous efficacy of radiation	lm/W_o								480	480	577	577	583
		Lumen fraction of white									0.383	0.383	0.710	0.710	0.367
		Wavelength	nm								538	538	548	548	535
		Wavelength FWHM	nm								75.0	75.0	50.0	50.0	1.0
Yellow	LED efficiencies after loss channels	Yellow LED													1.000
	Source properties	Power fraction of white													0.22
		Luminous efficacy of radiation	lm/W_o												631
		Lumen fraction of white													0.338
		Wavelength	nm												573
		Wavelength FWHM	nm												1.0
Red	LED efficiencies after loss channels	Red LED												0.729	1.000
		Joule												0.900	
		Internal non-radiative at low power												0.900	
		Droop at high power												1.000	
		Unextracted light												0.900	
	Phosphor and package efficiencies after loss channels	Phosphor and Package									0.51	0.51	0.67	0.95	1.00
		Internal non-radiative									0.90	0.90	0.95	1.00	
		Stokes deficit									0.71	0.71	0.74	1.00	
		Scattering & absorption									0.80	0.80	0.95	0.95	
	Source properties	Power fraction of white									0.65	0.65	0.33	0.33	0.36
		Luminous efficacy of radiation	lm/W_o								304	304	310	310	312
		Lumen fraction of white									0.612	0.612	0.270	0.270	0.277
		Wavelength	nm								615	615	614	614	614
		Wavelength FWHM	nm								95.0	95.0	17.6	17.6	1.0
White	Source properties	CRI (R_a)		100	68	41	85	85	85	85	85	85	85	85	85
		CRI (R_9)									28	28	21	21	21
		CCT	K	2768	4266	3047	3200	3200	3200	3100	3045	3045	3800	3800	3800
	Luminous efficacies	Lamp (η_L)	lm/W	14	71	93	17	17	22	30	58	128	211	268	400
		Equivalent lamp at *R*a 85 *CCT* 3,800K ($\underline{\eta}_L$)	lm/W	16	69	72	16	16	21	29	56.5	124	211	268	400
	Luminous efficacies of radiation	Luminous efficacy of radiation (K)	lm/W								323	323	387	387	400
		Maximal luminous efficacy of radiation at *CRI* and *CCT* (K_{max})	lm/W	361	414	518	411	411	411	412	413	413	400	400	400
	Efficiencies	Blue LED pump (ε_B)									0.33	0.73	0.73	0.73	1.00
		Phosphor & package (ε_P)									0.54	0.54	0.75	0.95	1.00
		Spectral (ε_S)									0.78	0.78	0.97	0.97	1.00
		White lamp (ε_L)		0.040	0.17	0.18	0.04	0.04	0.05	0.07	0.14	0.31	0.53	0.67	1.00
	Equivalent costs at R_a=85 CCT=3,800K	Lamp cost per input W ($\$_W$)	$/W	0.02	0.06	0.10	9.42	4.97	2.50	1.23	1.33	0.23	0.19	0.17	0.12
		Lamp cost per output klm ($\$_\Phi$)	$/klm	1.07	0.78	1.10	563.50	297.50	115.00	41.47	22.77	1.83	0.91	0.63	0.29
		Lifetime (τ)	kh	2.5	18.2	17.3	50	50	50	50	50	50	50	50	50
		Capital cost of light ($\underline{C}oL_{cap}$)	$/Mlmh	0.78	0.10	0.14	28.95	15.29	5.92	2.16	1.20	0.11	0.07	0.05	0.03
		Operating cost of light ($\underline{C}oL_{ope}$)	$/Mlmh	5.18	1.21	1.15	5.09	5.09	3.92	2.87	1.47	0.67	0.39	0.31	0.21
		$\underline{C}oL_{ope}/\underline{C}oL_{cap}$		6.60	12.17	8.20	0.18	0.33	0.66	1.33	1.22	6.00	6.00	6.00	6.00
		Ownership cost of light ($\underline{C}oL$)	$/Mlmh	5.97	1.31	1.29	34.04	20.38	9.84	5.03	2.66	0.78	0.46	0.36	0.24

Table 2. Performance and cost characteristics of the past and potential-future traditional and solid-state lighting technologies discussed and plotted in this article. Traditional lamp data taken from market-weighted (or lighting-consumption-weighted) aggregate averages of Navigant's comprehensive 2001 survey [2]. SSL lamp data taken from Philips Lumileds Luxeon K2 and Rebel specification sheets [1, 10-11], and from the Future Electronics website (http://www.futureelectronics.com) prices in small-to-medium (≤1000) lots. All dates, here and throughout the paper, are decimal (e.g., 2008.5 = June, 2008).

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