Theoretical maximum efficacy and color rendering assessment of energy-efficient light sources

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Roughly 22% of the electricity generated in the USA is consumed by lighting applications. If all conventional white-light fixtures in the world were converted to energy-efficient light sources, energy consumption could be reduced by approximately 1000 $TWHyr^{-1}$, the equivalent of about 230 typical 500-MW coal plants, reducing greenhouse gas emission by about 200 million tons. Market penetration of energy-efficient lighting has been poor, despite these potential benefits because, predominantly, of the low color quality of the light sources. Color Rendering Index (CRI), is currently adapted to include efficient light sources with poor spectral content, such as LED or fluorescent lamps. CRI has a tradeoff with efficacy (in lm/W): a shift to higher lamp efficacy implies spectral narrowing towards 555nm, (the peak of the luminosity function); but that reduces the number of colors that it can properly render.

We address here three dominant issues involving efficacy and color quality: (i) Efficacy and CRI in artificial light sources emulating natural illumination, (ii) spectral design and optimization of white LEDs (RGB and phosphor-based), and (iii) a new graphical representation of CRI over the extended set of 1269 Munsell color samples, providing a more complete color performance metric of a light source that does not rely on a single number (such as the current definition of CRI does).

In order to calculate the theoretical limits of efficacy and CRI, we start from a blackbody radiator of a given CCT and gradually reduce the spectral region from the full visible range (380-780 nm, as defined by CIE) by 10nm-thick zones, ultimately to one, centered at 555 nm. For each of these 40,000 restricted blackbody curves, we obtain a Restricted Visible Spectrum (RVS), and the efficacy and the CRI is calculated. Only shown are those spectra that satisfy a user-defined criteria for CRI, efficacy and Δuv (distance from the restricted spectrum to the Planckian locus in the CIE 1960 color space).

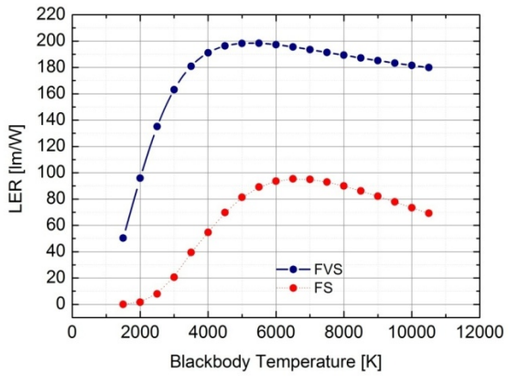


Figure 1: Luminous efficacy of radiation for full-spectrum (FS) and full-visible-spectrum (FVS)

	Efficacy	CRI (Ra)
FS@3000K	21 lm/W	100
FS@5500K	89 lm/W	100
FVS@3000K	163 lm/W	100
FVS@5500K	198 lm/W	100
RVS@3000K	> 163 (**363**)	< 100 (**90.5**)
RVS@5500K	> 198 (**321**)	< 100 (**94.8**)

Table 1: Efficacy and general color-rendering index of a blackbody at 3000K and 5500K obtained by considering three scenarios: full-spectrum (FS), full visible spectrum (FVS), and a restricted visible spectrum (RVS). Bold values represent the best trade-off between efficacy and CRI for a broad-band source trying to emulate natural illumination.

Defining "high color quality" as being CRI>=90 and Δuv<0.0054, results show the theoretical maximum efficacies of 364, 315 and 297 lm/W for 3000, 5500 and 7000 K, respectively. These values compare well against full spectrum or full visible blackbody spectra (depicted in Figure 1.), but good appearance is retained because the missing colors are in regions of low vision sensitivity. Results for 3000K and 5500K lamps, which are popular color temperatures for general lighting, are shown in Table 1 and Table 2.

References:

1. Zhang Lei, Guo Xia, Liang Ting, Gu Xiaoling, Lin Qiao Ming, Shen Guangdi, *Microelectronics Journal*, **38,** 1–6, (2007).
2. Y. Ohno, *Opt. Eng.*, **44**, 111302, (2005).
3. W. Davis and Y. Ohno, in Proc. Sixth International Lighting Research Symposium on Light and Color, Orlando, FL, (2006).

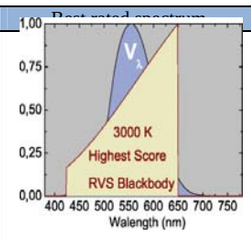
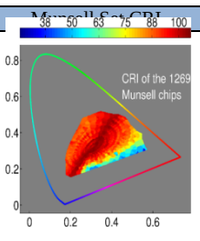
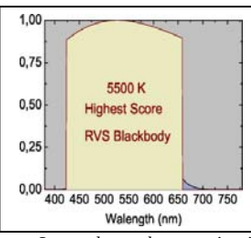
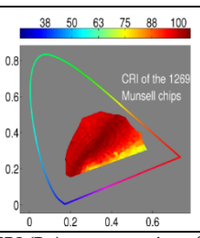
CCT	Target Eff.	Highest Eff.	Highest Ra	Highest Score	Best rated spectrum	Munsell Set CRI
@ 3000 K	364.41 lm/W	Eff:363 lm/W Ra:90.0 S:0.950 Duv:5.31e-3 Wave range: [421,648] nm CCT:3280 K R9: 35.7 R9-12: 75.0	Eff:250 lm/W Ra:99.7 S: 0.856 Duv: 1.67e-4 Wave range: [403,703] nm CCT: 3010 K R9: 98.4 R9-12: 99.2	Eff: 363lm/W Ra:90.5 S:0.951 Duv: 5.37e-3 Wave range: [424,649] nm CCT: 3260 K R9: 39.1 R9-12: 76.0		
@ 5500 K	314.92 lm/W	Eff: 315lm/W Ra:94.4 S:0.972 Duv: 5.37e-3 Wave range: [421,653] nm CCT: 5620 K R9: 56.5 R9-12: 85.7	Eff:262 lm/W Ra:99.2 S:0.916 Duv: 2.11e-3 Wave range: [421,709] nm CCT: 5370 K R9: 96.8 R9-12: 98.4	Eff: 313lm/W Ra:95.4 S:0.975 Duv: 5.31e-3 Wave range: [424,658] nm CCT: 5490K R9: 66.3 R9-12: 88.6		

Table 2: Results for the emulated spectra in terms of highest efficacy, highest Ra, and highest score. Last column shows an intuitive CRI (Ra) representation of how a hypothetical light source showing the spectrum with highest score would render colors over an extended Munsell set.