(Lighting and) Solid-State Lighting: Science, Technology, Economic Perspectives

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Acknowledgements
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Work at Sandia National Laboratories was supported by Sandia’s Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy’s National Security Administration under Contract DE-AC04-94AL85000.

Night arrives between Europe and Africa; digital composite of archived images taken by several Earth-orbiting satellites and ocean-faring ships; courtesy of NASA; http://apod.nasa.gov/apod/ap030324.html
Artificial Lighting and Human Productivity

**Efficiency**

\[ \text{CoL} \ (\$/\text{Mlmh}) = \frac{\text{CoE}}{\eta} \]

- \( \eta \) (lm/W_e)
- \( \text{Luminous efficacy} \)

**Consumption**

\[ 0.72\% = \frac{\text{US}\$440B}{\text{US}\$60T} \]
\[ 6.5\% = \frac{1 \ TW_c}{16 \ TW_c} \]

Tsao and Waide, “The World’s Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents,” to be submitted to LEUKOS
Characteristics of “100%-Efficient” Lighting

CCT = 3,800K
R₉ = Rₐ/4

Calculations based on white LED simulator 5-3 (Y. Ohno, NIST).
Efficiencies of Actual Lighting Technologies

Spectral Power Distribution (W/nm)

Human eye response (lumens/W)

Wavelength (nm)

Efficiencies of Actual Lighting Technologies

- **3.5%-Efficient Incandescent**
  - CCT 3,000K
  - 14 lm/W
  - Courtesy of Lauren Rohwer

- **21%-Efficient Fluorescent**
  - CCT 3,500K
  - 85 lm/W

- **14%-Efficient 58 lm/W SSL Commercial**
  - Warm-White CCT 3,100K
  - Driven at 0.7A

- **100%-Efficient SSL**
  - CCT 3,800K
  - 400 lm/W

All spectra normalized to 1W wallplug power

Human eye response (photopic)
# Anatomy of State-of-Art Commercial SSL

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>14%</td>
</tr>
<tr>
<td>$\eta$</td>
<td>58 lm/W</td>
</tr>
<tr>
<td>CRI</td>
<td>85</td>
</tr>
<tr>
<td>CCT</td>
<td>3,100K</td>
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</table>

**Spectral** 78%

**Phosphor/Package** 54%
- Internal quantum effic: 90%
- Stokes deficit: 76%
- Scattering/absorption: 80%

**Blue LED**
- Joule: 85%
- IQE at low power: 70%
- Droop at high power: 70%
- Light extraction: 80%

Thin-Film Flip Chip (TFFC) schematic courtesy of Jon Wierer

http://bobbymercerbooks.com
Technology Grand Challenges for Luminous Efficacy

1. **Eliminate blue LED droop**
   - Target: 200 A/cm²
   - Equation: $\varepsilon_{\text{IQE}} = \varepsilon_{\text{INJ}} \cdot \frac{Bn}{A + Bn + Cn^2}$

2. **Narrow-linewidth shallow-red color conversion**
   - Fig: Spectral power distribution (W/nm)
   - Fig: Luminous Efficacy (lm/W)
   - Human eye response

3. **Fill in the red-yellow-green gap**
   - Fig: External Quantum Efficiency
   - Fig: Peak Wavelength (nm)
   -Courtesy of M. Krames, Philips-Lumileds

What about Cost of Light?

\[
\text{CoL}_{\text{cap}} \text{ is already } \sim \frac{\text{CoL}_{\text{ope}}}{6}, \text{ so } \eta \text{ is the key}
\]

\[
\text{CoL}_{\text{ope}} = \frac{\text{CoE}}{\eta} \, ($/\text{Mlmh})
\]

2012 may be the beginning of “the transition”


CoL_{cap} is already \sim CoL_{ope}/6, so \eta is the key
