**Motivation**—Solid-state lighting (SSL) 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 broad-area illuminator. Moreover, SSL has considerable headroom for continued evolution even after this initial displacement. We have conducted a high-level analysis of solid-state lighting, with an emphasis on white lighting suitable for general illumination. We have examined 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.

**Accomplishment**—

**Human Factors:** With respect to human factors, we considered 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 \(R_a\); and correlated color temperature \(CCT\) (with the units Kelvin, 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. Indeed, we have found, through simulations, that the relationship between \(K\), \(R_a\) and \(CCT\) can be described by the equation:

\[
K(R_a, CCT) = 400 \text{ lm/W} \\
- 0.876 (R_a - 85) \\
- 0.0179 (CCT - 3800K) + 2.08 \times 10^{-7} (CCT - 3800K)^2
\]

**Technology:** With respect to technology, we analyzed in detail the current SSL state-of-the-art and, using the above relationship, determined both its overall efficiency (14%) as well as the sub-efficiencies associated with its component pieces: blue LED (33%), phosphor+package (54%) and spectral (78%). An understanding of these sub-efficiencies enables us to assess how improvements in the various component pieces translate to improvement of the overall SSL lamp.

**Economics:** With respect to economics, we analyzed the overall ownership cost of light (including both operating and capital costs), and assessed past and potential-future trajectories for SSL. From advances already demonstrated in the research laboratory, we anticipate that 2012 will be the year in which the ownership cost of light of SSL will just dip below that of fluorescent and high-intensity discharge lighting, initiating a massive transformation to SSL. However, continuing this trajectory to so-called “ultra-high” (>70%) efficiencies will require advances of a significantly more challenging nature, including the development of narrow-linewidth orange-red phosphors or LEDs, and very high efficiency blue LEDs or laser diodes driven at very high currents.

**Significance**—Through an integrated analysis combining human factors, technology and economics, we have mapped past and possible-future trajectories for SSL. These trajectories enable a quantitative understanding (a) of how improvements in various SSL component pieces translate to improvement of SSL as a whole, and (b) of the relative importance of these various improvements.
Figure 1.

**Top:** A lamp-efficiency ($\varepsilon_L = \varepsilon_B \cdot \varepsilon_P \cdot \varepsilon_S$) progress line illustrating the various classes of potential improvements in SSL. 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). We have deliberately chosen data points for solid-state white lamps that correspond to commercial products, have a high Ra and, most importantly, are driven fairly hard (operated at high power) so as to have lower capital and ownership costs of light.

**Middle:** Potential-future lamps corresponding to three classes of improvements. The first two of these classes are associated with the current RBGB 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.

**Bottom:** Power spectra with center wavelengths labeled.