

# The Cost of Light

## An Analysis of the Cost of Light for Solid State Lighting

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### 1. Background

LEDs, the key component in solid-state lighting systems, have increased in performance and decreased in price for several decades. As a result of this improvement, LEDs have successfully penetrated a variety of markets including signage, automotive, personal lighting and transportation. To date, these markets are primarily colored light sources but white LEDs are also on a rapid and inexorable march towards other applications, including general illumination.

The crossover point when the initial cost of an solid-state lighting system is equal to or less than a traditional lighting system has been cited as the 'holy grail' by many in the lighting industry. Some identify this confluence as the point at which solid-state lighting is finally viable for general illumination. This is shortsighted because the initial cost of a system is but one element of the cost of light. The true Cost of Light incorporates lifetime and operations costs as well as the initial cost. By this measure, as we will show, LED-based illumination is becoming economically viable for many applications today.

### 2. Purpose

This is an exercise in prediction. Beginning several years ago with some back-of-the-envelope calculations, this ongoing analysis has been refined and improved to provide a succinct picture of emerging trends in the Cost of Light for both traditional light sources and solid-state light sources. This paper details the data gathering process and the assumptions in the Cost of Light estimates.

$$\frac{1}{\text{lumens}} \left[ \left( \frac{\text{lamp\_cost} + \text{labor\_cost}}{\text{lifetime}} \right) + \text{power} * \text{energy\_cost} \right]$$

Equation 1: The Cost of Light formulation<sup>1</sup>

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<sup>1</sup> IES Lighting Handbook, 9<sup>th</sup> Edition. Lighting Economics, Section 25-1.

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The Cost of Light formulation, shown in Equation 1, is an accepted industry definition of the operating or lifetime cost of a light source. It takes six criteria into account:

- energy costs
- power consumption
- labor costs
- lamp costs
- lifetime
- light output

The result is a metric whose dimensions are dollars per million-lumen-hours. This is similar to another common cost metric that people are familiar with: the cost of energy which is expressed in dollars per kilowatt-hour.

In this document data sources and assumptions are revealed and examined. A companion annotated spreadsheet model is used to store the data, perform the calculations and plot the results. Also, a substantive list and discussion of additional factors that could affect the Cost of Light, but are not incorporated into the formulation, are also presented. Three specific regions show the current Cost of Light for the dominant lighting technologies: incandescent, halogen and fluorescent. Forward-looking data points are based on industry projections of performance and pricing improvements in LED devices.

### 3. Historical Performance and Pricing Trends in Lighting

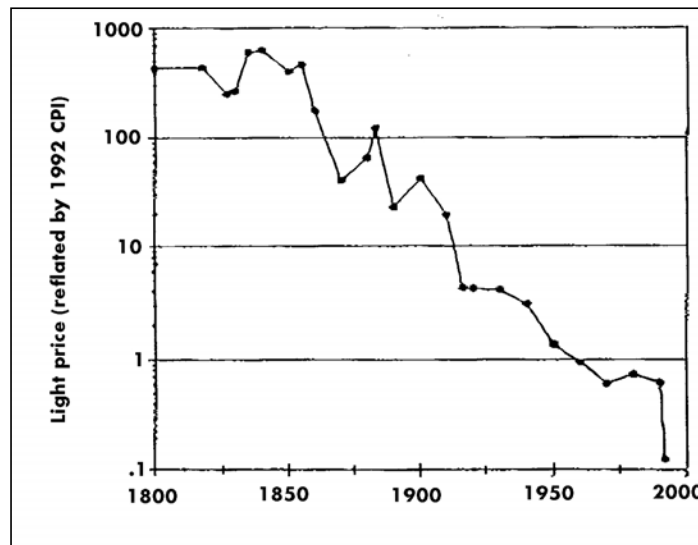


Figure 2. The cost of light as a service is shown in dollars per lumen for the last 200 years. (From Nordhaus)

From Nordhaus' economic study of the cost of light as a service, this chart shows two centuries of lighting history and associated costs.<sup>2</sup> Nordhaus used lighting as a case study to show that traditional measures of consumer prices do not reflect the true cost of

<sup>2</sup> Nordhaus, William D., "Do real-output and real-wage measures capture reality? The history of light suggests not". *The Economics of New Goods*. p29-70, 1997.

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services. The service was the amount of light delivered to the consumer and related that to real wages required to purchase an amount of light. Nordhaus represented the cost of light in dollars-per-lumen since he focused on the purchase of light (lumens) versus operational costs. His work accounted for several lighting technologies including wood, oil, candles, gas, and electricity. The overall trend is clear; a significant decrease in the upfront cost of light. The precipitous drop in the latter part of the 20<sup>th</sup> century is thought to be due to increasing competition, decreasing margins and the advent of mass merchandisers and big box retailers such as Wal-Mart, and DIY stores.<sup>3</sup>

### 4. LED Trends - Efficacy and Bucks for Flux

Figure 2, adapted from Lumileds, illustrates the evolution of lighting technology efficacy over time.<sup>4</sup> It shows the overall trends in traditional lighting technologies and the rapid progress and forecasted developments in LEDs<sup>5</sup>. Note that the efficacy of extant technologies has leveled off. They are not improving in efficacy very much, if at all. Theoretical limits for white LED efficacies are thought to be in the 200-220 lumens per watt range. Most importantly though, for this metric, is that the available headroom for conversion efficiencies is significant; upwards of 75% in large areas of the visible spectrum<sup>6</sup>.

Even LED improvements will level off at some point but target efficiencies of between 150-200 lpw for white light sources are viewed as practical over the next ten years<sup>7</sup>. This puts LED illumination on par with the most efficient light sources used today.

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<sup>3</sup> W. Nordhaus, Personal Conversation. 2001.

<sup>4</sup> Courtesy Lumileds. The chart itself has evolved over time and this version is current as of this writing (May 2004.)

<sup>5</sup>The term 'efficacy' is used because lumen is a photometric and not a radiometric measure. Also, efficacy, in this case, is lumens per watt whereas true efficiency measures are typically dimensionless. E.g. Watts out per Watts in.

<sup>6</sup> Craford, George and Mike Krames, Lumileds. Presentations to DARPA and

<sup>7</sup> OIDA Technology Roadmap, 2002. Efficacies are projected at 150lpw in 2012.

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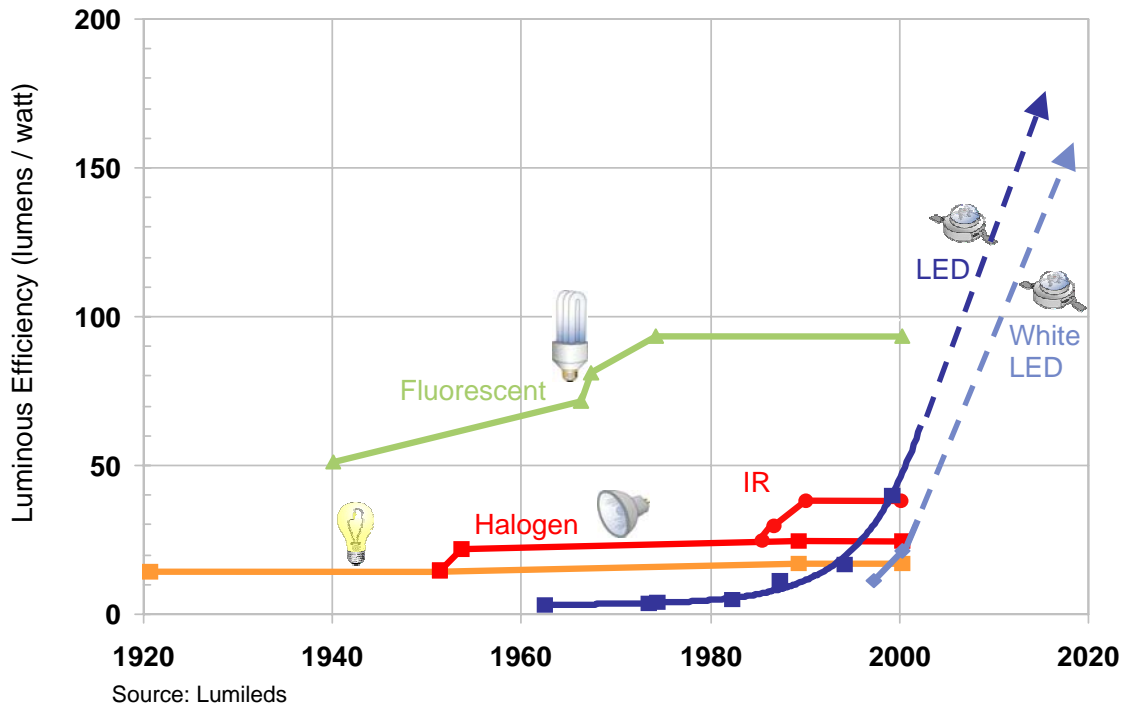


Figure 3. The efficacy of most lighting technologies has leveled off while LEDs continue to improve.

In the next chart in Figure 4, a remarkable set of historical data is shown along with some projections. These are dramatic exponential improvements in LED performance and costs. This chart has a semi-log scale on the Y-axis, which provides a straight line plotting of geometric or exponential change. Log scales are useful to show data over a very wide range, especially at small values. Also, importantly, a percentage difference is represented by the same linear displacement throughout a log plot.

Figure 4, also based on data from Agilent data, shows the improvements in both pricing and performance for LEDs over the past forty years. The chart illustrates red LED technology in particular but even more rapid progress has been made in other colors, including white over the past decade. The efficacy curves will begin to level off over the next several years and lamp or package outputs will be the important measure of performance. Continually increasing flux from a package argues for large LEDs but the point is that people will be buying flux per dollar, not necessarily efficiency.

In this chart the flux-per-package trendline shows a good fit to the data with an  $R^2$  fit of 0.9791 and illustrates the progress of LED flux outputs and pricing trends.

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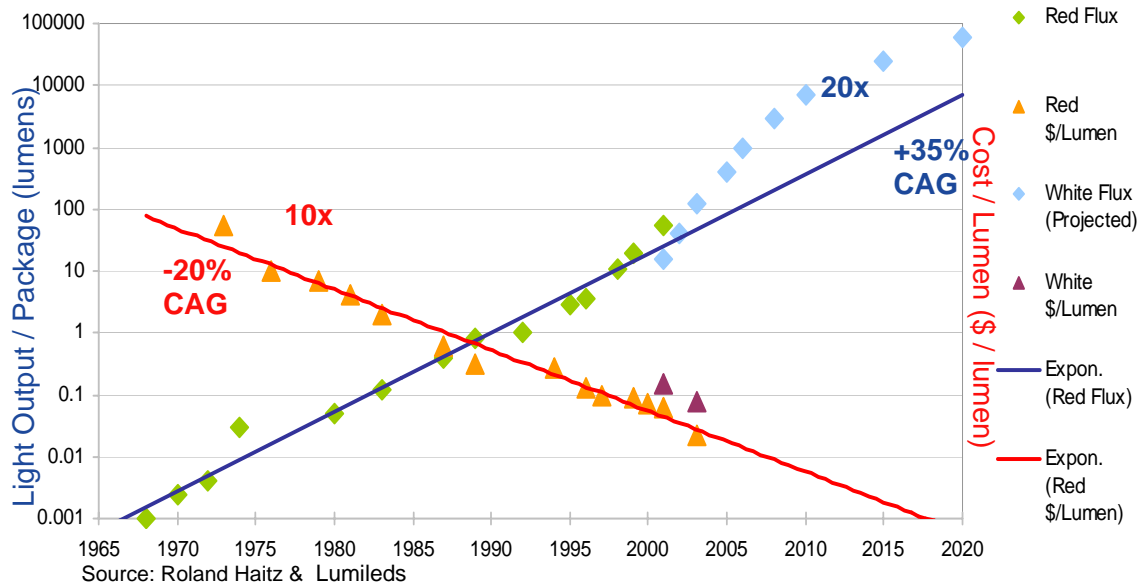


Figure 4. Improvements in LED output and pricing have been substantial over several decades.

The performance improvement trend is equivalent to a compound annual growth rate (CAGR) of 35 percent. Based on the fit of the exponential equation, the per-decade improvement is 19.2 which is close to the 20x cited in the Lumileds data.<sup>8</sup> Over a several decades the difference between 20 and 19.2 will matter, but for a single decade, i.e. the next ten years, it is a reasonable value to track improvement.

In previous years, this same graph has depicted a 30x per decade improvement in flux per package<sup>9</sup>. Lumileds has explained that they and Roland Haitz, a retired scientist who has been tracking this data while working with Hewlett-Packard, Agilent and Lumileds for many years, has re-plotted the data with an eye towards general industry data as well as being more conservative on the projections.<sup>10</sup>

These trends are likely to continue as levels of investment in LEDs continue and grow. Current laboratory research has revealed very promising results that will manifest itself in new generations of products over the coming years. These improvements are in a variety of areas including material compounds, dopants, geometries, processing tools and more. One large manufacturer of LEDs, Cree Semiconductor, has announced 74 lpw LED packages that will be shipping in 2004. Several others including Nichia and Lumileds offer white LEDs in the 35-40 lpw range.

<sup>8</sup> Since the trendline equation is an excellent fit to the data, the CAGR can be determined directly from the trendline equation by solving  $ce^{b(x+1)} / ce^{bx}$ . This is easily solved from the exponential but as an example, the improvement factor from 1970 to 2010 is over 100,000.

<sup>9</sup> For example: Intertech Light Emitting Diodes 2000 and Light Emitting Diodes 2001 Conferences.

<sup>10</sup> Personal conversation. Keith Scott, Marketing Development Manager, Lumileds, May 21, 2004.

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### 4.1 Intersection

A Department of Energy study from 2001 projected that LED lamp prices will drop from around 275 dollars per kilo-lumen (\$/klm) in 2000 to below \$50/klm in 2010<sup>11</sup>. However, volume pricing of high-flux-emitters mounted on PCBs are already priced in the range of \$100-\$200 per kilo-lumen today. If we look at price halving trends<sup>12</sup> using the Agilent data then the LED pricing will be down 50% within 3 years. However, we need to consider a complete fixture in any comparison and not simply the LEDs, which will constitute a decreasing fraction of system costs.

Figures from the ADL study indicate that the white light market is increasing at the rate of 0.25 Tera-lumens per year. The replacement lumen market is about 33% per year including replacements (27%), new construction (1%) and retrofits (5%). The study estimates that only 1% of floorspace per decade undergoes lighting retrofits purely for energy savings.

### 5. The True Cost of Light

An incandescent bulb may cost a quarter but will use more than ten times that in energy costs over its relatively short life. According to General Electric's Lighting group, the cost of the lamp can be as little as 4% of the total cost of light<sup>13</sup>. For example, a 100W light bulb x 800 hour lifetime x \$0.10/KWh energy costs = \$8.00 in energy costs. That light bulb today costs about \$0.24 and so the operating energy costs over the lifetime of the lamp are over 30 times greater than the initial cost of the lamp itself<sup>14</sup>. The cost of this light bulb is nearly insignificant compared to the energy costs and, in commercial establishments; the replacement cost can be high as well.

So what is the real cost of light then? The Cost of Light includes the following:

- **Performance.** The light output in Lumens as specified by the manufacturer.
- **Cost.** The upfront cost in dollars. This is the full retail or list price of a lighting product.
- **Replacement cost.** The labor cost to replace a lamp in dollars.
- **Lifetime.** The useful life in thousands of hours.
- **Power.** Power consumption during operation. Measured in Watts.
- **Energy Costs.** Measured in dollars per kilowatt-hour. According to the DOE, the national average for residential use is \$0.085. US residential electricity rates range from \$0.05/kWh to \$0.156/kWh. In general, electricity rates are divided into three major categories: residential, commercial and industrial. Over all sectors, rates were about \$0.72/kWh in 2002. However, electricity prices in New York, California and New England are substantially higher. Examples include New York at 11.29 cent per kWhr, Massachusetts at 10.18 cents/kWhr to 12.5

<sup>11</sup> Energy Savings Potential of Solid State Lighting in General Lighting Applications. Prepared by Arthur D. Little for US DOE. April 2001.

<sup>12</sup> 10x reduction per decade =  $(0.1)^{0.1} - 1 = -20.5\%$  per year. Time to halve =  $\log(0.5)/\log(1-i) = 3.1$  yrs.

<sup>13</sup> <http://www.gelighting.com/eu/specoem/costoflight.html>

<sup>14</sup> Using Phillips A-Lamp Model 100 A/W 120V. Pricing is from Home Depot, May 2004.

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cents per kWhr in California. It is not clear whether the average US cost of electricity reflects an average of state figures or is population based.<sup>15</sup>

### 5.1 Assumptions

LED costs are based on list prices for a commercially available fixture. For other lighting sources, retail prices or lamps at high-volume mass merchandisers such as Home Depot and drug stores are used. All data on lifetime on light sources is directly from the manufacturer labels or from catalogs. All data for a particular technology such as incandescent or halogen were taken from a variety of products and the Cost of Light values were averaged to obtain a mean cost for that particular technology. To make the comparisons relevant board-level LED products were used to compare to lamp sources.

The true cost of light can then be calculated as follows<sup>16</sup>:

$$\frac{1}{\text{lumens}} \left[ \left( \frac{\text{lamp\_cost} + \text{labor\_cost}}{\text{lifetime}} \right) + \text{power} * \text{energy\_cost} \right]$$

This equation allows us to use projections of LED trends and present and future cost comparisons between traditional lighting technologies and then the cross-over points when solid state lighting technologies become cost competitive with existing lighting technologies. Note that this particular form does not incorporate the time value of money which would further benefit the comparison to LEDs.

The dimension of this equation is in dollars per million lumen hours. This is closely akin to the metric used for energy: dollars per kilowatt-hour. Thus, instead of a measure of total electrons (energy), you measure photons (light). See the Appendix for details on dimensions and scaling of this metric.

### 5.2 Data Gathering

The data for traditional technologies is using retail pricing of lamps at mass merchandisers and online sources. In the spreadsheet model data is collected and stored to represent all necessary information for the model. This includes manufacturers published data on lumen output, power consumption, lifetime in hours and retail costs. Manufacturers' data from the big three, Philips, Osram Sylvania and GE is confirmed by the Lamp Testing Engineers Conference (LTEC), an industry metrology group, which insures that the three companies perform regular round-robin testing of lamp sources between their photometry laboratories. This insures consistency of testing procedures and test equipment between the large manufacturers of lamp sources.

For each lamp source the following is recorded:

- Date

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<sup>15</sup> [www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html](http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html)

<sup>16</sup> IES Lighting Handbook, 9<sup>th</sup> Edition. Lighting Economics, Section 25-1.

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- Store name
- Location
- Pricing information
- SKU number
- Model number, if available
- Lumen output
- Lifetime
- Power consumption
- Price

In some cases, if the information is not on the packaging, the model number is used and manufacturers' printed or online catalogs are used to determine other required data.



Figure 5. Mass merchandiser example of lamp displays. Home Depot.

In the initial CoL comparisons, from 2000 and 2001, the cost of LED-based light using this metric was in the \$45-\$50 range. Today, using a high-flux LED board of nearly 250 lumens output the Cost of Light has dropped into the \$20 range. This example is a lamp product and not a complete luminaire. However, at Lightfair in May 2003, Color Kinetics introduced the ColorBlaze, a complete RGB light where the CoL is below \$30. This unit includes power supplies and some on-board interface as well and thus reflects a true system cost. Thus the cost for LED-system components and complete fixtures is fast approaching parity and does well when compared to traditional lighting technologies. Remember too, this comparison is for white light and not colored light. When using gels and filters for traditional sources, the economics favor LED-based systems by a wider margin.

Figure 1 illustrates the confluence of LED trends and the cost of light for LED systems. LEDs are the highest cost component of LED lighting systems. Notice too, the inverse relationship with light output and lifetime; if light output or lifetime can be increased these will have the largest effect on the COL measure. As these improve, the CoL will certainly will become asymptotic over time as can be seen in Figure 1. This curve in the timeline chart is a projection incorporating the 40-year trend in LED cost and performance. Based on

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developments we see in the laboratories and clean-rooms of the LED manufacturers we believe that these cost and price trends will continue for at least the next 5-10 years.

For each category of incandescent, halogen and fluorescent lamps, a representative sample of products available at a mass-merchandise were used to calculate a series of averages. For the May 2004 calculations, the data source for pricing was a Home Depot. These prices and products reflect some of the lowest prices available. Additionally, the products available from the home centers are typically not the costlier high quality lamps used by designers. A quick perusal of any of the catalogs from Osram, GE and Philips will show thousands of products spanning a wide range of forms, light output and light quality.

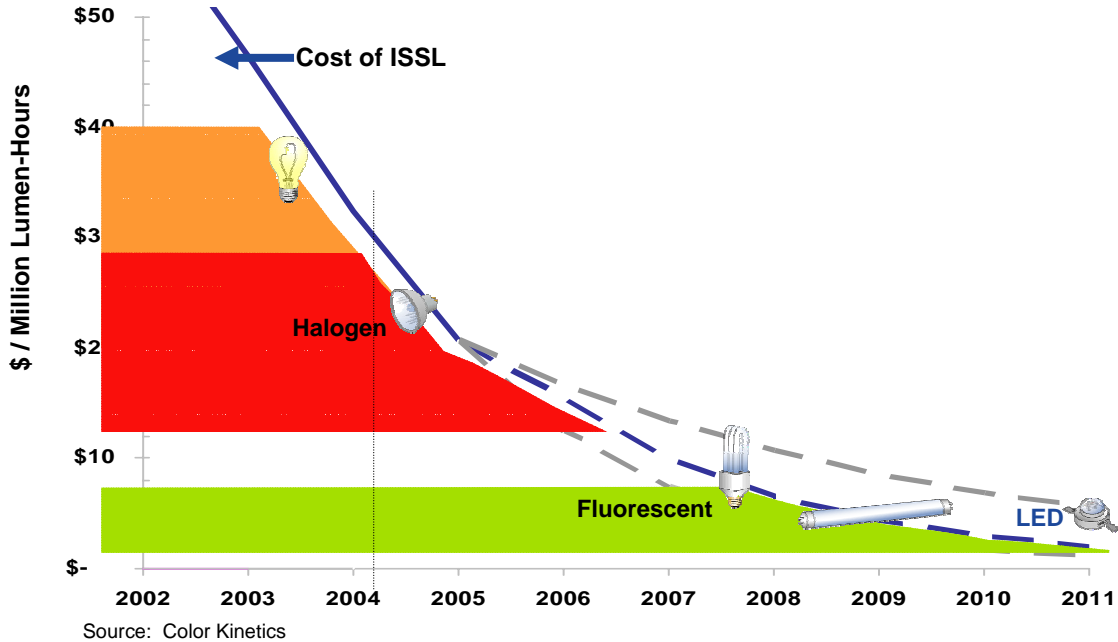
In each of the three lamp categories about a dozen or so lamp sources were used as examples and the average, median and mode of the Cost of Light was calculated. The average was used for the Cost of Light comparisons. In the fluorescent category however, the Cost of Light for compact fluorescent lamps (CFLs) differs from linear fluorescents differed due to their different prices. Additionally, traditional fluorescents incorporate a ballast and have additional labeling requirements. These and other differences meant that there were two regions in the Cost of Light curve for fluorescent sources.

The calculations do not incorporate weighted averages, but we believe the available selection represents the majority of lamps bought at retail. We do not know the ratios of lamp types in purchased volumes. This may be an additional factor to consider in the CoL calculations.

### 5.3 RGB and White

White light can be produced in one of several ways using LEDs. Additive mixing of red, green and blue LEDs will produce white light. Another way is the combination of a blue LED and a phosphor to down convert the light; this is similar, in principle, to the mechanism used by fluorescent sources. Until recently relatively few white LED-based lighting fixtures have been offered on the market. Color Kinetics has demonstrated white light products in April of 2004 at Lightfair but had also showcased a number of prototypes at earlier shows. White LEDs although available, have only recently reached performance and pricing levels where they can be seriously used for a variety of illumination applications. Previously, the high-flux packages were either unavailable or the reported lifetimes were not what was needed for general illumination applications. Now however, 1W devices with 25-35 lumen outputs are available and the price has reduced to the point where they make sense for these applications. Color Kinetics' IntelliWhite series of white light products was introduced in late 2004 and provides.

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The figure above is a snapshot from data in the summer of 2003. It shows a CoL comparison of LED-based lighting with incandescent, halogen and fluorescent technologies. The high CoL for incandescent and halogen sources arise primarily from energy costs.

### 5.4 Sensitivity

We can also use the Cost of Light model to examine the effects of particular assumptions and particular parameter values such as lifetime or energy costs. By changing those values independently of the others we can perform an analysis to determine the importance and effect of that parameter. For example, are energy costs more important than lifetime? Do improvements in output dramatically improve the Cost of Light? Examination of the Cost of Light formulation can give some insight in to some of these effects as well.

Lumen output has the strongest beneficial effect on the Cost of Light. If efficiency improves so that for a given amount of power more light is produced, the Cost of Light can decrease significantly.

For both lifetime and lumen output, as can be seen from the equation, there is an inverse relationship between larger values and the cost of light. This also means that there are diminishing returns, an asymptote, where improvements in those parameters result in little improvement in the Cost of Light. For example, in one analysis when lifetime is greater than 50,000 hours there is little improvement in the Cost of Light. Likewise, light outputs above 1000-1200 lumens result in diminishing returns. Since the Cost of Light is a collection of several parameters however, it is the whole mix that counts.

### 6. Conservative Factors

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Many of the factors in the comparisons are conservative. Listed here are many additional factors whose incorporation into the model could reduce the cost of light for LED system still further.

- **Lifetime.** The Lifetime definition for LEDs is different from traditional lighting sources. For traditional lighting sources, the lifetime is defined to be at the point at which half of the lamps fail. However, LEDs rarely burn out but do reduce in light output over time; this is termed lumen depreciation<sup>17</sup>. Lifetime for LED systems is assumed to be 75,000 hours based on manufacturers' data and this is only to the point when the output is 70% of initial output. The sources can continue to emit a high percentage of initial light output for a significant period after that period of time.<sup>18</sup>
- **Fixture efficiency.** The LED figures are based on a complete fixture<sup>19</sup> whose output has been measured by a third party NIST-traceable laboratory to IES standards. Complete test results and IES files are available for the fixture as well. *The incandescent, halogen and fluorescent figures are for lamps only and not for lamps sources in a fixture or luminaire.* Typically, fixtures can reduce the nominal output of a lamp source by 25-60% or more depending on the fixture and the installation. The Luminaire Efficiency Rating (LER) proposed and supported by several industry organizations is one way to incorporate fixture efficiency.<sup>20</sup> One way in which fixture efficiencies affect the Cost of Light calculations is readily apparent in the CoL for PAR-style flood and spot lamps. Their CoL is relatively low but they are very directional in nature. Thus the combination of the lamp and a well designed fixture can produce an improved CoL over an A-lamp in a recessed fixture. The same is true of LED sources.
- **Ballast efficiency.** Fluorescent lamps, with the exception of compact fluorescents, require separate high voltages to operate and those are provided by a ballast to provide start and operating currents. High-quality electronic ballasts are about 85% efficient and lower quality magnetic ballasts are both noisy and relatively inefficient.
- **Time value of money.** The current Cost of Light model does not reflect the time value of money. Since energy costs are paid at future times and if energy costs are higher for one technology versus another, those future payments can add significantly to overall costs.
- **Rapid progress in LED development.** Reports from several LED manufacturers indicate that recent developments in LED technology are outpacing the predictions of just a few years ago. In separate developments we have seen greater efficacies and higher outputs than were foreseen just a year or two ago. Recently 100lpw LED packages were announced in early 2005 by Cree. These are laboratory results and not production units but are still strong indicators.

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<sup>17</sup> Traditional lighting sources also have significant lumen depreciation but over their shorter lifetimes.

<sup>18</sup> Typically extrapolated to 50 or 70% lumen depreciation.

<sup>19</sup> <http://www.colorkinetics.com/products/pro/lights/colorblast12/>

<sup>20</sup> National Electrical Manufacturers Association Standard Publication No. LE 5 – 1993, "Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires – LE5. See also <http://www.lightsearch.com/reference/nlc.html>

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- **Rapid progress in LED pricing.** Increased production by more companies and specific efforts by countries such as Taiwan have resulted in rapid price decreases in many segments of the LED market especially in the GaN material-based LEDs such as blue and green. These are placing significant pricing pressure on high-flux HB-LED producers. Nichia for example, recently reduced the prices on white LEDs by 40% and prices on white LEDs are down 8% on average in Q1 of 2004.<sup>21</sup>
- **Energy Costs.** According to the UK's Department of Trade & Industry, [www.dti.gov.uk/energy/inform/energy\\_prices/](http://www.dti.gov.uk/energy/inform/energy_prices/) the cost of energy in Japan is significantly higher than in the US. Energy costs in other markets, if higher, can make the analysis even more favorable to the Cost of Light comparison for SSL. There is also no assumption that energy costs will rise or lower in the next several years.

Other related energy costs are related to additional HVAC loads in facilities due to the additional heating loads placed upon facilities due to energy consumption by lighting products. This factor is also not taken into account. Incandescent and fluorescents, in particular, generate far more heat than light. About 95% of the energy going into an incandescent source results in heat.

- **Labor Rates.** Another conservative factor is that it is assumed in this model that labor rates do not increase over time. Labor rates are based on numbers from the National Lighting Bureau, [www.nlb.org](http://www.nlb.org).
- **Quality of Light.** A typical measure of light quality is the Color Rendering Index or CRI which compares a light source to a reference source under a palette of other colors. This comparisons are used to produces a normalized scalar between 0-100 to represent the closeness of the light source to a reference source. High efficiency sources such as high-pressure sodium are not considered high-quality sources. The range of CRI for fluorescent lamps in this analysis is 62-85 CRI. White LED sources are already in the 80-85 CRI range and climbing as new phosphor combinations are created. Thus, even today LED sources provide excellent color quality for many applications.
- **Sources** The data for comparison purposes are from the least expensive sources: mass merchandisers. Supermarkets and discount stores dominate in retail sales of lamp sources but in the commercial world electrical distributors and their higher prices often are the source of lamps. It is well known that the big three fight tooth and nail for the mass merchandiser shelves and have very small margins on the products. However, the volumes are significant and help drive down costs for other retail and commercial outlets for their products.
- **The Experience Curve.** In addition to technical and engineering progress, competition and the experience curve will continue to drive down costs. The experience curve, by itself, can drive down prices significantly; prices drop 20-30% drop for a doubling of production. Indeed, if this does not occur it is often seen as a sign of poor management. Insights gained from economies of scale and

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<sup>21</sup> Compound Semiconductor.

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practical experience in production should translate into higher productivity and lower costs.<sup>22</sup>

- **Unique Benefits.** All of the comparisons in this analysis are related to economics and not with particular beneficial features of the light sources other than light output and lifetime. For example, LEDs make sense for environments with high vibration, extreme cold, elimination of thermal radiation, elimination of UV and more. These are separate from the Cost of Light evaluations but impact selection if the lighting applications demand certain performance criteria not taken into account in the Cost of Light. Even aspects of fluorescent sources such as the high-voltage ballasts or Mercury presence may affect decisions for their use.
- **Colors.** These comparisons are based on white light produced through RGB means as well as white LEDs. When producing color, traditional lighting sources require gels or filters to cut out sections of the spectral output and produce a desired color. This is subtractive mixing which makes any light source less efficient. Typical transmission efficiencies for filters are in the 20-80% range and thus, the relative efficacies of filtered light versus LED additive mixing are substantial and in favor of the LED source.<sup>23</sup>
- **Other Lighting Sources** The only other lighting technology predicted to have real improvement is HID. But restrike times and ballast costs are unlikely to make a large impact in the general illumination market. HID represents a small fraction of the general illumination market but does well for large area lighting.

### 7. Continued Progress

The trends of the past forty years brought continually improving LEDs into a number of mainstream applications. The LEDs that comprised the dim displays of early watches and calculators evolved into devices now widely used in high-brightness, direct view indicators such as automotive lighting and traffic lights as well as exit signs. From high brightness indicators they have moved into low-and medium luminance lighting applications such as accent and marker lighting. More recently, white LEDs have followed a similar, albeit rapid evolution into many applications. The rapid improvement of white LEDs is due to the advances and improvements in other LEDs, especially blue LEDs.

In 1997, Color Kinetics pioneered intelligent LED illumination systems using general purpose microprocessors, networks and high quality LED control. The continuing trends have enabled newer LED-based fixtures with many times the brightness at a fraction of the cost of those early fixtures. LEDs continue their journey into the light; moving again, this time towards general lighting.

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<sup>22</sup> Henderson, Bruce, "The Experience Curve Reviewed, Why Does It Work?" reprinted in Stern and Stalk, *Perspectives on Strategy*, 1998. Wiley

<sup>23</sup> Roscoe USA, Stamford, CT. <http://www.rosco.com/main.html>

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### Appendix: The Cost of Light – Dimensions and Scaling

There is some confusion in both the dimensions and final scaling of the CoL, so this exercise details both aspects of the CoL equation. The CoL formulation is as follows:

$$\frac{1}{\text{lumens}} \left[ \left( \frac{\text{lamp\_cost} + \text{labor\_cost}}{\text{lifetime}} \right) + \text{power} * \text{energy\_cost} \right]$$

The dimension of the Cost of Light (CoL) metric is in dollars per million-lumen-hours. This is very similar to the metric for the pricing of electricity, a related commodity which is specified in units of dollars per kilowatt-hour. In the CoL version in the IES Handbook, all costs are in cents, lifetime is thousands of hours and energy costs are in cents per kilowatt hour.

#### Dimensional Check

After removing all scaling factors, since they are dimensionless, then the units can be consolidated to dollars per lumen-hours as shown below:

$$\frac{1}{\text{lumens}} \left[ \frac{\$}{\text{hrs}} + W \frac{\$}{W\text{hrs}} \right]$$

Watts are eliminated resulting in:

$$\frac{1}{\text{lumens}} \left[ \frac{\$}{\text{hrs}} + \frac{\$}{\text{hrs}} \right] = \frac{\$}{\text{lumen hrs}}$$

#### Scaling Check

All costs are in cents (0.01 dollars) so that the right-hand side of the CoL formula is:

$$\left[ \frac{\text{cents} + \text{cents}}{\text{khrs}} + W \frac{\text{cents}}{\text{kWhrs}} \right]$$

k is kilo or 1000. Cents, of course, are actually units of dollars/100 so this becomes:

$$\left[ \frac{0.01 \text{ dollars}}{1000\text{hrs}} + \frac{0.01 \text{ dollars}}{1000\text{hrs}} \right]$$

Now the denominators are equivalent and the scaling of both sides of the sum is the same. Bringing the 0.01 into the denominator gives:

$$\left[ \frac{\text{dollars}}{100 * 1000 \text{ hours}} + \frac{\text{dollars}}{100 * 1000 \text{ hours}} \right] = \frac{\text{dollars}}{100,000 \text{ hours}}$$

To get to dollars per million lumen hours you need to multiply by an additional factor of 10 in both the numerator and denominator. This additional factor of 10 gives 1,000,000 in the denominator. Upstairs, in the numerator, it appears as a multiplier of 10 and is placed outside the inner sum giving the complete formulation shown above.

The reason that the CoL metric uses a “per million lumen hours” basis is most likely because the desired result is a comfortable number that does not require exponents or give a large range of values.