

A Market Diffusion and Energy Impact Model for Solid-State Lighting SAND2001-2830J

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ABSTRACT

Recent advances in the technology for light emitting diodes (LEDs) ensure that these super efficient, long life lights will soon be able to compete for market share in the white light market. This paper forecasts the potential role for this technology in the U.S. lighting market over the next 25 years in terms of market share, total electricity demand, and avoided carbon emissions. We assume that LED market share is a function of relative efficiencies and that gains in efficiencies are driven by the R&D devoted to the LED white light market. Market diffusion follows a typical S-shaped diffusion curve. The paper concludes that LEDs have the potential to reduce lighting demand by as much as 167 billion kWhrs per year or the equivalent of about 29 large (600 MW) power plants, saving consumers about \$12 billion annually.

Introduction

A quiet revolution in lighting technology is underway. Solid state lighting, or light emitting diodes (LEDs), have rapidly gained market share for several other monochrome applications, such as traffic lights, brake lights, outdoor signs, and exit signs. Recent advances in the basic technology make it possible that these super efficient, long life lights may soon be able to compete for the white light market. In addition to their potential to cut electricity usage for lighting, they'll offer several advantages over traditional lighting sources. Their small size will allow their use in a wide variety of applications. Clustered together in a traditionally shaped bulb, they'll be able to directly replace incandescent bulbs. In new construction, they might run along the moulding in strips, providing uniform lighting. Used for outdoor lighting, their highly directional beams will illuminate their intended target, rather than the surrounding area, thereby reducing light pollution. In commercial applications, the ability to control their color will enable owners to select the color most pleasing for any specific occasion.

Illumination accounts directly for about 16% of U.S. electricity generation². In addition, several analysts have noted the connection between cooling and heating requirements and lighting loads. One analysis, by Sezgen and Koomey (1998), suggests that if one considers the cooling load associated with removing excess heat generated by existing lighting sources, illumination accounts for about 19% of U.S. electricity generation.³

Increasing the efficacies⁴ of the existing lighting stock would significantly decrease electricity demand and associated carbon emissions. However, lighting efficacies have improved

² Includes generation losses; derived from EPRI 1997 and EIA 2000a.

³ Sezgen and Koomey's analysis concludes that, for the average commercial building, a one kWhrs lighting load requires an additional 0.48 kWhrs of cooling while offsetting a 0.29 kWhrs heating load (Table 1a.)

⁴ The energy efficiency of lighting is referred to as efficacy. Bulb efficacies, measured in lumens per Watt (lm/W), take into account the eye response curve. An infrared LRD could be 100% efficient, but have a zero efficacy since it emits in the non-visible part of the spectrum.

only incrementally over time, Figure 1. The inefficient incandescent bulb uses electricity to heat a tungsten filament, which then glows, providing light, but also heat. The fluorescent, while about six times more efficient than the incandescent, is not widely used in the residential sector because of the perceived quality of its light and higher initial costs. The compact fluorescent light bulb (CFL) offers an effective alternative to the incandescent bulb but has not captured significant market share for a variety of reasons, including its higher initial costs.

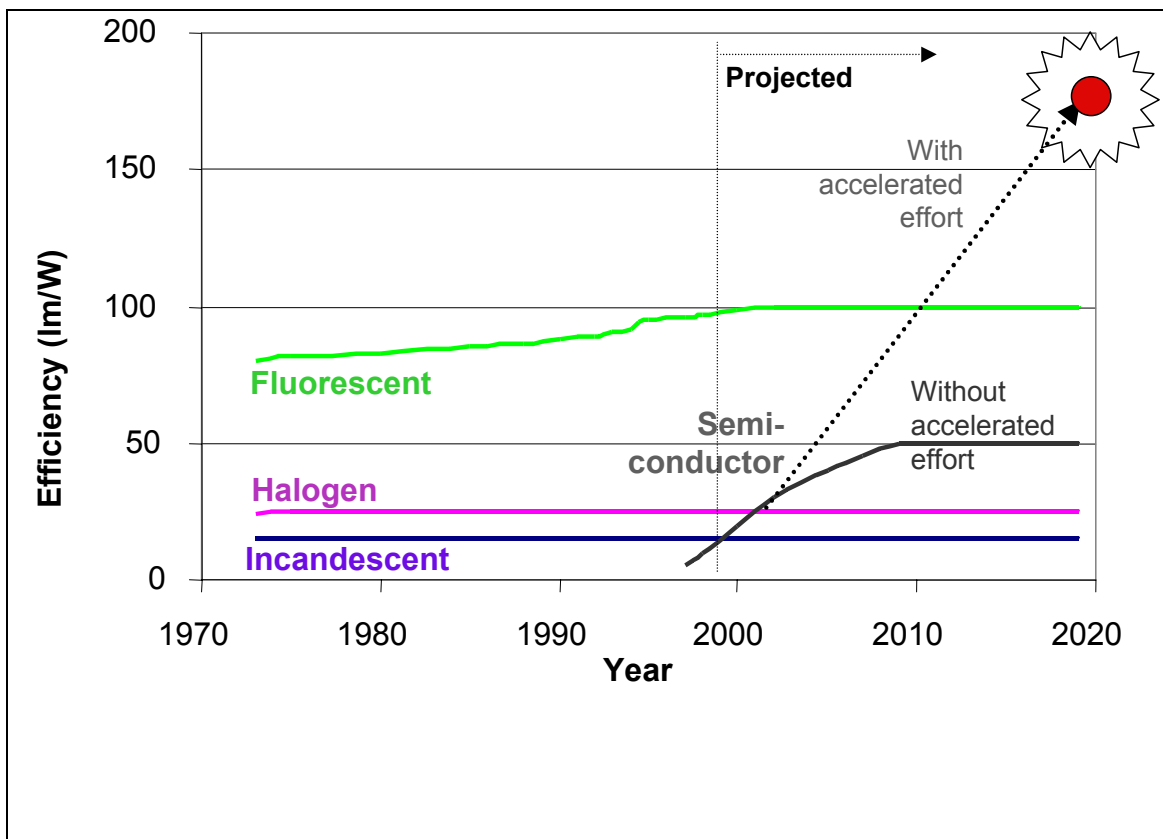


Figure 1. Comparison of existing and projected bulb efficacies of existing white light sources with white LEDs

LEDs have the potential to capture a significant market share over the next two decades. Driven by the demand for higher energy efficiencies and fluxes in monochrome applications,

LEDs will begin to compete for the white light market. They have the potential to achieve efficacies of at least twice that of fluorescents in the near future.

The purpose of this paper is to forecast the potential role for this technology in the U.S. lighting market over the next 25 years in terms of market share, total electricity demand, and the potential avoided carbon emissions. The paper begins with an overview of existing lighting demand by sector and type of lighting. We then discuss the evolution of LEDs from simple indicator lights to their use in traffic lights and discuss the problems in making the leap from monochrome markets to general lighting. The third section introduces a dynamic market diffusion model for the LED markets (LEDSim), which is used to derive market penetration estimates. Two representative investment cases are used to show the potential effect of this lighting technology on future electricity demand for lighting and its associated benefits. The paper concludes that LEDs have the potential to reduce lighting demand by as much as 167 billion kWhrs per year or the equivalent of about 29 large (600 MW) power plants.

U.S. Lighting Energy Demand

Table 1 summarizes estimated 1995 electricity consumption and projected growth rates by sector for lighting. Illumination accounts for approximately 28.6% of electricity use in the commercial sector, 11.4% in the residential sector, and 6.3% in the industrial sector.⁵ Table 2 summarizes power consumption, efficacies, and operating lifetimes for the most widely used lighting sources. The most popular incandescent lamps, with power ratings of 60-100W, have efficacies of around 15 lm/W and a rated life of 1,000 hours. The efficacy of incandescent lamps drops off at lower power ratings or for lamps with a longer rated life. Halogen bulbs have

⁵ Derived from EIA (2000a).

estimated efficacies of 14-20 lm/W, but last somewhat longer than incandescent bulbs.

Fluorescent bulbs are about five times as efficient as incandescent bulbs (70-80 lm/W), have a considerably longer life span, and dominate commercial and industrial lighting applications. The last three types of lights, mercury vapor, metal halide, and high pressure sodium, are collectively referred to as high intensity discharge, or HID lights, and are most often found in warehouses and grocery stores, where both efficacy and expected life span matters.

Table 1. Sectoral summary statistics for lighting demand, 1995, and projected annual growth rates, 1995 – 2015.

	Total Electricity Demand (Quads)	Lighting (Quads)	Lighting (billion kWhrs)	Lighting % of Total	Annual Growth (%)
Residential	11.4	1.3	126.2	11.4%	1.5%
Commercial	10.5	3.0	291.3	28.6%	0.1%
Industrial	11.1	0.7	68.0	6.3%	0.9%
Total	33.0	5.0	485.4	15.2%	

Notes: 1995 electricity consumption by sector derived from EIA (2000). Electricity use includes generation losses. Electricity consumption and annual growth rates by sector from EPRI (1997).

Table 2. Power consumption, efficacies, and operating lifetimes for existing lighting sources (Sources: Vorsatz et al. (1997); authors' estimates).

Lamp Type	Power (Watts)	Efficacy (lm/W)	Lifetime (hrs)
Standard Incandescent	15-250	8-19	750-2,500
Long Life Incandescent	135	12	5,000
Halogen	42-150	14-20	2,000-5,000
Compact Fluorescent	5-55	50-70	10,000
Standard Fluorescent	30-40	70-80	20,000
Mercury Vapor	40-1,000	50	29,000
Metal Halide	32-1,500	46-100	5,000-20,000
High Pressure Sodium	35-1,000	50-124	29,000

The commercial sector uses a larger share of high-efficacy lights than does the residential sector, Table 3. Vorsatz et al. (1997) estimates that, in terms of delivered lumens for the commercial sector, incandescents account for 5.2%, fluorescents, 79.8%, and high intensity discharge (HID) lights, 15.1%. Combined, fluorescents and HID lights account for 94.8% of the total lumens in the commercial sector. By contrast, the residential sector relies much more on relatively inefficient incandescent bulbs; only about 13% of the lumens are from fluorescents or other high efficacy lights.

Table 3. Estimated percentage of lumens delivered from high efficient light sources.

Sector	% Lumens from High Efficiency Sources
Residential	13.0
Commercial	94.8
Industrial	94.8

Notes: High efficient lights include standard fluorescents, compact fluorescents, and high intensity discharge (HID) lighting. Percentage of lumens delivered by HID is derived from Vorsatz et al. (1997.)

Despite having much higher efficacies than the widely used incandescents, compact fluorescent lights (CFLs) account for only about 1% of the total lumens in the residential sector (Vorsatz et al., 1997). With payback periods as short as a year, CFLs make economic sense for a wide variety of applications. For example, replacing a 60-Watt bulb used six hours per day with a 15 W CFL will have a payback period of just over a year.⁶ However, residential consumers have been unwilling to spend \$10-15 per bulb when they can purchase incandescent replacements for less than a dollar. In addition to the initial high cost, other reasons given by consumers include⁷: incompatibility with existing fixtures, inability to use CFLs with dimmer

⁶ A 60 W incandescent bulb operated 6 hours per day consumes 131 year/year of electricity. Assuming electricity costs \$0.10/kWhr and Cols cost \$12 per bulb, the payback would be 1.1 years.

⁷ Vorsatz et al. summarize the work of Campbell.

switches, unattractiveness of the bulbs, and a basic lack of information about the bulbs and their economics. CFL manufacturers have made good progress at addressing several of these issues, including manufacturing smaller bulbs that fit in a wider range of existing fixtures and CFLs that can be dimmed. Nevertheless, the major barrier for the residential consumer is the high initial cost, implying that consumers apply high discount rates to promised future savings. The lessons from CFL market diffusion must be considered when forecasting new lighting technologies. Generally, while residential users focus on initial costs in determining whether to purchase the new lights, commercial and industrial users are more willing to consider life cycle costs, including potential energy cost savings. However, some of the other characteristics of these solid-state lighting sources, such as size, directionality, and color range, may appeal to residential users and help overcome the initial cost barrier by offering a different set of lighting services.

The industrial sector trails in terms of total energy use for lighting sources. Unfortunately, the literature is also fairly incomplete in terms of industrial lighting uses. However, incidental evidence suggests the overall efficiency of use in the industrial sector is comparable to commercial sector. Therefore, we assume that the lighting mix in the industrial sector mirrors that of the commercial sector.

Evolution of LEDs⁸

LEDs have had a colorful history, alternately pushed by technology advances and pulled by key applications. GE demonstrated the first LED in 1962. The first products, introduced in 1968, were indicator lamps by Monsanto and the first truly electronic display by Hewlett-

⁸ This topic is documented more completely in Haitz et al. (1999).

Packard (a successor to the awkward Nixie tube⁹). The initial performance of these products was poor, providing a flux of just 0.001 lm (1 *mlm*) and the only color available was a deep red.¹⁰ Steady progress in efficacy made LEDs viewable in bright ambient light, even in sunlight, and the color range was extended to orange, yellow and yellow/green by 1976.

Until 1985, LEDs were limited to small-signal applications requiring less than 0.1 lm of flux per indicator function or display pixel. Around 1985, LEDs started to step beyond these low-flux small signal applications and to enter the medium-flux power signaling applications with flux requirements of 1-100 lm (see Figure 2). The first application was developed in response to the newly required center high-mount stop light (CHMSL) in automobiles. The first solutions were crude and brute-force: 75 indicator lamps in a row or in a two-dimensional array. It did not take long to realize that more powerful lamps could reduce the lamp count and provide a significant cost advantage. This was the first situation where bulb efficacy became an issue and for which the market was willing to pay a premium.¹¹ By 1990, efficacies reached 10 lm/W for gallium aluminum arsenide (GaAlAs) LEDs, exceeding that of equivalent red filtered incandescent lamps. Nevertheless, even higher efficacies were desired to continue to decrease the number of lamps required per vehicle.

⁹ Nixie tubes were trademarked by the Burroughs Corporation; a good history is available at: <http://fido.wps.com/texts/decimal-tubes/index.html>

¹⁰ For comparison, a 60W incandescent lamp emits 6 orders of magnitude higher light flux (about 900 *lm*).

¹¹ Back in the small signal days where one lamp was used per function, a 2x improvement in efficacy did not allow customers to use half a lamp. And, to reduce the power consumption from 20 mW to 10 mW did not matter very much in an instrument that used 10-100W for other electronic functions.

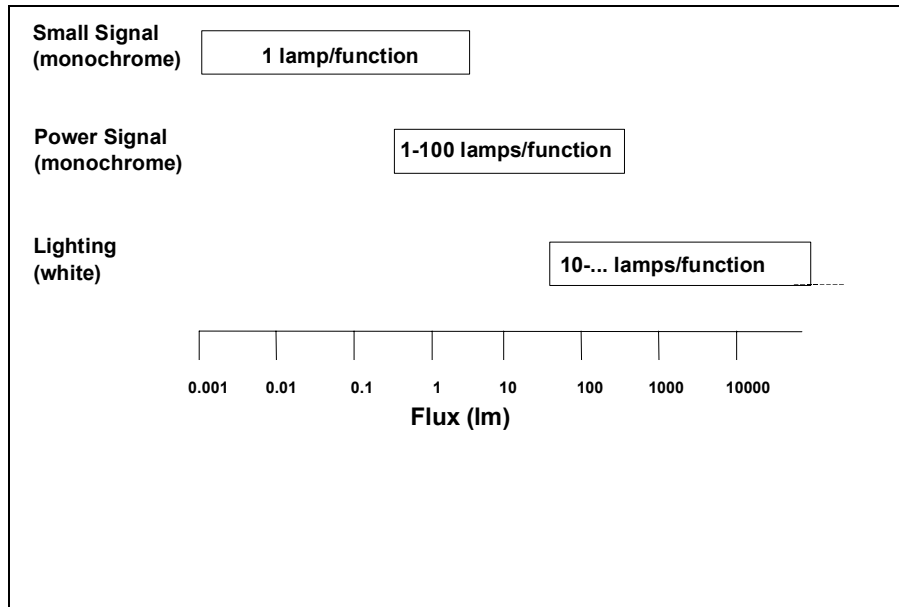


Figure 2. Flux and numbers of lamps required for various classes of LED applications: low-medium-flux "signaling" applications, in which lamps are viewed directly, and medium-high-flux "lighting" applications, in which lamps are used to illuminate objects. Current LED lamps emit 0.01-10lm of light.

This search for increased efficacies triggered the exploration for new materials with higher efficacies and a wider color range. First emerged gallium aluminum indium phosphide (GaAlInP) LEDs, covering the range of red to yellow/green, with efficacies exceeding 20 lm/W. In 1993, Nichia Chemical Corporation in Japan announced a fairly efficient blue material, gallium nitride (GaN). This discovery meant that LEDs could cover practically the entire visible spectrum, enabling their entry into additional power signaling applications such as traffic lights.

The evolution of flux and price for red LEDs is illustrated in Figure 3 covering the period from the first LED sales in 1968, projected to 2008. In a Moore's-law-like fashion, flux per unit has been increasing 30x per decade, and crossed the 10 lm level in 1998. Similarly, the cost per

unit flux has been decreasing 10x per decade to about 6 cents/lm in 2000. At this price, the LEDs in a typical 20-30 lm CHMSL contribute only \$1.50 to the cost of the complete unit.¹²

In summary, the power signaling market drove, and continues to drive, improvements in the design and manufacturing infrastructure of the compound semiconductor materials and devices on which LEDs are based.

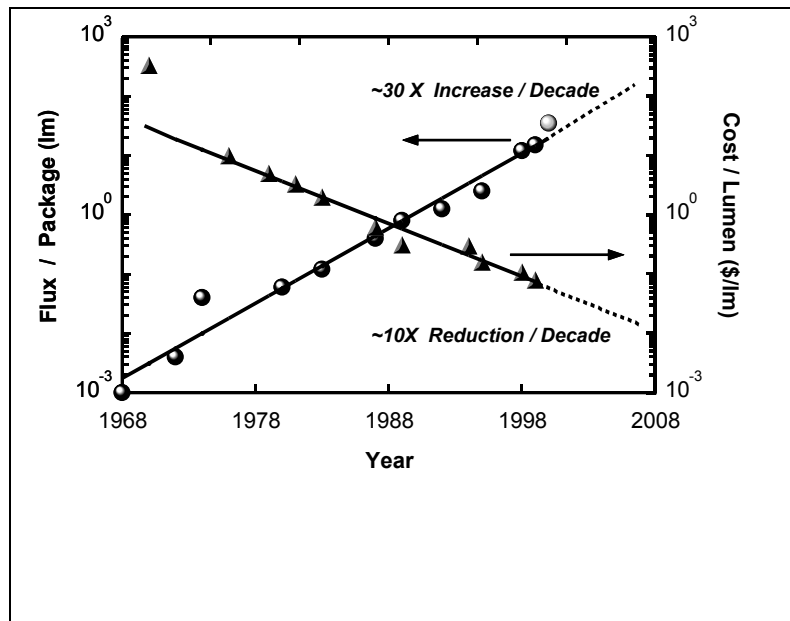


Figure 3. Historical and projected evolution of the performance (lm/package) and wholesale cost (\$/lm) for commercially available red LEDs. This data was compiled by R. Haitz from HP historical records.

Because LEDs of reasonable efficacies span virtually the entire visible wavelength range (with the exception of a narrow window in the yellow-green), it is possible to create white light sources. One approach involves combining blue, yellow, and red LEDs to create white, much like how white is created on television screens. Another approach involves coating a blue LED with a phosphor, which emits yellow light when struck by the blue photons. Together, blue light from the LED and yellow light from the phosphors combine to produce white light. Variations

¹² Although this cost is higher than that of an incandescent light bulb, it is low enough that other factors, such as compactness, styling

on the phosphor approach included a blue LED with red and green phosphors for improved color rendering capabilities, and an ultraviolet (UV) LED with red, green, and blue phosphors for improved color mixing. Both of these approaches (multi-chip LEDs and phosphors) involve some losses (color mixing in the former and photon down-conversion in the latter), but nevertheless can achieve good overall efficacies.

The further diffusion of LEDs into the signaling markets and the initial diffusion into the lighting markets is a complex issue. As with any new technology, in the early years LED solutions will be considerably more expensive than conventional solutions. To justify their selection, the higher initial cost has to be overcome by lower operating costs and/or other tangible benefits. Electricity cost savings and longer life are the driving forces for adoption of LEDs for traffic lights; ruggedness, long life and styling are important factors in automotive taillights; and lamp density and integrality are the key factors in outdoor TV screens¹³.

The diffusion of LEDs into the general white light market will be much more difficult. Due to the present efficacies and the relatively high price of LEDs, in the very near term the white light applications that can realistically be captured are the lower-flux "specialty" lighting applications in the 50-500 lm range, Figure 4. Incandescent and compact halogen lamps currently dominate these applications, which include accent, landscape lights, and flashlights.

freedom and absence of warranty cost, easily make up the difference.

¹³ For example, the NASDAQ display in Times Square reportedly uses 18 million LEDs to light 10,800 ft², about 1667 LEDs per square foot ("Exploring the Nanoworld").

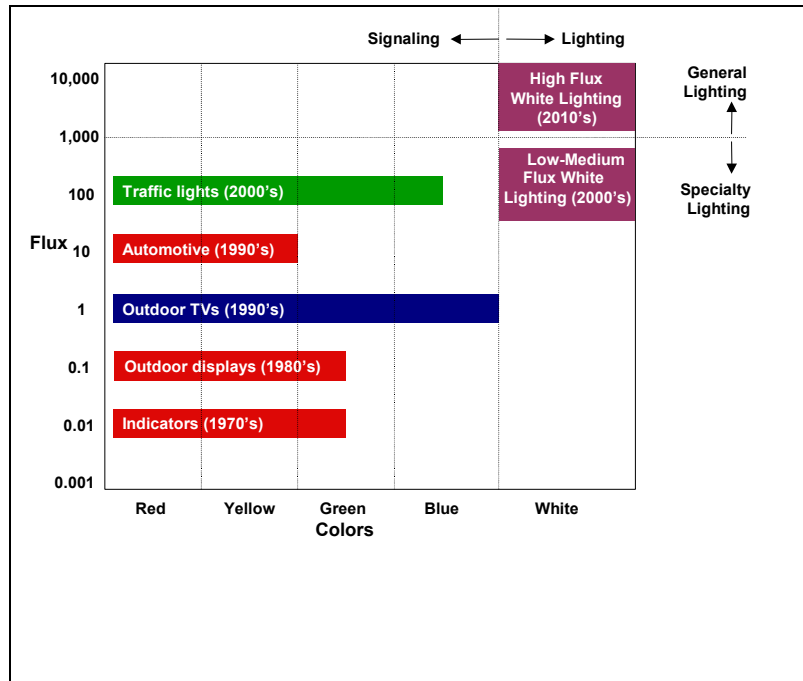


Figure 4. The stepping stones from LED indicators to LED illumination over half a century from 1970 to 2020. Signaling applications are mostly monochrome; lighting applications are mostly white. Specialty lighting includes monochrome and low/medium flux white lighting and is dominated by incandescent lamps. General lighting includes high flux white lighting and is dominated by a combination of incandescent, fluorescent, and HID lamps.

Breaking into the general lighting market, with required fluxes on the order of 1,000 lm or more, will require additional efficiency improvements in green and especially blue LEDs. Predicting efficacies of white LEDs is difficult. If efficacies level off around 50 lm/W, then LEDs may replace some incandescents and halogens, but they will not be suitable for penetrating the more lucrative high-efficacy lighting market encompassing fluorescents and HID lamps. However, if research leads to higher efficacies, LEDs will achieve much higher diffusion levels. Researchers at Sandia National Labs and elsewhere believe that given adequate R&D investment, LEDs could achieve efficacies that are double those of fluorescent lights within two

decades, Figure 1¹⁴. This optimism is based on experiences with red LEDs. As recently as the late 80's, red efficacies were only on the order of 5 lm/W; recent laboratory efficacies for red are now in the range of 75 lm/W (Haitz et al., 1999).

The LED Simulation Model

As discussed in the previous section, LED efficacies have improved rapidly over the last few years driven largely by the power signaling market. This trend is expected to continue; the next challenge will be to increase flux levels so that LEDs can compete in the general lighting markets. In order to forecast future LED market shares, we have developed the LED Simulation Model (LEDSim).¹⁵ LEDSim allows the user to rapidly explore alternative assumptions about R&D funding, efficacy improvements, and market penetration rates on the projected market share of white LED lights, as well as resulting electricity and carbon savings.

The model structure is illustrated in Figure 5. While lighting use is traditionally measured in terms of kWhrs consumed, the end user is interested in delivered lumens. Total lumens demanded is calculated based on estimated electricity demand for lighting for each of the three sectors, the estimated lighting mix in that sector, and the assumed efficacies of the various bulb types. For example, a 100 W incandescent bulb, operating with an efficacy of 15 lm/W will provide 1500 lumens. The same lumen output could be achieved using a 20 W fluorescent bulb. The values for electricity demand by sector and projected growth rates used in this model were summarized in Table 1. The assumed efficacies of the existing lighting stock by sector were summarized in Table 3.

¹⁴ See Haitz et al. (1999) for further information.

¹⁵ The model is written in Powersim, a dynamic simulation modeling language.

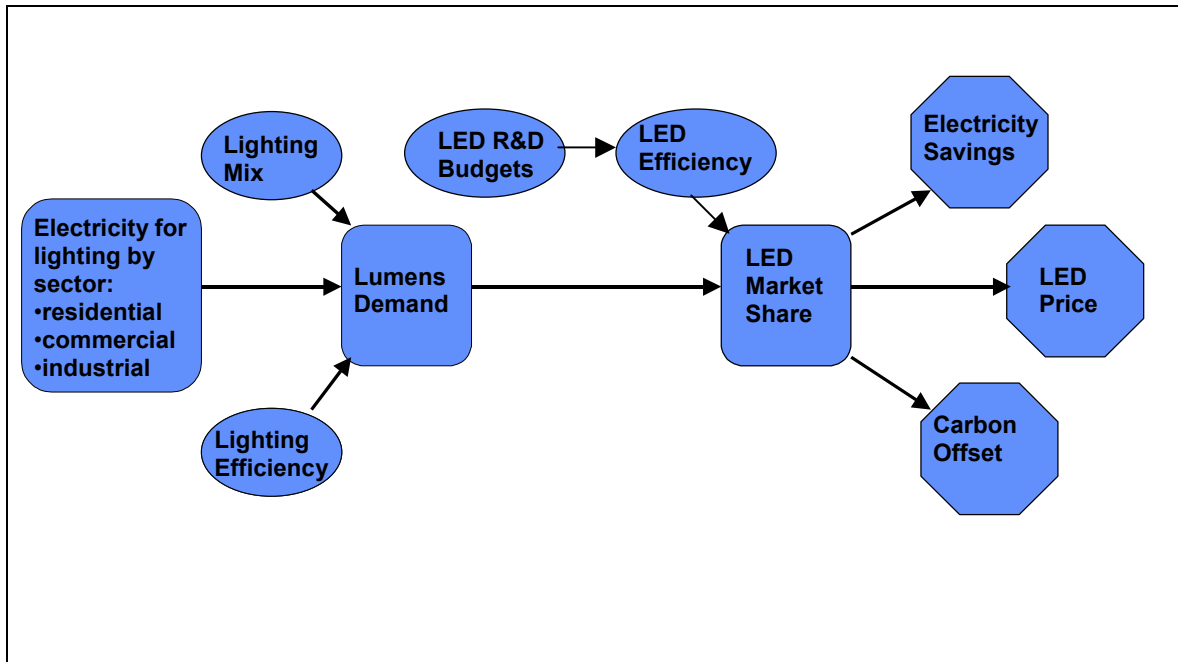


Figure 5. LEDSim model structure.

In the model, LED market share is a function of relative efficacies. R&D devoted to the white light market drives efficacy gains. Market diffusion follows a typical S-shaped diffusion curve. This approach is widely used for forecasting the potential market share of new technologies. The classic work by Fisher and Pry (1971) in this area demonstrated how market penetration typically follows an S-shaped or logistic pattern for a wide range of technologies.¹⁶ Penetration begins slowly as consumers first learn about the new lighting technologies. As efficacies increase and prices decrease, LEDs begin gaining market share. As is typical of new products, market share grows slowly at first. Once the product market share reaches about 10%, penetration speeds up and eventually reaches a maximum market share, or saturation level.

Forecasting LED prices is problematic. Consumer demand for this technology is based on prices. However, the supply cost of manufacturing and delivery of LEDs is largely a function of cumulative capacity and returns to scale. Manufacturing costs typically fall as companies gain

experience in the manufacturing process and expand production runs. In the marketplace, supply and demand interactions determine the market price, which affects supplier investment and consumer demand in subsequent periods, affecting future cost and price trends. As has been the case for computer chips, expanded capacity has lowered manufacturing costs and hence retail prices, and driven up demand, including the creation of new products that use lower cost chips. In our view, LEDs are likely to follow a similar supply driven approach. Thus, for simplicity, in this model, we make costs and retail prices a direct function of market share.¹⁷ We recognize that this is a potential weakness of our approach, and that if prices/costs do not fall as predicted, diffusion will clearly be delayed. But as noted above, supply costs appears to have been the key driver in the computer chip industry, which we feel has strong parallels to LED markets.

LEDSim compares total electricity demand in the LED scenarios to cases based on traditional lighting sources. Based on these results, LEDSim calculates the potential avoided electrical capacity, electricity cost savings to consumers, and the carbon offsets.

Each of these components is discussed in more detail below.

Lumens Demand

Total lumen hours demanded in 1995, in klmhrs, is summarized in Table 4. The totals are broken down by whether they are currently supplied by low efficacy (incandescents and halogens) or by high efficacy (fluorescents, HID) sources. The assumed average efficiencies of existing lighting technologies in 1995 and 2025 are also summarized in Table 4. An estimated 14.9% of all lumen hours were provided by the low efficacy sources in 1995 at an average efficacy of 15 lm/W. The projected efficacy of these bulbs is assumed to remain constant over

¹⁶ Fisher and Pry (1971) show how a simple logistic curve largely explains the market penetration in a wide range of industries, from synthetic fibers, water-based house paints, insecticides, and steel manufacturing.

the model life. High efficacy bulbs delivered the remaining 84.1% of the lumen hours in 1995. We assume the average efficacy of the high efficacy bulbs gradually increases from 85 lm/W in 1995 to 90 lm/W in 2025.

Table 4. Lumen hours supplied by lighting type in 1995; assumed efficiencies by lighting type in 1995 and 2025.

	klmhrs, 1995 (billions)	Efficiency (lm/W)	
		1995	2025
Low Efficiency Lights	4,219	15	15
High Efficiency Lights	28,332	85	90

Note: Low efficacy lights include incandescents and halogens; high efficacy lights include fluorescents, CFLs, and HIDs.

LED Market Diffusion

LEDs compete for market share with the low and high efficacy lighting sources according to the logistic formulation:

$$Y_t = \frac{k}{1 + e^{-b(t-t_m)}} \quad (1)$$

where: Y_t is the market penetration in year t ; k is the maximum market penetration, or saturation level; b is diffusion rate; and t_m is the time required to reach 50% of the saturation level and is the inflection point in the logistic curve.

The diffusion rate, b , is often expressed in terms of the time required to go from 10 to 90% of the market, Δt . The relationship between Δt and b is given by:

$$\Delta t = \frac{1}{b} \ln 81 \quad (2)$$

¹⁷ We assume retail prices include a 100% markup from wholesale costs.

LEDSim assumes that there are two distinct markets for the LEDs: the low efficacy market, characterized by the incandescent and halogen bulbs, and the high efficacy market, which includes the fluorescents and HID lights. Each of these lighting types constitutes a separate lighting market and penetration will proceed in each market at different speeds. Whether or not LEDs can capture a significant share of the high efficacy markets depends on the eventual efficiencies that they achieve. In each market, substituting (2) into (1) gives the market formulation:

$$Y_t = \frac{k}{1 + e^{-4.39\left(\frac{t-t_m}{\Delta t}\right)}} \quad (3)$$

We assume initially that LEDs are ultimately capable of capturing a maximum of 50% of the projected market share for both the low and high efficacy lighting markets. This assumption implies that there will always be some applications, such as infrequently used lights, that are not as well suited to LED replacements due to the higher capital costs.¹⁸

Lamp Efficiencies

As discussed in the previous section and illustrated in Figure 1, one of the greatest uncertainties in forecasting eventual market share is the rate of LED efficacy improvements. LEDSim ties gains in LED efficacy and the time to get 50% market share, t_m , to the cumulative level of R&D investment. We assume that R&D for the monochrome LED market continues, at least initially, to drive the research for white LED illumination. The efficacy of the lights

¹⁸As with any of the key assumptions discussed here, the user can easily change the assumptions and explore the results using the LEDSim model.

increases from 20 lm/W in 2000 to around 45 lm/W in 10 years. However, going beyond that level depends on R&D budgets. We assume it takes \$1 billion to achieve the breakthrough necessary to go beyond an efficacy of 45 lm/W. In our default scenarios, we assume that two years after cumulative investment reaches \$1 billion dollars, efficiencies begin to increase linearly from 45 to 200 lm/W over a 10-year period. This is an important assumption of this model and is based on discussions with scientists in the field about what they think is achievable in terms of efficiencies and the funding necessary to achieve those efficiencies.¹⁹

Even without the above-mentioned breakthrough, LEDs begin gaining market share against incandescents and halogen light. In terms of equation (3), for the low efficacy market, t_m occurs 10 years after cumulative R&D reaches \$500 million, or:

$$t_{m,low} = t_{500} + 10 \quad (4)$$

For the higher efficacy markets, t_m , occurs 10 years after the cumulative R&D reaches one billion dollars, or:

$$t_{m,high} = t_{1000} + 10 \quad (5)$$

where t_{500} is the year that cumulative relevant R&D reaches \$500 million and t_{1000} is the year that relevant R&D reaches \$1 billion.

The monochrome market is approximately \$400 million in 2000.²⁰ The four major monochrome market segments include: outdoor display screens, traffic lights, automotive taillights, and decorative/architectural lighting. Three US based consortia, LumiLeds/Phillips, Osram/Cree, and GELcore/Uniroyal/GE account for approximately 50% of the market share.

¹⁹ See Haitz et al. for a more complete discussion of the rationale behind this assumption.

²⁰ Estimate by R. Haitz, Agilent Technologies.

We estimate that these "Big Three" companies spent in the range of \$50-70 million dollars on R&D in 2000. However, not all R&D investments advance the state of knowledge of white LED illumination. For example, investments spent on the redesign of car taillights are not relevant towards white LED illumination. We assume that this "relevant" R&D amounts to six percent of total R&D for the monochrome applications.

Summarizing, efficacy improvements in LEDSim are driven by relevant R&D investment. This paper looks at the projected market share for two different scenarios of R&D investment, a low investment and a high investment case.

The low investment scenario assumes that the Big Three companies spend approximately 10% of total revenue on LED R&D; 6% of this is relevant to white LED illumination. Revenue grows from its current level of \$400 million at 15% per year through 2007, before decreasing to 10%. This translates into relevant R&D of \$12 million in 2000, growing to \$49 million in 2010. Cumulative relevant investment reaches \$1 billion in 2017.

The high investment scenario assumes that the government agrees to fund directed R&D at a level of \$50 million annually, starting in 2002, for a total investment of \$500 million. In exchange for this funding, the government requires increased industry spending; the Big Three increase funding to \$60 to \$110 million per year, or approximately \$1 billion over the next decade. Cumulative relevant investment reaches \$1 billion in 2008, 9 years earlier than the low investment scenario.

Average LED efficiencies for these two investment scenarios are shown in Figure 6.

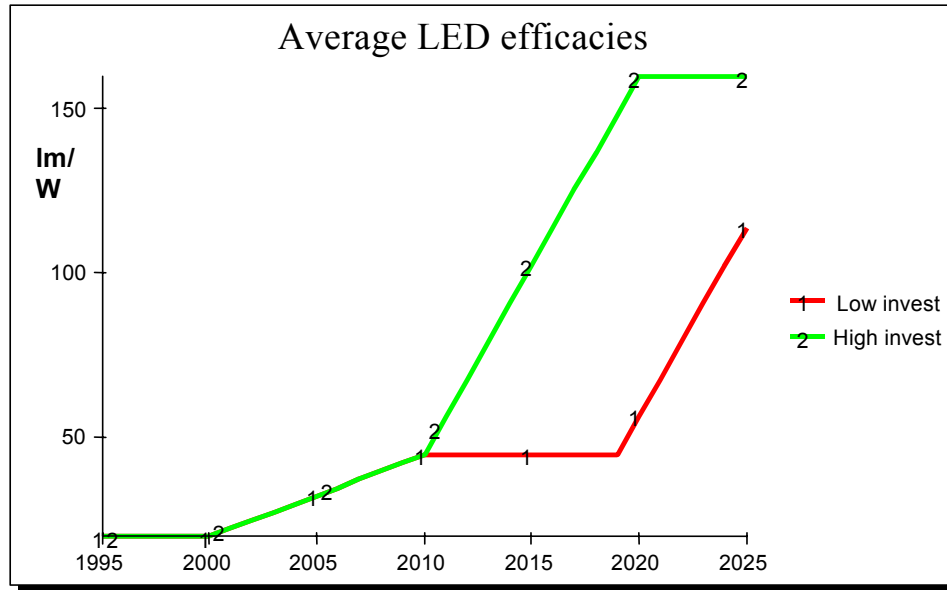


Figure 6. Assumed average LED efficacies for the two investment cases (low and high investment).

The time it takes for LEDs to go from 10 to 90% market share, Δt , is set at a fairly aggressive level: 6 years for the low efficacy lights and 8 years for the high efficacy lights. This implies that it will take longer for the LEDs to achieve comparable market shares in the higher efficacy markets. This makes sense as the higher efficacy bulbs have a long life expectancy and are therefore not as easily replaced. Support for this argument follows from the work of Grubler (1997, 1998), who provides estimates for the value of Δt for various historical transitions, including the diffusion of roads, cars, pollution control technologies, and various energy technologies. For example, for cars and technologies relating to cars, Grubler estimates Δt 's of approximately 12 years, the approximate life of the automobile and associated automotive technologies.

LED Prices

LEDs will not capture a significant portion of market share unless prices decline from their current levels. In LEDSim, LED prices decrease as a function of the cumulative installed capacity of the LEDs. Following the work of Grubler et al. (1998), we assume that prices decline in two distinct phases. The first phase corresponds to a pre-commercial, or R&D and technical demonstration phase. Grubler presents evidence that prices for other energy technologies have typically declined by approximately 20% per doubling of capacity during this phase. This phase is followed by an incremental phase, where the technology is on the verge of widespread application. During this phase, prices decline at approximately half the rate of the first phase, or 10% per doubling.

LEDSim assumes LED prices decline by 20% for every doubling of capacity during the first phase. We assume that the second phase begins once market share has reached two percent; prices decline 10% for every doubling of capacity through the end of the model run.

Results

In the absence of LED lights, LEDSim projects electricity demand for lighting increasing from 490 billion kWhrs in 1995 to 571 billion kWhrs in 2025, a 16.5% increase. This lighting load would require an installed electrical capacity of approximately 58.7 GW and result in the annual emission of about 97 million tons of carbon.²¹

The results of the two investment scenarios discussed in the previous section are summarized in Table 5. Figures 7 & 8 compare the projected electricity requirements for illumination for the low and high investment cases.

Table 5. Results of the LEDSim model runs for the year 2025 for both the low and high investment cases, compared to the case of no LEDs.

	Low Investment	High Investment
Electricity for lighting (billion kwhr)	531	404
Annual Savings	40	167
Cumulative Savings	82	1233
LED Market Share (% of delivered lumens)	16	49
Avoided Electrical Capacity (MW)	4,107	17,671
Electricity Savings (billion \$)		
Annual Savings	3	12
Cumulative Savings	6	87
Carbon Emissions (MtC)		
Annual Savings	7 - 10	28 - 41
Cumulative Savings	14 - 20	210 - 306

²¹ Results assume: heat rate of 10,300 BTU/kWhrs, capacity factors of 90%, and a carbon emissions coefficient of 16.5 MtC/Quad, the average number for 1995.

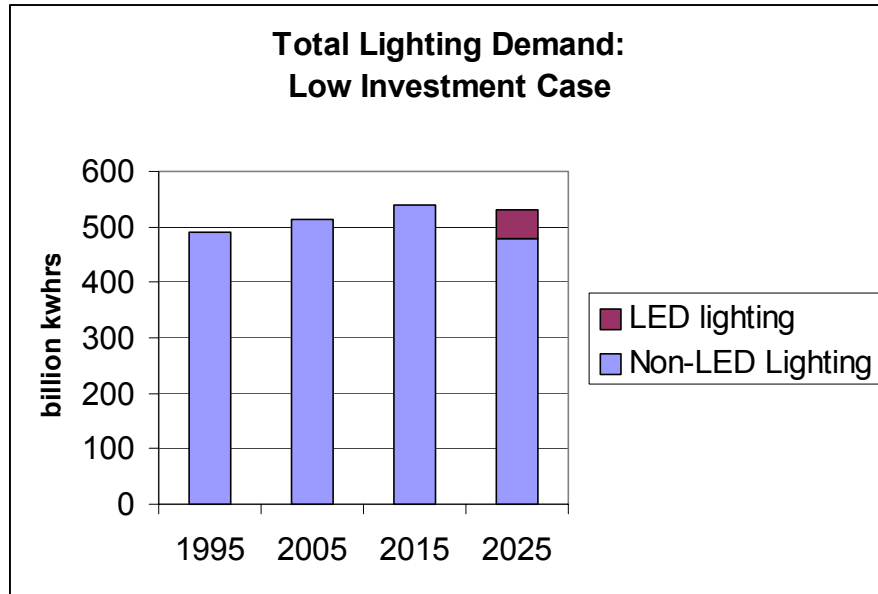


Figure 7. Electricity consumption for lighting for the Low Investment Case.

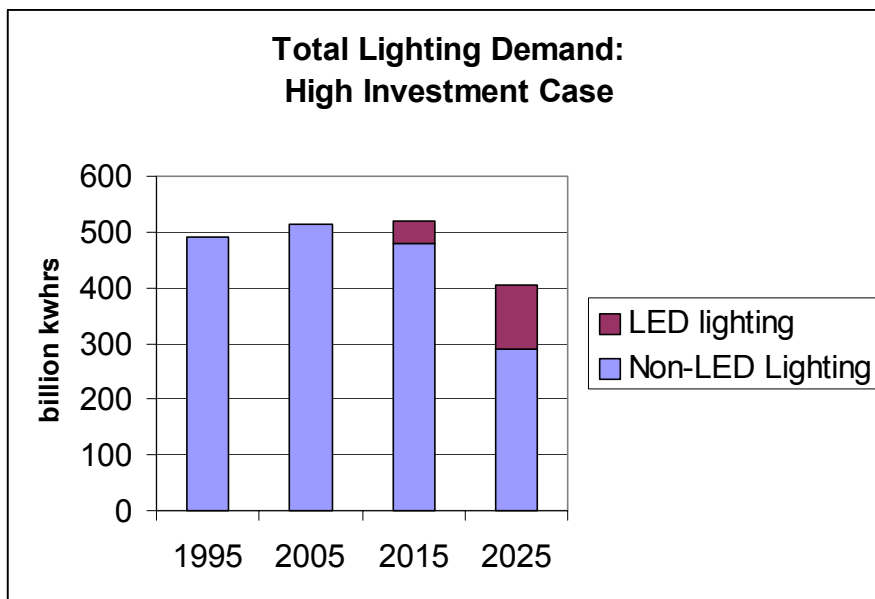


Figure 8. Electricity consumption for lighting for the High Investment Case.

In the low investment case, LEDs do not capture a significant market share over the next 25 years because their efficacies do not increase beyond the 45 lm/W level until 2017. LEDs

capture just over 16% of the market share for delivered lumens. Electricity consumption for lighting reaches 552 billion kWhrs in 2025, an annual savings of 40 billion kWhrs over the case of no LEDs. Cumulative savings by 2025 amount to 82 million kWhrs. This level of LED diffusion amounts to annual savings of \$2.8 billion in electricity bills.²²

In the high investment case, average LED efficacies reach 160 lm/W by 2017, making LEDs suitable substitutes for fluorescent lights as well. This leads to higher total market share than the low investment case; LEDs capture 49% of market share for delivered lumens by 2025. This results in annual electricity savings of 167 billion kWhrs, or about \$11.8 billion in saved electricity costs to the consumer. Cumulative savings by 2025 total \$86.9 billion. Total avoided capacity by 2025 is 17.2 GW, roughly equivalent to 29 new 600 MW power plants.

Carbon Emissions

LEDs offer the potential to significantly reduce carbon emissions worldwide by reducing the electricity requirements for the lighting sector. Estimates of total emissions savings depend on assumptions about the source of avoided electricity.²³ Our estimates suggest that depending on the mix of electricity generation offset by this new technology, LEDs could save 7 to 10 MtC per year in the low investment case and 28 to 41 MtC in the high investment case. Cumulative savings by 2025 range from 14 to 20 MtC in the low investment case to 210 – 306 MtC in the high investment case.

²² Assumes an average electricity price equivalent to the 1995 weighted average price in the U.S. of \$.0705/kWhr (DOE, 2000b).

²³ The average for existing fossil fuel plants in the U.S. is 0.248 kgC/kWhr; the average of all electricity generation is 0.17 kgC/kWhr.

LED Costs

Table 6 compares the projected end use costs of LEDs to other lighting sources. The table summarizes the capital, operating, and total costs in terms of delivered lumen hours (lmhrs). This methodology allows one to consider costs over the life cycle of the bulb, but does not consider the period over which the costs are incurred. Therefore, it does not take into account the timing of the costs, and hence the inclusion of discounted costs. This is an important caveat, as experience with CFLs suggests that consumers are hesitant to spend money up front in return for longer-term savings.

Table 6. Comparison of end use costs for LED lights and existing lights.

Bulb Type	Watts	Efficiency (lm/W)	Cost/bulb (\$)	Lifetime (hrs)	Purchase Cost (cents/klmhrs)	Operating Costs (cents/klmhrs)	Total Cost (cents/klmhrs)
Incandescent	75	15	0.75	1,000	0.067	0.470	0.536
CFL	18	60	12	10,000	0.111	0.117	0.229
Fluorescent	32	80	7	20,000	0.014	0.088	0.102
LED 2000	Any	20	121	100,000	0.121	0.352	0.473
LED 2010 (low invest)	Any	45	47	100,000	0.047	0.157	0.204
LED 2020 (low invest)	Any	56	13	100,000	0.013	0.126	0.139
LED 2010 (high invest)	Any	45	29	100,000	0.029	0.157	0.186
LED 2020 (high invest)	Any	160	13	100,000	0.013	0.044	0.057

Fluorescent bulbs are currently the least costly to operate, costing about .10 cents per klmhr. Based on the projected efficacies of LEDs, LEDs could already be less expensive to operate than incandescents.²⁴ In the high investment case, LEDs are competitive with CFLs by 2010 and clearly better than fluorescents by 2020 (.10 cents vs. .057 cents/klmhr).²⁵

²⁴ Comparable bulbs are not yet available, hence the use of the phrase "could already be less expensive."

Conclusions

Over the past decade, LEDs have gained rapid market share for several monochrome applications, such as automobile brake lights, outdoor TV screens, and traffic signals. Recent advances in efficacies and materials ensure that white LED illumination will be a viable substitute for existing lighting sources. The speed with which they diffuse into the market will depend on several factors, including efficacy gains, prices, and public acceptance. The purpose of this paper was to forecast potential market share based on various assumptions about future efficacies.

Market diffusion of white LEDs will initially be limited to low flux lighting applications, such as accent lighting. As fluxes increase, LEDs will become substitutes for the incandescent and halogen market. Depending on whether efficacies achieve the levels envisioned here, LEDs will then diffuse into the fluorescent and other high-efficacy bulb markets.

White LEDs have the potential to achieve efficacies as high as 200 lm/W, or 2.5 times the efficacy of current fluorescent bulbs. Efficacy improvements will be driven, at least initially, by monochrome bulb requirements. However, a national investment in basic R&D could speed substantially the process. The potential returns to a joint government/industry investment is large. In the high investment case, LEDs capture 49% of the market by 2025, reducing the need for 17 GW of installed electrical capacity, reducing consumer electricity bills by \$11.8 billion, and reducing projected carbon emissions by 41 MtC annually. Finally, the numbers presented here represent only savings in the U.S. market. Advances in LEDs will clearly result in LEDs diffusing into the global lighting markets as well, with proportionate additional reductions in electricity consumption and carbon emissions.

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