Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

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ABSTRACT

Solid-state lighting (SSL) has the potential to revolutionize the lighting market through its energy efficiency. Technical advances have made light emitting diodes (LEDs) cost-effective in not only many colored-light applications, but recently in outdoor white-light and indoor white-light applications as well. LED technology is capturing market share in several of these new applications because it offers energy savings, lower operating costs, and improved durability compared to conventional light sources such as incandescent, high intensity discharge (HID), and fluorescent.

This paper summarizes the analysis of six emerging niche markets for LEDs: traffic signals; exit signs; commercial refrigerated display cases; recessed downlights; street and area lighting; and step, path, and porch lighting. Estimates of energy savings in 2007 due to LED market penetration and the potential energy savings from 100% LED market penetration are presented in terms of both site (electricity) and source (primary) energy savings.

The combined energy savings of LEDs in these applications is approximately 7.45 Terawatt-hours (TWh) in 2007, equal to 80.4 trillion British thermal units (TBtu) of primary energy savings, the annual output of 1.2 large (1,000 MW) coal power plants or the annual electricity consumption of over 600,000 households. With complete market penetration of LEDs, 159.6 TWh (or 1723 TBtu) of electricity (or primary energy) savings are possible, equivalent to the electricity produced by 25 coal power plants or consumed by 13 million households per year. In addition to energy savings and market penetration, this paper discusses ancillary benefits of LEDs in these six niche applications.

Introduction

The first LEDs were produced in the 1950s by British scientists who discovered that the semiconductor Gallium Arsenide (GaAs) emitted a low-level of infrared light when passed with a current. Research on LEDs during the 1950s to the 1990s focused on producing light within the range of the visible light spectrum using various semiconductor materials. A breakthrough occurred in the 1990s with the formation of the first blue LEDs using Gallium Nitride (GaN). By coating blue LEDs with a yellow phosphor or by combining red, green, and blue LEDs, white LEDs, a promising, highly efficient technology for general illumination were created. While the efficacy[1] of the first LEDs was extremely low (approximately 1 lumen per watt (lm/W)), researchers have improved this technology over the past four decades. Today, white LED devices are capable of operating at 134 lm/W in the laboratory (Stevenson 2007). Present day white LED commercial devices have reached efficacies of 88 lm/W, comparable to the efficacies

[1] Efficacy is the efficiency metric for light sources, measured in lumens of light output per watt of input power.

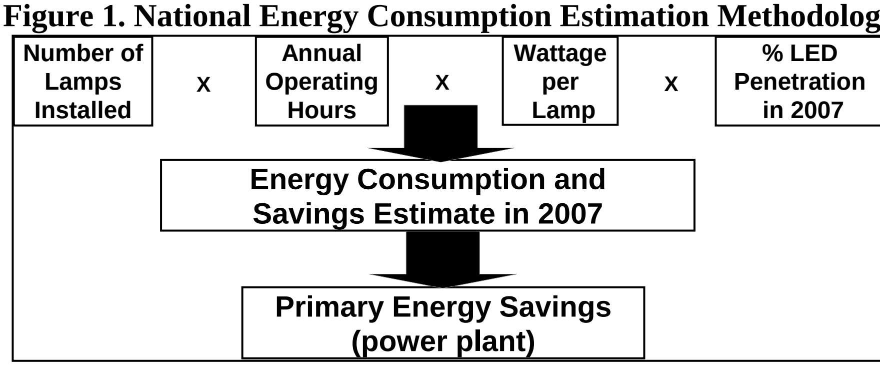
of certain fluorescent and high-intensity discharge (HID) lamps (Audin et al. 1997, 2.2.5; Seoul Semiconductor).

The Department of Energy commissioned this study to evaluate the energy savings potential of LEDs in six niche applications, consisting of two colored-light, two outdoor white-light and two indoor white-light applications. Energy savings are presented both in terms of on-site electricity savings in trillion watt-hours (TWh) and primary energy savings at the power station level in trillion British thermal units (TBtu). These six niche markets are part of a larger study where DOE is interested in quantifying the energy savings due to the penetration of more efficient LED devices in a variety of markets, to be published in its second edition in Fall 2008.

Methodology

The same general methodology was applied across the niche markets to estimate the national energy consumption and savings of each application in 2007 as was applied in the 2003 edition of the report, *Energy Savings Potential of LEDs in Niche Lighting Applications* (NCI). Figure 1 illustrates the four inputs used to estimate energy consumption in 2007 and the total electricity savings potential of each niche application. Energy savings are also presented in terms of primary energy savings, assuming the average national generation fuel mix in the U.S.[2] The four critical inputs are: number of lamps installed, annual operating hours, wattage per lamp and percent of LED market penetration. Estimates for these inputs originate from literature and market studies, available databases, and interviews with researchers and industry experts.

Figure 1. National Energy Consumption Estimation Methodology



The niche markets evaluated in this report do not represent an exhaustive list of all the applications where LED devices can be found today. In addition to these, other popular niche market illumination applications for LED devices include commercial signage, decorative holiday lights, task lighting, kitchen under-cabinet lights, retail display, automobile lights, indicator lights, flashlights, and display screen illumination. Some of these applications will be addressed in the DOE's forthcoming publication evaluating the energy savings potential from LEDs in a variety of niche market applications. This report, to be published in the Fall of 2008, is an update to a similar report published in November 2003 (NCI 2003). Summary results are

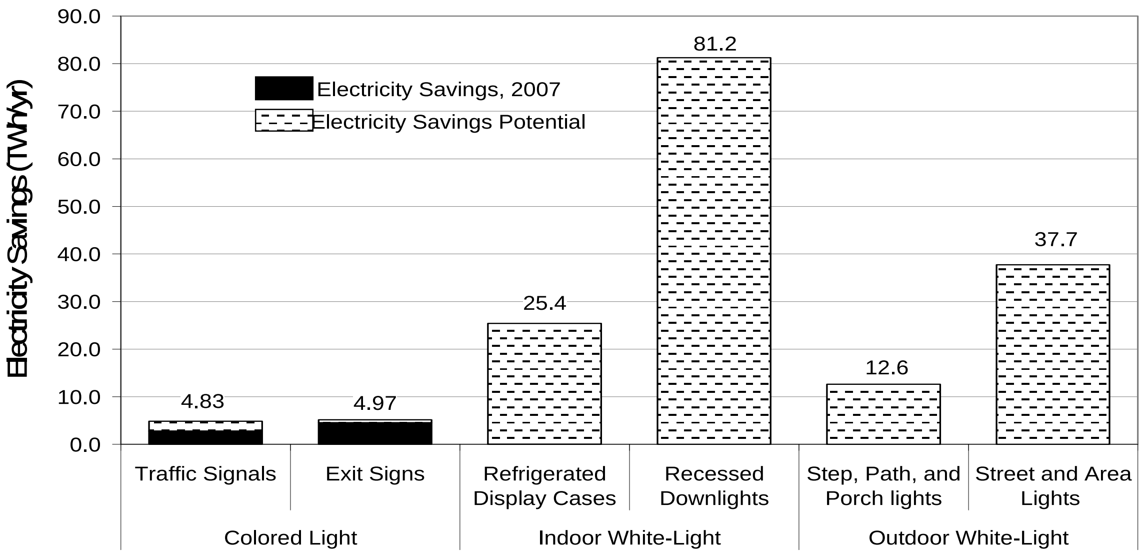
[2] Primary energy savings are calculated by multiplying electricity savings by the 2007 source-to-site conversion factor (EIA 2007b). Power plant and household numbers are estimated by dividing electricity savings by the annual output of a 1000 MW coal power plant with an average capacity factor of 72.6% (EIA 2007a) and by the average residential household electricity consumption (DOE 2007a), respectively.

discussed below. For the complete analysis, references, and documentation, a copy of the forthcoming report can be downloaded.[3]

Results/Discussion

Figure 2 summarizes the electricity savings (at the site) from the six niche markets at 2007 market penetration and with 100 percent LED penetration. Although LEDs may not fully penetrate any particular niche market, we calculate 100 percent LED penetration in order to highlight their untapped electricity savings potential. The electricity savings potential of LEDs is particularly relevant for applications such as refrigerated display cases, recessed downlights, step, path and porch lights, and street and area lights because the market penetration of LEDs in 2007 for these applications is negligible.

Figure 2. Electricity Saved and Potential Savings of Selected Niche Applications



Sources: Bhandarkar 2008a, 2008b; CEE 2002; Cook, Sommer & Pang 2008; DOE 2007a, 2007b, 2007c, 2008; Durgin 2008; EIA 1994, 1998, 1999, 2003, 2007a; English 2008; GE 2007; Ghaman 2008; Howe 2007; Kinzey & Myer 2008; Kobetsky 2008; LEDM 2006; Merritt 2007; Mueller 2007; NEMA 2003, 2005, 2006; NCI 2002, 2003; Owen 2008; Paget 2008; Raghavan 2002; RLW 2000a, 2000b, 2005a, 2005b; Steele 2008; Tarnoff 2008; U.S. Census, 1980-2001

Table 1 shows the annual electricity consumption, realized electricity savings in 2007, potential electricity savings, and the maximum electricity savings possible (equal to the sum of 2007 electricity savings and potential savings) for the six applications evaluated in this report. Of the six niche applications analyzed, LED exit signs and traffic signals were the only two applications that exhibited significant realized energy savings in 2007. The combined energy savings of LEDs in the six niche applications was 7.45 TWh per year, equal to 80.4 TBtu of primary energy savings, the equivalent annual output of 1.2 large (1,000 MW) coal power

[3] The full report will be available in August 2008 at http://www.netl.doe.gov/ssl/publications/publications-ssltechreports.htm

stations or the annual electricity consumption of over 600,000 households. Of the total amount of energy saved by LEDs in 2007 in these two applications, energy savings from LEDs in exit signs were the most significant, comprising 61% of energy savings, while energy savings from traffic signals was responsible for 38% of energy savings.

Table 1. Energy Consumption and Savings in 2007 of Applications Evaluated

Application	Annual Electricity Consumption (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Colored Light Applications				
Traffic Signals	2.38	2.82	2.03	4.85
Exit Signs	2.50	4.56	0.63	5.18
Colored Light Subtotal	4.88	7.38	2.66	10.0
Outdoor White-Light Applications				
Step, Path, and Porch Lights	22.0	0.0	12.6	12.6
Street and Area Lights	177.9	0.0	37.7	37.7
Outdoor White Light Subtotal	199.9	0.0	50.4	50.4
Indoor White-Light Applications				
Refrigerated Display Cases	165.2	0.08	25.4	25.4
Recessed Downlights	103.1	0.0	81.2	81.2
Indoor White Light Subtotal	268.3	0.08	106.6	106.6
Total	**473.2**	**7.45**	**159.6**	**167.1**

Sources: Bhandarkar 2008a, 2008b; CEE 2002; Cook, Sommer & Pang 2008; DOL 2002; DOE 2007a, 2007b, 2007c, 2008; Durgin 2008; EIA 1994, 1998, 1999, 2003, 2007a; English 2008; GE 2007; Ghaman 2008; Howe 2007; Kinzey & Myer 2008; Kobetsky 2008; LEDM 2006; Merritt 2007; Mueller 2007; NEMA 2003, 2005, 2006; NCI 2002, 2003; Owen 2008; Paget 2008; Raghavan 2002; RLW 2000a, 2000b, 2005a, 2005b; Steele 2008; Tarnoff 2008; U.S. Census, 1980-2001

Across the niche markets analyzed, significant opportunities for additional energy savings exist in both colored-light and white-light applications.[4] Presently, about 2.66 TWh of additional electricity savings are possible by increasing the market penetration of LEDs in colored-light applications, equal to 28.7 TBtu/yr of primary energy savings, the annual output of half a large coal power plant or the annual electricity consumption of 200,000 households. At least 50.4 TWh of additional site electricity savings are possible with outdoor white-light applications, amounting to 544 TBtu/yr of primary energy savings, the annual output of almost eight large coal power plants or the annual electricity consumption of more than four million households. For indoor white-light applications, 106.6 TWh of potential site electricity savings are available, equivalent to 1150 TBtu/yr of primary energy savings, the annual output of 16.8 large (1000 MW) coal power plants or the annual electricity consumption of 8.8 million households. In summary, at today's efficacy levels for LEDs, an additional 159.6 TWh per year of electricity savings is possible, equal to 1723 TBtu/yr of primary energy savings, the annual output of 25 large coal power plants or the annual electricity consumption of 13 million households if 100% of these niche markets switch to LEDs.

[4] DOE's Gateway Technology Demonstration program monitors LED products in many applications to provide independent performance data. Manufacturers and host sites may apply to participate in the program at http://www.netl.doe.gov/ssl/techdemos.htm.

Colored-Light Applications

LED sources began to enter colored-light applications in the early 1990s, with the incorporation of LEDs in traffic signal heads and building exit signs. In the early 2000s, due in part to technological improvements, reduced costs, and long operating lives (reducing maintenance costs), LEDs had already significantly penetrated these two markets by 30-35% for traffic signals and by 80% for exit signs (NCI 2003). In 2007, penetrations of LEDs reached even higher levels due to a provision in the Energy Policy Act of 2005 (EPACT 2005) that required all new installations of traffic signal heads and building exit signs to meet ENERGY STAR® requirements starting in January 2006, which can be met most cost-effectively with LEDs (ES 2006, 2007; English 2008).

Traffic signal heads. LEDs are already saving substantial amounts of energy in traffic signal heads. Because of national market transformation initiatives, such as the ENERGY STAR® program and the Consortium for Energy Efficiency's Energy-Efficient Traffic Signal Initiative, LEDs had already achieved 30% market penetration in 2002 (NCI 2003). Market penetration has increased to 50-60% in 2007 because EPACT 2005 required that all traffic signals manufactured after January 1, 2006 meet ENERGY STAR® energy consumption requirements of 12-17 watts per signal ball (Durgin 2008; ES 2006, 2008a).

Although the purchase price (i.e., first cost) of a red LED traffic signal lamp is higher than an incandescent signal, the total cost of ownership (purchase price plus operating cost) of red LED traffic signals is seventy percent less than incandescent traffic signal lamps over a seven-year period (CEE 2002; ES 2006). Operating cost savings are due both to lower energy costs and to lower maintenance costs. Because an LED has a longer lifetime than an incandescent lamp, maintenance costs are reduced primarily because of less frequent relamping requirements. Combining government and industry estimates of lamp and signal inventories, wattage, and operating hours, an estimate of the national energy consumption for traffic signal heads can be determined (Bhandarkar 2008b; Durgin 2008; Ghaman 2008; Kobetsky 2008; Steele 2008; Tarnoff 2008). Traffic signals considered in this analysis include: red-colored ball, yellow-colored ball, green-colored ball, red arrow, green arrow, yellow bi-modal arrow, green bi-modal arrow, and walking person, red hand – stop, and orange countdown pedestrian signals.

Table 1 presents this estimate in terms of electricity consumed in 2007 and the theoretical maximum electricity savings that would result if the entire market switched to LEDs. The level of LED penetration in 2007 in the traffic signal market decreased national energy consumption by 2.82 TWh/yr to 2.38 TWh/yr. Converting the remaining stock of incandescent traffic signals to LEDs would save an additional 2.03 TWh/yr. In terms of primary energy consumption, 30.4 TBtu/yr of energy is saved from existing market penetration, and a further 21.9 TBtu/yr of energy could be saved if the remainder of incandescent traffic signals convert to LEDs. Considering both present and potential energy savings, traffic signals could save approximately 4.85 TWh/year, over seventy percent of the annual output of one large (1,000 MW) coal power station, or the annual consumption of 400,000 typical U.S. households.

Exit signs. Buildings designed for public occupancy require exit signs that continuously operate to demarcate exit routes in the event of an emergency. Building safety standards mandate certain performance requirements for those exit signs; for example, self-luminous signs must have a minimum of 0.06 foot lamberts (0.21 candelas per square meter) (DOL 2002). For many years, exit signs relied on incandescent light sources to achieve these visibility requirements. However, in the last 20 years, other sources such as compact fluorescent and LED gained market share due to their lower life-cycle costs.

Today, LEDs have emerged as the technology of choice for exit sign illumination. LEDs offer more favorable economics, better performance, and more enhanced safety capabilities compared to conventional exit signs (Bhandarkar 2008a, 2008b; English 2008). Due to marketing programs such as ENERGY STAR® Exit Signs, and EPACT 2005 provisions that require all new exit sign installations to meet ENERGY STAR® requirements to consume no more than 5 watts per face, over 87% of the installed base of exit signs incorporated LEDs in 2007 (ES 2008b). Less than 5% of exit signs are still incandescent, and the remaining 8% are compact fluorescent. There are already more than 31 million LED exit signs; only 1.6 million incandescent exit signs remain in the market.

LED exit signs contributed 4.56 TWh of energy savings in 2007, compared to a baseline of incandescent and CFL exit signs. If the remaining incandescent and CFL exit signs convert to LED, an additional 0.63 TWh of energy can be saved yielding a theoretical maximum energy savings potential of 5.18 TWh/yr, the annual output of eighty percent of a large (1000 MW) coal power plant or the annual electricity consumption of over 300,000 typical U.S. households. If the entire installed base of exit signs were incandescent, LEDs would have yielded an energy savings of 7.49 TWh/yr. The primary energy savings of LED exit signs replacing the current installed base of incandescent and CFL exit signs, amounts to 49.2 TBtu/yr with a further 6.78 TBtu of annual primary energy savings potential. Thus, in total, 55.9 TBtu/yr in primary energy savings could be captured if 100% of the installed base moved to LED.

Indoor White-Light Applications

As with colored-light applications, energy can be saved in white-light applications where LED sources can be used to replace incandescent, halogen, and even fluorescent technologies. This report evaluates two indoor-white light niche market applications: refrigerator display case lighting and recessed downlights.

Refrigerated display case lighting. Almost half of the annual electricity costs for a supermarket is used to operate refrigerator and freezer display cases. Lighting to illuminate food items contributes to approximately 15% of the total energy consumed by refrigerated display cases. Lighting also adds to the heat load of the refrigerator, leading to greater compressor energy use and greater capital costs required for higher-power compressors. Linear fluorescent lamps are currently used in the majority of refrigerated display cases. Although fluorescents are highly efficacious at room temperature, their efficacy can be degraded by more than 25% in refrigerator and freezer temperatures of 38°F to -15°F. In addition, because of the geometry of the fluorescent lamp system and the lack of additional optics, only about 60% of the light is directed toward the food products on display. The remaining light is wasted as excess glare on the supermarket floor (Raghavan & Narendran 2002).

According to results from DOE's Commercially Available LED Product Evaluation and Reporting Program (CALiPER),[5] LED systems provide an efficient alternative to fluorescent refrigerated display case lighting. Not only do LED systems operate more efficiently at lower temperatures but light produced by the LED can be efficiently directed towards the displayed products. The annual electricity consumption of the lighting and compressor systems of the one million refrigerated display cases in the U.S. was 165.2 TWh/yr (DOE 2007b; GE 2007). Although Wal-Mart recently installed LED refrigerated display cases in 500 of its U.S. stores, the market penetration of LEDs in this application is still under one percent of the national installed base, saving 0.08 TWh of electricity in 2007 (LEDM 2006). If all refrigerated display cases convert to LEDs, an additional 25.4 TWh of energy can be saved. This corresponds to a theoretical maximum primary energy savings of 273.8 TBtu at the power plant, the energy consumption of four 1000 MW coal power plants or the annual electricity consumption or two million households.

Recessed downlights. Although originally intended for directional lighting, recessed downlights have become a common fixture used for general ambient lighting in both residential and commercial buildings. While some LED based products have been offered as "substitutes" for incandescent reflector lamps for these applications, only in 2007 were products introduced to the market which offered a sufficiently bright lumen level and quality of light that they could be considered adequate substitutes for incandescent reflector lamps. For this reason, the market penetration of LEDs in recessed downlights is assumed to be zero percent in 2007. These LED recessed downlight products, as measured by CALiPER can be more efficient than both conventional incandescent reflector and compact fluorescent technologies (DOE 2008). In fact, recessed LED products with superior efficacy, lumen output, color quality, thermal management, and off-state power characteristics now qualify for the ENERGY STAR® label. Although these LED products are not as directional as incandescent reflector lamps (less light is produced at the center of the beam), the amount of glare produced by the luminaire is reduced. Depending on the application, these attributes may be important to consider.

If LEDs achieved 100% market share of recessed downlights, a technical potential of 81.2 TWh of annual electricity savings could be realized (NCI 2002; RLW 2000a, 2000b, 2005a, 2005b; U.S. Census 1980-2000), greater than the electricity savings potential of the five other niche applications described in this report. In terms of primary energy consumption, the potential energy savings of LED recessed downlights is 877 TBtu/yr at the power plant, equivalent to the annual consumption of 12.8 large (1000 MW) coal power plants or the annual electricity consumption of 6.7 million typical U.S. households.

Outdoor White-Light Applications

As with indoor white-light applications, electricity can be saved in outdoor white-light applications where LED sources could replace incandescent, halogen, mercury vapor, metal halide and high-pressure sodium lamps. This report evaluates two outdoor white-light niche market applications: street and area lighting, and step, path, and porch lighting.

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[5] CALiPER test results of LED products for the white-light applications described in this report are available at: http://www.netl.doe.gov/ssl/comm_testing.htm.

The energy savings estimates given in this report could be even greater if the visible light output of these sources under outdoor "night time" conditions were taken into account. Light output is typically reported under "daytime" conditions when the eye uses its cones to perceive light. For this study, we have used these reported "daytime" light output values to establish the efficacy of the lighting systems. However, at night, when outdoor lights are used, the eye uses both rods and cones to sense light. Assuming equal quantities of "daytime" light produced, light sources rich in blue light, such as LEDs or metal halide lamps produce more visible light at night than light sources rich in yellow light such as high or low pressure sodium lamps (Bullough 2001). To capture these additional energy savings, manufacturers would need to report the efficacy of their light sources under nighttime conditions and lighting designers would need to take them into account.

Street and area lighting. Streetlights serve the purpose of illuminating the roadway to improve visibility for drivers at night while area lights serve to illuminate outdoor sites such as parking lots and garages, outdoor landscapes, pedestrian walkways, and municipal and downtown common outdoor spaces. In this study, we took into account only those street and area lights that use high-intensity discharge lamps such as mercury vapor, metal halide or high-pressure sodium lamps as these represent the vast majority of street and area lights.

LEDs are particularly advantageous in street and area lighting applications because they are better directional light sources, exhibit longer lifetimes, and enhance nighttime visibility. The efficacy of LED street and area lights also exceed the efficacy of many conventional sources (DOE 2007c). Because of these positive attributes, Raleigh, North Carolina became the first of a dozen U.S. cities to begin replacing their conventional street lighting technologies with LED fixtures in February 2007 (Howe 2007). Although several cities have begun to adopt LED technologies in street and area light applications, we assume the penetration of LEDs for this application is effectively zero percent as the number of LED streetlights these cities have installed is less than one fifth of one percent of the total installed base of streetlights in the U.S.

Of the 164.5 TWh/year of electricity consumed by street and area lights, approximately 37.7 TWh of annual electricity savings could be realized if LEDs achieved 100% market penetration (Cook, Sommer & Pang 2008; Howe 2007; Merritt 2007; Mueller 2007; Owen 2008; U.S. Census 1980-2001). This would equate to approximately 407.4 TBtu/yr of primary energy that can be saved at the power plant, the equivalent of 5.9 large (1000 MW) coal power plants or the annual electricity consumption of three million households.

Step, path, and porch lighting. A similar promising niche application for LEDs is residential step, path, and porch lighting. Several manufacturers have created specialized products for this application, with some designs winning the annual *Lighting for Tomorrow* prizes for innovative and energy-efficient LED product designs.[6] Because products have only recently been introduced in the marketplace, it is assumed that there is no market penetration for LEDs in this application. LED products are beneficial in this application because they provide enhanced nighttime visibility, longer lifetimes, and energy savings when replacing incandescent or halogen outdoor lighting (DOE 2007c). Currently, residential outdoor LED products with superior

[6] The winning designs from DOE's Lighting for Tomorrow can be viewed at http://www.lightingfortomorrow.com/

efficacy, lumen output, color quality, thermal management, and off-state power characteristics qualify for the ENERGY STAR® label.

Step, path, and porch lighting consumed approximately 22.0 TWh in 2007 (DOE 2007c; Paget 2008; U.S. Census 1980-2001). Electricity savings of 12.6 TWh/yr is possible if 100% of the market migrated towards LED products, equivalent to a primary energy savings of 136.3 TBtu/yr at the power plant. The theoretical maximum energy savings of LEDs in step, path and porch lighting is equivalent to the annual output of two large coal power plants or the annual electricity consumption of one million households.

Ancillary Benefits

LEDs provide benefits in addition to energy savings for the applications this report analyzed:

1. Reduced Heat Production - Because of their higher efficiency in certain applications, LEDs generate less heat. This reduces the need for air-conditioning or heat extraction technologies, particularly if the LED replaces an incandescent lamp. Industry research into LED heat management is ongoing, as it is a major engineering challenge in LED product development.[7]
2. Durability – The light production mechanism of LED devices enables it to resist vibration and impact, such as from opening and closing doors in refrigerated display cases. In contrast, hot (incandescent) filaments and the fragile ballast electronics and glass tubes of fluorescents are susceptible to failure under when exposed to vibration or impact during operation.
3. Longer Life – Most LED products in the market have a lifetime greater than 50,000 hours. In comparison, typical incandescent lamps last 1,000 hours, fluorescent lamps last 20,000 hours, and HID lamps last 24,000 hours.
4. Lower Operating Costs – Throughout their lifetime, LED lamps in most applications exhibit lower operating costs than conventional technologies because they consume less energy and have lower maintenance costs because of their longer lifetime.
5. Lower Lumen Depreciation – The light emitted by an LED can depreciate less over its lifetime than HID and fluorescent lamps. Therefore, given the same initial lumen output, an LED could provide more light over its lifetime than an HID or fluorescent lamp.
6. Improved Color Rendition – LEDs reproduce the colors of various objects more faithfully than both high and low pressure sodium lamps. High and low pressure sodium lamps have a color rendering index[8] (CRI) as low as 23 whereas LEDs can have a CRI as high as 90.
7. Light Pollution Reduction – In outdoor applications, the directional quality of LED luminaires can result in more lumens on the ground and fewer lumens scattered upward.

Conclusion

[7] LEDs produce conducted heat, unlike an incandescent source, which predominantly produces radiated heat.
[8] The color rendering index (CRI) measures the ability to reproduce colors accurately, up to a maximum CRI of 100.

LEDs are emerging as a competitive lighting technology, capturing market share in several niche applications because they save energy and offer other ancillary benefits, including increased durability and longer life. Of the six applications analyzed, the two colored light applications, namely exit signs and traffic signals, saved the largest amount of energy in 2007. Market penetration of LEDs in other applications, such as refrigerated display cases lighting, recessed downlights, street and area lights, and step, path, and porch lights, is negligible. Commercial LED products for these applications have become available recently; however, large-scale market adoption has yet to occur. If all six of these niche applications completely convert to LED lights, approximately 159.6 TWh of additional annual site electricity savings would be realized, including 2007 electricity savings. This equates to approximately 1.7 quadrillion Btu ("quads"), or almost two percent of total national energy consumption in 2007 (EIA 2007b).

In recent years, LEDs have entered the lighting market, offering consumers performance and features exceeding those of traditional lighting technologies. Particular applications where these benefits can be realized include those niche market applications involving colored light emission, such as exit signs and traffic signals, and white-light emission such as refrigerated display case lighting, recessed downlights, street and area lights, and step, path, and porch lighting. As LED technology advances–reducing costs and improving efficiency–LEDs may build market share in these and other niche markets.

References

Audin, L., D. Houghton, M. Shepard, and W Hawthorne. 1997. *Lighting Technology Atlas.* Boulder, Colo.: E Source, Inc. 2.2.5.

Bhandarkar, V. 2008a. "Market Perspectives and Timing." Presentation presented at *Solid State Lighting R&D Workshop,* Atlanta, Ga., January 29-31.

______. (Strategies Unlimited). 2008b. Personal communication. March 4.

Bullough, J. 2001. "Driving in Snow: Effect of Headlamp Color at Mesopic and Photopic Light Levels." In *SAE Technical Paper Series from the 2001 World Congress.* Detroit, Mich.: Lighting Research Center.

[CEE] Consortium for Energy Efficiency. 2002. "LED Traffic Signals Provide Dramatic Energy Savings." www.cee1.org/gov/led/led-cost.pdf.

Cook, T., A. Sommer, and T. Pang. 2008. "LED Street Lighting." *U.S. Solid State Lighting Technology Demonstration Gateway Program.* Oakland, Calif.: U.S. Department of Energy.

[DOE] Department of Energy. 2007a. *2007 Buildings Energy Databook.* Washington, D.C.: U.S. Department of Energy.

______. 2007b. *Commercial Refrigerated Equipment Energy Conservation Standard Advanced Notice of Proposed Rulemaking.* Washington, D.C.: U.S. Department of Energy.

______. 2007c, 2008. *DOE Solid-State Lighting CALiPER Program: Summary of Results: Round 2, 3, and 4 of Product Testing.* http://www.netl.doe.gov/ssl/comm_testing.htm

[DOL] Department of Labor. 2002. "Occupational Safety and Health Administration Final Rule: Exit Routes, Emergency Action Plans, and Fire Prevention Plans; Final Rule." *Federal Register* 67: 67949-67965.

Durgin, G. (Dialight Corporation). 2008. Personal communication. February 20, 22.

[EIA] Energy Information Administration. 1994, 1998. *Manufacturing Energy Consumption Survey*. Washington, D.C.: U.S. Department of Energy.

______. 1999, 2003. *Commercial Buildings Energy Consumption Survey.* Washington, D.C.: U.S. Department of Energy.

______. 2007a. *Electric Power Annual.* Washington, D.C.: U.S. Department of Energy.

______. 2007b. *Annual Energy Outlook.* Washington, D.C.: U.S. Department of Energy.

[ES] ENERGY STAR®. 2007, 2006. *Life-Cycle Cost Estimate for Energy Star-Qualified Exit Signs, Traffic Signals*. Washington, D.C.: U.S. Department of Energy and U.S. Environmental Protection Agency.

______. 2008a, 2008b. *Energy Star Program Requirements for Traffic Signals, Exit Signs.* Washington, D.C.: U.S. Department of Energy and U.S. Environmental Protection Agency.

English, C. (Acuity Brands). 2008. Personal communication. February 11.

[GE] General Electric Lumination. 2007. "Refrigerated Display LED Lighting System." http://ge.ecomagination.com/site/#gcfr/

Ghaman, R. Federal Highway Administration (FHWA). 2008. Personal communication. February 26.

Howe, D. A. (Raleigh, NC). 2007. Personal communication. December 19.

Kobetsky, K. (American Association of State Highway and Transportation Officials). 2008. Personal communication. February 22.

[LEDM] "Wal-mart fits refrigerated displays with GELcore LED lights." 2006. *LEDs Magazine*. November 17.

Merritt, G. (CREE). 2007. Personal communication. December 19.

Mueller, G. (BetaLED). 2007. Personal communication. December 19.

[NEMA] National Electrical Manufacturers Association. 2006. "High-Intensity Discharge Lamp Survey." *Energy Conservation Program for Commercial and Industrial Equipment: High-Intensity Discharge (HID) Lamps Rulemaking*, Docket # EE–DET-03-001.

______. 2005. "NEMA A-line Statistical Wattage Survey." *California Energy Commission, Appliance Rulemaking 1*, Docket # 05-AAER-2.

______. 2003. "Number of Mercury Vapor and PAR/R Lamps Survey for DOE." *Energy Conservation Program for Commercial and Industrial Equipment: HID Lamps Rulemaking*, Docket # EE–DET-03-001.

[NCI] Navigant Consulting, Inc. 2003. *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications.* Washington, D.C.: U.S. Department of Energy.

______. 2002. *U.S. Lighting Market Characterization. Volume: I: National Lighting Inventory and Energy Consumption Estimate.* U.S. Washington, D.C.: U.S. Department of Energy.

Owen, B. K. (GreenTBiz). 2008. Personal communication. January 3.

Paget, M. (Pacific Northwest National Laboratory). 2008. Personal communication. February 29, April 22.

Raghavan, R., and N. Narendran. 2002. "Refrigerated display case lighting with LEDs." In *Solid State Lighting II: Proceedings of the Society of Photo-Optical Instrumentation Engineers.* 4776: 74-81. Seattle, Wash.: Society of Photo-Optical Instrumentation Engineers.

[RLW] RLW Analytics, Inc. 2000a, 2000b, 2005a, 2005b. "Statewide Residential Lighting and Appliance Efficiency Saturation Survey and SMUD Specific Reports." Sonoma, Calif.: RLW Analytics, Inc. http://www.calresest.com/index.cfm

Seoul Semiconductor W42181 Z-Power LED.

Steele, R. (Strategies Unlimited). 2008. Personal communication. March 3.

Stevenson, R. 2007. "LED chip makers lock horns in Vegas." *Compound Semiconductor*. November 12.

Tarnoff, P. (University of Maryland, College Park). 2008. Personal communication. February 15.

[U.S. Census] U.S. Census Bureau. 1980-2001. *Current Industrial Reports: Electric Lighting Fixtures.* (1994 and after): http://www.census.gov/cir/www/335/ma335l.html.