Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

Prepared for:

Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Navigant Consulting Inc.
1801 K Street, NW Suite 500
Washington DC, 20006

Released: September 2008
Revised: October 2008

Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

Prepared for:

Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Navigant Consulting Inc.
1801 K Street, NW Suite 500
Washington DC, 20006

Released: September 2008
Revised: October 2008

Disclaimer

Copies of this Report

Electronic (PDF) copies of this report are available to the public from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Tel: 1-800-553-6847
Web: www.ntis.gov

Building Technologies Program
U.S. Department of Energy
Web: http://www.eere.energy.gov/buildings/info/publications.html#technicalreports

Foreword

This analysis of niche markets and applications for light emitting diodes (LEDs) was undertaken on behalf of the U.S. Department of Energy to develop a more complete understanding of the energy savings resulting from the use of LEDs and the factors that are motivating consumers to adopt this new technology.

Comments

The Department is interested in receiving input on the material presented in this report. If you have suggestions of better data sources and/or comments on the findings presented in this report, please submit your feedback to Dr. James R. Brodrick by November 30, 2008 at the following address:

James R. Brodrick, Ph.D.
Program Manager – Lighting Research and Development
EE-2J / **Forrestal Building**
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585

Acknowledgments

The authors would like to acknowledge the valuable support, guidance, and input offered in the preparation of this report. James R. Brodrick, Ph.D., of the U.S. Department of Energy, Building Technologies Program provided oversight of the assignment, helping to shape the approach, execution, and documentation. The authors are also grateful to the following list of experts for their respective contributions, guidance, and review, which proved invaluable in preparing the estimates contained in this report.

David Allen	Forever Bright
Steven Altamura	Seasonal Specialties
Vrinda Bhandarkar	Strategies Unlimited
Jill Bonilla	SloanLED
Jose Chavez	Westinghouse – Lighting Technologies
Kevin Dowling	Philips Lighting Company
Gary Durgin	Dialight
Cheryl English	Acuity Brands Lighting
Raj Ghaman	Federal Highway Administration
Kelly Gordon	Pacific Northwest National Laboratory
Daniel Howe	City of Raleigh
Damon Jackson	LEDTronics
Greg Merritt	CREE
Greg Mueller	Beta Lighting
Brian Owen	greenTBiz – LEDs MAGAZINE
Mia Paget	Pacific Northwest National Laboratory
Jim Sloan	SloanLED
Robert Steele	Strategies Unlimited
Wade Swormstedt	Signs of the Times
J. Bryan Vincent	AgiLight
Fred Welsh	Radcliffe Advisors

TABLE OF CONTENTS

TABLES

FIGURES

List of Acronyms and Abbreviations

ANSI	American National Standards Institute
ASM	Annual Survey of Manufacturers
CALiPER	Commercially Available LED Product Evaluation and Reporting Program
CASE	Codes and Standards Enhancement
CBECS	Commercial Buildings Energy Consumption Survey
CEE	Consortium for Energy Efficiency
CFL	Compact Fluorescent Lamp
CRI	Color Rendering Index
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
DSM	Demand Side Management
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 2005
FHWA	Federal Highway Administration
HID	High Intensity Discharge lamp
IESNA	Illuminating Engineering Society of North America
ITE	Institute of Transportation Engineers
LBL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LRC	Lighting Research Center
MECS	Manufacturing Energy Consumption Survey
MW	Megawatt
NCI	Navigant Consulting Incorporated
NEMA	National Electrical Manufacturers Association
PG&E	Pacific Gas and Electric
PNL	Pacific Northwest National Laboratory
RECS	Residential Energy Consumption Survey
RPI	Rensselaer Polytechnic Institute
SMUD	Sacramento Municipal Utility District
SSL	Solid State Lighting
STMG	*Signs of the Times* Magazine
TWh	Terawatt-hour
UIE	University of Illinois Extension
USITC	United States International Trade Commission
W	Watt
WSU	Washington State University

Executive Summary

Light Emitting Diodes (LEDs), a type of Solid State Lighting (SSL), offer the electric lighting market a new and revolutionary light source that saves energy and improves quality, performance, and service. Today, LEDs are competing successfully with conventional, incandescent light sources that use color filters to generate the desired colored light emission, such as those found in traffic signals and exit signs. In these and other applications, consumers choose LEDs because they offer more cost-effective performance than incandescent lamps.

This report presents research findings for twelve different niche markets where LEDs are competing or are poised to compete with traditional light sources, such as incandescent, halogen, fluorescent, neon, and high-intensity discharge (HID). LEDs are challenging traditional light sources, because the LED offers lower operating costs and better reliability and performance. This report presents estimates of the energy saved due to estimated current levels of LED market penetration. This report also estimates the "overnight" technical potential energy savings if these markets switched completely to LEDs. The markets analyzed in this report are classified into three groups:

Colored-Light Applications

- Traffic Signals and Pedestrian Crossings
- Decorative Holiday Lights
- Exit Signs
- Electric Signage

Indoor White-Light Applications

- Recessed Downlights
- Refrigerated Display Cases
- Retail Display
- Task Lights
- Office Undershelf Lights
- Kitchen Undercabinet Lights

Outdoor White-Light Applications

- Street and Area Lights
- Step, Path, and Porch Lights

This study found that the applications where LEDs have the highest level of market penetration are colored-light applications such as traffic signals, exit signs, holiday lights and electric signage. In these installations, LEDs have the advantage of only producing light in the color of interest to the end-user, thus they can do so more efficiently and reliably than filtered full-spectrum sources. The applications where market adoption is maturing or poised to grow include traffic signals and pedestrian crossings, decorative holiday lights, exit signs, electric signage, and refrigerated display case lighting. The applications where market adoption has yet to occur, but for which high quality LED products are currently available include recessed downlights, retail display, task lights, office undershelf and kitchen undercabinet lights, street and area lights, and outdoor step, path, and porch lights. In these and a growing list of other applications, well-designed LED products can save energy, and provide equivalent or better lighting quality, compared to conventional lighting technologies. In addition, the potential for very long service life of LED products, and greatly reduced lighting maintenance costs, is an important factor in light source selection for many applications. These and other ancillary benefits of using LEDs are discussed in Table 1-2.

This report presents the findings of analysis on these twelve LED niche applications, addressing four fundamental questions:

- How much energy is consumed by lighting technologies in these applications?
- What is the estimated market penetration of LED technology today?
- What are the energy savings resulting from the current level of LED market penetration?
- What would the energy savings be from 100% LED market penetration?

For colored-light, indoor and outdoor white-lighting applications, energy savings are reported in both trillion watt-hours (TWh) of national electricity savings as well as trillion British thermal units (TBtu) of primary energy consumption saved at the power plant level from the avoided electricity, assuming the average national generation fuel mix in the U.S.[1] To put these figures into perspective, energy savings are also presented in terms of the output of an equivalent number of large (1000 MW) coal power plants and the annual electricity consumption of thousands or millions of typical U.S. households.

Figure ES.1 summarizes the electricity savings (at the site) from the top two colored-light, indoor white-light, and outdoor white-light niche applications with the greatest electricity savings in 2007 or if no savings have yet occurred in that type of application, the greatest electricity savings potential. Also displayed is the corresponding number of coal power plants that could be avoided due to these potential electricity savings.

[1] Primary energy savings are calculated by multiplying electricity savings by the 2007 source-to-site conversion factor (EIA 2008). 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 2007b) and by the average residential household electricity consumption (DOE 2007a), respectively.

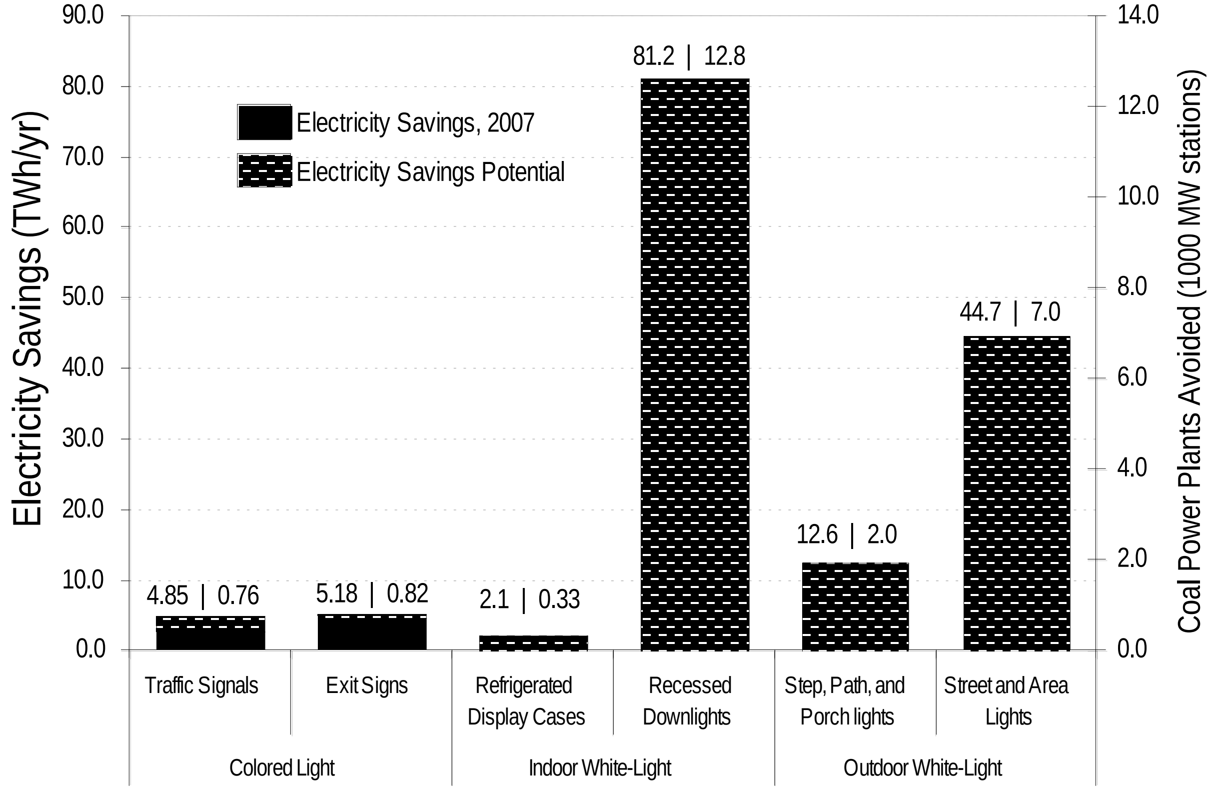

Figure ES.1 Electricity Saved and Potential Savings of Selected Niche Applications

In 2007, the current penetration of LEDs in the twelve niche applications analyzed in this report resulted in a realized electricity savings of 8.7 TWh per year. To put this figure in perspective, the Department of Energy estimates that the total annual energy consumption for all lighting technologies in the U.S. was 765 TWh in 2001 (DOE, 2002a).

Table ES.1 provides a detailed summary including both electricity consumption and primary energy consumption. Some sectors have estimates of zero percent LED penetration, thus contribute no savings to the total of 8.7 TWh. In general, the average luminaire efficacy of the LED for all twelve applications was assumed to be between 22.5 lm/W and 60.9 lm/W. More detailed information on this and other assumptions for all of the applications can be found in the body of the report.

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

Application	Annual Electricity Consumption (TWh)	LED Market Penetration	Electricity Savings 2007 (TWh)	Primary Energy Savings 2007 (TBtu)
Colored Light Applications				
Traffic Signals	2.38	52%	2.82	30.4
Decorative Holiday Lights	6.63	5.2%	0.33	3.53
Exit Signs	2.50	88%	4.56	49.2
Electric Signage	11.6	6.1%	0.95	10.3
Indoor White-Light Applications				
Recessed Downlights	103.1	0.0%	0.0	0.0
Refrigerated Display Cases	13.4	3.6%	0.08	0.81
Retail Display	32.0	0.0%	0.0	0.0
Task Lighting	18.8	0.0%	0.0	0.0
Kitchen Under-Cabinet Lighting	2.84	0.0%	0.0	0.0
Office Undershelf Lighting	3.43	0.0%	0.0	0.0
Outdoor White-Light Applications				
Street and Area Lights	178.3	0.0%	0.0	0.0
Step, Path, and Porch lights	22.0	0.0%	0.0	0.0
Total	**397 TWh**	**--**	**8.7 TWh**	**94 TBtu**

As shown in Table ES.1, the electricity savings in 2007 attributable to LEDs are dominated by exit signs, where they have achieved an estimated 88% market penetration. This niche market represents 52% of the total energy savings attributable to LEDs in 2007. The second most significant energy saving niche market in 2007 was traffic signal heads. In this application, approximately 52% of the signals are estimated to incorporate LED technology, representing approximately 32% of the total energy savings from LEDs in 2007. From negligible penetration in 2002, LEDs have reached 6.1% of the electric signage market and 5.2% of the decorative holiday lights market, contributing to 11% and 4% of the total energy savings from LEDs in 2007, respectively. LEDs have also begun to penetrate the refrigerated display case market, reaching 3.6% penetration in 2007. Other applications such as recessed downlights, retail display, task lighting, street and area lights, and step, path, and porch lights were estimated to have insignificant market penetration of LEDs. Commercial LED products are available in these markets; however significant market adoption has yet to occur.

Table ES.2 presents the potential energy savings in each market from converting the remainder of the sockets to LED technology. It also presents the theoretical maximum energy savings (i.e., the sum of 2007 electricity [or primary energy] savings and potential electricity [or primary energy] savings) attributable to LEDs for each market for a complete conversion to LED relative to the conventional lighting technology. For applications with no market penetration of LEDs and no energy savings in 2007, energy savings potential equals theoretical maximum energy savings.

Table ES.2 Potential and Theoretical Maximum Energy Savings of Applications Evaluated

Application	Electricity Savings Potential (TWh)	Primary Energy Savings Potential (TBtu)	Theoretical Maximum Electricity Savings (TWh)	Theoretical Maximum Primary Energy Savings (TBtu)
Colored Light Applications				
Traffic Signals	2.03	21.9	4.85	52.3
Decorative Holiday Lights	5.97	64.4	6.30	67.9
Exit Signs	0.63	6.78	5.18	55.9
Electric Signage	6.58	71.0	7.53	81.3
Indoor White-Light Applications				
Recessed Downlights	81.2	876.6	81.2	876.6
Refrigerated Display Cases	2.0	21.6	2.1	22.4
Retail Display	7.87	84.9	7.87	84.9
Task Lighting	13.0	140.1	13.0	140.1
Kitchen Under-Cabinet Lighting	2.22	24.0	2.22	24.0
Office Undershelf Lighting	1.37	14.8	1.37	14.8
Outdoor White-Light Applications				
Street and Area Lights	44.7	482.0	44.7	482.0
Step, Path, and Porch lights	12.6	136.3	12.6	136.3
Total	**180 TWh**	**1944 TBtu**	**189 TWh**	**2039 TBtu**

Of the applications analyzed in this report, recessed downlights, street and area lights, refrigerated display cases, task lights and outdoor step, path, and porch lighting represent the top five applications with the greatest future savings potential for LEDs. Of these, recessed downlights appear to be the most promising, with 81.2 TWh of potential savings.

The potential for greater energy efficiency with LED sources is an important consideration, along with other attributes that might induce lighting users to adopt this technology over conventional light sources. In several applications, well-designed LED products and luminaires can offer the following benefits, relative to conventional lighting products:

- Reduced Energy Consumption – LED devices can offer a more energy efficient means of producing light, particularly when compared to incandescent sources. In an application such as a traffic signal, an 8W LED red signal head replaces a 135W reflector lamp – a 94% reduction in energy consumption - while complying with the same safety standards. And as SSL technology evolves, the efficiency of these devices will continue to improve, enabling even greater energy savings through conversion to LED.

- Long Operating Life – Commercial and industrial specifiers are generally interested in using a light source that is reliable and lasts a long time. Frequent lamp replacements can be costly from a maintenance perspective, and failed lamps could expose lamp operators to liabilities (e.g., traffic signals or exit signs). In fact, maintenance savings are one of the primary reasons behind market adoption of LEDs in several markets, such as electric signage, street and area lights, and retail display lighting. Presently, LED technology offers operating lives that are approximately twenty-five times longer than those of incandescent sources.[2] Researchers indicate that operating life will continue to improve as the technology develops.

- Lower Maintenance and Life-Cycle Costs - The longer life of LEDs translates into less frequent relamping and lower maintenance costs. Although several LED products cost more than conventional products, the lower energy consumption and extended operating life (and associated maintenance savings) equate to lower life-cycle costs. For example, the cost of ownership, including energy and maintenance costs, of one intersection of LED traffic signals is about ninety percent less than that of an intersection of incandescent traffic signals (ENERGY STAR, 2006, 2008a).

- Reduced Radiated Heat – LEDs convert a higher proportion of electricity into visible light than incandescent sources. LED conversion efficiency has improved rapidly and is expected to continue; current LED luminaires can be equivalent to or more efficient than fluorescent and HID luminaires at converting power to visible light. Further, incandescent sources convert most of the power they use into infrared (IR) radiation (radiated heat), and some discharge sources emit both IR and ultraviolet (UV), but LEDs emit neither (unless specifically designed to do so). Instead, the waste heat generated by the LED must be removed by heat-conducting material (a “heat sink”). The reduction in heat radiated into conditioned space may reduce the air-conditioning or refrigeration load for some applications.

- Minimal Light Loss – Unlike conventional lamps, LED luminaires do not need color filters to produce colored-light. In colored-light applications, light loss can be minimized by matching the color of the LED chip emitter to the color of the translucent covering on the lighting fixture. Furthermore, light emitted from an LED device is more directional and controlled, meaning that fewer photons are trapped within the lighting fixture. By contrast, conventional lamps have a 360 degree emission range, which results in lower fixture efficiencies as light is lost as the light is dispersed to the back of the fixture.

- Dimmability and Controllability – For most applications, LED luminaires can be designed with dimming controls and motion sensors to adjust brightness levels. For example, LEDs can be dimmed more efficiently than fluorescents because rapid and frequent on/off cycles do not affect the life of the LED, enabling the use of movement-triggered controls. These controls can reduce the annual operating hours of the LED system and lead to greater energy savings than we calculate in this report.

- Directional Illumination – The LED sources can be targeted to illuminate particular parts of the packaging or prices in the display case, calling customer’s attention to aspects of the display case that may result in a sale. Similarly, LED task, office undershelf, or kitchen undercabinet lights can be targeted to illuminate particular parts of the work space, leading to higher fixture efficiencies and higher illumination to complete tasks, with less light scattered away from the work space.

---

[2] We assume that manufacturers’ claims of 50,000-hour LED lifetimes can be substantiated. However, these claims have not been independently verified by DOE.

- Durability – the light production mechanism for LED devices is fundamentally different from traditional light sources such as incandescent and fluorescent. LED sources produce light by passing a current through thin layers of a semi-conductive material, which causes the recombination of electron-hole pairs in the material which emit light. Inherent in this solid-state light production mechanism is the ability of the source to resist vibration and impact, making it an ideal light source for refrigerated display cases, office undershelf and kitchen undercabinet lighting. The LED is encased in a tough epoxy plastic resin instead of a fragile glass bulb, thus, they are more resistant to shattering or impact damage in these applications.

- Safety Improvements – For several applications, characteristics specific to LEDs lead to safety enhancements. LED luminaires are made of multiple diodes, and are less likely to fail simultaneously, leading to less down time for traffic signals, enhancing traffic flow and safety. In addition, LED holiday lights emit less heat than incandescents, and can reduce the current total of 210 home-structure fires per year due to ignited Christmas trees (Ahrens, 2007). LED electric signage is also typically operated at lower voltages and direct current which are safer for maintenance workers to handle than neon, which operates at 12,000 to 15,000 volts of alternating current.

- Color Maintenance - Monochromatic LEDs for colored light applications allow the elimination of filters and hence better color control and color life than conventional technologies.

- Smaller Package Size – Due to their compact size, LED devices are an excellent option where size or weight is a concern. For example, LED lighting provides more shelf space for merchandise in a refrigerated display case. This is because the LED and driver system is much smaller than a fluorescent lamp and ballast system, and can be distributed throughout the display case, unlike fluorescents.

- Uniform Illumination. – LED devices offer distinct advantages where light encroachment or glare is a problem. For example, through the use of lenses and lighting controls, LED street and area lights, and step, path, and porch light luminaires can better distribute the light across the ground, allowing more uniform illumination.

- Battery Back-Up Capability - Traffic signals that include red, green, and yellow LEDs consume around one-tenth as much power and LED exit signs consume about one-fifth as much power as with incandescent sources. For this reason, battery back-up power supplies are available which can operate during power failures to ensure smooth flow of vehicular traffic or continuous delineation of building routes of egress. Many agencies use yellow LED signals for battery back-up reasons in emergency situations. For instance, if yellow LED signals were used in flashing mode, work crews would have a few extra hours to handle emergency situations (Bullough, 2003b).

- Adjustable Color – Storeowners could also easily alter the intensity and color of the LED light to augment particular colors in the products. Recent marketing studies have shown that these features offer enhanced appeal to the human eye compared to other lighting systems.

Study subjects strongly preferred display cases with LED lighting systems at half the illumination levels of fluorescent systems (Narendran, 2003b).

- Light Pollution Reduction – The directional quality of LED street and area or step, path, and porch luminaires leads to more lumens to light the road plane or path and fewer lumens scattered upward, reducing light pollution.

These and other qualities of LED sources are encouraging the marketplace to adopt LED technology in niche applications today, and general illumination applications in the future. As the market for LED technologies expands, industry will continue to develop manufacturing processes that reduce the cost of LED lamps, which will accelerate market adoption.

1. Introduction

Solid-state lighting (SSL) has the potential to revolutionize the lighting market through the introduction of more energy efficient light sources. LEDs can be found in a range of niche market applications involving colored light emission, such as exit signs, traffic signals, and electric signage. Technical advances have made light emitting diodes (LEDs) competitive in not only in these colored-light applications, but recently in some outdoor white-light and indoor white-light applications as well, such as recessed downlights, refrigerated display cases, street and area lights and outdoor step, path, and porch lights. LED technology is capturing market share in these new applications because well-designed LED products exist that can provide energy savings, equivalent or better lighting quality, and cost-effective lighting service, depending on usage, electricity rates, and maintenance costs compared to conventional light sources such as incandescent, neon, high-intensity discharge (HID), and fluorescent. In addition to energy savings, LEDs can offer longer operating lifetimes (>50,000 hours), lower operating costs, improved durability, and improved color rendition. As LED technology advances – reducing costs and improving efficiency–LEDs will build market share in these and other niche markets.

1.1. LED Technology Background

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. This first LED had properties that resembled the transistor – high tolerance for shock and vibration and long operating life. While the efficacy[3] of the first LEDs was extremely low (approximately 1 lumen per watt), researchers have improved this technology over the past four decades. Today, white LED devices are capable of operating at 134 lumens per watt in the laboratory (Stevenson, 2007). Present day white LED commercial devices have reached efficacies of 101 lm/W, comparable to the efficacies of certain fluorescent and high-intensity discharge (HID) lamps, with efficacies still rising rapidly (Audin et al., 1997, 2.2.5; Nichia).[4]

Compared to incandescent, neon, fluorescent or high-intensity discharge lamps, LEDs produce light using a fundamentally different principle. Whereas the traditional light sources produce light by heating a filament to incandescence or establishing an electrical arc through a gas mixture, LEDs emit light from a small semiconducting chip when a current is applied to it. LEDs are semiconductors created by bringing together similar materials with slightly different electronic properties to create a "PN junction". In a PN junction, the "P" material contains an excess of positive charges (also called holes) due to the absence of electrons. The "N" material contains an excess of negative charges due to the presence of electrons. When a voltage is applied to this PN junction, the electrons and the holes combine, releasing energy that can take the form of visible light.

Unlike the incandescent lamp, LEDs can emit light in a narrow wavelength band, making the emission appear colored. Since the initial breakthrough in the 1950s, research has focused on

---

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

[4] Efficacies of incandescent, fluorescent, and HID lamps from Audin, L., Houghton, D., et al. *Lighting Technology Atlas.* E Source, Inc., Boulder, CO (1997). (p 2.2.5) Efficacy of LED: Nichia NS6W083B SMD Power LED.

developing new LED semiconductor materials that enable LEDs to emit each color in the visible spectrum. Research has also improved the efficacy and power handling capability of LED devices themselves, enabling them to now compete with conventional technologies in colored-lighting applications. Many of these applications where LEDs compete or are poised to compete are discussed in this report.

Today, the majority of white-light LEDs emit blue or ultraviolet light onto a phosphor. The phosphor then converts the blue or ultraviolet light emitted by the LED into white light. Assembling three or more LED chips that emit in the blue, green and red spectral zones can also create white-light LED packages. In this type of multi-chip design, the individual light emission from each of the chips will blend to create a white-light emission from the package. This approach, currently more expensive than the phosphor method, has the potential to reach higher efficacies (DOE, 2008). White light can also be created with just two LEDs, (e.g. yellow and blue), when good color rendering is not critical. When color rendering is critical, warm-white light, similar to the output of an incandescent lamp, can be created by using specific phosphors designed to emit light in the warmer spectral range. Alternatively, light from cool white LEDs and a monochromatic orange-red LED can be blended to produce a warm-white light.

1.2. Niche Markets Reviewed

The Department identified twelve LED niche market applications for this study. Shown in Table 1-1, these niche markets are grouped into three general categories: colored-light applications, indoor white-light applications, and outdoor white-light applications. The baseline energy consumption of some of these niche markets may be very small; however they were studied to understand some of the benefits of LED technology that are encouraging various markets to convert.

Table 1-1. Summary of Niche Markets Evaluated in this Report

Niche Market	Colored Light	White Light
Colored-Light Applications		
Traffic Signals and Pedestrian Crossings	X	
Decorative Holiday Lights	X	X
Exit Signs	X	
Electric Signage	X	X
Indoor White-Light Applications		
Recessed Downlights		X
Refrigerated Display Case Lighting		X
Retail Display	X	X
Task Lighting		X
Office Under-cabinet Lighting		X
Kitchen Under-cabinet Lighting		X
Outdoor White-Light Applications		
Street and Area Lighting		X
Step, Path, and Porch Lighting		X

The Department recognizes that the twelve niche markets evaluated in this report do not represent an exhaustive list of all the applications and installations where LED devices can be found today. In addition to these, other popular niche market applications for LED devices include: indicator lights on electronic goods, novelty sneaker flashing lights, bicycle safety lights, camping head-lamps, flashlights, machine vision, museum or art gallery display lighting, architectural accent lighting, automotive lights, and mobile device, computer monitor and television display screen illumination.

1.3. Estimated National Energy Consumption Methodology

This study evaluates the 2007 and "overnight" energy savings potential of LEDs in niche and emerging applications. Twelve applications are reviewed, consisting of four colored-light, five indoor white-light, and two outdoor white-light niche applications. Energy savings are presented both in terms of onsite electricity savings in trillion watt-hours (TWh) and primary energy savings at the power station level (in trillion British thermal units (TBtu), assuming the average national generation fuel mix in the U.S.[5] A general methodology was applied across the twelve niche applications to estimate the national energy consumption of each application.

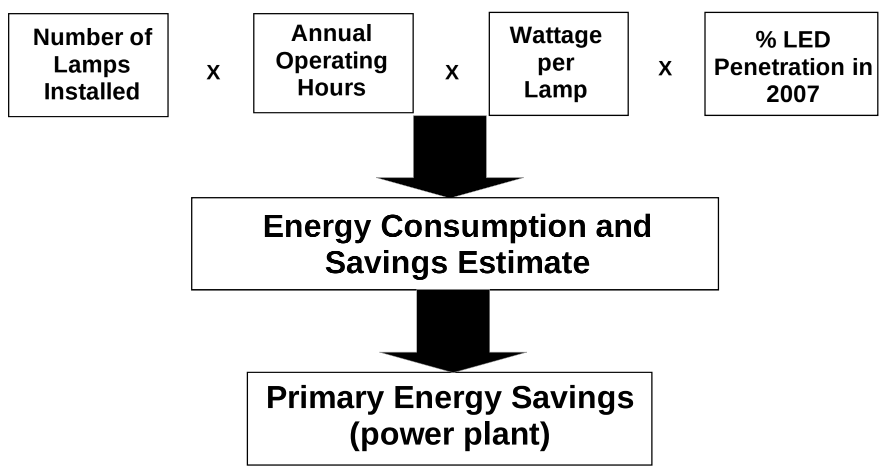

Figure 1-1: National Energy Consumption and Savings Methodology

Figure 1-1 illustrates the four critical pieces used to prepare an estimate of the energy consumption and the energy savings potential of each niche application. These include: the number of lamps installed, the annual operating hours, the wattage per lamp and the percent of LED market penetration. The four critical pieces were estimated by reviewing literature and market studies, examining available databases, and conducting interviews with researchers and industry experts. The specific sources and any variances on this methodology are described at the start of each niche application section.

[5] Primary energy savings are calculated by multiplying electricity savings by the 2007 source-to-site conversion factor (EIA 2008). 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.

The energy consumption and savings estimate results are highly sensitive to the state of LED technology. The methodology only considers currently available LED technology. For those applications where LEDs have not yet significantly penetrated the market, LED efficacies are equal to the best-in-class LED luminaires available. In the future, advances in LED technology will significantly increase potential energy savings compared to the calculations conducted in this report. LED device and luminaire efficacies are improving rapidly, and an ever increasing diversity of applications are becoming available. Since 2002, commercial white LED device efficacies have increased from 30 lumens/watt (DOE, 2006a) to about 100 lumens/W in 2008.[6] White LED luminaire efficacies are projected to advance from 47 lumens/watt in 2007 to 97 lumens/watt in 2010, and reaching 161 lumens/watt in 2015 (DOE, 2008a).

The energy consumption and savings of the twelve niche applications analyzed in this report are also highly dependent on the baseline conventional lamps used. Our estimates are based on data for conventional lamp efficacies and market penetration in 2007. However, the total energy consumed by conventional lamps may fall, as might LED energy savings, due to future energy conservation standards,[7] energy legislation, or technical advancement in the conventional light sources. For example, on December 19, 2007, the Energy Independence and Security Act of 2007 (EISA 2007) went into effect, which included provisions to set higher efficacy requirements for all general service incandescent lamps manufactured after 2014, and an efficacy requirement up to 45 lm/W in 2020, effectively banning the traditional incandescent lamp.[8] EISA 2007 will lower the annual energy consumption of the baseline conventional lighting technologies for the twelve applications analyzed in this report, thereby lowering the energy savings potential of LEDs in the future, compared to the calculations conducted in this report.

Energy consumption and potential savings from LEDs also depend on the underlying market dynamics of the twelve niche applications analyzed in this report. Some applications may grow in popularity in the future, such as recessed downlights, a light fixture that is more prevalent in new construction compared to older buildings. Other applications may decline due to decreasing market demand for the product, such as decorative holiday lights which have decreased from 371 million to 295 million miniature light strings during the past five years. These market-specific changes may increase or decrease the potential energy consumption and savings of LEDs according to the overall size of the niche application.

The magnitude of each of these effects – LED advancements, baseline efficacies, and market dynamics – is uncertain and so is the overall impact on energy consumption and savings. Thus,

---

[6] A CREE warm white LED reached 99 lm/W (Compound Semiconductor) and Nichia (NS6W083B) reached 101 lm/W in 2008.

[7] Energy conservation standards will be applicable for fluorescent and incandescent reflector lamps by 2012, and for fluorescent ballasts by 2014. A determination on whether standards are economically justified for HID lamps is currently underway. For more information, visit http://www.eere.energy.gov/buildings/appliance_standards/

[8] Section 321(a)(3) of EISA 2007 (P.L. 110-140) establishes energy conservation standards for general service incandescent lamps for rated lumen ranges, maximum rated wattage, and minimum rate lifetime, effective January 1, 2014 for general service and modified spectrum incandescent lamps. In effect, these standards establish minimum wattage requirements for general service lamps. For example, a lamp with the equivalent lumen output of a traditional 100W lamp must only consume 72 W, a lamp with the equivalent lumen output of a traditional 75W lamps must only consume 53 W, and a lamp with the equivalent lumen output of a traditional 60W lamp must only consume 43W.

the estimates for energy consumption and savings potential from LEDs presented in this report represent a brief snapshot of the state of the twelve analyzed lighting applications in 2007.

1.4. Technology Benefits in Addition to Energy Savings

There are several benefits outside of energy savings that are driving the adoption of LED technology in the twelve applications analyzed in this report. In addition to yielding more than 94 TBtu per year of primary energy savings, and potentially a further 2039 TBtu per year when the market reaches saturation, LED products offer other advantages over conventional products. These advantages as well as the niche market where these advantages are applicable are listed in Table 1-2.

Table 1-2: LED Benefits in Addition to Energy Savings

Benefit	Applicable Niche Markets
Long Operating Life – Commercial and industrial specifiers are generally interested in using a light source that is reliable and lasts a long time. Frequent lamp replacements can be costly from a maintenance perspective, and failed lamps could expose lamp operators to liabilities (e.g., traffic signals or exit signs). In fact, maintenance savings are one of the primary reasons behind market adoption of LEDs in several markets, such as electric signage, street and area lights, and retail display lighting. Presently, LED technology offers operating lives that are approximately twenty-five times longer than those of incandescent sources.[9] Researchers indicate that operating life will continue to improve as the technology develops.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights
Lower Maintenance and Life-Cycle Costs - The longer life of LEDs translates into less frequent relamping and lower maintenance costs. Although several LED products cost more than conventional products, the lower energy consumption and extended operating life (and associated maintenance savings) equate to lower life-cycle costs. For example, the cost of ownership, including energy and maintenance costs, of one intersection of LED traffic signals is about ninety percent less than that of an intersection of incandescent traffic signals (ENERGY STAR, 2006, 2008a).	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights

[9] We assume that manufacturers' claims of 50,000-hour LED lifetimes can be substantiated. However, these claims have not been independently verified by DOE.

Table 1-2: LED Benefits in Addition to Energy Savings (continued)

Benefit	Applicable Niche Markets
Reduced Radiated Heat – LEDs convert a higher proportion of electricity into visible light than incandescent sources. LED conversion efficiency has improved rapidly and is expected to continue; current LED devices are equivalent or more efficient than fluorescent and HID sources at converting power to visible light. Further, incandescent sources convert most of the power they use into infrared (IR) radiation (radiated heat), and some discharge sources emit both IR and ultraviolet (UV), but LEDs emit neither (unless specifically designed to do so). Instead, the waste heat generated by the LED must be removed by heat-conducting material (a "heat sink"). The reduction in heat radiated into conditioned space may reduce the air-conditioning or refrigeration load for some applications.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights
Minimal Light Loss – Unlike conventional lamps, LED luminaires do not need color filters to produce colored-light. In colored-light applications, light loss can be minimized by matching the color of the LED chip emitter to the color of the translucent covering on the lighting fixture. Furthermore, light emitted from an LED device is more directional and controlled, meaning that fewer photons are trapped within the lighting fixture. By contrast, conventional lamps have a 360 degree emission range, which results in lower fixture efficiencies as light is lost as the light is dispersed to the back of the fixture.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights
Dimmability and Controllability – For most applications, LED luminaires can be designed with dimming controls and motion sensors to adjust brightness levels. For example, LEDs can be dimmed more efficiently than fluorescents because rapid and frequent on/off cycles do not affect the life of the LED, enabling the use of movement-triggered controls. These controls can reduce the annual operating hours of the LED system and lead to greater energy savings than we calculate in this report.	Decorative Holiday Lights; Electric Signs; Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights

Table 1-2: LED Benefits in Addition to Energy Savings (continued)

Benefit	Applicable Niche Markets
Directional Illumination – The LED sources can be targeted to illuminate particular parts of the packaging or prices in the display case, calling customer's attention to aspects of the display case that may result in a sale. Similarly, LED task, office undershelf, or kitchen undercabinet lights can be targeted to illuminate particular parts of the work space, leading to higher fixture efficiencies and higher illumination to complete tasks, with less light scattered away from the work space.	Recessed Downlights; Refrigerated Display Cases; Retail Display; Task Lights; Office Undershelf; Kitchen Undercabinet; Street and Area Lights; Step, Path and Porch Lights
Durability – the light production mechanism for LED devices is fundamentally different from traditional light sources such as incandescent and fluorescent. LED sources produce light by passing a current through thin layers of a semi-conductive material, which causes the recombination of electron-hole pairs in the material to emit light. Inherent in this solid-state light production mechanism is the ability of the source to resist vibration and impact, making it an ideal light source for refrigerated display cases, office undershelf and kitchen undercabinet lighting. The LED is encased in a tough epoxy plastic resin instead of a fragile glass bulb, thus, they are more resistant to shattering or impact damage in these applications.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Refrigerated Display Cases; Task Lights; Step, Path and Porch Lights
Safety Improvements – For several applications, characteristics specific to LEDs leads to safety enhancements. LED luminaires are made of multiple diodes, and are less likely to fail simultaneously, leading to less down time for traffic signals, enhancing traffic flow and safety. In addition, LED holiday lights emit less heat than incandescents, and can reduce the current total of 210 home-structure fires per year due to ignited Christmas trees (Ahrens, 2007). LED electric signage is also typically operated at lower voltages and direct current which are safer for maintenance workers to handle than neon, which operates at 12,000 to 15,000 volts of alternating current.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs; Street and Area Lights
Color Maintenance - Monochromatic LEDs for colored light applications allow the elimination of filters and hence better color control and color life than conventional technologies.	Traffic Signals and Pedestrian Crossings; Decorative Holiday Lights; Exit Signs; Electric Signs

Table 1-2: LED Benefits in Addition to Energy Savings (continued)

Benefit	Applicable Niche Markets
Smaller Package Size – Due to their compact size, LED devices are an excellent option where size or weight is a concern. For example, LED lighting provides more shelf space for merchandise in a refrigerated display case. This is because the LED and driver system is much smaller than a fluorescent lamp and ballast system, and can be distributed throughout the display case, unlike fluorescents.	Refrigerated Display Cases; Retail Display; Task Lights
Uniform Illumination. – LED devices offer distinct advantages where light encroachment or glare is a problem. For example, through the use of lenses and lighting controls, LED street and area lights, and step, path, and porch light luminaires can better distribute the light across the ground, allowing more uniform illumination.	Refrigerated Display Cases; Retail Display; Street and Area Lights
Battery Back-Up Capability - Traffic signals that include red, green, and yellow LEDs consume around one-tenth as much power and LED exit signs consume about one-fifth as much power as with incandescent sources. For this reason, battery back-up power supplies are available which can operate during power failures to ensure smooth flow of vehicular traffic or continuous delineation of building routes of egress. Many agencies use yellow LED signals for battery back-up reasons in emergency situations. For instance, if yellow LED signals were used in flashing mode, work crews would have a few extra hours to handle emergency situations (Bullough, 2003b).	Traffic Signals and Pedestrian Crossings; Exit Signs
Adjustable Color – Storeowners could also easily alter the intensity and color of the LED light to augment particular colors in the products. Recent marketing studies have shown that these features offer enhanced appeal to the human eye compared to other lighting systems. Study subjects strongly preferred display cases with LED lighting systems at half the illumination levels of fluorescent systems (Narendran, 2003b).	Refrigerated Display Cases; Retail Display
Light Pollution Reduction – The directional quality of LED street and area or step, path, and porch luminaires leads to more lumens to light the road plane or path and fewer lumens scattered upward, reducing light pollution.	Street and Area Lights; Step, Path and Porch Lights

Table 1-2: LED Benefits in Addition to Energy Savings (continued)

Benefit	Applicable Niche Markets
Competitive on First-Cost Basis – - Even on a first cost basis, which can be an important purchasing determinant, LED exit signs have become competitive. While incandescent signs without battery backup are still marginally less expensive than LED signs, the price for both types of signs with battery backup is about the same because the incandescent system requires a much larger battery. LED first costs have fallen in part due to the red LED being a relatively mature and well-understood technology.	Exit Signs
Fewer Accessories – Another benefit of LED holiday lights is that they require fewer extension costs, reducing raw material use of PVC and copper. Starting in 2008, the Underwriters Laboratory changed the regulations to allow more LED sets to connect end-to-end than incandescent sets. Now, as many as 43 LED sets can be connected, end-to-end, compared to about 3-10 sets of incandescent light strings (Altamura, 2008).	Decorative Holiday Lights
Mercury Reduction – Neon light sources contain mercury, a toxic substance that requires special handling for disposal. Neon signs contain as much as 300 mg of mercury, creating an environmental health and safety hazard for workers who shape the neon tubes (Vincent, 2008). In contrast, LEDs contain no mercury and require no special handling for disposal.	Electric Signs
Design Flexibility – The small size of LEDs and their mounting surface (generally the conductor cable supplying power) enable flexible arrangements in any desired pattern for electric signage.	Electric Signs
Ease of Installation and Maintenance – Skilled neon workers are required to install and repair neon signage. However, LEDs are more robust and flexible, and could be installed by general electrical and lighting contractors	Electric Signs
Increased product shelf life – LED sources radiate less heat than fluorescents, limiting the growth of bacteria thus increasing shelf life of meat products in refrigerated display cases.	Refrigerated Display Cases

Table 1-2: LED Benefits in Addition to Energy Savings (continued)

Benefit	Applicable Niche Markets
Enhanced product appearance – Jewelry lit by LED lamps appear to sparkle more brightly because an LED lamp contains multiple diodes which create many reflections off the jewel's facets compared to a single incandescent or fluorescent bulb with equal lumen output.	Retail Display
Improved Color Rendition – Most LED street and area lighting products in the market have color temperatures of 3000-8000 K and color rendering indices of 70-85. With these color characteristics, LED street and area lights compare favorably with high pressure sodium lamps that have color temperatures of 1900-2200, providing a yellow/orange light, and color rendering indices as low as 23.	Street and Area Lights
Lower Lumen Depreciation – LEDs depreciate slowly over time in comparison with high intensity discharge (HID) lamps. The difference between HID initial and mean lumen output is significant, and leads to a lower efficacy over the lifetime of the HID lamp.	Street and Area Lights

2. Colored-Light Applications

LED sources began to penetrate 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 achieved significant penetration in these two markets, reaching 30-35% of the installed base for traffic signals and 80% of the installed base 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 meet ENERGY STAR® requirements starting in January 2006, which can be met most cost-effectively with LEDs (ENERGY STAR, 2006).

For this report, four colored-light applications were evaluated: traffic signals and pedestrian crossings, decorative holiday lights, exit signs, and electric signage. Colored-light LEDs are most commonly used in these applications, although white light is sometimes used as well. Exit signs have already saved 4.6 TWh of electricity due to the near saturation of LEDs in this application. Traffic signal heads have also achieved 52% LED market penetration, contributing to substantial energy savings. LED products are also available for decorative holiday lights and electric signage. These products are becoming more popular and are achieving higher market penetrations each year.

2.1. Traffic Signals and Pedestrian Crossings

LEDs have already begun to save 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 significant penetrations in 2002. During the past five years, market penetration has increased even further due to favorable economics (ENERGY STAR, 2006) and due to the minimum efficiency standards established in EPACT 2005 requiring that all new installations meet ENERGY STAR® requirements after January 1, 2006.

Estimated primary energy savings in 2007 from the current level of LED penetration into the traffic signal market is 30.4 TBtu per year. Nationally, it is estimated that if the remaining incandescent traffic signals were converted to LEDs, a further 21.9 TBtu per year of primary energy would be saved annually. Thus, if all of the previously incandescent traffic signals were converted to LED, approximately 5.2 TWh per year of electricity, or about 56.1 TBtu per year of primary energy would be saved.

2.1.1. Introduction

Traffic signals are an integral part of the transportation system in the United States, safely regulating the movement of vehicles and people. Installed primarily in urban areas, where vehicular and pedestrian traffic is concentrated, these signals operate 24 hours per day on a duty cycle that varies according to signal type.

For nearly the entire 20th century, traffic signals utilized incandescent light sources, as they were the only type of light source that could achieve the minimum performance requirements established by the Department of Transportation for light intensity. There are different performance standards for incandescent and LED traffic signals. However, in the past five to ten years, technology advances enabled LEDs to achieve the brightness, reliability, and control to compete in this niche market. In addition, EPACT 2005 required that all traffic signals manufactured after January 1, 2006 meet ENERGY STAR® energy consumption requirements of 12-17 watts (ENERGY STAR, 2008), which can most cost-effectively be met with LEDs over the lifetime of the product (ENERGY STAR, 2006).

Because of ENERGY STAR® requirements, LEDs are emerging as the technology of choice for traffic signal illumination. Municipalities all across the nation are retrofitting and installing new LED traffic signal heads. And, with continuing reductions in price and improvements in efficiency and performance, LED lamps offer a colored-light source that satisfies code requirements and displaces incandescent lamps. While they are initially more expensive than incandescent lamps, the long term cost savings and better quality of LEDs significantly outweigh the higher initial costs (Schmeltz, 2003). The market for traffic signals is clearly moving in the direction of LED light sources (Durgin, 2008).

A number of sources were contacted to update the national energy consumption estimate from the 2003 edition of this report. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 2-1. Traffic signals considered in the analysis include: red colored ball, yellow colored ball, green colored ball, red arrow, green arrow, yellow bi-modal arrow, green bi-modal arrow, walking person, red hand – stop, and countdown signals.

Table 2-1: Critical Inputs for Traffic Signals National Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Signalized Intersections: Gary Durgin, Dialight, 2008; Energy Savings Potential of LEDs in Niche Applications, NCI, 2003; Phillip Tarnoff, University of Maryland, 2008. Intersection Growth Rate: Estimated from U.S. Population growth between 2002 and 2007, U.S. Census Bureau; Ken Kobetsky, American Association of State Highway and Transportation Officials (AASHTO), 2008. Number of Pedestrian Signals: Gary Durgin, Dialight, 2008.
Annual Operating Hours	Estimates for Pedestrian Signals: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, Department of Energy, 2002a. Estimate for Three Colored-Ball Signals: Suozzo, 1997.
Lamp Wattages	Estimates of the Lamp Wattages: Gary Durgin, Dialight; Raj Ghaman, FHWA, 2008.
Lighting Technology Mix	Estimate of the Percent LED Penetration: Gary Durgin, Dialight, 2008; Robert Steele and Vrinda Bhandarkar, Strategies Unlimited, 2008.

2.1.2. Traffic Signal and Pedestrian Crossing Installed Base

In the United States, there are approximately 336,600 signalized intersections, representing a 1.5% annual growth rate from the 2002 installed base of 312,500 signalized intersections published in the earlier edition of this report (NCI, 2003; Durgin, 2008; Tarnoff, 2008; Kobetsky, 2008). At each intersection, up to three types of traffic signals, including the three-colored ball, arrow, and bi-modal arrow, can be found for the purposes of controlling traffic flow. In addition, approximately 75%, or about 252,450 intersections, also have pedestrian crossing signals (Durgin, 2008). The most common type of pedestrian crossing signal is the walking person and orange hand, although countdown pedestrian signals, implemented entirely with LEDs, have become more popular during the past five years.

To determine the installed base of each type of signal, data were acquired in 2002 from existing studies, manufacturers, and the Institute of Transport Engineers (ITE). The collected data from each source were then averaged to obtain the estimated number of signals per intersection. This estimate was multiplied by the corresponding number of signalized or pedestrian-signalized intersections to approximate the total number of signals in the U.S. The 2002 installed base was multiplied by a 1.5% annual growth rate, an estimate obtained from manufacturers and industry experts (Durgin, 2008; Tarnoff, 2008; Kobetsky, 2008), for 5 years to obtain the 2007 installed base. Table 2-2 provides the average number of signals per intersection and the estimated total.

Table 2-2: Estimated Number of Traffic Signals in the United States, 2007

Signal Type	Lamp Color	Average Number per Intersection	Estimated Number of Traffic Signals
Three-Colored Ball	Red	9.7	3,265,000
	Yellow	9.7	3,265,000
	Green	9.7	3,265,000
Arrow	Red	3	1,010,000
	Green	3	1,010,000
Bi-Modal Arrow	Yellow	1	336,500
	Green	1	336,500
Walking Person	White	8	2,019,500
Hand	Orange	8	2,019,500
Countdown	Red	0.21	53,000
Total			**16,527,000**

2.1.3. Traffic Signal and Pedestrian Crossing Operating Hours

Traffic signals operate 24 hours per day year-round, amounting to an annual operating cycle of 8,760 hours. Among these signals, less than two percent change to flashing mode for four to six hours at night (Larocca, 2003). For this reason, the impact of flashing time on a traffic signal's operational time is fairly negligible and thus signals are treated as being continuously on. In three-colored ball signals, the red lamp is illuminated 55% of the time over a 24-hour period, the green lamp 42%, and the yellow lamp 3% (Suozzo, 1998). Red and green arrows are estimated to operate approximately 9% of the time (DOE, 2002a). The analysis models "walk" and "don't walk" pedestrian signals to be off half the time, on for one-quarter, and flashing for one-quarter of the time (DOE, 2002a). Thus, pedestrian signals, such as white walking people and orange hands, are each illuminated about 31% of the time, or 7.5 hours per day (DOE, 2002a). In addition, we estimate countdown signals to be illuminated for 12% of the time, or 2.8 hours per day, however these signals do not contribute to energy savings as they are a new application for LEDs. The corresponding operating hours per year for each signal type and lamp color are presented in Table 2-3.

Table 2-3: Traffic Signal Operating Hours by Lamp Type and Color

Signal Type	Lamp Color	Utilization Factor	Operating Hours (hours/yr)
Three-Colored – Ball	Red	55%	4,818
	Yellow	3%	263
	Green	42%	3,679
Arrow	Yellow	9%	815
	Green	9%	815
Bi-Modal Arrow	Red	9%	815
	Green	9%	815
Walking Person	White	31%	2,716
Hand	Orange	31%	2,716
Countdown	Orange	12%	1,051

2.1.4. Traffic Signal and Pedestrian Crossing Lamp Average Wattages

Because they operate by shining full-spectrum light through a colored filter, incandescent lamps consume the same energy regardless of the color of the signal ball or arrow. As there are different luminous intensity standards for different diameter signals, the size of the signal ball (generally standardized around 8 and 12 inch diameters) will impact the wattage of the lamp, and thus the energy consumption (ITE, 2005; Bullough, 2003a). Nationally, it is estimated that about 75% of three-colored ball signals are 12-inch and the remainder are 8-inch (Durgin, 2008). Incandescent arrow and pedestrian signals are typically 12-inch.

LED light sources produce colored light (no color filter required), and the operating wattage does vary with light color, as the LED chip is made of different materials which produce the different colors. Incandescent and LED wattages from manufacturers were used to prepare average wattages for this analysis. The findings are presented in Table 2-4 along with the weighted average of the 8-inch and 12-inch wattages for each type and color of traffic signal (Durgin, 2008).

Table 2-4: Traffic Signal Wattage for Incandescent and LED Lamps by Color

		Incandescent Wattage			LED Wattage		
Signal Type	**Lamp Color**	**8 inch**	**12 inch**	**Avg.**	**8 inch**	**12 inch**	**Avg.**
Three-Colored – Ball	Red	78	135	121	6	8	8
	Yellow	78	135	121	12	20	18
	Green	78	135	121	8	9	9
Arrow	Red	-	132	132	-	7	7
	Green	-	132	132	-	9	9
Bi-Modal Arrow	Yellow	-	132	132	-	12	12
	Green	-	132	132	-	9	9
Walking Person	White	-	132	132	-	8	8
Hand	Orange	-	132	132	-	8	8
Countdown	Orange	-	-	-	-	9	9

In 2005, the Institute of Transportation Engineers (ITE) passed a wattage standard of 69 watts for 8-inch incandescent signal balls and 120 watts for 12-inch incandescent signal balls to set an acceptable level of brightness required to maintain driver safety and limit energy consumption. We estimate that all incandescent traffic signal replacements and new construction of traffic signals follow the ITE standard after 2005, amounting to 23% of the installed base of traffic signals.[10] The ITE standard lowers the average wattage of the installed base of traffic signal heads shown in Table 2-4 from the averages of 81 watts for 8-inch signal heads and 140 watts for 12-inch signal heads published in the 2003 edition of this report. In addition, in August 2005, the President signed the Energy Policy Act (EPACT) of 2005, mandating that all traffic signals manufactured after January 1, 2006 meet ENERGY STAR® requirements, which can most cost-effectively be met with LEDs (ENERGY STAR, 2006). The estimates of the percent LED penetration of traffic signals, shown in Table 2-5, take into account the impact of EPACT 2005.

2.1.5. Traffic Signal and Pedestrian Crossing Energy Saving Potential

Market penetration of LED traffic signal and pedestrian crossings has increased to approximately 52% of the market due to the energy saving benefits and reduced maintenance costs of the technology, as well as market transformation programs highlighting these advantages and the requirements of EPACT 2005 (Durgin, 2008). Red signal heads have seen the highest level of LED market penetration at 65%, while green signal heads are approximately 59% LED (Durgin, 2008, Bhandarkar, 2008). Because of their low duty-cycle, yellow LED traffic signals have a much longer payback period. This, coupled with the stringent luminosity specifications for yellow LED signals (Bullough, 2003a) results in a lower market penetration, estimated to be around 25%. Table 2-5 outlines the market penetration by type and lamp color (Durgin, 2008).

[10] We assume an average traffic signal fixture lifetime of 15 years to develop the estimate of ITE-standard-compliant traffic signals.

Table 2-5: Traffic Signal Percent LED Penetration by Type and Lamp Color

Signal Type	Lamp Color	Installed Base of LED Signals
Three-Colored Ball	Red	65%
	Yellow	25%
	Green	59%
Arrow	Red	60%
	Green	59%
Bi-Modal Arrow	Yellow	60%
	Green	60%
Walking Person	White	50%
Hand	Orange	50%
Countdown	Red	100%
Total		**52%**

With 52% market share, more than 8.5 million traffic signals already use LED sources while 8.0 million have not yet been converted. Table 2-6 describes the installed base of incandescent and LED traffic signals and their corresponding energy consumption.

Table 2-6: Traffic Signal Energy Consumption and Savings Estimate, 2007

Niche Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
Red colored ball	0.74	1.16	0.63	1.79
Yellow colored ball	0.08	0.02	0.07	0.09
Green colored ball	0.66	0.80	0.55	1.35
Red arrow	0.05	0.06	0.04	0.10
Green arrow	0.05	0.06	0.04	0.10
Yellow bi-modal arrow	0.02	0.02	0.01	0.03
Green bi-modal arrow	0.02	0.02	0.01	0.03
Walking person	0.38	0.34	0.34	0.68
Red hand – stop	0.38	0.34	0.34	0.68
Countdown	0.001	0.00	0.00	0.00
Total:	**2.38**	**2.82**	**2.03**	**4.85**

The increasing penetration of LEDs in traffic signal and pedestrian crossings has decreased this application's electricity consumption by 7% per year and increased its annual electricity savings since 2002. In 2002, traffic signals and pedestrian crossings yielded an electricity savings of 1.48 TWh/year. At the current level of LED penetration, traffic signal and pedestrian crossings have yielded 2.82 TWh/yr of energy savings, decreasing this application's national energy consumption from 5.20 TWh/yr (what it would have been if all installations were incandescent) to 2.38 TWh/yr. Converting the remaining stock of incandescent traffic signals to LED will 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 future energy savings, traffic signals could save approximately 4.85 TWh/year, or over 76% of the annual output of one large (1,000 MW) electric power station. This amount of electricity represents the annual electricity consumption of four hundred thousand typical U.S. households.

2.1.6. Technology Benefits in Addition to Energy Savings

There are several benefits outside of energy savings that are driving the adoption of LED technology in the traffic signal and pedestrian crossing application. In addition to saving more than 30.4 TBtu per year, and potentially a further 21.9 TBtu when the market reaches saturation, LED traffic signals offer other advantages over traditional incandescent traffic signals. These include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Durability
6. Safety Improvements
7. Color Maintenance
8. Battery Back-Up Capability

For more information about these additional LED benefits, refer to Table 1-2.

2.2. Decorative Holiday Lights

Even though the holiday season is just a few weeks of the year, the conversion of holiday lights from incandescent to LED sources would generate considerable energy savings. The potential annual energy savings of a complete market shift to LED holiday lights is approximately 64.4 TBtu of primary energy consumption, equivalent to the output of ninety percent of one large (1000 MW) electric power plant or the annual electricity consumption of almost five hundred thousand households. Along with significant energy savings, the adoption of LED sources would be accompanied by other benefits, including a longer operating lifetime as well as a safer and more durable product.

2.2.1. Introduction

Holiday lights serve an aesthetic function, using colored and white light to build a certain mood or evoke positive feelings and emotions. Most holiday lights operate for a limited part of the year, typically around the holiday season from late November to early January. These lights can be found donning the one hundred million real and artificial holiday trees on display annually in the U.S. (UIE, 2005) as well as decorating the exteriors of residential and commercial buildings.[11] The lights, a symbol of the yuletide season, are also commonly used at shopping malls, store displays, city streets, or hotel and motel decorations. When used in these applications, operation can span the whole year, and not just the holiday season.

Due to their intermittent annual use, energy efficiency has not been a significant market driver. Historically, users who wanted to control the energy consumption would move to smaller, lower wattage lamps, fewer light strings, or use timers to regulate on-time. Now, energy-saver incandescent light strings are available offering over 40% of the energy savings of regular incandescent light strings and LED holiday lights are available offering 90% energy savings per bulb. Due to their natural aptitude to produce a spectrum of colored light, depending on the chip substrate, LED technology is well suited to this application and may gradually replace conventional incandescent lights over time, saving significant energy and money.

A number of sources were consulted to prepare a national energy consumption estimate. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 2-7.

Table 2-7. Critical Inputs for Holiday Lights National Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Holiday Light Inventory: Unites States International Trade Commission (USITC), 2005-2007.
Annual Operating Hours	Operating Hour Estimate: Decorative Light String Market Assessment Report, prepared by Navigant Consulting, 2006.
Lamp Wattages	Lamp Wattage Estimate: David Allen, Forever Bright, 2008; Steve Altamura, Seasonal Specialties, 2008; Washington State University (WSU), 2007
Lighting Technology Mix	LED Market Penetration Estimate: David Allen, Forever Bright, 2008; Steve Altamura, Seasonal Specialties, 2008.

2.2.2. Decorative Holiday Lights Installed Base and Operating Hours

There are many different types of holiday lights, such as miniature, icicle, sphere, G30, G40, flame-tip, micro, button, pearl light, C-6, C-7, and C-9 lights, each of which differ slightly in bulb size and lamp wattage. LED replacements exist today for incandescent miniature, icicle, C-6, C-7 and C-9 light strings. As there is virtually no domestic production of holiday lights (Allen, 2008; Altamura, 2008), it was assumed for this analysis that all holiday lights are imported. The United States International Trade Commission (USITC) tracks the imports of "lighting sets of a kind used for Christmas trees," of which, approximately 122.9 million sets are imported each year (USITC, 2005-2007). Of this total, the estimated number of imported miniature light sets (including icicles) is 98.4 million per year, or about 80% of total holiday

[11] The number of holiday trees in the U.S. is based on annual sales of 32.8 million real trees in 2005, and the estimate that in 2002, 21% of U.S. households had a real tree, 48% had an artificial tree and 32% had no tree, assuming the same proportions in 2007.

light imports (USITC, 2007). These are average values from the past three years, as shown in Table 2-8, below. The remaining imported lights are a combination of all other types of holiday lamps (C-6, C-7, and C-9).

Table 2-8: Imports of Holiday Lights, 2005-2007

Lights	2005	2006	2007	Three Year Average
Imports of Miniature Lights	99,951,000	91,845,000	103,344,000	98,380,000
Imports of Other Lights	20,150,000	30,137,000	23,176,000	24,488,000
Total Imports	**120,101,000**	**121,982,000**	**126,520,000**	**122,868,000**

Table 2-9: Operating Hours for Holiday Lights

Application	Residential Use (90%)	Commercial Use (10%)
Primary Application (75 %)	180 to 360 hours	540 to 720 hours
Secondary Application (25 %)	180 to 450 hours	4,380 hours
Average	272 hours	818 hours
Weighted Average	**410 hours**	

The installed base of miniature holiday lights can be estimated by considering the typical lifetime of the lamps, which determines how long a particular string may remain in service. The typical lifetime of a string of miniature lights is three years (DOE, 2002b; Bruno, 2003). This estimate is based on the assumption of 90% residential use and 10% commercial use, and 75% seasonal (primary application) use and 25% extended (secondary application) use, operating at the average of 9 hours of operation per day, 45 days a year, or 410 hours per year (NCI, 2006; Allen, 2008; Altamura, 2008). This operating hour estimate is higher than the 2002 estimate of 150 hours per season, because of the inclusion of commercial-use holiday light strings in this year's report.

After 3 years, or about 1200 hours, approximately one third to one half of the bulbs will have failed, resulting in the disposal of the entire string (Altamura, 2008). Multiplying the average annual sales over the past three years by the three-year typical lifetime yields an installed base of 368 million holiday light strings of which 295 million are miniature or icicle light strings. We assume that miniature and icicle holiday lights contain 100 lamps per string, C-6 light strings contain 35 lamps, while C-7 and C-9 strings contain 25 lamps each. Thus, the installed base of holiday lamps is about 31.5 billion of which 27.9 billion are miniature or icicle lamps. This estimate is lower than the installed base of 37.1 billion miniature lamps in 2002, as annual sales of holiday lights have been declining.

2.2.3. Decorative Holiday Lights Energy Saving Potential

The annual energy consumption of holiday lights can be estimated as the product of the installed base, the operating hours, and the wattage of each light string. Table 2-10 shows the estimated market share and wattages of conventional, energy-saver, and LED holiday lights. Energy saver lamps consist of approximately a third of all incandescent holiday lights sold (Altamura, 2008). Our methodology differs from the earlier edition of this report in that commercial sector holiday lights, secondary application, and energy-saver incandescent light strings are included in the analysis, and C-6, C-7, and C-9 energy consumption and savings are provided as LED light strings have become available for these products during the past five years. As a result of including higher-wattage non-miniature light strings and commercial sector and secondary application holiday lights with longer operating cycles in the analysis, energy consumption and savings of holiday lights will be greater than in 2002, despite the overall decline in holiday light sales.

Table 2-10: Conventional and LED Holiday Light Lamp Average Wattage

Type	Market Share (%)	LED Penetration (%)	Incandescent Light String Wattage (W)	Energy Saver Incandescent Light String Wattage (W)	Average Incandescent Light String Wattage (W)	LED Light String Wattage (W)
C-9 Lights	5.0%	1.0%	175	125	159	2.5
C-7 Lights	7.0%	5.0%	100	75	92	2.5
C-6 Lights	8.0%	10.0%	36	NA	36	0.9
Miniature & Icicle Lights	80%	5.0%	42	24	36	5.0
Total	**100%**	**5.2%**	**62**	**40**	**55**	**4.4**

Over the past five years, LEDs have started to carve a small niche in the holiday light market. LEDs have significant benefits, such as operating lifetimes more than 30 times longer[12] than traditional miniature lights and 90 % lower energy consumption per lamp. Based on manufacturers' sales of LED holiday light strings to major retailers, we estimate that LEDs have a market penetration of 5.2% (Allen, 2008), compared to minimal market penetration of LEDs in 2002.

Table 2-11: Holiday Lights Energy Consumption and Savings Estimate, 2007

Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
C-9 Lights	1.13	0.06	1.11	1.18
C-7 Lights	0.92	0.05	0.89	0.94
C-6 Lights	0.41	0.02	0.40	0.43
Miniature & Icicle Lights	4.14	0.23	3.56	3.78
LED Holiday Lights	0.03	-	-	-
Total	**6.63**	**0.33**	**5.97**	**6.30**

In 2007, the current level of LED penetration yielded 0.33 TWh/yr of site electricity savings, compared to minimal energy savings in 2002. If the market shifted entirely to LED holiday lights, a potential 5.97 TWh per year could be saved. The 2007 energy savings potential of 5.97 TWh per year is equivalent to 64.4 TBtu per year of primary energy savings, the output of ninety percent of one large (1000 MW) electric power plant or the annual electricity consumption of almost five hundred thousand households. A theoretical maximum energy savings (2007 energy

[12] This lifetime claim is based in manufacturer product literature. However, ENERGY STAR requires only a 3-year warranty for an LED light string under normal residential use.

savings plus energy savings potential) of 6.30 TWh per year is possible if the market converted entirely to LED holiday light strings.

2.2.4. Technology Benefits in Addition to Energy Savings

In addition to the dramatic energy savings potential identified in Table 2-11, there are other benefits to end-users from selecting LED holiday lights.

1. Longer Operating Life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Durability
7. Safety Improvements
8. Color Maintenance
9. Fewer Accessories

For more information about these additional benefits of LEDs, refer to Table 1-2.

2.3. Exit Signs

Since their introduction in 1985, LED exit signs have become the most common type of exit sign installed because of lower energy consumption and lower maintenance costs than other types of lighting. National promotional initiatives such as ENERGY STAR® have helped to raise business awareness and expand market penetration. In addition, EPACT 2005 included a provision that mandated that all exit signs installed after January 1, 2006 must be compliant with ENERGY STAR® requirements that exit signs consume no more than 5 Watts per face, which can most cost-effectively be met with LEDs (ENERGY STAR, 2007b). In terms of primary energy savings, 49.2 TBtu per year are currently saved from existing LED exit signs, and a further 6.8 TBtu of savings could be captured if the remaining conventional sources in the installed base were to switch to LED. In total, the energy savings from 100% market saturation with LED exit signs would be approximately 55.9 TBtu per year.

2.3.1. Introduction

Buildings designed for public occupancy require exit signs that continuously operate to demarcate routes of egress 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 visibility requirements. However, in the last 20 years, other sources such as compact fluorescent and LED have become in use, due to their lower life-cycle costs.

Today, LEDs have emerged as the technology of choice for exit sign illumination. Thanks in part to the technology advancements of the last two decades, the LED has become a highly reliable, energy efficient colored-light source that satisfies code requirements while reducing energy consumption and maintenance costs. LEDs offer more favorable economics, better performance, and enhanced safety capabilities than conventional exit signs.

To prepare a national estimate of the energy savings potential of LED exit signs, estimates of the installed base, operating hours, and average wattage were assembled. These estimates draw upon publicly available literature as well as consultative interviews with manufacturers and industry experts. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 2-12.

Table 2-12. Critical Inputs for Exit Signs National Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Exit Signs: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Commercial Floorspace Growth Rate: Commercial Building Energy Consumption Survey (CBECS), 2003, 1999. Industrial Floorspace Growth Rate: Manufacturing Energy Consumption Survey (MECS), 1998, 1994.
Annual Operating Hours	Exit signs operate continuously: 8,760 hours per year.
Lamp Wattages	Estimates of the Lamp Wattages: PG&E, 2000; Efficiency Maine, 2003; E-Source, 2002; Virginia Department of Mines and Minerals, 1998; Light Panel, 2003; ENERGY STAR®, 2008.
Lighting Technology Mix	Estimate of the Percent LED Penetration: NEMA, 2003; Robert Steele and Vrinda Bhandarkar, Strategies Unlimited, 2008; Cheryl English, Acuity Brands, 2008.

2.3.2. Exit Signs Installed Base

The 2007 installed base of exit signs is the product of the growth rate of exit signs from 2002-2007 and the exit sign inventory estimate published in the previous edition of this report, which is derived from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). This study takes building audit and sub-metering data on lighting in commercial and industrial buildings and extrapolates the information to the nation as a whole, based on the building inventories published by the Energy Information Administration. Exit signs were one of the lighting fixtures tracked in the building audits conducted in the 1990s, which numbered more than 25,000 buildings.

The growth rate of exit signs from 2002 to 2007 is proportional to the growth rate of building floorspace during this period. The 1.6% annual growth rate of commercial floorspace was determined from the 2003 and 1999 *Commercial Building Energy Consumption Survey*, published by the Energy Information Administration (EIA). The 1.0% growth rate of industrial floorspace was determined from the 1998 and 1994 *Manufacturing Energy Consumption Survey*, also published by the EIA. Extrapolating the 2002 exit sign inventories from the earlier edition of this report, by building type, to a national level produces an estimated installed base of approximately 35.6 million exit signs in 2007, shown in Table 2-13(DOE, 2002a). Since 2002, the U.S. has added about 2 million exit signs.

Table 2-13: Number of Exit Signs in the United States, 2007

Sector	Estimated Number of Exit Signs
Commercial Exit Signs	31,893,000
Industrial Exit Signs	3,743,000
Total National Inventory	**35,636,000**

Due to highly favorable economics, better performance, enhanced safety capabilities, marketing programs such as ENERGY STAR® Exit Signs, and EPACT 2005 provisions that all new exit sign installations manufactured after January 1, 2006 meet ENERGY STAR® requirements that exit signs consume no more than 5 watts per face, over 85% of exit signs incorporated LEDs in 2007. Less than five percent of exit signs are still incandescent, and the remaining ten percent are compact fluorescent. There are already more than 30 million LED exit signs while only about 1.6 million incandescent and 2.7 million compact fluorescent exit signs remain in the market. Table 2-14 presents available estimates of the most recent shipment apportionments and estimates of the installed base from an industry expert (English, 2008).

Table 2-14: 2007 Exit Sign Percent Market Share by Lamp Type

Source	Shipment Estimate, 2007	Estimated Installed Base
Incandescent	0 percent	4.6 percent
Compact Fluorescent	0 percent	9.7 percent
Light Emitting Diode	100 percent	85.7 percent

2.3.3. Exit Signs Operating Hours

Exit signs, by building safety code requirement, operate 24 hours per day year-round, amounting to an annual operating cycle of 8,760 hours.

2.3.4. Exit Signs Lamp Average Wattages

The wattage of installed exit signs varies both by the light source (e.g., incandescent, compact fluorescent, LED) and within a given light source. For example, incandescent exit signs can be found which range between 10 and 50 watts for a two-sided sign (LightPanel, 2003; ENERGY STAR, 2008) and LED fixtures can be found between 2W and 10W, also for two-sided signs. For this application, LED sources produce light in the color spectrum required (e.g., red or green). This method differs from that of incandescent or compact fluorescent light sources, which produce full-color spectrum light, and then have a color filter that absorbs all the colors except red or green. Table 2-15 provides the range of wattages identified for each light type, along with an estimated average value used in the energy savings calculation.

Table 2-15: Exit Sign Wattage by Lamp Type

Source	Low	High	Estimated Average
Incandescent	10 watts	50 watts	32 watts
Compact Fluorescent	10 watts	24 watts	17 watts
Light Emitting Diode	2 watts	10 watts	6 watts

2.3.5. Exit Signs Energy Saving Potential

LED exit signs with an average luminaire efficacy of 45.5 lm/W[13] contributed 4.56 TWh of energy savings in 2007, using a baseline exit sign installed base of 37% incandescent and 63% CFL exit signs (the presumed technology mix of the exit sign market with no LED penetration). If the entire exit sign installed base converted to LEDs, an additional 0.63 TWh of energy can be saved yielding a theoretical maximum energy savings potential of 5.18 TWh/yr due to LEDs, equal to over 70% of the annual output of one large (1000 MW) electric power plants or the annual electricity consumption of over three hundred thousand households. The primary energy savings of LED exit signs in 2007 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. If the 2007 baseline of exit signs had been entirely incandescent, LEDs would have yielded 7.49 TWh of electricity savings, compared to 6.86 TWh of electricity savings in 2002.

Table 2-16: Exit Sign Energy Consumption and Savings Estimate, 2007

Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
Exit Signs	2.50	4.56	0.63	5.18

[13] The average efficacy for LED exit signs was estimated by dividing the average lumen output of an equivalent CFL or incandescent sign by the average wattage of an LED sign (6 watts). This assumes that LED exit sign luminaires produce an equivalent amount of lumens as the mix of CFL and incandescent exit signs. However, this assumption does not impact the energy consumption and savings potential calculations, which are based on the estimated average wattage of LED vs. incandescent or CFL exit signs.

2.3.6. Technology Benefits in Addition to Energy Savings

There are several additional benefits beyond energy savings that are driving the market to adopt LED exit signs, as described in greater detail in Table 1-2. In addition to saving about 55.9 TBtu per year, and potentially a further 6.78 TBtu when the market reaches saturation, LED exit signs offer advantages over traditional exit signs that compel building owners and managers to shift to LED sources. These include:

1. Longer Operating Life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Durability
6. Safety Improvements
7. Color Maintenance
8. Battery Back-Up Capability
9. Competitive on First-Cost Basis

2.4. Electric Signage

Electric advertising signage has become increasingly popular during the past five years, reaching 6.1% market penetration in 2007. The energy that would be saved if 100% of the installed base of neon signs switched to LED is approximately 81.3 TBtu of primary energy, equivalent to the output of one large (1000 MW) coal power station or the annual electricity consumption of six hundred thousand households.

2.4.1. Introduction

Advertising signs play an important role in our national economy, helping customers to locate retailers and service providers, identify products they may want to buy, or simply determine if a shop is open for business. Colorful, actively lit signage attracts the attention of customers and works to generate business for the establishment. Historically, advertising signs have relied on incandescent, fluorescent, or neon light sources for illumination. Recently, LED sources have started making inroads into this market, gradually replacing the traditional sources, particularly neon.

According to a 2007 state of the industry report published by *Signs of the Times* magazine (STMG), the number of companies offering signs that incorporate LED technology is increasing, as are the shipments of electric signs based on this light source (STMG, 2008a). The publication's survey of manufacturers found that in 2007 approximately 89% of electric signage companies offered products that incorporate LED illumination sources, up from 48% in 2002. The survey also found that shipments of electric signs that incorporate LED sources increased from 6.2% to 23.4% of total shipments over the same time period, a 277% increase. At the same time, shipments of neon and fluorescent electric signs decreased slightly (STMG, 2008). For the first time in 2007, *Signs of the Times* found through its annual online Lighting Survey that 30.2%

of electric signs sold by respondent companies were LED, surpassing the 22.8% share of neon signs sold (STMG, 2008b). These surveys show that LEDs, along with fluorescents, are becoming the technologies of choice for electric signage.

The energy savings estimate is based on LED replacement of electrically-lit neon signage. The electric signs encompassed in this estimate include shaped neon-tube channel letter signs, reverse channel letters, and border lighting. Other types of electric signs are not considered because suitable LED replacements do not yet exist. One of the advertising options offered by LED sources is outdoor video screens and message display boards. In applications such as the NASDAQ building in Times Square, New York, LEDs enable advertisers to actively engage their audience through video monitors and digital displays with news and other moving images presented in color on a billboard-sized screen. For this energy savings estimate, however, LED billboard screens are not considered, as this new application represents an increase in energy consumption over traditional billboards which in many cases use no energy.

There is no single published study available of energy consumption for electric signs; therefore a number of sources were contacted to prepare a national energy consumption estimate. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 2-17.

Table 2-17. Critical Inputs for Electric Signage Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Electric Signs: Annual Survey of Manufacturers, U.S. Census; 1992-2006, *Signs of the Times* Magazine (STMG), 2004; *SignCraft*, 2003. Percentage of Neon and LED Sign Shipments: *Signs of the Times* Annual State of the Industry Report, 2007. Average Sign Price: Interface Signs, Commercial Signs.
Annual Operating Hours	Estimates for Operating Hours: Signweb; Bryan Vincent, AgiLight, 2008.
Lamp Wattages	Estimates of LED Lamp Wattages: J. Bryan Vincent, AgiLight, 2008; Jill Bonilla and Jim Sloan, SloanLED, 2008. Estimates of Neon Wattages: J. Bryan Vincent, AgiLight, 2008; Universal Lighting, 2003. Estimate of LED efficacies: J. Bryan Vincent, 2008, Jill Bonilla, 2008.
Lighting Technology Mix	Estimate of the Percent LED Penetration: *Signs of the Times* Annual State of the Industry Report, 2008.

2.4.2. Electric Signage Installed Base, Operating Hours, Wattage

The number of electric signs sold per year, and presumably displayed, can be calculated by taking the total annual sales of the electric signage industry and dividing by an average electric sign price. In addition, electric signs were assumed to have an average operating life of 15 years

(D&R, 2003). Thus, the estimated installed base is the summation of the total number of electric signs sold in that time period (1993-2007).

The annual sales figures of electric signs were available from two different sources: the Department of Commerce's Annual Survey of Manufacturers (ASM) and from a sign industry trade magazine, *Signs of the Times*. For years when estimates from both the ASM and *Signs of the Times* magazine were available, an average was taken to prepare the estimate of installed base of electric signage; otherwise, the ASM value was used. The ASM provides annual sales data from 1993 to 2007, but another trade magazine, *Sign Craft*, estimates that the value reported by the ASM is actually only 50% of total sales of all sign shops (SignCraft, 2003). As a result, the ASM sales numbers were multiplied by two for this estimate. The second source, the *Signs of the Times* magazine conducts an annual industry survey of the electrical signage retailing industry. Analysts from this magazine who have studied these annual surveys prepared an estimate of the installed base of commercial advertising electric signs in the U.S.

After speaking to a number of sign manufacturers, an average price per sign of $5,000 was selected in 2003. It was assumed the average sign price was constant over the fifteen-year period, adjusted for inflation, yielding a 2007 average price per sign of $5,600. The installed base is given in Table 2-18.

Table 2-18: Electric Signs Annual Sales, Average Price, and Estimated Installed Base, 2007

Year	Total Sales *Signs of the Times* ($Billion)	Total Sales ASM, *Sign Craft* ($Billion)	% Difference in Sources	Inflation Adjusted Average Sign Price ($)	Estimated # of Signs Sold
1993	3.39	2.75	23%	$3,890	790,000
1994	3.70	3.23	15%	$4,010	864,000
1995	4.10	3.55	16%	$4,120	928,000
1996	4.30	3.88	11%	$4,240	964,000
1997	4.60	4.12	12%	$4,340	1,005,000
1998	5.00	3.79	32%	$4,450	988,000
1999	5.40	5.03	7%	$4,520	1,154,000
2000	5.60	4.84	16%	$4,620	1,130,000
2001	5.40	4.79	13%	$4,780	1,066,000
2002	5.10	5.16	-1%	$4,920	1,042,000
2003	5.10	5.33	-4%	$5,000	1,043,000
2004	--	5.60	0%	$5,110	1,096,000
2005	--	6.28	0%	$5,250	1,196,000
2006	--	7.05	0%	$5,430	1,299,000
2007	--	est. 7.35	0%	$5,600	est. 1,313,000
				Total Installed:	**15,878,000**

Table 2-19: Electric Signs Percent Market Share by Lamp Type

Light Source	Shipments, 2007	Estimated Installed Base, 2007
Neon	33.4 percent	42.1 percent
Fluorescent	47.7 percent	45.8 percent
LED	23.4 percent	6.1 percent
Other	5.5 percent	6.1 percent

The installed base of 15.9 million electric signs represents all electric signs, including signs illuminated from neon, fluorescent, HID, and fiber optic sources. Since currently, LED replacements only exist for neon signs, the potential market that is suitable for replacement is actually much smaller, about 7.6 million electric signs. Along with annual sales figures, *Signs of the Times* magazine also provides information on how electric signs are illuminated, classified by lighting type. Table 2-19 shows the estimated shipments and installed base of electric signs by lamp type, projected from annual electric sign shipments reported in *Signs of the Times'* annual "Electric Sign State of the Industry" reports from 2001 to 2007 (STMG, 2003-2008). The neon lamps illuminating these signs could be replaced by LEDs. The "Other" category includes electric signs illuminated by incandescents, fiber optics, and other technologies for which good LED replacements do not yet exist.

The term "neon" actually refers to more than just neon gas and generally extends to include any inert gas that emits color when ionized. Different gases produce different colors: neon glows bright red, and a mix of argon and mercury creates a blue/white color. The average wattage per foot of LED strip is 0.96W (GELcore, 2003; SloanLED, 2002; Vincent, 2008). The average nominal installation for a sign is 150 feet (Vincent, 2008; SloanLED, 2003). Channel letter signs are assumed to operate 10 hours per day, 365 days per year. Thus, the operating hours for channel letter lighting are estimated to be 3,650 hours per year (Vincent, 2008).

Table 2-20: Electric Sign Installed Base, Operating Hours, and Power Consumption

Source	Installed Base (units)	Operating Hours (hours/yr)	Average Wattage (W/ft.)	Nominal Installation (feet)	Power Consumption per Sign (W)
LED	913,000	3,650	0.96	150	180
Neon	6,711,000	3,650	3.0	150	450
Total	**7,624,000**	**3,650**	**--**	**150**	**--**

2.4.3. Electric Signage Energy Saving Potential

The current market penetration of LEDs into channel letter signs is estimated to be 6.1% percent, based on the technology mix of annual shipments of electric signs from 2001-2006. Table 2-21 presents the energy consumption estimate for neon commercial advertising electric signs, based on the aforementioned data and inventory estimates.

Table 2-21: Electric Signs Energy Consumption and Savings Estimate, 2007

Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
Electric Signs	11.6	0.95	6.58	7.53

Since 2002, the annual electricity consumption of electric signs has increased from 10.0 TWh per to 11.6 TWh/year in 2007, due to the growth in electric sign sales. However, the growth in electric sign energy consumption has been tempered by the increasing penetration of LEDs in this application. Already, LED electric signs with an average luminaire efficacy of 49.3 lm/W[14] have reduced energy consumption in this application by 0.95 TWh/year, from 12.6 TWh/year to 11.6 TWh/yr. This compares to negligible electricity savings from converting neon signs to LED electric signs in 2002. Converting all of the remaining neon signs in the 2007 baseline inventory to LED would save approximately 6.58 TWh/yr. In terms of primary energy consumption, 71.0 TBtu per year could be saved based on 2007 LED penetration and if the remaining neon signs converted to LED sources. To put these potential energy savings into perspective, the annual output of one large (1000 MW) electric power plant or the annual electricity consumption of five hundred thousand households could be avoided if the national neon electric signage stock entirely shifted to LED.

2.4.4. Technology Benefits in Addition to Energy Savings

There are several benefits in addition to energy savings that are driving the adoption of LEDs in electric advertising signs. These include:

1. Longer Operating Life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Durability
7. Safety Improvements
8. Color Maintenance
9. Mercury Reduction
10. Design Flexibility
11. Ease of Installation and Maintenance

For more information about these additional benefits of LEDs, refer to Table 1-2.

[14] This luminaire efficacy is an average of estimates from industry experts (Bonilla, 2008; Vincent, 2008)

3. Indoor White-Light Applications

In addition to colored-light applications, LED sources have begun to penetrate white-light applications during the past few years. Improved light output and efficiencies of monochromatic blue LEDs have enabled the manufacture of high-brightness white LEDs, produced by combining a blue LED with a yellow phosphor or by mixing red, green, and blue LEDs. Warm white LEDs, which are more pleasing to the U.S. consumer, can be produced by using different different phosphors in the LED, or by combining white LEDs with monochromatic red or amber LEDs. LED penetration in indoor white-light applications has the potential to save substantial amounts of energy if LEDs can achieve the stringent color quality and color-rendering requirements that consumers demand in general lighting applications. As with colored-light applications, electricity is saved in white-light applications where LED sources are used to replace incandescent, halogen, and in some cases, CFL and certain types of fluorescents..

This report evaluates six indoor white-light niche market applications: recessed downlights, refrigerated display case lighting, retail display, task lighting, office undershelf lighting and kitchen undercabinet lighting. LED products for these indoor white-light applications are currently being manufactured, although the market has not yet adopted them in large numbers.

- LED recessed lights have the greatest energy savings potential of all the applications studied in this report.
- LED refrigerated display case lighting is a promising niche application because LEDs perform better in cold temperatures compared to room temperature, and they can provide more uniform lighting of the display area than the incumbent fluorescent lamp systems, due to the directional light output of LEDs. Wal-Mart has recently converted to LED refrigerated display case lighting in 500 of its U.S. stores, which may influence other storeowners to shift toward LEDs as well (LEDs Magazine, 2007).
- LED retail display lighting is beneficial in several respects: LEDs' small size allows them to be integrated unobtrusively into display cases; LED directionality allows precise targeting of products to be illuminated; LEDs do not damage heat or UV-sensitive merchandize, and, for products like jewelry and crystal, the multiple diodes of the LED lamp lead to more reflections and increased sparkle.
- LED task lighting such as portable desk lamps, office undershelf lighting, and kitchen undercabinet lights have the potential to provide brighter, more directed illumination for work spaces than the incandescent and fluorescent products they replace.

If LEDs become standard technology in these six indoor white-light niche market applications, 108 TWh per year of electricity savings could be possible, equal to 1.1% of total annual primary energy consumption and 13% of electrical energy consumption for lighting in the U.S. in 2007.

3.1. Recessed Downlights

The energy savings potential of LEDs for recessed downlights is significant, more than the energy savings potential of any other niche application described in this report. We estimate that there is no market penetration of LEDs in recessed downlight applications as of 2007 because LED recessed downlight products only recently have become available in the market. However, we estimate that if all recessed downlights in the U.S. were converted to LEDs, 877 TBtu of primary energy would be saved annually, the annual consumption of 12.8 large (1000 MW) electric power plants. This represents the annual electricity consumption of 6.7 million typical U.S. households.

3.1.1. Introduction

Although originally intended for directional lighting, recessed downlights have become the most common fixture used for general ambient lighting in both residential and commercial buildings. Recessed downlights represent 12% of all installed residential light fixtures and 15% of lighting energy use in the U.S. (Calwell et al., 1999). These fixtures are popular because they are inexpensive and can provide inconspicuous, directional or ambient light for most room types. For the energy consumption and savings analyses in this report, recessed downlights include insulated ceiling-rated, air-tight (ICAT) fixtures and non-insulated ceiling fixtures (non-IC), with open or enclosed reflector lamps, but not recessed troffer fixtures commonly used with linear fluorescent lamps.

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. In 2007, LED Lighting Fixtures Inc. (now Cree LED Lighting Solutions) won the grand prize in the *Lighting for Tomorrow* competition for an LED LR6 recessed downlight that could replace the common BR30 incandescent reflector, or CFL reflector lamps (Lighting for Tomorrow, 2008).

These LED recessed downlight products, as measured by the DOE's Commercially Available LED Product Evaluation and Reporting Program (CALiPER), can be more efficient *in situ* than both conventional incandescent reflector and compact fluorescent technologies (DOE, 2007b). In addition to being an efficient lighting technology, LED reflector lamps can also be designed for either directional or ambient lighting unlike reflector compact fluorescent lamps which are best suited for ambient lighting conditions.

A number of sources were used to prepare the national energy consumption and potential energy savings estimate. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-1. The analysis considers the case of LEDs replacing incandescent or CFL recessed downlights in commercial or residential buildings.

Table 3-1: Critical Inputs for Recessed Downlights Energy Consumption and Savings Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Recessed Downlights Inventory: U.S. Census Bureau, Electric Light Fixture Current Industrial Reports, 1980-2001; California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, 2000a, 2000b, 2005a, 2005b.
Annual Operating Hours	Distribution of Building Types: Commercial Building Energy Consumption Survey (CBECS), 2003; Residential Energy Consumption Survey (RECS), 2001. Operating Hours per Building Type: U.S. Lighting Market Characterization (LMC), Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.
Lamp Wattages	U.S. LMC, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a; NEMA Mercury Vapor and Parabolic Reflector (PAR/R) Lamp Survey 2003. LED Efficacy: CALiPER Round 3 Summary Results, DOE, 2007c. Fixture Efficiencies: CALiPER Round 3 Summary Results, DOE, 2007c
Lighting Technology Mix	U.S. Census Bureau, Electric Light Fixture Current Industrial Reports, 1980-2001. California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, 2000a, 2000b, 2005a, 2005b.

3.1.2. Recessed Downlights Installed Base

We estimate that there are 829 million recessed downlight fixtures in the U.S., as shown in Table 3-2. The commercial sector installed base of recessed downlights is derived from the *Electric Light Fixture Current Industrial Reports* published by the U.S. Census Bureau from 1980 to 2001. This study tracks electric light fixture sales by fixture type in the U.S. for the residential, commercial, industrial, and outdoor stationary sectors. Recessed downlights, both ICAT and non-IC, open and enclosed, were among the fixtures tracked by this study. Based on the historical growth rate of recessed downlight shipments and an average fixture lifetime of 20 years, an inventory of 394 million commercial recessed downlights could be estimated for 2007.

For the residential sector, the recessed downlight inventory was estimated by using data from the U.S. Census Bureau's *Electric Light Fixture Current Industrial Reports* and the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys*, conducted on randomly selected samples of residential rate payers from four investor-owned utilities (IOUs), San Diego Gas and Electric, Southern California Gas Company, Southern California Edison, and Pacific Gas and Electric and one municipal-owned utility, the Sacramento Municipal Utility District (SMUD). The California household survey reports the average number of lighting fixtures per room for Californian residences, including the average number of recessed can fixtures per residence. The technology mix of recessed downlights is also provided in the household survey.

From the Census Bureau's *Electric Light Fixture Current Industrial reports*, an estimate of 371 million incandescent recessed downlight fixtures in the residential sector was calculated. Residential CFL recessed downlight fixtures were not tracked in the survey. The CFL recessed downlight inventory in the residential sector was estimated by assuming that the percentage of CFL recessed downlights in California (14.7%) was the same nationwide. (RLW Analytics, 2000a, 2000b, 2005a, 2005b) This assumption yields a total of 64 million CFL recessed cans in the residential sector. The national residential inventory of recessed downlights, equal to the addition of the number of incandescent recessed downlights and compact fluorescent recessed downlights, is estimated to be 435 million fixtures, as shown in Table 3-2.

At this time, well-designed LED recessed downlights are able to replace incandescent and screw-based compact fluorescent recessed downlights, which represent the majority of the 435 million residential recessed downlight fixtures installed in the U.S.

Table 3-2: Installed Base of Recessed Downlight Fixtures in the U.S., 2007

Sector	Incandescent Recessed Downlights	CFL Recessed Downlights	Total
Residential	370,765,000	64,103,000	434,868,000
Commercial	313,548,000	80,538,000	394,086,000
Total	**684,313,000**	**144,641,000**	**828,954,000**

3.1.3. Recessed Downlights Operating Hours

Recessed downlight fixtures in the commercial and residential sectors have different operating hour patterns. In the residential sector, the operating cycle of residential recessed downlights is approximately 2 hours per day, while in the commercial sector, the operating cycle of recessed downlights is approximately 9 hours per day.

The average operating hours for recessed downlights used in various types of commercial and residential buildings was obtained from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). The *Residential Energy Consumption Survey* (RECS) and *Commercial Building Energy Consumption Survey* (CBECS), both published by the EIA, were used to obtain the distribution of building types in the residential and commercial sectors. From these sources, the average operating hours in the residential and commercial sectors was obtained, as shown in Table 3-3.

Table 3-3: Average Operating Hours for Recessed Downlights

Year	Residential Average Operating Hours (hrs)	Commercial Average Operating Hours (hrs)
2007	843	3347

3.1.4. Recessed Downlight Lamp Average Wattages

For this analysis, we assume that only the reflector lamps are used in recessed downlight fixtures.[15] The average compact fluorescent lamp wattages for residential and commercial recessed downlights were estimated from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). The 2003 National Electrical Manufacturers Association (NEMA) *Mercury Vapor and Parabolic Reflector (PAR/R) Lamp Survey* for the Department of Energy (DOE) was used to determine the average wattage of residential and commercial incandescent reflector lamps. This study tracks the number of mercury vapor, incandescent, and halogen reflector lamps sold in the U.S. by wattage and application sector. The replacement LED wattage was determined by matching the lumen output for the conventional technologies and LED products, given efficacies found from conventional lamp catalogs (GE, OSI, Philips, 2006) and LED efficacies for the best-in-class products measured by DOE's CALiPER program (DOE, 2007c). Fixture efficiencies measured by the CALiPER program for both LED lamps and conventional lamps in recessed cans were also used to determine equivalent lamp wattages (DOE, 2007c).

Table 3-4: Average Lamp Wattage for Recessed Downlights

Reflector Lamp Type	Residential Average Wattage (W)	Equivalent Residential LED (W)	Commercial Average Wattage (W)	Equivalent Commercial LED (W)
Incandescent	72	14	72	14
CFL	11	7	16	11

3.1.5. Recessed Downlights Energy Saving Potential

We assume that there is currently no market penetration of LEDs in recessed downlights, as LED products for this application have only recently become available in the marketplace. Table 3-5 presents the energy consumption estimate for recessed downlights, based on the aforementioned data and inventory estimates.

Table 3-5: Recessed Downlight Energy Consumption and Savings Estimate, 2007

Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
Recessed Downlights	103.1	0.0	81.2	81.2

Thus, if LEDs with a luminaire efficacy of 60.9 lm/W (DOE, 2007c) achieved 100% market share of recessed downlights, a potential electricity savings of 81.2 TWh could be realized per year, the greatest electricity savings potential of any niche application described in this report. In terms of primary energy consumption, the potential energy savings of LED recessed downlights

[15] Due to lack of data, we assume that all recessed downlight fixtures are equipped with incandescent or CFL reflector lamps. However, non-reflector incandescent and CFL lamps are also used in recessed downlight fixtures. Because fixture efficiencies for non-reflector lamps in recessed cans are much lower than reflector lamps and efficacies of reflector vs. non-reflector lamps are approximately the same, energy consumption and potential energy savings of LEDs in this application may be understated.

is 877 TBtu/yr at the power plant, equivalent to the annual consumption of 12.8 large (1000 MW) electric power plants and representing the annual electricity consumption of 6.7 million households.

3.1.6. Technology Benefits in Addition to Energy Savings

There are several benefits outside of energy savings that are driving the adoption of LED technology in this application. In addition to saving potentially 877 TBtu/yr of primary energy when the market reaches saturation, LED recessed downlights offer other advantages over traditional recessed downlights. These include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination

For more information about these ancillary benefits of LEDs, refer to Table 1-2.

3.2. Refrigerated Display Cases

While in its nascent stage of development in the first half of this decade, LED refrigerated display case lighting systems did not provide any energy savings. However, during the past five years, technical advances in white LEDs have enabled LED refrigerated display case lighting systems to offer energy savings when replacing fluorescent systems in 2007. These LED systems have just recently entered the market, and we estimate that less than one percent of the market has switched to LED refrigerated display case systems, amounting to a small 0.08 TWh in electricity savings in 2007.

In contrast, if 100% of the market switched to LED systems there is the potential to save 2.1 TWh of electricity. This corresponds to a primary energy savings of 22.4 TBtu, equivalent to the annual consumption of one third of a (1000 MW) coal power plant or the annual electricity consumption of over one hundred and sixty thousand households.

3.2.1. Introduction

The common supermarket is the main source of produce and household goods for the majority of the U.S. population. Supermarkets are major energy consumers, requiring high-quality lighting throughout the store to illuminate merchandise and ample space heating and cooling to keep produce fresh and customers comfortable. Almost half of the annual electricity costs for a supermarket are used to operate refrigerated display cases (EPA, 2006), a term which includes both refrigerators and freezers. Lighting to illuminate food items contributes about 15% of the total electricity consumed by refrigerated display cases (DOE, 2007a). 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.

The most common light source for refrigerated display cases is fluorescent lighting. Although fluorescent lamps are highly efficient operating at room temperature (providing 70-90 lumens per watt), their efficiency decreases by more than 25% when operating at refrigeration or freezer temperatures of 38°F to -15°F (Narendran, 2003a). In addition, because of the geometry of the fluorescent lamp system in a refrigerated display case and the lack of additional optics, only about 60% of the light generated by the fluorescent lamp is directed toward the food products on display. The remaining light is wasted as excess glare on the supermarket floor (Raghavan, 2002). When one takes into account the temperature of operation and the lack of optical controls, the system efficiency of fluorescent lamp is approximately 38 lumens per watt (Narendran, 2003a). Fluorescent lamps not only degrade in efficiency in refrigerated display cases but they also radiate excess heat into the refrigerated space, increasing the energy consumed by the cooling system.

LED systems provide a compelling alternative to fluorescent refrigerated display case lighting. Not only do LED systems operate efficiently at colder temperatures but light produced by the LED can be directed towards the displayed products. LED refrigerated display case lighting systems have an efficacy of 31-33 lm/W. Although, the LED systems have a slightly lower efficacy than the fluorescent refrigerated display case systems, the uniform lighting distribution of the LED system leads to similar brightness levels (measured in lux or lumens/m^2) on the display area. Thus, LEDs using less power can be used to replace higher wattage fluorescents, leading to overall energy savings.

LEDs are especially suited to refrigerated display cases for meat. The shelf life of beef is usually limited to 2 to 3 days due to the progressive discoloration of the beef as bacteria grow on the surface and oxidize the pigments in the meat. Excess heat accelerates the spoilage of meat, as the growth rate of bacteria increases as meat surface temperatures rise. Experiments have shown that lighting from general illumination and refrigerated display cases can increase meat surface temperatures and accelerate spoilage compared to the absence of illumination (Greer, 1984). In addition, surveys of retail outlets show that typical meat surface temperatures are 4 ^oC to 25 ^oC higher than the refrigerator temperature (Jeremiah and Gibson, 1997). LEDs are ideal for meat display applications because they provide similar levels of illumination while radiating less heat than fluorescents, which slows the growth of bacteria and increases the meat products' shelf life. As this example shows, LED refrigerated display cases are a compelling product with benefits beyond energy savings.

Previous studies and energy conservation standard analyses were used to update the national energy consumption estimate from the 2003 edition of this report. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-6. The analysis considers the case of LEDs replacing fluorescent refrigerated display case systems.

Table 3-6: Critical Inputs for Refrigerated Display Case Lighting Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Refrigerated Display Cases: Commercial Refrigerated Equipment Advanced Notice of Proposed Rulemaking National Energy Savings spreadsheets.
Annual Operating Hours	Refrigerated display cases operate continuously, amounting to 8,760 hours/year.
Lamp Wattages	Commercial Refrigerated Equipment Notice of Proposed Rulemaking Engineering Analysis spreadsheets.
Lighting Technology Mix	Number of Stores with LED Cases: LEDs Magazine, 2006. Average Number of Case-Doors per Store: GE, 2007. Average Number of Doors per Case: Commercial Refrigerated Equipment Notice of Proposed Rulemaking Engineering Analysis spreadsheets.

3.2.2. Refrigerated Display Cases Installed Base

Industry manufactures at least 48 different refrigerated display case systems. However, the majority of refrigerated display cases in the market consists of four system types: vertical without doors, remote condensing, medium temperature (38 ^{o}F) systems [VOP.RC.M]; semi-vertical without doors, remote condensing, medium temperature systems [SVO.RC.M]; vertical with transparent doors, remote condensing, medium temperature systems [VCT.RC.M]; and vertical with transparent doors, remote condensing, low temperature (0 ^{o}F) systems [VCT.RC.L]. This analysis only considers the four main system types in the installed base calculation.

The installed bases for the four main types of refrigerated display cases systems were obtained from the National Energy Savings spreadsheets from DOE's Energy Conservation Standard Advanced Notice of Proposed Rulemaking on Commercial Refrigerated Equipment, and are shown in Table 3-7.

Table 3-7: Installed Base of Refrigerated Display Case Lighting Systems in the U.S, 2007

Light Source	Percent of Stock	SVO.RC.M Stock	VOP.RC.M Stock	VCT.RC.M Stock	VCT.RC.L Stock	Total Stock
Fluorescent	96.4%	229,430	300,780	21,480	298,760	850,450
LED	3.6%	8,600	11,300	850	11,250	32,000
Total	**100.0%**	**238,030**	**312,080**	**22,330**	**310,010**	**882,450**

With Wal-Mart's recent installation of LED refrigerated display cases in 500 of its U.S. stores, we estimate that 32,000 LED refrigerated display cases are installed in the U.S. (LEDs Magazine 2007). The total number of LED refrigerated display cases was developed by multiplying the number of stores with LED cases and the average number of case-doors per store, and dividing by the average number of doors per case. The percent LED penetration in the refrigerated display case market was determined by dividing the total number of LED cases by the installed base of refrigerated display cases in the U.S., which equals 3.6%. The remaining 96.4% of refrigerated display cases are assumed to be fluorescent, the standard technology in this application.

3.2.3. Refrigerated Display Cases Operating Hours

For this analysis, refrigerated display cases lighting systems for both conventional and LED systems are assumed to operate 24 hours per day year-round, amounting to an annual operating cycle of 8,760 hours. However, it should be noted that additional energy savings can be achieved through the use LED refrigerated display cases with lighting controls. LEDs can be dimmed more efficiently than fluorescents because rapid and frequent on/off cycles do not affect the life of the LED, enabling the use of movement-triggered controls. These controls can reduce the annual operating hours of the LED system and lead to even greater energy savings calculated in this report.

3.2.4. Refrigerated Display Cases Lamp and Ballast/Driver Average Wattages

The average lamp and ballast or driver wattages were determined from the Engineering Analysis spreadsheets for the DOE's Energy Conservation Standard Notice of Proposed Rulemaking for Commercial Refrigerated Equipment. The lighting system wattages for each of the four main types of systems were weighted by the 2007 installed base of each of those refrigerated display case lighting systems to obtain the total average wattage for fluorescent and LED refrigerated display case lighting systems. Each 16-watt LED strip was modeled to replace a single four-foot, 76 CRI, 85 lm/W, nominally 32-watt, T8 lamp powered by a standard two-lamp electronic ballast.

Table 3-8: Average System Wattages for Refrigerated Display Case Lighting Systems

Light Source	SVO.RC.M Average Wattage	VOP.RC.M Average Wattage	VCT.RC.M Average Wattage	VCT.RC.L Average Wattage	Total Average Wattage
Fluorescent	458	642	348	348	482
LED	244	342	224	224	271

3.2.5. Refrigerated Display Cases Energy Saving Potential

The annual electricity consumption of the over ten million refrigerated display cases in the U.S. was 3.7 TWh per year of lighting electricity use and 9.7 TWh per year of compressor electricity use for a total of 13.5 TWh/yr with the potential for reduction through the use of LEDs with an average luminaire efficacy of 30.4 lm/W. Almost four percent of the national installed base of refrigerated display case lighting systems consists of LEDs, saving 0.08 TWh/yr of electricity in 2007 through reductions in lighting (0.06 TWh/yr) and compressor (0.02 TWh/yr) electricity use. However, the potential to save an additional 2.0 TWh/yr of electricity exists if the commercial refrigerated display case market completely switched to LED systems, through reductions of 1.6 TWh/yr of lighting electricity use and 0.4 TWh/yr of compressor electricity use. This corresponds to 21.6 TBtu/yr of primary energy savings at the power plant, the energy consumption of one third of a 1000 MW coal power plant or equivalent electricity consumption of one hundred and sixty thousand households.

Table 3-9: Refrigerated Display Case Lighting and Compressor Energy Consumption and Savings Estimate, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Refrigerated Display Cases	13.4	0.08	2.00	2.1

3.2.6. Technology Benefits in Addition to Energy Savings

White LED lamps offer several advantages that will make them suitable to this niche application. LED light sources for commercial refrigerated display cases offer several benefits and features to storeowners that set them apart from fluorescent. These features can help improve the marketing and enhance the sales of products displayed. These benefits include:

1. Longer operating life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination
7. Durability
8. Smaller Package Size
9. Uniform Illumination
10. Adjustable Color
11. Increased product shelf life

These features, both financial and aesthetic, make LED light sources a compelling alternative to fluorescent. For more information about individual ancillary benefits, refer to Table 1-2.

3.3. Retail Display

LED retail display products have recently been introduced on the market and have reached efficiencies high enough to displace incandescent, halogen, CFL and certain types of fluorescent spot-, flood-, and track-lights used to display merchandise in retail stores. LED retail display lights have the potential to save 7.87 TWh/yr if 100% of the market shifted to LEDs, equal to 84.9 TBtu/ yr of primary energy consumption. This amounts to the annual consumption of one large (1000 MW) electric power plant or the annual electricity consumption of seven hundred thousand U.S. households. We estimate that there is no penetration of LEDs in retail display applications as of 2007 because products have only recently entered the market.

3.3.1. Introduction

Shopping centers rely on bright, high-quality lighting to highlight merchandise and attract customers into stores. Lighting can help indicate to customers the quality of products inside, the price point, and the type of service they can expect (Lane, 2007). Window displays and display cases require high brightness levels to distinguish products from the background. Empirical research on consumer behavior in retail environments shows that consumers are more likely to examine and handle merchandise under bright lighting than under soft lighting (Summers, et. al 2001). As a result, lighting is the biggest energy-related expense for retailers at 37% of annual energy expenditures, not including the added space cooling costs associated with the heat loads from lighting (DOE, 2006b). Energy-efficient lighting can boost the bottom line for retailers, since "saving $1 in energy costs can improve profits as much as increasing sales by $80" (Vrabel, 2003).

Several types of lighting systems can be found in a typical retail environment such as ambient lighting, task lighting, perimeter lighting, and display case lighting. Retail display lighting is of particular interest for energy efficiency measures because they are high-power, high-brightness fixtures. These lighting systems typically supply 30 to 100 footcandles (fc) on merchandise and 150 to 500 fc on feature displays to provide contrast between highlighted merchandise and the surrounding area, which is typically lit at a lower 10 to 30 fc brightness level (Lane, 2007). Retail display lighting includes three main types of systems: (1) *accent lighting* is accomplished using track-, spot-, or flood-light luminaires to draw customer attention to specific merchandise and should be illuminated at least three times brighter than the surroundings to be noticeable and five times brighter to be meaningful, according to IESNA recommendations (Vrabel, 2003; IESNA, 2001); (2) *focal-point lighting* should be ten times brighter than the surroundings, and usually uses spotlights to highlight specific central displays of merchandise; and (3) *display case lighting* illuminates merchandise in glass or open shelves or cases, and uses linear fluorescent or spot lighting (Vrabel, 2003).

The most common light source for retail display lighting is linear fluorescent track lighting to provide accent or display case lighting, followed by halogen or incandescent spot lights to provide high-brightness focal-point lighting. Carefully designed LED systems can be viable alternatives to all three of these conventional lighting systems. One strategy is to replace high power white incandescent or halogen spotlights with colored LEDs for feature displays to draw the customer's attention. Controlled experiments in retail stores have shown an increase in positive consumer emotions and greater handling of products lighted under colored LED lighting (Freyssinier, et al., 2006; Summers, et. al, 2001; Tullman, 2000). Another strategy is to replace high wattage incandescent, halogen and even CFL reflector lamps with LED reflector lamps. As discussed previously, LED reflector lamps, unlike CFL reflector lamps can be serve for both directional and ambient lighting applications. Efficient linear LED fixtures are also available to replace magnetic T12 linear fluorescent track lighting systems less than 4-feet in length and magnetic U-bent T12 fluorescent systems with low fixture efficiencies. Since LED retail display products have only recently entered the market, we assume that there is no LED penetration in this application as of 2007.

One retail display application especially suited to LED lighting is jewelry display cases. Light from each LED in the jewelry case lighting system is reflected by the gem's facets leading to more reflections and greater perceived sparkle than gems lit by a single incandescent, halogen, or fluorescent lamp with equal lumen output. Increased sparkle makes LED-lit jewelry appear to be of higher quality and enhances sales according to an industry case study (Costco, 2007). LED jewelry cases can also be designed to conceal the lighting system as much as possible for clear display of merchandise.

Previous studies and researchers were consulted to create the national energy consumption and savings estimates for retail display lighting. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-10. The analysis considers the case of LEDs replacing incandescent, halogen, CFL, and T12 fluorescents less than 4-feet in length, or U-bent T12 fluorescent retail display lighting systems.

Table 3-10: Critical Inputs for Retail Display Lighting Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Retail Display Lighting Systems per Square Foot: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Commercial Floorspace Growth Rate: EIA's Commercial Building Energy Consumption Survey (CBECS), 2003, 1999.
Annual Operating Hours	U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.
Lamp Wattages	Conventional Product Lamp Wattages: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.; NEMA Mercury Vapor and Parabolic Reflector (PAR/R) Lamp Survey 2003; NEMA A-line Statistical Wattage Survey 2005. Conventional Product Fixture Efficiencies: CALiPER 5: Summary Results, DOE, 2008b, Mia Paget, Pacific Northwest National Laboratory, 2008. LED Product Efficacies: CALiPER 5: Summary Results, DOE, 2008b, CALiPER 3: Summary Results, DOE, 2007c.
Lighting Technology Mix	Conventional Technology Mix: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.

3.3.2. Retail Display Installed Base

We estimate that there are approximately 171 million retail display lighting fixtures in the U.S., as shown in Table 3-11. The installed base of retail display lights is derived from commercial building survey from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a), which provides data on display lighting fixtures per square foot of retail (open, enclosed, and strip-mall) floorspace. This survey also provides the technology mix of display lighting fixtures in 2001. Assuming a 1.6% annual commercial floorspace growth rate (EIA, 2003, 1999), we calculate the inventory of retail display lighting fixtures in 2007. We assume the technology mix of display lighting fixtures has not changed substantially between 2001 and 2007.

Table 3-11: Installed Base of Retail Display Fixtures in the U.S., 2007

Light Source	Technology mix of Retail Display lights (%)	Number of Installations
Standard - General Service	2.2%	3,829,000
Standard – Reflector	5.5%	9,454,000
Halogen – Quartz	2.4%	4,063,000
Halogen - refl. - low volt	8.3%	14,223,000
T8 – less than 4’	2.2%	3,767,000
T8 – 4’	50.1%	85,678,000
T8 – U-bent	2.8%	4,738,000
T12 – less than 4’	0.8%	1,387,000
T12 – 4’	15.8%	27,095,000
T12 – More than 4’	7.9%	13,505,000
T12 – U-bent	1.0%	1,757,000
Compact – Screw base	0.9%	1,498,000
Total	**100.0%**	**170,994,000**

3.3.3. Retail Display Operating Hours

The average operating hours for retail display lighting was estimated from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). Retail buildings such as open stores, enclosed shopping malls, and strip malls provided data on display lamp operation in the commercial building survey. Assuming that hours of operation have not changed between 2001 and 2007, retail display lights are on throughout the open hours of the store, for an average of 3937 hours per year or 10.8 hours per day.

3.3.4. Retail Display System Average Wattages

Table 3-12 shows the average retail display lighting system wattage obtained from the lamp wattages published in the commercial building survey of the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). Using average ballast factors for fluorescent lamps and published average fixture efficiencies (DesignLights, 2003), system wattages for the retail display systems could be calculated. LED replacements for the retail display products were determined by matching the lumen output of the LEDs and conventional products, assuming an average LED retail display lighting efficacy from best-in-class products measured by the CALiPER testing program (DOE, 2008b,2007c) and conventional product efficacies from manufacturer datasheets and published reports (GE, 2006; DOE, 2002a). Since LED retail display products are less efficient than all types of T8 fixtures and 4-foot and greater length T12 fixtures, LEDs are only modeled to replace incandescent, halogen, T12s less than 4-foot in length, U-bent T12s, and compact fluorescent fixtures, representing 21% or 36.2 million fixtures of total retail display fixtures.

Table 3-12: Conventional and LED Retail Display System Wattage

Light Source	Retail Display System Power (W)	LED Replacement (W)
General Service – Incandescent	67	9
Incandescent – Reflector	72	13
Halogen – Quartz	226	69
Halogen - refl. – low volt	48	8
T12 – less than 4'	31	29
T12 – U-bent	49	46
Compact – Screw base	16	11

3.3.5. Retail Display Energy Saving Potential

The approximately 171 million retail display lighting systems in the U.S. consumed 32.0 TWh/yr of electricity, excluding the heating loads from the lighting systems, as shown in Table 3-13. There were no energy savings from LED retail display lighting systems as LED products have only recently become available on the market. However, the retail display lighting market has the potential to save 7.87 TWh/yr of electricity if the 36.2 million retail display fixtures containing incandescents, halogens, T12s less than 4-feet in length, U-bent T12s, and CFLs switched to LED systems with an average luminaire efficacy of 46.5 lm/W (DOE 2008b, 2007c). This corresponds to 84.9 TBtu per year of primary energy savings at the power plant, the energy consumption of one 1000 MW coal power plant or the equivalent electricity consumption of seven hundred thousand households.

Table 3-13: Retail Display Case Energy Consumption and Savings Estimate, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Retail Display Lighting	32.0	0.0	7.87	7.87

3.3.6. Technology Benefits in Addition to Energy Savings

White and colored LED lamps offer several advantages that will make them suitable to this niche application. LED light sources for retail display lighting offer several benefits and features to storeowners that set them apart from incandescent, halogen, and fluorescent products. These features can help improve marketing efforts and enhance the sales of products displayed. These features, both financial and aesthetic, make LED light sources a compelling alternative to fluorescent, as described in Table 1-2. These benefits include:

1. Longer operating life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination
7. Smaller Package Size
8. Uniform Illumination
9. Adjustable Color
10. Enhanced product appearance

.

3.4. Task Lighting

In the last five years, LED task lighting products have been introduced on the market as replacements to inefficient incandescent, halogen, and T12 and circline fluorescent task lights used in the commercial, industrial, and residential sectors. LED task lights have the potential to save 13.0 TWh/yr if the entire market shifted to 2007 LED technology, equal to 140.1 TBtu/yr of primary energy consumption. This amounts to the annual consumption of two large (1000 MW) coal power plants or the annual electricity consumption of one million U.S. households. We estimate that there is no penetration of LEDs in task lighting applications as of 2007 because products have only recently entered the market.

3.4.1. Introduction

Task lighting is used to increase illumination on work surfaces above ambient levels. Two specific types of task lights, office undershelf and kitchen undercabinet fixtures, are described in sections 3.5 and 3.6; this section focuses on the energy consumption and savings of other (usually portable) task lights such as desk, table, or reading lamps. Studies have shown that when task lights provide brightness levels necessary to perform work tasks, as much as 33% energy savings can be achieved by lowering overhead lighting (Waste Reduction Partners, 2004; LBL, 1997). The IESNA has established standards for how much illumination is required for performing various tasks, ranging from “Category D”, 10 to 50 footcandles (lumens per square foot), for typical office tasks such as reading computer screens or typed original documents on white paper to “Category E”, 50 to 100 fc, for reading books or handwritten notes (ANSI/IESNA, 2004).

Task lights are used in all sectors of the economy, from commercial offices and industrial facilities to residential households. The most common task light technologies in use depend on the sector; commercial and industrial settings rely heavily on T8 and T12 systems while the residential stock of task lights are mostly incandescent. The efficiencies of these systems vary widely based on luminaire design. Optimal luminaire design maximizes fixture efficiency while limiting direct (bare bulb), reflected (from a shiny surface) or veiling (contrast-limiting) glare (Wolsey and Miller, 1994).

Task lights are especially important for applications where most occupants are over 55 years old, such as retirement homes. Starting around age 45, the eye's capacity to focus at close range progressively decreases and stabilizes around ages 60 to 65. The eye's crystalline lens capsule begins to harden and thicken, absorbing more light so that less light reaches the retina. This effect is intensified as the pupil becomes smaller in size with increasing age. At the same light level, a typical 60-year old receives about one-third the retinal illuminance of a 20-year old (Figueiro, 2001). As a result, the typical 60- to 65-year old requires 2.5 times more light than a 20- to 25-year old to achieve the same level of visual acuity for tasks such as reading (Tetlow, 2007). Through adjustable task lights, offices and residences can provide light levels necessary for all age levels.

LED task lights are starting to appear in the market. These task lights are able to take advantage of both the directional light output and high efficacies of LEDs. DOE's CALiPER program has tested the luminaire efficacies of several LED desk lamps (DOE, 2008a). These LED task lights can be more efficient than incandescent, halogen, and even some fluorescent fixtures. Since LED task lights have only recently become available in the market, we estimate that there is no significant market penetration of LEDs in this application.

Previous studies, researchers, and results from DOE's CALiPER program were consulted to create the national energy consumption and savings estimates for task lighting. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-14. The analysis considers the case of LEDs replacing incandescent, halogen, T12 and circline fluorescent task lighting systems, which represent about 96% of the total task light inventory, as described in the next section.

Table 3-14: Critical Inputs for Task Lighting Energy Consumption and Savings Potential Estimate

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Commercial and Industrial Task Lights: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Number of Residential Task Lights: California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, 2000, 2005; Residential Lighting: The Data to Date, Jennings, et. al., 1996. Commercial Floorspace Growth Rate: EIA's Commercial Building Energy Consumption Survey (CBECS), 2003, 1999. Industrial Floorspace Growth Rate: EIA's Manufacturing Energy Consumption Survey (MECS), 1998, 1994.
Annual Operating Hours	U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.
Lamp Wattages	Conventional Product Lamp Wattages: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.; NEMA Mercury Vapor and Parabolic Reflector (PAR/R) Lamp Survey 2003; NEMA A-line Statistical Wattage Survey 2005. Conventional Product Fixture Efficiencies: Mia Paget, PNL, 2008. LED Product Efficacies: CALiPER Round 3 and 4 Summary Results, DOE, 2007c, 2008c.
Lighting Technology Mix	Commercial and Industrial Technology Mix: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Residential Technology Mix: California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, 2000, 2005.

3.4.2. Task Lighting Installed Base

We estimate that there are 432 million task lighting fixtures in the U.S., as shown in Table 3-15. The installed base of task lights is derived from a variety of sources for the commercial, industrial, and residential sectors. The inventory of commercial and industrial task lights were estimated from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a), which provides data on task lighting fixtures per square foot of commercial and industrial floorspace. This survey also provides the technology mix of task lighting fixtures in 2001. Assuming a 1.6% annual commercial floorspace growth rate (EIA, 2003, 1999) and 1.0% annual industrial floorspace growth rate (MECS), we calculated the inventory of commercial and industrial task lighting fixtures in 2007.

We assume the technology mix of task lighting fixtures has not changed substantially between 2001 and 2007.

For the residential sector, we estimated the task light inventory from the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys*, conducted on randomly selected samples of residential rate payers from four investor-owned utilities (IOUs) and one municipal-owned utility. The survey reports on the average number of lighting fixtures per room for California residences, including the average number of table lamps per residence.[16] Assuming that the prevalence of task lights is equally likely in California and nationwide, we were able to develop an inventory by multiplying the average number of task lights per California household by the number of U.S. households in 2007 (U.S. Census Bureau, 2007). The technology mix of task lights were also provided in the survey. At this time, LED task lamps are able to replace incandescent, halogen, T12 and circline fluorescent task lighting systems, which represent about 97% of the total task light inventory, or 420 million task lighting systems.

Table 3-15: Task Lighting Installed Base and Technology Mix, 2007

Light Source	Commercial Technology mix of task lights(%)	Industrial Technology mix of task lights(%)	Residential Technology mix of task lights(%)	Number of Installations
General Service Incandescent	28.9%	2.24%	74.7%	308,784,000
Incandescent Reflector	22.7%	4.35%	0.00%	5,258,000
General Service Halogen	0.00%	0.00%	4.71%	19,044,000
Halogen – Quartz	5.03%	0.79%	0.00%	1,159,000
T8 – less than 4’	34.7%	39.2%	0.00%	9,529,000
T12 – less than 4’	1.98%	0.63%	0.00%	471,000
T12 – 4’	0.00%	11.5%	0.00%	521,000
T12 – More than 4’	0.00%	32.7%	0.00%	1,485,000
Circline	0.35%	8.22%	0.00%	453,000
Compact – Screw base	6.35%	0.44%	20.6%	84,799,000
Total	**100.0%**	**100.0%**	**100.0%**	**431,503,000**

3.4.3. Task Lighting Operating Hours

The average operating hours for task lighting was estimated from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a) for the residential, commercial, and industrial sectors. Assuming that hours of operation have not changed between 2001 and 2007, annual operating hours by sector are shown in Table 3-16.

[16] The only lighting fixtures tracked in the California household survey that resembles a portable task light is a table lamp. Because we assume that all of these table lamps serve a task light function versus an ambient lighting function, we may be overestimating the energy consumption and savings potential due to LEDs in this application.

Table 3-16: Task Lighting Annual Operating Hours by Lamp Type

Light Source	Commercial Task Lights (Hrs)	Industrial Task Lights (Hrs)	Residential Task Lights (Hrs)
Sector Average Annual Operating Hours	3,509	3,150	623

3.4.4. Task Lighting Lamp Average Wattages

Table 3-17 and Table 3-18 show the average task lighting system wattage obtained from the lamp wattages published in the commercial and industrial buildings survey of the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). Table 3-19 shows residential task lighting system wattages which were determined using the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys*. Using average ballast factors and efficiencies for fluorescent lamps and an average fixture efficiency of 50% for task lighting (Paget, 2008), system wattages for the task lighting systems could be calculated. LED replacements for the task lighting products were determined by matching the lumen output of the LEDs and conventional products, assuming an LED task light luminaire efficacy of 38.3 lm/W from the best-in-class product measured by the CALiPER program (DOE, 2008c, 2007c). Since LED task lights are less efficient than products with T8 fluorescents less than or equal to 4-feet in length and T12 fluorescents greater than 4-feet in length, these products are not included in the energy savings calculations.

Table 3-17: Commercial Conventional and LED Task Light System Wattages

Light Source	Commercial Task Light System Power (W)	Commercial LED Replacement (W)
General Service Incandescent	83	15
Incandescent – Reflector	72	11
Halogen – Quartz	78	15
T12 – less than 4’	31	25
Circline Fluorescent	33	16
Compact – Screw base	16	11

Table 3-18: Industrial Conventional and LED Task Light System Wattages

Light Source	Industrial Task Light System Power (W)	Industrial LED Replacement (W)
Incandescent – Reflector	102	18
Halogen – Quartz	452	124
T12 – less than 4’	34	28
T12 – 4’	47	40
Circline Fluorescent	39	20

Table 3-19: Residential Conventional and LED Task Light System Wattages

Light Source	Residential Task Light System Power (W)	Residential LED Replacement (W)
General Service Incandescent	67	12
Halogen – General Service	72	13
Circline Fluorescent	11	8

3.4.5. Task Lighting Energy Saving Potential

The 432 million task lighting systems in the U.S. consumed 18.8 TWh/yr of electricity (excluding the heating loads from the lighting systems), as shown in Table 3-20. There were no energy savings from LED task lighting systems in 2007 as LED products have only recently become available on the market. However, if LED task lights with an average luminaire efficacy of 38.3 lm/W (DOE, 2008c, 2007c) replaced the 420 million task lights with incandescent, halogen, T12s ≤ 4-feet in length, and circline fluorescent lamps the task lighting market has the potential to save 13.0 TWh/yr of electricity. This corresponds to 140.1 TBtu per year of primary energy savings at the power plant, the energy consumption of two 1000 MW coal power plants or equivalent electricity consumption of one million households.

Table 3-20: Task Lights Energy Consumption and Savings Estimate, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Task Lights	18.8	0.0	13.0	13.0

3.4.6. Technology Benefits in Addition to Energy Savings

White LED lamps offer several advantages that will make them suitable to this niche application, as described in Table 1-2. LED light sources for task lighting offer several benefits and features to residential, commercial, and industrial users that set them apart from incandescent, halogen, and some fluorescent products. These benefits include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination
7. Smaller Package Size

3.5. Office Undershelf Lighting

A type of task lighting, LED office undershelf lighting systems have been introduced on the market as replacements for T12 and T8 fluorescent products used in the commercial offices. LED office undershelf lights have the potential to save 1.37 TWh/yr if the entire market shifted to 2007 LED technology, equal to 14.8 TBtu/yr of primary energy consumption. This amounts to about 20% of the annual consumption of one large (1000 MW) electric power plant or the annual electricity consumption of one hundred thousand U.S. households. We estimate that there is no penetration of LEDs in office undershelf lighting in 2007 because products have only recently entered the market.

3.5.1. Introduction

Office undershelf lighting is the main type of task lighting in commercial offices. Approximately one-third of office workers in the U.S. use partitioned workstations, which commonly include undershelf task lights. These task lights account for about 90 percent of all office task lighting sold (Wolsey and Miller, 1994). Task lighting can minimize the ambient light needed in offices, leading to overall electricity savings. Task lighting, as described in Section 3.4, is important to achieve IESNA-recommended lighting levels for reading and other tasks and minimize eye strain (ANSI/IESNA, 2004).

Office undershelf lighting should be designed to minimize glare and reflections off the work surface that cause visual discomfort. The efficacy of an office undershelf lighting product depends heavily on fixture efficiency and the distribution of light over the desk. Luminaire efficacies for undershelf lighting depend on the light output on the desk plane instead of total light output from the luminaire. This definition excludes light that illuminates areas other than the work space (LRC-ASSIST, 2007).

Fluorescent lamps, T8s and T12s, are most commonly used for office undershelf lighting. However, fixture efficiencies are typically less than 40% for these fluorescent undershelf lighting systems (DOE, 2008e). Because of the directional quality of LEDs, more lumens are directed on the work space, and fewer wasted lumens are directed upward or on the back of the shelf.

A number of sources were used to prepare a national estimate of the energy consumption and savings of office undershelf lighting products. As with the other niche market assessments, there were four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-21.

Table 3-21: Critical Inputs for Office Undershelf Lighting Energy Consumption and Savings Potential Estimate

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Office Undershelf Lighting Systems: U.S. Census Bureau, Electric Light Fixture Current Industrial Reports, 1991-2001.
Annual Operating Hours	Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture, Energy Solutions, 2004.
Lamp Wattages	Conventional Product Lamp Wattages: Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture, Energy Solutions, 2004. LED Product Efficacies: CALiPER 3 Summary Report, DOE, 2007c. Fixture Efficiency: Undercabinet factsheet, DOE, 2008e.
Lighting Technology Mix	Conventional Technology Mix: Energy Solutions, Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture, 2004; NEMA, Special Statistical Bulletin for the Lamps Section, 2006.

3.5.2. Office Undershelf Lighting Installed Base

We estimate that there are 53 million office undershelf lighting fixtures in the U.S., as shown in Table 3-22. Assuming an average fixture lifetime of 20 years, we calculated the national inventory of office undershelf lighting systems from annual shipments of undershelf electric light fixtures collected by the U.S. Census Bureau from 1991 to 2001. The technology mix of T12 versus T8 fluorescent lamps for undershelf lighting systems was determined from the 2006 National Electrical Manufacturers Association (NEMA)'s *Special Statistical Bulletin for Lamps*.

Table 3-22: Office Undershelf Installed Base, 2007

Light Source	Market Share (%)	Installed Base
T12 Fluorescent, Magnetic Ballast	44.7%	23,663,000
T8 Fluorescent, Electronic Ballast	55.3%	29,297,000
Total	**100.0%**	**52,950,000**

3.5.3. Office Undershelf Lighting Operating Hours

Office undershelf lighting systems operate for an average of 2000 hours per year, amounting to about 5.5 hours per day or 8 hours per work day. This estimate is from the *Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture* (Energy Solutions, 2004), a report that estimates the energy savings of more stringent energy efficiency standards for fluorescent office undershelf lamps and ballasts in California. We assume that hours of operation have not changed during 2001 to 2007.

3.5.4. Office Undershelf Lighting System Average Wattages

Table 3-23 shows the average office undershelf lighting system wattage obtained from the lamp wattages published in *Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture* (Energy Solutions, 2004). Using average ballast factors and efficiencies for fluorescent lamps, system wattages for the office undershelf lighting systems could be calculated. LED replacements for the office undershelf lighting products were determined by matching the lumen output of the LEDs and conventional products, assuming an average LED undershelf lighting system efficacy from the best-in-class products measured by the CALiPER program (DOE, 2007c) and including measured undershelf fixture efficiencies for LED and conventional products (DOE, 2008e).

Table 3-23: Office Undershelf System Average Wattage and LED Equivalent

Light Source	System Watts (W)	LED Equivalent (W)
T12 Fluorescent, Magnetic Ballast	36	19
T8 Fluorescent, Electronic Ballast	29	20

3.5.5. Office Undershelf Lighting Energy Saving Potential

The 53 million office undershelf lighting systems in the U.S. consumed 3.43 TWh/yr of electricity, as shown in Table 3-24. There were no energy savings from LED office undershelf lighting systems in 2007 as LED products have only recently become available on the market. However, the office undershelf lighting market has the potential to save 1.37 TWh/yr of electricity if the market completely shifted to LED systems with an average efficacy of 45.5 lm/W (DOE, 2007c). This corresponds to 14.8 TBtu per year of primary energy savings at the power plant, equal to 20% of the annual output of one 1000 MW coal power plant or the equivalent annual electricity consumption of one hundred thousand households.

Table 3-24: Office Undershelf Energy Consumption and Savings Potential, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Office Undershelf Lighting	3.43	0.0	1.37	1.88

3.5.6. Technology Benefits in Addition to Energy Savings

White LED lamps offer several advantages that will make them suitable to this niche application. LED light sources for office undershelf lighting offer several benefits and features to office workers that set them apart from fluorescent products. These benefits, as described in Table 1-2, include:

1. Longer Operating Life
2. Lower Maintenance and Life Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination

3.6. Kitchen Undercabinet Lighting

A similar promising niche application for LEDs is kitchen undercabinet lighting, a form of residential task lighting. LED kitchen undercabinet lighting systems have been introduced on the market as replacements to incandescent, halogen, T12 and T8 fluorescent products used in U.S. kitchens. LED kitchen undercabinet lights have the potential to save 2.22 TWh/yr if the entire market shifted to 2007 LED technology, equal to 24.0 TBtu/yr of primary energy consumption. This amounts to the 35% of the annual output of one large (1000 MW) coal power plant or annual electricity consumption of almost two hundred thousand U.S. households. We estimate that there is no penetration of LEDs in kitchen undercabinet lighting as of 2007 because products have only recently entered the market and widespread adoption has yet to occur.

3.6.1. Introduction

Kitchens require high-quality lighting to illuminate various surfaces of differing heights and materials. Counters are often made of shiny or dark materials that require glare control or high-brightness fixtures. Much of the counter area is severely shadowed even though this is where the majority of food preparation is conducted. Kitchen lighting designs should have high CRI (color rendering index) because color is a main indicator of food freshness. Optimal designs avoid glare and excess heat, which accelerates food spoilage and is uncomfortable to the kitchen occupant. An increasingly popular task lighting fixture in kitchens is the undercabinet light, which illuminates the counters during food preparation and cooking. We estimate that 26.1% of kitchens in the U.S. use undercabinet lighting products. This number is growing as they are becoming more common in new houses and lighting retrofit projects (RLW Analytics, 2000, 2005).

Fluorescent lamps, T12s and T8, are commonly used for kitchen undercabinet lighting. Incandescent or halogen bi-pin lamps, puck lights, wedge lamps, festoons and light strips are also popular. LEDs are good substitutes because of the low efficacies of incandescent and halogen lamps and the low fixture efficiencies (less than 40%) of fluorescent undercabinet lighting systems due to the geometry of the fluorescent lamp (DOE, 2008e). The directional quality of LEDs leads to more lumens on the countertop, and fewer wasted lumens trapped within fixture or directed away from the work plane. Warm-white LEDs with high CRI are preferred to render the food as attractively and realistically as possible.

A number of sources, including previous studies and databases, were consulted to prepare a national estimate of the energy consumption and savings of kitchen undercabinet lighting systems. As with the other niche market assessments, there were four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 3-25.

Table 3-25: Critical Inputs for Kitchen Undercabinet Lighting Energy Consumption and Savings Potential Estimate

Critical Input	Notes and Sources
Installed Base of Lamps	Percentage of Homes with Kitchen Undercabinet Lights: California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, Inc., 2000, 2005. U.S. Household Population: 2000 Demographic Profile, U.S. Census Bureau. 2000-2007 Residential Household Growth Rate: EIA's Residential Energy Consumption Survey (RECS), 2001, 1997.
Annual Operating Hours	U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.
Lamp Wattages	Conventional Product Lamp Wattages: California Residential Lighting and Appliance Efficiency Saturation Survey, 2000, 2005; U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Conventional Product Fixture Efficiencies: DOE Undercabinet Factsheet, 2008e. LED Product Efficacies: CALiPER Round 3 Summary Results, DOE, 2007c.
Lighting Technology Mix	Conventional Technology Mix: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a; California Statewide and SMUD Residential Lighting and Appliance Efficiency Saturation Survey Database, RLW Analytics, Inc., 2005c, 2005d.

3.6.2. Kitchen Undercabinet Lighting Installed Base

We estimate an installed base of 53 million kitchen undercabinet lighting fixtures in the U.S., as shown in Table 3-26. The kitchen undercabinet installed base was determined using the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys.* Using a linear projection between 2000 and 2005 data, we find that 26.1% of homes have kitchen undercabinets in California in 2007. Assuming that kitchen undercabinets are just as common in California as they are nationwide, we determined the national installed base of kitchen undercabinets by multiplying the average number of kitchen undercabinets per household in California by the number of U.S. households in 2007 (DOE, 2007a; EIA, 2001, 1997). An online database from the 2005 IOU and SMUD survey was used estimate the market penetration of various undercabinet technologies in 2007 (RLW Analytics, 2005c, 2005d).

Table 3-26: Kitchen Undercabinet Installed Base and Technology Mix, 2007[17]

Light Source	Market Share (%)	Installed Base
General Service Incandescent	45.6%	24,340,000
General Service Halogen	12.4%	6,620,000
CFL – Screw Base	2.8%	1,474,000
T12 Fluorescent Tube	34.0%	18,142,000
T8 Fluorescent Tube	5.3%	2,806,000
Total	**100.0%**	**53,382,000**

3.6.3. Kitchen Undercabinet Lighting Operating Hours

Kitchen undercabinet lighting systems operate for an average of 1107 hours per year, amounting to about three hours per day. This estimate comes from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a), which includes survey data on kitchen light operating hours. We assume that hours of operation have not changed between 2001 to 2007.

3.6.4. Kitchen Undercabinet Lighting System Average Wattages

Table 3-27 shows the average kitchen undercabinet lighting system wattage obtained from the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys*. Using average ballast efficiencies for fluorescent lamps, system wattages for the kitchen undercabinet lighting systems could be calculated. LED replacements for the kitchen undercabinet lighting products were determined by matching the lumen output of the LEDs and conventional products, assuming a LED undercabinet lighting system efficacy of 45.5 lm/W from the best-in-class products measured by the CALiPER program (DOE, 2007c) and including measured undercabinet fixture efficiencies for LED and conventional products (DOE, 2008e).

Table 3-27: Kitchen Undercabinet Lighting System Average Wattage and LED Equivalent

Light Source	System Watts (W)	LED Equivalent (W)
General Service Incandescent	60	9
General Service Halogen	55	6
CFL – Screw Base	18	8
T12 Fluorescent Tube	45	13
T8 Fluorescent Tube	28	20

[17] Due to lack of data, we assume that 4-foot T12s and T8s are most commonly used in kitchen undercabinets. However, less efficacious 2-foot or 3-foot fluorescents may also be in use in kitchen undercabinets. Therefore, we may be understating the energy consumption and potential energy savings of LEDs in this application.

3.6.5. Kitchen Undercabinet Lighting Energy Saving Potential

The 53 million kitchen undercabinet lighting systems in the U.S. consumed 2.84 TWh/yr of electricity, as shown in Table 3-28. LED kitchen undercabinet lighting systems did not lead to significant energy savings in 2007 as widespread adoption of LED products has yet to occur. However, the kitchen undercabinet lighting market has the potential to save 2.22 TWh/yr of electricity if the market completely shifted to LED systems with an average luminaire efficacy of 45.5 lm/W (DOE, 2007c). This corresponds to 24.0 TBtu/yr of primary energy savings at the power plant, equivalent to 35% of the annual output of one large (1000 MW) coal power plant or annual electricity consumption of just under two hundred thousand households.

Table 3-28: Kitchen Undercabinet Energy Consumption and Savings Potential, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings (TWh)	Theoretical Maximum Electricity Savings (TWh)
Kitchen Undercabinet Lighting	2.84	0.0	2.22	2.22

3.6.6. Technology Benefits in Addition to Energy Savings

White LEDs offer several advantages that will make them suitable to this niche application, as described in Table 1-2. LED light sources for kitchen undercabinet lighting offer several benefits and features to homeowners that set them apart from incandescent, halogen, and fluorescent products. These benefits include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination

4. Outdoor White-Light Applications

As with indoor white-light applications, electricity is saved in outdoor white-light applications where LED sources are used to replace incandescent, halogen, mercury vapor, metal halide and high-pressure sodium lamps. The case for energy savings for outdoor white-light applications is unique from colored-light and indoor white-light applications because of the eye's response to light under nighttime conditions. The savings for outdoor installations are presented in TWh per year for the nation under daytime conditions, which may represent the lower bound of the energy savings potential of LEDs in these applications. Even more energy could potentially be saved if lighting designers took into account the effects of night time conditions on vision. This report evaluates two outdoor white-light niche market applications: street and area lighting, and step, path, and porch lighting.

4.1. Photopic vs. Scotopic Vision

According to some experts, the energy efficiency benefits of LED outdoor lights cannot be determined simply by comparing efficacy, the energy efficiency measure for lamps. Studies comparing the perceived brightness of LED sources and sodium lamps at night have shown that LEDs can achieve the same level of perceived brightness with lower lumen output than sodium lamps (Raleigh 2007). This affect could be explained by the eye's response to light in outdoor "night time" conditions.

Light, measured in lumens, is defined according to the visual sensation it produces in "daytime" conditions. However, the visibility of light varies with external conditions. During "daytime" or indoor lighting conditions, where there is a high level of ambient light, the eye uses its cone sensors to perceive light. This type of vision is referred to as photopic (photon-rich) vision. During "night time" conditions, where there is a low level of ambient light, the eye uses its rod sensors to perceive light. This type of vision is referred to as scotopic (scarcity of photons) vision. The rods have a different color response than the cones in the eye, as shown in the photopic and scotopic V-λ curves, Figure 4-1. Under outdoor lighting at night, the eye operates in an intermediate range, called mesopic vision, using both rods and cones.

The energy savings estimates given in this report could possibly be greater if the visible light output of light sources under outdoor lighting conditions were taken into account. Assuming equal quantities of "daytime" lumens produced, light sources rich in blue light, such as LEDs or metal halide lamps produce more visible lumens at night than light sources rich in yellow light such as high or low pressure sodium lamps (Bullough 2001). However, the commercial applicability of these additional energy savings is limited until regulatory bodies and the lighting industry change specifications and design requirements to take the efficacy of light sources under nighttime conditions into account. As of 2007, lighting organizations such as the Illuminating Engineering Society of North America (IESNA) and the International Commission on Lighting [Commission Internationale de l'Eclairage] (CIE) do not accept scotopically enhanced design factors as industry-recognized standard practice.

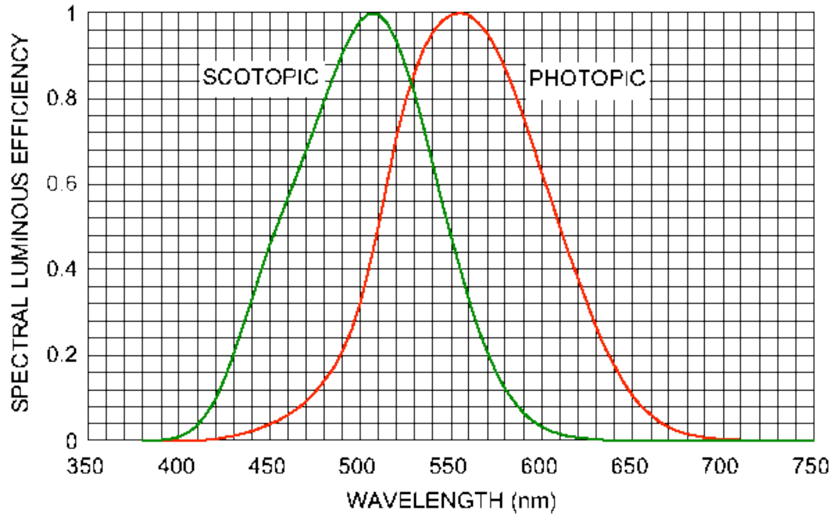

Figure 4-1: Photopic and Scotopic V-λ Curves
Source: Electro-Optical Industries, 2007.

4.2. Street and Area Lighting

Streetlights serve the purpose of illuminating roadways, highways, or tunnels 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 street and area lights that use incandescent, halogen quartz, fluorescent, and 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.

Substantial energy savings can be realized if the market shifted toward LED street and area lights. A potential electricity savings of 44.7 TWh per year may be realized if LEDs achieved 100% market penetration. The potential primary energy savings is 482.0 TBtu/yr at the power plant, the equivalent of seven large (1000 MW) electric power plants or the annual electricity consumption of 3.7 million households if 100% of the installed base moved to LED.

4.2.1. Introduction

The earliest street and area lights were oil or gas lamps that required a lamp-lighter to light each streetlight by hand at dusk. The first electric street and area lighting technology was the carbon arc lamp, invented by Pavel Yablochkov in 1875. A low voltage applied to the lamp's two carbon electrodes produces an electric arc. As the two electrodes are pulled apart, an electric current maintains the arc and heats the electrodes until they incandesce and emit light. By the 1890s, the United States had installed over 130,000 streetlights.

In 1879, Thomas Edison invented the incandescent lamp, which soon replaced arc lamps for street and area lighting applications because of its higher reliability, longer life, and warm-white light. Incandescent lamps produce light by sending an electrical current through a tungsten filament, which heats until it incandesces to produce light. Incandescent street and area lights were popular throughout the 1930s and 1940s as automobile use expanded. The incandescent lamp soon replaced the carbon arc lamp as the most common streetlight, because of the arc lamp's harsher light quality and lower lamp life.

In 1938, the first mercury vapor streetlights were installed. Mercury vapor lamps produce light by exciting mercury in a small quartz arc tube with an electrical current. The excited mercury then releases its energy by emitting light. Mercury vapor street and area lights became popular because they were much brighter and more efficient than incandescent lamps. However, the mercury contained in and ultraviolet light emitted by these lamps are safety hazards if the lamps break (Comer, 2000).

In the 1970s, high-pressure sodium lamps, which produce light by exciting sodium, were put into service. These lamps are recognizable by their virtually monochromatic yellow/orange (589.0 and 589.6 nm) light. High-pressure sodium lamps are beneficial because they are far more efficient than incandescent or mercury vapor lamps, and they contain no mercury. Today, yellow/orange high-pressure or low-pressure sodium lamps are among the most common street and area lighting technologies in use because of their high efficacies. Their main disadvantage is their poor color rendering because they are nearly monochromatic light sources (Comer, 2000).

Metal halide is now becoming the light source of choice for street and area lighting applications where color rendering is important. A close variation of mercury vapor lamps, a metal halide lamp produces light through a mixture of mercury and other chemicals such as sodium iodide or scandium iodide in an excited state (Comer, 2000). Since a metal halide lamp's spectrum contains more blue light than sodium lamps, they render blues and violets more accurately and appear to be brighter at night when the eye uses mesopic vision.

In the early 2000s, researchers recognized the potential for LEDs in street and area lighting applications. LEDs are particularly advantageous in street and area lighting applications because they are better directional light sources, exhibit longer lifetimes, and enhance night time visibility. Because of these positive attributes, Raleigh, North Carolina became the first of a dozen U.S. cities to begin testing and replacing their conventional street and area lighting technologies with LED fixtures in February 2007. A major LED manufacturer has also launched the *LED Cities* program, to accelerate the adoption of LED technology in street and area lighting applications (CREE, 2007). In addition, DOE has launched the *Gateway* demonstration program to monitor LED products in many applications, including street and area lighting, and provide independent performance data.[18] Although several cities have begun to adopt LED technologies in street and area light applications, we assume the penetration of LEDs is effectively zero as the number of LED streetlights these cities have installed amounts to less than one-tenth of one percent of the total installed base of streetlights in the U.S.

A number of sources were contacted to prepare a national estimate of the energy consumption of street and area lights. Sources used for the four critical inputs to the energy consumption and savings estimates are summarized in Table 4-1. The analysis takes into account only those street and area lights that use incandescent, halogen quartz, fluorescent, and high intensity discharge

[18] Manufacturers and host sites may apply to participate in the program at http://www.netl.doe.gov/ssl/techdemos.htm.

lamps such as mercury vapor, metal halide or high-pressure sodium lamps as these represent the vast majority of street and area lights.

Table 4-1: Critical Inputs for Street and Area Lighting Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Street and Area Light Fixtures: U.S. Census Bureau, Electric Light Fixture Current Industrial Reports, 1980-2001 Number of Lamps: NEMA HID Lamp Survey, 2004.
Annual Operating Hours	Street and area lights operate 12 hours per day throughout the year, amounting to 4,380 hours per year
Lamp Wattages	U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a; NEMA HID Lamp Survey, 2004; GE, 2006; OSI, 2006; Philips, 2006. LED Efficacy: Cook, Sommer and Pang, 2008.
Lighting Technology Mix	U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a.

4.2.2. Street and Area Lighting Installed Base

The installed base of street and area lights in the U.S. is approximately 131 million luminaires as of 2007, which includes 47.8 million area lighting fixtures, 45.8 million floodlighting fixtures, 34.7 million street lighting fixtures, and 3.1 million parking lot/garage lighting fixtures. The national inventory of street and area lights was estimated from annual shipments of electric light fixtures collected by the U.S. Census Bureau until 2001 and the 2004 National Electrical Manufacturers Association (NEMA) *High Intensity Discharge (HID) Lamp Survey*, collected from 1990 to 2002. This study tracks annual HID lamp shipments in the U.S. by wattage and base types for the largest U.S. manufacturers. The street and area light inventory estimate assumes an average lifetime of 20 years for the street and area light fixtures. The technology mix of street and area lights was estimated from the lamp inventory developed from NEMA HID shipments data and from the *U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate report*.

Table 4-2: Street and Area Light Installed Base, 2007

Light Source	Percentage	Number of Street and Area Lights
Incandescent	2%	3,159,000
Halogen Quartz	8%	9,917,000
Fluorescent	6%	7,530,000
Mercury Vapor	13%	17,675,000
Metal Halide	27%	38,330,000
High Pressure Sodium	39%	54,745,000
Total	**100%**	**131,356,000**

4.2.3. Street and Area Lighting Operating Hours

The typical street or area light is run throughout the night, for 12 hours per day, amounting to 4380 hours per year.

4.2.4. Street and Area Lighting Average Wattages

The conventional system wattages for the national street and area light installed base were developed from the 2004 *NEMA HID Lamp Survey*, and average fluorescent and HID ballast efficiencies and factors (GE, 2006; OSI, 2006; Philips, 2006), as shown in Table 4-3. The equivalent LED replacement wattages were developed by matching the lumens delivered by the conventional light source, using the best-in-class reported efficacies of street and area luminaire products tested by DOE's *Gateway* demonstration program (Cook et al, 2008). The LED and conventional systems were matched on a mean lumen basis, taking into account the 30 to 50 percent depreciation of light output from the fluorescent and HID sources over their respective lifetimes.

Table 4-3**:** Lamp Wattage of Street and Area lights

Light Source	Conventional System Wattage (W)	2007 LED Replacement Wattage (W)
Incandescent	150	26
Halogen Quartz	150	31
Fluorescent	159	151
Mercury Vapor	254	108
Metal Halide	458	327
High Pressure Sodium	283	276

4.2.5. Street and Area Lighting Energy Savings Potential

Table 4-4 shows the potential energy savings if the national base of street and area lights was converted overnight to LEDs using 2007 technology. A potential electricity savings of 44.7 TWh/yr may be realized if LEDs with an average luminaire efficacy of 57.5 lm/W (Cook et al, 2008) achieved 100% market penetration. The potential primary energy savings is 482.0 TBtu/yr at the power plant, the equivalent of seven large (1000 MW) electric power plants or the annual electricity consumption of 3.7 million residential households if 100% of the installed base moved to LED.

Table 4-4: Energy Consumption and Savings Potential of LED Street and Area Lighting, 2007

Niche Application	Annual Electricity Consumption 2007 (TWh)	Electricity Savings 2007 (TWh)	Potential Electricity Savings TWh)	Theoretical Maximum Electricity Savings (TWh)
Street and Area Lights	178.3	0	44.7	44.7

4.2.6. Technology Benefits in Addition to Energy Savings

There are several benefits outside of energy savings that are driving the adoption of LED technology in this application. In addition to saving potentially 482.0 TBtu/yr of primary energy when the market reaches saturation, LED street and area lights offer other advantages over traditional technologies, as described in Table 1-2. These include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination
7. Safety Improvements
8. Uniform Illumination
9. Improved Color Rendition
10. Lower Lumen Depreciation
11. Light Pollution Reduction

4.3. 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. Because products have only recently been introduced on the marketplace, we assume that market penetration for LEDs in this application is essentially zero. 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.

Step, path, and porch lighting consumed 22.0 TWh in 2007. An additional electricity savings of 12.6 TWh/yr is possible if 100% of the market switched to 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 1000 MW coal power plants or the annual electricity consumption of one million residential households.

4.3.1. Introduction

The task of residential step, path, or porch luminaires is to allow clear facial identification or identifiable walkway illumination near the lamp. These luminaires are usually wall-, step-, or path-mounted. The Illuminating Engineering Society of North America (IESNA) recommends that walkways and stairways average a horizontal illuminance level of about 0.5 footcandles (fc) (5 lux). The recommended level for vertical illuminance is 0.8 fc (8 lux), measured 5 feet (1.5 meters) above the doorway threshold (LBL 2007).

Step, path, or porch luminaires face cooler operating temperatures because they are primarily used at night. LEDs are attractive for this application because they operate more efficiently in cooler temperatures (Shakir 2002). LEDs systems are also low-voltage, which enhances safety, and have small form factors, beneficial for applications in which the lighting system is designed to be inconspicuous. LED luminaires typically consume less power than incandescent or halogen systems, leading to substantial energy savings. LED products also have longer lifetimes, requiring less frequent lamp replacements.

Previous studies, databases, and researchers were consulted to prepare an energy consumption and savings potential estimate for step, path, and porch lighting. As with the other niche market assessments, there are four critical inputs used in preparing the energy consumption and savings estimates, summarized in Table 4-5. The analysis takes into account the case of LED step, path, and porch lighting systems replacing incandescent and halogen outdoor luminaires.

Table 4-5: Critical Inputs for Step, Path and Porch Light Energy Consumption and Savings Potential Estimates

Critical Input	Notes and Sources
Installed Base of Lamps	Number of Street and Area Light Fixtures: U.S. Census Bureau, Electric Light Fixture Current Industrial Reports, 1980-2001.
Annual Operating Hours	Operating Hours per Building Type: U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate, DOE, 2002a. Distribution of Building Types: Residential Energy Consumption Survey, EIA, 2001.
Lamp Wattages	California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, Inc., 2000a, 2000b, 2005a, 2005b. Fixture Efficiencies: Mia Paget, PNL, 2008. LED product efficacies: CALiPER Round 4 Summary of Results, DOE, 2008c, CALiPER Round 3 Summary of Results, DOE, 2007c.
Lighting Technology Mix	California Residential Lighting and Appliance Efficiency Saturation Survey, RLW Analytics, Inc., 2000a, 2000b, 2005a, 2005b.

4.3.2. Step, Path, and Porch Installed Base

The national inventory of step, path, and porch lights was estimated from the U.S. Census Bureau's *Electric Light Fixture Current Industrial Reports*, which tracked annual shipments of residential outdoor electric light fixtures until 2001. Extrapolating these inventories, by fixture type, to the national level in 2007 produces an estimated installed base of approximately 265 million step, path, and porch lights, as shown in Table 4-6. The inventory assumes an average lifetime of 20 years for the step, path, and porch fixtures.

The technology mix of the step, path, and porch lights was estimated from the 2000 and 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys* (RLW, 2000a, 2000b, 2005a, 2005b). Outdoor porch lights were one of the lighting fixtures tracked in the surveys of households in investor-owned utility and municipal utility districts in California.

Table 4-6: National Installed Base and Technology Mix of Step, Path and Porch Lights, 2007

Light Source	Percent of Installed Base (%)	Number of Installations
General Service Incandescent	75.0%	198,572,000
Halogen General Service	6.7%	17,819,000
Halogen Quartz	0.6%	1,526,000
Fluorescent	0.3%	926,000
CFL	17.3%	45,837,000
Total	**100%**	**264,680,000**

4.3.3. Step, Path, and Porch Operating Hours

For this report, the average operating hours for step, path, and porch lights was estimated from the *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate* (DOE, 2002a). Outdoor residential spaces were one of the room-types tracked by this study. The *Residential Energy Consumption Survey* (RECS) published by the EIA, was used to obtain the distribution of building types in the residential sector. The average operating hours in outdoor residential spaces, weighted by lamp inventories, was 766 hours per year or approximately 2 hours per day for all lamp types.

4.3.4. Step, Path, and Porch Lamp Average Wattages

Table 4-7 shows the average lamp wattages for step, path, and porch lights which were estimated from the 2005 *California Residential Lighting and Appliance Efficiency Saturation Surveys* (RLW, 2000, 2005). From this study, lamp wattages for the residential sector were determined for outdoor porch applications. The replacement LED wattage was determined by matching the lumen output for the conventional technologies and LED products, given efficacies found from conventional lamp product catalogs and published efficacies from best-in-class LED outdoor products tested by the CALiPER program (DOE 2007,2008). Conventional outdoor luminaires have fixture efficiencies in the range of 40-80%; and for this energy consumption and savings calculation, a fixture efficiency of 60% was used to obtain the lumen output of the conventional products (Paget, 2008). Current LED outdoor residential step, path, and porch lighting systems are less efficacious than HID, fluorescent and CFL fixtures, thus LEDs are modeled to replace only incandescent and halogen fixtures, representing 82% or 218 million fixtures, in the energy savings analysis.

Table 4-7: Average Lamp Wattage for Step, Path, and Porch Lights

Lamp Type	Average Wattage (W)	LED Replacement Average Wattage (W)
Incandescent General Service	119	46
Halogen General Service	158	64
Halogen Quartz	432	211

4.3.5. Step, Path, and Porch Lighting Energy Saving Potential

The current market penetration of LEDs in step, path, and porch lights is assumed to be zero percent, as the technology has only recently become available in the marketplace. Table 4-8 presents the energy consumption estimate for step, path, and porch downlights, based on the data and inventory estimates described above.

Table 4-8: Step, Path and Porch Lighting Energy Consumption and Savings Estimate, 2007

Application	Annual Electricity 2007 (TWh/yr)	Electricity Savings 2007 (TWh/yr)	Potential Electricity Savings (TWh/yr)	Theoretical Maximum Electricity Savings (TWh/yr)
Step, Path, Porch Lighting	22.0	0	12.6	12.6

Step, path, and porch lighting consumed 22.0 TWh in 2007. A potential electricity savings of 12.6 TWh/yr is possible if all of the 217.9 million incandescent and halogen outdoor step, path, and porch lights were replaced with LED products with an average luminaire efficacy of 22.5 lm/W (DOE, 2008c, 2007c). These potential electricity savings are equivalent to a primary energy savings of 136.3 TBtu/yr at the power plant. The maximum energy savings of LEDs in step, path and porch lighting is equivalent to the annual output of two large (1000 MW) electric power plants or the annual electricity consumption of one million households.

4.3.6. Technology Benefits in Addition to Energy Savings

In addition to energy savings, there are other benefits driving the adoption of LED technology in this application. In addition to saving potentially 136.3 TBtu/yr of primary energy when the market reaches saturation, LED step, path and porch lights offer other advantages over traditional technologies, as described in Table 1-2. These benefits include:

1. Longer Operating Life
2. Lower Maintenance and Life-Cycle Costs
3. Reduced Radiated Heat
4. Minimal Light Loss
5. Dimmability and Controllability
6. Directional Illumination
7. Durability
8. Light Pollution Reduction

5. Conclusion

In the last few years, LEDs have emerged as a competitive lighting technology, capturing market share in several niche applications from incandescent, halogen, neon, high intensity discharge, and certain types of fluorescent light sources. Most cost-effective in colored-light applications, LEDs have proven to be an economically viable replacement in applications such as exit signs, where they are the least cost option, and traffic signal heads, where the initial LED light source can be more than 20 times as expensive as the incandescent light source it replaces while the lifetime costs are lower (ENERGY STAR, 2006). Furthermore, substitutions like these are taking place, without subsidies or coupon schemes, because LEDs make financial sense and offer customers a better quality, more reliable lighting service.

Niche applications evaluated in this report cut across colored-light, indoor and outdoor white-light installations. In the colored-light sector, LED technology is being used in traffic signal heads, decorative holiday lights, exit signs, and electric signage. In all of these applications, LEDs are replacing incandescent, fluorescent or neon lamps, which typically produce colored light using a color-filter lens or encasement. LEDs have the advantage of only producing light in the desired emission color, enabling them to do so using less energy. To date, approximately 2.82 TWh of electricity are saved every year because of the LED traffic signals that have replaced incandescent technology. LED exit signs save even more electricity, 4.56 TWh per year, since they have become the technology of choice in this application. Substantial energy savings have also been realized through LED holiday lights and electric signage, saving 0.33 TWh and 0.95 TWh per year, respectively. If these four colored-light applications switched entirely to LEDs, a potential of 15.2 TWh per year of electricity could be saved, equivalent to the annual output of approximately two large coal power plants or the annual electricity consumption of approximately one million typical U.S. households.

In the indoor white-light installations, LED products are available for recessed downlights, refrigerated display cases, retail display lighting, task lighting, office undershelf, and kitchen undercabinet lighting fixtures. In all of these applications, LED products have only recently become available in the marketplace and we assume that there is no significant market penetration of LEDs as of 2007. In all of these applications, luminaire designers are taking advantage of the directional light output of LEDs to design highly efficient fixtures that have the potential to save substantial amounts of electricity. Indoor white-light applications have the greatest potential of all the applications studied in this report to save substantial amounts of energy. If the six indoor white-light applications switched entirely to LEDs, a potential of 108 TWh per year of electricity could be saved, equivalent to the annual output of approximately seventeen large (1000 MW) electric power plants or the annual electricity consumption of nine million typical U.S. households.

Finally, in the outdoor white-light applications, street and area lights represent the most significant niche market opportunity for LEDs. Designers can take advantage of the enhanced visibility of LEDs at night, due to their high blue content relative to high or low pressure sodium lamps. LEDs in outdoor white-light applications are the focus of major marketing programs such as *LED Cities*, DOE's *Gateway* demonstration program, as well as the DOE ENERGY STAR® program for solid state lighting. A few pioneering cities have installed LED street and area lights and are reporting significant energy and cost savings, as well as better nighttime visibility from white LED products compared to high-intensity discharge lamps. LED outdoor step, path, and porch light products have won the *Lighting for Tomorrow* prize for innovative, energy-saving SSL product design. As these programs gain in popularity, LED market share in these applications will grow. As of 2007, we assume that there is no significant market penetration of LEDs in these applications as LED products have just recently entered the market. However, if the market switched entirely to LEDs, street and area lights have the potential to save 44.7 TWh per year and outdoor step, path, and porch lights have the potential to save 12.6 TWh per year of electricity, yielding a total of 57.3 TWh/year of electricity savings, the annual output of approximately nine large (1000 MW) electric power plants or the annual electricity consumption of almost five million households.

Figure 5-1 presents the energy savings in 2007 from the niche applications considered in this analysis. The five niche applications appearing in this diagram represent those markets where LEDs have some level of market penetration. The other seven markets have an assumed market penetration of zero percent, due to the lack of significant market adoption as of 2007.

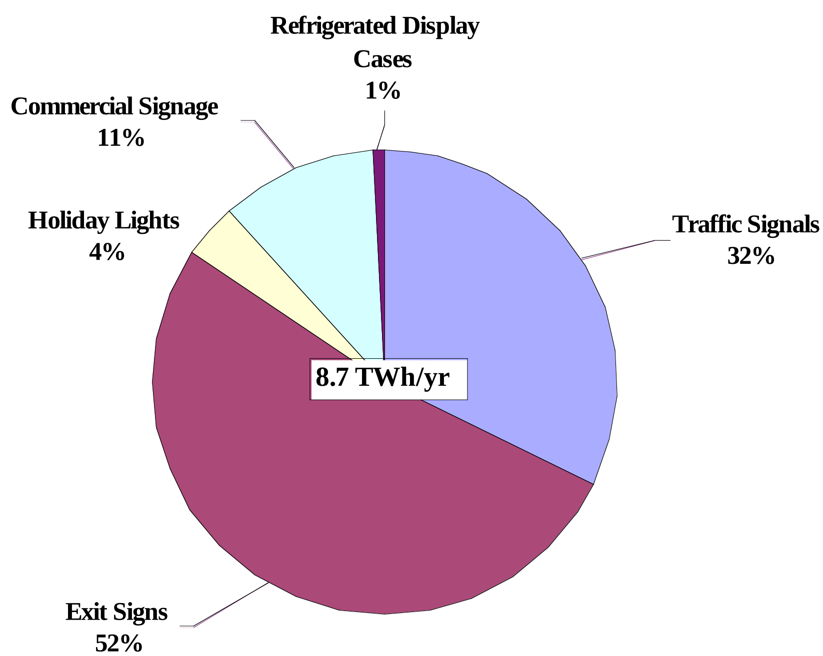

Figure 5-1: Site Electricity Savings in 2007 Attributable to LED Market Penetration

Clearly exit signs are the dominant energy saver from an LED perspective in 2007, providing over half of the realized electricity savings. Other niches, such as traffic signals – the second most significant energy saver – contribute a third of the total site electricity savings in 2007. Some sectors such as refrigerated display case lighting have low levels of LED penetration, thus contribute only one percent to the 2007 savings.

Figure 5-2 apportions the electricity savings if 100% of these twelve niche markets convert to LED technology. This total represents the combined 2007 energy savings and future potential energy savings if the remainder of each market converts to LED luminaires with efficacies between 22.5 and 60.9 lm/W. This savings estimate may be understated, because it fixes LED technology at today's performance levels. Over the coming years, researchers and manufacturers will continue to develop and commercialize more energy efficient, higher quality LED devices. This trend means that as more market share is captured in the future, the LED technology adopted will have better performance characteristics, and contribute to even more significant energy savings. This situation is particularly true for white-light LED devices, which today are significantly more efficacious than an incandescent, but are outperformed by the best T8 fluorescent and high-intensity discharge lamps. White-light LED technology is presently the focus of many research initiatives around the United States and the world, and continued advancements in efficacy, lumen output, operating life, and other critical performance metrics are anticipated.

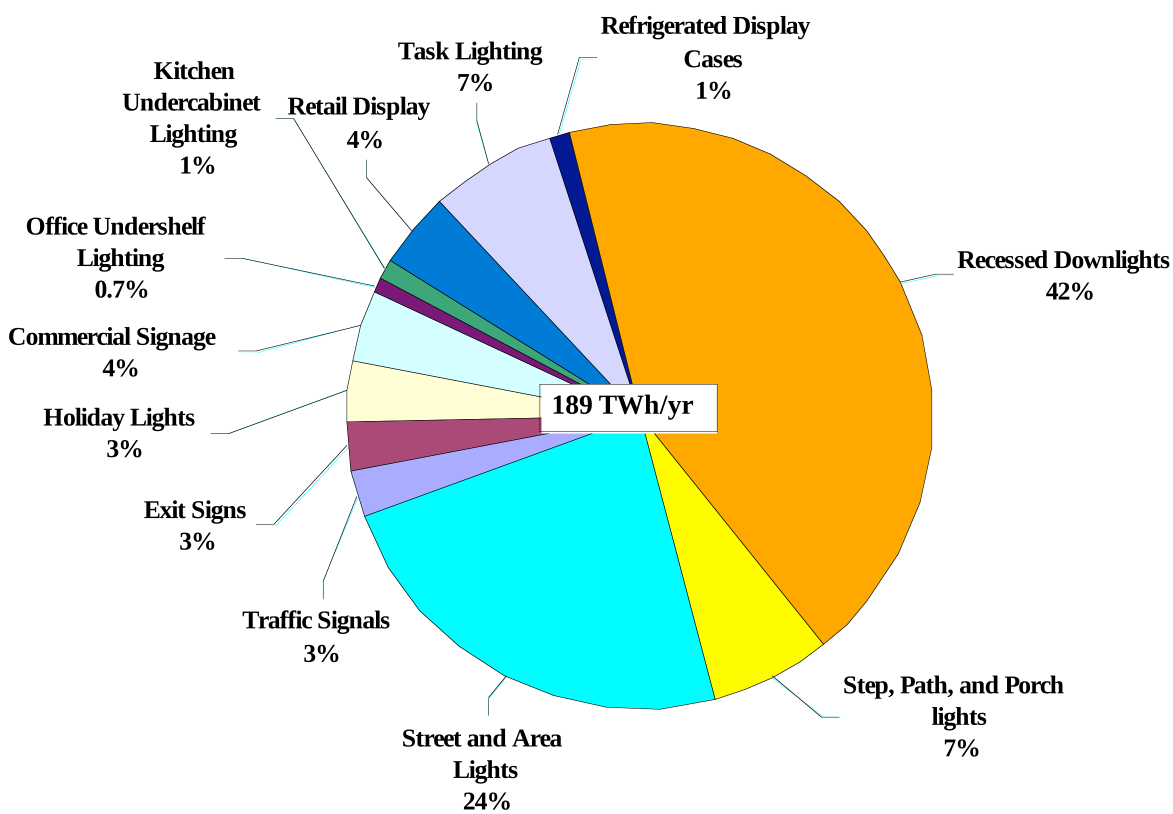

Figure 5-2: Maximum Site Electricity Savings With 100% LED Market Penetration

Table 5-1 summarizes the current energy savings of the analysis in detail, both electricity consumption and primary energy consumption. Some sectors have estimates of zero percent LED penetration, thus contribute no savings to the total of 8.7 TWh. Energy savings estimates were not prepared for seven applications analyzed: recessed downlights, retail display, task lighting, office undershelf, kitchen undercabinet, street and area lights, and step path and porch lights. This was because significant adoption of LEDs has yet to occur.

Table 5-1. Energy Consumption and Savings in 2007 of Applications Evaluated

Application	Annual Electricity Consumption (TWh)	LED Market Penetration	Electricity Savings 2007 (TWh)	Primary Energy Savings 2007 (TBtu)
Colored Light Applications				
Traffic Signals	2.38	52%	2.82	30.4
Decorative Holiday Lights	6.63	5.2%	0.33	3.53
Exit Signs	2.50	88%	4.56	49.2
Electric Signage	11.6	6.1%	0.95	10.3
Indoor White-Light Applications				
Recessed Downlights	103.1	0.0%	0.0	0.0
Refrigerated Display Cases	13.4	3.6%	0.08	0.81
Retail Display	32.0	0.0%	0.0	0.0
Task Lighting	18.8	0.0%	0.0	0.0
Kitchen Under-Cabinet Lighting	2.84	0.0%	0.0	0.0
Office Undershelf Lighting	3.43	0.0%	0.0	0.0
Outdoor White-Light Applications				
Street and Area Lights	178.3	0.0%	0.0	0.0
Step, Path, and Porch lights	22.0	0.0%	0.0	0.0
Total	**397 TWh**	**--**	**8.7 TWh**	**94 TBtu**

In 2007, electricity savings attributable to LEDs are dominated by exit signs, where LEDs have an estimated 88% market penetration. This niche market represents 52% of the total energy savings attributable to LEDs in 2007. The second most significant energy saving niche market in 2007 was traffic signal heads. In this application, approximately 52% of the signals are estimated to be LED, representing approximately 32% of the total energy savings from LEDs in 2007. From negligible penetration in 2002, LEDs have reached 6.1% of the electric signage market and 5.2% of the decorative holiday lights market, contributing to 11% and 4% of the total energy savings from LEDs in 2007, respectively. LEDs have also gained marketshare in the refrigerated display case market, achieving almost 4% penetration in 2007. Other applications, such as recessed downlights, retail display, task lighting, street and area lighting, and step, path and porch lighting are estimated to have zero market penetration of LEDs. Commercial LED products for these applications are available; however market adoption has yet to occur.

Table 5-2 presents the future energy savings potential from converting the remainder of each market entirely to LEDs. It also presents the cumulative (total) energy savings that would result from the energy savings in 2007 and the additional energy savings from the conversion of each market to 100% LED.

Table 5-2. Potential and Cumulative Energy Savings of Applications Evaluated

Application	Electricity Savings Potential (TWh)	Primary Energy Savings Potential (TBtu)	Theoretical Maximum Electricity Savings (TWh)	Theoretical Maximum Primary Energy Savings (TBtu)
Colored Light Applications				
Traffic Signals	2.03	21.9	4.85	52.3
Decorative Holiday Lights	5.97	64.4	6.30	67.9
Exit Signs	0.63	6.78	5.18	55.9
Electric Signage	6.58	71.1	7.53	81.3
Indoor White-Light Applications				
Recessed Downlights	81.2	876.6	81.2	876.6
Refrigerated Display Cases	2.0	21.6	2.1	22.4
Retail Display	7.87	84.9	7.87	84.9
Task Lighting	13.0	140.1	13.0	140.1
Kitchen Under-Cabinet Lighting	2.22	24.0	2.22	24.0
Office Undershelf Lighting	1.37	14.8	1.37	14.8
Outdoor White-Light Applications				
Street and Area Lights	44.7	482.0	44.7	482.0
Step, Path, and Porch lights	12.6	136.3	12.6	136.3
Total	**180 TWh**	**1944 TBtu**	**189 TWh**	**2039 TBtu**

Across the niche markets analyzed, there are significant opportunities for energy savings in the colored-light applications as well as the indoor and outdoor white-light applications. A total of 15.2 TWh per year of potential site electricity savings are available in commercial advertising signs, traffic signals, holiday lights, exit signs and the other applications that are grid-connected. Similarly, 107.7 TWh per year of site electricity savings are available if the installed base of recessed downlights, refrigerated display cases, retail display lights, task lights, office undershelf, and kitchen undercabinet lights switched to LEDs. In the outdoor white-light market, 57.3 TWh per year of site electricity savings are available in the street and area light and outdoor step, porch, and walkway applications. If these opportunities are fully realized, combined with the savings already captured to day, approximately 2039 TBtu of national energy consumption could be avoided. This represents 2.0 quadrillion Btus, "quads", or approximately two percent of total national energy consumption in 2007.

5.1. Benefits and Capturing Market Share

LEDs offer many benefits that have enabled them to capture market share from conventional light sources. As discussed earlier, LEDs are proving successful at capturing market share in colored-light applications such as traffic signals and exit signs. Each niche market analyzed in this report covers the particular LED benefits that are most relevant to a given application. Benefits impacting multiple applications are summarized here:

- Reduced Energy Consumption – LED devices can offer a more energy efficient means of producing light, particularly when compared to incandescent sources. In an application such as a traffic signal, an 8W LED red signal head replaces a 135W reflector lamp – a 94%

reduction in energy consumption - while complying with the same safety standards. And as solid state lighting technology evolves, the efficiency of these devices will continue to improve, enabling even greater energy savings through conversion to LED.

- Long Operating Life – Commercial and industrial specifiers are generally interested in using a light source that is reliable and lasts a long time. Frequent lamp replacements can be costly from a maintenance perspective, and failed lamps could expose lamp operators to liabilities (e.g., traffic signals or exit signs). In fact, maintenance savings are one of the primary reasons behind market adoption of LEDs in several markets, such as electric signage, street and area lights, and retail display lighting. Presently, LED technology offers operating lives that are approximately twenty-five times longer than those of incandescent sources.[19] Researchers indicate that operating life will continue to improve as the technology develops.

- Lower Maintenance and Life-Cycle Costs - The longer life of LEDs translates into less frequent relamping and lower maintenance costs. Although several LED products cost more than conventional products, the lower energy consumption and extended operating life (and associated maintenance savings) equate to lower life-cycle costs. For example, the cost of ownership, including energy and maintenance costs, of one intersection of LED traffic signals is about ninety percent less than that of an intersection of incandescent traffic signals (ENERGY STAR, 2006, 2008a).

- Reduced Radiated Heat – LEDs convert a higher proportion of electricity into visible light than incandescent sources. LED conversion efficiency has improved rapidly and is expected to continue; current LED luminaires can be equivalent to or more efficient than fluorescent and HID luminaires at converting power to visible light. Further, incandescent sources convert most of the power they use into infrared (IR) radiation (radiated heat), and some discharge sources emit both IR and ultraviolet (UV), but LEDs emit neither (unless specifically designed to do so). Instead, the waste heat generated by the LED must be removed by heat-conducting material (a “heat sink”). The reduction in heat radiated into conditioned space may reduce the air-conditioning or refrigeration load for some applications.

- Minimal Light Loss – Unlike conventional lamps, LED luminaires do not need color filters to produce colored-light. In colored-light applications, light loss can be minimized by matching the color of the LED chip emitter to the color of the translucent covering on the lighting fixture. Furthermore, light emitted from an LED device is more directional and controlled, meaning that fewer photons are trapped within the lighting fixture. By contrast, conventional lamps have a 360 degree emission range, which results in lower fixture efficiencies as light is lost as the light is dispersed to the back of the fixture.

- Dimmability and Controllability – For most applications, LED luminaires can be designed with dimming controls and motion sensors to adjust brightness levels. For example, LEDs can be dimmed more efficiently than fluorescents because rapid and frequent on/off cycles do not affect the life of the LED, enabling the use of movement-triggered controls. These

[19] We assume that manufacturers’ claims of 50,000-hour LED lifetimes can be substantiated. However, these claims have not been independently verified by DOE.

controls can reduce the annual operating hours of the LED system and lead to greater energy savings than we calculate in this report.

- Directional Illumination – The LED sources can be targeted to illuminate particular parts of the packaging or prices in the display case, calling customer's attention to aspects of the display case that may result in a sale. Similarly, LED task, office undershelf, or kitchen undercabinet lights can be targeted to illuminate particular parts of the work space, leading to higher fixture efficiencies and higher illumination to complete tasks, with less light scattered away from the work space.

- Durability – the light production mechanism for LED devices is fundamentally different from traditional light sources such as incandescent and fluorescent. LED sources produce light by passing a current through thin layers of a semi-conductive material, which causes the recombination of electron-hole pairs in the material which emit light. Inherent in this solid-state light production mechanism is the ability of the source to resist vibration and impact, making it an ideal light source for refrigerated display cases, office undershelf and kitchen undercabinet lighting. The LED is encased in a tough epoxy plastic resin instead of a fragile glass bulb, thus, they are more resistant to shattering or impact damage in these applications.

- Safety Improvements – For several applications, characteristics specific to LEDs lead to safety enhancements. LED luminaires are made of multiple diodes, and are less likely to fail simultaneously, leading to less down time for traffic signals, enhancing traffic flow and safety. In addition, LED holiday lights emit less heat than incandescents, and can reduce the current total of 210 home-structure fires per year due to ignited Christmas trees (Ahrens, 2007). LED electric signage is also typically operated at lower voltages and direct current which are safer for maintenance workers to handle than neon, which operates at 12,000 to 15,000 volts of alternating current.

- Color Maintenance - Monochromatic LEDs for colored light applications allow the elimination of filters and hence better color control and color life than conventional technologies.

- Smaller Package Size – Due to their compact size, LED devices are an excellent option where size or weight is a concern. For example, LED lighting provides more shelf space for merchandise in a refrigerated display case. This is because the LED and driver system is much smaller than a fluorescent lamp and ballast system, and can be distributed throughout the display case, unlike fluorescents.

- Uniform Illumination. – LED devices offer distinct advantages where light encroachment or glare is a problem. For example, through the use of lenses and lighting controls, LED street and area lights, and step, path, and porch light luminaires can better distribute the light across the ground, allowing more uniform illumination.

- Battery Back-Up Capability - Traffic signals that include red, green, and yellow LEDs consume around one-tenth as much power and LED exit signs consume about one-fifth as much power as with incandescent sources. For this reason, battery back-up power supplies are available which can operate during power failures to ensure smooth flow of vehicular traffic or continuous delineation of building routes of egress. Many agencies use yellow LED signals for battery back-up reasons in emergency situations. For instance, if yellow LED signals were used in flashing mode, work crews would have a few extra hours to handle emergency situations (Bullough, 2003b).

- Adjustable Color – Storeowners could also easily alter the intensity and color of the LED light to augment particular colors in the products. Recent marketing studies have shown that these features offer enhanced appeal to the human eye compared to other lighting systems. Study subjects strongly preferred display cases with LED lighting systems at half the illumination levels of fluorescent systems (Narendran, 2003b).

- Light Pollution Reduction – The directional quality of LED street and area or step, path, and porch luminaires leads to more lumens to light the road plane or path and fewer lumens scattered upward, reducing light pollution.

6. References

Ahrens, M. 2007. "Home Christmas Tree and Holiday Light Fires." *Fire Analysis and Research Factsheet*. National Fire Protection Association. Quincy, MA. http://www.nfpa.org/assets/files//PDF/Christmastreefactsheet.pdf

Altamura, S. (Seasonal Specialties). 2008. Personal communication. April 21.

[ANSI-IESNA] American National Standards Institute (ANSI) and Illuminating Engineering Society of North America (IESNA). 2004. "American National Standard Practice for Office Lighting." ANSI/IESNA RP-1-04.

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

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

Bhandarkar, V. (Strategies Unlimited). 2008b. Personal communication. March 4.

Bonilla, J. (SloanLED). 2008. Personal communication. May 23 and June 10.

Bullough, 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, Michigan: Lighting Research Center.

Comer, Virginia. *Urban Details Los Angeles: Streetlights.* Glendale, CA: Princeton Architectural Press. 2000.

Compound Semiconductor. Dec. http://compoundsemiconductor.net/articles/magazine/9/12/1/1.

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

Cook, T., Sommer, A., and Pang, T. 2008. "LED Street Lighting." *U.S. Solid State Lighting Technology Demonstration Gateway Program.* Oakland, CA: Department of Energy. January 2008. http://www.netl.doe.gov/ssl/PDFs/EmergingTechReport-LEDStreetLighting.pdf

"Cree and Raleigh, North Carolina Launch Nation's First "LED City" With Cost-Saving Municipal Lighting." Raleigh, NC: CREE, Inc. February 12, 2007. http://www.cree.com/press/press_detail.asp?i=1171295242023

"Cree touts another high-power LED breakthrough." *Compound Semiconductor.* http://compoundsemiconductor.net/cws/article/news/31137

[DOC] Department of Commerce, 1987-2001. Shipment Value of Electric Signs. Annual Survey of Manufacturers. Washington, D.C.: U.S. Department of Commerce. Data available online: <http://www.census.gov/mcd/asm-as2.html> and <http://www.census.gov/prod/1/manmin/92mmi/mci39df.pdf>

[DOE] Department of Energy. 2008a. *Multi-Year Program Plan FY'09 to FY'14: Solid-State Lighting Research and Development.* Washington, D.C.: U.S. Department of Energy. http://www.netl.doe.gov/ssl/PDFs/SSLMYPP2008_web.pdf

DOE. 2008b. *DOE Solid-State Lighting CALiPER Program: Summary of Results: Round 5 of Product Testing.* http://www.netl.doe.gov/ssl/comm_testing.htm

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

DOE. 2008d. "Portable Desk/Task Lighting." *LED Application Series*. DOE. 2007d. "Undercabinet Lighting." LED Application Series. http://www.netl.doe.gov/ssl/PDFs/PortableDeskTask.pdf

DOE. 2008e. "Undercabinet Lighting." *LED Application Series*. http://www.netl.doe.gov/ssl/PDFs/UndercabinetLigting.pdf

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

DOE. 2007b. *Commercial Refrigerated Equipment Energy Conservation Standard Advanced Notice of Proposed Rulemaking.* Washington, D.C.: U.S. Department of Energy. http://www.eere.energy.gov/buildings/appliance_standards/commercial_products.html

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

DOE. 2006a. *Multi-Year Program Plan FY'07 to FY'12: Solid-State Lighting Research and Development.* Washington, D.C.: U.S. Department of Energy. http://www.netl.doe.gov/ssl/PDFs/SSLMultiYearPlan.pdf

DOE. 2006b. "Energy Solutions for Your Buildings: Retail Buildings." http://www.eere.energy.gov/buildings/info/retail/.

[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.

Design Lights. 2003. "Small Retail Lighting Know How." *Lighting Know How Series*. Design Lights Consortium. www.designlights.org/downloads/retail_guide.pdf

Dowling, Kevin. (Color Kinetics). 2008. Personal communication. April 29.

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

Electro-Optical Industries. 2007. "The Unit of Luminous Intensity: Candela." http://www.electro-optical.com/whitepapers/candela.htm

[EIA] Energy Information Administration. 1994, 1998. *Manufacturing Energy Consumption Survey.* Washington, D.C.: Department of Energy. http://www.eia.doe.gov/emeu/mecs/contents.html

EIA. 1999, 2003. *Commercial Buildings Energy Consumption Survey*. Washington, D.C.: Department of Energy. http://www.eia.doe.gov/emeu/cbecs/

EIA. 2008. *Annual Energy Outlook.* Washington, D.C.: Department of Energy. http://www.eia.doe.gov/oiaf/aeoindex.html

EIA. 2007b. *Electric Power Annual.* Washington, D.C.: Department of Energy. http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

EIA. 2001, 1997. *Residential Energy Consumption Survey.* http://www.eia.doe.gov/emeu/recs/recs2001/datafile2001.txt

Energy Solutions. 2004. "Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture." Pacific Gas and Electric Company. May 5, 2004.

ENERGY STAR. 2007. *Life-Cycle Cost Estimate for ENERGY STAR-Qualified Exit Signs.* http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/Calc_Exit_Signs.xls

ENERGY STAR. 2006. *Life-Cycle Cost Estimate for ENERGY STAR-Qualified Traffic Signals*. Washington, D.C.: U.S. Department of Energy. http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/LED_Traffic_Signal_Bulk.xls

ENERGY STAR. 2008a. *ENERGY STAR Program Requirements for Traffic Signals.* Washington, D.C.: U.S. Department of Energy. http://www.energystar.gov/ia/partners/product_specs/eligibility/traffic_elig.pdf

ENERGY STAR. 2008b. *ENERGY STAR Program Requirements for Exit Signs.* Washington, D.C.: U.S. Department of Energy. http://www.energystar.gov/ia/partners/product_specs/eligibility/exit_signs_elig.pdf

[EPA] Environmental Protection Agency. 2006. "Supermarket Energy Use Profile." Washington, D.C.: U.S. Environmental Protection Agency. PDF file location: http://www.epa.gov/cleanenergy/documents/sector-meeting/4biii_supermarket.pdf

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

Figueiro, Mariana. 2001. "Lighting the Way: A Key to Independence." Troy, NY: Lighting Research Center. http://www.lrc.rpi.edu/programs/lightHealth/AARP/pdf/AARPbook3.pdf.

Freyssinier, J. P., Frering, D.,Taylor, J., Narendran, N., and Rizzo, P. 2006. "Reducing lighting energy use in retail display windows." *Sixth International Conference on Solid State Lighting, Proceedings of Society of Photo-Optical Instrumentation Engineers (SPIE).* 6337: 63371L. San Diego, CA: Society of Photo-Optical Instrumentation Engineers. http://www.lrc.rpi.edu/programs/solidstate/pdf/Freyssinier-SPIE6337-51.pdf

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

GE. 2006. Lamp and Ballast Catalog.

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

Greer, G. Gordon. 1984. “Improved Quality of Retail Beef through Control of Bacterial Spoilage.” *Technical Bulletin 1984-13E*. Lacombe, Alberta: Research Branch Agriculture Canada in “Retail Meat Display Lighting.” Safe Spectrum Lamps Website, 2008. http://www.safespectrum.com/applications_meat.html

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

Holonyak, N., and Bevaqcua. 1962. *Applied Physics Letters*. 1: 82-83.

IESNA. 2001. “Lighting Merchandising Areas.” IESNA RP-2-01

[ITE] Institute of Transportation Engineers. 2007, 2005. *National Traffic Signal Report Card Technical Report 2007*. http://www.ite.org/reportcard/technical_report%20final.pdf

Jeremiah, L.E. and Gibson, L.L. 1997. “The Influence of Storage and Display Conditions on the Retail Properties and Case-life of Display-ready Pork Loin Roasts.” *Meat Science*. vol. 47, no. 1/2: 17-27. In “Retail Meat Display Lighting.” Safe Spectrum Lamps Website, 2008. http://www.safespectrum.com/applications_meat.html

Jevelle, 2003. Personal Communication with Paula Jevelle of LEDtronics, Rendon Virginia; July, 2003.

Kinzey, B. R. and Myer, M. A. 2008. “Demonstration Assessment of LED Walkway Lighting Technology Gateway, FAA Outdoor Walkway.” *U.S. Solid State Lighting Technology Demonstration Gateway Program*. Richland, WA: Department of Energy. March 2008. http://www.netl.doe.gov/ssl/PDFs/Gateway_FAA.pdf

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

Lane, Michael. 2007. “Introduction to Retail Lighting.” Lighting Design Lab. http://www.lightingdesignlab.com/articles/retail/design_space.htm.

[LBL] Lawrence Berkeley National Laboratory. 2007. “Guidelines for LED Porch Lighting Design.” http://lighting.lbl.gov/ld_LED_summary.html

LBL. 1997. “News from the D.C. Office: Monitored Savings from Energy-Efficient Lighting in D.C. Office.” *CBS Newsletter*. Spring 1997: p 3. http://www.eetd.lbl.gov/newsletter/cbs_nl/nl14/dcoffice.html.

Ledpac, 2007. “Costco Jewelry Case Lighting Assessment.” November 6. www.ledpac.com/costco/ledpac-costco_case-study_11.6.07.pdf

Lewin, I. “Lumen Effectiveness Multipliers for Outdoor Lighting Design.” Lighting Sciences. 1998.

Lighting for Tomorrow website. 2008. http://www.lightingfortomorrow.com/2007/index.shtml (accessed March 2008).

Lighting Research Center – Alliance for Solid-State Illumination Systems and Technologies (ASSIST). 2007. “Recommendations for Testing and Evaluating Under-cabinet Luminaires.” Assist Recommends Series. Troy, NY: Lighting Research Center. vol 2, issue 3.

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

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

[NEMA] National Electrical Manufacturers Association. 2005. "NEMA A-line Statistical Wattage Survey." *California Energy Commission, Appliance Rulemaking 1*, Docket # 05-AAER-2. http://www.energy.ca.gov/appliances/2006rulemaking1/documents/ 2006-03-10_NEMA_A-LINE_SURVEY_REPONSE_12-14-2005.PDF.

NEMA.2004. "High-Intensity Discharge Lamp Survey." *Energy Conservation Program for Commercial and Industrial Equipment: High-Intensity Discharge (HID) Lamps Rulemaking*, Docket # EE–DET-03-001.

NEMA. 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. 2006. *Decorative Light String Market Assessment Report.* Prepared by Navigant Consulting, Inc. for Natural Resources Canada. Washington, D.C. September 2006.

NCI. 2003. *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications.* Washington, D.C.: U.S. Department of Energy. http://www.netl.doe.gov/ssl/PDFs/Niche%20Final%20Report.pdf

NCI. 2002. *U.S. Lighting Market Characterization. Volume: I: National Lighting Inventory and Energy Consumption Estimate.* U.S. Washington, D.C.: Department of Energy. http://www.eere.energy.gov/buildings/info/documents/pdfs/lmc_vol1_final.pdf

Nichia NS6W083B. http://www.nichia.co.jp/product/led-smd-powerled.html

[OSI] Osram Sylvania, Inc. 2006. Lamp and Ballast Catalog.

Owen, B. K. (greenTBiz – LEDs MAGAZINE). 2008. Personal communication. January 3.

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

Philips. 2006. Lamp and Ballast Catalog.

Raghavan, R. and Narendran, N. 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, WA: Society of Photo-Optical Instrumentation Engineers. http://www.lrc.rpi.edu/programs/solidstate/pdf/SPIE4776-13_Raghavan.pdf

RLW Analytics, Inc. 2000a. "Statewide Residential Lighting and Appliance Efficiency Saturation Survey." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm

RLW Analytics, Inc. 2000b. "Statewide Residential Lighting and Appliance Efficiency Saturation Survey: SMUD Specific Report." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm

RLW Analytics, Inc. 2005a. "California Statewide Residential Lighting and Appliance Efficiency Saturation Survey." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm

RLW Analytics, Inc. 2005b. "SMUD Residential Lighting and Appliance Efficiency Saturation Survey." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm

RLW Analytics, Inc. 2005c. "California Statewide Residential Lighting Database." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm.

RLW Analytics, Inc. 2005d. "SMUD Residential Lighting Database." Sonoma, CA: RLW Analytics, Inc. http://www.calresest.com/index.cfm

Shakir, I. and Narendran, N. 2002. "White LEDs in Landscape Lighting Applications." *Solid State Lighting II: Proceedings of the Society of Photo-Optical Instrumentation Engineers.* http://www.lrc.rpi.edu/programs/solidstate/pdf/evaluatingWhiteLEDs.pdf

Signcraft, 2003. "Understanding the Sign Industry." http://www.signcraft.com/UnderstandingTheIndustry.pdf

Sloan, J. (SloanLED). 2008. Personal communication. May 2.

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

Steele, R. 2007. "The Market Outlook for High-Brightness LEDs in Lighting Applications." Presentation at *International Workshop on Status, Prospects, and Strategies for LEDs in General Lighting.* Ispra, Italy, May 3-4.

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

Summers, Teresa A., and Hebert, Paulette R. 2001. "Shedding some light on store atmospherics: Influence of illumination on consumer behavior." *Journal of Business Research.* vol 54: 145-150.

Swormstedt, Wade. 2008a. "2007 Electric State of the Industry Report." *Signs of the Times Magazine*.

Swormstedt, Wade. 2008b. "2007 Lighting Survey." *Signs of the Times Magazine.*

Swormstedt, Wade. 2007. "2006 Electric State of the Industry Report." *Signs of the Times Magazine.*

Swormstedt, Wade. 2006. "2005 Electric State of the Industry Report." *Signs of the Times Magazine.*

Swormstedt, Wade. 2005. "2004 Electric State of the Industry Report." *Signs of the Times Magazine.*

Swormstedt, Wade. 2004. "2003 Electric State of the Industry Report." *Signs of the Times Magazine.*

Swormstedt, Wade. 2003. "2002 Electric State of the Industry Report." *Signs of the Times Magazine.*

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

Tetlow, Karin. 2007. "Task Lighting Solutions: Their Economic and Ergonomic Benefits." *Architectural Record*. November 2007. http://continuingeducation.construction.com/article.php?L=95&C=262&P=1

Tullman, Matthew L. 2000. "Dynamic Full-Spectrum Digital Lighting of Retail Displays Positively Affects Consumer Behavior." *Color Kinetics, Inc. White Paper.* June 28. http://www.colorkinetics.com/support/whitepapers/retailwhitepaper.pdf.

[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.

U.S. Census. 1992-2006. Annual Survey of Manufactures. http://www.census.gov/mcd/asmhome.html

U.S. Census. 2002-2006. Fluorescent Lamp Ballasts. http://www.census.gov/cir/www/335/mq335c.html

U.S. Census. 2004. "U.S. Interim Projections." http://www.census.gov/ipc/www/usinterimproj/

U.S. Census. 2000. "Profile of General Demographic Characteristics: 2000." http://censtats.census.gov/data/US/01000.pdf

[USITC] United States International Trade Commission. 2008. USITC Interactive Tariff and Trade DataWeb. Data available online: http://dataweb.usitc.gov/scripts/user_set.asp

Universal Lighting, 2003. "Neon & Cold Cathode Transformer Watts/Ft of Tubing." PDF file location: <http://www.franceformer.com/application/neon/Watts_per_foot_table.pdf>

Universal Lighting Technologies, 2003. "Neon Transformer Quick Reference." Signa Sign and Neon Solutions. HTML file location: <http://www.signasign.com/tech/neon_quickref.html>

[UIE] University of Illinois Extension. 2005. Urban Horticulture and Environment, "Christmas Tree Facts." http://www.urbanext.uiuc.edu/trees/treefacts.html.

Vincent, J Bryan. (AgiLight). 2008. Personal communication. March 13.

Vrabel, Paul. 2003. "Design Focus Report: Retail Lighting." *Architectural Lighting Magazine.* March 2003. www.icfi.com/Markets/Energy/doc_files/vrabel-retail-lighting.pdf

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

Waste Reduction Partners. 2004. "Task Lighting: Utility Savings Initiative Factsheet."
http://www.energync.net/resources/docs/pubs/task.pdf
Whitaker, T. 2003. "Backlights, Airports and Vehicles Boost LED Market."

Wolsey, Robert and Miller, Naomi. "Lighting Answers: Task Lighting for Offices." National Lighting Product Information Program. Troy, NY: Lighting Research Center. vol. 1, no. 3. p 1-8.

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy