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Adoption of Light-Emitting Diodes in Common Lighting Applications

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List of Acronyms and Abbreviations

BR	bulged reflector
CALiPER	Commercially Available LED Product Evaluation and Reporting
CFL	compact fluorescent lamp
CRI	color rendering indices
CRT	cathode ray tube
DLP	Digital Light Processing®
DOE	U.S. Department of Energy
EISA 2007	Energy Independence and Security Act of 2007
EPA	Environmental Protection Agency
EPACT 1992	Energy Policy Act of 1992
EPACT 2005	Energy Policy Act of 2005
ER	elliptical reflector
FHWA	Federal Highway Administration
GLS	general lighting service
HB	high-brightness
HID	high intensity discharge
HPS	high pressure sodium
IALD	International Association of Lighting Designers
IR	infrared
IRL	incandescent reflector lamp
K	Kelvin
LED	light-emitting diode
LMC	2010 U.S. Lighting Market Characterization
lm	lumens
mg	milligrams
MR	multifaceted reflector
NEMA	National Electrical Manufacturers Association
OLED	organic LED
PAR	parabolic aluminized reflector
R	reflector
SSL	solid-state lighting
tBtu	trillion British thermal units
TWh	terawatt-hours
W	watts

Executive Summary

This report presents the findings for nine major lighting applications where light-emitting diodes (LEDs) are competing with traditional light sources. This analysis estimates the energy saved due to current levels of LED penetration, as well as the potential energy savings if these markets switched completely to LEDs. The selected applications are classified into three groups: indoor lamps, indoor luminaires, and outdoor luminaires. For indoor lamps, four applications are analyzed: A-type, directional, MR16 and decorative. For indoor luminaires, three applications are analyzed: downlight, troffer and other common fluorescent fixtures, and high-bay. And lastly for outdoor luminaires, two applications are analyzed: streetlight and parking lot and garage. The major findings of the analysis include:

- In 2012, about 49 million LED lamps and luminaires were installed in the nine applications. LED A-type lamps are about 41 percent of these installations, but currently only have a penetration rate in this application of less than one percent. LED MR16 lamps have the highest penetration rate at about 10 percent of all MR16 lamps.
- Annual source energy savings from LEDs in 2012 from the nine applications analyzed was about 71 trillion British thermal units (tBtu), which is equivalent to an annual energy cost savings of about $675 million.
- Annual source energy savings could approach 3,873 tBtu, about 3.9 quadrillion Btu (quads), if all nine markets switched to LEDs "overnight." Energy savings of this size would results in an annual energy cost savings of about $37 billion.

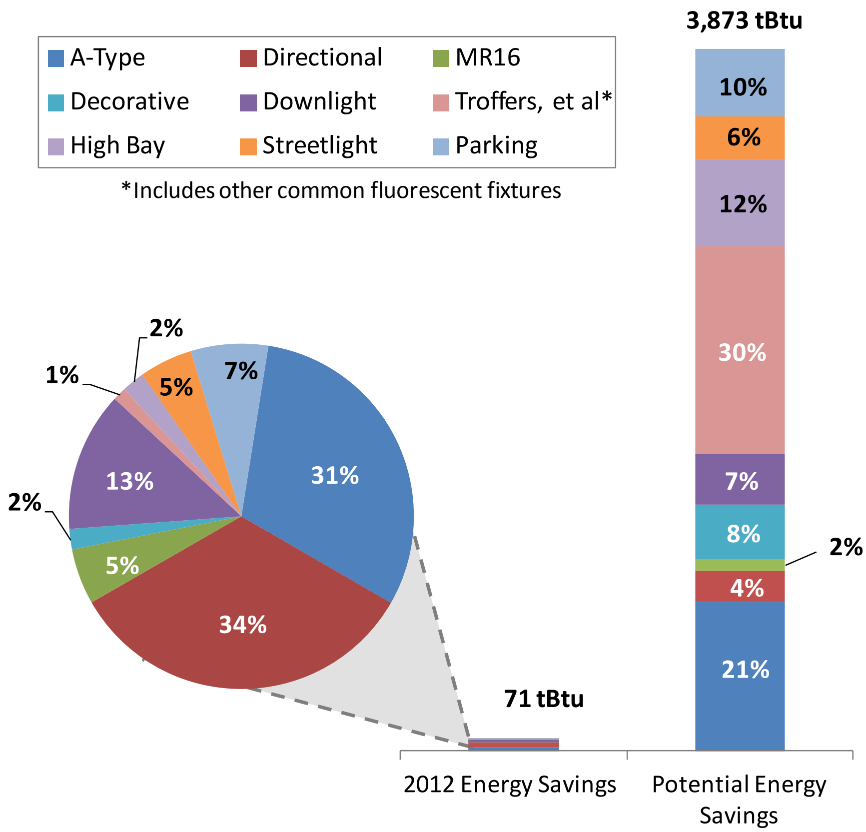

Figure ES.1 – Comparison of Current and Potential Source Energy Savings

1. Introduction

Light-emitting diodes (LEDs), a type of solid-state lighting (SSL), are revolutionizing the lighting market. LEDs have surpassed many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and due to their increasing cost competitiveness are beginning to successfully compete in a variety of lighting applications. It is forecasted that LED lighting will represent over 75 percent of all lighting sales by 2030, resulting in an annual primary energy savings of 3.4 quads.[1]

Since 2003, the Department of Energy (DOE) has evaluated the U.S. lighting market to report on lighting applications where LEDs are having greatest energy savings impact. The 2013 *Estimated Adoption of LEDs in Common Lighting Applications* (previously named the *Energy Savings Estimates of LEDs in Niche Lighting Applications*) represents the fourth iteration of this report. This 2013 report investigates the current adoption and resulting energy savings of LEDs in nine common white-light applications. Past versions of this report have included analyses of colored-light, as well as consumer electronics applications. However, colored-light and consumer electronics LEDs have matured, reaching market saturation in many applications, and are no longer analyzed in this study. The energy savings of LEDs in colored-light applications are analyzed in the 2003[2] and 2008 editions[3] and consumer electronics are analyzed in the 2011 edition.[4]

1.1 Common Lighting Applications

The nine different lighting applications for this study were selected based on interviews with lighting designers, retailers, and manufacturers as well as an LED applications survey facilitated by the International Association of Lighting Designers (IALD). These various stakeholders were asked to indicate the most common and most energy saving LED lighting applications being utilized today, and to provide guidance on emerging market trends and potential growth for LED usage, as well as those applications that have the most to benefit from converting to LED technology both in terms of improvement to efficiency and overall lighting performance. The applications most frequently identified by these stakeholders included: A-type, directional,

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[1] Navigant, Energy Savings Potential of Solid-State Lighting in General Illumination Applications, January 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.pdf

[2] The 2003 report is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/niche_final_report.pdf

[3] The 2008 report is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_october2008.pdf

[4] The 2011 report is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf

decorative, MR16, downlights, troffers and other common fluorescent fixtures, high-bay, parking, and streetlight, are shown below in Figure 1.1.

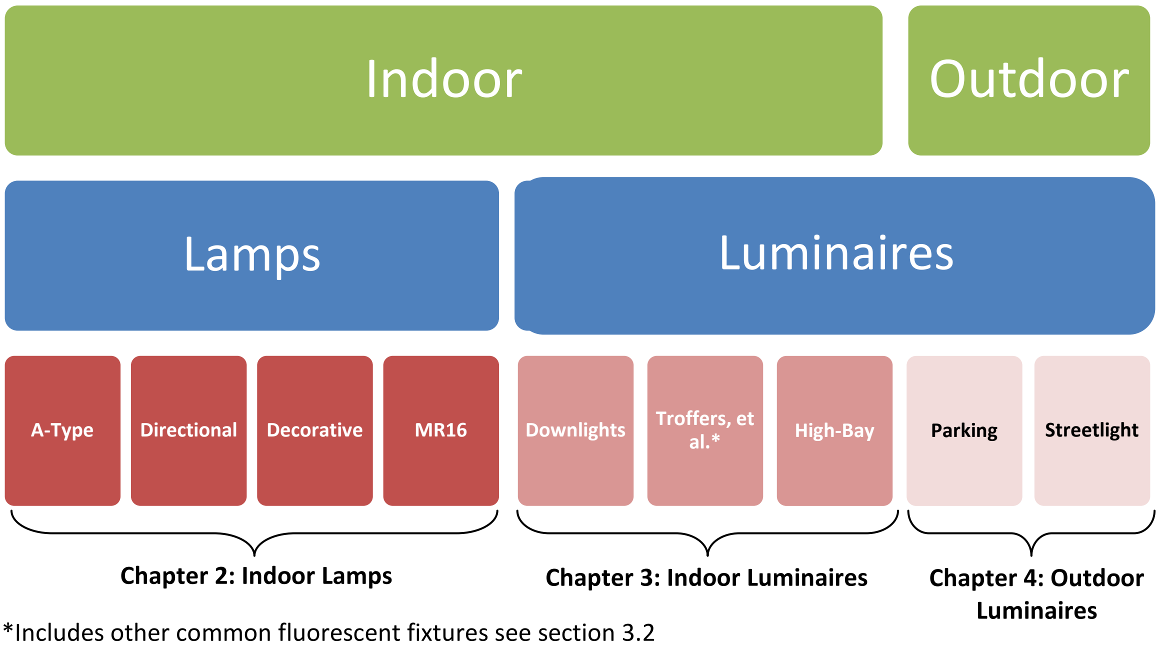

Figure 1.1 – Summary of Common LED Applications Evaluated in this Report

LED lighting products are most commonly classified as lamp replacements or luminaires. An LED lamp is an assembly with a standardized base designed for connection to the branch circuit through a corresponding standard lamp holder (i.e., a socket). Most commonly LED lamp products are "integrated" meaning the LED driver component, which operates and controls the LED package, is contained within the lamp housing structure. An LED luminaire is a complete lighting product which consists of the LED-based light emitting elements as well as the driver component. An LED luminaire connects directly to a branch circuit.[5]

Due to these technical differences, the designs of LED lamps and luminaires vary significantly. Typically LED lamps are designed to be direct replacements for existing general service incandescent and halogen lamps, while LED luminaires represent a holistic change-out of the existing lamp and fixture system. Considering these differences the report divides the evaluated LED applications into one of three classifications: indoor lamps, indoor luminaires, and outdoor luminaires. For each of the nine LED applications, this report addresses the following four questions:

[5] Lamp and luminaire definitions from the Illuminating Engineering Society Standard RP-16-10, http://www.iesna.org/store/product/nomenclature-and-definitions-for-illuminating-engineeringbr-rp1605-1013.cfm

- How much energy in the year 2012 was consumed by lighting technologies in these applications?
- What is the 2012 estimated penetration of LED technology in each application?
- What are the actual energy savings resulting from the 2012 level of LED penetration?
- What would the theoretical energy savings be from 100% LED penetration?

1.2 Methodology for Estimating Application Energy Use

Figure 1.2 illustrates the four critical variables used to estimate the 2012 energy consumption and savings potential for each LED application. These include: 1) the 2012 lighting inventory; 2) LED market adoption; 3) annual operating hours; and, 4) wattage per lamp/luminaire.

The 2012 inventory calculation begins with installed stock figures from the *2010 U.S. Lighting Market Characterization* (LMC).[6] These figures are projected to 2012 using the DOE's forecast model, which utilizes assumptions of projected efficacy, retail price, and operating life.[7] The 2012 projection estimates the installed base of LED lighting as well as conventional lighting technologies, such as incandescent, fluorescent, and high intensity discharge (HID). However, the LED projections are not utilized in this report. Instead the 2012 adoption of LED lighting in the selected nine applications is calculated using LED sales and financial reports provided by manufacturers, retailers, industry experts, as well as the shipment data from National Electrical Manufacturers Association (NEMA) and ENERGY STAR. The following sections describe the specific sources and any variances on this methodology for each application.

[6] Navigant, 2010 U.S. Lighting Market Characterization, January 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

[7] Navigant, Energy Savings Potential of Solid-State Lighting in General Illumination Applications, January 2012, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_energy-savings-report_jan-2012.pdf

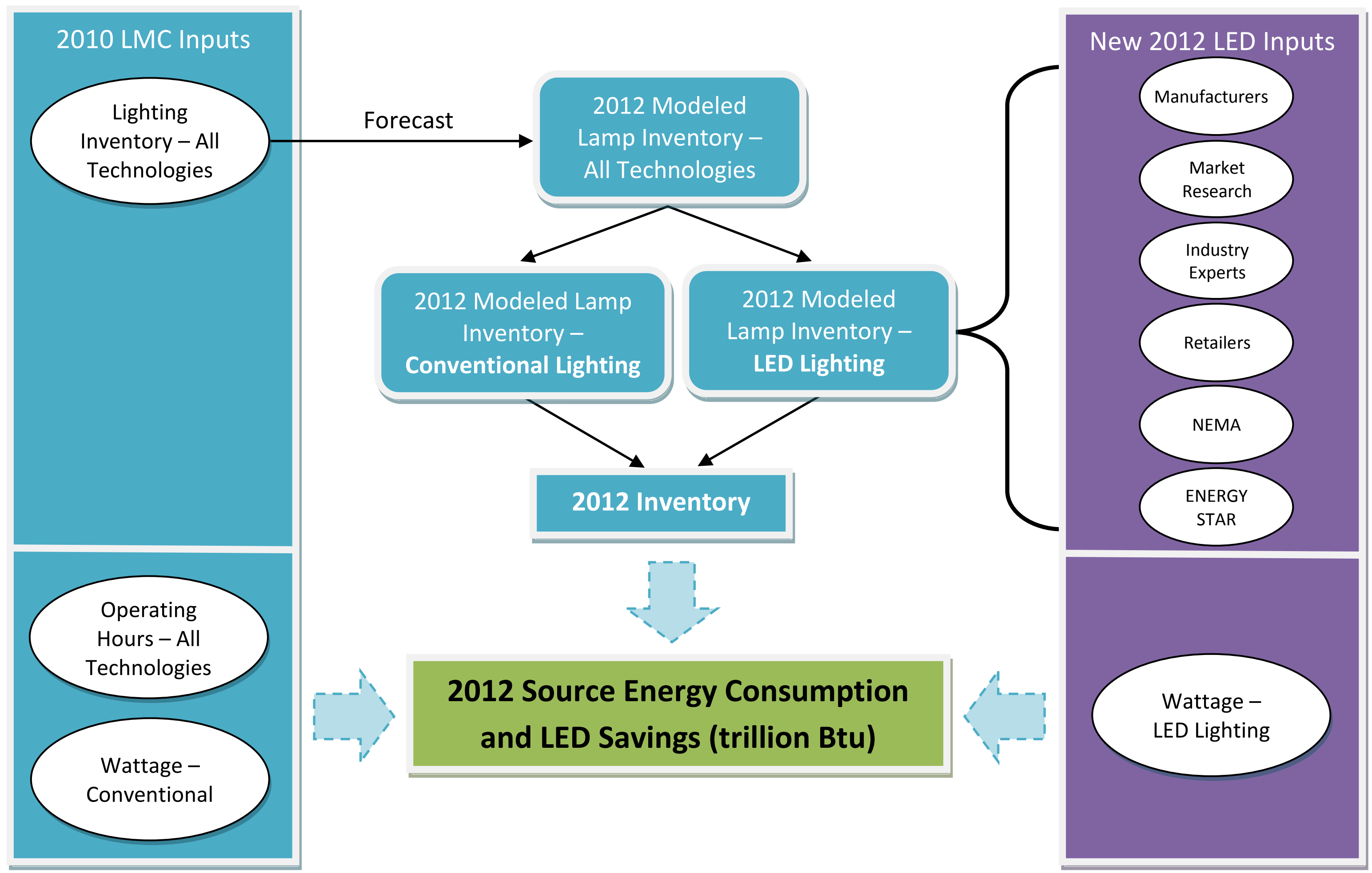

Figure 1.2 – Application Energy Consumption and Savings Methodology[8]

[8] Source energy savings are calculated by multiplying electricity savings by the 2012 source-to-site conversion factor (3.05) as determine by the EIA, Annual Energy Review, http://www.eia.gov/totalenergy/data/annual/diagram5.cfm

The 2012 energy consumption and savings of the nine common lighting applications analyzed in this report are highly dependent on the baseline wattages of conventional lamps used compared to that of their LED replacements as well as the annual operating hours. In addition, wattage within each application also varies for lamps and luminaires in residential, commercial, industrial, and outdoor installations. Assumptions for average wattages and annual operating hours for each lighting type installed in each sector are provided by the 2010 LMC report. Table 1.1 below lists the average operating hour and wattage assumptions of the conventional lighting technologies considered within each of the nine applications.

Table 1.1 – Wattage and Operating Hour Assumptions for Conventional Technologies

Application	Lighting Type	System Wattage (Watts)			Daily Operating Hours (hrs)		
Indoor Lamps		**RES**	**COM**	**IND**	**RES**	**COM**	**IND**
A-type	Incandescent	64	58	46	1.8	10.5	12.7
	Halogen	50	46	36	2.0	12.1	11.7
	CFL	17	20	17	1.8	10.7	13.0
Directional	Incandescent	69	79	65	1.7	9.8	11.9
	Halogen	68	78	64	1.9	12.4	11.7
	CFL	17	20	16	1.8	10.0	13.0
MR16	Halogen	44	60	--	1.7	12.6	--
Decorative	Incandescent	44	44	--	1.8	10.5	--
	CFL	11	11	--	1.8	10.7	--
Indoor Luminaires		**RES**	**COM**	**IND**	**RES**	**COM**	**IND**
Downlights	Incandescent	69	79	65	1.7	9.8	11.9
	Halogen	68	78	64	1.9	12.4	11.7
	CFL	17	20	16	1.8	10.7	13.0
	CFL - pin	22	19	19	1.9	10.4	13.2
	Metal Halide	--	32	32	--	10.4	13.2
Troffers, et al.*	T5	38	72	115	2.5	11.7	12.6
	T8 Less than 4ft	31	40	47	2.1	11.2	12.6
	T8 4ft	52	60	60	1.9	11.1	12.6
	T8 Greater than 4ft	82	109	147	1.7	11.0	12.6
	T12 Less than 4ft	32	70	65	2.0	11.3	12.0
	T12 4ft	53	86	77	1.9	11.1	12.4
	T12 Greater than 4ft	101	157	169	1.7	11.1	12.5
	T8 U-Shaped	54	62	60	2.1	11.0	12.6
	T12 U-Shaped	53	83	81	1.9	11.0	12.5
High-Bay[9]	High Pressure Sodium	--	295	295	--	11.0	17.9
	Mercury Vapor	--	451	451	--	11.1	16.5
	Metal Halide	--	434	434	--	11.1	16.5
	T5	--	231	231	--	11.7	12.6
	T8 4 ft	--	240	240	--	11.1	12.6
	T8 Greater than 4ft	--	293	293	--	11.0	12.6
	T12 4ft	--	310	310	--	11.1	12.4
	T12 Greater than 4 ft	--	338	338	--	11.1	12.5
Outdoor Luminaires			**OUT**			**OUT**	
Parking[10]		**Garage**		**Lot**	**Garage**		**Lot**
	Incandescent	79		50	15.9		15.9
	Halogen	114		75	17.9		17.9
	Linear Fluorescent	71		--	18.0		18.0
	Mercury Vapor	196		307	13.5		13.5
	Metal Halide	203		449	15.0		15.0
	High Pressure Sodium	160		280	16.0		16.0
	Induction	97		--	13.1		--
Streetlights	Mercury Vapor		243			12.0	
	Metal Halide		233			12.0	
	High Pressure Sodium		230			12.0	
	Low Pressure Sodium		78			12.0	

Source: Navigant, 2010 U.S. Lighting Market Characterization, January 2012
***Includes other common fluorescent fixtures see section 3.2**

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[9] Commercial sector wattages for high-bay applications are assumed to be equivalent to industrial sector wattages.
[10] Parking wattages shown above in Table 1.1 have been revised from the estimates provided in the *2010 U.S. Lighting Market Characterization*.

LED lamps and luminaires are assumed to have the same operating hours as the most energy efficient conventional lighting type within each of the nine applications. For example, in the A-type application, LED replacement lamps are assumed to have the same operating hours as CFLs. Average wattages for LED lamps and luminaires were determined by averaging the performance of products listed by DOE LED Lighting Facts.[11] To ensure that the LED wattage represents a viable replacement option, performance was averaged if the LED product's characteristics matched that of a typical conventional lighting system within each of the nine lighting applications. For example, LED products within the DOE LED Lighting Facts database that were categorized as PAR, BR and R20, R30, or R38 lamps with a lumen output between 600 and 1,300 lumens were considered viable LED replacements for the directional lamp application. The performance characteristics of these products were then averaged to determine the average performance of an LED directional replacement lamp. It is important to note that the average LED replacement criteria for parking applications was divided into parking garage and lot since each of these has very different lumen output requirements.

The energy consumption and savings estimate results are highly sensitive to the state of LED technology. The methodology only considers currently available LED technology, and the technical potential analysis only considers the most efficacious, currently available LED technology. To determine the potential energy savings for each application it is assumed that the entire lighting stock is converted instantaneously to the most efficacious LED product that meets the replacement criteria. Table 1.2 below highlights the viable LED replacement criteria as well as the average and most efficacious LED product for each application.

[11] More information on the DOE's LED Lighting Facts program can be found at: www.lightingfacts.com

Table 1.2 – Average and Most Efficacious LED Products from DOE's Lighting Facts Database[12]

	LED Replacement Criteria		LED Efficacy (lm/W)	
Application	**Product Description**	**Lumen Range (lm)**	**Average**	**Best[13]**
A-type	A-type replacement lamps	700-1,100	69	94
Directional	PAR, BR and R 20, 30, 38 lamps	600-1,300	57	89
MR16	MR16 lamps	400-600	55	77
Decorative	Decorative replacement lamps	400-700	58	77
Downlights	Recessed/surface-mounted downlight luminaires	600-1,500	49	88
Troffers, et al.*	Recessed/surface-mounted troffer luminaires	1,000-8,000	83	119
High-Bay	High and low bay luminaires	15,000-35,000	88	110
Parking Garage	Parking garage luminaires	1,000-6,000	72	106
Parking Lot	Outdoor area/roadway luminaires	10,000-20,000	78	101
Streetlights	Outdoor area/roadway/decorative luminaires	10,000-20,000	79	110

*Includes other common fluorescent fixtures see section 3.2

1.3 Sensitivities of this Analysis

This analysis estimates the current and energy savings potential of LEDs. The final estimates are highly sensitive to the performance and efficacy of LEDs, which are rapidly changing, as well as the performance and efficacy of the conventional lighting technologies they replace. More details on the several key factors that affect this analysis are provided below:

The 2012 annual energy savings of LED technology is highly dependent on the conventional technology it replaces. This analysis assumes that LED lighting is replacing the least efficient incumbent lighting technology being used within each of the nine applications analyzed in this report. For example, for A-type applications it is assumed that LEDs are replacing incandescent lamps since these lamps represent the least efficient lighting option. The assumption that LED replaced the least efficient source in each application is reasonable since the value proposition is typically greatest in that situation. Replacing an incandescent lamp with LED will pay back more quickly than replacing a CFL with an LED, for example. However, it is possible that this simplification has the effect of overestimating the annual energy savings from LED technology in 2012.

Future advances in LED technology will significantly increase potential energy savings compared to the calculations conducted in this report. Commercially available white LED package efficacies have increased from 100 lm/W in 2008 to as high as 166 lm/W in 2012[14] and are projected to reach 235 lm/W by 2020. LED luminaire efficacies are projected to advance from 119 lm/W in 2012[15] to 170 lm/W in 2020.[16]

[12] LED efficacy values based on Lighting Facts database query from March 2013.
[13] See Appendix A for list of most efficacious products.
[14] A Cree cool white LED (Cree XLamp XT-E) reached 166 lm/W in 2012.
[15] A Cree recessed troffer (CS14-40LHE-40K) reached 119 lm/W in 2012.

Conventional lamps energy consumption will likely to decrease due to future energy conservation standards or technical advancement. For example, on December 19, 2007, the Energy Independence and Security Act of 2007 (EISA 2007) went into effect. Section 321 of EISA 2007 prescribes maximum wattage standards for medium screw-base general service incandescent lamps which take effect between 2012 and 2014 and an efficacy requirement of 45 lm/W in 2020, effectively phasing out the traditional incandescent lamp.[17] EISA 2007 will lower the annual energy consumption of the baseline conventional lighting technologies for several of the applications analyzed in this report, thereby lowering the future energy savings potential of LEDs compared to the estimates presented in this report.

Energy savings will only be realized if customers accept the technology. The current market penetration of LEDs, as presented in this report, is in single digits in most applications. The theoretical potential savings are based on complete market transformation, which is highly unlikely. Market changes may increase or decrease the potential energy consumption and savings of LEDs according to the overall size of the application.

The magnitude of each of these effects is uncertain. Thus, the estimates for energy consumption and savings potential from LEDs presented in this report only represent the best current estimate of the nine analyzed lighting applications in 2012.

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[16] Solid-State Lighting Research and Development: 2013 Multi-Year Program Plan, http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html

[17] See Appendix C for discussion of lighting efficiency standards.

2. Indoor Lamps

This analysis evaluates the 2012 impact of LED penetration into four indoor lamp applications: A-type, directional, MR16, and decorative replacements. Combined these lamp types represent about 57 percent of all indoor and outdoor lighting installations nationwide. These lamps serve multiple purposes, including ambient lighting for office spaces and households, as well as accent, task, and display lighting in architectural lighting applications such as in museums, art galleries, retail stores, offices, residential settings, landscaping, and entertainment venues. In addition, directional lamps are commonly used in downlighting applications.

To avoid overlap between the directional and downlight applications evaluated in this report, all conventional (incandescent, halogen and compact fluorescent) general service reflector lamps installed in recessed can fixtures are classified as a downlight application. All of these products are assumed to be replaced by an LED downlight luminaire, and hence evaluated in the indoor luminaire section of this report (section 3.1). All other installations of conventional general service reflector lamps are considered to be a directional application evaluated in section 2.2 of this report, and are assumed to be replaced by an LED reflector lamp. These assumptions are an over simplification, however, this enables two key LED product types to be accounted for while avoiding overlap.

LED lighting products have begun to penetrate a variety of indoor lighting applications during the past few years, and recent technical advances have made many cost-effective, particularly when accounting for the lifetime of the lamp. The average price of LED A-type lamp products has dropped dramatically from $250/klm in 2008 to $40/klm in 2012 while the average efficacy has increased from 40 lm/W in 2008 to over 65 lm/W in 2012.[18] In addition to cost and energy savings, LED lamps offer high light quality, longer operating life (>25,000 hours), limited light loss and directionality, lower operating costs, improved durability, compact size, and dimmability (see Appendix B for more details on the additional benefits of LED lighting technology). All of these factors have led to the increasing adoption of these products.

[18] Average prices and efficacies for 2008 and 2012 are based on LED product data collected from manufacturer catalogs.

In order to accelerate the penetration of energy efficient lighting products, such as LEDs, the U.S. Federal government has developed a variety of legislation[19] aimed at promoting energy efficient lighting products. For instance, EISA 2007 directed DOE to establish the Bright Tomorrow Lighting Prize (L Prize)[20] competition. The L Prize rewards manufacturers who develop a superior LED replacement lamp for the standard A-type incandescent 60W lamp and the PAR38 halogen lamp. In August 2011, Philips Lighting North America was declared the L Prize winner in the 60W replacement category. The L Prize has helped incentivize manufacturers to develop high-quality, high-efficiency LED lamps that set leading-edge performance benchmarks for the industry.

L Prize – 60W Competition Winner

In late 2009, the L Prize competition received its first entry – an LED A-type product from Philips Lighting North America. The 2,000 samples submitted by Philips went through a rigorous 18-month evaluation, and in August 2011 this lamp was declared the L Prize winner in the 60W replacement category, which is now closed. The product hit retail shelves on Earth Day 2012 and has a tested efficacy of over 90 lm/W, making it the most efficient A-type lamp on the market.

2.1 A-Type Lamps

This section addresses the potential for LED replacements in the general service A-type lamp market, which includes standard incandescent A-type lamps, incandescent halogen, CFLs, and LED replacement lamps. A-type lamps include all A-series lamp shapes and are considered the classic type of light bulb that has been used for general purpose lighting for over 100 years. These lamps have a medium screw base and typically have a pear-like shape. CFLs with a spiral/twister or mini-spiral/twisters shape are also included in this section.

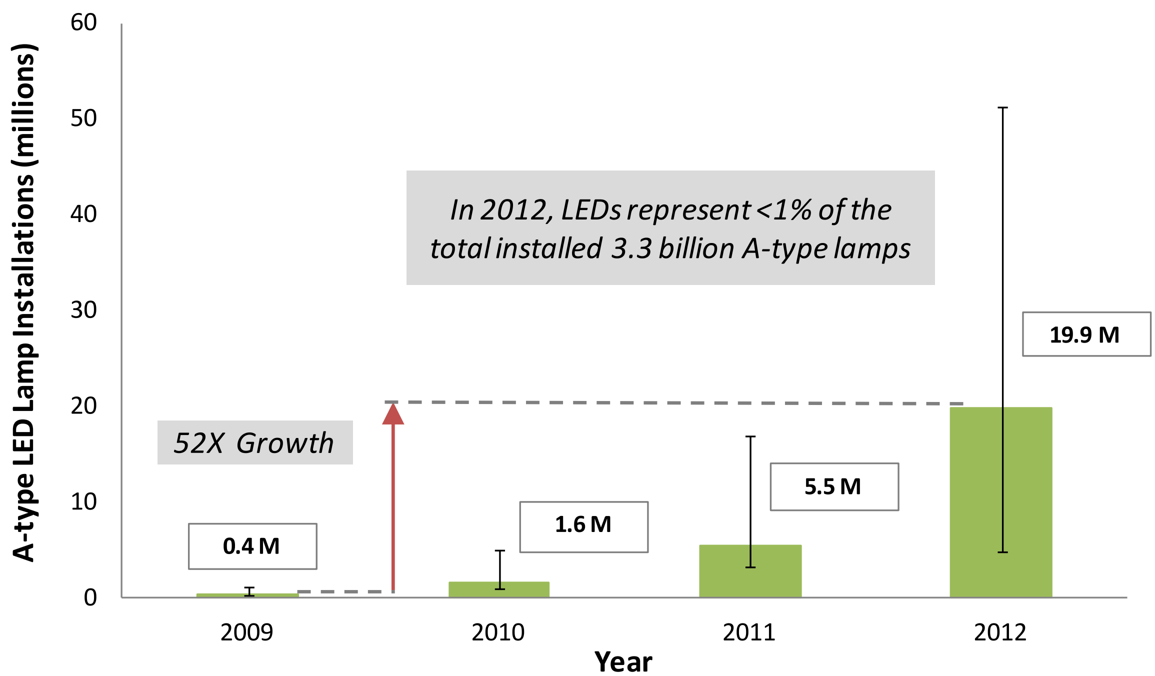
The LED A-type market represents one of the greatest opportunities for the LED lighting industry in terms of number of available sockets and hence energy savings. LED A-type replacements have been offered for the past several years, and became broadly available to residential consumers starting in late 2009 when The Home Depot began offering a select number of LED lamp products. Now in 2013, Home Depot offers 56 LED A-type options in-stores and on-line.[21] LED A-type replacement lamps can offer energy savings and lamp lifetimes beyond that of CFLs, with efficacies reaching over 90 lm/W.[22]

[19] See Appendix C for details regarding the U.S. DOE appliance energy efficiency standards for lighting equipment.
[20] More information about the DOE L Prize contest can be found at: http://www.lightingprize.org/
[21] Home Depot LED A-type lamp product offerings as of April 16, 2013. www.homedepot.com
[22] L Prize 60W Replacement Competition – Lab Testing for Philips Winning Entry, http://www.lightingprize.org/60watttest.stm

However, LEDs still face a variety of barriers to reach significant penetration, most notably their high initial cost. Although the price of LED A-type lamps has decreased significantly since 2008 averaging at about $40/klm in 2012, this is still about 60 times the price of conventional incandescent lamps and over 10 times that of CFLs. As LED A-type technology has improved, to help reduce the high initial cost of these lamps state, local and utility energy efficiency programs have begun offering various price discounts. Currently, 19 utilities and energy efficiency organizations from across North America have established rebates, incentives, and other promotions for the purchase of the Philips L Prize winning A-type LED lamp to help ensure that it gets into the hands of consumers. In total, LED lamp retrofit and new construction rebates are offered in 27 different states.[23] In addition, in March 2013, Cree announced that a new line of LED A-type bulbs will be sold through Home Depot with price points ranging between $9.97 and $13.97. These price points are the most competitive to-date.

2.1.1 LED A-Type Penetration

Shown in Figure 2.1 is DOE's estimate for the installed base of LED A-type lamps from 2009 to 2012. The data suggests that the 2009 installed stock was approximately 0.4 million LED A-type lamps and that the 2012 installed stock has grown to 19.9 million units, this represents over a 50x growth rate.



*Upper and lower bounds on each bar represent the range of market estimates

Figure 2.1 – Installed Base Estimates for LED A-Type Lamps

[23] Database of State Incentives for Renewables & Efficiency, http://www.dsireusa.org/incentives/index.cfm?EE=1&RE=0&SPV=0&ST=0&technology=lighting&sh=1

Based on the projected LMC data, in 2012 there were 3.3 billion A-type lamps installed within the U.S., of which about 97 percent are in residences. The A-type lamp market is experiencing a transition away from traditional incandescent lamps towards higher efficiency halogen lamps, CFLs, and LED lamps.

As seen in Figure 2.2, from 2010 to 2012 the installed base of incandescent A-type lamps decreased from 65 percent to 55 percent, while CFLs increased from 34 percent in 2010 to 43 percent in 2012. While nearly 20 million LED A-type lamps are installed in the U.S. this is less than one percent of the total A-type lamp installed base.

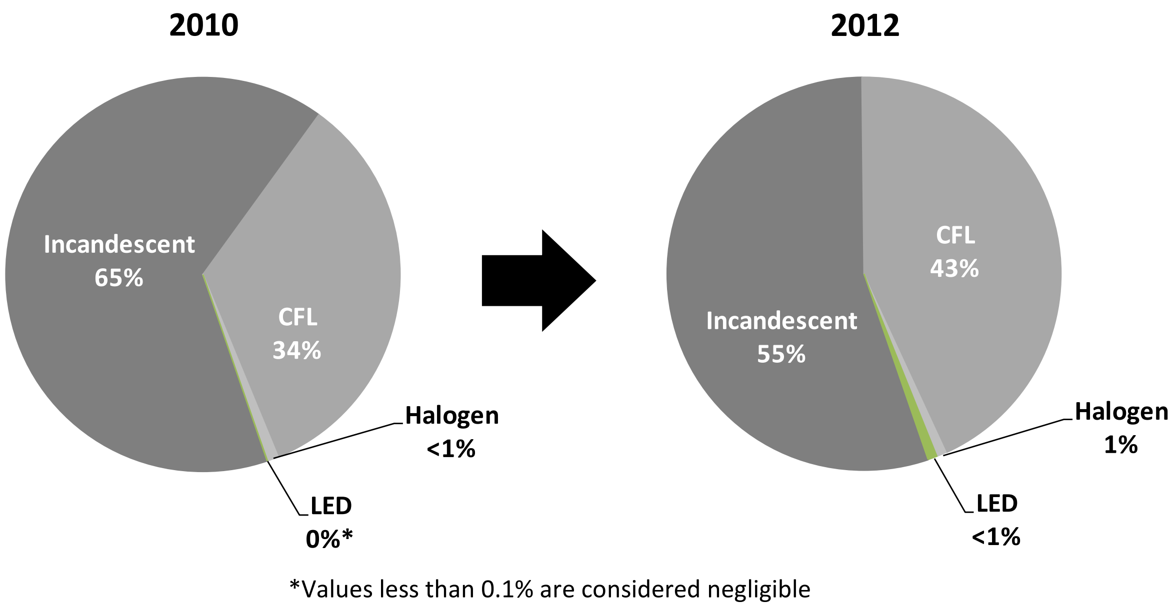
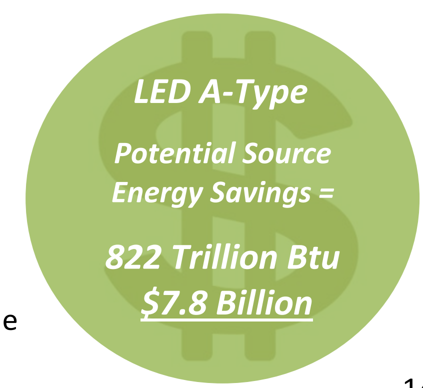


Figure 2.2 – A-Type Lamp Installed Base

2.1.2 A-Type Lamp Energy Savings

The total energy consumption of general service A-type lamps has decreased from approximately 1,134 trillion British thermal units (tBtu) in 2010 to 1,057 tBtu in 2012. This trend is largely due to the implementation of the EISA 2007 standards (see Appendix C). EISA 2007 likely also contributed to the increase in CFL installations from 34 to 43 percent as well as the increase in LED usage.



The 2012 estimated energy savings from LED A-type lamps is highly dependent on the percentage installed in commercial versus residential buildings due to the large difference in average operating hours (see Table 1.1), as well as the lamp type that the LED is assumed to replace. It is estimated that the

LED A-type lamps installed in 2012 saved about 21.9 tBtu. Table 2.1 depicts the total energy consumption of general service A-type lamps and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED replacement lamps.

Compared to the average baseline savings in 2012, a potential electricity savings of 822 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of nearly $8 billion.

Table 2.1 – Energy Consumption and Savings Potential of LED A-Type Lamps

 A-Type Lamps	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	19.9	1,057 (101.8)	21.9 (2.1)	822 (79.1)

2.2 Directional Lamps

Directional lamps are commonly used for accent, track, pendant, and architectural lighting in spaces including households, retail displays, restaurants, museums, and office buildings. Directional lamps are predominately reflector type and include incandescent reflector (R), bulged reflector (BR), halogen parabolic aluminized reflector (PAR), CFL reflector, and their qualified LED replacements. These descriptors, “R,” “BR” and “PAR,” refer to the different shapes of reflector lamps. Halogen multifaceted reflector (MR) or MR16 lamps are also considered directional lamps; however, because MR16 lamps have a significantly smaller form-factor and lower light output they are generally used in different applications compared to PAR, BR, and R lamps. MR16 lamps are evaluated separately in section 2.3 of this report. In addition, this section only considers PAR, BR, and R lamps that are used in directional lighting applications. Therefore, PAR, BR, and R lamps that are installed in general area downlighting applications are accounted for separately in section 3.1. This section also assumes that all LED reflector replacement lamps are installed in directional applications. While some LED reflector replacements are likely installed in ambient or general lighting applications, such as downlighting, there is currently no data available to help distinguish where these LED products are being installed.

DOE has regulated the energy efficiency level of many directional lamps since 1992, and currently the reflector lamp market is undergoing significant changes due to the recent enactment of energy conservation standards.[24] These standards promote the adoption of higher efficiency reflector lamp products including halogen infrared (IR) lamps, CFLs, and LED

[24] See Appendix C for discussion of relevant lighting efficiency standards.

replacement lamps. Halogen IR lamps are more expensive than standard halogen lamps on the market today (gas mixtures and IR capsules largely contribute to increased cost), which increases the competitiveness of CFLs and LEDs in directional lamp applications.

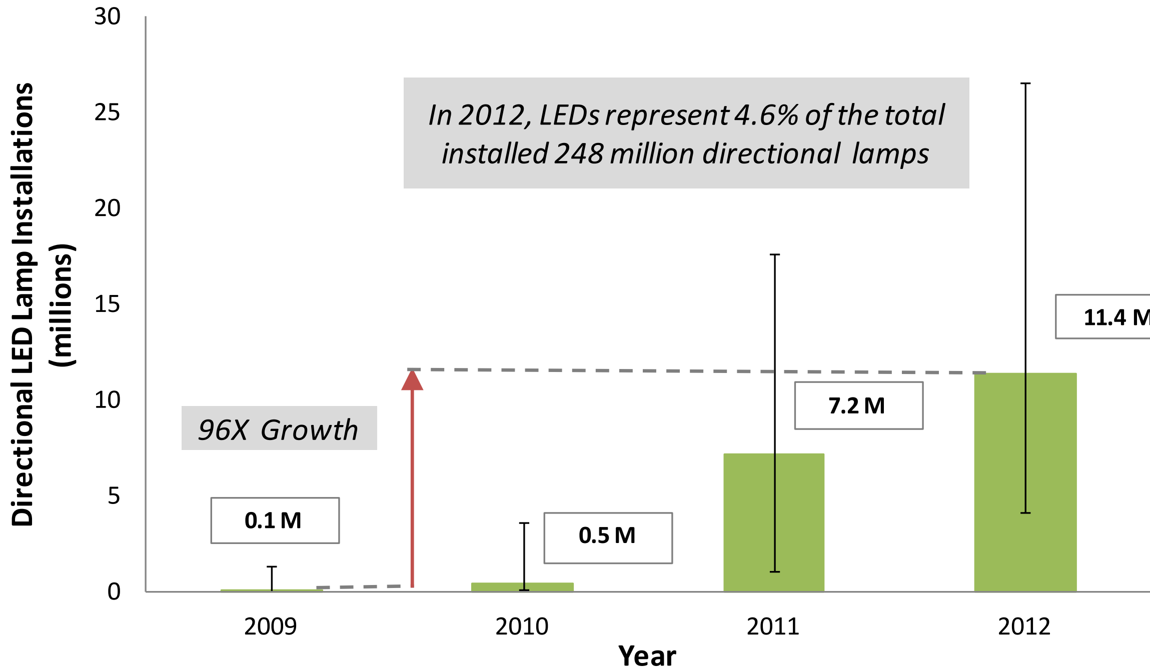
DOE's LED Lighting Facts product list indicates that the efficacy of listed LED directional replacements (see LED replacement criteria in Table 1.2) can range from 40 lm/W to as high as 95 lm/W with the average at about 57 lm/W. This is significantly greater than the incandescent or halogen lamps they replace which typically have an efficacy of about 10 to 15 lm/W. The efficacy of these LED lamps has even surpassed that of CFL reflectors which have efficacies that vary from between 35 and 45 lm/W.[25]

LEDs biggest barrier to adoption continues to be the price. In 2012, CFL reflector prices average at roughly $10 per lamp, while the average LED reflector price is $46 per lamp. However, adopting fluorescent technology for directional lamp applications presents several problems. Reflector CFL products are typically bulky and emit light from a larger area compared to an incandescent reflector making it difficult to create an effective directional lighting source. On the other hand, LED replacements for reflector lamps have distinct advantages and eliminate several of the issues associated with reflector CFLs due to their inherently small form factor and design flexibility for directional or ambient lighting applications.

2.2.1 LED Directional Lamp Penetration

Shown in Figure 2.3 is DOE's estimate for the installed base of LED directional lamps from 2009 to 2012. Similar to LED A-type lamps, the installed stock of LED directional lamps has also seen significant growth, increasing from 0.1 million units in 2009 to 11.4 million units in 2012.

[25] DOE's LED Lighting Facts product list is available at: http://www.lightingfacts.com/content/products



*Upper and lower bounds on each bar represent the range of market estimates

Figure 2.3 – Installed Base Estimates for LED Directional Lamps

In total it is estimated that there are 248 million lamps installed in directional applications within the U.S., of which over 80 percent are residential lamps. Similar to the A-type, the directional lamps are also experiencing a transition away from traditional incandescent lamps towards higher efficiency halogen lamps, CFLs, and LED lamps. As seen in Figure 2.4, from 2010 to 2012 the installed base of incandescent lamps decreased from 36 percent to 25 percent, while halogen increased from 49 percent in 2010 to 59 percent in 2012. Figure 2.4 also indicates that the installed base of reflector CFLs has decreased between 2010 and 2012 and are losing market share to LED reflector lamps which offer better performance as well as lighting quality.

In 2012 LEDs have reached an installed base of 11.4 million lamps, or about 4.6 percent of the total directional lamp sockets. This penetration rate is one of the highest for any of the applications analyzed in this report, and has increased dramatically from 2010 which had an LED installed base of less than one percent.

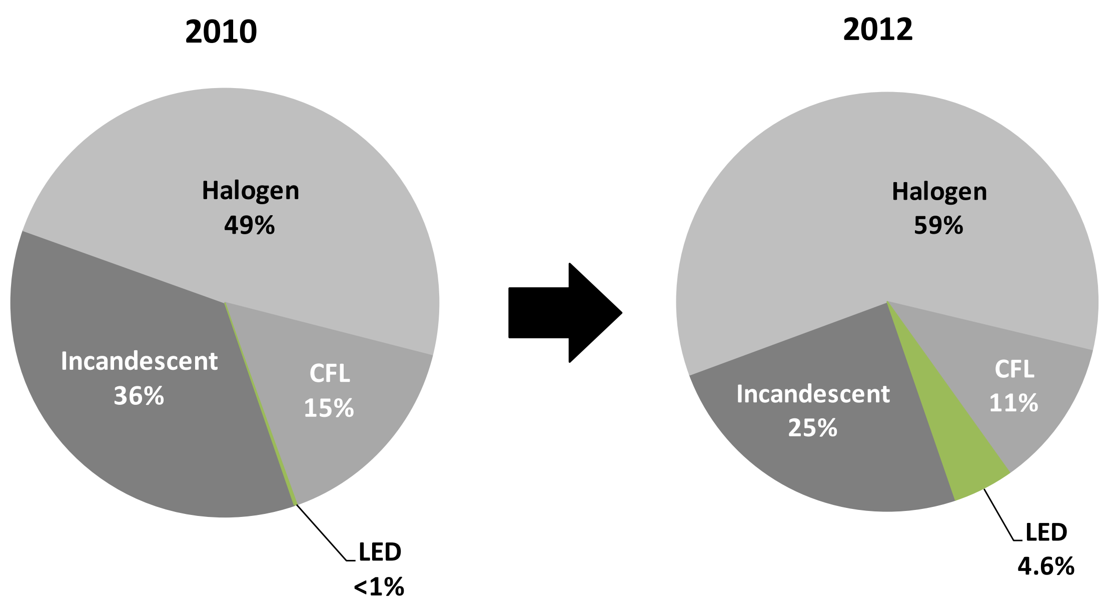


Figure 2.4 – Directional Lamp Installed Base

2.2.2 Directional Lamp Energy Savings

The total energy consumption of directional lamps was 195 tBtu in 2012. It is estimated that the 11.4 million LED reflector lamps installed in 2012 saved about 24 tBtu. Table 2.2 depicts the total energy consumption of directional lamps, as well as the potential energy savings if the entire U.S. installed base was converted instantaneously to LED lamps. Compared to the baseline savings in 2012, a potential electricity savings of 174 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of $1.7 billion.

Table 2.2 – Energy Consumption and Savings Potential of LED Directional Lamps

 Directional Lamps	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	11.4	195 (18.7)	23.7 (2.3)	174 (16.7)

2.3 MR16 Lamps

Similar to the directional lamps (PAR, BR, and R) discussed in the previous section, MR16 lamps are primarily halogen incandescent light sources that also provide directional light. However, MR16 lamps are unique amongst directional lamps because they are most often operated at low voltage and their design is constrained by a small form factor.[26] These lamps are widely used for accent, task, and display lighting in museums, art galleries, retail stores, residential settings, and entertainment venues. Although MR16 lamps are used in similar spaces to the directional lamps discussed in section 2.2, MR16 lamps are particularly optimal for jewelry and other display applications due to their high CRI and well-controlled, high-intensity beam.[27]

The small form factor and required dimmability and optical control of MR16 lamps cannot be duplicated with CFL technology, but can be met by LEDs. In addition, the efficiencies of LEDs greatly outpace that of the incumbent halogen technology. LED MR16 replacement lamps have efficacies approaching 80 lm/W and according to DOE's LED Lighting Facts product list LED MR16s average at about 50 lm/W. Traditional halogen MR16 lamps are only capable of efficacies between 10 and 25 lm/W. For MR16 lamps, beam angle and center beam intensity are typically the most important performance attributes. Center beam intensity values for halogen MR16 lamps range from 230 to 16,000 cd and are affected by both the lamp wattage (as it relates to light output) and the beam angle of the lamp.[28] Depending on the application, a narrow beam (nominal 10 or 12 degree) with a high center beam intensity may be needed, or a wider beam (nominal 25 to 40 degree) with lower center beam intensity may be appropriate. Currently fewer than 20% of the 436 LED Lighting Facts listed MR16 lamps report beam angle and center beam intensity, as these are not mandatory reporting items. Of those, the average beam angle reported is 35 degrees and center beam intensity is 880 candela, as reported in the Lighting Facts product database.

However, there are performance and equivalency issues with LED MR16s due to the challenge of combining the high lumen output out with the small MR16 form factor. The most common halogen MR16 lamp wattages are the 20, 35, 50, and 75 Watt while recent Commercially Available LED Product Evaluation and Reporting (CALiPER) testing results indicate that the lumen output of most LED MR16 lamps is less than or equal to the output of a 35 Watt halogen lamp. In addition, as of April 2013, the maximum lumen output of an LED MR16 lamp listed in DOE's LED Lighting Facts product list was 590 lumens, while halogen MR16 lamps can offer light output more than twice that amount. Another barrier to adoption, as is with most LED lighting products, is still the price. In 2012, halogen MR16 prices average at roughly $4.60 per lamp,

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[26] Most MR16 lamps are operated using voltages lower than 120 volts, typically 12 volts (Lighting Research Center (b), 2002).

[27] Rensselaer Polytechnic Institute – Lighting Research Center, Lighting Answers: MR16 Lamps, http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/mr16/abstract.asp

[28] Performance of Halogen Incandescent MR16 Lamps and LED Replacements, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/mr16_benchmark_11-08.pdf

while the average LED MR16 price is $23 per lamp. Regardless, because LEDs offer significant energy savings over halogen MR16 lamps, LED replacements have been commercially successful within this lamp application and their market presence continues to grow. The following sections describe the estimated energy savings from the increased use of MR16 LED replacement lamps.

2.3.1 LED MR16 Lamp Penetration

Shown in Figure 2.5 is DOE's estimate for the installed base of LED MR16 lamps from 2009 to 2012. The LED MR16 market has also seen tremendous growth, with the installed base increasing from 0.1 million units in 2009 to nearly five million in 2012.

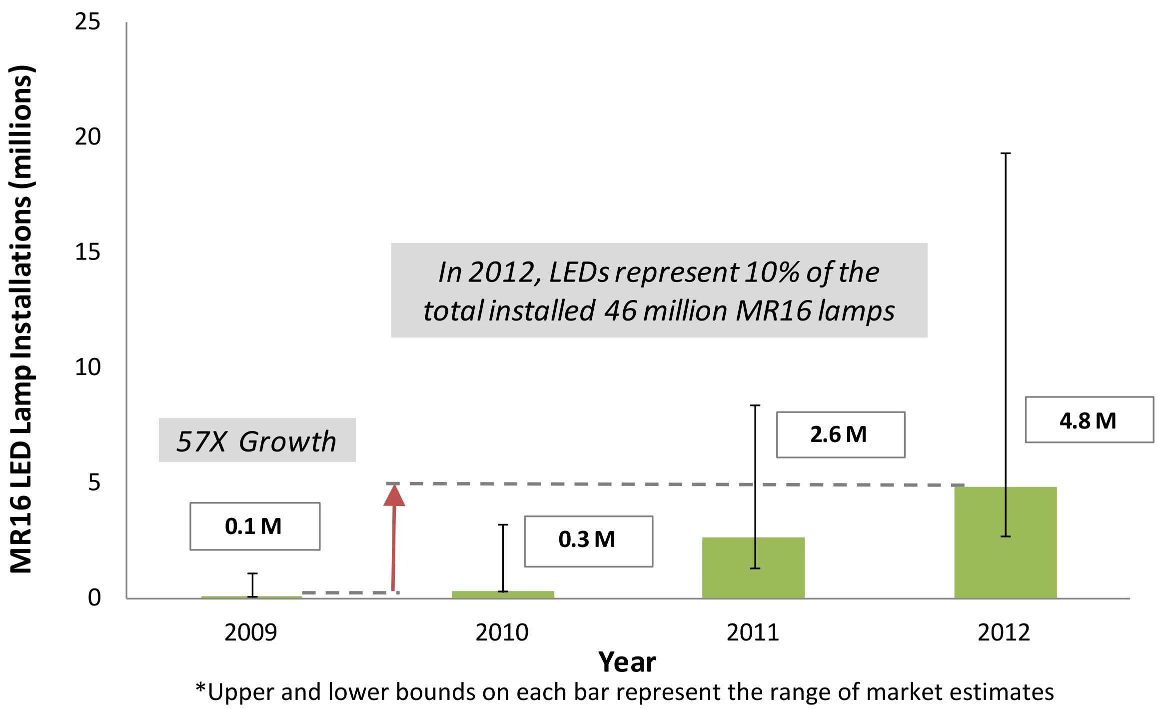


Figure 2.5 – Installed Base Estimates for LED MR16 Lamps

In 2012, there were about 46 million MR16 lamps installed within the U.S., of which it is estimated that about 56 percent are commercial installations while the remaining 43 percent are in households. In the past few years there has been a significant shift in the MR16 lamp market. Due to the recent development of LED MR16 replacement lamps, there has been a rapid transition away from inefficient halogen MR16s. Of all the applications analyzed in this report, LED MR16 lamps have had the most success in terms of installed base penetration. As seen in Figure 2.6, from 2010 to 2012 the installed base of halogen MR16 lamps decreased from 99 percent to 90 percent, while LEDs increased from one percent in 2010 to about ten percent in 2012 equal to approximately 4.8 million units.

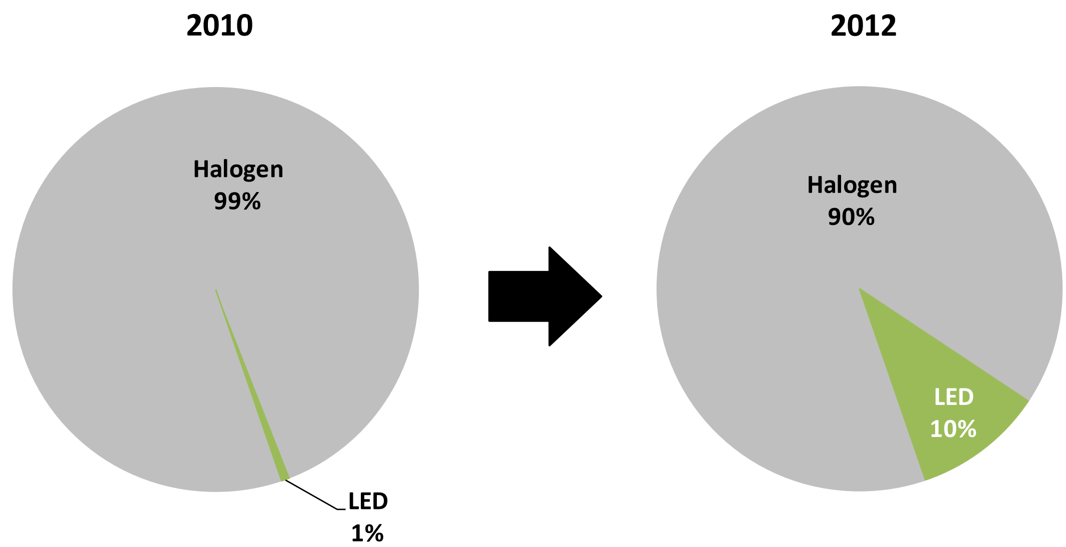


Figure 2.6 – MR16 Lamp Installed Base

2.3.2 MR16 Lamp Energy Savings

The total energy consumption of MR16 lamps was 70 tBtu in 2012. It is estimated that the 4.8 million LED MR16 replacement lamps installed saved about 3.7 tBtu in 2012. Table 2.3 depicts the total energy consumption of MR16 lamps, as well as the potential energy savings if the entire U.S. installed base was converted instantaneously to LED lamps. Compared to the baseline savings a potential energy savings of 65 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of $0.6 billion.

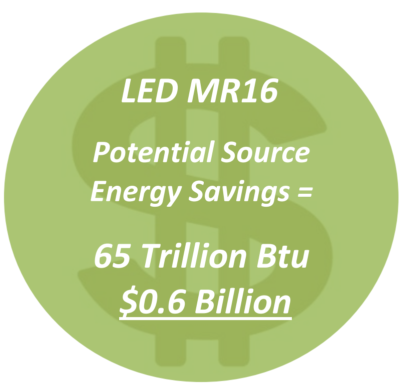


Table 2.3 – Energy Consumption and Savings Potential of LED MR16 Lamps

 MR16 Lamps	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	4.8	70 (6.7)	3.7 (0.4)	65 (6.2)

2.4 Decorative Lamps

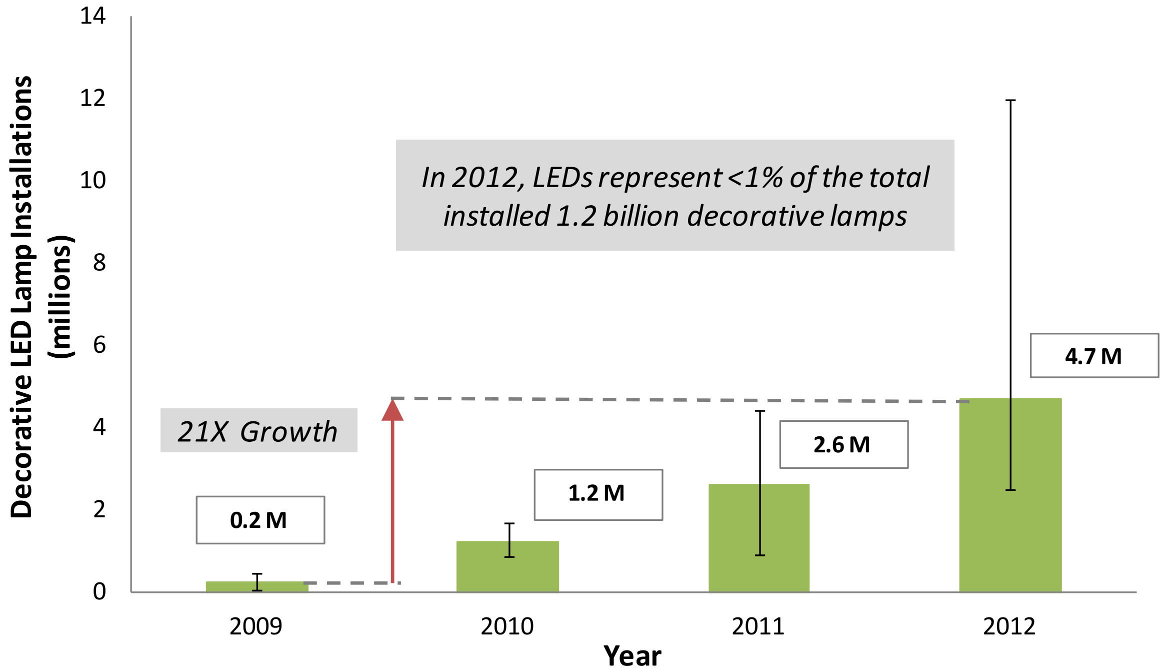
Decorative is a fairly generic term that is used to cover a wide range of bulb shapes including bullet, globe, flame, and candle among others. Though separate in this study, A-type lamps are often given the decorative label. These lamps are intended for use in decorative fixtures, including chandeliers, pendants, wall sconces and lanterns, and nightlights. Given their intended decorative function, these lamps typically require low lumen output, but may have high color quality requirements depending on the use. As these bulbs are in installations where they are not encased by a luminaire or shade, technologies with broader lumen distribution, such as incandescent, is generally preferable.

Unlike A-type and directional lamps, decorative lamps are largely exempt from the energy efficiency standards set by EISA 2007 and little incentive has existed to motivate the transition away from incandescent technology. However, for many of the smaller candelabra lamp shapes LEDs – an application that favors compact form factor – are becoming the go-to replacement for traditional incandescent lamps. This is because CFL replacement options are often bulky and LED replacement lamps may address several CFL shortcomings, including dimming and color temperature which tend to be of particular importance for decorative lighting applications. LED decorative replacements have also seen vast improvement. In 2008, CALiPER evaluated five LED decorative replacement lamps and reported that many did not meet manufacturer performance claims, with products typically producing only 10 to 60 percent of their claimed light output. They also discovered that the distribution of LED decorative lamps was also not up to par with incandescent replacements.[29]

2.4.1 LED Decorative Lamp Penetration

Shown in Figure 2.7 is DOE's estimate for the installed base of LED decorative lamps from 2009 to 2012. Although, the installed base of LED decorative lamps is less than that of LED A-type, directional, and MR16 lamps there has still been a significant amount of growth. Between 2009 and 2012 it is estimate that the installed stock of LED decorative lamps have increased from 0.2 million to 4.6 million units in 2012. However, as seen in Figure 2.7, there is large uncertainty surrounding this 2012 estimate, as market estimates for this application vary anywhere from 2 to 12 million LED decorative installations.

[29] CALiPER, Performance of Incandescent A-Type and Decorative Lamps and LED Replacements, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/a-type_benchmark_11-08.pdf

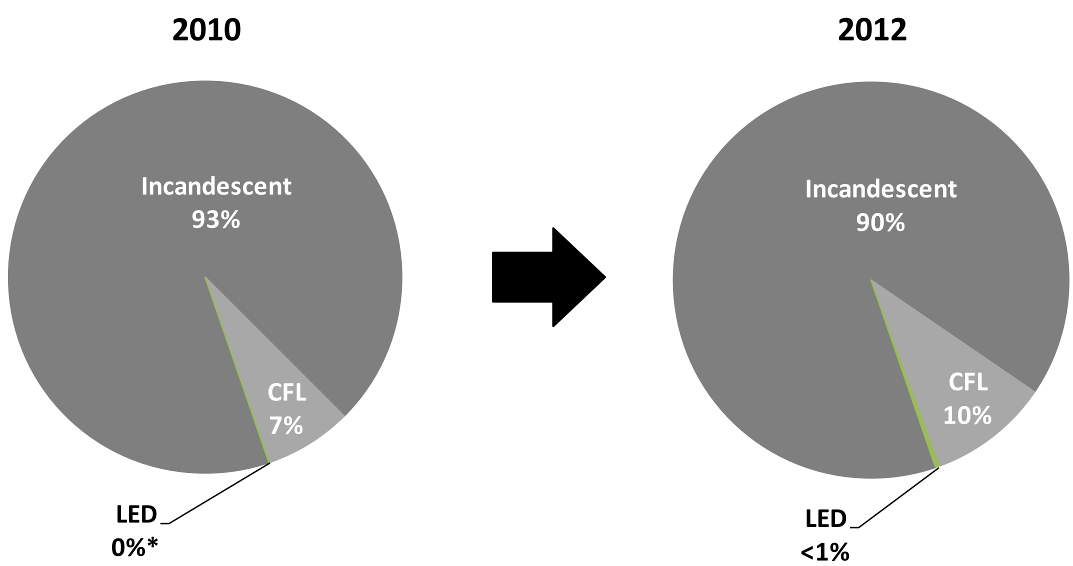


*Upper and lower bounds on each bar represent the range of market estimates

Figure 2.7 – Installed Base Estimates for LED Decorative Lamps

In 2012, the national inventory of decorative lamps was approximately 1.2 billion. Similar to the A-type market nearly all of these installations are in residential residences and about 90 percent are incandescent bulbs. However, the decorative lamp market has been much slower to adopt more efficient lighting technologies with only about 10 percent representing CFL installations. As seen in Figure 2.8, from 2010 to 2012 the installed base of incandescent decorative lamps decreased marginally from 93 percent to 90 percent, while CFLs increased from 7 percent in 2010 to 10 percent in 2012.

Figure 2.8 below indicates that the installed base of LED decorative lamps is less than one percent of the total U.S. decorative lamp installed base.



*Values less than 0.1% are considered negligible

Figure 2.8 – Decorative Lamp Installed Base

2.4.2 Decorative Lamp Energy Savings

From 2010 to 2012, the total energy consumption of decorative lamps has increased from about 353 tBtu to 367 tBtu. This is largely because of the slow transition to energy efficiency CFL and LED lighting technologies within this lighting market. LED decorative lamps are still emerging and it is estimated that the 4.7 million LED decorative lamps installed saved about 1.4 tBtu in 2012. Table 2.4 depicts the total energy consumption of decorative lamps and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED. Compared to the baseline savings in 2012, a potential electricity savings of 298 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of $2.8 billion.

Table 2.4 – Energy Consumption and Savings Potential of LED Decorative Lamps

 Decorative Lamps	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	4.7	367 (35.4)	1.4 (0.1)	298 (28.7)

3. Indoor Luminaires

An indoor luminaire refers to a lighting system comprised of lamp(s), electrical controls such as a ballast or driver, and a fixture which connects directly to a branch circuit. Indoor luminaires are most common in commercial and industrial buildings and serve multiple purposes and are largely utilized for providing ambient lighting. The indoor luminaire analysis evaluates the penetration and energy savings impact of LED lighting within three distinct applications: downlights, troffers, and high-bay fixtures. Combined these applications represent about 34 percent of all lighting installations, but are responsible for well over half of the total electricity consumption for all lighting in the U.S. This is the near inverse compared to the indoor lamp applications evaluated in the previous Chapter 2, which represent nearly 60 percent of all installations, but only slightly over 20 percent of the total lighting energy consumption. This distinction is largely due to the high operating hours and light output of luminaire fixtures. Because conventional indoor luminaires represent such a large portion of the total U.S. lighting energy consumption, LED luminaire options have the potential to offer significant energy savings well beyond that of LED lamps.

Indoor LED luminaires are a rapidly growing segment of the overall LED lighting market as many of these products now meet or exceed the performance of conventional products. One of the drivers that has helped to push performance to the next level is the DOE co-sponsored “Next Generation Luminaires” (NGL) competition.[30] The most recent indoor luminaire contest winners were announced in March 2013 – with the winners averaging 75 lm/W, versus 65 lm/W in 2012, and 37 lm/W in 2008. Of the 28 recognized contest winners LED downlight, troffer, and high-bay products were all represented. Several of these 2013 Next Generation Luminaires winners are shown in Figure 3.1.

Next Generation Luminaires is a competition that encourages manufacturers to develop innovative commercial luminaires that are energy efficient and provide high lighting quality and consistency, glare control, lumen maintenance, and luminaire appearance needed to meet specification lighting requirements. In its first year, 2008, the NGL competition recognized 22 products from among a total of 68 entries covering both indoor and outdoor product classifications. The most recent indoor luminaire contest winners were announced in March 2013 with the number of entries more than doubling – to 156 entries – since the contest started in 2008. Of these entries, 28 were chosen as "recognized" winners and three of were chosen as "best in class."

[30] For more information on the Next Generation Luminaires Solid-State Lighting Design Competition visit: http://www.ngldc.org/

Best in Class – Digital Lumens High-Bay Luminaire

Notable – BeveLED 2.0 Color Curved Downlight

Recognized – Peerless Mino 2x2 LED Luminaire

Figure 3.1 – Selection of 2013 Next Generation Indoor Luminaire Contest Winners

In addition, to improved performance, LED indoor luminaires continue to become more economical. While first costs are still high, LED luminaires are becoming more and more appealing in commercial and industrial buildings where facility maintenance professionals are better able to see the potential of LED lighting solutions to significantly reduce maintenance costs due to the long lifetime of these products.

3.1 Downlight Luminaires

This section examines the current and potential energy savings of LED downlight luminaires, including downlight retrofits and integrated LED downlights. This report assumes that all LED directional replacement lamps are installed in directional applications which are evaluated in section 2.2.

Although originally intended for directional lighting applications, downlights have become commonly used for ambient lighting in both residential and commercial buildings. These fixtures can be recessed or surface mounted and have become popular because they are inexpensive and can provide inconspicuous ambient lighting for most room types. This market most commonly includes incandescent, halogen, and compact fluorescent reflector lamps (e.g., PAR, BR, and R lamps), pin-base CFLs, as well as LEDs. Although, PAR, BR, and R lamps are designed for directional lighting applications (see section 2.2), they are commonly installed in downlight fixtures to increase the optical efficiency of the overall luminaire system.[31]

LED downlights, one of the earliest applications for solid-state lighting in general illumination, became largely viable starting in 2007 with the release of the Cree LED LR6 recessed downlight. In addition to its superior efficacy of 54 lm/W, its high lumen output and quality of light made it the first adequate downlight substitute for incandescent and CFL reflector lamps. In 2012, CALiPER published that the tested efficacy of eleven commercially available LED downlight products were equal to or better than the system efficacy for a typical CFL downlight luminaire, with a range of 39 to 69 lm/W and an average of 49 lm/W. This is substantially better than downlights using incandescent or halogen lamps. In addition, CALiPER indicates that tested LED downlights have performed well offering good color quality as well as light output and are a viable option for residential and light-commercial downlights.[32] In addition, the LED Lighting Facts product list indicates that LED downlight performance has continued to improve, with manufacturers now offering LED downlight products with efficacies upwards of 80 lm/W.[33]

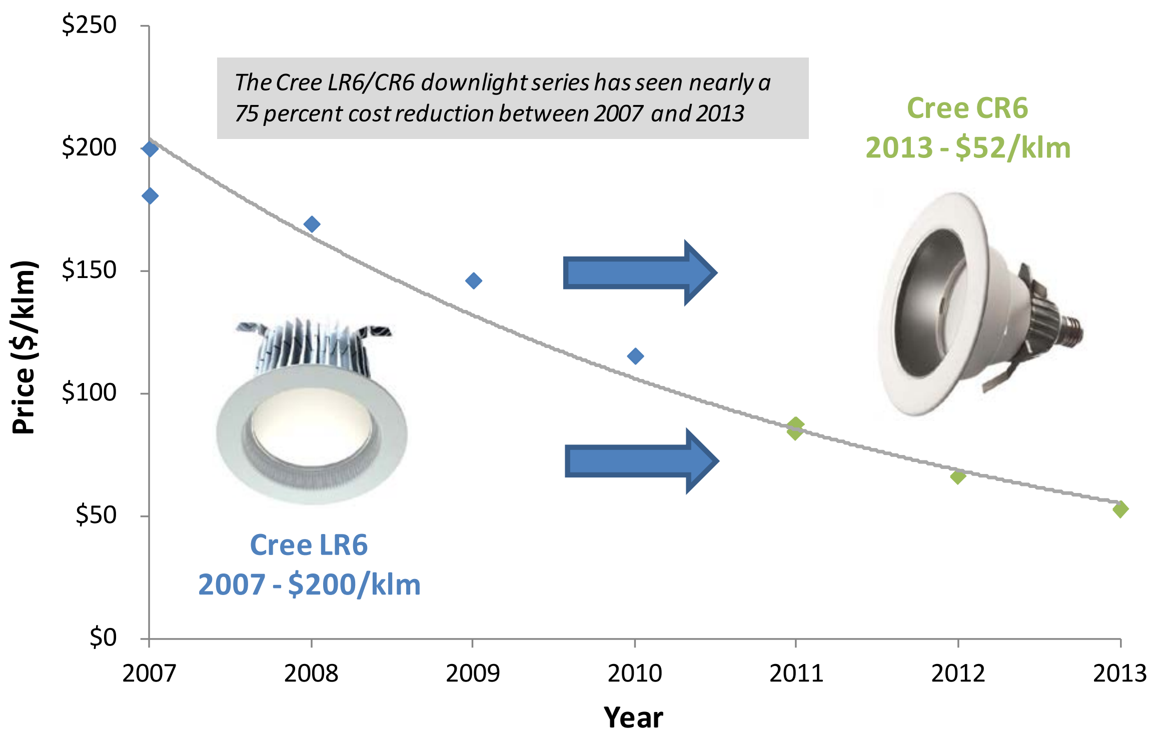


Figure 3.2 – Price Reduction for Cree LR6/CR6 Downlight

[31] CALiPER, Summary of Results: Round 11 of Product Testing, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round-11_summary.pdf

[32] CALiPER, Application Summary Report 14: LED Downlight Retrofit Units, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_14_summary.pdf

[33] Acuity, Lithonia Lighting, LED Downlight, REAL6 D6MW ESL 1000K 35K

In addition to improved performance, LED downlights have seen rapid price reductions. One example is the Cree LR6 and its transition to the CR6 downlight model. Released in mid-2010, the Cree CR6 was designed to optimize performance and cost using what was learned from the LR6 product line. The CR6 costs roughly 30 percent less to manufacture, requires fewer LEDs compared to the LR6 to achieve a lumen output of nearly 600 lumens, and the heat sink uses 50 percent fewer materials (by weight). As seen in Figure 3.2, this progress has enabled the Cree LR6/CR6 downlight series to achieve nearly a 75 percent cost reduction between 2007 and 2013.

3.1.1 LED Downlight Penetration

Of all the indoor luminaire applications evaluated in this analysis, LED downlights have had the greatest success in terms of installed stock penetration. In 2010, the installed stock of LED downlights had not yet approached one million units; however, since then it has grown to over 5.5 million in 2012 representing an 11x increase. This increase can largely be attributed to continued performance improvements, cost reductions as well as the increasing availability of LED downlight products in home improvement stores such as The Home Depot and Lowe's.

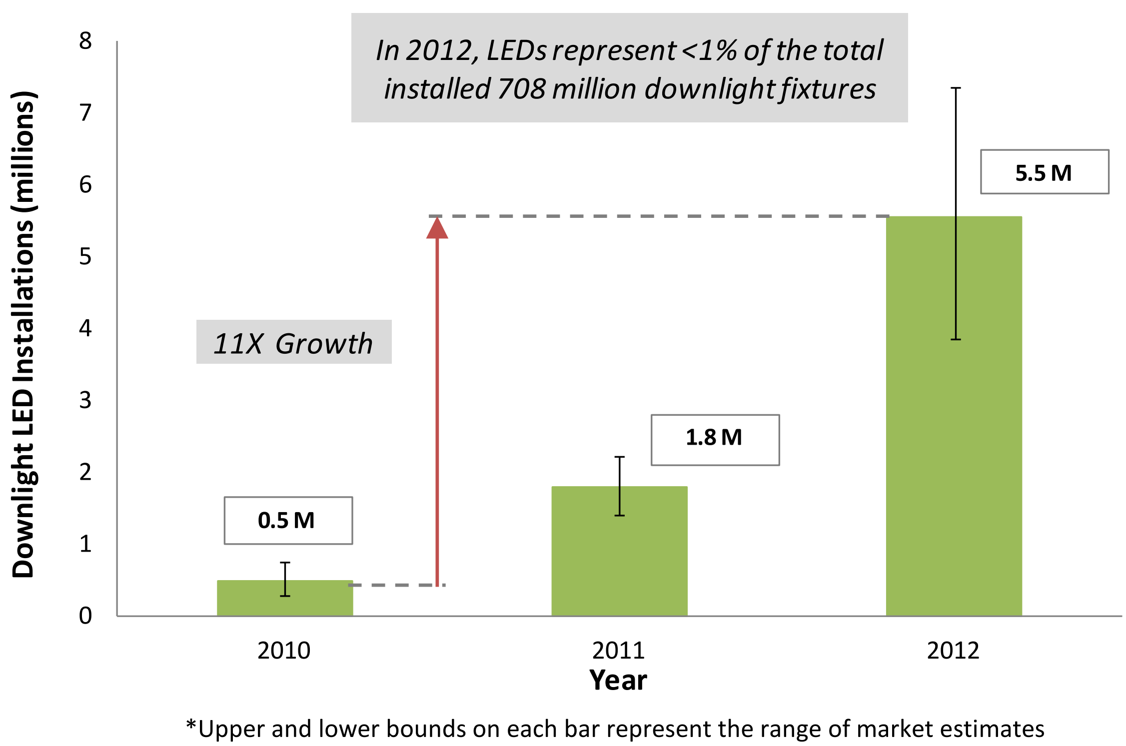


Figure 3.3 – Installed Base Estimates for LED Downlights[34]

[34] Unlike many of the other applications 2009 figures are not provided. This is primarily due to lack of data from years prior to 2010, however it is fair to assume that LED installations prior to 2010 are negligible.

It is estimated that in 2010 there were about 703 million downlight fixtures installed within the U.S. Since then the forecast analysis predicts that this has increased to about 708 million fixtures due to building stock growth in both the residential and commercial sectors. While LED downlights have become increasingly popular, as seen in Figure 3.4, they still only represent a small percentage of overall downlight installations, still shy of one percent in 2012.

Incandescent and halogen lighting products continue to be the technology of choice for downlighting applications and have maintained their installed base share between 2010 and 2012 at roughly 67 percent. However, taking effect in 2012, DOE energy conservation regulations for incandescent reflector lamps, which are commonly used in downlighting applications, have promoted the adoption of halogen reflector technologies (see Appendix C). This transition can been seen in Figure 3.4 below, with the installed base percentage of incandescent decreasing from 54 to 47 percent, while halogen increased from 13 to 20 percent.

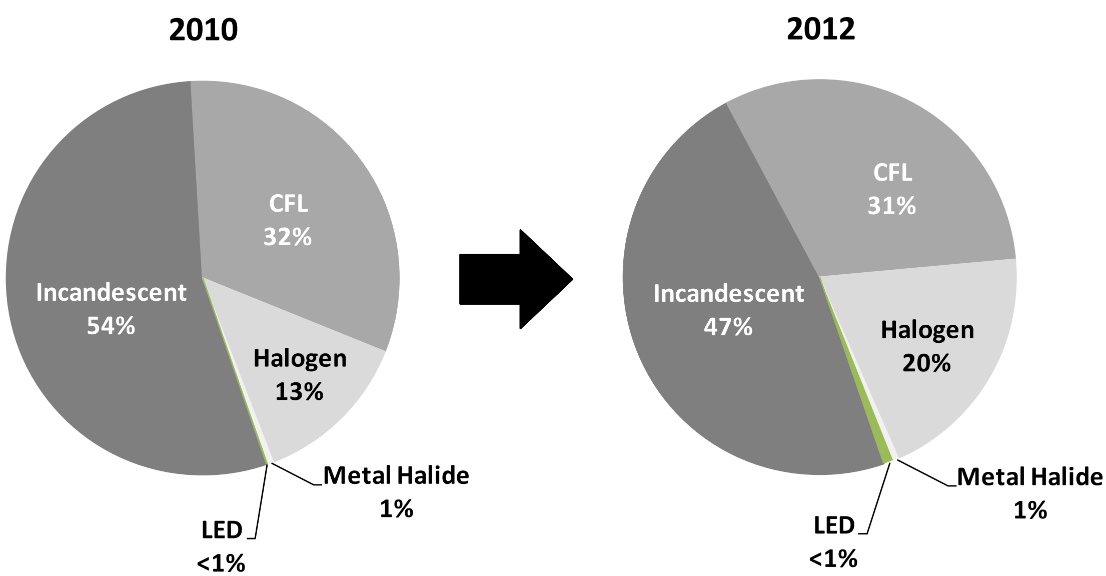


Figure 3.4 – Downlight Installed Base

Interestingly, the market share of CFLs in downlighting applications has slightly decreased between 2010 and 2012. The CFL installed base is divided between CFL reflector lamps and pin-base CFLs. While the installed base of CFL pin-base lamps has remained constant between 2010 and 2012, the use of CFL reflector lamps has decreased. The inherent attributes of CFL technology does not lend itself well to the reflector lamp design and is likely the cause for this slight decline.

3.1.2 LED Downlight Energy Savings

From 2010 to 2012, the total energy consumption of downlights in the U.S. has increased slightly from about 376 tBtu to 382 tBtu. This increase can be explained by the rise in the number of downlight installations while there has been only miniscule improvement to installed stock efficiency. While the number of LED downlights is still small in comparison to the entire installed base, it is estimated that in 2012 approximately 9.3 tBtu of energy were saved due to the penetration of LEDs. If LEDs were to saturate this market about 278 tBtu of energy could be saved annually. This equates to an annual energy cost savings of $2.6 billion.

LED Downlights

Potential Source Energy Savings =

278 Trillion Btu

$2.6 Billion

Table 3.1 – Energy Consumption and Savings Potential of LED Downlights

 **Downlights**	**LED Installed Base Units** millions	**Total Energy Consumption** Source– tBtu (Site – TWh)	**LED Energy Savings** Source– tBtu (Site – TWh)	**Potential LED Energy Savings** Source– tBtu (Site – TWh)
2012	5.5	382 (36.8)	9.3 (0.9)	278 (26.8)

3.2 Troffer and Other Common Fluorescent Fixtures

This section examines the current and potential energy savings of LEDs in recessed troffers, surface-mounted fixtures, suspended fixtures, and other direct-lighting fixtures that customarily house a linear fluorescent or u-shaped fluorescent lamp(s) and ballast system. The term "troffer et al." is used in this report to describe these applications collectively.

The Illuminating Engineering Society defines a troffer fixture as a long recessed lighting unit usually installed with the opening flush with the ceiling. As mentioned in the call out box above, this section examines these standard troffers, as well as other common fluorescent fixtures. Examples of fixtures included within this section are shown in Figure 3.5. These fluorescent fixture systems are widely utilized for commercial and industrial establishments because they offer a low cost, highly efficient and long lifetime lighting source. These luminaires are selected for flexibility of output and distribution, as well as aesthetics.[35]

[35] CALiPER, Summary of Results: Round 13 of Product Testing, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round13_summary.pdf

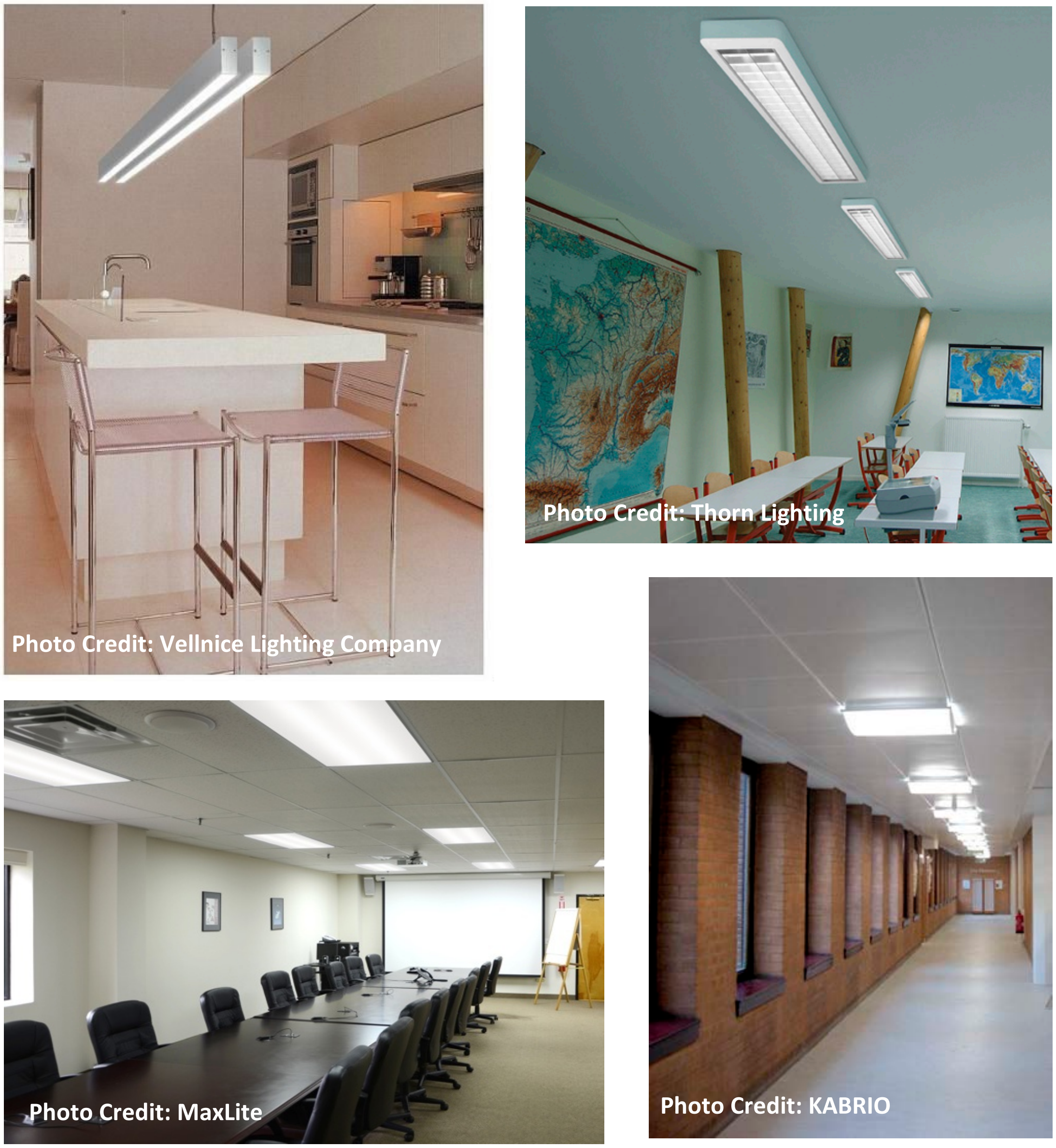


Figure 3.5 – Examples of Troffers and Other Common Fluorescent Fixtures

CALiPER's latest study on recessed troffer lighting indicates that dedicated LED troffers are ready to compete with fluorescent troffers in terms of efficacy as well as lighting quality issues such as glare, light distribution, visual appearance, and color quality.[36] On the other hand, CALiPER reported that troffer fixtures retrofitted with LED lamps demonstrated similar efficacies to that of fluorescent lighting. Due to their superior efficiency, this analysis only considers the energy savings from LED troffer luminaires, since in most cases LED linear lamp replacements are not yet competitive with their fluorescent counterparts, in terms of both cost and performance.[36] The LED Lighting Facts product list indicates that LED replacements are

[36] CALiPER, Exploratory Study: Recessed Troffer Lighting, March 2013, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_recessed-troffer_2013.pdf

available for all of the most common troffer sizes (i.e., 2-ft by 2-ft, 1-ft by 4-ft, and 2-ft by 4-ft) and offer efficacies as high as 120 lm/W, while a fluorescent system can have an efficacy between 40 and 85 lm/W. In addition, DOE's CALiPER Program indicates that LED troffers are increasingly competitive with incumbent technologies with respect to light output levels and light distribution, and are increasingly able to provide similar or better color characteristics and comparable or better luminaire efficacies. LEDs also offer several benefits for general illumination compared to fluorescent technology, such as their directionality (i.e., LED sources emit light into one hemisphere unlike fluorescent technology, which is omni-directional), which results in reduced light loss. However there are still large differences in performance across available LED products and there are still issues with color inconsistencies among products and flicker under dimmed conditions.

3.2.1 LED Troffer and Other Common Fluorescent Fixture Penetration

While LEDs in this application are not nearly as prominent as LED downlights, these luminaires have seen significant growth in the past three years, increasing from an installed stock of approximately 40 thousand units in 2010 to nearly 700 thousand in 2012. As seen below in Figure 3.6, much of this growth was seen between 2011 and 2012 and is largely due to the vast performance and cost improvements recently made by LED products.

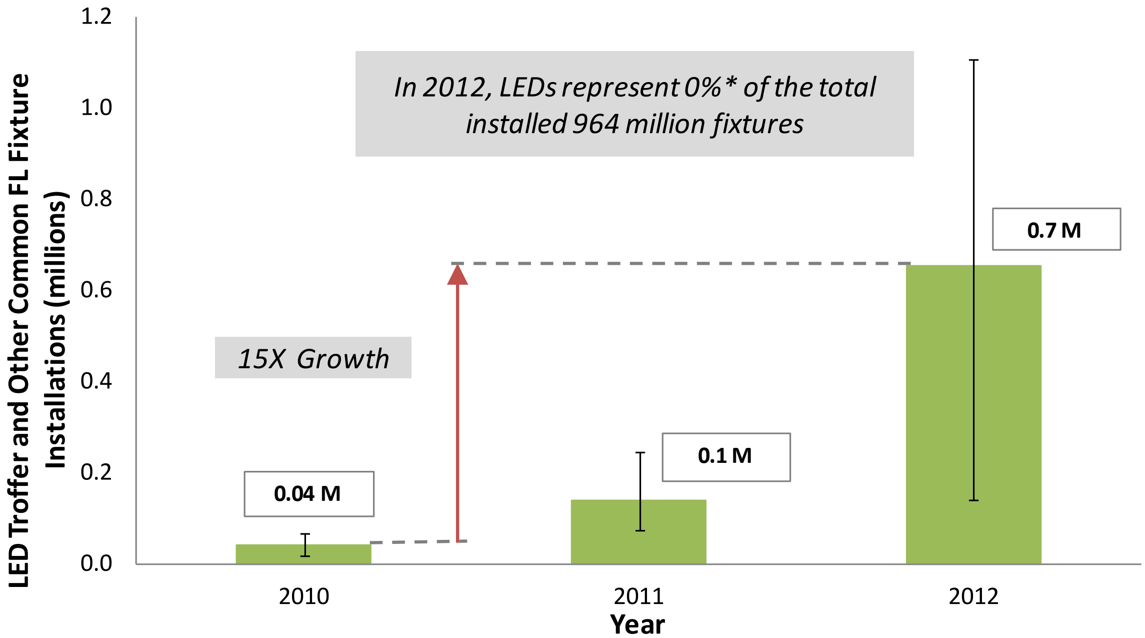
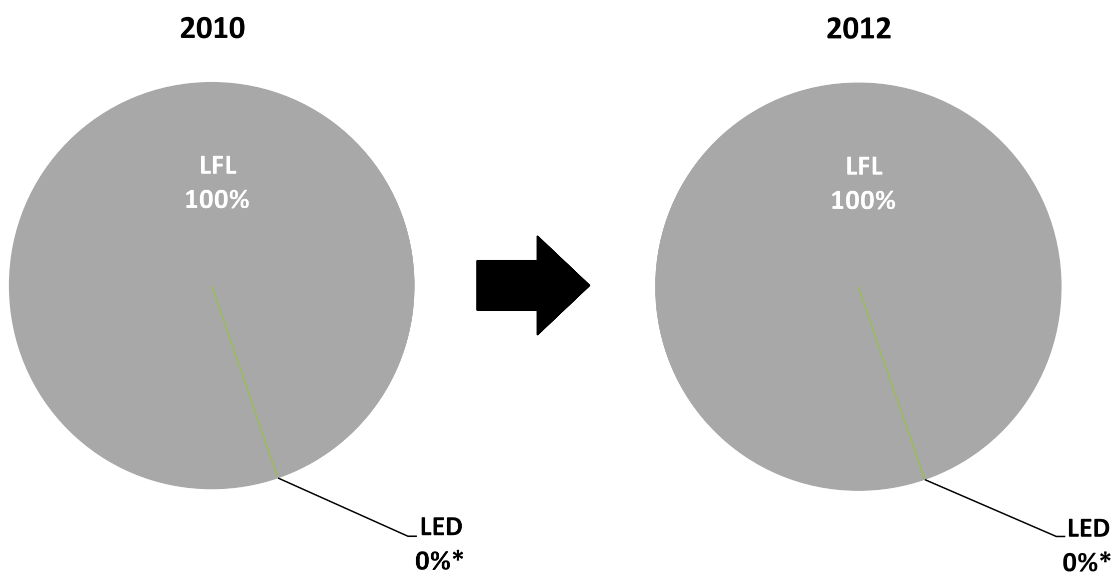


Figure 3.6 – Installed Base Estimates for LED Troffers and Other Common Fluorescent Fixtures[37]

As seen in Figure 3.7, compared to the entire U.S. installed stock, LED have barely begun to scratch the surface. The 2010 installed stock is estimated at about 957 million total troffer et al. fixtures, while the forecast suggests this has increased slightly in 2012 to 964 million due primarily to growth in the commercial sector.

[37] Unlike many of the other applications 2009 figures are not provided. This is primarily due to lack of data from years prior to 2010, however it is fair to assume that LED installations prior to 2010 are negligible.

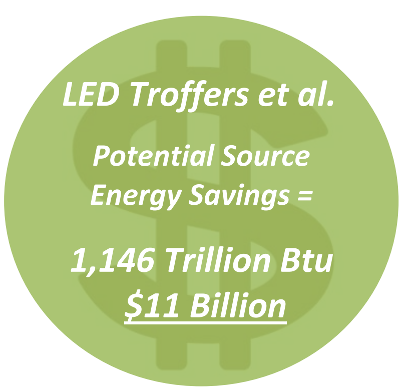


*Values less than 0.1% are considered negligible

Figure 3.7 – Troffer and Other Common Fluorescent Fixture Installed Base

Fluorescent lighting dominates these applications to the point that it is basically the only lighting technology used due to its high efficiency and low cost. However, when considering the different fluorescent lighting tube diameters (i.e., T12, T8 and T5); there has been a continuing trend away from T12 lamps due to the emergence of higher efficiency T8 and T5 lamp options. The transition to these higher efficiency fluorescent lamps has also been propelled by energy efficiency standards (see Appendix C). Between 2010 and 2012 the percent of troffers using T12 lamps has decreased from 44 percent to 36 percent, while the T8 lamps has absorbed this, increasing from 53 percent to 60 percent of the installed stock.

3.2.2 LED Troffer and Other Common Fluorescent Fixture Energy Savings



Despite the increase in the total installed stock of troffer et al. fixtures, from 2010 to 2012, the total energy consumption has decreased slightly from about 2,445 tBtu to 2,374 tBtu. This is largely because of the continuing transition to energy efficient T8 and T5 lamps. The relative size of the LED installed base is still negligible compared to the number of fluorescent fixtures, however, LEDs did provide about 0.9 tBtu of energy savings for 2012. Table 3.2 depicts the total energy consumption of troffer applications and the potential energy savings if the entire nationwide installed base was converted instantaneously to

LED. Compared to the baseline savings in 2012, a potential energy savings of 1,146 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of nearly $11 billion.

Table 3.2 – Energy Consumption and Savings Potential of LED Troffer and Other Common Lighting Fixtures

 **Troffers et al.***	**LED Installed Base Units** millions	**Total Energy Consumption** Source– tBtu (Site – TWh)	**LED Energy Savings** Source– tBtu (Site – TWh)	**Potential LED Energy Savings** Source– tBtu (Site – TWh)
2012	0.7	2,374 (228.6)	0.9 (0.1)	1,146 (110.4)

*Includes other common fluorescent fixtures

3.3 High-Bay Luminaires

High-bay luminaires are a common luminaire used in both commercial and industrial applications to illuminate large open indoor spaces for ceiling heights of 20 feet or more, as are typical in big-box retail, warehouses, and manufacturing facilities. Because of the large area, these spaces require high lumen-output luminaires often above 15,000 lumens per fixture in order to deliver the lighting effectively over long distances. This market was historically dominated by HID lamps, though fluorescent lamps, particularly high output T5 lamps, have become a major player due to their superior lumen maintenance and enhanced control options.

It is only in the past few years that technological and cost improvements have allowed LEDs to penetrate the market in significant quantities. Early generation high-bay LED luminaires lacked the lumen output to compete in this market. As late as 2010, CALiPER testing found that many of the LED products available on the market struggled to match traditional technologies in efficacy, and could not achieve claimed lumen output levels.[38] A year later, in 2011, CALiPER testing showed improved light distribution and lumen output were making some products competitive with HID sources.[39] Now in 2013, the DOE's LED Lighting Facts has over 100 listed high-bay luminaire products that emit over 15,000 lumens. LED manufacturers have even begun to sell products that produce over 25,000 lumens at efficacies up to 100 lm/W.[40] These

[38] CALiPER, Summary of Results: Round 11 of Product Testing, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round-11_summary.pdf
[39] CALiPER, Summary of Results: Round 13 of Product Testing, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round13_summary.pdf
[40] LEDs Magazine, *Dialight secures orders, introduces 25,000-lumen LED high-bay fixture*, http://ledsmagazine.com/news/9/11/20

technological gains combined with LEDs inherent advantages in lifetime, color quality, and controllability, are making the energy savings potential calculated in this report realistic.

3.3.1 LED High-Bay Penetration

Provided below in Figure 3.8 is DOE's estimate for the installed base of LED high-bay fixtures from 2010 to 2012. The data suggests that the installed base was fairly close to zero in 2010, rising to a few hundred thousand luminaires in 2012.

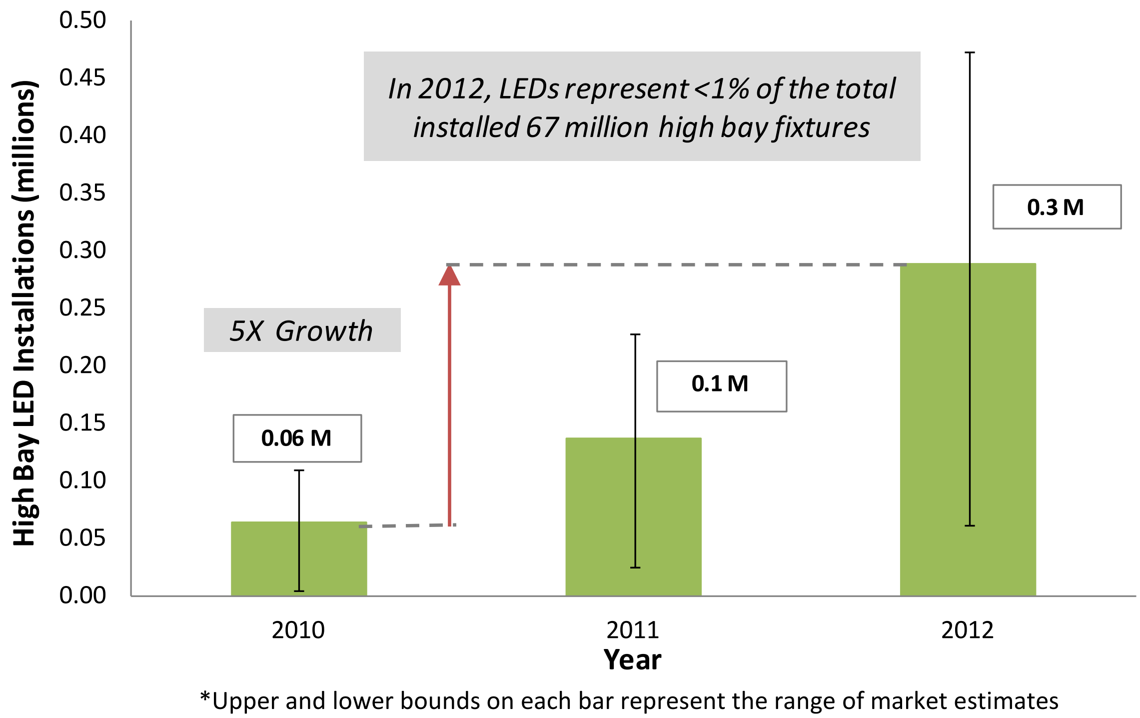
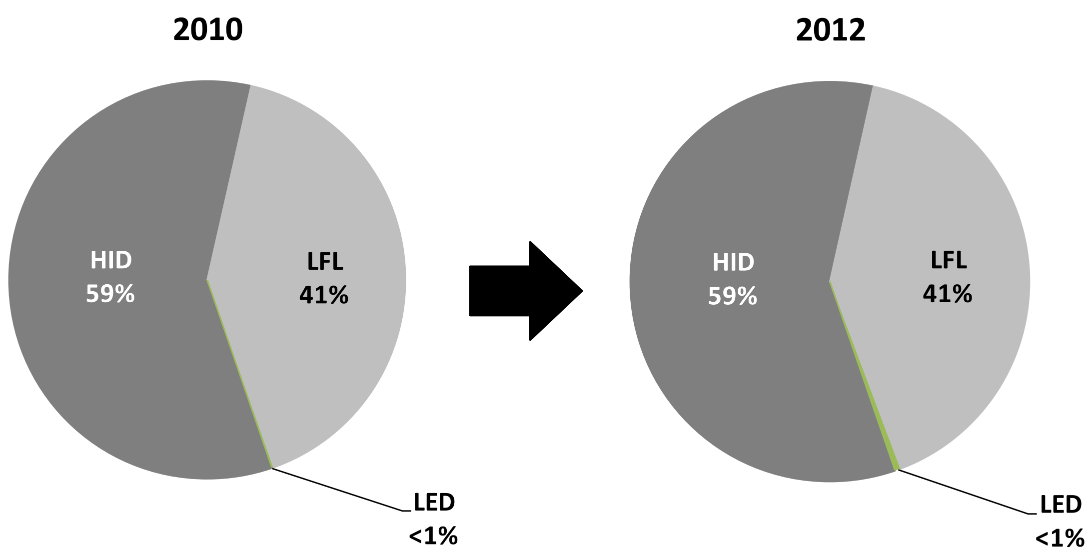


Figure 3.8 – Installed Base Estimates for LED High-Bay Fixtures[41]

The *2010 U.S. Lighting Market Characterization* report data indicates that there were approximately 66 million high-bay fixtures in the U.S. in 2010. The forecast estimates that this installed base has increased slightly in 2012 to nearly 67 million fixtures. This is likely due to the increasing installation in large commercial retail facilities such as Home Depot, Costco, and other big-box retail stores. Fluorescent lamps comprised approximately 41 percent of these applications, with the remainder being HID. While fluorescent market share as a whole has only slightly increased from 2010 to 2012, there has been a transition to high output T5 lamps. Between 2010 and 2012 the percent of installed T12 has decreased from 11 percent to only 4 percent, while T5 has increased from 14 percent to 21 percent of the entire high-bay stock.

[41] Unlike many of the other applications 2009 figures are not provided. This is primarily due to lack of data from years prior to 2010, however it is fair to assume that LED installations prior to 2010 are negligible.



*Values less than 0.1% are considered negligible

Figure 3.9 – High-Bay Fixture Installed Base

3.3.2 LED High-Bay Energy Savings

The total energy use of high-bay luminaires was about 1,096 tBtu in 2012. Because of their low installed stock, LEDs are currently saving 1.5 tBtu each year. However, a complete technology switch to LEDs would nearly cut the energy use in half, saving nearly 483 tBtu per year. This potential savings equates to an annual energy cost savings of $4.6 billion. This energy savings is due to both the improved efficacy offered by LED high-bay fixtures and from better compatibility with controls which affects the required lumen output of the luminaire.

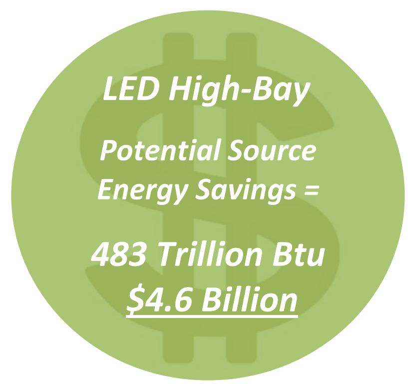


Table 3.3 – Energy Consumption and Savings Potential of LED High-Bay Fixtures

 High-Bay	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	0.3	1,096 (105.6)	1.5 (0.2)	483 (46.5)

4. **Outdoor Luminaires**

The outdoor luminaire analysis includes those that are used for streetlights as well as parking lot and garage facilities. These luminaires serve multiple purposes including providing proper illumination for pedestrian and automobile traffic, creating a sense of personal security, and attracting attention and business to spaces. Typically, HID luminaires have been relied upon in these applications due to their ability to affordably achieve illumination requirements. However, in the past several years newer technologies, such as induction (electrodeless fluorescent) and LEDs, have begun to make inroads into these markets.

Lighting designed for outdoor applications must address multiple issues such as proper light distribution, glare, light pollution, energy usage, and lifetime. Lifetimes are of particular interest to facility managers as they directly affect maintenance costs, which can be an important part of the economic equation as outdoor lights are often spread out over a large geographic region and owned by one organization. For example, the City of Los Angeles (LA) maintains over 210,000 streetlights contained within 503 square miles. In 2009, LA launched a program to convert 140,000 of these streetlights to LED. To date, LA has converted more than 115,000 to LED, and as a result the city is already achieving an estimated 63.5 percent energy savings over the incumbent high pressure sodium streetlights, which translates into an annual cost savings $5.4 million. In addition, largely because of the longer life of the LED fixtures (10-15 years), the city's annual streetlight maintenance costs have dropped by an estimated $2.5 million.[42]

In addition to energy and maintenance cost savings, LEDs are particularly advantageous in outdoor lighting applications because their inherent characteristics address many of the key issues associated with these types of lighting. LEDs offer extremely long lifetimes, are directional light sources, and thus able to limit light pollution and light trespass, are highly efficacious, function well in cold temperatures, are greatly resilient to vibration, and are able to provide a high quality light. Furthermore, studies in Raleigh, North Carolina, and the City of Los Angeles indicate that comparing the perceived brightness of LED sources and high and low pressure sodium lamps at night have shown that LEDs can achieve the same level of perceived brightness with lower lumen output than sodium lamps.[43]

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[42] DOE, SSL Posting: LA Achieves More Than Savings with LED Streetlights, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/postings_01-29-13.pdf

[43] Responsible Purchasing Network, Responsible Purchasing Guide for LED Exit Signs, Street Lights, and Traffic Signals http://www.seattle.gov/purchasing/pdf/RPNLEDguide.pdf

However, the major obstacle to greater market penetration continues to be the initial cost of LED luminaires. A review of DOE SSL GATEWAY Demonstrations revealed that the initial cost of outdoor LED luminaires is between two to seven times more than equivalent HID luminaires.[44]

In order to obviate the cost hurdle, the Federal government has provided financial incentives directly to facility owners that install energy efficient lighting. For example, EPACT 2005 provided a set of tax deductions, and the American Recovery and Reinvestment Act of 2009 awarded $3.2 billion through the Energy Efficiency and Conservation Block Grant Program to cities, counties, states, territories, and Indian tribes. A portion of these funds have been used to transition roadway lights, parking facility lights, and outdoor area lights to LEDs.[45]

4.1 Streetlight Luminaires

Streetlights serve the purpose of illuminating roadways, highways, or tunnels to improve visibility for drivers as well as to illuminate outdoor pedestrian walkways. In this study, we took into account streetlights that use MV, MH, LPS, HPS, and LEDs as these represent the vast majority of streetlight installations.

In the early 2000s, researchers recognized the potential for LEDs in streetlighting applications. LEDs are particularly advantageous in streetlighting applications because they are better directional light sources, and exhibit longer lifetimes. Because of these positive attributes, Raleigh, North Carolina, became the first U.S. city to begin testing and replacing their conventional streetlighting technologies with LED luminaires back in 2007. Since then, the DOE's Municipal Solid-State Street Lighting Consortium (Consortium)[46] founded in 2010 has helped LED streetlights to be installed in many U.S. cities. The Consortium is a voluntary group of representatives from interested municipalities, utilities and lighting professionals with the goal to build a repository of valuable field experience, data, and resources that will significantly accelerate the learning curve for buying and implementing high-quality, energy efficient LED streetlights.[47]

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[44] More information on the GATEWAY Demonstrations can be found at http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html

[45] More on the EECBG Program and funding allocations can be found at: http://www1.eere.energy.gov/wip/eecbg.html

[46] For additional information regarding the DOE's Municipal Solid-State Street Lighting Consortium visit: http://www1.eere.energy.gov/buildings/ssl/consortium.html

[47] DOE Solid-State Lighting Program, About the DOE Municipal Solid-State Street Lighting Consortium, http://www1.eere.energy.gov/buildings/ssl/consortium_about.html

The success of the Consortium has been aided by the nonstop improvement of LED luminaire performance as well as continued price decreases. As mentioned in the previous section, the City of Los Angeles has installed over 115,000 LED streetlights. Since the project began the average price of LEDs that LA has purchased dropped from $432 in 2009 to $245 in 2012.[42] Price decreases such as this along with current LED products boasting more than 110 lm/W have helped to increase the number of municipalities undergoing LED streetlight projects. Major cities including San Francisco[48] and Oakland,[49] California, as well as San Antonio, Texas,[50] Seattle, Washington,[51] and Portland, Oregon,[52] are all scheduled to complete large scale LED streetlight retrofits between 2013 and 2015. Combined these projects will result in the conversion of over 150,000 streetlights to LED technology.

History of Streetlighting Technology

Carbon arc streetlight from early 1900s

Streetlights are one of the oldest forms of lighting within the U.S. and date back to the 17th and 18th centuries when streets were lit using oil and gas lamps. The U.S. began rapidly installing incandescent lamps because of their higher reliability, longer life, and warm-white light. At the start of the 20th century it is estimated that the U.S. had installed over 130,000 electric incandescent streetlights. Since that time, the streetlight landscape has changed significantly, moving to mercury vapor lamps in the 1940s and high pressure sodium lamps by the 1970s. To this day high pressure sodium lamps are a tough competitor in both in terms of efficiency and low cost, and are still by far the most commonly used streetlight technology.

4.1.1 LED Streetlight Penetration

As seen in Figure 4.1, the number of LED streetlight installations has been steadily climbing since 2010. Increasing from a little over 0.2 million luminaires, or about half a percent of the total U.S. installed streetlights in 2010 to one million in 2012 representing a little over two percent of all installations. Note that the LED installed stock value for 2010 is less than the value reported in the LMC, which has been revised down due to new data provided by the Consortium.

[48] San Francisco, CA: http://sfwater.org/bids/projectDetail.aspx?prj_id=270
[49] Oakland, CA: http://oaklandlocal.com/article/city-council-approves-contract-led-streetlight-conversion
[50] San Antonio, TX: http://www.energymanagertoday.com/cps-energy-retrofits-20000-street-lamps-to-led-087890/
[51] Seattle, WA: http://www.seattle.gov/light/streetlight/
[52] Portland, OR: http://www.energymanagertoday.com/portland-gets-led-streetlights-088034/

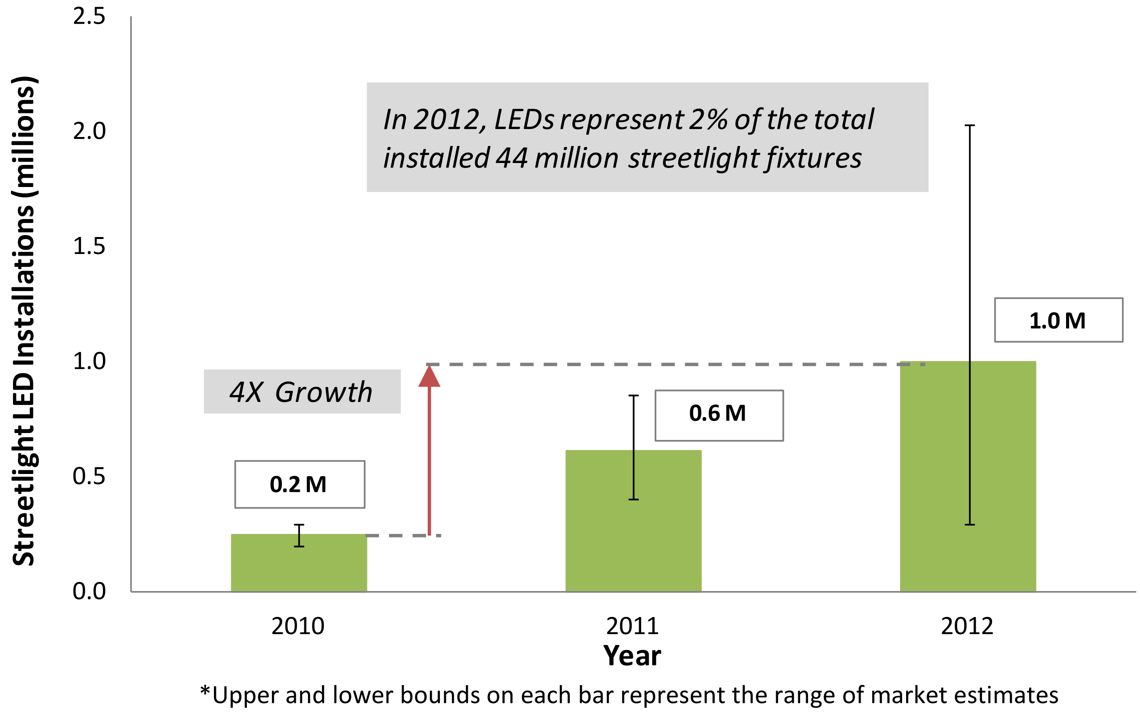

Figure 4.1 – Installed Base Estimates for LED Streetlight Luminaires[53,54]

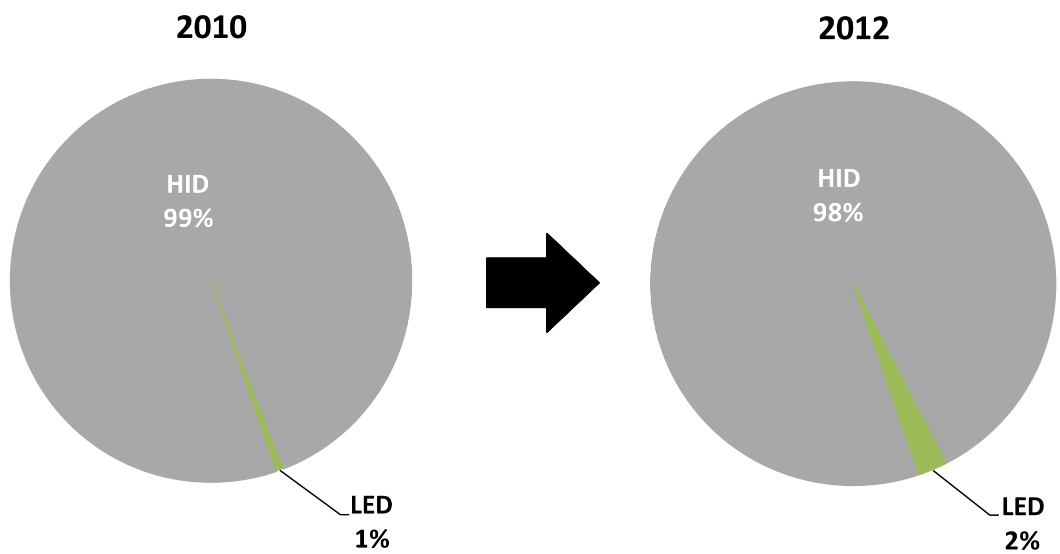

Figure 4.2 – Streetlight Luminaire Installed Base

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[53] Unlike many of the other applications 2009 figures are not provided. This is primarily due to lack of data from years prior to 2010, however it is fair to assume that LED installations prior to 2010 are negligible.

[54] The LED streetlight estimates shown above are a revision to the number previously estimated in the 2010 U.S. Lighting Market Characterization report. For more details on the 2010 U.S. Lighting Market Characterization report please visit: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

The installed base of all streetlighting has increased slightly from about 43 million fixture installations in 2010 to nearly 44 million in 2012. Since their introduction in the 1970s, HPS fixtures have held the majority of streetlight installations, and represent over 80 percent of all U.S. streetlights. Over the past two years there has been little change to the streetlight technology mix, however, there has been a slight increase in the number of metal halide and LED luminaires, while installations of HPS, LPS, and mercury vapor have seen somewhat of a decline.

4.1.2 LED Streetlight Energy Savings

The total source energy use of streetlight luminaires was about 452 tBtu in 2012. LEDs are currently saving 3.5 tBtu each year, but a complete technology switch to LEDs would more than cut the energy consumption in half, saving 238 tBtu per year. This potential savings equates to an annual energy cost savings of $2.3 billion.

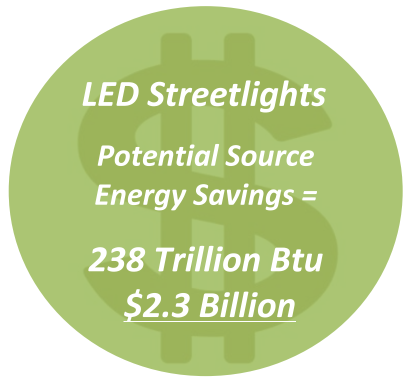


Table 4.1 – Energy Consumption and Savings Potential of LED Streetlights

 Streetlights	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
2012	1.0	452 (43.5)	3.5 (0.3)	238 (22.9)

4.2 Parking Luminaires

In this analysis, parking lighting only includes off-street parking and has been divided into covered parking garage lighting and parking lot lighting. Parking garages and lots face unique issues concerning their lighting. The near constant vehicle traffic in garages creates particularly harsh operating conditions, with high levels of vibration. And public safety concerns demand that lamps produce a high quality light with a low probability of failure. Given these operating conditions, the type of lighting used for parking lots closely mimics the technologies used for streetlight. This application is dominated by HID light sources such as mercury vapor, high pressure sodium, and metal halide lamps because they offer high efficacy, operate effectively for a wide temperature range, and produce high lumen output enabling them to be mounted on widely spaced poles. While HID lamps are also used for lighting parking garage structures, the low mounting heights of these facilities typically require a large number of fixtures in order to reach the desired illumination distribution. These conditions favor fluorescent lighting, which offers a relatively low cost, high efficiency, and long life.

CALiPER testing conducted back in 2009 and 2010 revealed that many LED parking garage and lot fixtures already met or exceeded the light output and efficacy levels of their metal halide, high-pressure sodium, and induction counterparts, while also displaying more uniform light distribution.[55] Some facilities also view LEDs relatively high CRIs as welcome replacements for the poor quality of light that some incumbent technologies emit. LEDs are also well suited for operating in a wide temperature range, unlike fluorescent lamps which can have difficulty starting in extreme cold temperatures. Because of this, LEDs are becoming more and more popular in parking applications as their long lifetime helps facility managers reduce costly lamp replacements.

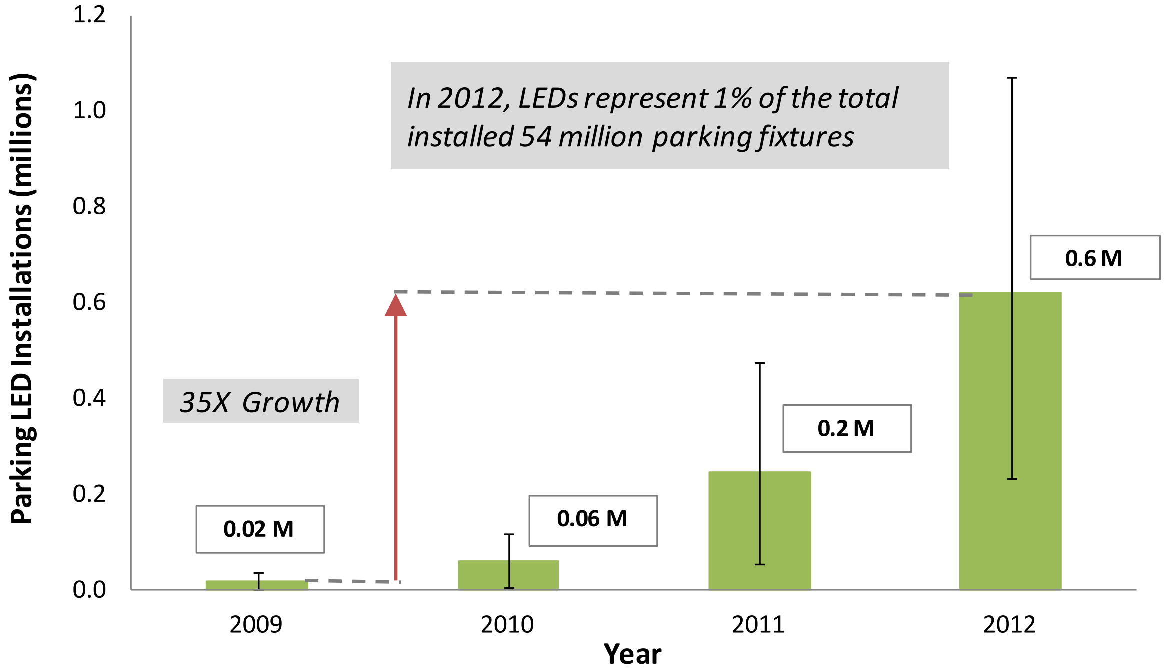
Furthermore, LED technology has enabled the combination of motion detection equipment with parking lot and garage lighting because it offers instantly variable output without the adverse effects of some traditional products such as long restrike and warm-up times. The combined use of lighting controls with LED technology has opened the door to even greater potential energy savings as well as enhanced security, and reduced light pollution. One of the most recent GATEWAY studies investigated the use of occupancy sensors with at two parking structures and two parking lots revealing that these combined systems have the ability to provide an additional 76% in energy savings compared to traditional high pressure sodium systems.[56]

4.2.1 LED Parking Luminaire Penetration

Shown in Figure 4.3 is DOE's estimate for the installed base of LED parking luminaires both in garage and lot installations from 2009 to 2012. In 2009, the installed stock was basically negligible; however, LED penetration has grown increasing the number of installations to over 0.6 million in 2012. This represents about a 35x growth rate.

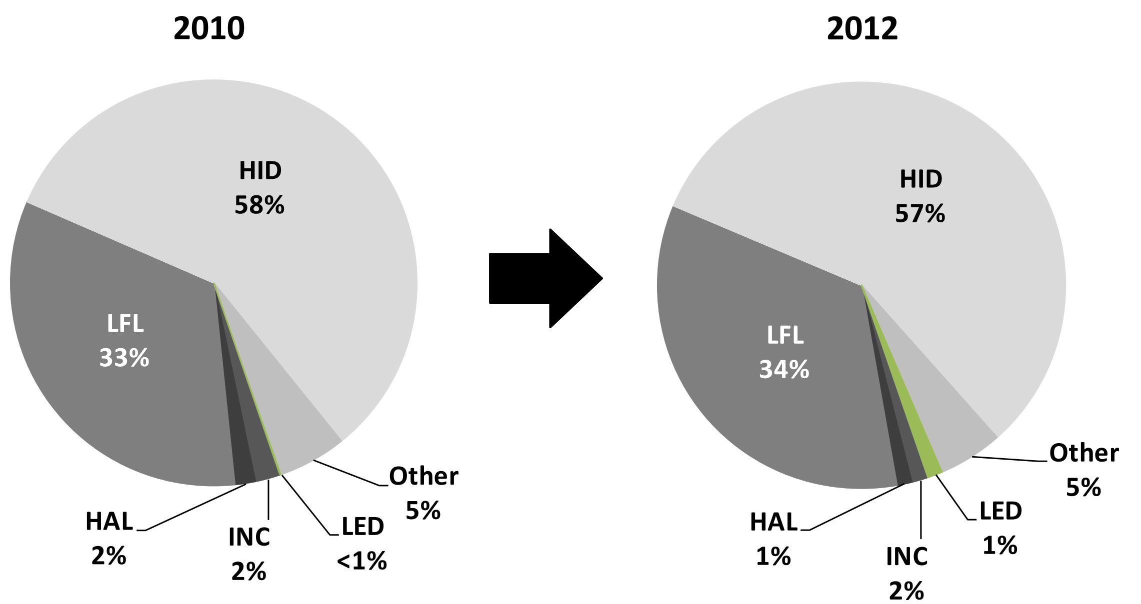
[55] DOE, Solid-State Lighting Program, "Where Can We Use SSL Today?" http://www1.eere.energy.gov/buildings/ssl/where_ssl_today.html

[56] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway_sensors.pdf



*Upper and lower bounds on each bar represent the range of market estimates

Figure 4.3 – Installed Base Estimates for LED Parking Luminaires[57]



*Values less than 0.1% are considered negligible

Figure 4.4 – Parking Luminaire Installed Base

[57] The LED parking estimates shown above are a revision to the number previously estimated in the 2010 U.S. Lighting Market Characterization report. For more details on the 2010 U.S. Lighting Market Characterization report please visit: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

Based on the projected 2010 U.S. lighting inventory data, in 2012 there were about 54 million parking light luminaires of which about 38 million were installed in parking garages and the remaining 16 million were in parking lots. The majority of parking lighting is near equally divided between metal halide, HPS, and linear fluorescent fixture installations. The fluorescent fixtures are predominately installed in garage applications, while metal halide and HPS are used in both parking application types. The above Figure 4.4 indicates that there has been little transition between lighting technologies from 2010 to 2012 however there has been a slight increase in LED installations while all other lighting types have seen a small decrease.

4.2.2 LED Parking Luminaire Energy Savings

From 2010 to 2012, the total source energy consumption of LED parking luminaires has increased from about 573 to 622 tBtu. LED parking installations are still emerging and it is estimated that the 0.6 million LED luminaires installed saved about 5.1 tBtu in 2012. Table 4.2 depicts the total energy consumption of parking lot and garage installations and the potential energy savings if the entire installed base was converted instantaneously to LED. A potential source energy savings of 370 tBtu per year would be realized if LEDs achieved complete and immediate market penetration. This equates to an annual energy cost savings of $3.5 billion.

Table 4.2 – Energy Consumption and Savings Potential of LED Parking Luminaires

2012	LED Installed Base Units millions	Total Energy Consumption Source– tBtu (Site – TWh)	LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
 Parking Garage	0.4	267 (25.7)	3.5 (0.3)	144 (13.8)
 Parking Lot	0.2	355 (34.2)	1.6 (0.2)	226 (21.8)
Total	**0.6**	**622 (59.9)**	**5.1 (0.5)**	**370 (35.6)**

5. Conclusion

Over the past decade, LEDs have emerged as a competitive lighting technology, capturing market share in several general illumination applications from traditional light sources. Although LED light sources have higher upfront costs, these costs continue to decrease and in many applications this is offset by reduced electricity and maintenance costs over the lamp's lifetime. For example, one of DOE's most recent GATEWAY demonstrations at the Smithsonian American Art Museum in Washington, DC, involved replacing 82 incandescent and halogen lamps with LED MR16 and PAR30 lamps, saving the museum approximately $28,000 over ten years. This lifetime cost savings was achieved despite the fact that the LED MR16 and PAR30 lamps cost nearly ten times more than the conventional halogen lamps they replaced.[58] Substitutions like these are taking place, without subsidies or coupon schemes, because LEDs can make financial sense and have the ability to offer customers a better quality, more reliable lighting service.

The applications evaluated in this report cut across indoor lamp and luminaire as well as outdoor luminaire installations. For the baseline year of 2012, it was found that the installation of LEDs has increased since 2010 in all of the nine applications identified for this analysis. In 2012, the installed stock of nearly 20 million LED A-type lamps saved approximately 22 tBtu due to the replacement of highly inefficient incandescent lamps. LED directional lamps which include PAR, BR, and R lamp shapes, represent the greatest energy savings of any of the applications analyzed, saving about 24 tBtu in 2012. Energy savings have also been realized through the replacement of traditional halogen MR16 lamps. The flexible form factor and inherent directionality of LEDs give them distinct advantages in this lighting application leading to an energy savings of approximately 3.7 tBtu. The replacement of traditional decorative incandescent lamps with LED globe and candelabra lamps has also resulted in energy savings. LEDs in this application saved about 1.4 tBtu in 2012. Combined the installation of LED indoor lamps in each of these four applications have saved about 51 tBtu. If all the indoor lamp applications evaluated in this report switched entirely to LEDs, a potential of nearly 1,358 tBtu per year could be saved, equivalent to an energy cost savings of $13 billion per year.

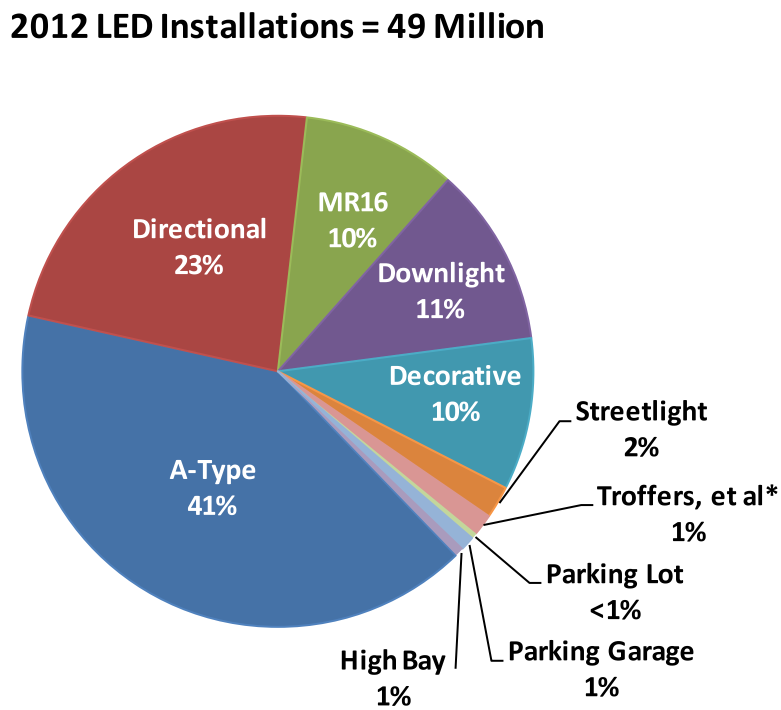
For indoor luminaire installations, LED products face tough competitors, namely highly efficient linear fluorescent and HID lamps. However, significant performance and efficacy gains as well as cost reductions have enabled LEDs in downlight, troffer et al., and high-bay applications to gain significant ground. Combined the total installations of indoor LED luminaires has increased by a factor of eleven from 2010 to 2012. In 2012, approximately 9.3 tBtu of energy were saved because of the installation of LED downlights that have replaced incumbent incandescent, halogen and even CFL technologies. Energy savings have also been realized through LED troffer et al. and high-bay fixture replacements, which combined save approximately 2.4 tBtu per year.

[58] GATEWAY Demonstration of LED Retrofit Lamps, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway_smithsonian.pdf

These indoor luminaire applications have the greatest potential of all the applications studied in this report to save substantial amounts of energy. If these three applications switched entirely to LEDs, an annual potential energy savings of nearly 1,907 tBtu would be possible, equivalent to an energy cost savings of over $18 billion.

The benefits of LEDs in outdoor luminaire installations were recognized earlier than any other of the other applications analyzed in this report. This is because LEDs are particularly advantageous in outdoor lighting applications due to the fact that their inherent characteristics address many of the key issues associated with outdoor lighting. LEDs offer extremely long lifetimes, are directional light sources, and thus able to limit light pollution and light trespass, are highly efficacious, function well in cold temperatures, are not affected by vibration, and are able to provide a high quality light. In 2012, approximately 3.5 tBtu of energy were saved because of the installation of LED streetlights that have replaced incumbent HID technologies. LED parking lot and garage lamps have saved even more energy at approximately 5.1 tBtu per year. If the entire installed stock of streetlight and parking garage and lot fixtures switched entirely to LEDs, a potential of 608 tBtu per year could be saved, equivalent to an energy cost savings of $5.8 billion.

In 2012, about 49 million LEDs were installed in indoor lamps, indoor luminaires, and outdoor luminaires applications. Figure 5.1 depicts the relative LED installations within each of the nine applications analyzed in this report as well as a comparison the baseline energy savings in 2012.



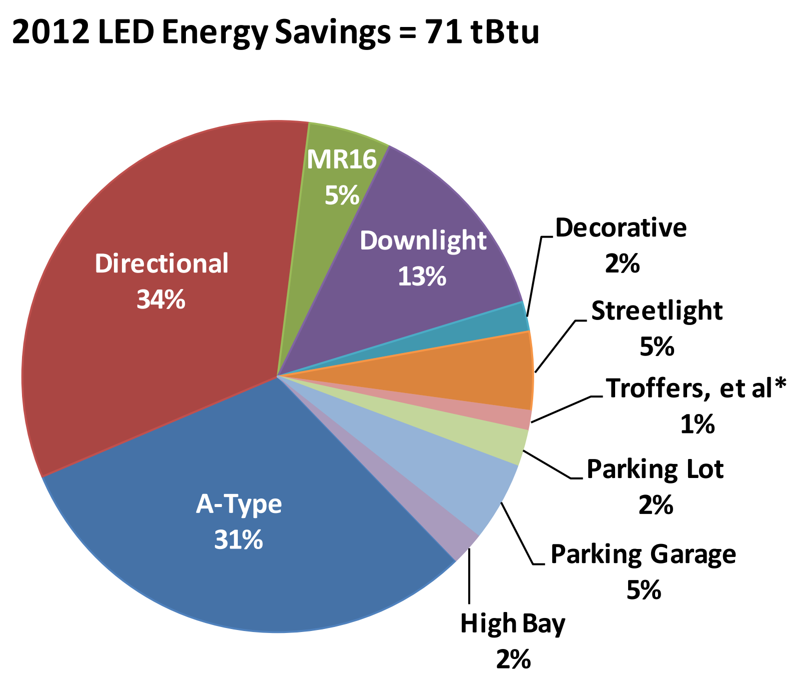


Figure 5.1 – Total 2012 LED Unit Installations and Energy Savings by Application
*Includes other common troffer fixtures see section 3.2

These two figures have many similarities. LED A-type, directional, MR16, and downlights, provide the majority of unit installations about 42 million units as well as energy savings about 61 tBtu in 2012 or about 85 percent of the total in each case. However, LED directional lamps are providing the greatest energy savings of any of the nine applications even though there are more LED A-type installations. This is because LED directional lamps, including PAR, BR, and R lamps, are largely installed in commercial buildings, which have significantly longer operating hours, compared to LED A-type lamps which are split equally between residential and commercial installations. This operating hour distinction enables the 11.4 million directional lamps, which comprise 23 percent of all LED installations to provide 24 tBtu of energy savings per year or 34 percent of the total LED energy savings realized for 2012. The penetration rate of LED directional lamps is also one of the greatest, with an estimated 4.6 percent of all directional sockets having LED installations.

As discussed above, the second most significant energy saving market in 2012 is LED A-type lamps, which contributed to about 31 percent of the total electricity savings, and represent the majority of all LED installations at about 41 percent. LED downlight fixtures and MR16 lamps also provide considerable energy savings, combined representing about 18 percent of the total and accounting for a near equivalent percentage of the total installations at 21 percent. LED MR16 lamps also have the highest LED penetration rate of any application analyzed in this report and represent about 10 percent of all MR16 installations in the U.S. The other applications including decorative lamps as well as troffer et al., high-bay, parking and streetlight luminaires account for about 18 percent of the 2012 energy savings and about 15 percent of the total unit installations.

The next figure, Figure 5.2, apportions the energy savings if these nine markets convert entirely to LED technology. This total represents the 2012 potential energy savings if the remainder of each market converts to LED lamps or luminaires.

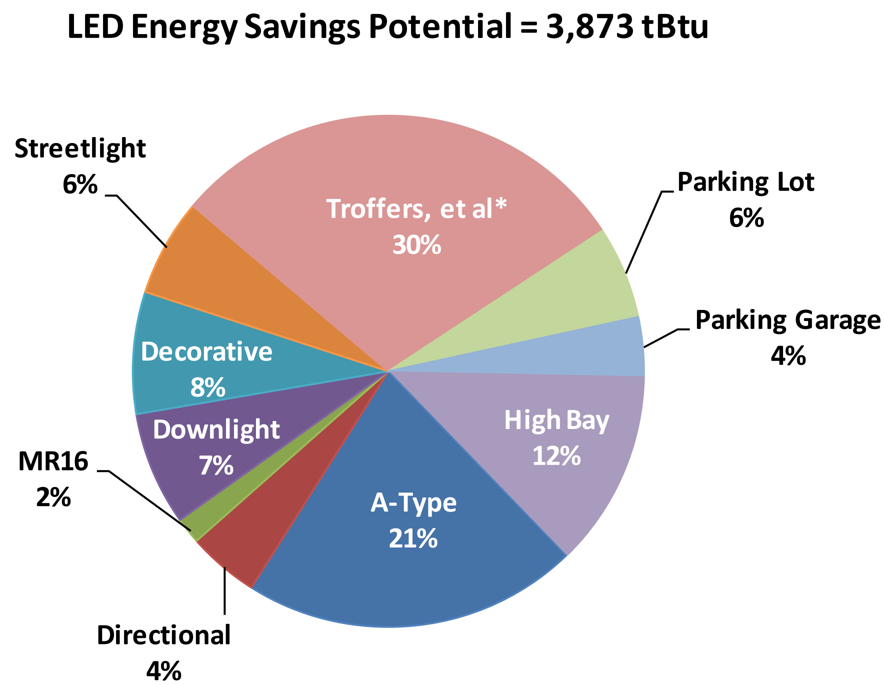
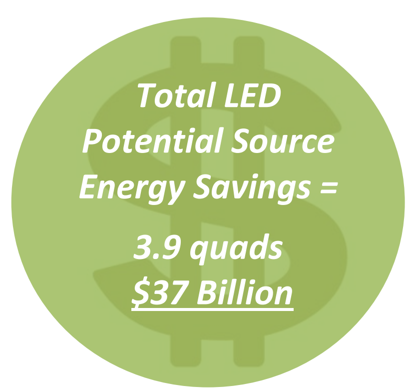


Figure 5.2 – Potential Energy Savings With 100% LED Market Penetration
*Includes other common troffer fixtures see section 3.2

There are significant opportunities for energy savings across the markets analyzed within the indoor lamp, indoor luminaire, and outdoor luminaire applications. A total of savings of about 1,146 tBtu per year are available in troffer and other common fluorescent fixture applications followed by 822 tBtu in A-type, and 483 tBtu in high-bay. The high potential for LED lighting in troffer et al. and high-bay applications stems from the vast efficiency improvements seen in both of these luminaire products as well as the significant number of fixtures available for replacement and the high average operating hours. A-type lamps still hold significant energy savings potential due to the sheer number of lamp installations within this application. Well over three billion A-type sockets are available for replacement with LED A-type products. Combined, LED troffer and high-bay fixture and A-type lamp applications represent 63 percent of the total estimated energy saving potential.



The remaining energy savings potential, about 37 percent, is available within the decorative, directional, and MR16 lamp and downlight, streetlight, and parking luminaire applications. If all of these opportunities are fully realized within each of the nine applications the consumption of 3,873 tBtu or about 3.9 quads of energy per year could be avoided saving nearly $37 billion in energy costs. This amount represents approximately half of the total national lighting energy consumption in 2012. Table 5.1 summarizes the 2012 energy savings in detail, both on-site electricity consumption and source energy consumption.

Table 5.1 – Installations and Energy Consumption and Saving by Application

Applications	Unit Installations millions	LED Penetration %*	Total Application Energy Use Source– tBtu (Site – TWh)	2012 LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
Indoor Lamp					
A-Type	19.9	<1%	1,057 (101.8)	22 (2.1)	822 (79.1)
Directional	11.4	4.6%	195 (18.7)	24 (2.3)	174 (16.7)
MR16	4.8	10%	70 (6.7)	3.7 (0.4)	65 (6.2)
Decorative	4.7	<1%	367 (35.4)	1.4 (0.1)	298 (28.7)
Indoor Luminaire					
Downlight	5.5	<1%	382 (36.8)	9.3 (0.9)	278 (26.8)
Troffers, et at**	0.7	0%*	2,374 (228.6)	0.9 (0.1)	1,146 (110.4)
High-Bay	0.3	<1%	1,096 (105.6)	1.5 (0.2)	483 (46.5)
Outdoor Luminaire					
Streetlight	1.0	2.3%	452 (43.5)	3.5 (0.3)	238 (22.9)
Parking	0.6	1.2%	622 (60.0)	5.1 (0.5)	370 (35.7)
Total	**48.8**	--	**6,614 (637.1)**	**71 (6.8)**	**3,873 (373.1)**

* Values less than 0.1% are considered negligible

**Includes other common troffer fixtures see section 3.2

In a way, this potential savings estimate is understated, because it fixes the theoretical replacement LED technology at the peak 2012 performance levels (see Table 1.2). 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 likely have better performance characteristics, and contribute to even more significant energy savings.

Appendix A **Most Efficacious LED Products**

Table A.1 – Most Efficacious LED Products from the DOE's Lighting Facts Database[59]

	LED Replacement Criteria		Performance		
Application	**Manufacturer**	**Product Description**	**Wattage (W)**	**Lumens (lm)**	**Efficacy (lm/W)**
A-type	Philips Lighting	L-Prize Winner A-Type	10.0	940	94
Directional	Lumena SSL Inc.	PAR38 replacement	13.7	1,226	89
MR16	Halco Lighting Technologies	MR16 25W replacement	6.5	500	77
Decorative	Philips Lighting	B12 Dimmable Candle	4.0	320	80
Downlights	Acuity Brands	6-inch downlight	11.6	1,026	88
Troffers, et al*	Cree	4-ft Linear Luminaire	34.6	4,139	119
High-Bay	LSI Industries Inc.	High-Bay Luminaire	196.7	21,686	110
Parking Garage	Kenall Lighting	Parking Garage Luminaire	54.7	5,814	106
Parking Lot	Cree	Flood/Area Luminaire	129.5	13,083	101
Streetlights	Kenall Lighting	Post-mounted Luminaire	108.9	12,019	110

*Includes other common fluorescent fixtures see section 3.2

[59] Most efficacious products were selected from the DOE's LED Lighting Facts list of qualified products on November 15, 2012, http://www.lightingfacts.com/content/products

Appendix B LED Attributes

In addition to energy savings, LED products offer other advantages over conventional lighting products. These advantages include: long operating life, reduced radiated heat, minimal light loss, dimmability and controllability, durability, enhanced performance at low temperatures, safety improvements, smaller package size, uniform illumination, mercury reduction, enhanced product appearance, improved color rendition, and lower lumen depreciation. These benefits are further discussed below.

Long Operating Life

Commercial and industrial consumers 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., busy highways and roadways). In fact, maintenance savings is one of the primary drivers of market adoption of LEDs in several markets, such as streetlights and parking lights. Presently, LED technology offers operating lives that are up to fifty times longer than those of incandescent sources.[60] Researchers indicate that operating life will continue to improve as the technology develops.

Reduced Radiated Heat

LED conversion efficiency (i.e., efficacy) has improved rapidly and is expected to continue; current LED devices meet or exceed efficacies of fluorescent and HID sources. As a higher proportion of electricity is converted into visible light, a smaller proportion generates waste heat. For example, incandescent sources convert most of the power they use into infrared (IR) radiation (radiated heat), which then dissipates to the surroundings. LEDs do not emit IR (unless specifically designed to do so); instead, the waste heat generated by the LED must be removed by a 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

Conventional lamps generally have uniform emission in all directions, which can result in lower fixture efficiencies due to the light is lost as the light is absorbed in the back of the fixture. Light emitted from an LED device is more directional and controlled, meaning that fewer photons are trapped within the lighting fixture. LED sources can be targeted to illuminate particular parts of an object or area. For example, LED MR16 lamps can be targeted to illuminate particular parts of a retail display with higher fixture efficiencies and less light scattering. In outdoor applications, the directional quality of LEDs can also reduce light pollution. In comparison with

[60] Based on manufacturers' claims of 50,000-hour LED lifetimes.

conventional light sources, through the use of lenses and lighting controls LED streetlights and parking luminaires direct more lumens to the road plane or ground and scatter fewer lumens skyward.

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. LED A-type replacements have also recently become commercially available, and unlike compact fluorescent lamp (CFL) alternatives offer dimming capabilities similar to that of conventional incandescent lamps. However, LED A-type lamps are not compatible with all dimmer controls designed for incandescent lamps. As LED lighting becomes more common for household applications, fully integrated LED dimming controls may become a reality in new construction with the potential to save even more energy in the future.

Durability

The light production mechanism for LED devices is fundamentally different than those of traditional light sources, such as incandescent and fluorescent lamps. 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 streetlight and parking light applications. The LED is encased in a tough epoxy plastic resin instead of a fragile glass bulb. Therefore, the device is more resistant to shattering or impact damage in these applications.

Enhanced Performance at Low Temperatures

LED performance inherently improves as operating temperatures drop. This gives LED outdoor lighting an advantage over other light sources as its efficacy increases when exposed to winter weather conditions. It should also be noted that due to their reduced radiated heat, LEDs do not automatically melt away snow and ice, and this needs to be considered when installing LEDs in winter weather conditions.

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 downtime for streetlighting, and thereby enhancing roadway safety.

Smaller Package Size

Due to their compact size, LED devices are an excellent option where size or weight is a concern. For example, unlike compact fluorescent technology, LEDs and be designed for decorative lighting applications as well as MR16 lamps which have a very space constraining form factor. This is because the LED and driver system is much smaller than a CFL and integrated ballast system.

Mercury Reduction

Fluorescent lamps and CFLs contain mercury, a toxic substance that requires special handling for disposal. CFLs contain an average of 4 milligrams (mg) of mercury (EPA ENERGY STAR® (a), 2010); in contrast, LEDs contain no mercury and require no special handling for disposal.

Enhanced Product Appearance

LED lamps are ideal for retail lighting due to their directional control and minimal heat radiation. Additionally, jewelry lit by LED lamps appears 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.

Improved Color Rendition

Most LED outdoor area and streetlights in the market have color temperatures of 3,000 to 6,000 Kelvin (K) and can have color rendering indices (CRI) of approximately 90. With these color characteristics, LED outdoor area and streetlights compare favorably with high pressure sodium (HPS) lamps that have color temperatures of approximately 2,000 K, providing a yellow/orange light, and color rendering indices as low as 21 (CALiPER, 2010).

Appendix C Legislation Affecting the Lighting Market

The Energy Independence and Security Act of 2007 (EISA 2007) establishes energy conservation standards for general service and modified spectrum incandescent lamps for rated lumen ranges, maximum rated wattage, and minimum rate lifetime, effective January 1, 2014. In effect, these standards establish minimum wattage requirements for general service lamps. For example:

- A lamp with the equivalent lumen output of a traditional 100 W lamp (1490-2600 lumens) must only draw 72 W;
- A lamp with the equivalent lumen output of a traditional 75 W lamp (1050-1489 lumens) must only draw 53 W;
- A lamp with the equivalent lumen output of a traditional 60 W lamp (750-1049 lumens) must only draw 43 W;
- A lamp with the equivalent lumen output of a traditional 40 W lamp (310-749 lumens) must only draw 29 W.

These efficiency requirements are phased in between 2012 and 2014 and require the efficacy of all general service incandescent lamps be 45 lm/W or greater starting in 2020. EISA 2007 also mandates energy savings standards incandescent reflector lamps. The 2009 Final Rule for incandescent reflector lamps applies to lamps manufactured on or after July 14, 2012 and prescribes minimum efficacy standards for products in the 40-205 Watt range, determined by lamp spectrum, lamp diameter, and rated voltage. These standards promote the adoption of higher efficiency reflector lamp products including halogen infrared (IR) lamps, CFLs, and LED replacement lamps. Halogen IR lamps are more expensive than standard halogen lamps on the market today (gas mixtures and IR capsules largely contribute to increased cost), which increases the competitiveness of CFLs and LEDs in directional lamp applications.

Lastly, in a 2009 Final Rule, the DOE also established energy conservation standards for general service fluorescent lamps (GSFLs). These standards apply to GSFLs manufactured on or after July 14, 2012 and set energy efficiency requirements that affect 4-foot and 8-foot T5,[61] T8,[62] and T12 linear fluorescent lamps and 2-foot U-Shaped fluorescent lamps. The 2009 Final Rule has helped propel the transition to higher efficiency fluorescent lamps and have basically eliminated the sale of T12 lamps.

[61] T5 fluorescent lamps are not produced in 8-foot lengths.

[62] On April 16, 2012 the Office of Hearings and Appeals (OHA) issued a decision granting relief from the 2009 Final Rule for 700 series T8 fluorescent lamps, http://energy.gov/oha/downloads/exc-12-0001-exc-12-0002-exc-12-0003-matter-philips-lighting-company. This exception is not expected to have an impact on the transition from T12 to T8 GSFLs.