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Adoption of Light-Emitting Diodes in Common Lighting Applications

Prepared for the U.S. Department of Energy
Solid-State Lighting Program

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Prepared by Navigant

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Disclaimer

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Executive Summary

This 2017 report presents the findings for major general illumination lighting applications where light-emitting diode (LED) products are competing with traditional light sources. The lighting applications selected for this study include: A-type, decorative, directional, small directional (MR16), downlighting, linear fixtures, low/high bay, area/parking lot, parking garage, street/roadway, and building exterior. To estimate how LED lighting penetration has changed in 2016, *U.S. DOE Lighting Market Model* is used as the foundation and analytical engine for this study. The following three scenarios were developed to estimate the cumulative installed penetration[1] of LED technology, the resulting energy savings, and the technical potential for LED and connected lighting systems in 2016.

No-SSL A hypothetical scenario that assumes LED technology never entered the lighting market. LED lamps and luminaires are not available for competition, only conventional incandescent, halogen, fluorescent and HID sources. The "No-SSL" scenario is used as the reference condition from which LED and connected lighting systems are calculated.

2016 LED Adoption The estimated actual 2016 energy savings due to the existing installed stock of LED lamps, retrofit kits and luminaires, and connected lighting systems.

2016 Energy Savings Potential The theoretical energy savings if 100% penetration was achieved with LED products that are enabled with connected lighting systems and represent the top 95th percentile of efficacy based on products available in 2016.

The 2016 LED Adoption scenario estimates the U.S. lighting inventory in general illumination applications for 2016, including LED lighting, connected lighting controls and conventional lighting technologies. The 2016 Energy Savings Potential scenario represents the technical potential of LED lighting and connected controls based on 2016 performance levels. The hypothetical "No-SSL" scenario, as indicated above, is used as a reference condition from which SSL energy savings are calculated for both the 2016 LED Adoption and 2016 Energy Savings Potential scenarios. In the "No-SSL" scenario, LED products are assumed to have never entered the general illumination market, but all other market conditions, such as energy conservation standards for conventional technologies, are unchanged.

For both the 2016 LED Adoption and 2016 Energy Savings Potential scenarios, connected lighting systems are assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate with each other and transmit data.

The additional potential savings for connected lighting systems is estimated separately, and represents additional savings beyond those achieved through LED lighting efficacy improvement alone.

The summary results for the 2016 LED Adoption and 2016 Energy Savings Potential are provided below in Table ES.1.

[1] Cumulative installed penetration refers to the installed inventory of LED lighting products relative to the installed inventory of all other lighting technologies.

Table ES.1 – 2016 LED Lighting Installations and Energy Savings by Application

Application	2016 LED Adoption			2016 Energy Savings Potential (tBtu)
	2016 LED Installed Penetration (%)	2016 LED Units Installed[1] (Millions)	2016 LED Energy Savings (tBtu)	
A-Type	13.5%	436	99.1	491
Decorative	6.7%	58.9	10.3	283
Directional	15.3%	82.4	37.9	129
Small Directional	47.6%	21.0	35.6	58.9
Downlighting	19.8%	137	92.5	231
Linear Fixture	6.0%	68.0	62.0	432
Low/High Bay	9.4%	8.6	46.4	373
Total Indoor	**12.3%**	**812**	**384**	**1998**
Street/Roadway	28.3%	12.5	14.9	106
Parking Garage	32.5%	8.5	14.4	79.5
Parking Lot	26.2%	7.1	18.6	124
Building Exterior	31.2%	18.1	14.0	36.1
Total Outdoor	**29.7%**	**46.1**	**61.9**	**346**
Other	7.7%	15.6	12.4	109
Connected Controls	**<0.1%**	**4.0**	**11.4**	**1974**
Total All	**12.6%**	**874**	**469**	**4428**

1. Installations are the total cumulative number of all LED lighting systems that have been installed as of 2016.

The major findings of the analysis include the following:

- From 2014 to 2016, installations of LED products have increased in all applications, more than quadrupling to 874 million units, increasing penetration to 12.6% of all lighting.
- A-type lamps represent nearly half of all LED lighting installations, and have increased to an installed penetration of 13.5% in this application. In 2016, penetration of LED lighting into linear fixture applications represents the lowest of all general illumination applications; however, it has increased from 1.3% in 2014 to 6.0% in 2016. Penetration of connected lighting controls remains small, with only less than 0.1% of lighting installed with these systems in 2016.
- In the outdoor sector, parking garages are estimated to have the highest penetration of LED lighting at 32.5% in 2016. In 2016, when comparing indoor versus outdoor applications, LED lighting has a higher penetration in outdoor applications, at 29.7%, compared to indoor applications where LED lighting has a total penetration of 12.3%; however, the indoor LED lighting penetration estimate is heavily skewed by A-type lamp installations.
- The increased penetration of LED lighting in 2016 provided approximately 469 trillion British thermal units (tBtu) in annual source energy savings, which is equivalent to an annual cost savings of about $4.7 billion.

- Annual source energy savings could approach 2,454 tBtu, about 2.4 quadrillion Btu (quads), if top tier 2016 LED products instantaneously reach 100% penetration in all applications. If these same top tier products were also configured with connected lighting controls, they would enable an additional 1,974 tBtu of energy savings for a total of 4,428 tBtu or 4.4 quads. Energy savings of this magnitude would result in an annual energy cost savings of about $44 billion.

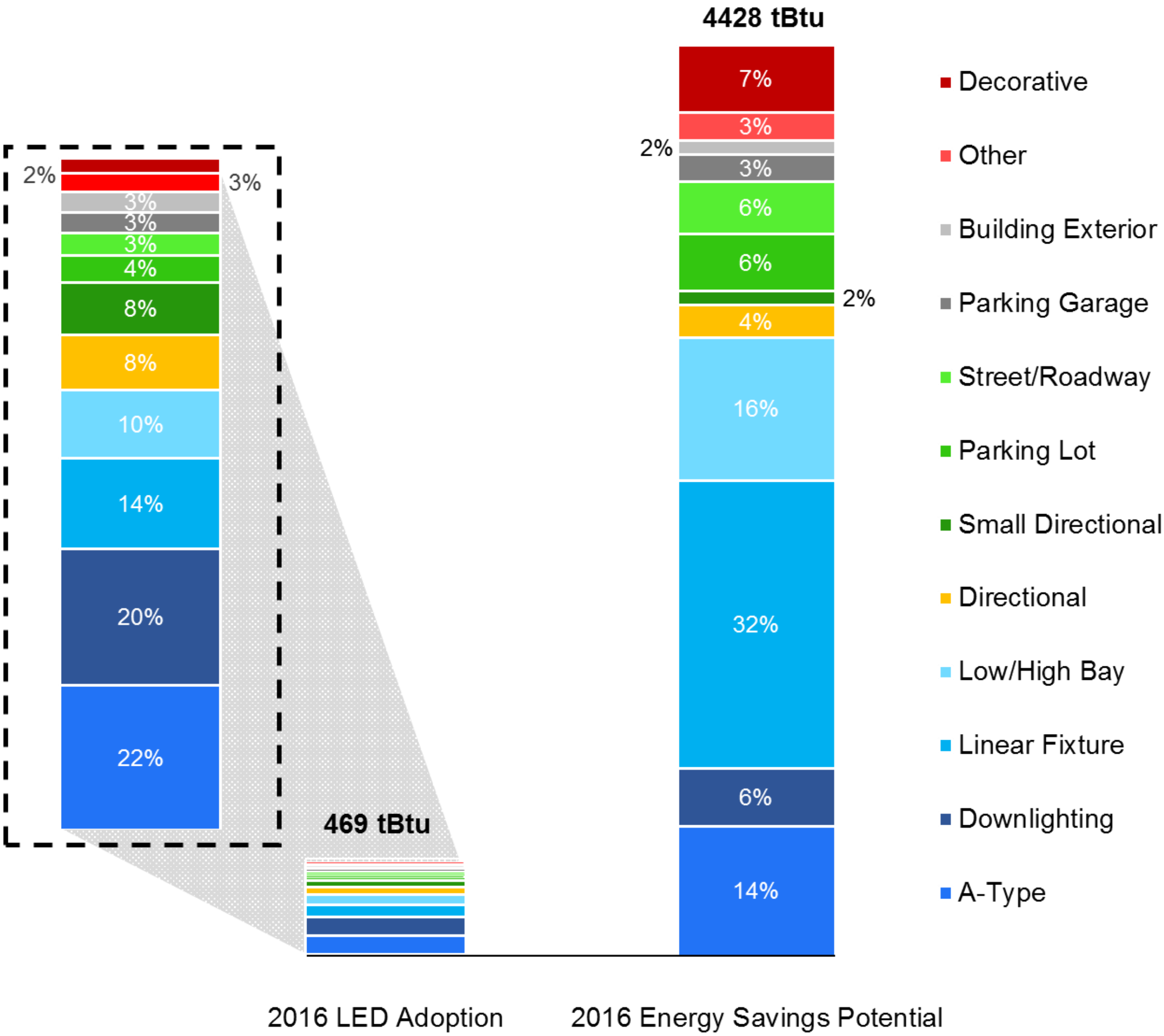

Figure ES.1 – Comparison of 2016 and Potential Energy Savings from LED Lighting

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1 Introduction

Light-emitting diodes (LEDs), a type of solid-state lighting (SSL), are revolutionizing the lighting market. LED lighting has surpassed many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and due to their increasing cost competitiveness LED products are beginning to successfully compete in a variety of lighting applications. The Department of Energy's (DOE) 2016 study, *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, (hereafter referred to as the DOE SSL Forecast) forecasts that LED lighting will represent 86% of all lighting sales by 2035, resulting in an annual primary energy savings of 3.7 quadrillion British thermal units (quads). (1)

Since 2003, the U.S. Department of Energy (DOE) has evaluated the lighting applications where LED technologies is having the greatest energy savings impact. This assessment provides an update to the 2015 *Adoption of LEDs in Common Lighting Applications*[2] report, and investigates the 2016 adoption and resulting energy savings of both LED and connected lighting systems in general illumination applications. The lighting applications selected for this study include: A-type, decorative, directional, small directional (MR16), downlighting, linear fixtures, low/high bay, parking lot, parking garage, street/roadway, building exterior, and an "other" category, which includes indoor and outdoor lighting products that account for less common LED products and those that occupy unknown applications.

For each of the above listed applications, this report addresses the following four questions:

- In the year 2016, how much energy was consumed by lighting technologies?
- What is the 2016 estimated cumulative installed penetration[3] of LED lamps, retrofit kits, luminaires, and connected lighting systems?
- What are the actual energy savings resulting from the 2016 level of LED and connected lighting penetration?
- What would the theoretical energy savings be if 100% penetration was achieved with LED products that are enabled with connected lighting systems and represent the top 95th percentile of efficacy based on products available in 2016?

For this report, connected lighting systems are assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate with each other and transmit data. The energy savings for connected lighting systems is estimated separately and represents additional savings beyond those achieved through LED lighting efficacy improvement alone.

Furthermore, since the designs of LED lighting products vary significantly, products installed in each of the analyzed applications are classified as LED lamp replacements, retrofit kits or luminaires. In some applications, LED lamps, retrofit kits and luminaires are competing for market share, while in some there is only one product type. Typically, LED lamps and retrofit kits are designed to be direct replacements for existing incandescent, halogen and compact fluorescent lamps and function using the existing fixture and possibly the ballast. In contrast, LED luminaires represent a holistic change-

[2] The 2014 report is available at: http://energy.gov/sites/prod/files/2015/07/f24/led-adoption-report_2015.pdf
[3] Cumulative installed penetration refers to the installed inventory of LED lighting products relative to the installed inventory of all other lighting technologies.

out of the existing lamp, ballast and fixture system. Table 1.1 indicates which LED product types (lamps, retrofit kits and/or luminaires) are analyzed within each of the applications, provides a description, and includes example LED product images.

Table 1.1 Summary of LED Product Descriptions for Each Application Evaluated in 2016[4]

Application	Type	Description	Examples
A-type	Lamp	A-type lamp shapes with a medium-screw base.	
Decorative	Lamp and Luminaire	Bullet, candle, flare, globe, and any other decorative lamp shapes, as well as integrated chandelier, single head pendant, wall sconce, lantern, and cove luminaire products.	
Directional	Lamp and Luminaire	Reflector (R), bulged reflector (BR), and parabolic reflector (PAR) lamps, as well as track heads and integrated track luminaires.	
Small Directional	Lamp	Multifaceted reflector (MR) lamps.	
Downlighting	Lamp, Retrofit Kit and Luminaire	Reflector (R), bulged reflector (BR), and parabolic reflector (PAR) lamps used for downlighting, as well as, retrofit kits and integrated downlight luminaires.	
Linear Fixture	Lamp, Retrofit Kit and Luminaire	Lamp replacements for T12, T8 and T5 fluorescent lamps, as well as retrofit kits and luminaires replacing traditional fluorescent fixtures (i.e., troffers, linear pendants, strip, wrap around, and undercabinet).	
Low/High Bay	Lamp and Luminaire	High wattage lamp replacements as well as low and high bay integrated fixtures.	
Indoor Other	No Distinction	Lamps with uncommon base types (i.e., festoon, mini bi-pin, etc.), luminaires designed for portable, specialty and emergency applications (white), and rope/tape lights.	
Parking (Lot)	No Distinction	High wattage lamp replacements as well as luminaires used in parking lot and top deck parking garage illumination.	
Parking (Garage)	Lamp and Luminaire	Replacement lamps and luminaires for attached and stand-alone covered parking garages.	
Streetlights/ Roadway	No Distinction	Replacement lamps and luminaires installed in street and roadway applications.	
Building Exterior	No Distinction	Lamps and luminaires installed in façade, spot, architectural, flood, wall pack, bollard and step/path applications. Not including solar cell products.	
Outdoor Other	No Distinction	Lamps and luminaires used in signage, stadium, billboard (white) and airfield lighting.	

[4] Image Sources: Grainger and Home Depot Websites.

1.1 Analysis Enhancements

This iteration of the LED Adoption report improves upon past years' iterations in multiple ways. These enhancements are outlined below:

1. Addition of LED lamps, retrofit kits and luminaires into new and existing applications. In this study, the penetration of LED lamps, retrofit kits (where feasible) and luminaire products are tracked separately to more accurately describe competition with incumbent technologies. Several improvements have been made to the organization and tracking of the LED product categories, including, a greater disaggregation of LED lighting products for both downlighting and low and high bay applications. Due to increases in data quality, these product groupings can be disaggregated – downlighting separate from directional applications and high lumen output replacement lamps separate from indoor "other" applications.

   In addition, in previous iterations, lamps were the only product type evaluated within decorative applications, now because increased data granularity, decorative luminaires are included.

   Note that because of these enhancements, the LED lighting penetration results for 2016 may show inconsistencies with previous DOE SSL Program market analyses. All enhancements to LED product and application classifications are summarized in Appendix A.

2. Connected controls penetration and energy savings analysis. The results presented in DOE SSL Forecast report indicate that of the forecasted 5.1 quads in annual energy savings by 2035, one-third is made possible by the penetration of connected lighting systems. (1) Therefore, connected lighting provides a large opportunity for energy savings in the U.S., and it represents a significant portion of the technical potential. In previous analyses, connected LED products were not explicitly analyzed and the impacts of connected lighting were not included. Now, due to improvements made to the *U.S. DOE Lighting Market Model*, the penetration and energy savings for connected lighting systems can be evaluated.

   The energy savings from connected lighting represent the additional savings beyond those achieved through LED efficacy improvement alone. See Section 2.2 for more information.

3. Updated LED efficacy assessment. The data sources used to characterize the range of LED product efficacy performance have been updated to include the DOE's LED Lighting Facts®, DesignLight Consortium (DLC), and ENERGY STAR database. The range of 2016 LED product efficacy is then determined by calculating the 5^{th} percentile, average, and 95^{th} percentile for product available in 2016. Only tested (not rated) efficacy performance data are utilized. These metrics are calculated in each database for each of the evaluated lighting applications and averaged to determine the overall range of 2016 LED product efficacy. These improvements increase data population for the analysis, while the using the 5^{th} and 95^{th} percentile of tested efficacy eliminates the influence of outliers.

2 Analytical Approach

The *U.S. DOE Lighting Market Model*, described in the DOE SSL Forecast report, predicts LED market penetration and energy savings compared to conventional lighting sources – incandescent, halogen, fluorescent, and high-intensity discharge (HID) – in general illumination applications from present-day through 2035. (1) *U.S. DOE Lighting Market Model* is used as the foundation and analytical engine for this study. The following three scenarios were developed in the model to estimate the cumulative installed penetration[5] of LED technology, the resulting energy savings, and the technical potential for LED and connected lighting systems in 2016.

No-SSL A hypothetical scenario that assumes LED technology never entered the lighting market. LED lamps and luminaires are not available for competition, only conventional incandescent, halogen, fluorescent and HID sources. The "No-SSL" scenario is used as the reference condition from which LED and connected lighting energy savings are calculated.

2016 LED Adoption The estimated actual 2016 energy savings due to the existing installed stock of LED lamps, retrofit kits and luminaires, and connected lighting systems.

2016 Energy Savings Potential The theoretical energy savings if 100% LED penetration was achieved with LED products that are enabled with connected lighting systems and represent the top 95th percentile of efficacy based on products available in 2016.

The 2016 LED Adoption scenario estimates the U.S. lighting inventory in general illumination applications for 2016, including LED lighting, connected lighting controls and conventional lighting technologies. The 2016 Energy Savings Potential scenario represents the technical potential of LED lighting and connected controls based on 2016 performance levels. The hypothetical "No-SSL" scenario, as indicated above, is used as a reference condition from which SSL energy savings are calculated for both the 2016 LED Adoption and 2016 Energy Savings Potential scenarios. In the "No-SSL" scenario, LED products are assumed to have never entered the general illumination market, but all other market conditions, such as energy conservation standards for conventional technologies, are unchanged.

For both the 2016 LED Adoption and 2016 Energy Savings Potential scenarios, connected lighting systems are assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate with each other and transmit data.

The following Sections 2.1 and 2.2 explain the assumptions and methodology used to determine the resulting energy savings in the 2016 LED Adoption and 2016 Energy Savings Potential scenarios, respectively.

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[5] Cumulative installed penetration refers to the installed inventory of LED lighting products relative to the installed inventory of all other lighting technologies.

2.1 2016 LED Adoption

To estimate the energy savings for the 2016 LED Adoption, the *U.S. DOE Lighting Market Model* results presented in the DOE SSL Forecast report are used as a starting place to determine the 2016 lighting inventory. The *U.S. DOE Lighting Market Model* uses assumptions of projected efficacy, retail price, lighting control usage, and operating life to predict trends in lighting technology use – and ultimately provides estimates for the installed base of LED lighting as well as conventional lighting technologies.

The 2016 LED lighting outputs from the model are then updated and calibrated using sales and financial reports provided by manufacturers, retailers, industry experts, and utilities, in addition to shipment data from the National Electrical Manufacturers Association (NEMA), retailer point-of-sale (POS) and ENERGY STAR. As depicted in Figure 2.1, this data collection and interview process serves as the primary source for updating the 2016 outputs. All input provided by the contributing parties is kept confidential and is used to revise and calibrate the 2016 U.S. lighting inventory estimate. A list of contributing stakeholders is provided in the Acknowledgements Section of this report.

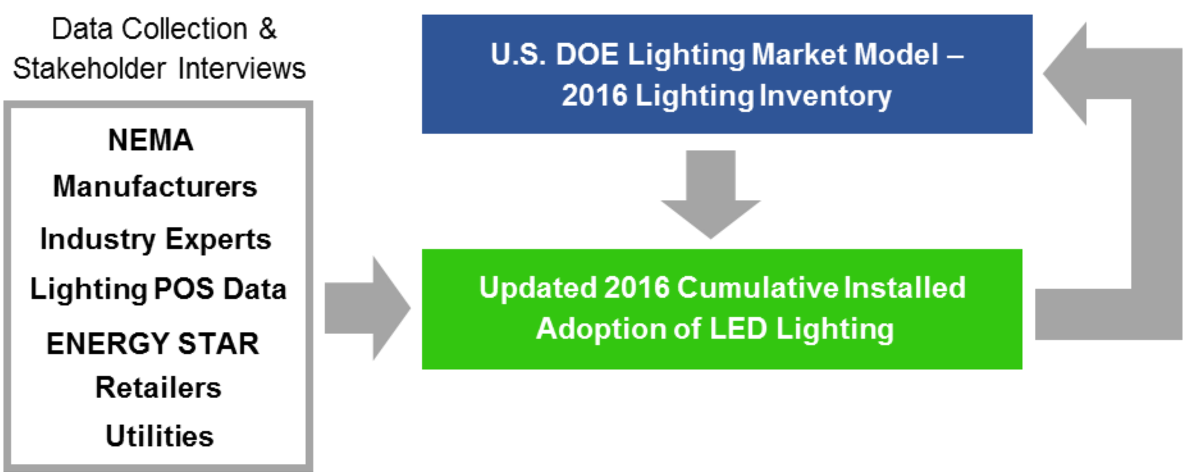

Figure 2.1 2016 LED Adoption Estimation Methodology

As indicated by Figure 2.1 above, the results discussed in this report are in terms of cumulative installations and not shipments of lighting products. As such, the LED lighting penetration in terms of cumulative installations is lower compared to its market share of unit shipments. The reason for this is twofold: (1) the total number of lighting products installed (i.e., the U.S. inventory of lighting) is significantly larger than the total number shipped each year – this is because the lifetime of lighting products in several applications exceeds one year; (2) the cumulative installed penetration of LED lighting increases as it replaces conventional lighting technologies. Therefore, when an existing LED product installed is replaced by a newer LED product, either due to failure or lighting upgrade, this results in no net-gain to the installed penetration of LED lighting. The significance of this phenomenon increases the longer a technology is available on the market and is effecting the cumulative installed stock of LED lighting.

Once the 2016 lighting inventory is determined, the model uses the "No-SSL" scenario to calculate the resulting LED energy savings. As previously mentioned, in the "No-SSL" scenario, LED products are assumed to have never entered the general illumination market, but all other market conditions, such as energy conservation standards for conventional technologies, are unchanged. Therefore, taking the difference in energy consumption of the "No-SSL" and 2016 LED Adoption scenarios best represents the resulting energy savings impact of LED lighting technology in general illumination applications.

The energy savings estimates for the 2016 LED Adoption scenario are highly dependent on which conventional technologies are replaced by LED lamps, retrofit kits and luminaires, as well as the installation and use of lighting controls and connected lighting systems. 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 taken from the *U.S. DOE Lighting Market Model*. LED products are assumed to have the same operating hours as the most energy efficient conventional lighting type within each of the applications. Average wattages for LED lamps, retrofit kits and luminaires were determined by averaging the performance of products listed in the DOE's LED Lighting Facts®, DesignLight Consortium (DLC), and ENERGY STAR database as available in 2016 (i.e., products added but not archived before December 31, 2016).[6] These updated LED product wattages used for each application are provided in Table 2.1.

More information on how the *U.S. DOE Lighting Market Model* analyzes lighting stock and energy savings is provided in the DOE SSL Forecast report. (1)

[6] More information on the DOE's LED Lighting Facts program, DLC, and ENERGY STAR can be found at: www.lightingfacts.com, https://www.designlights.org/ and https://www.energystar.gov/.

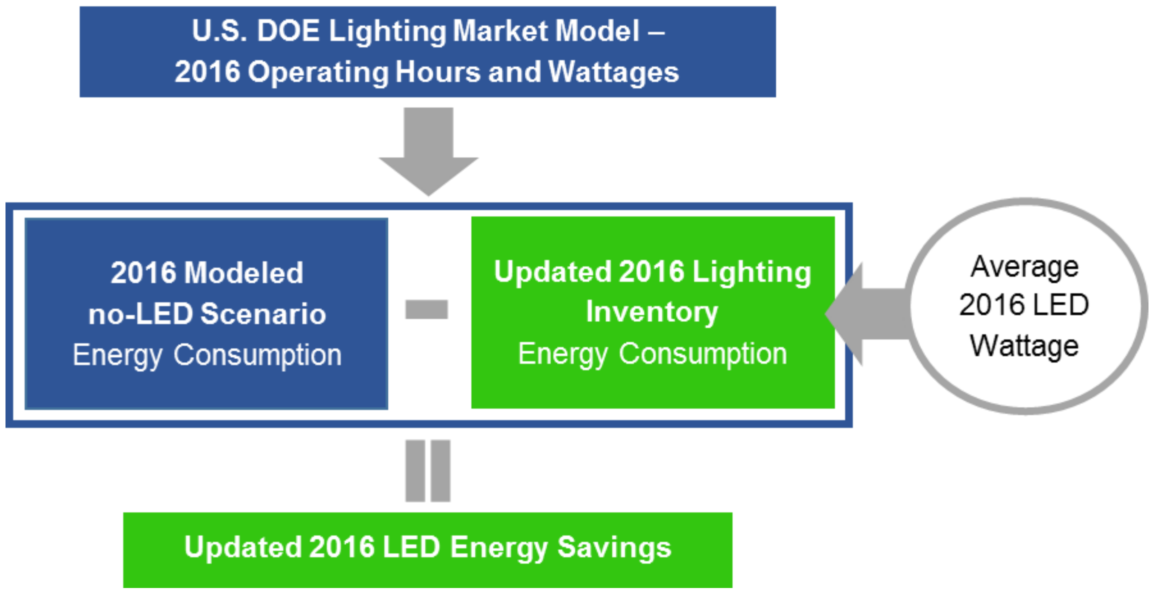

Figure 2.2 2016 LED Energy Savings Methodology[7]

The *U.S. DOE Lighting Market Model* also calculates the market share of various control systems, including single strategy (i.e., dimming, occupancy sensing, timers, daylighting), multi-strategy, energy management systems, and connected lighting[8] for both the "No-SSL" and the 2016 LED Adoption scenarios. The energy savings per control system are calculated, accounting for the energy saving effect of the control (turning lights off or reducing wattage) and the percent of time that each control strategy is used.

A discussion of how the lighting market model determines energy savings from the penetration of LED lighting installed with connected controls is discussed in the following Section 2.2.

2.2 2016 Energy Savings Potential

The methodology used in the 2016 Energy Saving Potential scenario has been updated to better reflect the technical potential for LED lighting technology. For this report, the following assumptions are used:

- LED products instantaneously reach 100% penetration, representing all U.S. lighting installations.[9]
- These installed LED products are enabled with connected controls and represent the top 95th percentile of efficacy performance based on products available in 2016.

[7] Source energy consumption is calculated by multiplying electricity consumption by a source-to-site conversion factor of 3.03. (3)

[8] It is assumed that connected controls systems are exclusive to LED lighting and are not available with conventional lighting technologies (i.e., incandescent, halogen, fluorescent and HID). However, for all other control systems including single-strategy, multi-strategy and energy management systems, any lighting technology can be employed.

[9] 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 per the overall size of the application.

As indicated above, connected lighting systems represent a substantial opportunity for energy savings. The results presented in the DOE SSL Forecast report indicate that of the forecasted 5.1 quads in annual energy savings by 2035, one-third is made possible by the penetration of LED lighting installed with connected controls. (1) Therefore, connected lighting systems provides a large opportunity for energy savings in the U.S., and represents a significant portion of the technical potential.

These additional savings for connected controls are estimated separately and represent the theoretical maximum savings achieved if the top-performing connected lighting systems of 2016 reach 100% penetration.

In terms of "top tier" 2016 efficacy performance, this is assumed to be characterized by the 95th percentile for each application, and it is determined by averaging the 95th percentile of tested (not rated) efficacy performance of products listed in the DOE's LED Lighting Facts®, DLC, and ENERGY STAR as available in 2016 (i.e., products added but not archived before December 31, 2016). Rather than the most efficacious LED product available based on rated performance, the 95th percentile of tested efficacy is used in efforts to eliminate outliers and more accurately identify the top tier of 2016 LED performance. It is also important to note that the DLC and ENERGY STAR databases do not cover the full range of LED applications analyzed in this report, therefore as seen below in Table 2.1, the 95th percentile for the individual dataset cannot be determined in these instances.

To illustrate the wide range of performance in available products within each application, Table 2.1 shows the 5th percentile, average, and 95th percentile of efficacious LED product listed in each of the above-mentioned LED product databases.

Table 2.1 Range of 2016 Product Efficacy in DesignLight Consortium, DOE LED Lighting Facts®, ENERGY STAR

Application	Product Type	LED Replacement Description	2016 LED Efficacy Range (lm/W)			Design Light Consortium			DOE's LED Lighting Facts®			ENERGY STAR®		
			5th Percentile	Avg.	95th Percentile	5th Percentile	Avg.	95th Percentile	5th Percentile	Avg.	95th Percentile	5th Percentile	Avg.	95th Percentile
A-type	Lamp	A-type replacement lamps.	**74**	**91**	**112**				67	92	116	80	91	107
Decorative	Lamp	B, BA, C, CA, F, and G replacement lamps.	**58**	**80**	**107**				52	80	110	65	80	104
	Luminaire	Integrated chandelier, single head pendant, wall sconce, lantern, and cove luminaires.	**50**	**83**	**117**	49	95	123	38	71	121	62	83	108
Directional	Lamp	PAR, BR, and R lamps.	**61**	**77**	**96**				56	78	100	65	76	91
	Luminaire	Track heads and integrated track luminaires.	**45**	**71**	**106**	45	69	104	46	74	108			
Small Directional	Lamp	MR16 lamps.	**59**	**74**	**90**				53	73	90	65	75	90
Downlighting	Lamp & Retrofit Kit	Downlight retrofit kits.	**61**	**76**	**96**				59	76	99	62	76	93
	Luminaire	Integrated downlight luminaires.	**50**	**73**	**97**				43	72	100	57	73	94
Linear Fixtures	Lamp	Linear tube replacements.	**101**	**118**	**142**	101	121	145	100	116	139			
	Retrofit Kit & Luminaire	Panels and recessed/surface-mounted troffer retrofit kits & luminaires.	**70**	**91**	**118**	85	108	135	74	94	114	52	72	106
Low/High Bay	Lamp	High wattage lamp replacements.	**76**	**103**	**131**	79	103	129	72	102	132			
	Luminaire	High and low bay luminaires.	**80**	**107**	**136**	81	111	143	80	102	130			
Street/ Roadway	No Distinction	Outdoor area/roadway/decorative lamps and luminaires.	**65**	**94**	**119**	70	103	129	60	84	108			
Parking Lot	No Distinction	Outdoor area/roadway lamps and luminaires.	**65**	**90**	**116**	70	95	124	60	84	108			
Parking Garage	Lamp	Linear T8 tube replacements.	**84**	**105**	**132**	65	91	121	103	120	142			
	Luminaire	Integrated parking garage luminaires.	**73**	**97**	**125**	75	96	122	71	98	129			
Building Exterior	No Distinction	Spot and flood lights, architectural, wall pack, and step/path lamps and luminaires.	**65**	**92**	**122**	80	104	131	47	92	129	67	81	106
Other	Indoor	Lamps and luminaires for portable, specialty and emergency applications (white), and rope/tape lighting.	**60**	**85**	**116**	75	99	128	44	71	104			
	Outdoor	Lamps and luminaires used in signage, stadium, billboard (white) and airfield lighting.	**62**	**89**	**116**	70	95	117	49	89	116	68	82	117

The lighting controls module of the *U.S. DOE Lighting Market Model* was used to determine the impacts of connected lighting in the 2016 Energy Savings Potential scenario. Connected lighting is assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate with each other and transmit data. As shown below in Table 2.2, the analysis assumes that the best available connected lighting systems of 2016 include four traditional control strategies (dimming, daylighting, occupancy sensing, and timing) and thus would have the capability of both reducing wattage and turning the light off.

Table 2.2 Connected Lighting Scope

Control System	Wattage Reduction Effect	On/Off Effect	Lighting Technologies Included	Categories Included
Connected Lighting	✓	✓	LED	Luminaire Level Lighting Controls “Smart” Lamps Advanced Networked

For connected lighting, the savings are calculated by “layering” all four traditional control strategies. Thus, if one control strategy has already turned the light off (e.g., an occupancy sensor), further savings cannot be achieved at that time from using another control strategy (e.g., dimming). An adjustment factor is then applied to account for the additional savings offered by connected systems due to their ability to communicate and the opportunity for use optimization through machine learning. The following equation shows how the energy savings for connected control systems are calculated.

$$Connected\ Control\ Energy\ Savings =$$

$$Baseline\ Load\ Profile - \left(Baseline\ Load\ Profile\ x \sum_{Control\ Strategies} (Control\ Effect_{Control\ Strategy})\right)$$

Where:

$$Control\ Effect_{Control\ Strategy} =$$

$$\sum_{Day\ Types} \sum_{Hours} \Big((Percent\ of\ Time\ Control\ Used\ x\ Energy\ Reduction_{Control\ Strategy}) + (Percent\ of\ Time\ Control\ Not\ Used\ )\Big)$$

The potential energy savings from connected controls is then calculated assuming all U.S. lighting installations operate with these systems and represents the additional savings beyond those achieved through LED lighting efficacy improvement alone. In addition, this analysis of connected lighting considers 100% penetration in all applications regardless of current product availability.

Using the control energy savings calculation method described above, the estimated energy reduction achieved per connected lighting installation based on 2016 performance is provided below in Table 2.3.

Table 2.3 Estimate of Additional Energy Savings per Connected LED Lighting Installation

Application	Connected Controls Energy Savings (%)[1]
A-Type	71%
Decorative	67%
Downlight	68%
Small Directional	67%
Directional	69%
Linear Fixture	63%
Low/High Bay	62%
Street/Roadway	61%
Parking Garage	53%
Area/Parking Lot	53%
Building Exterior	57%
Other	71%

1. Estimates consider 100% penetration of connected lighting in all applications regardless of current product availability.

More information on how the *U.S. DOE Lighting Market Model* analyzes connected lighting is provided in the DOE SSL Forecast report. (1)

3 Estimating LED Product Pricing

This iteration of the LED Adoption study also presents estimates for the typical annual purchase price from 2012 to 2016 for LED lamps, retrofits, and/or luminaires in each application. The LED product price estimates were derived using data collected through automated web-scraping software and validated through interviews with manufacturers, retailers and utility stakeholders. Web-scraping is a technique used for extracting information from websites, thereby transforming unstructured data on the web into structured data that can be stored and analyzed. This technique was used to automatically collect LED lighting sale prices and performance specification data from online retailer and distributor sites, including Home Depot, Lowes, Walmart, Sears, Target, Ace Hardware, Menards, Best Buy, ATG Stores, Grainger, Platt, GSA Advantage, 1000bulbs.com, Amazon, E-conolight.com, BulbAmerica.com, and ProLighting.com. Data collection from these retailer and distributor websites has been done routinely and includes pricing along with specification information such as wattage, lumen output, and dimensions. This extensive data resource enables the development of historical, current, and forward-looking estimates of retailer sale price for a variety of product categories ranging from LED lamps (A-type, globe, decorative, BR, PAR, R, MR, etc.) to luminaires (downlights, track fixtures, surface mounted/recessed troffers, panels, high/low bay, etc.) and outdoor fixtures.

As mentioned above, the web-scraping tool automatically collects pricing and specification data and organizes it into spreadsheet form. However, in order to maintain high data quality, the web-scraped data must be thoroughly checked and cleaned, as this is essential to producing robust extrapolations of LED product prices.

To correct for any organizational issues and errors in the pricing information, several queries were run to ensure that products were classified in the correct lighting technology and product category bins (A-type, PAR38, panel, 2x4 troffer, etc.). In addition, efforts were made to remove utility rebates for LED products offered at the big box retailers such as Home Depot, Lowes, Walmart, and Ace Hardware.

To further organize this data into a structure compatible with the *U.S. DOE Lighting Market Model*, LED product types tracked in the web-pricing database were grouped into the application analyzed in this report. These groupings are based on assumptions of how that product is most commonly used. For example, it is assumed that BR30, R30, BR40, R40 and 6 in. downlight retrofit lamps are the most common lamp products used in large downlight applications, while 6 in., 7 in. and 8 in. downlight fixtures are the most common luminaires. The product type groupings, shown in Table 3.1, represent a simplification of possible lighting installations and do not represent all LED product types used in practice for each application.[10]

[10] Grouping assumptions were limited by the data collected from the online retailer and distributor websites listed above.

Table 3.1 LED Product Type Groupings for Pricing Analysis

Application		Description of Web-Based LED Product Types Groupings
LED Lamps	A-Type	A15, A19 and A21 lamp shapes
	Downlighting	BR40, R30, BR40, R40, and 6 in. downlight retrofit lamps
	Small Directional	MR16, PAR16 and R16 lamp shapes
	Directional	PAR20, PAR30 and PAR38 lamp shapes
	Decorative	Candle, flame, torpedo, and globe lamp shapes
	Linear Fixture	2 ft. and 2 ft. U-shape linear lamps, 4 ft. linear lamps, 5 ft., 6 ft. and 8 ft. linear lamps
	Low and High Bay	High wattage retrofit and low and high bay lamps
	Garage	High wattage retrofit and 4 ft. linear lamps
LED Luminaires	Downlighting	4 in., 5 in., 6 in., 7 in. and 8 in. downlight fixtures
	Directional	Track head fixtures
	Decorative	Decorative surface, flush and wall mounted indoor fixtures
	Linear Fixture	2x2 ft., 1x2 ft., 2x4 ft. and 1x4 ft. panel, troffer, suspended and strip light fixtures
	Low and High Bay	Low and high bay fixtures
	Street and Roadway	Roadway, street and area fixtures
	Parking Lot	Shoebox and area fixtures
	Garage	Garage, strip and canopy
	Building Exterior	Flood, wall pack, bollard and landscape fixtures

To estimate the typical LED product purchase price each year, the findings of Lawrence Berkeley National Laboratory's (LBNL) 2014 report were leveraged. (2) In this study, LBNL describes how they conducted a consumer survey that indicated that more than 80% of respondents purchased an LED lamp at or below the 25th percentile of their collected web-based pricing data. LBNL also concluded that the mean and median are volatile metrics that represent the tail of the purchase distribution, while the 25th percentile of their web-scraped data best represents the characteristic price. While this analysis was conducted for LED A-type lamps, it is assumed that the same conclusion can be made for LED luminaires and retrofit kits. As an example, Figure 3.1 below shows the distribution for LED 2'x4' LED recessed troffers, which has a significant positive right-tailed skew. Therefore, given the results of the LBNL analysis and the distribution of our web-based data, we believe the 25th percentile continues to best represent the typical purchase price.

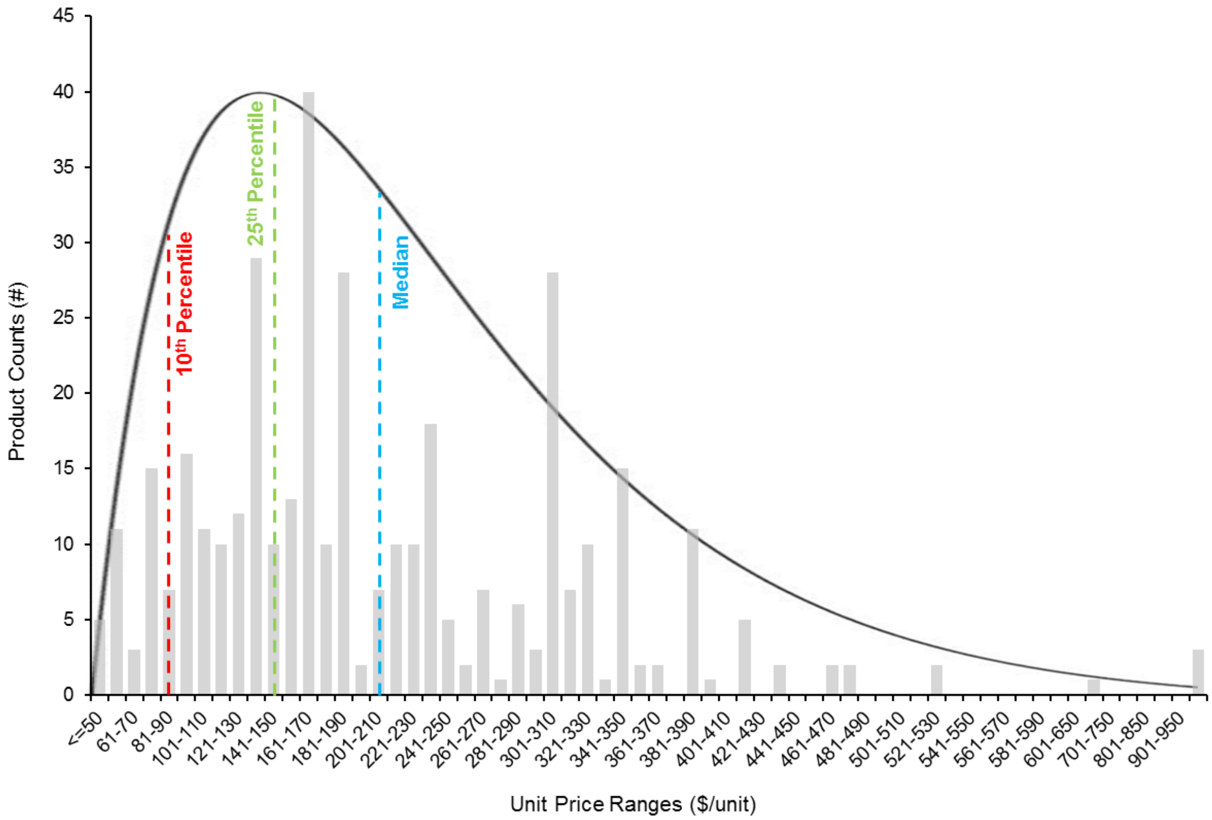

Figure 3.1 Price Distribution for 2'x4' LED Recessed Troffers Q12016

While this approach to utilize web-data has the advantage of tracking price changes by collecting several thousand price points on a regular timescale, there are shortcomings in this assessment. The availability of government and utility incentives, volume purchases, and sales negotiation, can lower LED product prices considerably, and the estimates presented in this report are not adjusted to account for any discounts that could be obtained through other sales channels.

4 Results

In 2016, the total energy consumption in the U.S. was 96.5 quads of primary energy, according to the U.S. Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2017. Roughly 37.5 quads, or 39%, of this energy was consumed for electricity use. (3) DOE estimated that in 2016, there were 6.9 billion lighting systems[11] installed in the U.S. and that they consumed approximately 5.5 quads of energy annually. Thus, lighting accounted for 5.7% of the total energy and 15% of the total electricity consumed in the U.S. in 2016.[12]

The results of this analysis indicate that by the end of 2016, there were 874 million cumulative LED lighting system installations in the U.S. These LED products are estimated to have saved 458 trillion British thermal units (tBtu) of source energy in 2016. As described in Section 2, the following three scenarios were developed using the *U.S. DOE Lighting Market Model* to estimate the cumulative installed penetration of LED technology, the resulting energy savings, and the technical potential for LED and connected lighting systems in 2016.

No-SSL A hypothetical scenario that assumes LED technology never entered the lighting market. LED lamps and luminaires are not available for competition, only conventional incandescent, halogen, fluorescent and HID sources. The "No-SSL" scenario is used as the reference condition from which LED and connected lighting energy savings are calculated.

2016 LED Adoption The estimated actual 2016 energy savings due to the existing installed stock of LED lamps, retrofit kits and luminaires, and connected lighting systems.

2016 Energy Savings Potential The theoretical energy savings if 100% LED penetration was achieved with LED products that are enabled with connected lighting systems and represent the top 95th percentile of efficacy based on products available in 2016.

This section considers 12 lighting applications to investigate the results of the 2016 LED Adoption and 2016 Energy Savings Potential scenarios.

The 2016 LED Adoption scenario estimates actual 2016 energy savings due to the existing installed stock of LED lamps, retrofit kits and luminaires, and connected lighting systems. When comparing the 2016 LED lighting stock to that of 2014, installations of LED lighting has increased in all applications, more than quadrupling from 215 million to 874 million units. Of these LED lighting installations, 94% were in indoor applications, largely led by A-type lamps (roughly 50%) and followed by downlighting lamps, retrofit kits and luminaires (roughly 16%). The breakdown of the 2016 LED lighting installed base by application is shown in Figure 4.1.

[11] Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit). For example, a commercial troffer fixture operating two lamps on a single ballast is counted as one lighting system, and hence, one unit.
[12] Based on a total electricity consumption of 37.5 quads of source energy for residential, commercial, and industrial sectors from EIA's AEO 2017.

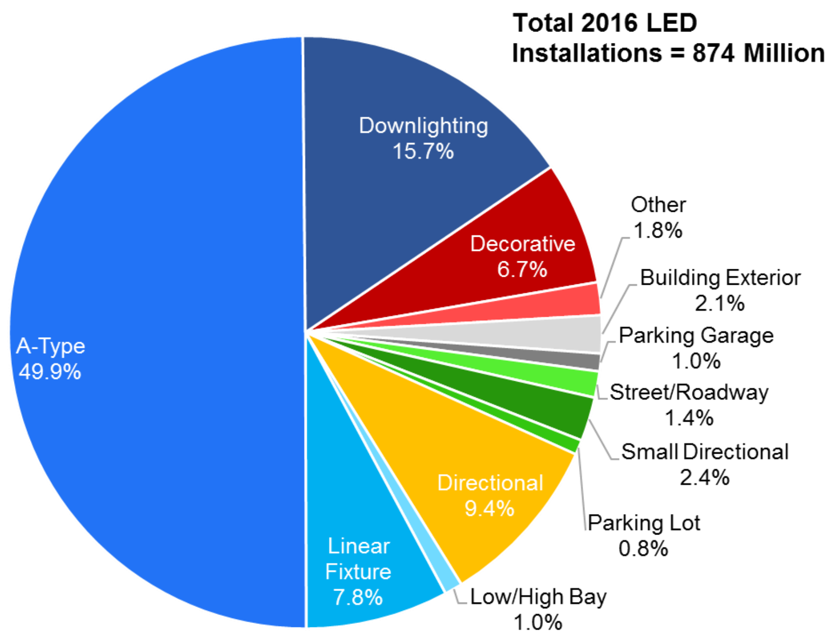

Figure 4.1 Total 2016 LED Unit Installations by Application

While LED A-type lamps may lead the current LED installed base in terms of units, their overall penetration is still the minority. LED products in A-type applications have grown dramatically in the past four years, starting at less than 1% in 2012 and increasing to 2.4% in 2014 and 13.5% in 2016. As seen in Figure 4.2, overall the adoption of LED lighting for general illumination is still just beginning with those applications clustered in the "early majority" phase. LED products in small directional applications, mainly MR16 lamps, had early success and they continue to have the highest penetration of any application, growing from 10% in 2012, to 22% in 2014, and 47.6% in 2016. LED lighting has had the least success penetrating the linear fixture market due to comparable performance from linear fluorescent lamps at a much lower cost. However, LED products in linear fixture applications continue to improve, with the best products offering energy savings over the best linear fluorescent products.

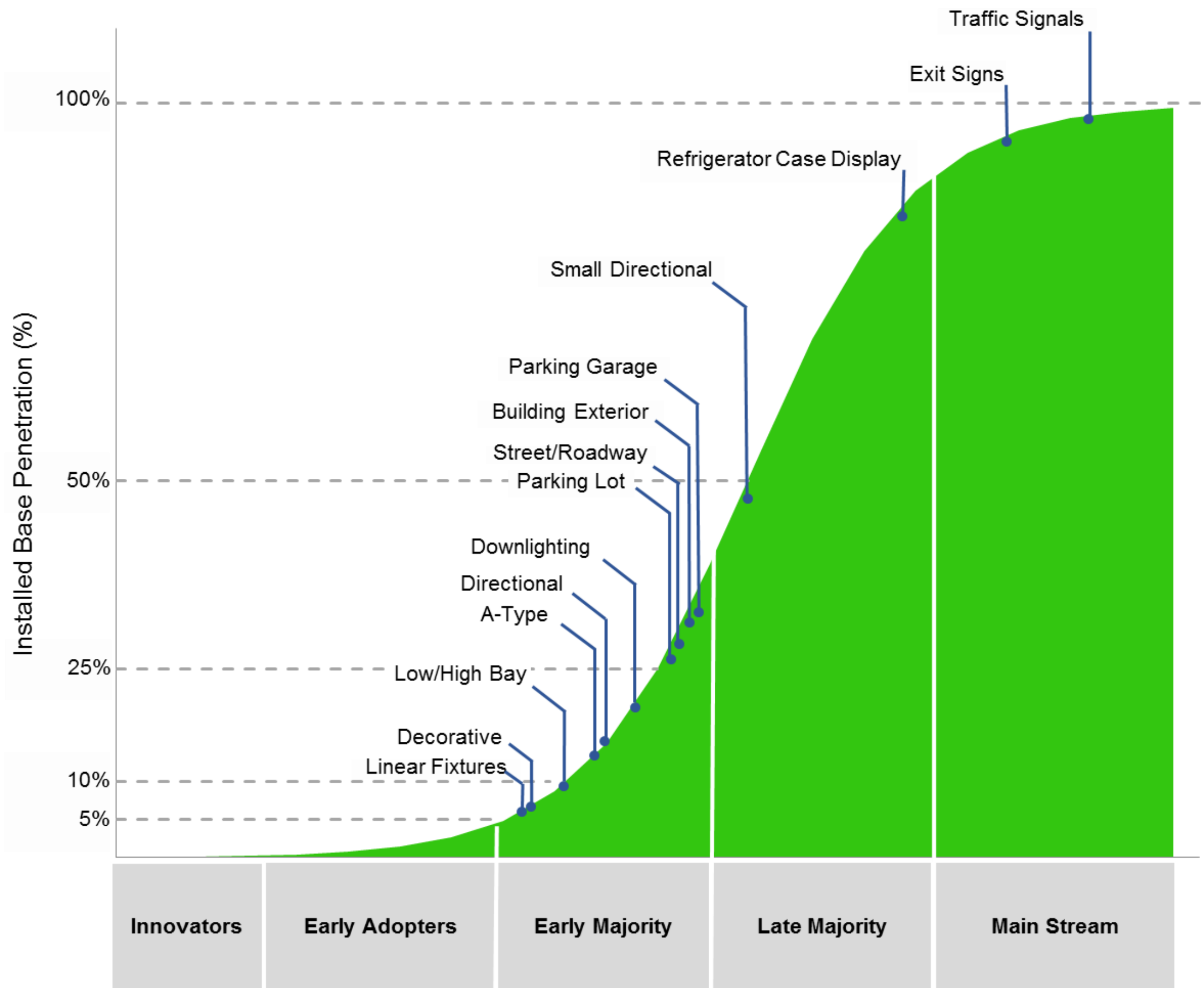

Figure 4.2 2016 Installed Adoption of LED Lighting Applications

As the installation of LED lighting continues to grow in general lighting applications, so do the energy savings. As seen in Figure 4.3 below, annual source energy savings in 2016 have more than tripled since 2014, growing from 143 to 458 tBtu, which is equivalent to an annual energy cost savings of about $4.6 billion. LED lamps in A-type applications have resulted in the greatest energy savings of any of the evaluated applications, providing approximately 22% of the total realized energy savings. The next most significant energy saving markets in 2016 are LED downlights, linear fixtures and low/high bay, which contributed about 20%, 14% and 10% respectively. This is followed by LED directional, small directional, parking lot, street/roadway, parking garage, building exterior, other and decorative applications, which combined represent about 35% of the total.

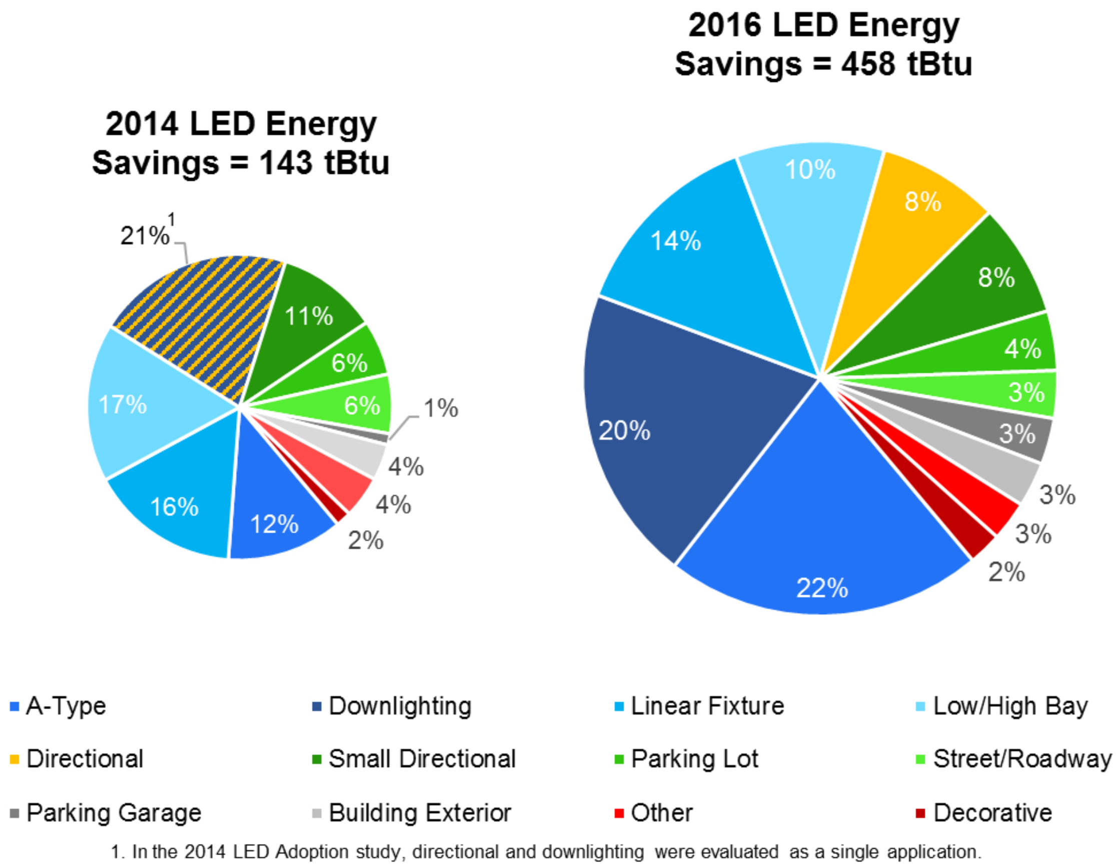

Figure 4.3 Comparison of 2014 and 2016 LED Energy Savings

In addition to the 2016 energy savings from LED lighting, it is estimated that connected lighting systems installed in the U.S. saved 11.4 tBtu, increasing the overall energy savings enabled by LED technology to 469 tBtu.

When considering the results of the 2016 Energy Savings Potential scenario, it becomes clear that LED lighting combined with connected controls have much more to offer. If all 6.9 billion lighting systems in the U.S. were switched instantaneously to LED products that offer top-tier 2016 efficacy performance, they would provide 2,454 tBtu or about 2.5 quads of energy savings. If these same top-tier LED products were also configured with connected controls, they would enable an additional 1,974 tBtu of energy savings for a total of 4,428 tBtu or about 4.4 quads. Energy savings of this magnitude would result in a total annual energy cost savings of about $44 billion.

While the energy savings results for the 2016 LED Adoption and 2016 Energy Savings Potential scenarios are significant, the extent of energy savings depends not only on efficiency, but also the number of installations and the hours each installation is operated. For example, in 2016, 45% of U.S. lighting installations were A-type lamps, with over three billion units in use. However, the majority of A-type lamps are used in the residential sector and operate an average of less than two hours per day. Meanwhile, only 91 million low/high bay fixtures were installed in the U.S. in 2016, but they operate for an average of about 12 hours per day in the commercial and industrial sectors. Therefore, as shown in Figure 4.4, low/high bay fixtures have a potential energy savings greater than

A-type lamps (695 tBtu compared to 630 tBtu, respectively) despite the huge disparity in number of available installations.

Linear fixture applications also represent a significant portion of the total 2016 energy savings at 62 tBtu, and they contribute more than any other application to the total 2016 potential energy savings. From Figure 4.4, the impact of connected controls is particularly evident for linear fixture applications, where these savings represent 69% of total linear fixture potential. However, in the future this could be much larger. In 2016, the 95th efficacy percentiles for LED linear fixture lamp and luminaire products were 142 lm/W and 118 lm/W, respectively, while the U.S. DOE SSL Program anticipates that troffer luminaires will reach 200 lm/W by 2020. (4) If expected LED efficacy increases are realized, linear fixture applications will represent an even greater opportunity for potential LED energy savings.

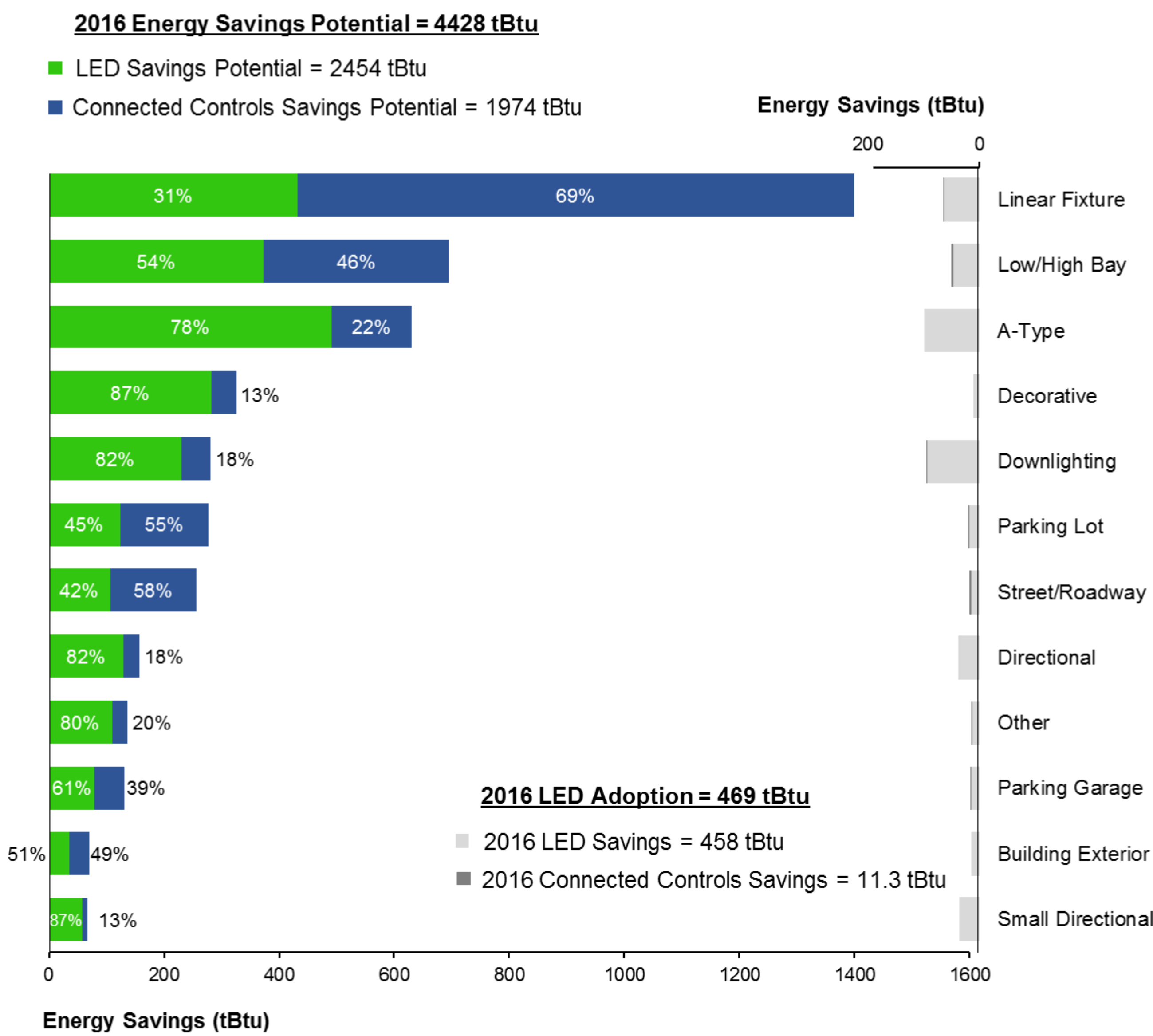

Figure 4.4 Current and Potential Energy Savings for LED Lighting and Connected Controls

4.1 A-Type

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED replacements in the A-type lamp market, which includes standard incandescent A-type lamps, incandescent halogen lamps, CFLs, and LED replacement lamps. A-type lamps 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/twister 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 energy savings, with over 3.2 billion A-type lamps installed in 2016. Incandescent A-type lamps are still the most familiar to consumers; however, their market share has dropped significantly in recent years. This shift is largely due to the implementation of Energy Independence and Security Act (EISA) of 2007 general service lamp standards. The maximum wattage standards, which began to take effect on January 1, 2012, require a 25% efficiency increase for all general service lamps. As a result, a significant number of CFLs and EISA-compliant halogen lamps have begun to replace the traditional incandescent lamps in many applications.[13]

Halogen lamps, while currently representing nearly half of all A-type sales because of their low cost and similarity to traditional incandescent A-type lamps, are estimated to make-up over one-third of the installed stock. On the other hand, CFLs are currently only about a quarter of sales, but as seen in Figure 4.5 below, are roughly 43% of the installed stock. While much of the phased-out incandescent lamp stock has been replaced by halogen lamps, LED lamps are currently on the rise largely at the expense of CFLs. The continuously-decreasing price of LED lamps enabled them to capture nearly 14% of the installed stock in 2016, growing to 436 million from a mere 19.9 million in 2012.

While LED A-type products that offer color changing and wireless controllability have become more prevalent in the A-type market, the penetration of LED lamps with connected controls is estimated to be near negligible, with an estimated stock of fewer than 0.4 million in 2016.

[13] EISA 2007 does not ban incandescent light bulbs, but its minimum efficiency standards are high enough that incandescent lamps most commonly used by consumers today will not meet the requirements. This Act essentially eliminates 40W, 60W, 75W, and 100W medium screw based incandescent light bulbs. More information can be found at: http://energy.gov/eere/buildings/appliance-and-equipment-standards-program

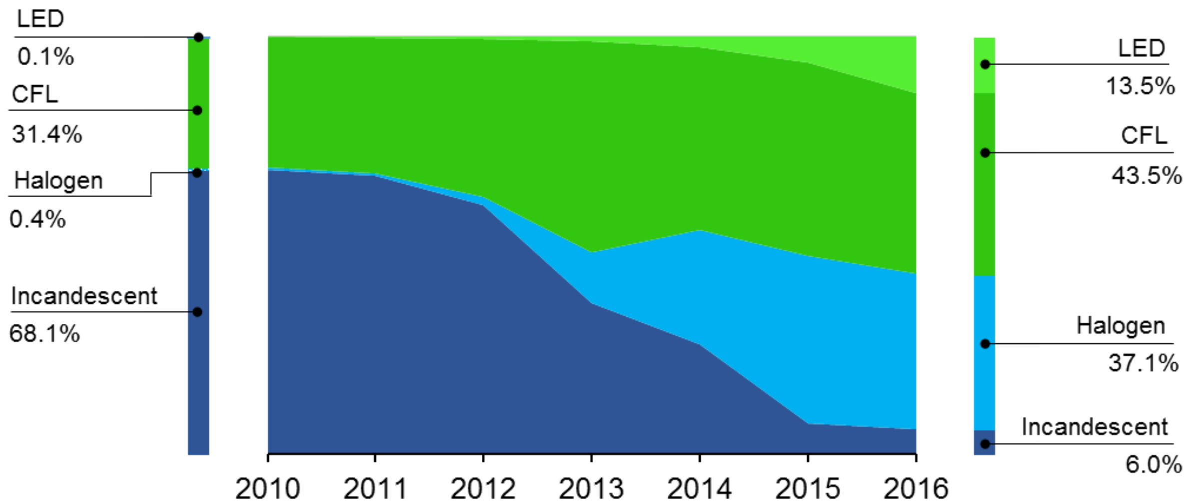

Figure 4.5 U.S. A-Type Installed Stock Penetration from 2010 to 2016

This boom in LED A-lamp stock is also due to residential utility energy efficiency programs. Many provide rebate incentives that lower the cost of LED A-lamps substantially. LED replacement lamps in the A-type application became available to consumers between 2007 and 2009 at a typical cost over $50 per lamp. However, in recent years, significant improvements have been made. In 2016, a typical LED-based dimmable A19 60 Watt-equivalent replacement lamp could be purchased for a price of less than $8 per bulb ($9/klm). Rebates and incentives can further reduce the price to below $5 or at times even below $3. In contrast, a top-performing LED A19 lamp is typically priced closer to $14/klm. (4) While now lower than the first cost of dimmable CFL replacements ($10/klm), the $9/klm LED price is still about five times that of halogen ($2/klm) and non-dimmable CFL replacements ($2.50/klm). (5)

Many utility programs have struggled to keep up with the rate of price decline of LED A-type lamps, and based on price projections provided in the DOE SSL Forecast report, many LED A-type lamps could hit cost parity with the majority of CFLs and halogen A-type lamps by 2020. (1) This could have the effect of slowing future LED A-type lamp adoption as utility rebate incentives become less cost effective for these products.

Figure 4.6 below illustrates the recent decline in typical purchase price for LED lamps in A-type applications.

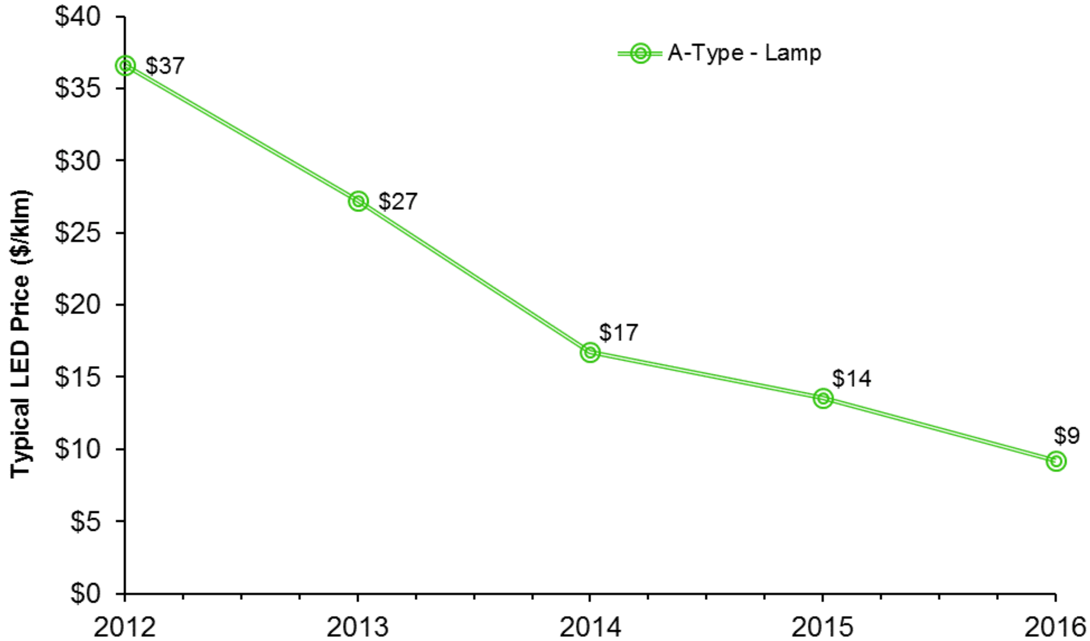

Figure 4.6 A-Type LED Price ($/klm) from 2012 to 2016

The total energy consumption of A-type lamps has decreased by roughly 7.0% to 594 tBtu since 2014. This decrease in energy use is largely due to the implementation of the EISA 2007 standards, which contributed to the reduction of incandescent lamps in favor of more efficient options (including LED lighting options). LED A-type lamps are still the minority of installations; however, it is estimated that they saved about 9.6 TWh of site electricity, or about 99.1 tBtu of source energy in 2016. Table 4.1 depicts the total energy savings due to LED A-type lamps to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were over 3.2 billion A-type lamps installed in the U.S., 436 million of which were LED products. If all 3.2 billion installations were to switch to LED lamps that represented 95th percentile of efficacy performance in 2016 (112 lm/W), the switch would save 47.5 TWh of site electricity, or about 491 tBtu of source energy. If these same LED lamps were also configured with connected controls, they would enable savings of an additional 13.4 TWh of site electricity, or about 138 tBtu of source energy, for a total of 630 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $6.3 billion.

Table 4.1 A-Type LED Energy Savings Summary

A-Type	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	13.5%	100%
LED Installed Base (Millions of units[1])	436	3,238
LED Energy Savings (tBtu)	99.1	491
Connected Controls Installed Penetration (%)	<0.1%	100%
Connected Controls Installed Base (Millions of units[1])	0.4	3,238
Connected Controls Energy Savings (tBtu)	<0.1	138

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.2 Decorative

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in decorative applications. Decorative is a generic term that is used to cover a wide range of bulb shapes including bullet, globe, flame, and candle, among others. These lamps are most common in the residential and commercial sectors and are intended for use in decorative fixtures, including chandeliers, pendants, wall sconces, lanterns, and nightlights. Unlike CFLs, which are not well suited for decorative applications due to size and form factor constraints, LED products are available for all existing decorative lamp shapes. Recently, manufactures have begun to develop a "filament" style design that arranges very small LED emitters in a linear strip inside the bulb to mimic the appearance of a traditional filament of an incandescent lamp. These "filament" and "vintage" style LED bulbs are becoming increasingly popular as they offer an aesthetic appearance as well as a significant energy savings compared to incandescent products. Additionally, fully integrated decorative LED luminaires, which typical offer even greater energy savings due to more freedom of design, are available to replace decorative fixtures entirely.

Because of their relative low cost, aesthetic appeal, and absence of federal efficiency standards, incandescent lamps remain the dominant player in the decorative submarket, representing 83.6% of the 874 million decorative installations in 2016. LED products, while available for all existing decorative lamp shapes, only recently began offering replacements that meet the aesthetic criteria demanded by some consumers. LED lighting has largely grown at the expense of fluorescent, and particularly CFLs, which have declined in installed penetration continuously since 2010. As seen in Figure 4.7, LED lamps and luminaires have grown from a negligible penetration in 2010 to roughly 6.7% in 2016, with an estimated 58.9 million installations in the U.S. Compared to 2014, the penetration of LED lighting in decorative applications has more than quadrupled. Of these 58.9 million installations, it is estimated that 73.8% were LED lamps, while the remaining 26.2% were LED luminaires. The penetration of connected controls in decorative applications is estimated to be negligible in 2016.

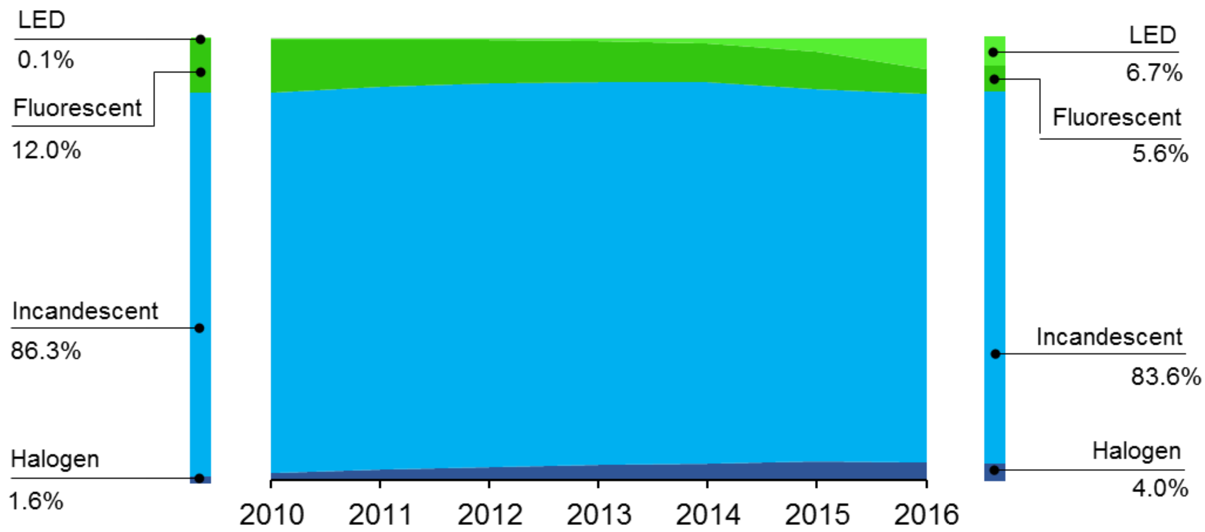

Figure 4.7 U.S. Decorative Installed Stock Penetration from 2010 to 2016

There is a wide range of prices for LED decorative lamps due to variations in size, shape, and lumen output. However, as seen in Figure 4.8 below, it is estimated that the typical 2016 purchase prices for LED lamps and luminaires were $15/klm and $150/klm, respectively. While prices have declined substantially since 2012, incandescent options are still available for less than $5/klm. While many LED lighting options are not competitive on a first cost basis, when considering cost of electricity to operate the lamp, the much higher efficiency makes them more attractive.

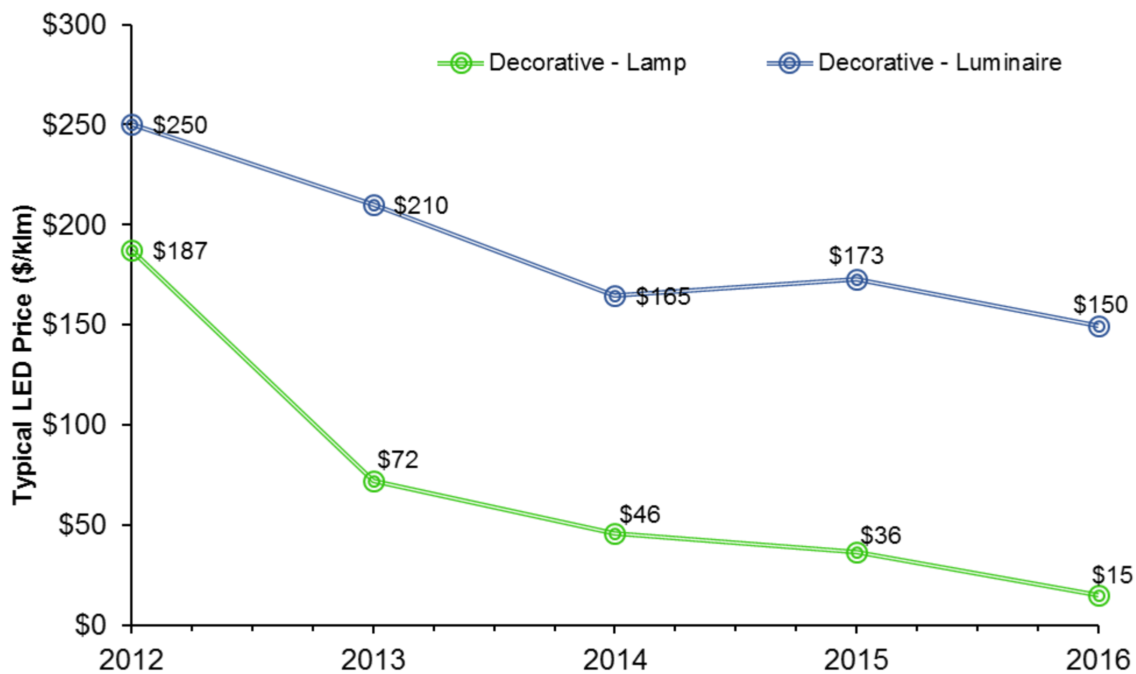

Figure 4.8 Decorative LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of decorative applications decreased by about 2.1% to 345 tBtu largely due to the increasing penetration of LED lighting. LED decorative lamps and luminaires are still the minority of installations; however, it is estimated that LED lighting saved about 1.0 TWh of site electricity, or about 10.3 tBtu of source energy in 2016. Table 4.2 depicts the total energy savings due to LED decorative lamps to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were 874 million decorative systems installed in the U.S., 58.9 million of which were LED lamps and luminaires. If all 874 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (110 lm/W and 122 lm/W, respectively), the change would save 27.3 TWh of site electricity, or about 283 tBtu of source energy. If these same products were also configured with connected lighting controls, they would enable savings of an additional 4.2 TWh of site electricity, or about 42.9 tBtu of source energy, for a total of near 325 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $3.2 billion.

Table 4.2 Decorative LED Energy Savings Summary

Decorative	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	6.7%	100%
LED Installed Base (Millions of units[1])	58.9	874
LED Energy Savings (tBtu)	10.3	283
Connected Controls Installed Penetration (%)	--	100%
Connected Controls Installed Base (Millions of units[1])	--	874
Connected Controls Energy Savings (tBtu)	--	42.9

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.3 Directional

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in directional applications. Directional fixtures are commonly used for accent, track, pendant, recessed, and architectural lighting in spaces including households, retail displays, restaurants, museums, and office buildings. Directional lamps are predominately reflector type and include incandescent, halogen, CFL, and LED reflector (R), bulged reflector (BR), and parabolic aluminized reflector (PAR) shaped lamps. Multifaceted reflector (MR), such as MR16, lamps are also considered directional lamps; however, because MR 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. As such, small directional lamps are evaluated separately in Section 4.4 of this report.

This section considers large LED directional lamps and integrated LED luminaires that replace incandescent, halogen, and CFL reflector lamps (e.g., PAR, BR, and R lamps) installed in accent and track fixtures. In previous iterations of this study, downlighting was included within the directional applications analysis; however, due to improved data quality and synchronization with the *U.S. DOE Lighting Market Model*, downlighting is now evaluated separately in Section 4.5 of this report.

The DOE has regulated the energy efficiency level of many directional lamps since 1992,[14] and the reflector lamp market has undergone significant changes due to the enactment of energy conservation standards. 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 LED directional lamps. However, adapting 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. LED replacements for reflector lamps, on the other hand, have distinct advantages due to the directionality of emitted light and the small form factor.

Despite the enactment of energy efficiency standards, in 2016 incandescent and halogen lamps together are still estimated to represent the majority of the 538 million directional lighting installations, at 38.9% and 29.1%, respectively. However, particularly in commercial installations where building owners place higher value on efficiency and lifetime, LED products have begun to penetrate substantially. Overall, LED lighting has largely grown at the expense of fluorescent lighting – particularly CFLs – which has declined in installed penetration continuously since 2010. However, the combined stock of incandescent and halogen lamps has been declining steadily since roughly 2013. As seen in Figure 4.9, LED lighting has grown exponentially to roughly 15.3% in 2016, with an estimated 68.7 million lamps and 13.8 million luminaires installed. Compared to 2014, the penetration of LED lamps and luminaires in directional applications has more than doubled. The penetration of connected controls in directional applications is estimated to be negligible in 2016.

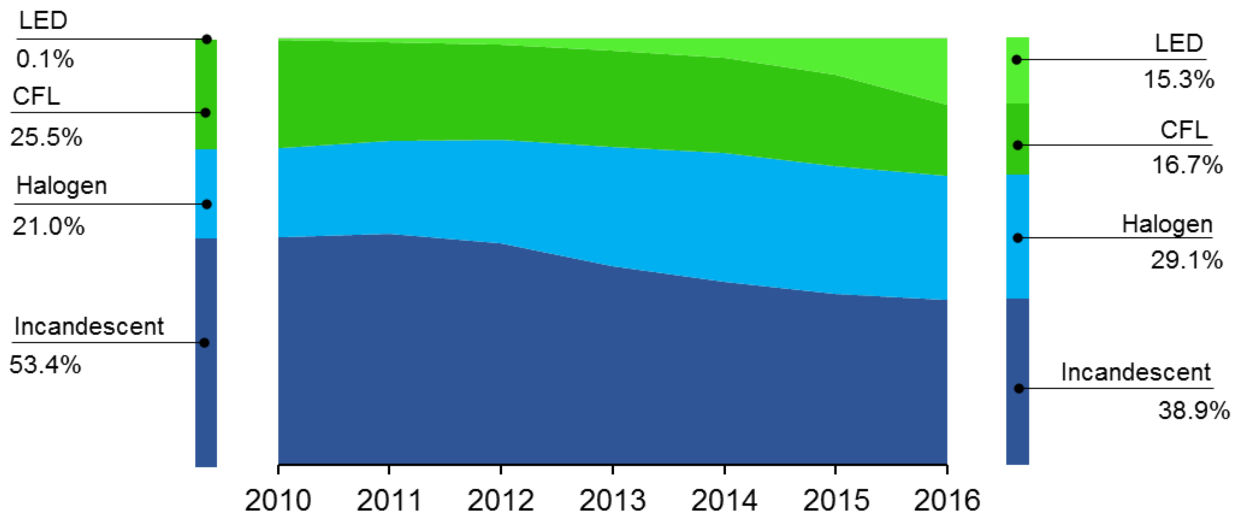

Figure 4.9 U.S. Directional Installed Stock Penetration from 2010 to 2016

The biggest barrier to LED lighting adoption continues to be price. However, as seen in Figure 4.10, prices have been decreasing. In 2016, the typical purchase price of an LED directional lamp was $18/klm, while the price of an integrated LED track luminaire was $74/klm. These remain more

[14] U.S. DOE EERE, "Appliance & Equipment Standards – Incandescent Reflector Lamps", Accessed June 16, 2017. https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=23

expensive than CFL and halogen reflector lamps, which have prices between $5/klm and $10/klm, but due to significant energy savings and longer life, LED products can be competitive when comparing the total cost of ownership of the different lamps.

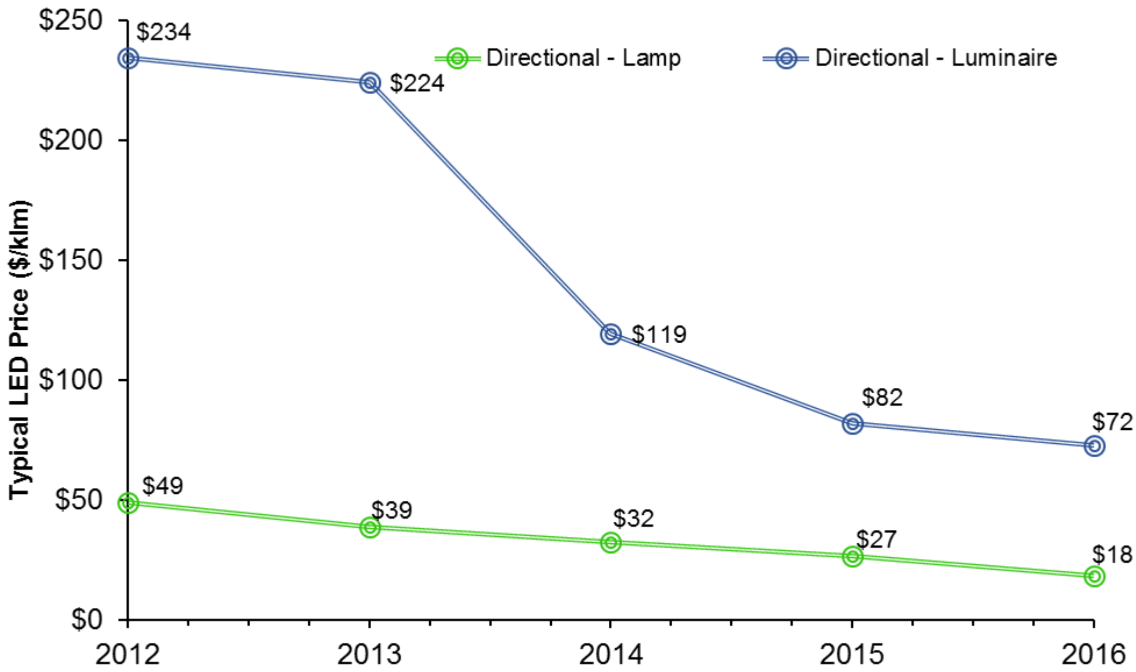

Figure 4.10 Directional LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of directional applications decreased substantially by about 17.6% to 133 tBtu largely due to the increasing penetration of LED lighting. LED directional lamps and luminaires are still the minority of installations; however, it is estimated that LED directional lighting saved about 3.7 TWh of site electricity, or about 37.9 tBtu of source energy in 2016. Table 4.3 depicts the total energy savings due to LED directional products to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were 538 million directional lighting systems installed in the U.S., 82.4 million of which were LED products. If all 538 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (100 lm/W and 106 lm/W, respectively), the switch would save 12.5 TWh of site electricity, or about 129 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 2.8 TWh of site electricity, or about 28.5 tBtu of source energy, for a total of 158 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $1.6 billion.

Table 4.3 Directional LED Energy Savings Summary

Directional	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	15.3%	100%
LED Installed Base (Millions of units[1])	82.4	538
LED Energy Savings (tBtu)	37.9	129
Connected Controls Installed Penetration (%)	--	100%
Connected Controls Installed Base (Millions of units[1])	--	538
Connected Controls Energy Savings (tBtu)	--	28.5

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.4 Small Directional

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in small directional applications. Similar to the directional lamps (PAR, BR, and R) discussed in the previous section, small directional applications, largely comprised of MR16 lamps, were traditionally comprised of halogen incandescent light sources. However, MR16 lamps are unique among directional lamps because they are often operated at low voltage and their design is constrained by a small form-factor.[15] 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 applications discussed in section 4.3, MR16 lamps are particularly optimal for jewelry and other display applications due to their high color rendering index (CRI) values and tightly-controlled, high-intensity beams.

The small form-factor, required dimmability, and optical control of MR16 lamps cannot be duplicated with CFL technology, but it can be met by LED lighting products. In addition, the efficiencies of LED lighting greatly outpace that of the incumbent technology. Traditional halogen MR16 lamps are only capable of efficacies between 10 lm/W and 25 lm/W, while the average of MR16 products are around 73 lm/W, with the top 5% of products reaching efficacies of 90 lm/W or greater.

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 candelas and are affected by both the lamp wattage (as it relates to light output) and the beam angle of the lamp. 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. These metrics still are not mandatory reporting items; however, increasingly, manufacturers are providing this data to end-users.

Overall, small directional applications represent a small percentage of total U.S. indoor lighting installations, with only about 44.1 million lights in 2016. However, this application currently has the highest LED lighting penetration. As seen in Figure 4.11, in 2016, it is estimated that LED lamps represented nearly half of all small directional installations. Several of the market actors interviewed

[15] Most MR16 lamps are operated using voltages lower than 120 volts, typically 12 volts; however, GU10 options at 120 volts are also available.

reported that many of the technology challenges of LED MR16 lamps have been addressed and product solutions offer improved dimming, thermal management, and efficiency that have enabled LED technology to continue to grow. The penetration of connected controls in small directional applications is estimated to be negligible in 2016.

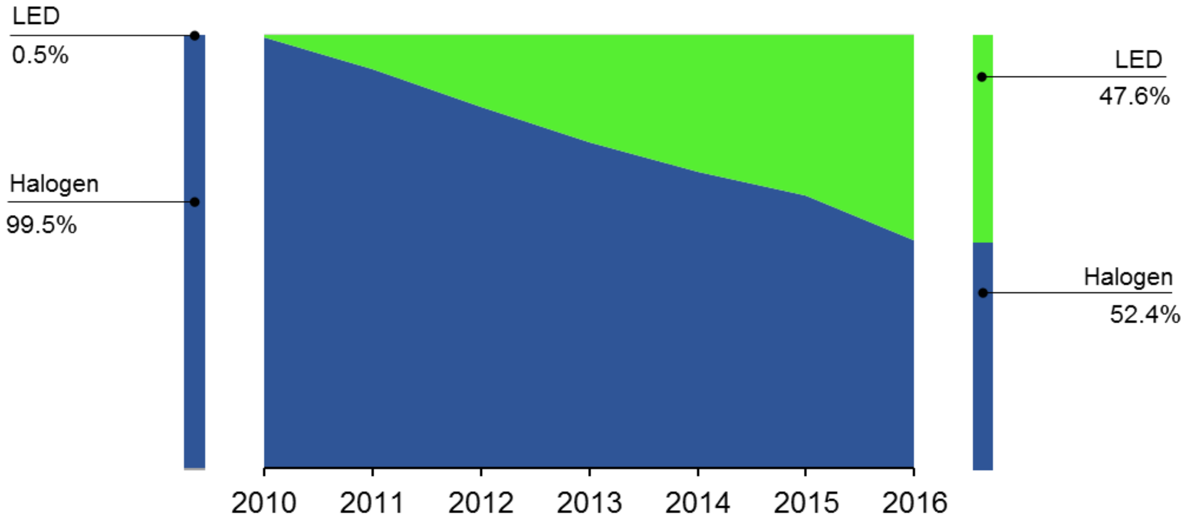

Figure 4.11 U.S. Small Directional Installed Stock Penetration from 2010 to 2016

Another barrier to adoption, as with most LED lighting products, is still price. As seen in Figure 4.12, prices have continued to decline, with the typical purchase price of LED MR16 lamps reaching $22/klm in 2016. While still more expensive than halogen reflectors (at about $11/klm), because LED lighting offers significant energy savings over halogen MR16 lamps, they are competitive on a total cost of ownership basis. LED replacements have been commercially successful within this application, and their market presence continues to grow.

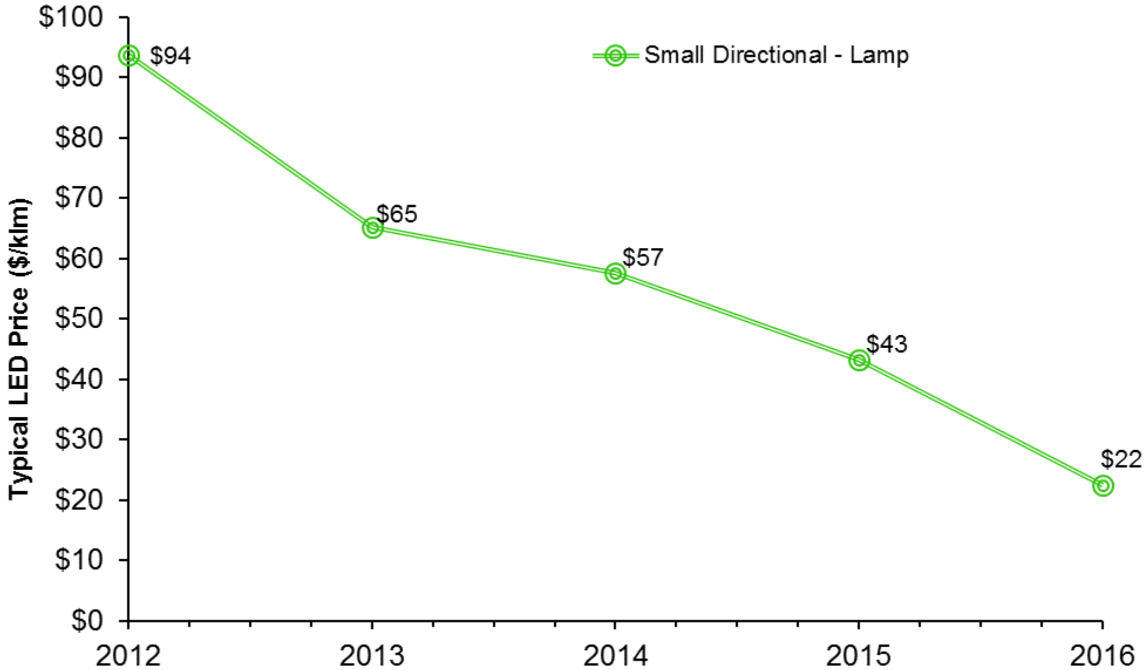

Figure 4.12 Small Directional LED Price ($/klm) from 2012 to 2016

Due to the increasing penetration of LED lighting, from 2014 to 2016, the total energy consumption of small directional applications decreased substantially by about 27.4% to 30.8 tBtu. LED small directional lamps and luminaires are nearly the majority of installations and it is estimated that LED lamps saved about 3.4 TWh of site electricity, or about 35.6 tBtu of source energy in 2016 compared to a scenario in which LED technology never existed. Table 4.4 depicts the total energy savings due to LED small directional products to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were 44.1 million small directional lighting systems installed in the U.S., 21.0 million of which were LED lamps. If all 44.1 million installations were to switch to LED lamps that represented 95th percentile of efficacy performance in 2016 (90 lm/W), the switch would save 5.7 TWh of site electricity, or about 58.9 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 0.8 TWh of site electricity, or about 8.6 tBtu of source energy, for a total of 67.6 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $0.7 billion.

Table 4.4 Small Directional LED Energy Savings Summary

Small Directional	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	47.6%	100%
LED Installed Base (Millions of units[1])	21.0	44.1
LED Energy Savings (tBtu)	35.6	58.9
Connected Controls Installed Penetration (%)	--	100%
Connected Controls Installed Base (Millions of units[1])	--	44.1
Connected Controls Energy Savings (tBtu)	--	8.6

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.5 Downlighting

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in downlighting applications. Downlights are a staple of residential, hospitality, and commercial lighting, usually providing ambient illumination but sometimes focal lighting. These fixtures can be recessed or surface mounted and have become popular because they are inexpensive and can provide inconspicuous ambient lighting. Originally, downlights featured directional incandescent or halogen lamps – although, in some cases, omnidirectional lamps were installed, with substantial reductions in efficiency. Later, CFL downlights became a dominant part of the market, offering higher efficacy and longer lifetimes. However, CFL-based downlights often have low luminaire efficiency due to the omnidirectional lamp emissions, as well as some lighting quality issues.

Although originally intended for directional lighting applications, downlights have become commonly used for ambient lighting in both residential and commercial buildings. (6) In previous iterations of this study, downlighting was included within the directional applications analysis. However, due to improved data quality and synchronization with the *U.S. DOE Lighting Market Model*, downlighting is now evaluated separately. This section considers LED downlight lamps, retrofit kits, and integrated LED luminaires that replace incandescent, halogen, and CFL reflector lamps (e.g., PAR, BR, and R lamps) installed in downlight fixtures.

LED downlight luminaires were some of the earliest applications for SSL in general illumination. The release of the Cree LED LR6 recessed downlight in 2007 marked the beginning of viable LED downlight luminaire products. While the efficacy of LED downlights is lower than most other LED luminaire products, it is much higher than the efficacy of conventional sources. The lower performance is at least partly due to different optical requirements in downlights, but the relatively low performance of conventional halogen and CFL downlights provides less incentive for continued efficacy gains in LED downlights, compared to luminaire types competing against linear fluorescent or high-intensity discharge incumbents. Despite these challenges, LED downlight products has steadily improved, with estimated efficacy gains tracking at about 10 lm/W per year. (7)

In 2016, incandescent and halogen lamps together are still estimated to represent the majority of the 692 million directional lighting installations, at 52.8% and 10.4%, respectively. However, particularly in commercial installations where building owners place higher value on efficiency and lifetime, LED lighting has begun to penetrate substantially. Overall, LED lighting has largely grown at the expense of fluorescent lighting – particularly pin-based CFLs – which has declined in installed penetration continuously since 2010. However, the combined stock of incandescent and halogen lamps has been declining steadily since roughly 2012. As seen in Figure 4.13, LED lighting has grown exponentially to 19.8% in 2016, with an estimated 91.1 million lamps and retrofits and 45.2 million luminaires installed. Compared to 2014, the penetration of LED lighting in directional applications has more than doubled. The penetration of LED lamps, retrofit kits, and luminaires with connected controls in downlight applications is small. However, it is estimated to have reached nearly 0.6 million in 2016.

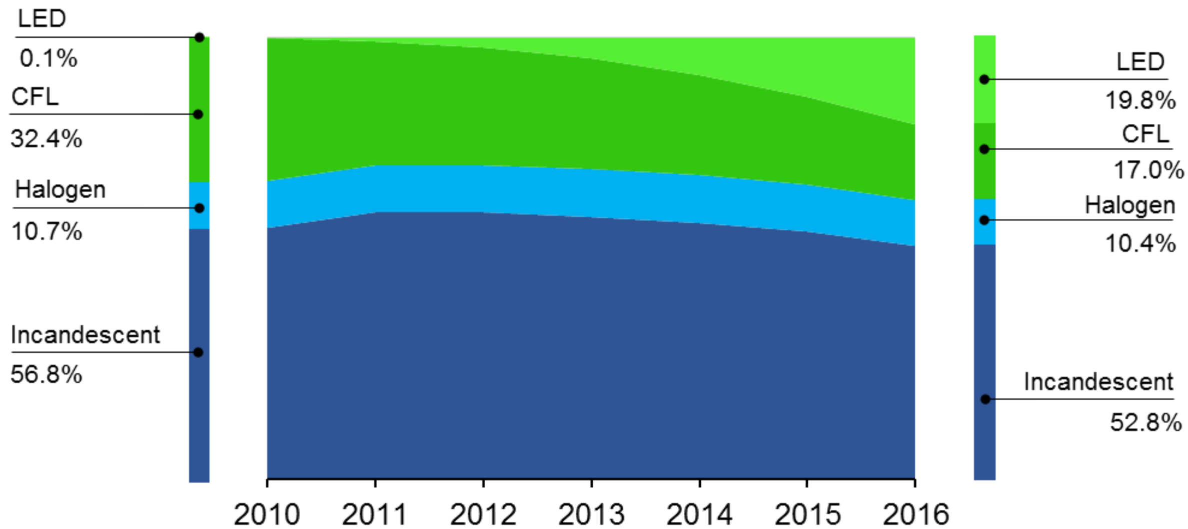

Figure 4.13 U.S. Downlight Installed Stock Penetration from 2010 to 2016

LED downlight products have seen substantial price decline since 2012; however, the pace has begun to slow. As seen in Figure 4.14 below, in 2016, the typical purchase price of LED lamp and retrofit products was $13/klm, while the price of an integrated LED downlight luminaire was $41/klm. This remains more expensive than pin-based CFLs and incandescent reflector lamps, which have prices between $5/klm and $10/klm. However, due to significant energy savings and longer life, LED products can be competitive when comparing the total cost of ownership of the different lamps.

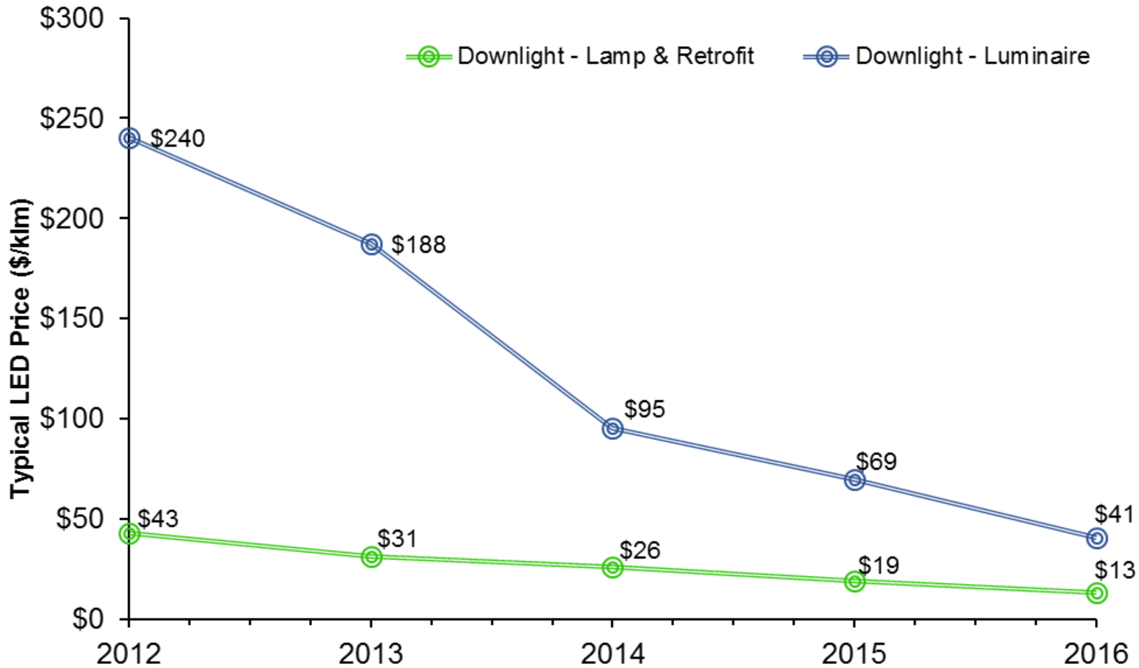

Figure 4.14 Downlight LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of downlighting applications decreased by about 14.1% to 221 tBtu largely due to the increasing penetration of LED lighting. LED downlight products are still the minority of installations; however, it is estimated that LED lighting saved about 8.9 TWh of site electricity, or about 92.5 tBtu of source energy in 2016. Additionally, the nearly 0.6 million connected lighting systems are estimated to have saved about 0.6 tBtu of source energy in 2016. Table 4.5 depicts the total energy savings due to LED downlight products to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were 692 million directional lighting systems installed in the U.S., 137 million of which were LED products. If all 692 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (99 lm/W and 100 lm/W respectively), the switch would save 22.3 TWh of site electricity, or about 231 tBtu of source energy. If these same LEDs were also configured with connected lighting controls, they would enable savings of an additional 4.8 TWh of site electricity, or about 49.8 tBtu of source energy, for a total of 281 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $2.8 billion.

Table 4.5 Downlight LED Energy Savings Summary

Downlighting	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	19.8%	100%
LED Installed Base (Millions of units[1])	137	692
LED Energy Savings (tBtu)	92.5	231
Connected Controls Installed Penetration (%)	<0.1%	100%
Connected Controls Installed Base (Millions of units[1])	0.6	692
Connected Controls Energy Savings (tBtu)	0.6	49.8

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.6 Linear Fixture

This Section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in linear fixture applications and covers LED replacement of linear fixtures including all troffer, panel, suspended, and pendant luminaires. However, linear fixture systems used in low/high bay and parking garage applications are covered separately in Sections 4.7 and 4.9, respectively.

Linear fluorescent systems (with T5, T8, and T12 lamps) are widely utilized for commercial and industrial establishments because they offer a low-cost, highly efficient, and long-lifetime light source. As a result, these fluorescent systems represent nearly half of all lighting energy consumption in the U.S. across all sectors, creating a significant energy savings opportunity for LED lighting. However, modern linear fluorescent systems (lamp and ballast) remain tough competitors in terms of efficacy, as well as initial and lifecycle costs, with efficacies as high as 108 lm/W and prices as low as $4/klm. (5) Although fluorescent troffers have evolved into a well-defined system of modular products, the LED market is more fragmented, especially in retrofit applications. LED products intended for use in troffer applications include lamps, retrofit kits, and dedicated LED luminaires – and sometimes the lines between these can be blurry. These three product types, are all available in multiple sizes and match – or exceed – the performance of fluorescent troffers to varying degrees.

Similar to directional lamps, manufacturers have been required to comply with the DOE energy conservation standards for general service fluorescent lamps (GSFLs) since 1992,[16] and as a result linear fixture applications have undergone significant changes. Specifically, DOE published standards which became effective July 14, 2012, setting new efficacy requirements for 4-foot medium bipin, 2-foot U-shaped, 8-foot slimline, 8-foot high output, 4-foot miniature bipin standard output, and 4-foot miniature bipin high output GSFLs by specific correlated color temperature (CCT) ranges. (10 CFR 430.32(n)) These standards have had the effect of causing a transition away from inefficient T12 lamps towards higher efficiency T8 and T5 lamps, as well as LEDs.

In 2016, fluorescent lamps are still estimated to represent the majority of the 1.1 billion linear fixture installations, with T12 at 15.7%, T8 at 69.3% and T5 at 8.9%. However, LED products have begun

[16] U.S. DOE EERE, "Appliance & Equipment Standards – General Service Fluorescent Lamps", Accessed June 16, 2017. https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=22

to penetrate. Shown in Figure 4.15 is the DOE's estimate for the installed base of linear fixture applications from 2010 to 2016. At only 1.1 million installations in 2012, LED lighting has grown to an estimated 68.0 million installations in 2016, of which 26.4 million are lamp replacements and 41.6 million are retrofit kits and luminaires. The penetration of LED luminaires with connected controls in linear fixture applications is small. However, it is estimated to have reached 1.4 million in 2016.

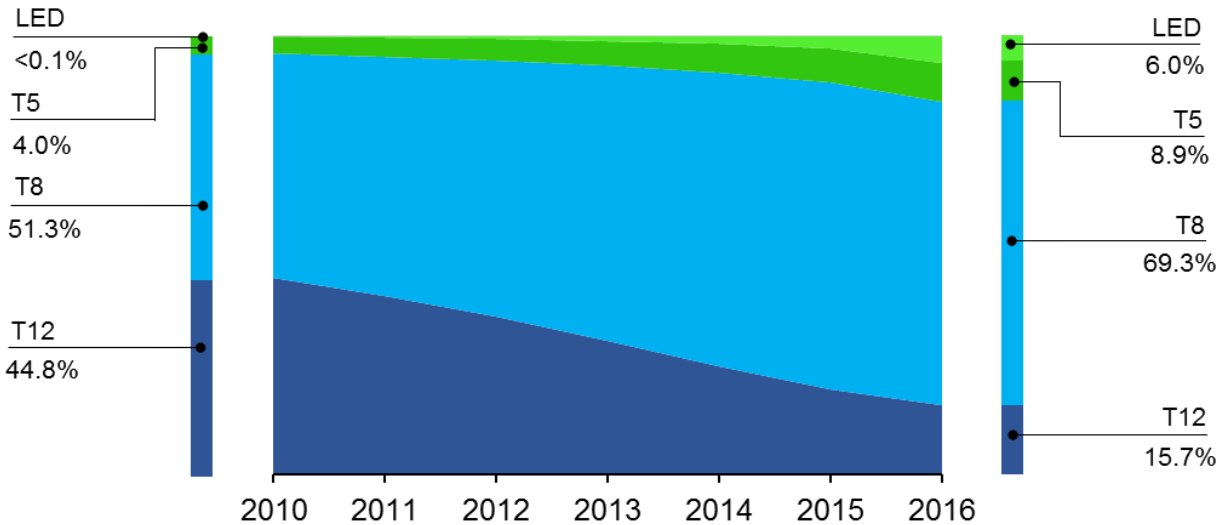

Figure 4.15 U.S. Linear Fixture Installed Stock Penetration from 2010 to 2016

LED products designed for linear fixture applications have seen substantial price decline since 2012; however, starting in 2014 the pace has begun to slow. As seen in Figure 4.16 below, in 2016, the typical purchase price of LED linear replacement lamps was $8/klm, nearly five times the price of linear fluorescent lamps. LED retrofit kits and integrated luminaires are offered at a higher cost compared to LED linear replacement lamps at an estimated $30/klm in 2016.

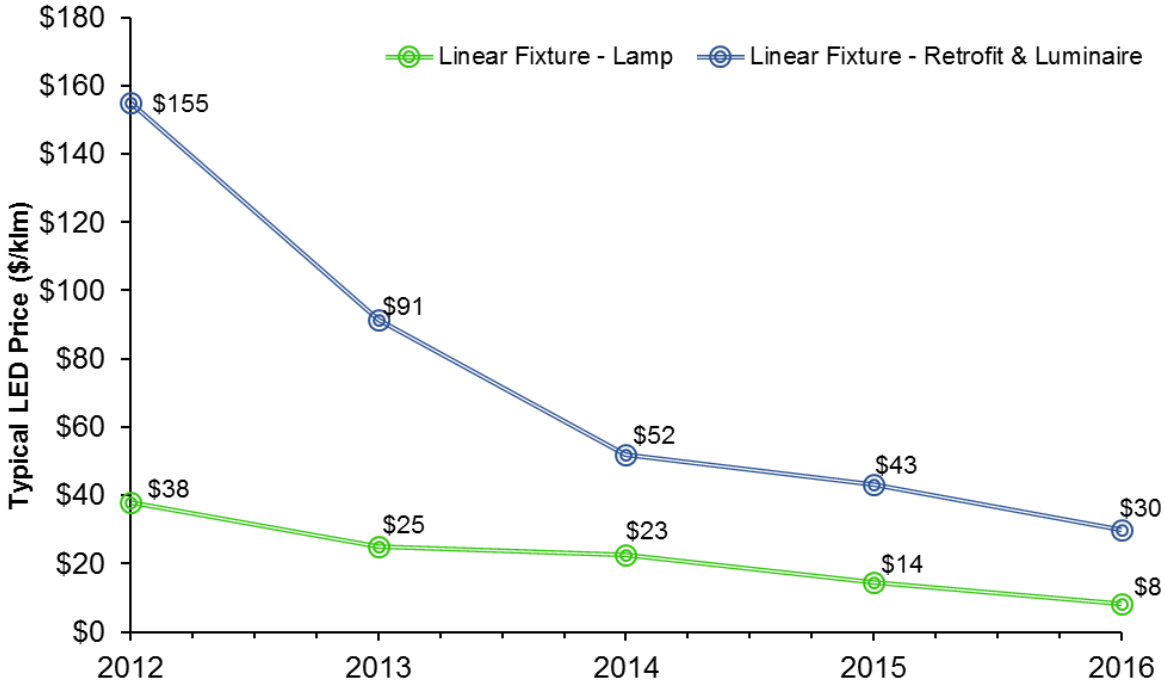

Figure 4.16 Linear Fixture LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of linear fixture applications decreased slightly by about 3.9% to 1,947 tBtu due to the transition to more efficient linear fluorescent T8 and T5 options as well as the increasing penetration of LED lighting. LED products are still far in the minority of installations; however, it is estimated that linear LED lighting saved about 6.0 TWh of site electricity, or about 62 tBtu of source energy in 2016. Additionally, the 1.4 million connected lighting systems are estimated to have saved about 1.8 tBtu of source energy in 2016. Table 4.6 depicts the total and potential energy savings due to LED linear fixture products and connected controls to date.

In 2016, there were 1.1 billion linear fixture lighting systems installed in the U.S., 68.0 million of which were LED products. If all 1.1 billion installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (142 lm/W and 124 lm/W respectively) it would save 41.8 TWh of site electricity, or about 432 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 93.5 TWh of site electricity, or about 967 tBtu of source energy, for a total of 1,399 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $13.9 billion.

Table 4.6 Linear Fixture LED Energy Savings Summary

Linear Fixture	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	6.0%	100%
LED Installed Base (Millions of units[1])	68.0	1,129
LED Energy Savings (tBtu)	62.0	432
Connected Controls Installed Penetration (%)	0.1%	100%
Connected Controls Installed Base (Millions of units[1])	1.4	1,129
Connected Controls Energy Savings (tBtu)	1.8	967

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.7 Low/High Bay

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in low and high bay applications. Low and high bay fixtures are commonly used in both the commercial and industrial sectors to illuminate large open indoor spaces in big-box retail stores, warehouses, and manufacturing facilities. Typically, low bay fixtures are used for ceiling heights of 20 feet or less, while high bay is used for heights of greater than 20 feet. Because of the large areas and lofted ceilings, these spaces require high lumen-output luminaires, with low bay options offering between 5,000 and 15,000 lumens per fixture and high bay providing 15,000 to as much as 100,000 lumens per fixture. This market was historically dominated by HID lamps, although fluorescent lamps, particularly high output T5 lamps, have become a major player due to their superior lumen maintenance and enhanced control options.

Only in the past few years have technological and cost improvements allowed LED lighting to penetrate the market in significant quantities. In addition, while less efficient than LED luminaire options, LED retrofit lamps designed for direct replacement for HID and fluorescent lamps are now also available and penetrating low and high bay applications. In 2016, the low and high bay submarket represented 15% of all lighting energy use – the second highest energy consumption of all the applications evaluated, making this a key application for LED lighting energy savings.

As seen in Figure 4.17, fluorescent lamps made up the majority of the 2016 low and high bay installations at 63.3%. Of this, T8 systems dominate, followed by T5 and T12 respectively. Similar to linear fixture applications, DOE energy efficiency standards for GSFLs have had the effect of causing a transition away from inefficient T12 lamps towards higher efficiency T8 and T5 lamps, as well as LED lighting. From 2010 to 2016, the population of T12 lamp installations halved, while T8 and T5 penetration increased. The installed stock of HID lamps in low and high bay applications has also steadily decreased. Overall, LED lighting represented 8.6 million installations in 2016, of 8.1% were LED replacement lamps, and 91.9% were integrated LED luminaires. Of these total 8.6 million LED installations in 2016, 0.5 million operated with connected lighting controls.

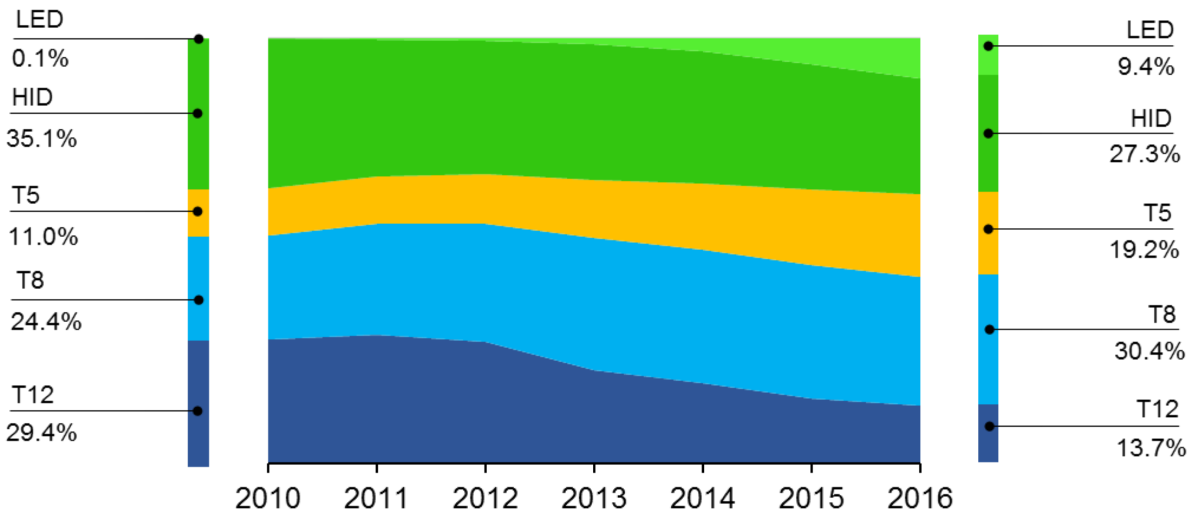

Figure 4.17 U.S. Low/High Bay Installed Stock Penetration from 2010 to 2016

LED lamps and luminaires for low and high bay applications have seen substantial price decline. As seen in Figure 4.18 below, in 2016, the typical purchase price of an LED high wattage replacement lamp was $14/klm, nearly four times the price of equivalent linear fluorescent lamps. LED retrofit kits and integrated luminaires are offered at a higher cost compared to LED linear replacement lamps at an estimated $19/klm in 2016.

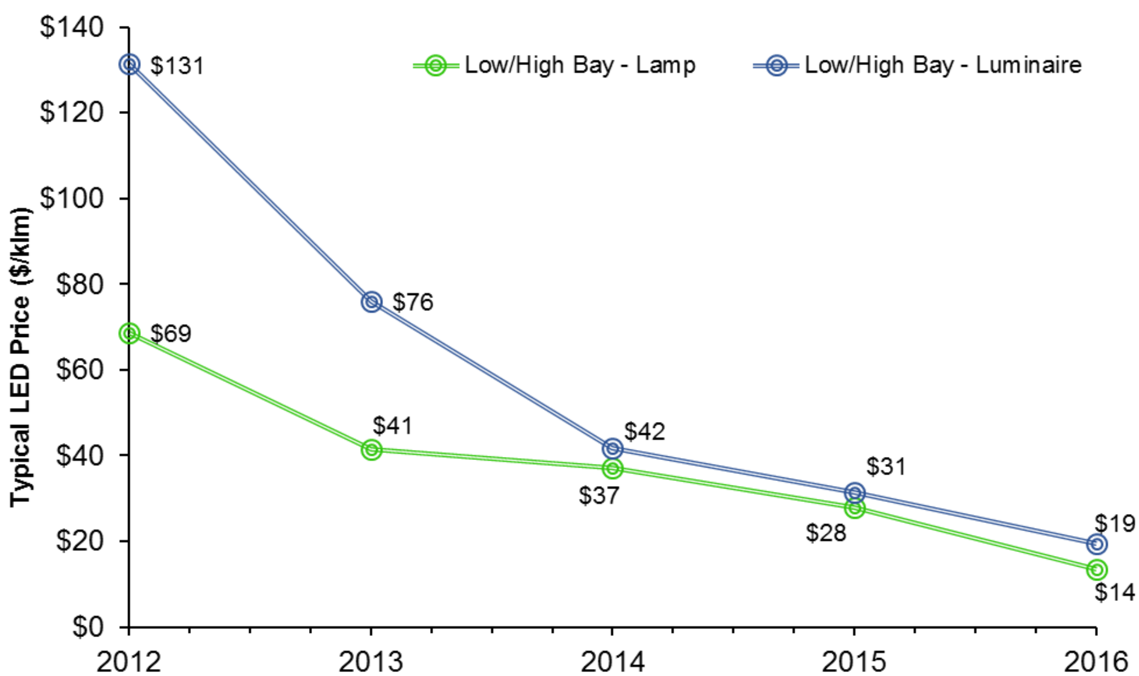

Figure 4.18 Low/High Bay LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of low and high bay applications decreased slightly by about 5.6% to 853 tBtu due to the transition to more efficient linear fluorescent T8 and T5 options as well as the increasing penetration of LED lighting. LED products are still far in the minority of installations; however, it is estimated that they saved about 4.5 TWh of site electricity, or about 46.4 tBtu of source energy in 2016. Additionally, the 0.5 million connected lighting systems are estimated to have saved about 3.6 tBtu of source energy in 2016. Table 4.7 depicts the total and potential energy savings due to LED low and high bay installations and connected controls to date.

In 2016, there were 91 million low and high bay lighting systems installed in the U.S., 8.6 million of which were LED products. If all 91 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (131 lm/W and 136 lm/W respectively) it would save 36.1 TWh of site electricity, or about 373 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 31.2 TWh of site electricity, or about 322 tBtu of source energy, for a total of 695 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $6.9 billion.

Table 4.7 Low/High Bay LED Energy Savings Summary

Low/High Bay	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	9.4%	100%
LED Installed Base (Millions of units[1])	8.6	90.9
LED Energy Savings (tBtu)	46.4	373
Connected Controls Installed Penetration (%)	0.5%	100%
Connected Controls Installed Base (Millions of units[1])	0.5	90.9
Connected Controls Energy Savings (tBtu)	3.6	322

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.8 Street/Roadway

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lighting in street and roadway applications. Street and roadway luminaires serve to illuminate streets and roadways to improve visibility for drivers as well as to illuminate outdoor pedestrian walkways. Traditionally, this application has been dominated by HID light sources such as high pressure sodium (HPS), metal halide (MH), and mercury vapor (MV) lamps because they offer relatively high efficacy, operate effectively over a wide temperature range, and produce high lumen outputs which enable them to be mounted on widely spaced poles.

LED products are particularly advantageous in street and roadway lighting applications because they are excellent directional light sources, are durable, and exhibit long lifetimes. LED street and roadway luminaires also significantly decrease the amount of light pollution compared to incumbent HID fixtures because their improved optical distribution substantially reduces the amount of light wasted upward into the atmosphere. In addition to offering energy savings, LED street and roadway luminaires have typical rated lifetimes exceeding 50,000 hours, more than three times that of many HID systems. This is particularly attractive when considering the long operating hours along with the difficulty and expense of required maintenance.

Because of these advantages, many local jurisdictions have initiated projects to completely transition to LED area and roadway lighting. For example, the City of Los Angeles has completed a citywide street lighting replacement program and has installed over 170,000 LED streetlights, reducing energy usage by 64% and saving $9 million in annual energy costs. (8) In addition, New York City is in the process of converting it's over 250,000 streetlights to LED – the largest such project in the country. The LED lighting is estimated to save New York City approximately $6 million in energy cost and $8 million in maintenance a year.

As of 2016, HPS lamps still represent the majority of the 44.1 million street and roadway installations, at 61.9%. However, their majority has declined significantly since 2010, largely due to the increasing adoption of LED lighting. As seen in Figure 4.19, LED lighting has grown near exponentially to an estimated 28.3% in 2016, with an estimated 12.5 million installed units. Of these total 12.5 million LED installations in 2016, 0.6 million operated with connected lighting controls.

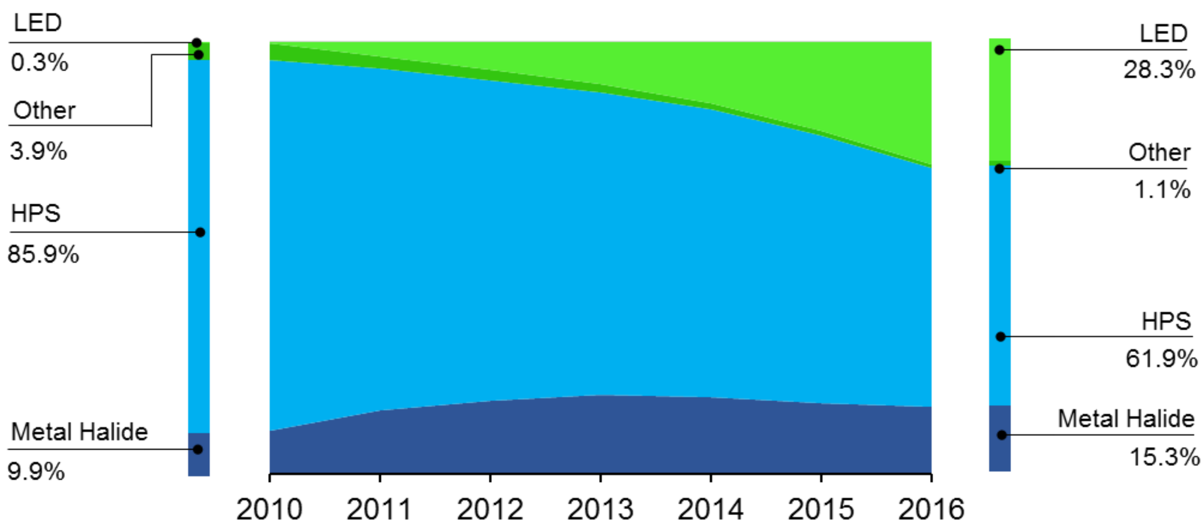

Figure 4.19 U.S. Street/Roadway Installed Stock Penetration from 2010 to 2016[17]

Although still more expensive than incumbent competitors, HPS and MH lamps, at approximately $1.2/klm and $2.1/klm, respectively, as seen in Figure 4.20 the typical price of LED street and roadway luminaires has more than halved from 2012 to 2016, reaching about $39/klm.

[17] The "other" category includes incandescent, fluorescent, mercury vapor, low pressure sodium and induction lighting products.

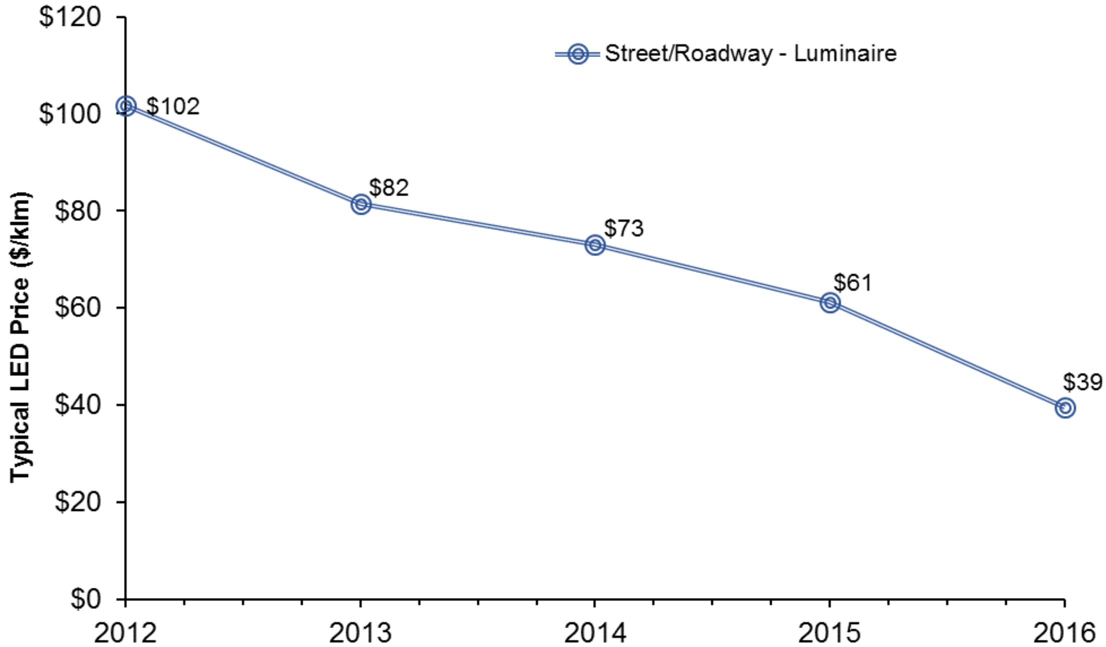

Figure 4.20 Street/Roadway LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of street and roadway applications decreased slightly by about 1.5% to 411 tBtu largely due to the increasing penetration of LED lighting. While gaining quickly, LED products are still the minority of installations; however, it is estimated that they saved about 1.4 TWh of site electricity, or about 14.9 tBtu of source energy in 2016. Additionally, the 0.6 million connected lighting systems are estimated to have saved about 3.3 tBtu of source energy in 2016. Table 4.8 depicts the total and potential energy savings due to LED street and roadway installations and connected controls to date.

In 2016, there were 44.1 million street and roadway lighting systems installed in the U.S., 12.5 million of which were LED products. If all 44.1 million installations were to switch to LED luminaires that represented 95th percentile of efficacy performance in 2016 (119 lm/W) it would save 10.3 TWh of site electricity, or about 106 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 14.5 TWh of site electricity, or about 149 tBtu of source energy, for a total of 256 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $2.6 billion.

Table 4.8 Street/Roadway LED Energy Savings Summary

Street/Roadway	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	28.3%	100%
LED Installed Base (Millions of units[1])	12.5	44.1
LED Energy Savings (tBtu)	14.9	106
Connected Controls Installed Penetration (%)	1.4%	100%
Connected Controls Installed Base (Millions of units[1])	0.6	44.1
Connected Controls Energy Savings (tBtu)	3.3	149

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.9 Parking

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lamps and luminaires in parking applications. In this analysis, the parking application has been divided into parking lots and covered garages, and it does not consider street-side parking, as those areas are covered in the street and roadway application discussed in Section 4.8. In addition, outdoor area lighting for pedestrianized spaces and outdoor parks and recreation areas is included within the parking lot analysis.

4.9.1 Parking Lot

Given these operating conditions, the type of lighting used for parking lots closely mimics the technologies used for street lighting (discussed in Section 4.8). Despite the similarities, penetration of LED lighting in parking lot lighting is estimated to exceed that of street and roadway. While adoption of LED lighting in street and roadway applications has come from local municipalities embarking on city-wide upgrades, several barriers stand in the way of widespread conversion. For street and roadway lighting, high upfront costs and undepreciated legacy lighting equipment impede broad adoption of newer technologies. Most importantly, regulatory lag and the delayed utility adoption of tariffs have impeded widespread conversion to LED lighting technologies. (9) In contrast, the majority of parking lot lighting is curated by private businesses and not subject to the same regulatory constraints or utility tariffs.

LED lighting offers a distinct advantage in both area and parking lot applications, and, in particular, it can significantly improve light utilization.[18] For example, a recent parking lot lighting retrofit using LED-based fixtures demonstrated a 66% reduction in energy usage compared with HID fixtures due to improved efficiency and reduced total light generation. In addition, significantly more of the parking lot area is illuminated, which is particularly advantageous for both driver and pedestrian safety. (10)

Despite the increasing penetration of LED lighting, as of 2016, metal halide fixtures still represent the majority of the 27.0 million parking lot installations, at 51.7%. However, their majority is starting to decline significantly as just two years ago in 2014, metal halide was roughly 63.0% of parking lot

[18] These energy savings benefits are also due to improved uniformity ratios and minimum illuminance criterion for parking lot applications in IES RP-20-14 – Lighting for Parking Facilities.

installations. As seen in Figure 4.21, LED lighting now outpaces the use of HPS and is estimated to represent 26.2% of total 2016 stock with 7.1 million installations. Of these total 7.1 million LED installations in 2016, 0.2 million are estimated to operate with connected lighting controls.

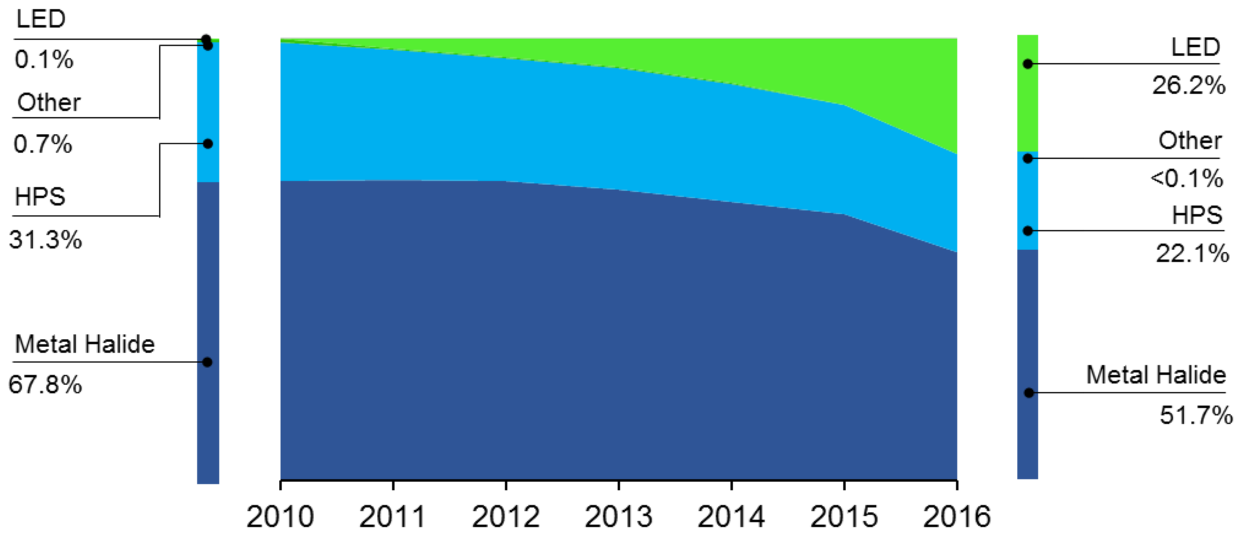

Figure 4.21 U.S. Parking Lot Installed Stock Penetration from 2010 to 2016

LED products designed for parking lot applications have seen substantial price decline since 2012. As seen below in Figure 4.22, the typical purchase price of an LED outdoor area luminaire was $30/klm in 2016. This represents over a four times reduction from 2012. However, despite the rapid drop in typical price, outdoor area luminaires are still more expensive than incumbent competitors, HPS and MH lamps, at approximately $1.2/klm and $2.1/klm, respectively.

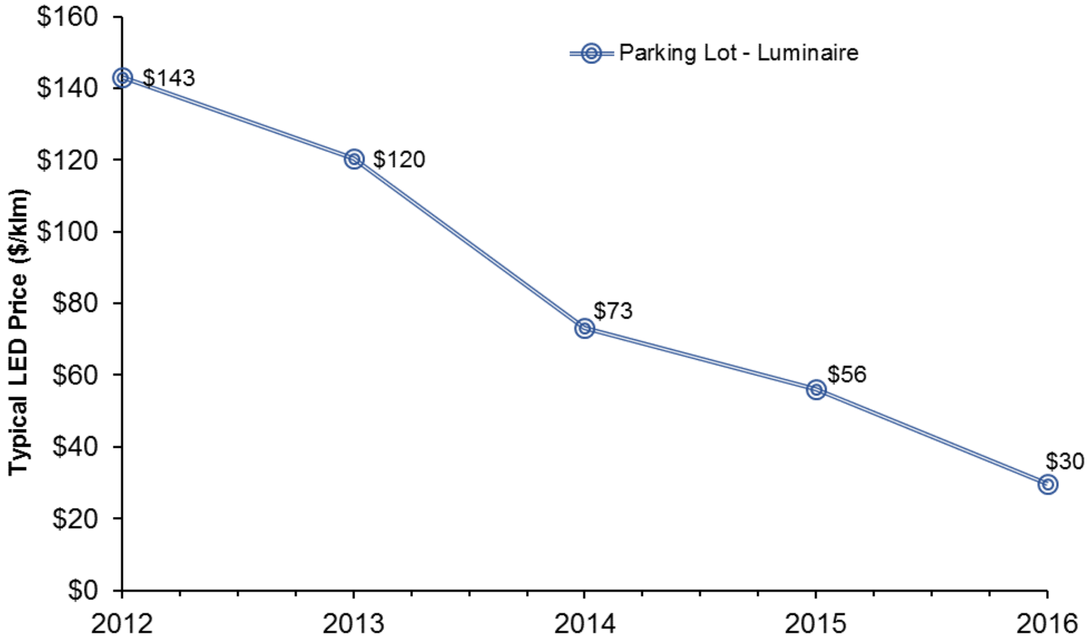

Figure 4.22 Parking Lot LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of parking lot lighting applications decreased slightly by about 1.8% to 436 tBtu due to the increasing penetration of LED lighting. LED products are still the minority of installations; however, it is estimated that they saved about 1.8 TWh of site electricity, or about 18.6 tBtu of source energy in 2016. Additionally, the 0.2 million connected lighting systems are estimated to have saved about 1.0 tBtu of source energy in 2016. Table 4.9 depicts the total and potential energy savings due to LED parking lot installations and connected controls to date.

In 2016, there were 27.0 million parking lot lighting systems installed in the U.S., 7.1 million of which were LED products. If all 27.0 million installations were to switch to LED lamps and luminaires that represented 95^{th} percentile of efficacy performance in 2016 (131 lm/W) it would save 12.0 TWh of site electricity, or about 124 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 14.9 TWh of site electricity, or about 154 tBtu of source energy, for a total of 278 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $2.8 billion.

Table 4.9 Parking Lot LED Energy Savings Summary

Parking Lot	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	26.2%	100%
LED Installed Base (Millions of units[1])	7.1	27.0
LED Energy Savings (tBtu)	18.6	124
Connected Controls Installed Penetration (%)	0.7%	100%
Connected Controls Installed Base (Millions of units[1])	0.2	27.0
Connected Controls Energy Savings (tBtu)	1.0	154

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.9.2 Parking Garage

Parking garage structures are unique in the outdoor sector because lighting fixtures are well protected from the elements and mounting height is generally limited by low ceilings. While HID lamps are used for lighting parking garage structures, the low-mounting heights of lighting fixtures require a large number of fixtures in order to meet desired illumination distributions. These conditions favor linear fluorescent fixtures, although MH and HPS systems are also prominent in this market.

Building code requirements are also helping to bolster the prevalence of LED lighting in parking garage applications. LED lighting is well suited for use with control systems and have been shown to provide additional energy savings of 20% to 60% depending on the application and use-case. (11) Due to this large energy savings potential of lighting controls, in the most recent Title 24 building code,[19] the state of California expanded its requirements for the use of advanced dimming controls, along with occupancy and daylight sensors. As a result, lighting in parking garages in California must have occupancy controls, with power required to reduce by a minimum of 30% when there is no activity detected within a lighting zone for 20 minutes.[20] While these building code requirements are only effective in California, this represents a significant opportunity for LED lighting to help impact energy savings in parking garage applications across the U.S.

Figure 4.23 shows the estimate for the installed base of LED parking garage lamps and luminaires from 2010 to 2016. In 2012, there were only about 400,000 LED parking garage installations, and since then growth has been near exponential. LED products are estimated to represent approximately one third of lighting installations for parking garages with about 8.5 million, or 32.5% of the total. Of these, 8.5 million LED installations, roughly 33.8%, are lamp systems while the remaining 66.2% are luminaires. Connected controls are also penetrating garage applications. In 2016, it is estimated that 0.3 million LED lighting systems in parking garage applications operated with connected lighting controls.

[19] For more information on Title 24 please see: http://www.dgs.ca.gov/dsa/Programs/progCodes/title24.aspx
[20] ANSI/ASHRAE/IES Standard 90.1-2013, Energy Standard for Buildings except Low-Rise Residential Buildings.

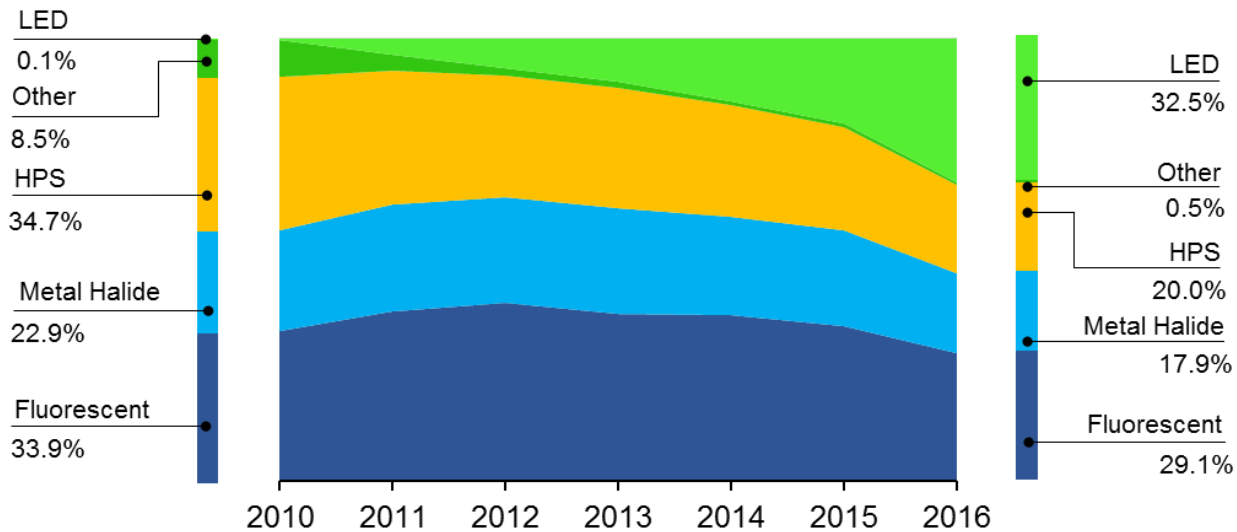

Figure 4.23 U.S. Garage Installed Stock Penetration from 2010 to 2016

LED products in parking garage applications have seen substantial price decline since 2012. As seen in Figure 4.24 below, in 2016, the typical purchase price of LED linear replacement lamp for garage applications was $15/klm, nearly six times the price of equivalent linear fluorescent lamps; however, the price is comparable with HID options, which average around $13/klm. LED garage and canopy luminaires are offered at an even higher cost compared to LED lamps at an estimated $32/klm in 2016.

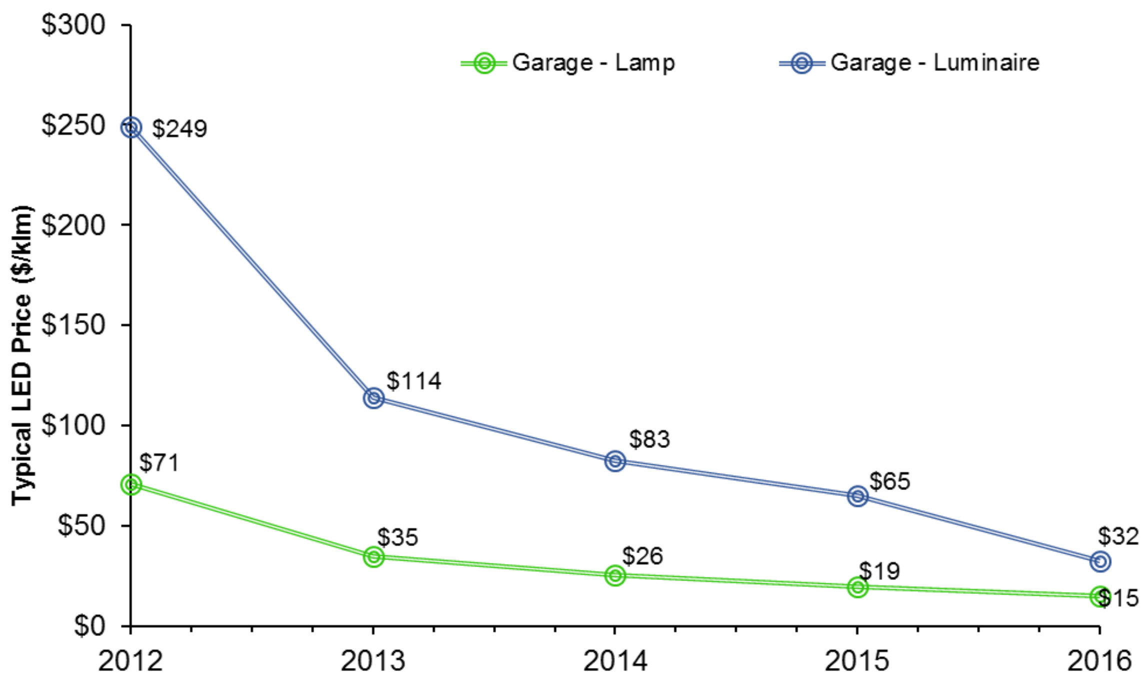

Figure 4.24 Garage LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of parking garage applications decreased slightly by about 2.4% to 223 tBtu due to the increasing penetration of LED lighting. LED products are now nearly a third of all garage installations, and it is estimated that they saved about 1.4 TWh of site electricity, or about 14.4 tBtu of source energy in 2016. Additionally, the 0.3 million connected lighting systems are estimated to have saved about 1.1 tBtu of source energy in 2016. Table 4.10 depicts the total and potential energy savings due to LED parking garage installations and connected controls to date.

In 2016, there were 26.0 million parking garage lighting systems installed in the U.S., 8.5 million of which were LED products. If all 26.0 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (131 lm/W), it would save 7.7 TWh of site electricity, or about 79.5 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 5.0 TWh of site electricity, or about 51.9 tBtu of source energy, for a total of 132 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $2.8 billion.

Table 4.10 Garage LED Energy Savings Summary

Garage	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	32.5%	100%
LED Installed Base (Millions of units[1])	8.5	26.0
LED Energy Savings (tBtu)	14.4	79.5
Connected Controls Installed Penetration (%)	1.0%	100%
Connected Controls Installed Base (Millions of units[1])	0.3	26.0
Connected Controls Energy Savings (tBtu)	1.1	51.9

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

4.10 Building Exterior

This section addresses the 2016 LED Adoption and 2016 Energy Savings Potential results for LED lamps and luminaires in building exterior applications. Building exterior lighting is designed to illuminate walkways, steps, driveways, porches, decks, building architecture, or landscape areas, and it can be used to provide security outside of residential, commercial, and industrial buildings. Wall packs and floodlights are a common choice for these applications, with CFL, MH and HPS systems historically being the most commonly used, especially where a high lumen output is required.

LED lighting has penetrated virtually every aspect of building exterior lighting as qualities such as instant-on, white-color, low maintenance, and good performance have made them increasingly viable options. The ability of LED products to offer low-profile lighting has also made installation easier in areas with tight clearance and offers building managers and specifiers more effective options for lighting narrow areas, such as under benches or accent planters. These small form-factors and the ability to precisely place light sources can result in less light pollution in building exterior applications. LED products may also offer better wall-washing or wall-grazing options for building façades through color tunability and better controllability, thus making them a top choice over incumbent sources.

Building exterior LED lighting includes both lamp and luminaire products; however, reporting in this section has been combined due to the lack of available data on each separately.

As of 2016, fluorescent sources, and in particular CFLs, represent over one-third of the 58.0 million building exterior installations, at 34.2%. However, their share of installed stock has decline significantly since 2010, and LED products are a close second at 31.2%, or 18.1 million installations. As seen in Figure 4.25, the remaining installations are comprised primarily of halogen, HPS and metal halide conventional lamp products. The penetration of connected controls in building exterior applications is estimated to be negligible in 2016.

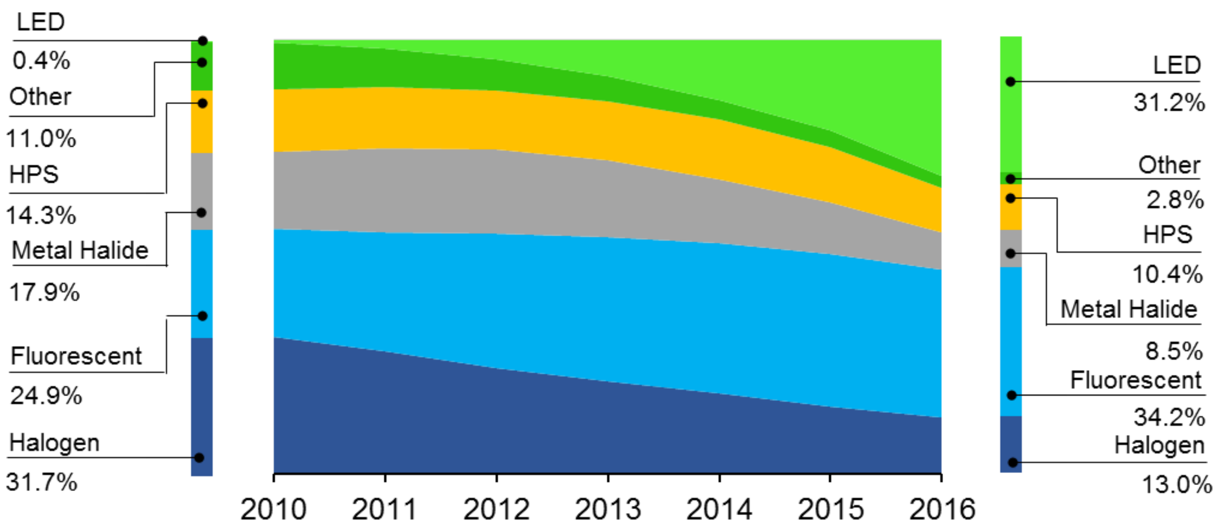

Figure 4.25 U.S. Building Exterior Installed Stock Penetration from 2010 to 2016

LED products for building exterior applications, including flood, wall pack, bollard and landscape luminaires have seen substantial price decline since 2012; however, starting in 2014, the pace has slowed. As seen below in Figure 4.26, the typical purchase price of an LED luminaire for building exterior applications was $51/klm in 2016. Despite the drop in typical price, conventional lighting options are still less expensive with CFL, HPS and metal lamps at approximately $6.1/klm, $1.2/klm and $2.1/klm, respectively.

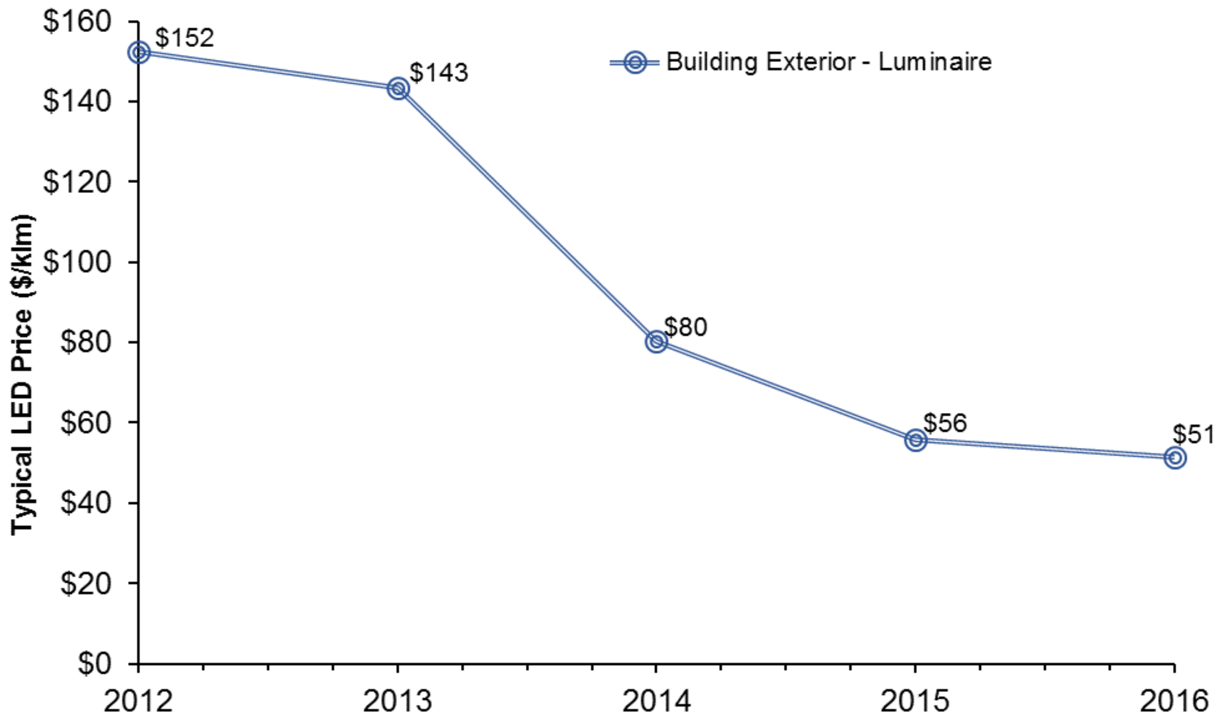

Figure 4.26 Building Exterior LED Price ($/klm) from 2012 to 2016

From 2014 to 2016, the total energy consumption of building exterior applications decreased by about 7.1% to 95.9 tBtu largely due to the increasing penetration of LED lighting. LED products represent a growing minority of installations, and it is estimated that they saved about 1.4 TWh of site electricity, or about 14.0 tBtu of source energy in 2016. Table 4.11 depicts the total energy savings due to LED building exterior products to date and the potential energy savings if the entire nationwide installed base was converted instantaneously to LED technology.

In 2016, there were 58.0 million building exterior lighting systems installed in the U.S., 18.1 million of which were LED products. If all 58.0 million installations were to switch to LED lamps and luminaires that represented 95th percentile of efficacy performance in 2016 (100 lm/W and 106 lm/W respectively), it would save 14.0 TWh of site electricity, or about 36.1 tBtu of source energy. If these same LED products were also configured with connected lighting controls, they would enable savings of an additional 3.3 TWh of site electricity, or about 34.2 tBtu of source energy, for a total of 70.2 tBtu. Energy savings of this magnitude would result in an annual energy cost savings of about $0.7 billion.

Table 4.11 Building Exterior LED Energy Savings Summary

Building Exterior	2016 LED Adoption	2016 Energy Savings Potential
LED Installed Penetration (%)	31.2%	100%
LED Installed Base (Millions of units[1])	18.1	58.0
LED Energy Savings (tBtu)	14.0	36.1
Connected Controls Installed Penetration (%)	--	100%
Connected Controls Installed Base (Millions of units[1])	--	58.0
Connected Controls Energy Savings (tBtu)	--	34.2

1. Installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

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Appendix A Summary of 2016 LED Product and Application Improvements

Application	Product Type	Updates to Description
A-type	Lamp	NA
Decorative	Lamp Luminaire	Provides a break-out of decorative luminaire penetration. Previously included in the "Other" application.
Directional	Lamp Luminaire	NA
Small Directional	Lamp	NA
Downlighting	Lamp & Retrofit Kit Luminaire	Provides a break-out of downlight lamps, retrofits and luminaire penetration. Previously included in the "Directional" application.
Linear Fixtures	Lamp Retrofit Kit & Luminaire	Includes retrofit kits within the luminaire penetration. LED retrofit kits were previously included in the "Other" application.
Low/High Bay	Lamp Luminaire	Provides a break-out of low/high bay lamp penetration. Previously included in the "Other" application.
Street/Roadway	Luminaire	NA
Parking Lot	Luminaire	Includes area lighting applications in addition to parking lot and top deck parking garage illumination. LEDs for area lighting were previously included in the "Street/Roadway" application.
Parking Garage	Lamp Luminaire	Includes canopy lighting applications in addition to parking garage. LEDs for canopy lighting were previously included in the "Building Exterior" application.
Building Exterior	Luminaire	Includes bollard lighting applications. LEDs for bollard lighting were previously included in the "Other" application.
Other	Indoor Outdoor	NA

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