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APPLICATION OF CENTERPOINT	§	BEFORE THE STATE OFFICE
ENERGY HOUSTON ELECTRIC, LLC	§	OF
FOR AUTHORITY TO CHANGE RATES	§	ADMINISTRATIVE HEARINGS

REBUTTAL TESTIMONY

OF

JULIENNE P. SUGAREK

ON BEHALF OF

CENTERPOINT ENERGY HOUSTON ELECTRIC, LLC

June 2019

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LIST OF EXHIBITS

REBUTTAL TESTIMONY OF JULIENNE P. SUGAREK

I. INTRODUCTION

Q. PLEASE STATE YOUR NAME AND POSITION.

A. My name is Julienne P. Sugarek and I am employed by CenterPoint Energy Houston Electric, LLC ("CenterPoint Houston" or the "Company") as Vice President of Power Delivery Solutions.

Q. ARE YOU THE SAME JULIENNE P. SUGAREK WHO SUBMITTED DIRECT TESTIMONY IN THIS PROCEEDING?

A. Yes.

Q. WAS THIS REBUTTAL TESTIMONY PREPARED BY YOU OR UNDER YOUR DIRECT SUPERVISION AND CONTROL?

A. Yes.

Q. WERE THE EXHIBITS LISTED IN THE TABLE OF CONTENTS PREPARED UNDER YOUR DIRECTION, SUPERVISION AND CONTROL?

A. Yes.

Q. WHAT IS THE PURPOSE OF YOUR REBUTTAL TESTIMONY?

A. My rebuttal testimony addresses certain reliability perceptions and cost allocation recommendations made by several intervenor witnesses and Public Utility Commission of Texas ("PUC" or "Commission") Staff in this proceeding. Specifically, I respond to assertions made in the testimony of City of Houston ("COH") witness Scott Norwood, COH witness Kit Pevoto, H-E-B witness George W. Presses, Texas Industrial Energy Consumers ("TIEC") witness Jeffrey Pollock and Commission Staff witness Brian T. Murphy.

II. CENTERPOINT HOUSTON'S RELIABILITY

Q. HOW DO THE INTERVENOR WITNESSES ADDRESS THE COMPANY'S RECORD ON RELIABILITY?

A. Two intervenors, COH and H-E-B appear to have different opinions on the Company's record related to reliability. Mr. Norwood, on behalf of the City of Houston, notes:

> [o]ver the last five years CEHE has received only approximately 120 customer complaints per year related to outages or adequacy of service. This number of complaints represents less than 0.005% of the Company's 2.5 million customers, which indicates a high level of customer satisfaction with CEHE's service reliability.[1]

Mr. Presses, on the other hand, on behalf of H-E-B, argues that the Company's return on equity should be limited "given CenterPoint's failure to reliably serve its customers."[2]

Q. WHAT IS THE COMPANY'S ACTUAL RECORD AS IT RELATES TO RELIABILITY AND QUALITY OF SERVICE?

A. Mr. Norwood is correct that CenterPoint Houston consistently seeks to provide reliable high-quality service.[3] In fact, CenterPoint Houston's diligent efforts to build and maintain a reliable transmission and distribution system result in reliability metrics that usually meet or beat the Commission's reliability standards. The Figure below, also presented in the Direct Testimony of Company witness Dale Bodden shows the Company's SAIDI from 2008-2017.

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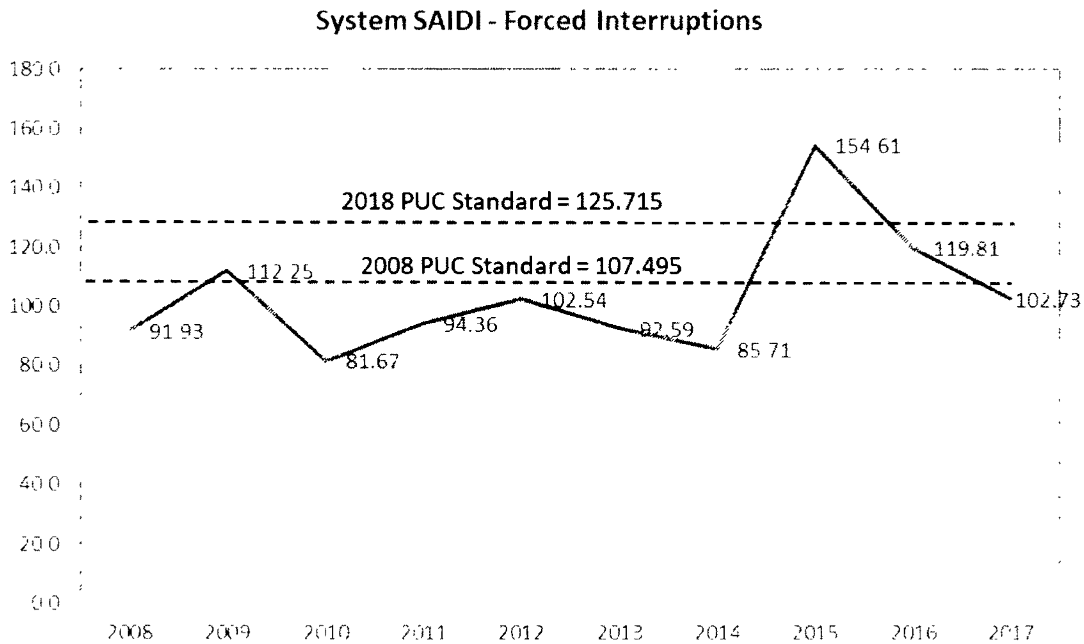
[1] Direct Testimony of Scott Norwood at 9:15-18.

[2] Direct Testimony of George W. Presses at 26:16-17.

[3] The Company disagrees with Mr. Norwood's contention that the Company's high-quality reliability record should result in the disallowance of reasonable and prudent proactive reliability programs, as addressed in the rebuttal testimonies of Randal M. Pryor and Martin W. Narendorf.

Figure 1. System SAIDI



Among ERCOT investor-owned utilities, CenterPoint Houston also consistently receives the lowest annual penalty amounts related to violations of the Commission's SAIDI standard. For 2018, the test year in this case, the Company expects to receive $0 in Commission penalties due to its outstanding performance. To put its 2018 performance in context, it is not unusual for ERCOT investor-owned utilities to be assessed annual quality of service fines ranging from $50,000 to $400,000. While each utility's transmission and distribution system faces different challenges when attempting to meet the Commission's SAIDI standard, CenterPoint Houston is proud of the fact that, when measured against its investor-owned peers in the context of quality of service violations, it ranks as the most reliable investor-owned utility in the State of Texas. Please see Exhibit R-JPS-1 for a listing of Reliability Violation History for Major ERCOT Utilities.

Q. WHAT TYPES OF CHALLENGES DOES CENTERPOINT HOUSTON FACE WHEN ATTEMPTING TO MEET OR BEAT THE COMMISSION'S QUALITY OF SERVICE STANDARD?

A. The Company's geographic position on the Gulf Coast, with a climate that produces above average rainfall, routine thunderstorm activity and annual exposure to tropical depressions, storms and hurricanes, presents its primary challenge when attempting to meet or beat the Commission's Quality of Service Standard. CenterPoint Houston's service territory receives the second highest number of lightning strikes in the country—beaten only by locations in Florida. Thus far in 2019 alone, prior to hurricane season, the Company's service territory has seen significant rainfall and at least four major thunderstorm events that caused outages. In related fashion, the past four years of above average rainfall have resulted in faster vegetation growth, which, if not addressed, may be the cause of future outages.

Q. WHY DO YOU ADDRESS THE COMPANY'S QUALITY OF SERVICE RECORD IN YOUR REBUTTAL TESTIMONY?

A. While Company witness Robert B. Hevert addresses the Company's reliability record in the Context of Intervenors overall return on equity recommendations, my testimony addresses CenterPoint Houston's quality of service record as it relates to Mr. Presses' allegations concerning H-E-B. As demonstrated below, Mr. Presses' comments on the Company's reliability record are not supported by CenterPoint Houston's data and the facts.

III. H-E-B'S RELIABILITY HISTORY

Q. DOES CENTERPOINT HOUSTON PROVIDE SERVICE TO H-E-B?

A. Yes, the Company's records reflect that CenterPoint Houston provided service to 166 H-E-B metered accounts from 2014 through 2018. These sites consist of active metered accounts that serve stores, distribution centers, car washes, large signs and other facilities.

Q. HAS THE COMPANY BEEN ABLE TO DETERMINE THE RELIABILITY HISTORY FOR H-E-B LOCATIONS IN ITS SERVICE TERRITORY BETWEEN 2015 AND 2018?

A. Yes. Exhibit HSPM R-JPS-2 presents the outage history of all 166 H-E-B locations from 2015 to 2018. On average, each meter sustained approximately [redacted] outages per year, [redacted] of those outages were momentary operations and [redacted] outages were sustained outages.

Q. WHAT CONSTITUTES A MOMENTARY OPERATIONS OUTAGE?

A. CenterPoint Houston defines a momentary operation as the instantaneous opening and closing of a substation breaker. Momentary operations outages are all less than one minute in duration. To the customer, many momentary outages are perceived as a "flicker" of lights or minor power loss lasting a matter of a second or seconds.

Q. HOW LONG DOES AN OUTAGE HAVE TO LAST TO BE CONSIDERED A SUSTAINED OUTAGE?

A. CenterPoint Houston defines a sustained interruption to include any interruption that lasts longer than one minute. CenterPoint Houston utilizes a one-minute time definition, while most of our counterparts in Texas utilize a five-minute time definition, making the Company's definitions more stringent than the average definition. This distinction is important when comparing CenterPoint Houston's outage data against other utilities.

Q. DOES THE ANALYSIS CONDUCTED BY THE COMPANY SUPPORT MR. PRESSES' CLAIM THAT H-E-B FACILITIES ARE SUBJECT TO "ROUTINE DISRUPTIONS THAT ARE EVERYDAY FOR MANY HOURS?"

A. No. CenterPoint Houston's study shows that for [redacted]% of days, or [redacted] days per year on average, no premise experienced an outage of two hours or more. Additionally, the Company's study compared the four-year average annual SAIFI and momentary average interruption frequency indices ("MAIFI") to the frequency of outages the H-E-B experienced. The study shows that [redacted]% of H-E-B premises have a better than average MAIFI as compared to the average for all customers in CenterPoint Houston's territory. Further, the study demonstrates that [redacted]% of H-E-B premises have a better than average SAIFI as compared to all customers, which is a result we would expect.

Q. MR. PRESSES CLAIMS THAT ALL H-E-B OUTAGES ARE NOT DUE TO STORMS OR MAJOR EVENTS. DOES YOUR ANALYSIS CONFIRM THAT CLAIM?

A. Mr. Presses is correct that not all H-E-B outages are related to storms and major events. However, the Company's analysis shows that [redacted]% of the outages on H-E-B premises occurred on storm days. There were [redacted] times as many outages on storm days as compared to non-storm days.

Q. MR. PRESSES ALSO ALLEGES THAT H-E-B HAS CONTACTED CENTERPOINT HOUSTON TO ADDRESS ITS RELIABILITY ISSUES. ARE YOU AWARE OF PREVIOUS CONVERSATIONS BETWEEN CENTERPOINT HOUSTON AND H-E-B REGARDING RELIABILITY OF SERVICE?

A. Yes. The Company's records reflect that H-E-B reached out to CenterPoint Houston on June 18, 2015 with concerns about its reliability. Those records also reflect that on June 24, 2015, Mr. Joe Lopez (Energy Manager at H-E-B) provided a list of five of its points of service that H-E-B was primarily concerned with. Exhibit HSPM R-JPS-3 presents this communication exchange. CenterPoint Houston also performed an analysis of outage events at all 151 of H-E-B's then existing points of service. Exhibit HSPM R-JPS-4 presents that analysis. These discussions between Mr. Lopez and Company personnel appear to have led to an executive meeting between leaders with H-E-B and CenterPoint Houston on July 22, 2015.

Q. ARE YOU AWARE OF THE CONTENT OF THE COMPANY'S DISCUSSION WITH H-E-B ON JULY 22, 2015?

A. CenterPoint Houston presented H-E-B with a presentation that provided an overview of service provided to H-E-B, an overview of how electricity is delivered from the point of generation to the end use meter, covered common causes of outages, H-E-B outage data during storm and non-storm days and a detailed analysis of five H-E-B sites including 2015 outage events, remediation already performed and pending remediation. The presentation is attached to my testimony at Exhibit HSPM R-JPS-5.

Q. DID THE PRESENTATION INCLUDE A REVIEW OF H-E-B OUTAGES CAUSED BY STORMS?

A. Yes. As shown in Exhibit HSPM R-JPS-5, part of the analysis performed by CenterPoint Houston was a review of reliability data for the then existing 151 H-E-B active metered accounts. Contrary to the testimony provided by Mr. Presses, the presentation contained a slide with data that showed that 83% of the outage minutes for these locations were during storm events.

Q. DID CENTERPOINT HOUSTON MAKE ANY COMMITMENTS TO TAKE ACTIONS TO ADDRESS THE RELIABILITY CONCERNS RAISED BY H-E-B?

A. Yes. CenterPoint Houston developed a specific action plan for each of the five sites addressed in the presentation (as seen in slides 12-16 in Exhibit HSPM R-JPS-5). For the five sites, CenterPoint Houston outlined actions previously taken and committed to take specific action to remediate these reliability concerns. The actions identified included replacing poles, replacing crossarms, performing infrared inspections, root cause analysis on specific circuits, transformer replacements, and fuse inspections.

Q. WERE ANY ACTIONS TAKEN PRIOR TO THE DISCUSSION IN THE JULY 22, 2015 MEETING?

A. Yes. Actions completed included performing tree trimming at 14 locations, replacing various equipment (including a transformer, cross arm and lightning arrestor), repairing a fuse, and installing a monitor. The work orders associated with these actions are attached to my rebuttal testimony at Exhibit HSPM R-JPS-6.

Q. WERE THE PLANNED REMEDIATIONS COMPLETED?

A. Yes. Inclusive of all nine sites studied between Exhibit HSPM R-JPS-4 and

Mr. Lopez's email, CenterPoint Houston completed 12 infrared inspections, with seven of those being complete circuit inspections. Remediations that were completed included installation of three new capacitor banks, installation of three new pole top switches, replacement of wooden cross arms with fiberglass arms in seven locations, replacing various equipment (such as poles, connectors, lugs, lightning arrestors, and jaw connections) and replacing a recloser with an Intelligent Grid Switching Device. These remediations totaled $250,768 in total cost. Exhibit HSPM R-JPS-7 presents the work orders for the completed activities.

Q. ARE YOU AWARE OF OTHER CONVERSATIONS WITH H-E-B REGARDING RELIABILITY?

A. Yes. On January 17, 2019 I contacted George Presses after receiving notification that he had discussed his reliability concerns with the Commission. Exhibit HSPM R-JPS-8 contains my email to Mr. Presses.

Q. WHAT WAS YOUR PURPOSE IN CONTACTING MR. PRESSES?

A. My purpose was to respond to what appeared to be a customer complaint and to obtain data and analyze it to see whether there were opportunities to improve reliability for H-E-B.

Q. DID YOU OBTAIN DATA FOR H-E-B?

A. Yes. Mr. Presses provided the requested data approximately one month after my initial email, on February 26, 2019. Exhibit HSPM R-JPS-8 also includes this data.

Q. DID CENTERPOINT HOUSTON ANALYZE THE DATA PRESENTED BY H-E-B?

A. Yes. My team analyzed the data and compared it to CenterPoint Houston outage data records for each of the locations provided. In order to compare like data sets, events from 2018 were pulled from both H-E-B provided data and the CenterPoint Houston outage data. An internal meeting was held on April 1, 2019 to review the results of the analysis. The analysis showed a mismatch between the records H-E-B provided and the CenterPoint Houston outage data captured at the substation by SCADA equipment and Company outage records. Exhibit HSPM R-JPS-9 contains the detailed analysis.

Q. YOU REFERENCE A DATA MISMATCH BETWEEN THE STATISTICS PROVIDED BY H-E-B AND CENTERPOINT HOUSTON'S RECORDS. WHAT CAN CAUSE A DATA MISMATCH?

A. It is unclear from the data provided by H-E-B exactly how that outage data was captured, quantified and defined. For CenterPoint Houston's data, we incorporate the event definitions which, as I note above, define a "momentary operation" as the instantaneous opening and closing of a substation breaker and a "sustained" outage as any event exceeding 60 seconds in duration. These events are captured via SCADA at the substation by circuit level. Outages at the recloser, line fuse, transformer and location levels are tracked through our outage system. For circuit operations and lockouts at the substation breaker, duration data are time stamped with high resolution, other events are time stamped based on the original notification.

Q. HOW DOES THE OUTAGE DATA PROVIDED BY H-E-B COMPARE TO THE OUTAGE DATA RECORDED BY CENTERPOINT HOUSTON?

A. Excluding outages caused by customer requested work, CenterPoint Houston's data shows 8,345 total outage minutes, which is 24% less than the data provided by H-E-B.

Q. WHAT ELSE DID THE ANALYSIS OF CENTERPOINT HOUSTON'S DATA SHOW?

A. CenterPoint Houston's outage data showed that [redacted] of the [redacted] stores, or [redacted]%, accounted for 5,240 of the 8,345 outage minutes, or 64% of the total minutes. Fourteen of those [redacted] locations had the majority of their total outage minutes caused by transformer fuse outages, which impacted no other customers. Further research showed only one transformer failure at these sites. The first responders who were dispatched to repair these outages found that the transformer fuses were melted, not blown; indicating potential issues with the transfer mechanism at these locations. Two of the work orders reflecting these findings are attached to my testimony in Exhibit HSPM R-JPS-10 and Exhibit HSPM R-JPS-11.

Q. WHAT IS THE ROOT CAUSE OF MELTING TRANSFORMER FUSES?

A. There are several scenarios that can lead to melting transformer fuses. Most commonly, the transformer has had an internal fault. That was not the case in the outages under review. Another factor can be gross, sustained overloading of 200% or greater. The Company's records indicate that these transformers were not subjected to gross, sustained overloading. See page 3, column titled Max TLM ("Transformer Load Management") of Exhibit HSPM R-JPS-9. Another potential cause of transformers melting occurs when voltage and phase angles are outside of limits during a transfer. In the case of back up facilities, the end use customer (H-E-B, in this instance) was receiving power from its back up facilities and then wanted to transfer back to receiving power from CenterPoint Houston's distribution system. When the backup facilities initiate that transfer, the voltage and/or phase angles between the generator and the Company's system must be within certain limits to allow for proper synchronization. If the voltage and/or phase angles or the mechanical transfer are outside those limits at the moment of paralleling and fail to synchronize with the distribution system properly, they can, over time, melt the transformer fuse causing an outage for customers served off that transformer. Put simply, H-E-B's own on-site generation appears to be generating a substantial amount of its own outages.

Q. FOR THE OUTAGES THAT APPEAR TO BE CAUSED BY H-E-B'S ON-SITE GENERATION FAILING TO SYNCHRONIZE PROPERLY TO THE DISTRIBUTION GRID, HOW MANY OUTAGE MINUTES DO THOSE ACCOUNT FOR?

A. For 2018, the outages account for [redacted] minutes of outage time which is [redacted]% of the total outage minutes.

Q. WERE THERE ANY OTHER FINDINGS IN THE COMPANY'S ANALYSIS?

A. Yes. H-E-B Store #[redacted] had significant outage minutes in 2018. CenterPoint Houston's data set showed [redacted] minutes or [redacted]% of the total outage minutes. Investigation revealed that there was a significant single-phase line exposure beyond H-E-B's point of service. Any faults that occurred beyond H-E-B's point of service resulted in a partial (single phasing) outage for H-E-B Store #[redacted].

Q. DID THE COMPANY TAKE ANY ACTION TO REMEDIATE THE ISSUES FOR H-E-B STORE #[redacted]?

A. Yes. On April 5, 2019, four days after an internal meeting, a fuse was installed at that location. Please see Exhibit HSPM R-JPS-12.

Q. **HAS H-E-B EXPERIENCED ANY SIGNIFICANT OUTAGES FOR STORE #[redacted] SINCE ACTION WAS TAKEN?**

A. No. There have been no sustained outages through June 7, 2019. Exhibit HSPM R-JPS-13 presents Store #[redacted]'s subsequent outage history.

Q. **AS A RESULT OF THE COMPANY'S MOST RECENT ANALYSIS, WHAT NEXT STEPS WERE IDENTIFIED?**

A. CenterPoint Houston wanted to engage a third party, at our expense, to study the issues related to the melting transformer fuses.

Q. **DID THE COMPANY SHARE THE RESULTS OF ITS ANALYSIS WITH H-E-B?**

A. It attempted to. In an email dated April 12, 2019, I proposed a meeting to discuss the results of our findings with Mr. Presses and other representatives from H-E-B. That email is attached at Exhibit HSPM R-JPS-14.

Q. **DID THE EMAIL INCLUDE INFORMATION ABOUT THE ACTION TAKEN AT H-E-B STORE #[redacted]?**

A. Yes. Contrary to Mr. Presses' testimony, my email noted that there was a lateral with a high degree of exposure to vegetation that was causing the outages to Store #[redacted] and that CenterPoint Houston had installed a fuse to prevent sustained interruptions caused downstream. See Exhibit HSPM R-JPS-14.

Q. **DID THE EMAIL INCLUDE INFORMATION ABOUT THE DESIRE TO ENGAGE A THIRD PARTY AT NO COST TO H-E-B TO STUDY THE ISSUES REVEALED BY THE ANALYSIS?**

A. Yes.

Q. **DID YOU RECEIVE A RESPONSE FROM H-E-B?**

A. Shortly after sending the email, Mr. Presses said he would provide dates for a meeting the following week. When no dates were received, I followed up with him on April 26, 2019 again requesting dates to meet. On May 1, 2019 he provided three potential meeting dates in mid to late May. Exhibit HSPM R-JPS-14 also contains this correspondence.

Q. DID THE MEETING OCCUR?

A. No. The meeting was scheduled to occur on May 28, 2019. Mr. Presses reached out to me on May 25, 2019 to cancel the meeting. On May 26, 2019, I again requested a meeting and communicated our desire to bring a third party in to study the issues and the hope to partner with H-E-B to learn from its history and to improve the resiliency of the Company's system. Exhibit HSPM R-JPS-15 includes my email.

Q. ASIDE FROM THE REMEDIATIONS COMPLETED AFTER THE 2015 AND 2019 STUDIES, HAS ANY ADDITIONAL RELIABILITY WORK BEEN PERFORMED THAT WOULD BENEFIT H-E-B?

A. Yes. CenterPoint Houston has a number of major programs and initiatives that are implemented to increase the reliability of the electric delivery system for CenterPoint Houston customers. These programs include the Pole Maintenance Program, the Underground Residential Distribution Cable Life Extension Program, the Meter Maintenance Program, the Vegetation Management Program, the Feeder Inspection Program, the Pole Top Switch Inspection Program and the Service Restoration Process. These seven programs are discussed by Mr. Pryor in his direct testimony. The Company also has a Power Factor Program and certain reliability standards, which Ms. Bodden addresses in her direct testimony. I address the Company's Infra-red Program, the Root Cause Analysis Program, the Hot Fuse

Program and the Distribution Automation Program in my direct testimony. These programs resulted in investments in reliability for many customers, including H-E-B.

Q. **MR. PRESSES NOTES THE IMPACT THAT OUTAGES CAN HAVE ON STORES LIKE H-E-B THAT MAINTAIN COLD INVENTORY. DOES THE COMPANY SERVE OTHER CUSTOMERS THAT MAINTAIN COLD INVENTORY?**

A. Yes. Customers similar to H-E-B in the Company's service territory include such stores as Costco, Sam's, Walmart, Buc-ee's, Randall's, Kroger and other grocery chains.

Q. **TO YOUR KNOWLEDGE, HAVE ANY OF THESE OTHER CUSTOMERS COMPLAINED OF CONSISTENT RELIABILITY ISSUES SIMILAR TO H-E-B?**

A. No. Just as it did in each instance involving a raised H-E-B complaint or reliability concern, the Company works diligently to resolve any customer complaint or concern related to reliability as quickly and diligently as possible. I am unaware of any other similarly-situated customer having a concern over the Company's general reliability or service quality.

IV. <u>LED STREET LIGHTS</u>

Q. **HAS ANY PARTY CHALLENGED THE INCLUSION OF O&M COSTS IN THE CALCULATION OF STREET LIGHTING RATES?**

A. Yes. Ms. Pevoto asserts the O&M cost for LED street lights should be excluded from T&D rates. Please see Company witness Matthew A. Troxle's rebuttal testimony for further details regarding the prudent calculation of the rates of O&M street lighting costs.

Q. MS. PEVOTO CLAIMS THE COMPANY INCURRED NO O&M COSTS IN THE TEST YEAR FOR LED STREET LIGHTS. IS THIS TRUE?

A. No. The Company initially misunderstood the information sought by COH Request for Information No. 02-12. Specifically, CenterPoint Houston's initial response to COH 02-12 read that request to ask for O&M associated with the initial installation of an LED street light. After reviewing Ms. Pevoto's testimony, the Company revised its response based on the apparent confusion. In LED installations, the job as a whole is capitalized, therefore no O&M costs exist at that time. Once the LED light is installed, however, there are various O&M costs, including, but not limited to: fuse replacement, maintaining the post, conduit replacement, and clamp/connector replacement, over its used and useful life to maintain their standard performance. These costs occurred during the test year and are accurately reflected in the cost of service information presented by the Company in its Rate Filing Package and the Company's revised response to COH 02-12.

Q. DOES THE COMPANY HAVE ANY WORK ORDERS DEMONSTRATING THAT O&M COSTS FOR STREET LIGHTS WERE INCURRED DURING THE TEST YEAR?

A. Yes. CenterPoint Houston has a standing work order for all O&M costs associated with all street lights in our territory. This work order is representative of the time sheets and material utilized to operate and maintain all light types including: high pressure sodium, metal halide, mercury vapor, and LED.

Q. WHEN DID THE DISCUSSIONS TAKE PLACE BETWEEN THE CITY OF HOUSTON AND CENTERPOINT HOUSTON REGARDING THE LED STREET LIGHT CONVERSION?

A. The discussions occurred in 2014 to determine and finalize the conversion process terms agreed upon by both parties, shown in Exhibit R-JPS-16.

Q. PLEASE EXPLAIN THE COMPANY'S AGREEMENT WITH THE CITY OF HOUSTON.

A. The City of Houston ("City") approved Ordinance No. 2014-546[4] which allows CenterPoint Houston to convert the City's existing mercury vapor, high pressure sodium vapor and metal halide luminaires to LED luminaires. The Ordinance provides that CenterPoint Houston may seek to recover used and useful capital and reasonable and necessary expenses associated with LED street light installation through a rate proceeding.

Q. IF MS. PEVOTO'S RECOMMENDATION TO DISALLOW RECOVERY OF O&M COSTS FOR LED STREET LIGHTS IS ADOPTED IN THIS PROCEEDING, WILL CENTERPOINT HOUSTON CONTINUE TO OFFER ITS STREET LIGHT REPLACEMENT PROGRAM TO CITIES?

A. No.

Q. HAVE ANY OTHERS CHALLENGED THE COMPANY'S PROPOSAL TO MODIFY ITS EXISTING STREET LIGHTING TARIFF?

A. Yes. Mr. Murphy proposes to deny CenterPoint Houston's proposed modification. Specifically, Mr. Murphy claims that moving the Company's standard lighting installation to LED will eliminate customer choice in lighting options and will

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[4] Houston, Tex., Ordinance 2014-546 (June 10, 2014).

result in higher upfront costs and replacement lighting costs on the customer in the short term. Mr. Murphy also expresses concerns about the payback period for LED lighting services and that LED lighting will fail prior to yielding any financial benefits.

Q. DOES THE PROPOSAL TO MAKE LED THE STANDARD LIGHTING TYPE ELIMINATE CUSTOMER CHOICE?

A. No. As LED has become more widely adopted, suppliers are providing more LED lighting options. There are LED lighting solutions of various wattages, lumen and color temperatures. Today LED-equivalents of all our current standard and decorative street lighting options are available, giving customers a variety of choices to fulfill their street lighting needs.

Q. WILL THE PROPOSAL RESULT IN HIGHER UPFRONT COSTS AND REPLACEMENT LIGHTING COSTS ON THE CUSTOMERS IN THE SHORT TERM, AS MR MURPHY SUGGESTS?

A. No. As discussed in the Company's response to Staff Request for Information No. 03-19, CenterPoint Houston plans to convert non-LED lamps to their LED-equivalent at no cost to the customer during the normal course of maintenance when individual lamps burn out. For new installations, the cost of installing the LED-equivalent standard offering is the same as the non-LED equivalent, resulting in no additional upfront cost to the customer.

Q. HOW DO YOU RESPOND TO MR. MURPHY'S CONCERNS REGARDING THE PAYBACK PERIOD FOR LED LIGHTING?

A. While an analysis has not been completed on the payback period for High Pressure Sodium ("HPS") lighting, by comparing some of the key inputs from the original business case (see discovery response to PUC 09-03) we can arrive at the conclusion that the payback period for HPS lighting service is longer than for that of LED lighting service. As with any financial analysis, the key inputs are the costs and benefits of the project being analyzed. From a cost perspective, the life of an HPS luminaire is estimated to be 29 years and the capital cost of installation is $153.78. Given that the life of the bulb is only five years, on average, a luminaire will require five bulb replacements over its used and useful life. These replacements cost $66.89 per replacement. Thus, the total cost of ownership is $488.23 [$153.78 + (5 * 66.89)]. The life of an LED luminaire is estimated to be 15 years and the capital cost is $201.20. Given that the life of an LED bulb is equivalent to that of a luminaire, no bulb replacements should be required. Two LED luminaire replacements will be required over 30 years. Thus, the total cost of ownership is $402.40 ($201.20 * 2). Due to the cost of LED lighting being lower over a comparable life, it can be inferred that the payback period for the least expensive option is lower. Additionally, the source of benefit in the analysis is the reduction of O&M expenses associated with having to maintain fewer HPS lights. In summary, the costs of continuing to install HPS lighting are higher as compared to LED lighting and the benefits are non-existent. Therefore, there is no payback associated with continuing to install HPS lighting. Further, by delaying the replacement of HPS lighting with LED lighting, and continuing to incur O&M expenses associated with maintaining those lighting solutions, the payback period for LED lighting is lengthened.

Q. MR. MURPHY IS CONCERNED THAT LED LIGHTING WILL FAIL PRIOR TO YIELDING FINANCIAL BENEFITS. HOW DO YOU RESPOND TO THAT CONCERN?

A. In the financial business case (see response to discovery PUC 09-03), the useful life for LED lighting is estimated to be 15 years and the standard deviation is five years. LED lighting is a new technology and these numbers will be evaluated and refined. It is also important to note that unlike other lighting options, LED lights have a 10-year manufacturer's warranty for replacement of the luminaire. The financial business case that Mr. Murphy is relying on to make his assertion account for financial benefits to CenterPoint Houston and does not account for one of the most important benefits of LED lighting. That benefit is the reduced cost to ratepayers for the electricity to power street lights. LED luminaires may provide up to approximately 60% kWh energy savings for the end-use customer. Over the life of an LED luminaire, these savings are significant.

Q. DO YOU HAVE CONCERNS WITH MR. MURPHY'S RECOMMENDATION TO NOT REVISE CENTERPOINT HOUSTON'S LIGHTING TARIFF AS PROPOSED?

A. Yes. As evidenced in the U.S. Department of Energy's 2017 report on "Adoption of Light-Emitting Diodes in Common Lighting Applications," HPS lamp installations for streets and roadways declined from 85.9% in 2010 to 61.9% in 2016. At the same time, the LED luminaire installations for streets and roadways increased from .3% in 2010 to 28.3% in 2016. This shift is affecting manufacturers of lighting products. For example, GE announced in 2015 that it was discontinuing production of certain traditional lighting products as of January 1, 2016 and is prioritizing more efficient LED and smart lighting technology (see Exhibit R-JPS-17). Further, see the Manufacturing Prospects White Paper from October of 2016, which states in pertinent part that "luminaire manufacturers estimate that they'll be manufacturing solid-state light ("SSL," which refers to types of lighting that use semi-conductor light-emitting diodes like LED as opposed to other sources of illumination) exclusively within five years." See Exhibit R-JPS-18. The indication is that our current standard providing for older technology lighting is not sustainable. Further, maintaining an inventory of these products will result in additional costs that will ultimately be borne by ratepayers.

V. TRANSMISSION SERVICE FACILITY EXTENSIONS

Q. DOES MR. POLLOCK ACCURATELY DESCRIBE THE COST OF THE FACILITIES EXTENSION FOR A TRANSMISSION SERVICE CUSTOMER?

A. No. On page 37 of his testimony, Mr. Pollock states that "the customer must fund construction of (and agree to operate and maintain) a retail customer-owned substation to be constructed by CenterPoint." This is untrue. The customer must build, own, and operate their own substation. CenterPoint Houston constructs transmission interconnection facilities to the customer owned substation in accordance with the Transmission Voltage Facility Extension Agreement.

Mr. Pollock also incorrectly states that the customer may enter into a Utility Construction Services Study Agreement to determine the scope of the construction services and would be responsible for covering the costs of the services upfront. The Utility Construction Services Study Agreement he references, which is proposed Tariff Section 6.3.4.7, is not used for transmission customers. This agreement is for other non-standard types of service such as premium rollover distribution service.

Q. ARE MR. POLLOCK'S CONCERNS REGARDING THE COMPANY'S TRANSMISSION FACILITY EXTENSIONS POLICY VALID?

A. No, they are not. First, Mr. Pollock states that he is concerned that the customer is required to pay upfront for the cost of the facility extension and that there is no tariff provision that requires CenterPoint Houston to refund the customer's payment if actual costs are lower than estimated costs. Section 5(b)(ii) of the Transmission Facility Extension Agreement is a placeholder for negotiated payment terms. This section of the agreement states that at the completion of the Project, the difference between the Actual Facilities Extension Cost and the sum of any Project Payment made by the customer will be calculated. If the Actual Facilities Extension Cost is less than the Project Payments, a refund will be issued. If the Actual Facilities Extension Cost is greater than the Project Payments, an invoice will be issued. Please see Exhibit R-JPS-19.

Second, Mr. Pollock expresses concern for when customer-funded facilities are subsequently used to serve other customers. CenterPoint Houston determines which facilities are needed solely to interconnect the transmission customer, and are therefore not eligible for rate recovery, and requests upfront payment for those facilities. Please refer to Exhibit R-JPS-19 for a description of the System Improvement Costs, which are meant to address any part of the Project that could be used by others in the future, and how they are handled during the course of the Project. The System Improvement Costs are identified and are subtracted from the

Actual Cost, resulting in the Initial CIAC Estimate.

Q. DOES THIS CONCLUDE YOUR REBUTTAL TESTIMONY?

A. Yes, it does.

AFFIDAVIT FOR AUTHENTICATION OF BUSINESS RECORDS

AFFIDAVIT OF JULIENNE P. SUGAREK

THE STATE OF TEXAS	§	
	§	
COUNTY OF HARRIS	§	

Before me, the undersigned authority, personally appeared Julienne P. Sugarek who, being duly sworn, deposed and said:

1. My name is Julienne P. Sugarek. I am the Vice President of Power Deliver Solutions at CenterPoint Energy Houston Electric, LLC ("CenterPoint Houston"). I am of sound mind, capable of making this affidavit, and have personal knowledge of the facts stated which are all true and correct.
2. I am an authorized custodian of records for CenterPoint, and as such, I am the custodian of the records attached to my rebuttal testimony in Docket No. 49421, *Application of CenterPoint Houston Electric, LLC for Authority to Change Rates.*
3. The records attached to my rebuttal testimony, consisting of presentations, analysis, data, work orders, outage data, trouble orders, a facilities extension agreement, and correspondence are kept by CenterPoint Houston in the regular course of its business.
4. It was the regular course of business for an employee or representative of CenterPoint Houston with knowledge of the acts, events, conditions, or opinions recorded to make the records or to transmit information thereof to be included in such records.
5. The attached records were made at or near the time of the act, event, condition, or opinion recorded, or reasonably soon thereafter.
6. The attached records are the originals or exact duplicates of the originals.

Julienne Sugarek
Signature

Julienne Sugarek
Printed Name

SUBSCRIBED AND SWORN before me on the 18th day of June, 2019.

Alice S Hart
Signature of Notary

ALICE S HART
Notary Public, State of Texas
My Commission Expires 07-17-2019

STATE OF Texas §
§
COUNTY OF Harris §

AFFIDAVIT OF JULIENNE P SUGAREK

BEFORE ME, the undersigned authority, on this day personally appeared Julienne P Sugarek who having been placed under oath by me did depose as follows:

1. "My name is Julienne P Sugarek. I am of sound mind and capable of making this affidavit. The facts stated herein are true and correct based upon my personal knowledge.

2. I have prepared the foregoing Rebuttal Testimony and the information contained in this document is true and correct to the best of my knowledge."

Further affiant sayeth not.

JULIENNE P SUGAREK

SUBSCRIBED AND SWORN TO BEFORE ME on this 17th day of June, 2019.

PANDY LIVINGSTON
NOTARY ID #547552-2
My Commission Expires
March 21, 2022

Notary Public in and for the State of ______

My commission expires: 3-21-22

Reliability Violation History for Major ERCOT Utilities
2014-2018
Summary as of 6/12/2019

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations

2014	**CEHE**	45103	8	• No system-wide SAIDI or system-wide SAIFI violations.
				• Feeders having SAIDI more than 300.0% greater than system average for two consecutive years:
				    • one feeder in violation of the rule for the first year.
				• Feeders having SAIFI more than 300.0% greater than system average for two consecutive years:
				    • three feeders in violation of the rule for the first year.

2015	**CEHE**	46001	27	• SAIDI exceeded its system-wide standard by 25% or more.
				• SAIFI exceeded its system-wide standard by 5% or more.
				• Feeders having SAIDI more than 300.0% greater than system average for
				• two consecutive years:
				    • three single feeders in violation of the rule for the first year.
				• Feeders having SAIFI more than 300.0% greater than system average for two consecutive years:
				    • two single feeders in violation of the rule for the first year.

2016	**CEHE**	47471	23	• SAIDI exceeded system-wide standard by 11.45%.
				• SAIDI exceeded system-wide standard by 43.825% in previous year, which makes violation of rule for two consecutive years.
				• Feeders having SAIDI more than 300.0% greater than system average for two consecutive years:
				    • one single feeder in violation of the rule for the first year; and
				    • one single feeder in violation of the rule for two consecutive years.
				• Feeders having SAIFI more than 300.0% greater than system average for two consecutive years:
				    • two single feeders in violation of the rule for two years in a row.

2017	**CEHE**	48573	40	• Feeders having SAIDI more than 300.0% greater than system average for two consecutive years:

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations

				• One single feeder in violation of the rule for three consecutive years.
				• Feeders having SAIFI more than 300.0% greater than system average for two consecutive years:
				  • Two single feeders in violation of the rule for the first year; and
				  • Two single feeders in violation of the rule for three consecutive years.

2018	**CEHE**	None	0	• PUC intends to not fine CEHE

2014	**AEP TCC**	45362	57	• SAIDI exceeded system-wide standard by more than 25%;
				• SAIDI was at least 25% above system-wide standard for two or more years in a row;
				• SAIFI was more than 5% above system-wide standard;
				• SAIFI was 5% above standard for two consecutive years.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				  • five single feeders in violation of the rule for the first year,
				  • two single feeders in violation of the rule two years in a row, and;
				  • one single feeder in violation of the rule for four consecutive years.

2015	**AEP TCC**	46361	89	• SAIDI exceeded system-wide standard by more than 25%,
				• SAIDI was at least 25% above system-wide standard for two or more years in a row,
				• SAIFI was more than 5% above system-wide standard,
				• SAIFI was 5% above standard for two consecutive years.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				  • four single feeders in violation of the rule for the first year,
				  • three single feeders in violation of the rule two years in a row,
				  • one single feeder in violation of the rule for three consecutive years, and
				  • one single feeder in violation of the rule five consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				  • two single feeders in violation of the rule for the first year.

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations

2016	**AEP TCC**	47781	85	• SAIDI exceeded system-wide standard by 72.4%,
				• SAIDI was at least 25% above system-wide standard for two or more years in a row,
				• SAIFI was 18.3% above system-wide standard, and
				• SAIFI was 15% above system-wide standard for two consecutive years.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • Nine single feeders in violation of the rule for the first year,
				    • One single feeder in violation of the rule two years in a row,
				    • One single feeder in violation of the rule for three consecutive years; and
				    • One single feeder in violation of the rule five consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • Two single feeders in violation of the rule for the first year; and
				    • One single feeder in violation of the rule for two consecutive years.

2014	**AEP TNC**	45363	25	• SAIDI exceeded system-wide standard by more than 25%;
				• SAIDI was at least 25% above system-wide standard for two or more years in a row.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • five single feeders in violation of the rule for the first year, and
				    • two single feeders in violation of the rule two years in a row.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • two single feeders in violation of the rule for the first year.

2015	**AEP TNC**	46362	76	• SAIDI exceeded system-wide standard by more than 25%;
				• SAIDI was at least 15% above system-wide standard for two or more years in a row.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • seven single feeders in violation of the rule for the first year,
				    • two single feeders in violation of the rule two years in a row, and;
				    • two single feeders in violation of the rule three consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations
				• two single feeders in violation of the rule for the first year, and; • one single feeder in violation of the rule two consecutive years.

2016	**AEP TNC**	47782	72	• SAIDI exceeded system-wide standard by 64.8%
				• SAIDI reported was 71% for 2015 which was 25% above system-wide standard for two or more years in a row.
				• SAIFI exceeded system-wide standard by 13.4%.
				• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				  • Three single feeders in violation of the rule for the first year,
				  • Three single feeders in violation of the rule two years in a row, and;
				  • Two single feeders in violation of the rule three consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				  • One single feeder in violation of the rule for the first year.

2017	**AEP TX**	48774	84	• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				  • Two single feeders in violation of the rule for the first year,
				  • Four single feeders in violation of the rule two years in a row,
				  • Two single feeders in violation of the rule for three consecutive years,
				  • One single feeder in violation of the rule for four consecutive years; and
				  • One single feeder in violation of the rule more than five consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				  • One single feeder in violation of the rule for the first year.

2018	**AEP TX**	None Yet	?	• No information available

2014	**Oncor**	45305	220.5	• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				  • Twenty-five single feeders in violation of the rule for the first year;
				  • Nine single feeders in violation of the rule for two years in a row;

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations

				• Three single feeders in violation of the rule for three years in a row;
				    • Four single feeders in violation of the rule for four years in a row; and
				    • Two single feeders in violation of the rule for five consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • Thirteen single feeders in violation of the rule for the first year, and
				    • One single feeder in violation of the rule for two years in a row.

2015	**Oncor**	46733	288.5	• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • Twenty-one single feeders in violation of the rule for the first year;
				    • Fifteen single feeders in violation of the rule for two years in a row;
				    • Seven single feeders in violation of the rule for three years in a row;
				    • Two single feeders in violation of the rule for four years in a row;
				    • Two single feeders in violation of the rule for five years in a row; and
				    • One single feeder in violation of the rule seven consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • Twelve single feeders in violation of the rule for the first year,
				    • Four single feeder in violation of the rule for two years in a row; and
				    • One single feeder in violation of the rule three consecutive years.

2016	**Oncor**	47783	329	• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • Twenty-two single feeders in violation of the rule for the first year;
				    • Seven single feeders in violation of the rule for two years in a row;
				    • Eleven single feeders in violation of the rule for three years in a row; and
				    • Seven single feeders in violation of the rule for four years in a row.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • Nine single feeders in violation of the rule for the first year,
				    • Two single feeders in violation of the rule for two years in a row;
				    • One single feeder in violation of the rule three consecutive years; and
				    • One single feeder in violation of the rule four consecutive years.

Report Year	Utility	PUC Docket No.	Fine ($000)	Violations

2017	**Oncor**	48841	432	• Feeders having SAIDI more than 300% greater than system average for two consecutive years:
				    • Thirteen single feeders in violation of the rule for the first year,
				    • Nine single feeders in violation of the rule for two years in a row;
				    • Four single feeder in violation of the rule three consecutive years;
				    • Nine single feeder in violation of the rule four consecutive years; and
				    • Six single feeders in violation of the rule five consecutive years.
				• Feeders having SAIFI more than 300% greater than system average for two consecutive years:
				    • Seven single feeders in violation of the rule for the first year,
				    • One single feeders in violation of the rule for two years in a row;
				    • One single feeder in violation of the rule three consecutive years;
				    • One single feeder in violation of the rule four consecutive years; and
				    • One single feeders in violation of the rule five consecutive years.

2018	**Oncor**	None Yet	?	• No information available

Exhibits HSPM R-JPS-2 through R-JPS-15 are Highly Sensitive and will be provided pursuant to the terms of the Protective Order issued in Docket No. 49421.

075829
2014-0544

LED STREET LIGHT INSTALLATION AND TARIFF AGREEMENT

This LED Street Light Installation and Tariff Agreement is entered into by and between CenterPoint Energy Houston Electric, LLC ("CenterPoint" or the "Company") and the City of Houston, Texas ("City") (collectively, the "Signatories").

1. CenterPoint will procure and install LED luminaires and new photoelectric relays for all street lights within the City for which replacements satisfactory to the City and CenterPoint are commercially available (hereinafter the "Project"). A current list of satisfactory and commercially available LED luminaire replacements for existing mercury vapor, high pressure sodium, and metal halide street lights is attached as Exhibit "A."

2. The Project shall commence within three months of the date of final approval of the initial rates described in paragraph 4 below and subject to paragraph 3 below, shall be complete no later than five years after commencement. The deployment plan for the Project will be designed to proceed no slower than replacing approximately 20% of the existing street lights in year 1, 25% in both years 2 and 3, and 15% in both years 4 and 5. After commencement of the Project, all new streetlights installations within the City will consist of LED luminaires satisfactory to the City and CenterPoint that are commercially available, unless otherwise agreed to in writing by CenterPoint and the City or unless the Project is terminated in accordance with paragraph 8.

3. The City acknowledges that the Company's ability to commence and complete the Project on the timeline set forth in paragraph 2 above is dependent upon factors such as workforce availability and vendor production constraints which could affect the commencement and completion dates. The Company will notify the City upon the occurrence of any event that will affect the commencement and completion dates.

4. Within 15 days of the approvals in paragraph 10, CenterPoint will submit initial rates for the Project for approval by the City and may also submit those rates for approval by all of its other original jurisdiction regulators. The Signatories agree that the initial rates for the Project shall be those reflected on the attached Exhibit B and agree to support those initial rates if they are challenged in proceedings before the Public Utility Commission of Texas (PUC). In the event that the PUC approves initial rates that are different from those set forth on Exhibit B, either CenterPoint or the City may terminate this Agreement. The Signatories acknowledge that the initial rates set forth in Exhibit B may be changed in subsequent rate proceedings. Any such change in the initial rates shall not be grounds for the termination of this Agreement.

5. The City acknowledges that CenterPoint may request recovery of the capital (including a reasonable return) and expenses associated with the Project through either a distribution capital recovery factor application under Public Utility Commission of Texas Substantive Rule 25.243 or other rate proceeding. The City agrees that the Project is prudent, reasonable and necessary and acknowledges that CenterPoint may request recovery by CenterPoint of all used and useful capital (including a reasonable return) and the reasonable and necessary expenses associated with the Project.

6. During the 2015 session of the Texas Legislature, the City agrees not to oppose legislation extending to January 1, 2023 the expiration date of the periodic rate adjustment currently set forth in Texas Utilities Code section 36.210.

7. During the Project period, CenterPoint will work in good faith with vendors to identify satisfactory LED replacement luminaires for those street light luminaires within the City that are not currently part of the Project. As the Company and the City agree on additional LED replacement luminaires, the Company will seek regulatory approval of rates for those street lights not currently part of the Project, if different than the rates described in paragraph 4 above, and following regulatory approval, if needed, will add those street lights to the Project.

8. CenterPoint shall have the right to terminate the Project upon thirty days written notice to City if (a) CenterPoint's rates for distribution service are reduced below the levels in place as of the date of this LED Street Light Installation and Tariff Agreement as a result of a proceeding in which the City participates in a manner adverse to CenterPoint; or (b) the periodic rate adjustment currently set forth in Texas Utilities Code section 36.210 is not extended until at least January 1, 2023 or replaced by a substantially equivalent capital cost recovery mechanism.

9. The Signatories agree that this LED Street Light Installation and Tariff Agreement may be executed in multiple counterparts.

10. This agreement is subject to approval by the board of directors of CenterPoint Energy, Inc. and the City Council of the City.

11. Subject to the condition in paragraph 8, this agreement is effective on the date of the countersignature by the City Controller.

CENTERPOINT ENERGY HOUSTON ELECTRIC, LLC

By: [signature]
Name: TRACY BRIDGE
Title: EVP & President, Electric Division
Date: 5/21/14

CITY OF HOUSTON, TEXAS

Annise D. Parker
Mayor Date

Annanda Washington

ATTEST/SEAL:

6/12/14

Anna Russell
City Secretary Date

COUNTERSIGNED:

Ronald C. Green Leonard Polk
City Controller Date 6-16-14

APPROVED AS TO FORM:

5.22.2014

Steven E. Kirkland Date
Sr. Assistant City Attorney

APPROVED:

6/4/14

Tina Paez, Date
Director, Administration
and Regulatory Affairs Department

APPROVED:

6/5/14

Laura Spanjian, Date
Director, Mayor's Office of Sustainability

Exhibit A

- All non-decorative 70-100 watt high pressure sodium, metal halide, and mercury vapor lights will be replaced with a cobra 45 watt LED or equivalent
- All non-decorative 150 watt high pressure sodium and 175 watt mercury vapor and metal halide lights will be replaced with a cobra 95 watt LED or equivalent
- All non-decorative 250 watt high pressure sodium and metal halide lights will be replaced with a cobra 115 watt LED or equivalent
- All non-decorative 400 watt metal halide and mercury vapor lights will be replaced with a cobra 180 watt LED or equivalent

Exhibit B

Lamp Type Initial Lumen	Watt (Bulb Only)	Schedule A*	Schedule B*	Schedule C*	Schedule D*	Schedule E*	Monthly KWH
Mercury Vapor							
58,000 Lumen	1,000	$8.82	$22.97	$14.01	$23.28	$16.75	365
22,600 Lumen	400	$5.15	$17.75	$11.50	$19.75	$13.14	150
7,800 Lumen	175	$3.64	N.A.	N.A.	$15.89	$10.40	69
4,200 Lumen	100	$3.54	$16.91	N.A.	$13.70	N.A.	41
High Pressure Sodium Vapor							
50,000 Lumen (Set Back)	400	$14.22	N.A.	N.A.	$24.16	$21.30	160
50,000 Lumen	400	$7.93	$20.65	$14.01	$23.28	$15.50	160
28,000 Lumen (Set Back)	250	$14.45	N.A.	N.A.	$24.16	$21.30	106
28,000 Lumen	250	$5.15	$17.75	$11.66	$19.75	$13.15	106
15,000 Lumen	150	$3.64	$16.20	$10.77	$15.89	$10.40	58
9,500 Lumen	100	$3.64	$16.20	N.A.	$12.92	$8.88	38
6,000 Lumen	70	$3.58	$16.13	N.A.	$12.46	N.A.	29
Metal Halide							
32,200 Lumen	400	$9.49	N.A.	N.A	$23.94	$18.56	159
19,475 Lumen	250	$10.34	N.A.	N.A.	$26.43	$18.35	96
12,900 Lumen	175	$11.01	N.A.	N.A	$23.52	$17.09	70
7,900 Lumen	100	$11.69	N.A.	N.A.	$23.29	$19.68	40
Light Emitting Diode (LED)[1]							
4,800 Lumen	60	N.A	N.A.	N.A.	$17.31	N.A	17
LED Alternative For 400W Mercury Vapor							
15,100 Lumen	180	$5.15	$17.75	$11.50	$19.75	$13.14	64
LED Alternative For 175W Mercury Vapor							
7,900 Lumen	95	$3.64	N.A.	N.A.	$15.89	$10.40	32
LED Alternative For 100W Mercury Vapor							
4,800 Lumen	45	$3.54	$16.91	N.A.	$13.70	N.A	17
LED Alternative For 250W High Pressure Sodium							
15,100 Lumen	180	$5.15	$17.75	$11.66	$19.75	$13.15	64

2nd LED Alternative For 250W High Pressure Sodium							
10,850 Lumen	115	$5.15	$17 75	$11 66	$19 75	$13.15	38
LED Alternative For 150W High Pressure Sodium							
7,900 Lumen	95	$3.64	$16 20	$10 77	$15 89	$10.40	32
LED Alternative For 100W High Pressure Sodium							
4,800 Lumen	45	$3.64	$16 20	N A.	$12.92	$8.88	17
LED Alternative For 70W High Pressure Sodium							
4,800 Lumen	45	$3.58	$16 13	N.A.	$12 46	N.A	17
LED Alternative For 400W Metal Halide							
15,100 Lumen	180	$9.49	N.A.	N A.	$23 94	$18.56	64
LED Alternative For 250W Metal Halide							
15,100 Lumen	180	$10.34	N.A.	N.A.	$26 43	$18.35	64
2nd LED Alternative For 250W Metal Halide							
10,850 Lumen	115	$10 34	N A.	N.A.	$26 43	$18 35	38
LED Alternative For 175W Metal Halide							
7,900 Lumen	95	$11.01	N.A.	N.A.	$23.52	$17.09	32
LED Alternative For 100W Metal Halide							
4,800 Lumen	45	$11.69	N.A.	N.A.	$23.29	$19.68	17

[1]The initial rate levels shown in this Rate Schedule for LED luminaires are subject to change, perhaps significantly, in the next Cost of Service rate filing.

* DESCRIPTION OF LIGHTING CONFIGURATIONS

Schedule A -one or more lamps/luminaires mounted on existing distribution poles and served by overhead conductors.

Schedule B -single lamp/luminaire mounted on ornamental standard and served by overhead conductors. Limited to existing installations.

Schedule C -twin lamps/luminaires mounted on ornamental standard and served by overhead conductors. Limited to existing installations.

Schedule D -single lamp/luminaire mounted on ornamental standard and served by underground conductors, or decorative residential streetlights.

Schedule E -twin lamps/luminaires mounted on ornamental standard and served by underground conductors.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Adoption of Light-Emitting Diodes in Common Lighting Applications

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

July 2017

Prepared by Navigant

Adoption of Light-Emitting Diodes in Common Lighting Applications

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy

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July 2017

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Disclaimer

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COMMENTS

The Energy Department is interested in feedback or comments on the materials presented in this document. Please write to James Brodrick, Lighting Program Manager:

James R. Brodrick, Ph.D.
Lighting Program Manager
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585-0121

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.

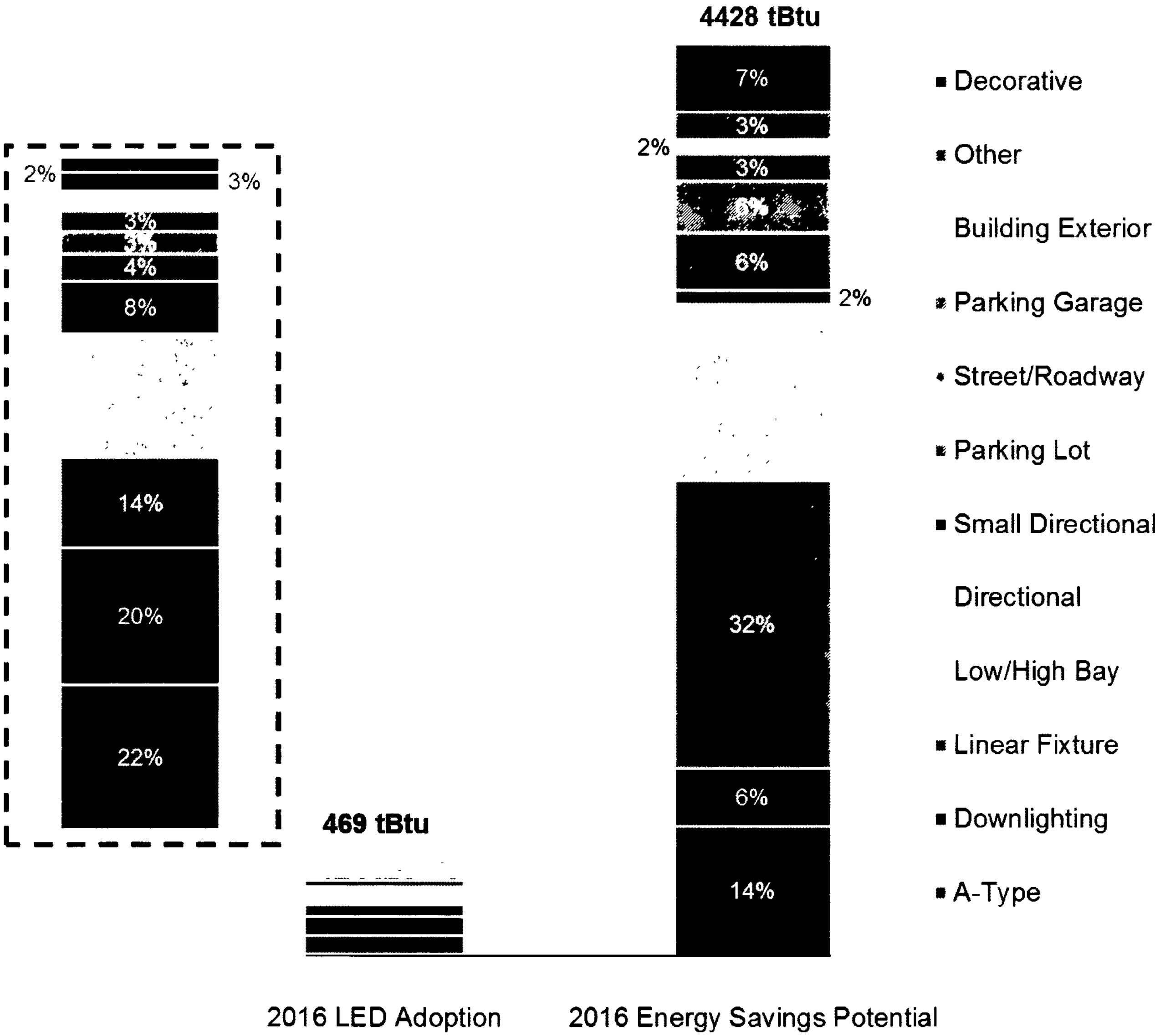

Figure ES.1 – Comparison of 2016 and Potential Energy Savings from LED Lighting

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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?

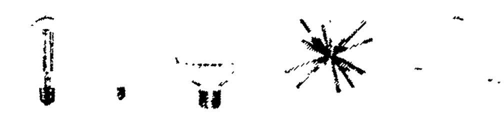
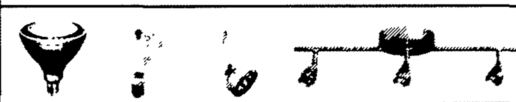
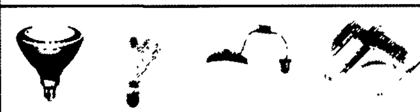
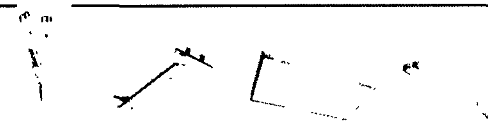
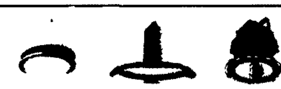
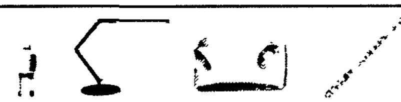
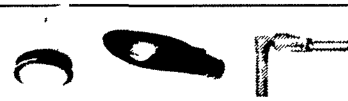
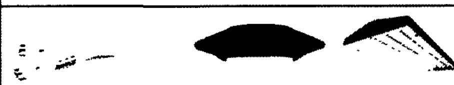
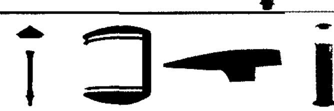
For this report, connected lighting systems are assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate with each other and transmit data. The energy savings for connected 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.

[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.

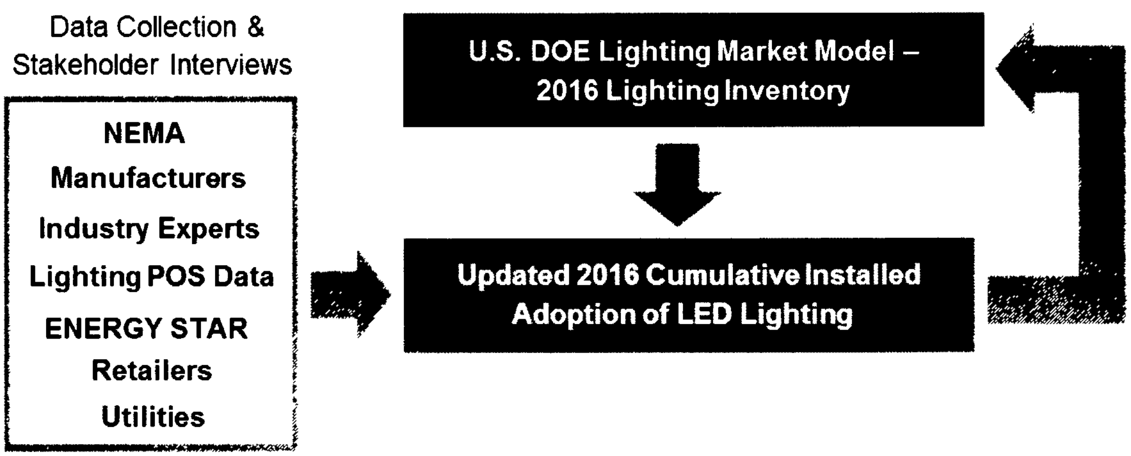


Figure 2.1 2016 LED Adoption Estimation Methodology

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/.

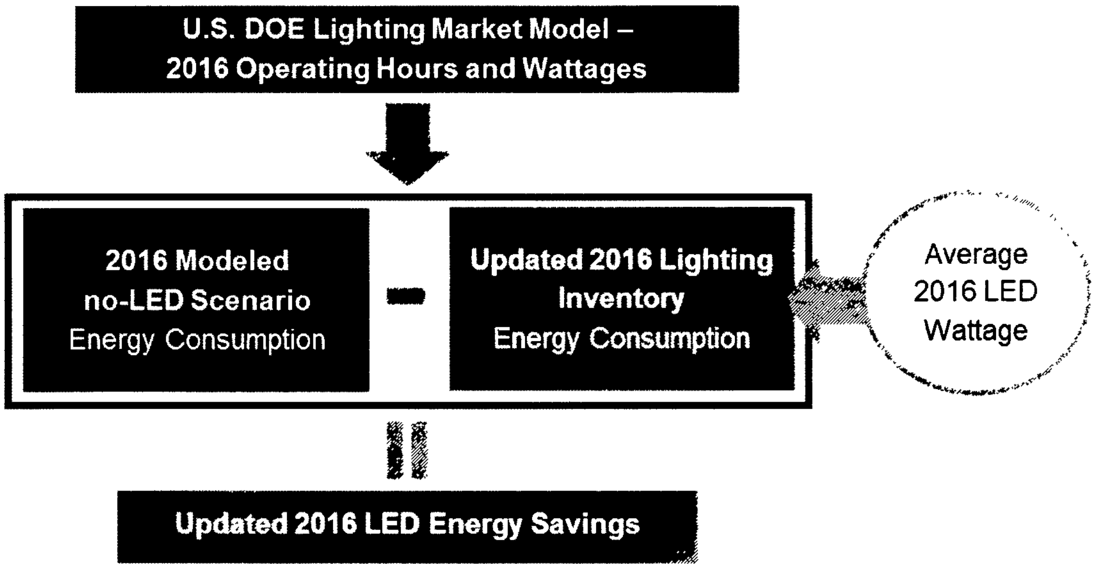


Figure 2.2 2016 LED Energy Savings Methodology[7]

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.

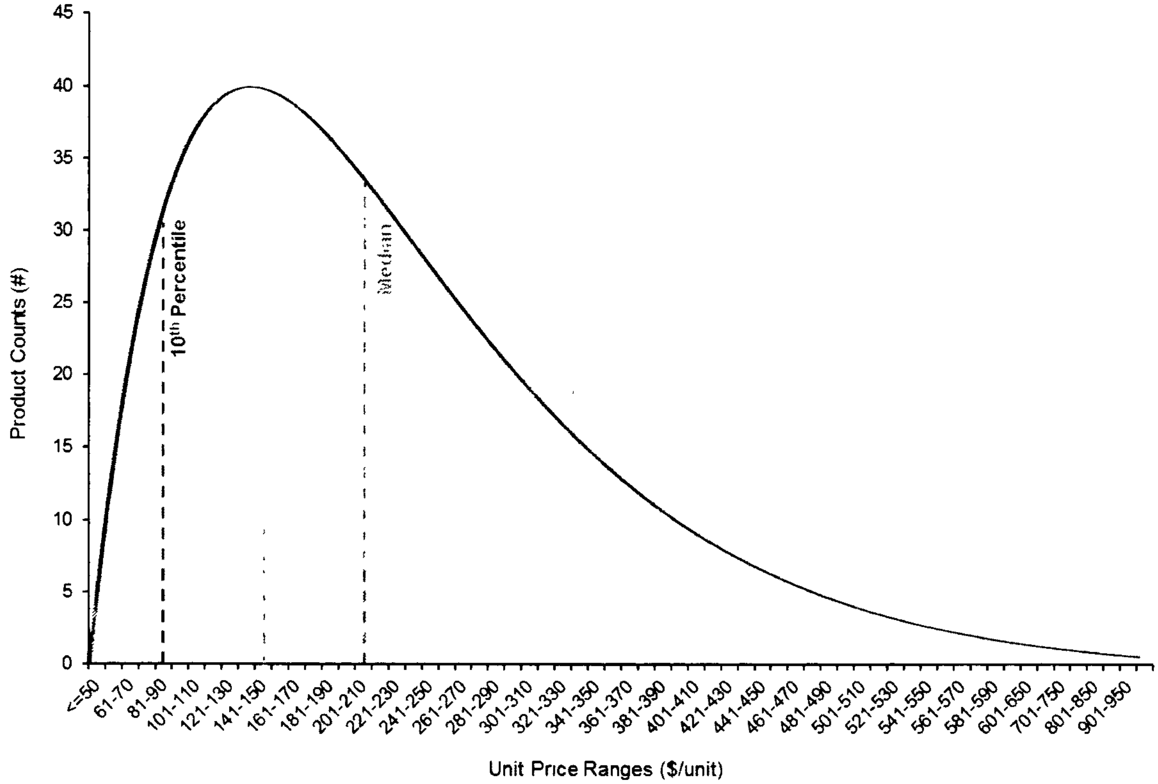


Figure 3.1 Price Distribution for 2'x4' LED Recessed Troffers Q12016

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.

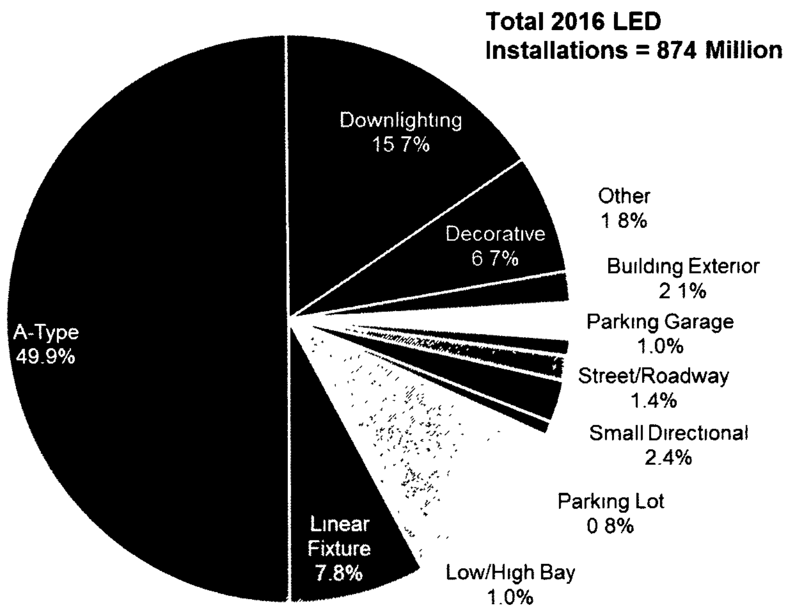


Figure 4.1 Total 2016 LED Unit Installations by Application

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.

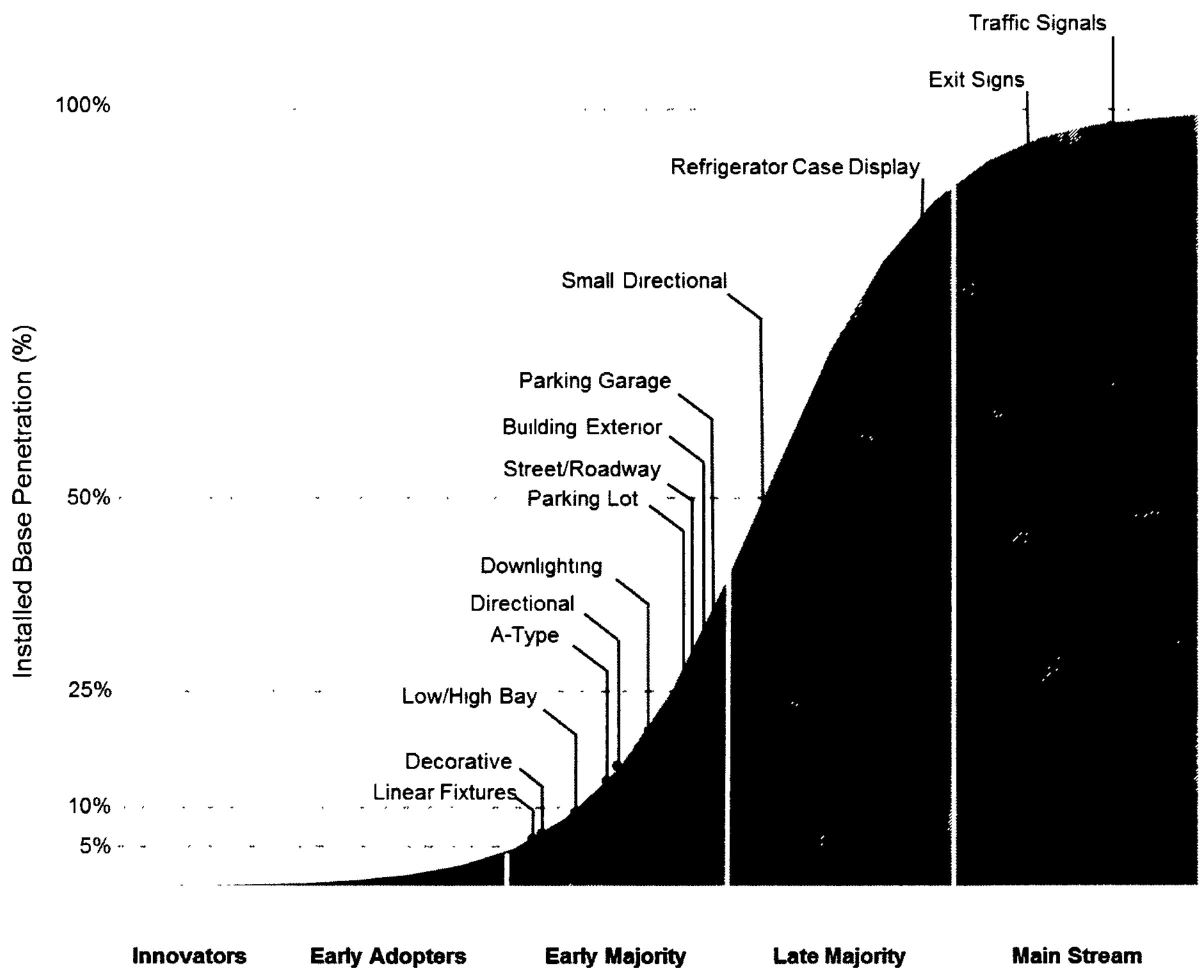


Figure 4.2 2016 Installed Adoption of LED Lighting Applications

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.

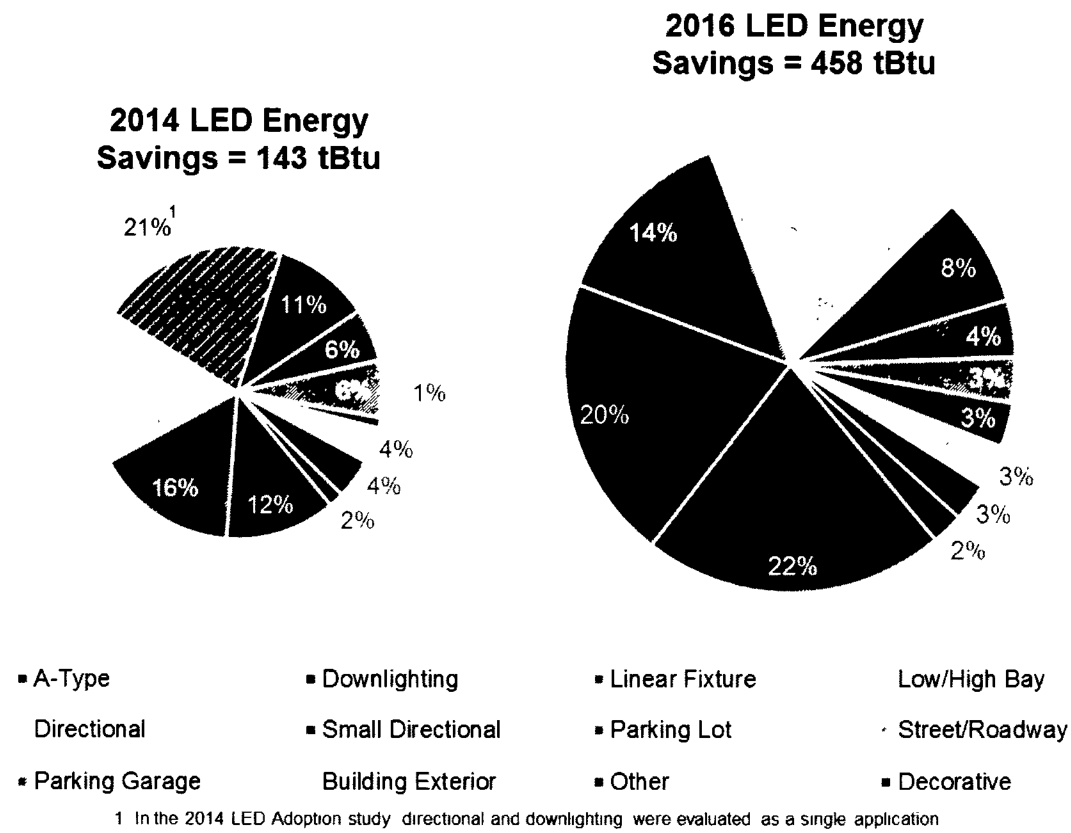


Figure 4.3 Comparison of 2014 and 2016 LED Energy Savings

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.

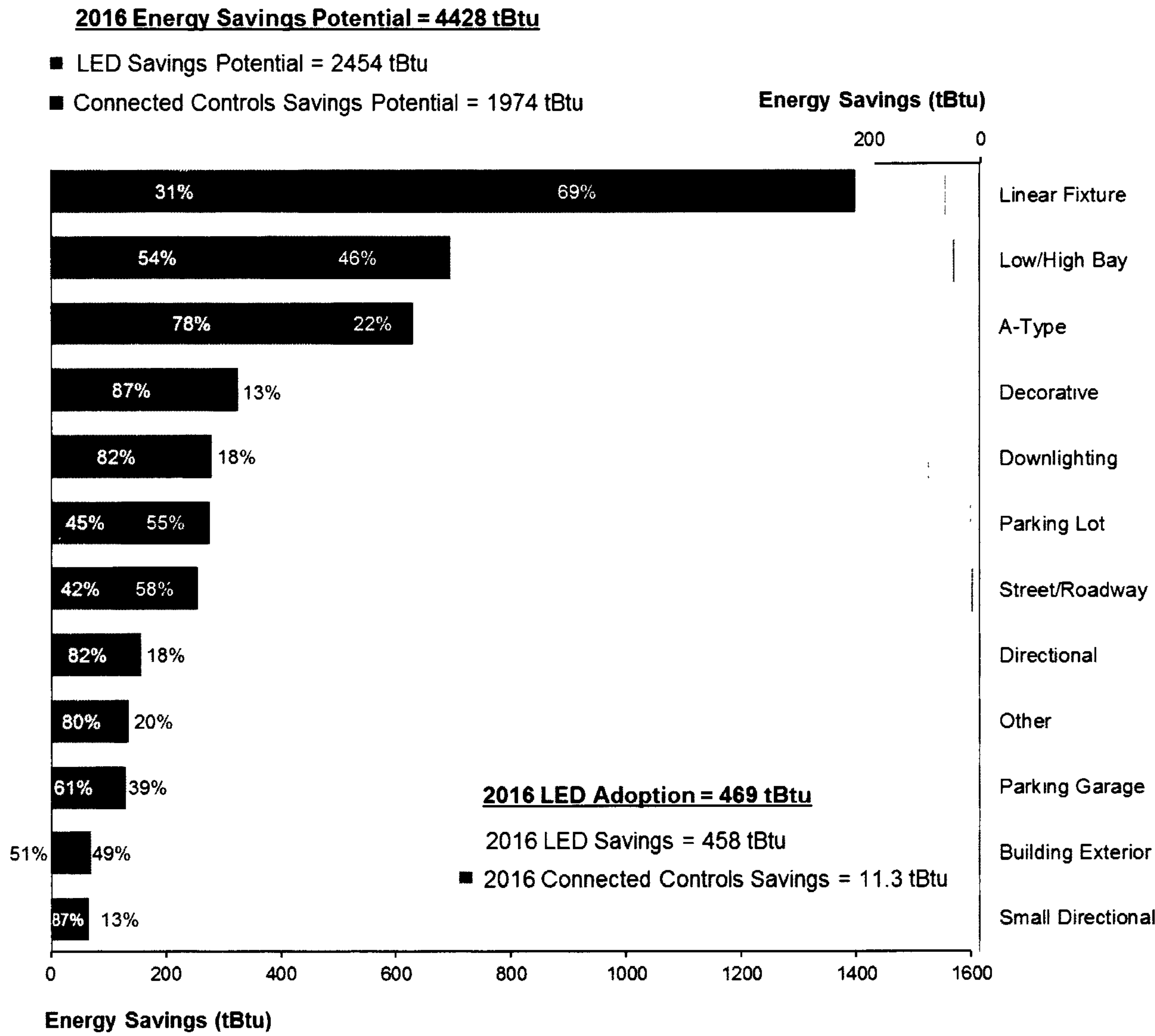


Figure 4.4 Current and Potential Energy Savings for LED Lighting and Connected Controls

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

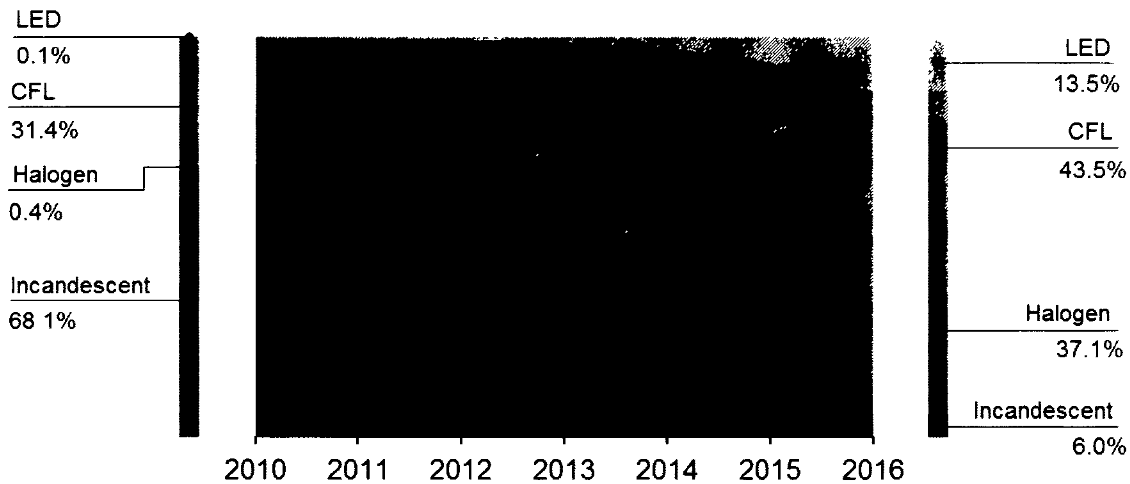


Figure 4 5 U S A-Type Installed Stock Penetration from 2010 to 2016

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.

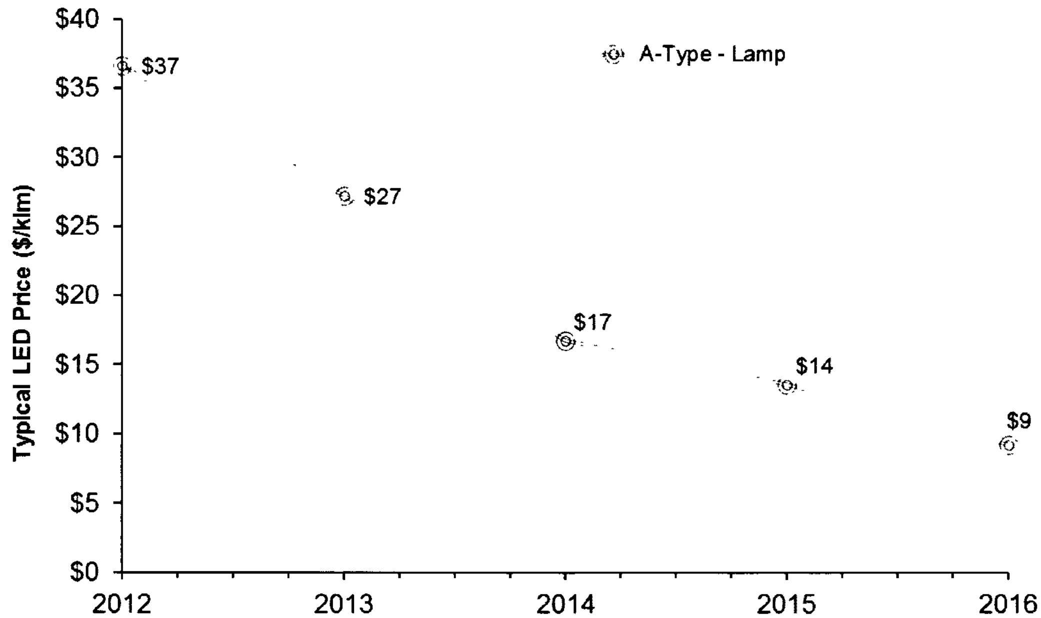


Figure 4.6 A-Type LED Price ($/klm) from 2012 to 2016

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.

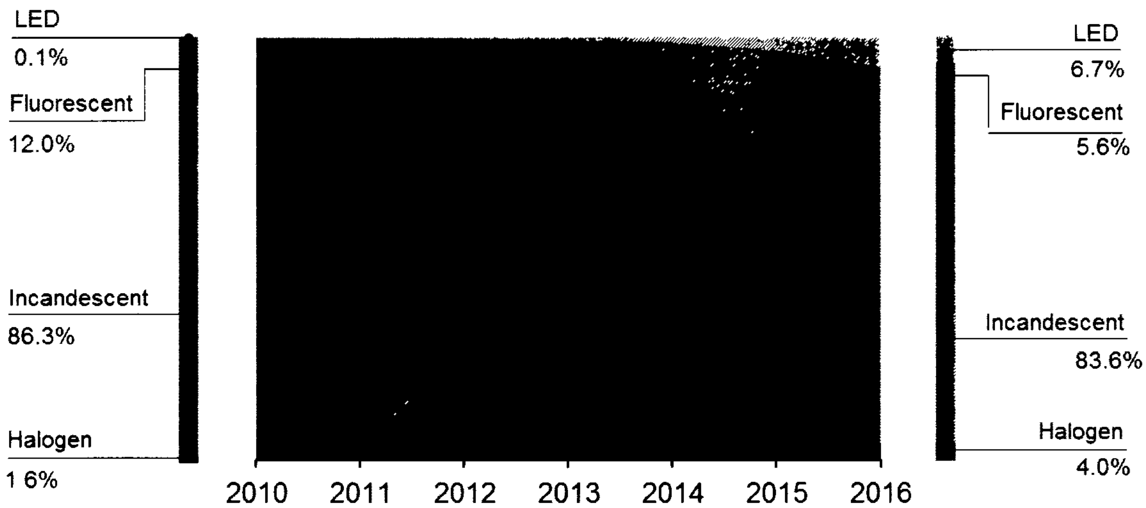


Figure 4.7 U.S. Decorative Installed Stock Penetration from 2010 to 2016

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.

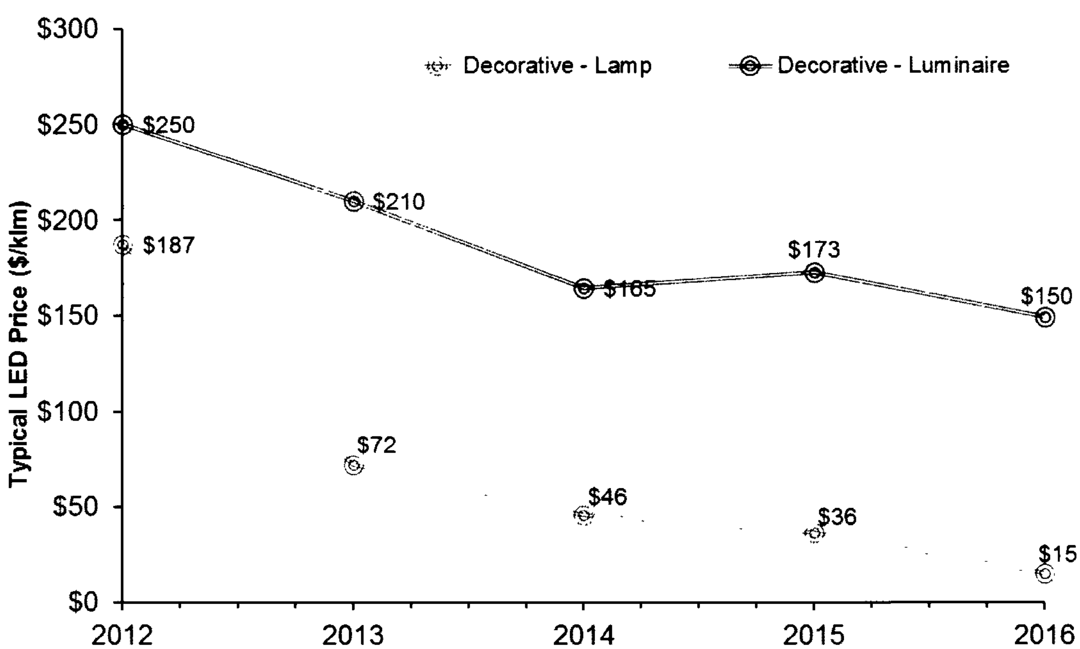


Figure 4.8 Decorative LED Price ($/klm) from 2012 to 2016

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.

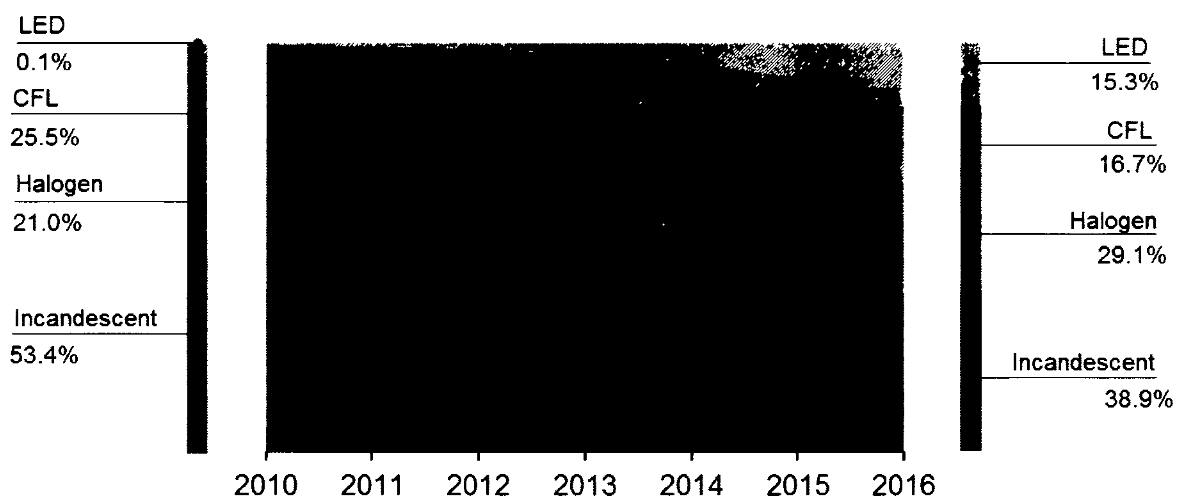


Figure 4.9 U.S. Directional Installed Stock Penetration from 2010 to 2016

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.

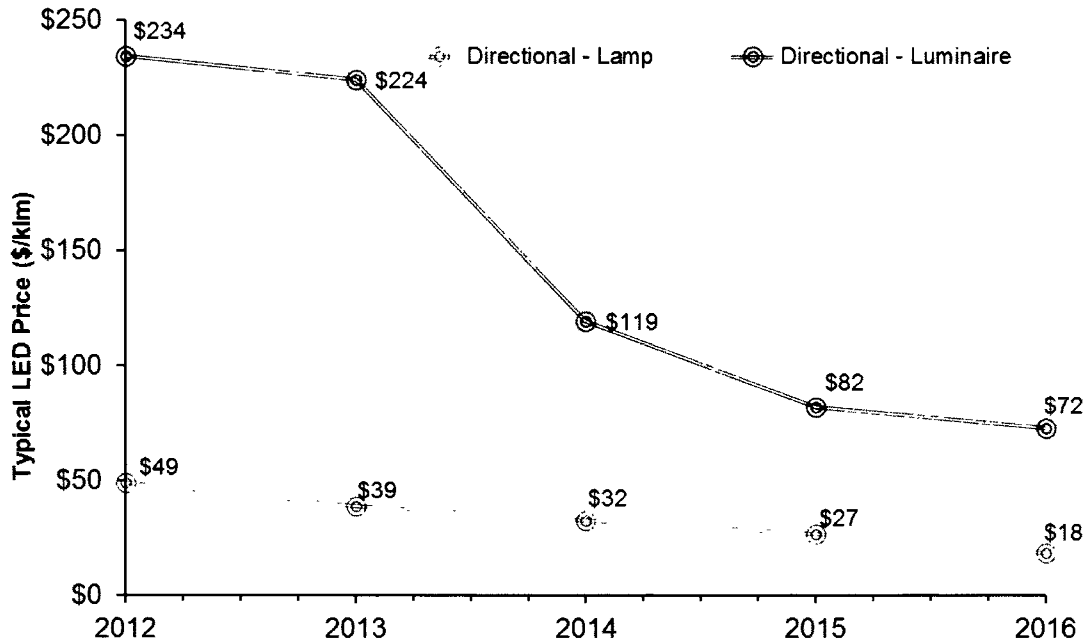


Figure 4.10 Directional LED Price ($/klm) from 2012 to 2016

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.

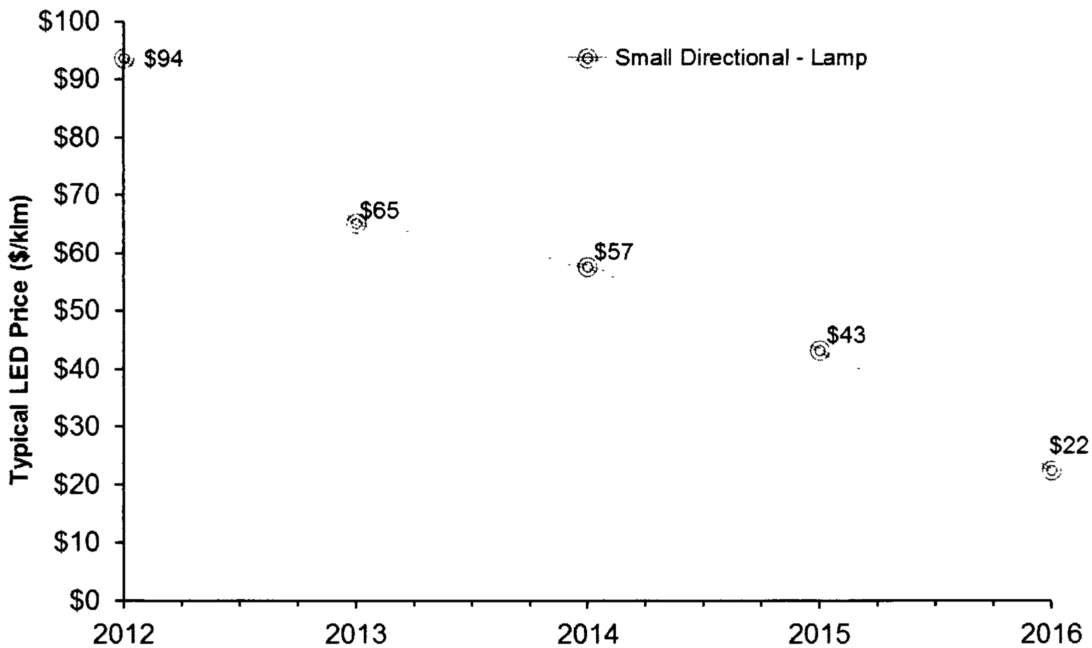


Figure 4.12 Small Directional LED Price ($/klm) from 2012 to 2016

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.

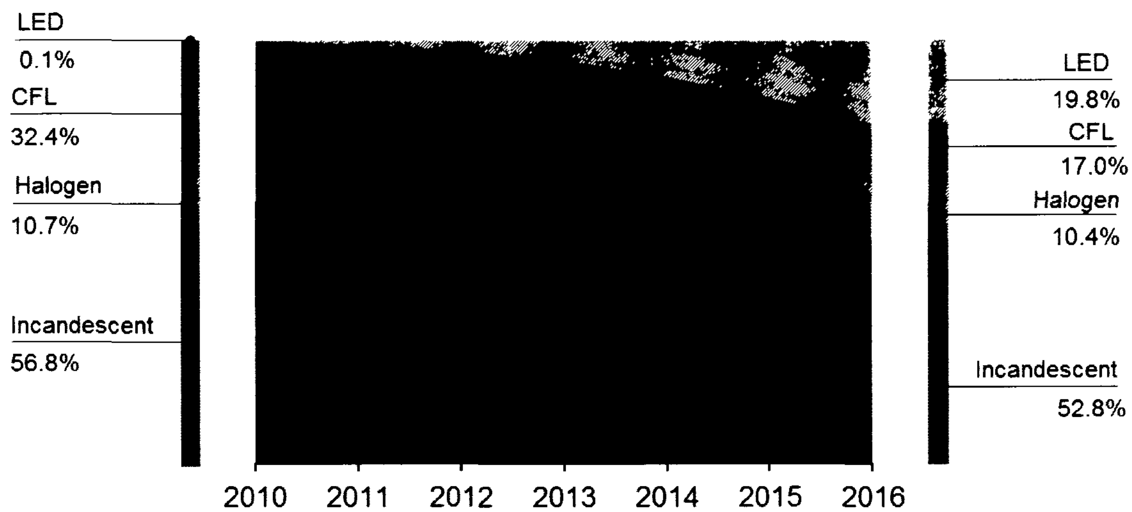


Figure 4.13 U.S. Downlight Installed Stock Penetration from 2010 to 2016

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.

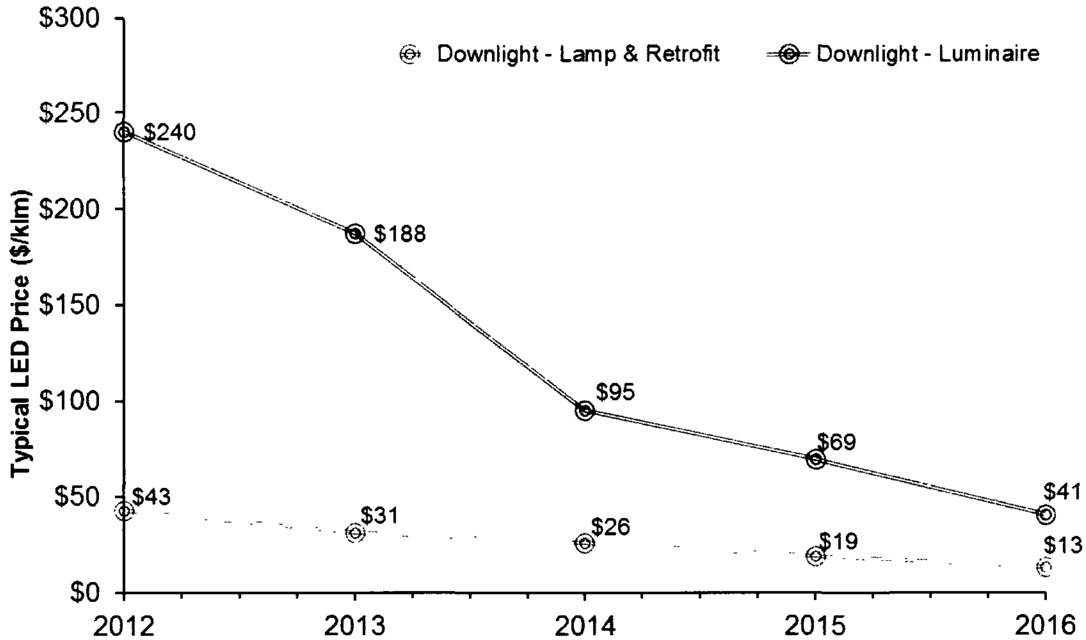


Figure 4.14 Downlight LED Price ($/klm) from 2012 to 2016

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.

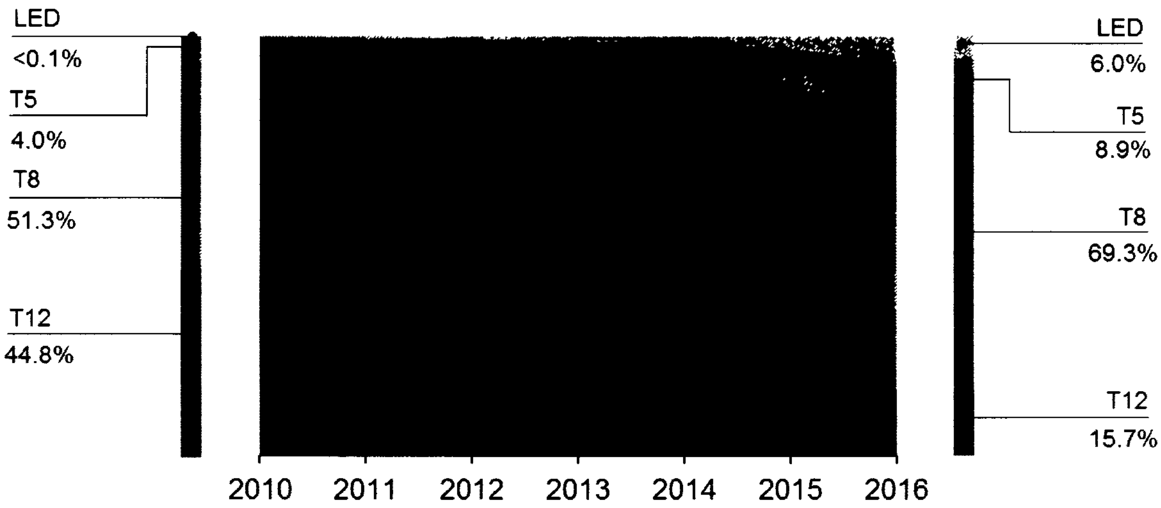


Figure 4.15 U.S. Linear Fixture Installed Stock Penetration from 2010 to 2016

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.

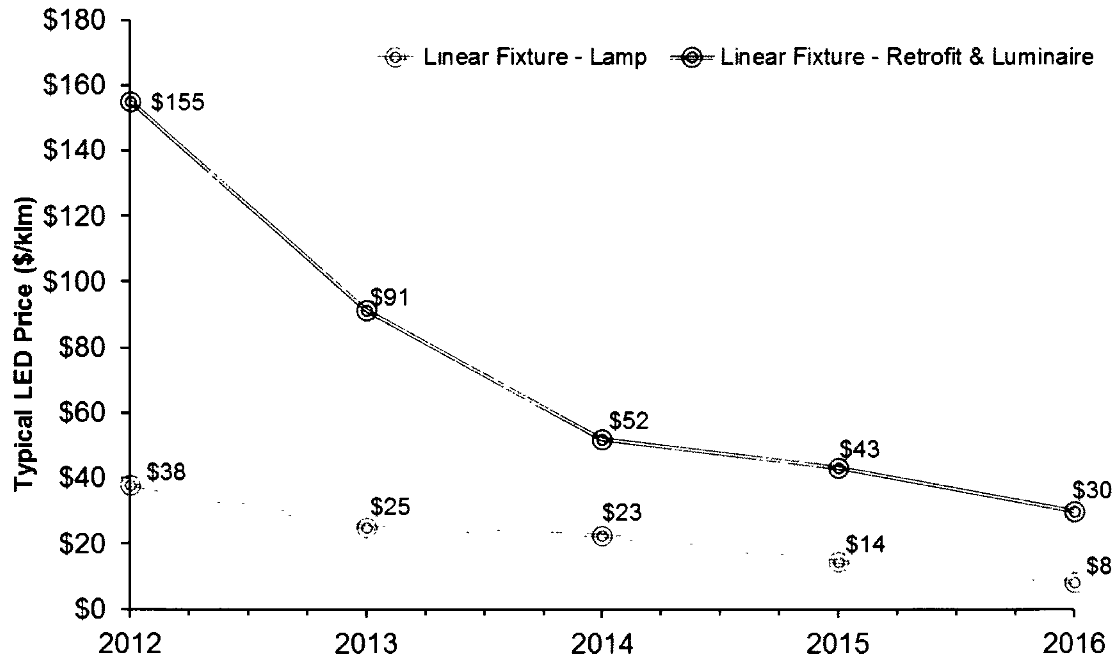


Figure 4.16 Linear Fixture LED Price ($/klm) from 2012 to 2016

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.

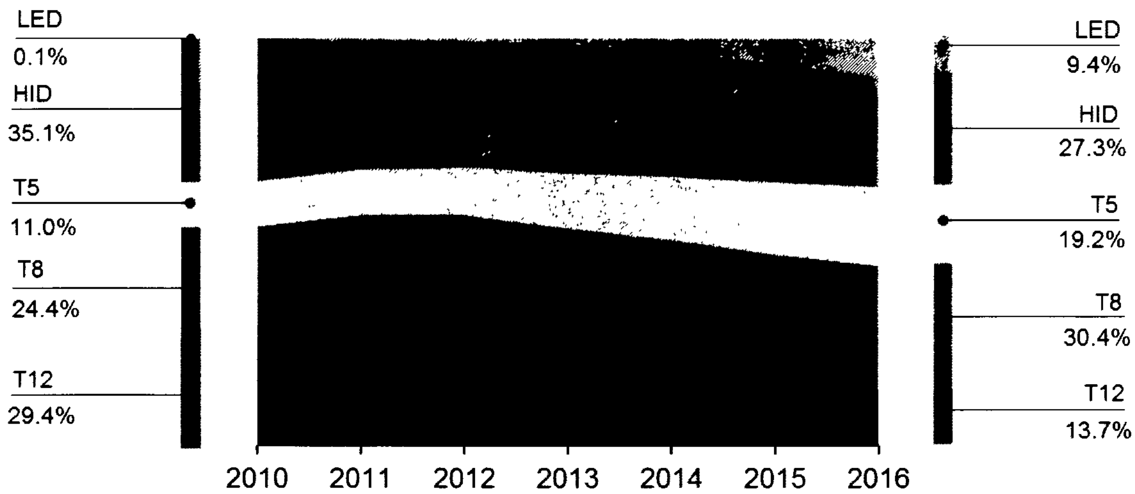


Figure 4.17 U.S. Low/High Bay Installed Stock Penetration from 2010 to 2016

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.

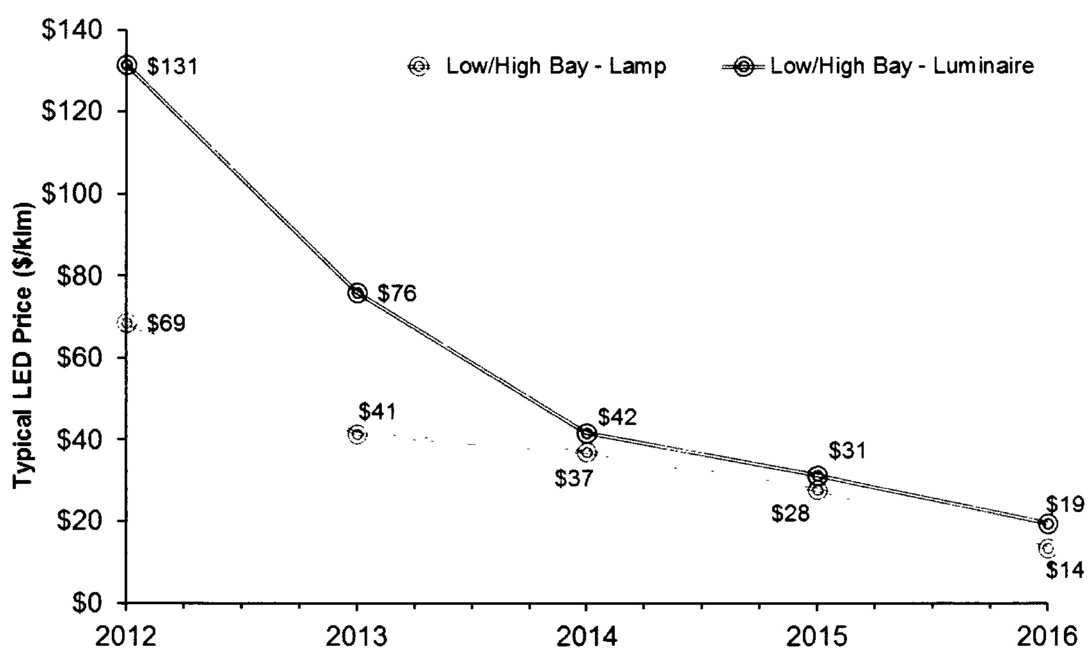


Figure 4.18 Low/High Bay LED Price ($/klm) from 2012 to 2016

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.

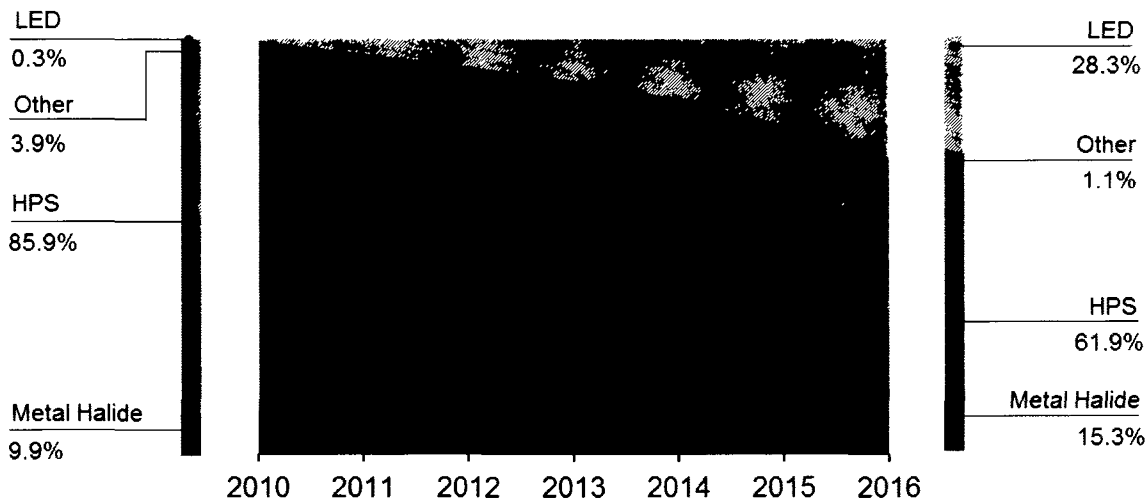


Figure 4.19 U.S. Street/Roadway Installed Stock Penetration from 2010 to 2016[17]

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.

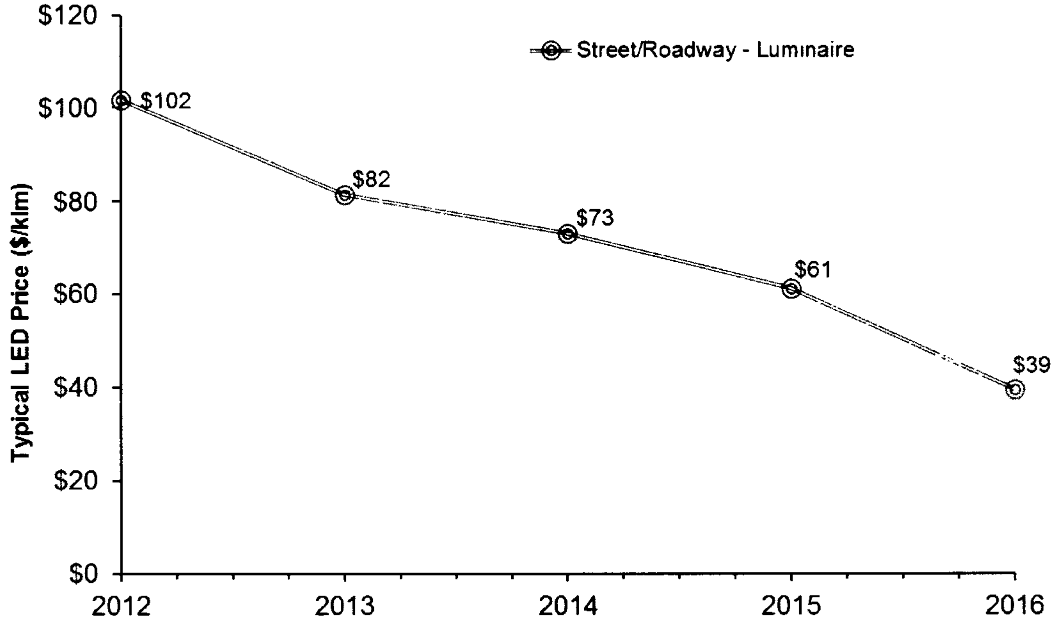


Figure 4.20 Street/Roadway LED Price ($/klm) from 2012 to 2016

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.

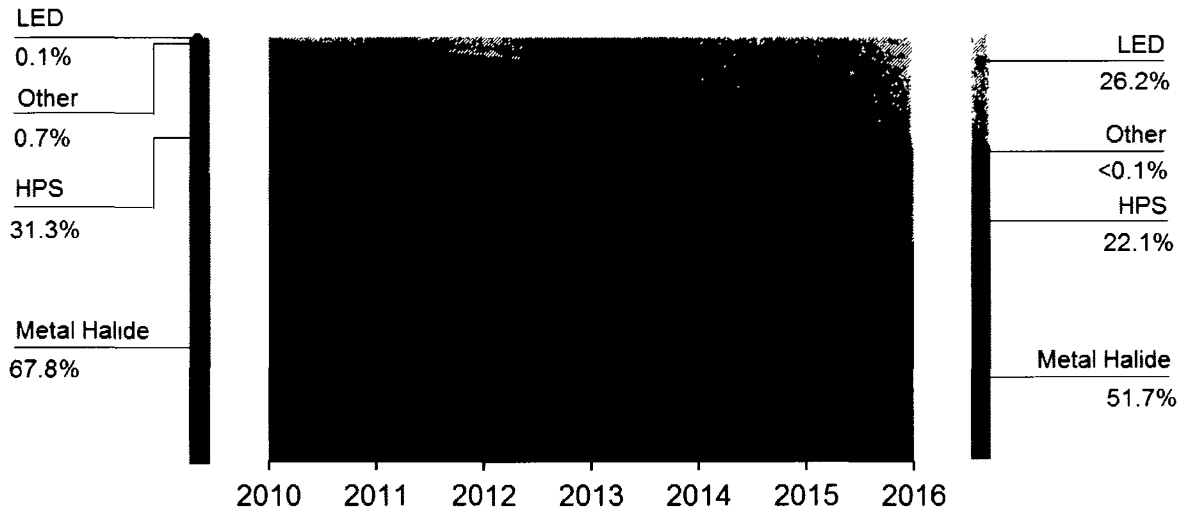


Figure 4 21 U.S. Parking Lot Installed Stock Penetration from 2010 to 2016

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.

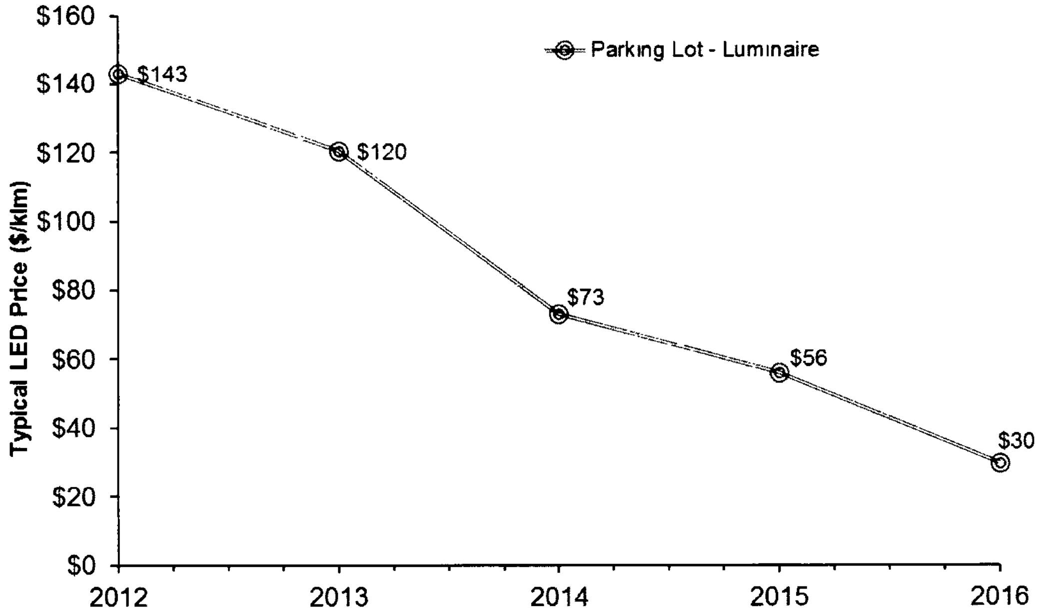


Figure 4.22 Parking Lot LED Price ($/klm) from 2012 to 2016

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 95th 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.

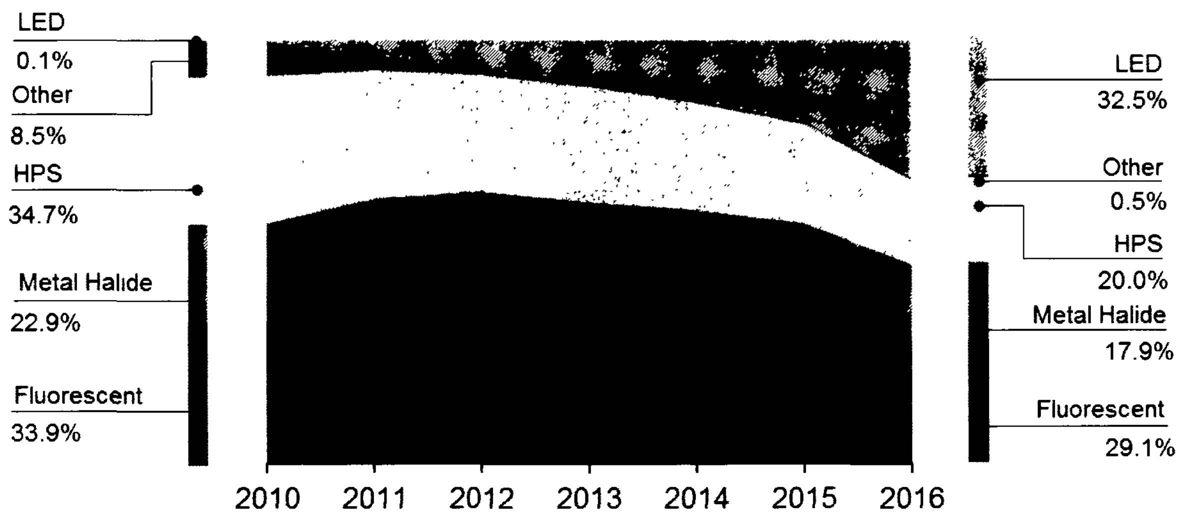


Figure 4.23 U.S. Garage Installed Stock Penetration from 2010 to 2016

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.

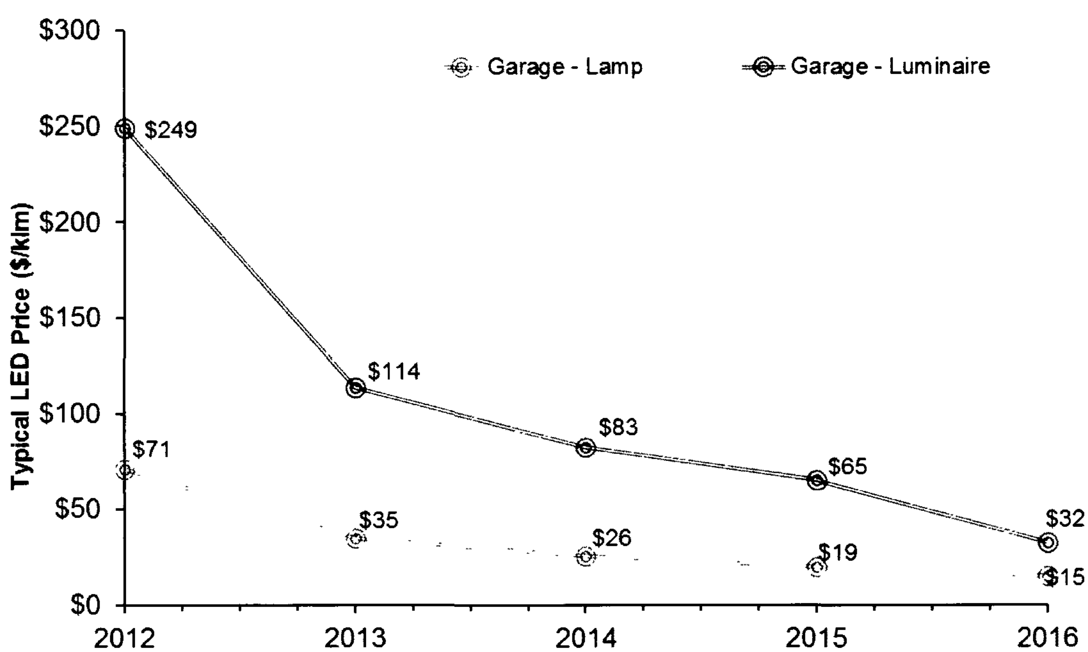


Figure 4.24 Garage LED Price ($/klm) from 2012 to 2016

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.

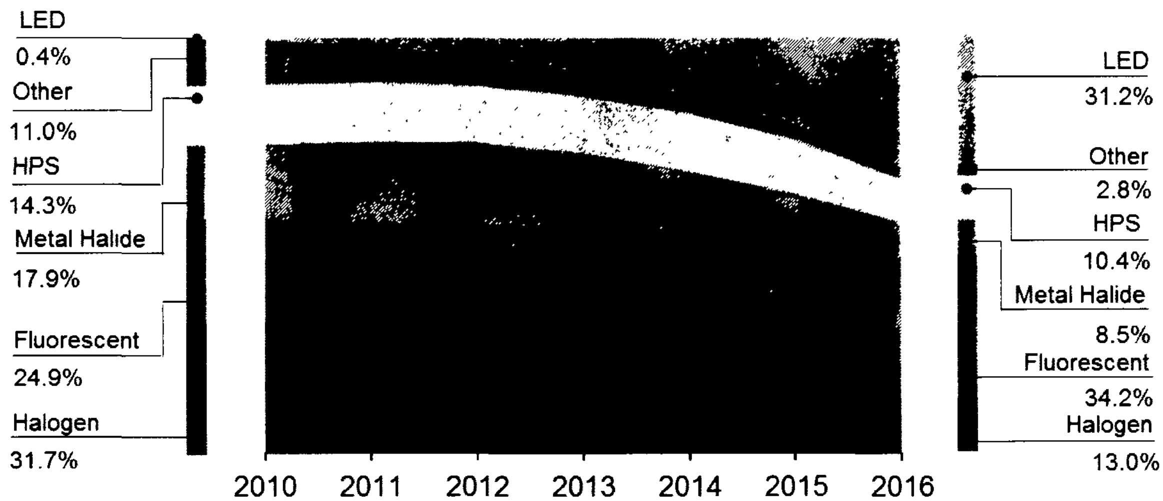


Figure 4.25 U.S. Building Exterior Installed Stock Penetration from 2010 to 2016

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.

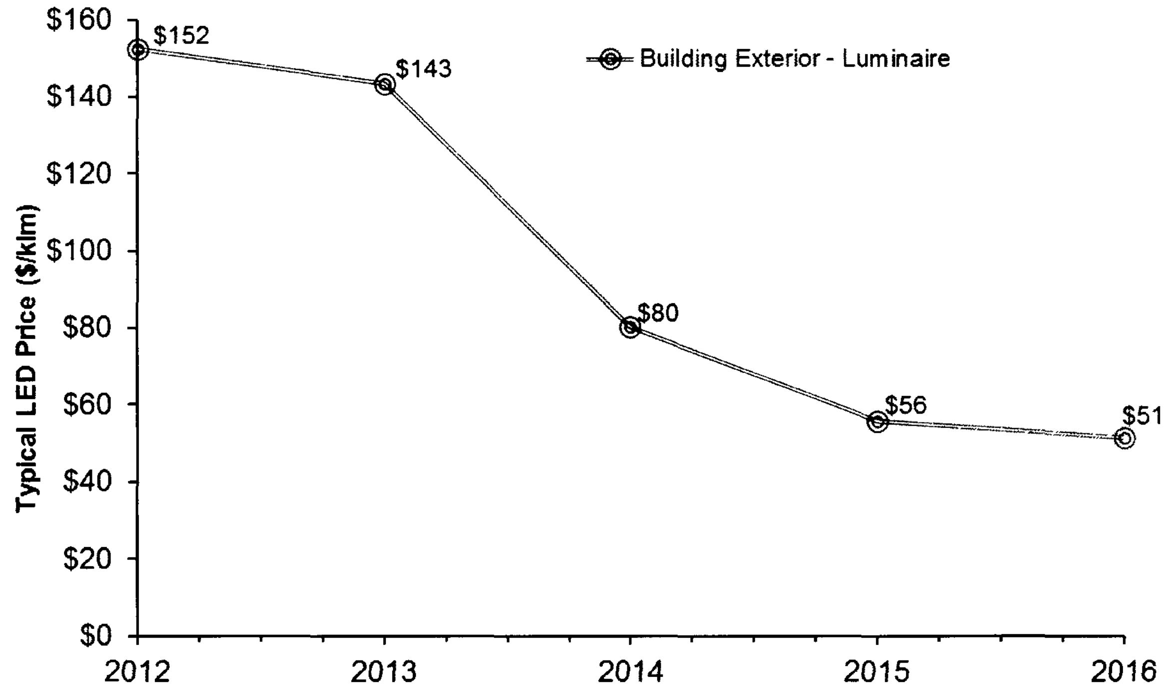


Figure 4.26 Building Exterior LED Price ($/klm) from 2012 to 2016

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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Solid-State Lighting

Prospects for U.S.-Based Manufacturing in the SSL Industry

Public-sector investments in energy-efficient lighting technology in particular those made through the U.S. Department of Energy Solid-State Lighting Program, are yielding excellent returns for taxpayers in the form of savings on electricity bills and reductions in carbon emissions. These benefits will compound in coming decades as LED (light-emitting diode) and OLED (organic LED) lighting continues to improve in efficiency and value for consumers.

Meanwhile, a question looms, to what extent will the U.S. economy also benefit from the robust business and job creation that will emerge as a result of the transition to solid-state lighting (SSL)?

Writing the Future

The United States has been at the epicenter of SSL innovation, with private and public R&D initiatives driving solutions that capitalize on the energy savings and unique benefits of LED- and OLED-based lighting. U.S.-based researchers and product developers have been instrumental in toppling cost and performance barriers, and in positioning SSL for rapid market growth. A 2016 DOE study[1] projects that LEDs will account for about 30% of U.S. lighting installations by 2020 and about 86% by 2035. Other studies have reached similar conclusions about the global market.

To date, the United States has attracted SSL investments by major lighting multinationals as well as hundreds of small and medium-sized companies, representing all parts of the SSL value chain. However, early technology leadership does not necessarily translate into sustained U.S.-based manufacturing and employment strength, as the histories of the semiconductor and solar panel industries illustrate.

Some speculate that SSL will ultimately follow the trajectory of these industries, with manufacturing, then engineering and R&D, gravitating to countries such as China, drawn by low labor costs and generous government subsidies for capital investments and infrastructure. But many industry analysts believe this viewpoint is far too simplistic to capture all the dynamics of the SSL industry and the changing nature of global competition.

1 *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, U.S. Department of Energy, September 2016

The future of SSL is still unwritten ... and technology, manufacturing, and policy decisions being made today will influence the shape of the industry for decades to come. The industry is global, the market potential is enormous and rapidly emerging, and the stakes are high. Clearly, companies will weigh decisions on capital investment and facility location with extreme rigor.

Six Key Factors

What *would* lead a company to invest in U.S.-based manufacturing or engineering facilities? Through roundtable meetings and workshops sponsored by DOE, industry executives have shared valuable insights on this question.

Strategic considerations about sourcing and manufacturing—whether to make or buy, build or acquire—are unique for each company. Decisions also hinge on access to capital, which is often a pressing concern for small businesses, and they vary depending on what part of the SSL value chain is being addressed. Competitive drivers differ substantially for suppliers of substrates, phosphors, chemicals, production and test equipment, LED die, LED packages, LED modules, and lamps and luminaires—as well as for OLED suppliers and manufacturers, where markets to date have remained small and niche-oriented.

Despite all these variables, industry executives have identified six closely interrelated factors that affect location decisions:

- Access to markets
- Access to supply chains
- Access to innovation
- Intellectual property protection
- Labor costs, productivity, and quality
- Government incentives

Following are brief discussions of the six factors and their impacts on various parts of the SSL value chain, along with recent examples illustrating how these factors may play into decisions on where to base manufacturing and engineering operations.

Factor 1: Access to Markets

Market access issues differ for each part of the SSL value chain. For smaller commodity-like products with low shipping costs, manufacturers can successfully serve global markets from virtually any location. LED packaging is now performed almost entirely in Asia to serve customers around the world. In another example, LED replacement lamps, which account for the largest portion of current SSL unit sales, are assembled in highly automated operations in North America, Europe, and Asia, and marketed globally; Asian manufacturers have been gaining an edge because of their low-cost labor and synergies with the strong existing semiconductor packaging infrastructure.

Steps in Value Chain

LED DIE MANUFACTURING	LED PACKAGING	LAMP AND LUMINAIRE PRODUCTION
Growth of LED wafer by metal organic chemical vapor deposition (MOCVD) Wafer processing (by mostly conventional semiconductor processes); separation into LED chips	Packaging of LED chips, including deposition of phosphor material to convert blue LED emission to white light	Integration of LED packages into luminaire or lamp Integration of driver, heat sink, optical components, and mechanical structure for luminaire

For other products, manufacturing in close proximity to markets and customers is a competitive advantage. Manufacturers assess where their growth and profit potentials are most attractive and establish engineering and production nearby, often locating in multiple parts of the world to serve multiple markets. A case in point is Veeco Instruments, which conducts engineering and R&D for its MOCVD equipment in Somerset, N.J., and uses contract manufacturers in Kingston, N.Y., and Singapore to serve its global customers, many of whom are in Asia.

Luminaire manufacturers have strong incentives to localize manufacturing and engineering as they strive to deliver high-value lighting solutions to commercial and industrial customers while minimizing turnaround time, inventories, and shipping costs. The need to localize will likely intensify with the integration of increasingly customized systems for monitoring and control, color tuning, and smart communications into SSL luminaires. Because the United States is an enormous market for SSL luminaires, the case for locating manufacturing and engineering here is compelling for many companies. The three largest lighting manufacturers in the U.S.—Acuity Brands, Eaton-Cooper, and Hubell—have historically manufactured here to serve domestic customers. They plan to continue manufacturing domestically and are transitioning their factories from conventional to SSL products. The same logic, of course, also drives companies to manufacture luminaires outside the United States for proximity to fast-growing markets in Asia, Europe, and other parts of the world.

Factor 2: Access to Supply Chains

Most SSL manufacturers, of all sizes, source from suppliers around the globe based on competitive pricing, quality, and service. Munich-headquartered industry giant OSRAM Sylvania, for example, sources its LED lighting components globally and has assembly operations around the world, including in the United States. Considerable engineering expertise in SSL companies goes into supply chain management and control.

Locating in proximity to suppliers can speed adaptation to constantly evolving product designs and customer demands. Cree is a case in point. While portions of its manufacturing processes are handled in Asia, Cree has found many of the building blocks for its vertical integration model in the United States, and often selects domestic suppliers when close collaboration is needed to ensure high quality and tight operational integration.

Sometimes supplier considerations weigh against a U.S. location—when, for example, key parts of the supply chain are based overseas, thus making it easier to do certain portions of the manufacturing overseas. Almost all LED package manufacturing nowadays is done in Asia, which tends to draw related links in the supply chain there as well. In contrast, the material supply chain for luminaire manufacturer Finelite is centered in California, which the company says has helped it to rapidly respond to market requirements.

Factor 3: Access to Innovation

Constant innovation is a competitive necessity in SSL manufacturing. Luminaire and light-engine producers seek solutions that are increasingly optimized for flexibility, materials efficiency, weight reduction, ease of assembly, and integration of sensors and controls, and that enhance product life as well as performance factors such as color stability over time. LED manufacturers seek improvements in efficiency within the LED epitaxy-phosphor-package system, which translate to lower production costs. They also look for improved manufacturing and integration techniques, such as improved application of down-converter materials in order to increase production volume and improve color consistency. Companies at every stage of LED lighting manufacturing

Status of Manufacturing

LED DIE

Despite enormous growth in epitaxy in Asia (mostly devoted to LED displays), MOCVD remains strong in North America. Most top-level manufacturers perform MOCVD near their headquarters. Lumileds and Cree in North America, Osram Semiconductors in Europe, and Nichia in Japan.

Wafer processing, often handled locally, is increasingly moving to Asia.

North America is strong in producing tools and equipment for LED manufacturing, including tools for MOCVD (dominated by Aixtron in Europe and Veeco in North America), specialty wafer processing, packaging, and testing and inspection. U.S.-based Plasma-Therm, Ultratech, and KLA-Tencor sell to manufacturers worldwide.

want high-speed, non-destructive test equipment. And technology breakthroughs are essential in bringing down the costs of producing OLED panels.

For many companies, staying on the cutting edge in addressing such issues means collaborating with the right partners. Lumileds, for example, draws a lot of its employees from the materials science departments of top U.S. universities, such as the University of California Santa Barbara, the University of Illinois, the Massachusetts Institute of Technology, Georgia Tech, and Purdue University. The company also benefits a great deal from collaborating with those universities, as well as with national laboratories such as Sandia and Brookhaven. And access to innovative partners is paramount to OLEDWorks, which conducts research, engineering, and fabrication at its Rochester, N.Y., headquarters. The only OLED panel maker in the United States, the firm was the brainchild of a cadre of former Kodak employees. OLEDWorks recently expanded its production and technology expertise by acquiring the Philips OLED assets in Aachen, Germany. With expertise in device manufacturing, the firm partners with material suppliers and customers to help fuel future growth. OLEDWorks generally selects U.S.-based partners to facilitate creative collaboration, ranging from equipment makers that can support development of the small, fast machines that will be vital to keeping capital costs in line, to end product designers that integrate the OLED lighting panels.

Since proximity to a critical mass of expertise—embodied in the regional supply chain, related industries, universities, consulting firms, and the labor force—can be a powerful competitive advantage, companies continually monitor "where the action is" on innovation. Regional levels of R&D investment are one significant indicator. SSL R&D, under way throughout the developed world, is funded predominantly by industry in the United States, Europe, Taiwan, South Korea, Japan, and China, augmented by government co-funding of strategically selected precompetitive technologies. Such investments not only advance the technology and associated energy savings, but also encourage manufacturers to locate in those regions.

Factor 4: Intellectual Property Protection

Many executives cite intellectual property protection as an essential factor that favors U.S.-based manufacturing, one that is especially relevant for companies utilizing proprietary techniques. A prime example of this involves U.S. LED manufacturers such as Lumileds and Cree, who keep MOCVD production close to headquarters to protect not only patents, but also trade secrets and the industrial knowhow surrounding the MOCVD process. This enables those companies to continue to produce the best LED material in the world.

Factor 5: Labor Costs, Productivity, and Quality

While labor rates in the United States are higher than in many other areas of the world,[2] productivity and quality considerations can provide a competitive counterbalance. Indeed, data indicate that U.S. manufacturing productivity and output have been trending positive, keeping pace with or exceeding those of some key Asian and European competitors,[3] and that U.S. manufacturing, particularly of durables, is increasing productivity and output faster than other areas of the U.S. economy.[4]

Status of Manufacturing

LED PACKAGING

Almost all LED die packaging is performed in Asia. Packaging is labor-intensive due to the need for process flexibility and for handling a wide range of product types on the same production line, favoring regions with relatively low labor costs. Shipping costs for small and light LED packages are low, also contributing to the decision to manufacture such products at offshore facilities. More automated wafer-level packaging approaches could change the equation for packaging location.

U.S.-based suppliers such as Intematix serve global markets for phosphors and other materials.

The competitiveness of the U.S. labor force, particularly in highly skilled and automated operations, is borne out by several instances of companies deciding to onshore SSL manufacturing. Examples include Carclo, which moved its optic molding operations from the United Kingdom to the United States in 2008 and has since added considerable capacity to its U.S. operations; and TOGGLED, which initially manufactured commercial-grade LED replacements for fluorescent tubes in China, but automated and relocated a substantial portion of its manufacturing to the United States.

Manufacturing quality control is another factor that can favor U.S.-based operations. As a *New York Times* article noted, many Chinese producers "have a poor and worsening reputation for quality, which may hurt them in the long term. Instead of lasting a decade like well-made LEDs, the low-priced LEDs occasionally burn out after less than a year ... ".[5]

As luminaire manufacturing transitions to solid-state lighting, domestic luminaire manufacturers estimate that they'll be manufacturing SSL luminaires exclusively within five years. Because SSL manufacturing requires new skills and expertise, these manufacturers are retraining their employees to deal with such things as electronic component pick-and-place, thin-film deposition, power supply characterization, and LED characterization, as they capitalize on existing workforces, supply chains, and market understanding to make their transition to manufacturing the new technology.

2 U.S. Bureau of Labor Statistics, International Labor Comparisons, August 2013

3 U.S. Bureau of Labor Statistics, Percent changes in manufacturing output per hour, 2009-2010, 2010-2011

4 U.S. Bureau of Labor Statistics, Percent change in productivity, output, and hours from first quarter 2012 to first quarter 2013, preliminary

5 *New York Times*, "As LED Industry Evolves, China Elbows Ahead," Keith Bradsher, June 17, 2014

Factor 6: Government Incentives

Many Asian countries offer substantial incentives to attract manufacturing investments, including monetary support for capital equipment purchases, as well as recruiting and relocation support, subsidies for land and building development, subsidies for energy and water, workforce training, export incentives, corporate tax breaks, refunds of the value-added tax, tariff protections from foreign competition, and streamlined permitting. In contrast, U.S. federal, state, and local taxes are relatively high, monetary support for manufacturing has been comparatively modest, and support for SSL has come primarily in the form of market-side rebates and other incentives that indirectly benefit manufacturers by spurring demand. Nevertheless, state and local tax incentives have been a factor in attracting such companies as Cree and OLED developer Universal Display Corporation to make significant investments in U.S.-based infrastructure and R&D.

Interestingly, some role reversal has been happening lately. China has been deemphasizing incentives such as low-interest loans to manufacturers in favor of measures to stimulate demand,[6] in an attempt to accelerate growth in Chinese residential and commercial markets for SSL; and, like their American and European counterparts, Chinese regulators are phasing out incandescent bulbs in favor of energy-efficient lighting. At the same time, some states and localities in the United States are instituting more high-profile tax incentive policies to attract manufacturing and R&D in targeted sectors such as SSL. For example, Cecil County, Maryland, has provided some assistance to local LED luminaire manufacturer I-Lighting, including underwriting the extensive training of the company's staff in how to operate the complex equipment that populates the circuit boards, and I-Lighting has gotten additional financial aid from the state of Maryland.

Challenges to Competitiveness

Despite the positive indicators for U.S.-based manufacturing, SSL industry leaders cite a host of challenges that may dampen future business and job creation in this country. Some report a thinning out of the U.S. supply chain and knowledge base in such core manufacturing operations as extrusions and mold-making, as well as in LED fabrication. Others perceive an erosion of the U.S. innovation edge, with R&D and technical support from university and government laboratories diminishing, especially relative to other regions.

Many industry leaders advocate active roles for federal, state, and local governments in increasing the competitiveness of the United States as an SSL manufacturing location.

6 *New York Times*, "As LED Industry Evolves, China Elbows Ahead," Keith Bradsher, June 17, 2014

LAMP AND LUMINAIRE PRODUCTION

Status of Manufacturing

Lamp manufacturing can be highly automated and is distributed worldwide. Very low prices have allowed Chinese companies to capture about 30% of global share for replacement lamps, with Japan, South Korea, Germany, Taiwan, and the United States sharing the rest of the market in fairly even proportions.

Cree and Philips Lighting have LED lamp manufacturing facilities in the United States.

Local manufacturers typically dominate markets for luminaires, which are designed for local building types and can entail high shipping costs.

Recommendations include maintaining ongoing government support of SSL applied research to help maintain an edge in innovation, growing government co-funding of R&D for automated and flexible manufacturing, increasing incentives to defray capital costs, facilitating development of a highly educated workforce, and further bolstering U.S. demand for SSL through consumer education and accurate product labeling, as well as through effective "Buy American" procurement policies.

Regardless of the challenges, it is clear that the United States is well positioned to attract SSL engineering and manufacturing investments—some of the time, in some circumstances. The relative weighting of the six factors cited in this discussion not only varies widely by industry sector, but also changes over time. Generally, as a sector matures, the advantages of a U.S. manufacturing location diminish. Some companies may strategically divest some manufacturing, while others will continue to manufacture while seeking to move up the value-added food chain. Lumileds, for example, is going beyond supplying LED packages to offering customized solutions at the module level.

In this dynamic and fast-growing SSL industry, one thing remains certain: innovation, flexibility, and efficiency will be essential in keeping the United States competitive as a manufacturing location. ■

Unless otherwise noted, data for this paper come from four DOE sources the *Solid-State Lighting Research and Development Manufacturing Roadmap* (September 2014), the *Solid-State Lighting R&D Plan* (June 2016 update), the online *SSL Postings* series "SSL in America" (www ssl energy gov/sslamericapostings html), and annual DOE workshops that attract leaders in the SSL industry Subscribe to the *SSL Postings* mailing list by contacting postings@akoyaonline.com

5. Payment for Construction Services. Customer shall pay Company for the provision of the Construction Services by Company in accordance with the terms in this Section 5.

(a) Customer shall pay Company the Actual Facilities Extension Cost as a contribution in aid of construction. As of the date of this Agreement, the Actual Facilities Extension Cost is estimated to be $2,220,000 (the "**Initial CIAC Estimate**"). The term "**Actual Facilities Extension Cost**" means the Actual Cost less the System Improvement Cost. The term "**Actual Cost**" means the sum of (i) all costs actually incurred for the design, modification, upgrade, procurement, construction, installation, removal, project management and commissioning of any Transmission System facilities and equipment provided by Company for the Project, including all such costs attributable to any Customer Scope Changes, plus (ii) any overhead costs, general and administrative fees, plus (iii) any applicable tax gross up respecting the foregoing, plus (iv) in the event this Agreement is terminated prior to completion of the Project, any costs that Company incurs from third parties as a consequence of the cancellation of any purchases or rentals of necessary equipment, materials or work to construct the Project that Company does not reasonably expect to recover through its Tariff. The term "**System Improvement Cost**" means the portion, if any, of the Actual Cost that, in Company's sole judgment in accordance with Good Utility Practice, would be deemed by the PUCT to be necessary and reasonable costs for the overall Transmission System and recoverable by Company through the Transmission Service rates approved for Company by the PUCT.

(b) Company will invoice Customer for the Initial CIAC Estimate following Customer's execution and delivery of this Agreement to Company, and Customer shall pay the Initial CIAC Estimate to Company in accordance with the terms therein.

(i) Customer acknowledges and agrees that Company may increase the Initial CIAC Estimate pursuant to Good Utility Practice at any time after the date of this Agreement as new information becomes known or if changes by Company or Customer are made to the scope or design of the Project, including Customer Scope Changes accepted by Company. Company will issue an invoice to Customer for the amount of such increase (the "**Additional Amount**"), and Customer shall pay the Additional Amount to Company in accordance with the terms therein.

(ii) After completion of the Project or termination of this Agreement pursuant to Section 10 hereof, whichever occurs first, (the "**Completion Date**"), the difference between (i) the Actual Facilities Extension Cost as of the Completion Date and (ii) the sum of the Initial CIAC Estimate paid by Customer plus any Additional Amounts paid by Customer (that sum, the "**Project Payments**"), shall be paid to (x) Customer if the Actual Facilities Extension Cost is less than the Project Payments, or (y) Company if the Actual Facilities Extension Cost is greater than the Project Payments. Company shall issue a refund or invoice for that difference, as the case may be, within 30 days after the Completion Date, and Customer shall pay any such invoice in accordance with the terms therein.