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Energy Savings Forecast of Solid-State Lighting in General Illumination Applications

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

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Prepared by Navigant

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Disclaimer

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The DesignLights Consortium and Pacific Gas and Electric have been working with TRC Energy Services and Vistar Energy Consulting to develop an Advanced Lighting Controls Energy Estimator tool. This tool will use the best available data and methodologies to estimate energy savings for layered lighting controls and automatically calculate savings compared to existing conditions and several energy codes. DOE acknowledges and appreciates their assistance in developing the methodology for the lighting controls energy savings component of the lighting market model.

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:

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Executive Summary

The United States (U.S.) Department of Energy (DOE) has been at the forefront of the solid-state lighting (SSL) revolution. Among its various activities, DOE has supported studies forecasting the market penetration of light-emitting diodes (LEDs) in general illumination applications since 2002. These forecasts provide a comprehensive overview of the expected path of LED adoption within the U.S. and estimate the energy savings offered by LED products out to year 2035. This, the seventh iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, presents the results of the 2016 U.S. lighting market model. This study forecasts the expected annual lighting energy consumption based on three different scenarios:

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 high intensity discharge sources. The No-SSL scenario is used as the reference condition from which LED lamp and luminaire energy savings are calculated.

Current SSL Path The expected future path for LED lamps and luminaires given continuation of current levels of solid-state lighting (SSL) investment and effort from DOE and industry stakeholders.

DOE SSL Program Goal The future path for SSL given DOE goals outlined in the annual SSL R&D Plan are met, representing the ultimate potential of what DOE has determined is technically feasible in the given time frame.

The Current SSL Path scenario estimates the expected future adoption of LEDs based on historical data and the current trajectory for the technology. The DOE SSL Program Goal scenario estimates the potential future adoption of LEDs based on what DOE has determined is technically feasible in the given time frame, but additional efforts and funds would likely be required to meet these aggressive targets. The hypothetical "No-SSL" scenario, as indicated above, is used as a reference condition from which SSL energy savings are calculated for both the Current SSL Path and DOE SSL Program Goal scenarios.

The lighting market model assumes the market adoption of LED lighting technology is driven primarily by projected improvements in LED product efficacy and price, as well as established technology diffusion rates. At the end of the analysis period, LEDs are anticipated to hold the majority of lighting installations in each of the submarkets examined, comprising 86% of all unit installations. Of the submarkets examined, the lighting market model anticipates that LEDs will grow most rapidly in the area and roadway, low and high bay and A-type submarkets in terms of the percentage of total lighting installations. In the area and roadway submarket, already a popular area for LED upgrades, LEDs are predicted to comprise over 90% installed penetration by 2025 and nearly 100% by 2035. Low and high bay LEDs have seen recent growth in adoption – achieving an estimated 5% of all installations in 2015. This is expected to grow to 86% by the end of the analysis period. The A-type submarket will shift to LEDs a bit more slowly, with a projected 56% installed penetration by 2025, but will consist of 90% LEDs by 2035.

Without LEDs, the model projects that the energy consumption of the lighting sector would grow to approximately 6.7 quadrillion British Thermal Units (quads). However, as seen in Figure ES.1, if the DOE SSL Program Goal for LED efficacy are met and accelerated consumer adoption of connected lighting is achieved, the market penetration of LEDs is projected to drive a 75% reduction in energy consumption, or a total annual energy savings of 5.1 quads, in 2035 alone, which is nearly equal to the energy consumed by 45 million U.S. homes. This energy savings opportunity is driven largely by the linear fixture, outdoor, and low and high bay submarkets. These applications, characterized by high light output and long operating hours, are where increased controllability and networked capabilities will have the greatest value to customers. With these three submarkets leading the charge, LEDs installed with traditional control strategies as well as connected capabilities will contribute to a significant portion of the forecasted energy savings. Of the total 5.1 quads in annual energy savings by 2035, one-third is made possible by the penetration of connected-LEDs.

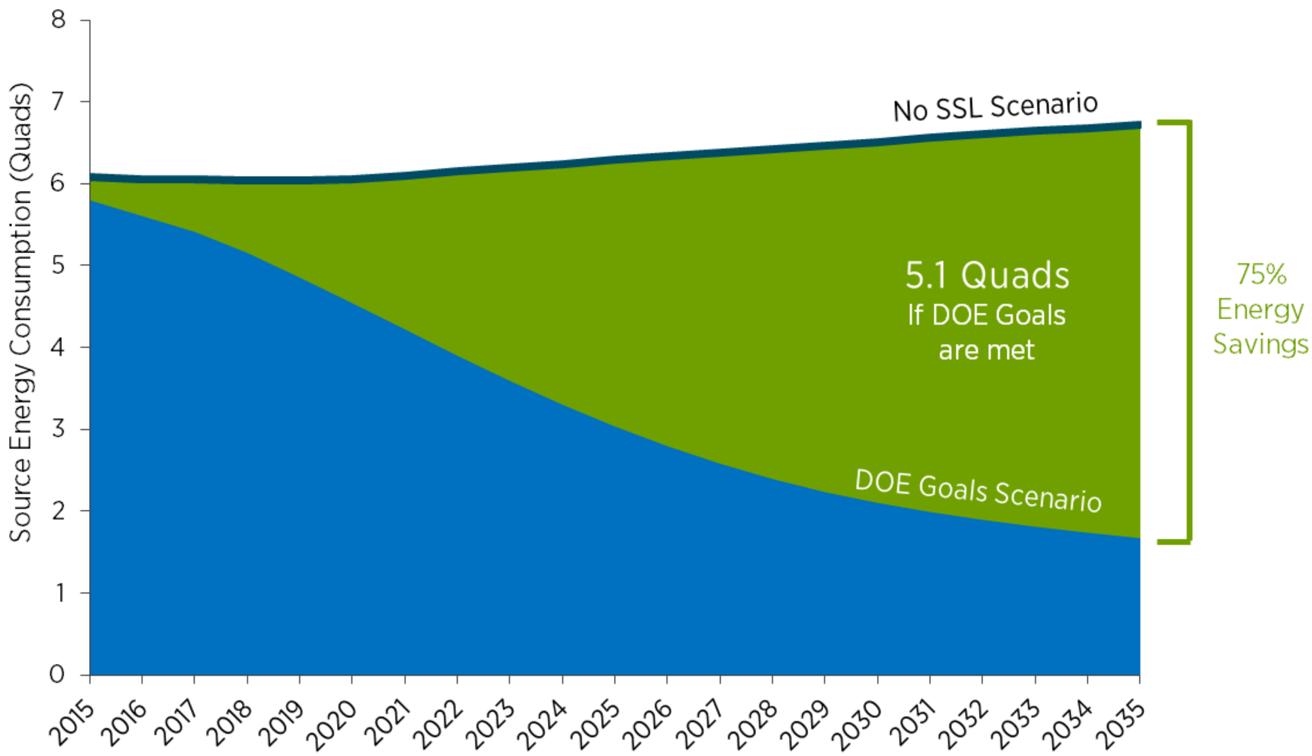

Figure ES.1 DOE SSL Program Goal Annual Energy Savings Forecast, 2015-2035

Decreasing lighting energy consumption by 75% in 2035 represents an even greater opportunity when the cumulative savings are considered. From 2015 to 2035, a total cumulative energy savings of 62 quads is possible if the DOE SSL Program Goal for LED efficacy and connected lighting are achieved – equivalent to nearly $630 billion in avoided energy costs.

Though all forecasts lack certainty, the findings present a thorough overview of where the lighting market is currently headed and will be of use to manufacturers, suppliers, and other stakeholders in the lighting industry as the transition to LED technology moves forward.

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1 Introduction

In 2015, the total energy consumption in the United States (U.S.) was 97.8 quadrillion British Thermal Units (BTU), or quads, of primary energy according to the Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2015. Roughly 40% of this energy was consumed for electricity use (1). The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program estimated that in 2015, lighting consumed approximately 5.8 quads of energy[1] and accounted for 6% of the total energy and 15% of the total electricity consumed in the U.S. in 2015.[2] Light-emitting diodes (LEDs), a type of SSL, are revolutionizing the lighting market. LEDs have surpassed many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and, due to their increasing cost competitiveness, LEDs are beginning to successfully compete in a variety of lighting applications. Going forward, LED technology is expected to continue to improve, with increasing efficacy and decreasing prices as well as enabling new opportunities for lighting design and energy savings.

This study is the seventh iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* forecast analysis, hereafter referred to as the "Forecast Report", a now biennial report from the DOE SSL Program. As in past iterations, this study provides updated predictions of LED market penetration and energy savings compared to conventional lighting sources – incandescent, halogen, fluorescent, and high-intensity discharge (HID) – in all general illumination applications from present-day through 2035.[3] An econometric lighting market model forecasts the expected annual lighting energy consumption based on three different scenarios:

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 lamp and luminaire energy savings are calculated.

Current SSL Path The expected future path for LED lamps and luminaires given continuation of current levels of SSL investment and effort from DOE and industry stakeholders.

DOE SSL Program Goal The future path for SSL given DOE goals outlined in the annual SSL R&D Plan are met, representing the ultimate potential of what DOE has determined is technically feasible in the given time frame.

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The Current SSL Path scenario estimates the expected future adoption of LEDs based on historical data and the current trajectory for the technology. The DOE SSL Program Goal scenario estimates the potential future adoption of LEDs based on what DOE has determined is technically feasible in the given time frame as outlined in the annual SSL R&D Plan, but additional efforts and funds would

[1] Source energy consumption is calculated by multiplying electricity consumption by using a source-to-site conversion factor of 3.03. (1)

[2] Based on a total electricity consumption of 38.8 quads of source energy for residential, commercial, and industrial sectors from EIA's AEO 2015.

[3] Past iterations of the Forecast Report are available at: http://energy.gov/eere/ssl/market-studies.

likely be required to meet these aggressive targets. (2) The hypothetical "No-SSL" scenario, as indicated above, is used as a reference condition from which SSL energy savings are calculated for both the Current SSL Path and DOE SSL Program Goal scenarios.

This study is presented in five main sections, including this introduction and:

Section 2 provides a high level overview of the analytical approach used to forecast LED energy savings. The approach consists of eight steps starting with the development of 2015 lighting installed stock estimates and ending with calculation of the energy savings due to LED penetration as well as lighting controls. The lighting market model utilizes an econometric logit model to award available market share to multiple competing lighting technologies, similar to the model used in the National Residential Sector Demand Module of NEMS 2013 for the lighting technology choice component. (3) The logit model is discussed in detail in Appendix E.

Section 3 provides an overview of the U.S. lighting market. This includes a description of each of the application-based submarkets used in the model and the technologies that are commonly used in each.

Section 4 provides a detailed look at the results of the lighting market model. The section begins with a high level overview of the results for both the Current SSL Path and the DOE SSL Program Goal scenarios. Then, the results of the forecast are explored in more depth, looking at the installed stock and resulting energy use of specific technologies, submarkets, and sectors as well as the impact of connected lighting.

Additionally a set of Appendices provide a much deeper dive into the different elements of the analytical approach.

2 Analytical Approach

The methodology followed in developing the U.S. lighting market model and forecasting aggregate consumer lighting purchases consists of an eight-step process. The summary of this process is outlined below and additional discussion is provided in the appendices.

Step 1: Calculate national lighting inventory and service. Utilizing the lighting inventory data published in the 2010 Lighting Market Characterization (4), the Residential Lighting End-Use Consumption Study (5),[4] Northwest Energy Efficiency Alliance (NEEA) 2014 Commercial Building Stock Assessment (6), and the Adoption of Light Emitting Diodes in Common Lighting Applications referred to hereafter as the "Adoption Report" (7), the lighting market model uses the lamp installations, average efficacies, average lumen output, and operating hours to estimate a national lighting inventory of installed lighting systems for each sector (i.e., residential, commercial, industrial, and outdoor). The base year for the inventory considered in this analysis is 2015.

Step 2: Develop arenas for competition.[5] As depicted in Figure 2.1, the current lighting market model examines eight submarkets across four sectors where a total of 15 technology categories may compete. An "other" technology category was also considered in some submarkets where there is uncertainty in the existing inventory. Additionally, an "other" submarket was also included in each sector to accommodate lighting products with unknown applications; however, it will not be explored in great detail in this report. This model structure enables a single lighting technology, such as linear fluorescent lamps, to compete in multiple submarkets (e.g., linear fixtures, low and high bay, and parking).

[4] The *Residential Lighting End-Use Consumption Study* is used for the operating hour estimates for lighting installed in the residential sector, while the *2010 Lighting Market Characterization* is used for the operating hour estimates for lighting installed in the commercial, industrial and outdoor sectors.
[5] Additional detail on how the arenas for competition were developed is included in Appendix A.

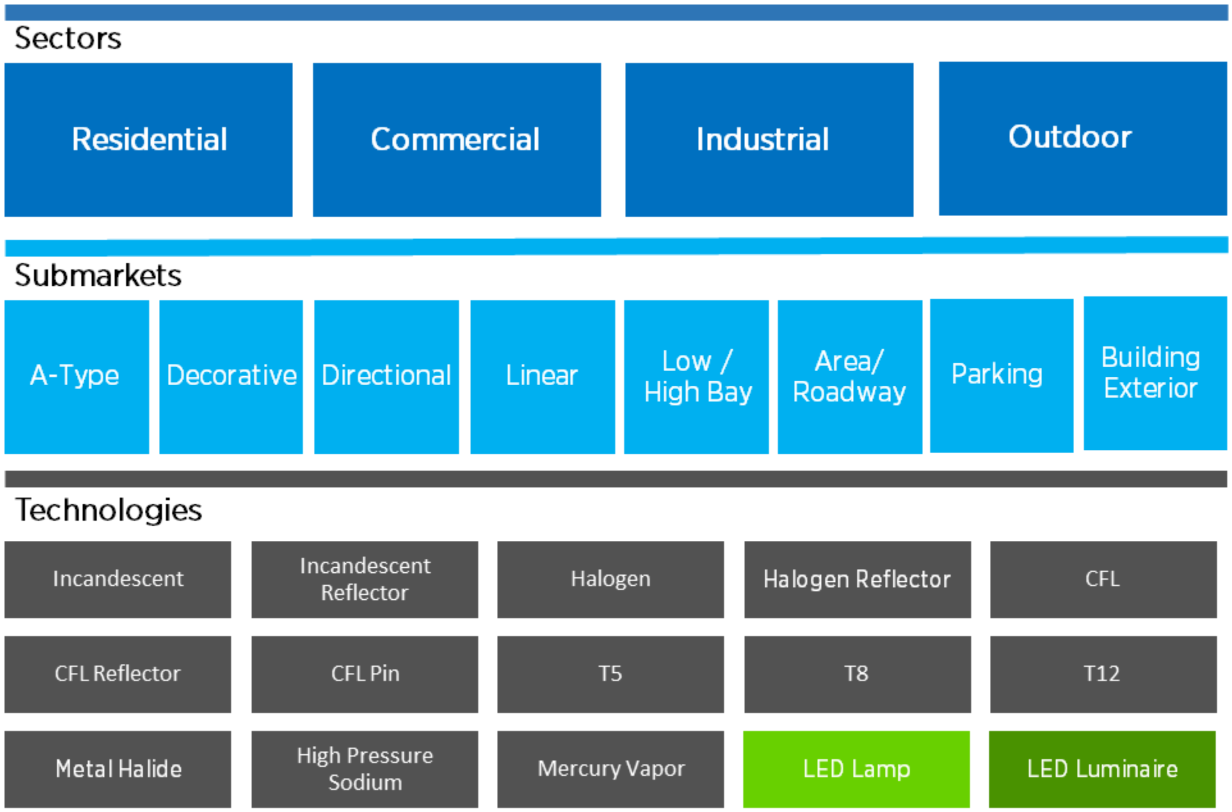

Figure 2.1 Lighting Market Competition Arenas

Step 3: Project annual lighting demand forecast.[6] The EIA's AEO 2015 provides annual average growth forecasts of floor space in the residential and commercial sectors, which are used to project increases in lighting demand moving forward. (1) Projections suggest that residential floor space will increase by an average of 1.17% per annum over the 20-year analysis period, and the commercial sector floor space will increase by an average of 0.99% per annum. AEO 2015 does not provide floor space growth forecasts for the industrial or outdoor sectors. Because the outdoor sector includes buildings-related outdoor lighting, it was assumed that its growth rate would match that of the commercial sector. For the industrial sector, the AEO 2015 annual projections for manufacturing employment indicate an average decline of 0.59% per annum. This estimate was used as a proxy for the expected annual decline in industrial floor space.

Step 4: Calculate the available market.[7] Each year, new lamps enter the market as old lamps are replaced or fixtures are installed or retrofitted. This creates an annual market turnover, which may be satisfied by a suite of lighting technologies. The lighting market model considers three possible events that create market turnover: 1) new installations due to new construction; 2) units replaced upon failure of existing lamps; and 3) units replaced due to lighting upgrades and renovations. The quantity of turnover due to new installations is derived from the projected new building floor space in the various sectors, as discussed in Step 3. The quantity of turnover due to replacements is based on the lamps, ballasts and fixtures that fail in a calendar year, which is calculated using a Weibull

[6] Additional detail on how the annual lighting demands were calculated can be found in Appendix B.
[7] Additional detail on how the market turnovers were calculated can be found in Appendix B.

probability distribution,[8] typical lighting operating hours, and product lifetimes. The quantity of turnover due to renovation is assumed to be a constant 10% of all fixtures per year, or a mean renovations cycle of 10 years.

Step 5: Project conventional and LED lighting technology improvement.[9] Recognizing that the incumbent conventional lighting technologies will compete with new LED lighting products, the lighting market model allows for both cost reductions and performance improvements in efficacy and lifetime for conventional lighting technologies (i.e., incandescent, halogen, fluorescent, and HID) and LEDs. Technology performance improvements are also adjusted to account for existing legislative and regulatory energy conservation standards that take effect in future years. The lighting market model uses performance curves for LED lighting developed from public LED product databases (i.e., ENERGY STAR Qualified Products, LED Lighting Facts, and Design Lights Consortium Qualified Products) and prices of LED products available for purchase that have systematically been collected quarterly since 2010. More information on the LED price and performance projections can be found in Appendix D.

Step 6: Model the market share of all lighting technologies.[10] The lighting market model predicts market share as an aggregate of many individual purchase decisions using three analytic components: an econometric logit model that considers economic factors, a technology diffusion curve that considers existing marketplace presence, and an acceptance factor that considers non-economic biases. Additionally, LED penetration is calibrated by comparing past LED market share values predicted by the model to actual historical values. Figure 2.2 summarizes this approach. This approach of using a logit model and a technology diffusion model in concert is well tested and has been previously used in many forecast models (8); (9).

[8] The Weibull distribution is a commonly used function for modeling survival and/or reliability. The formula for the survival function of the Weibull distribution is described by the National Institute of Standards and Technology, http://www.itl.nist.gov/div898/handbook/eda/section3/eda3668.htm

[9] Additional detail on how the cost and efficacy improvements were determined can be found in Appendix C and Appendix D.

[10] Additional detail on the logit model, the diffusion curve, and the calibration can be found in Appendix E.

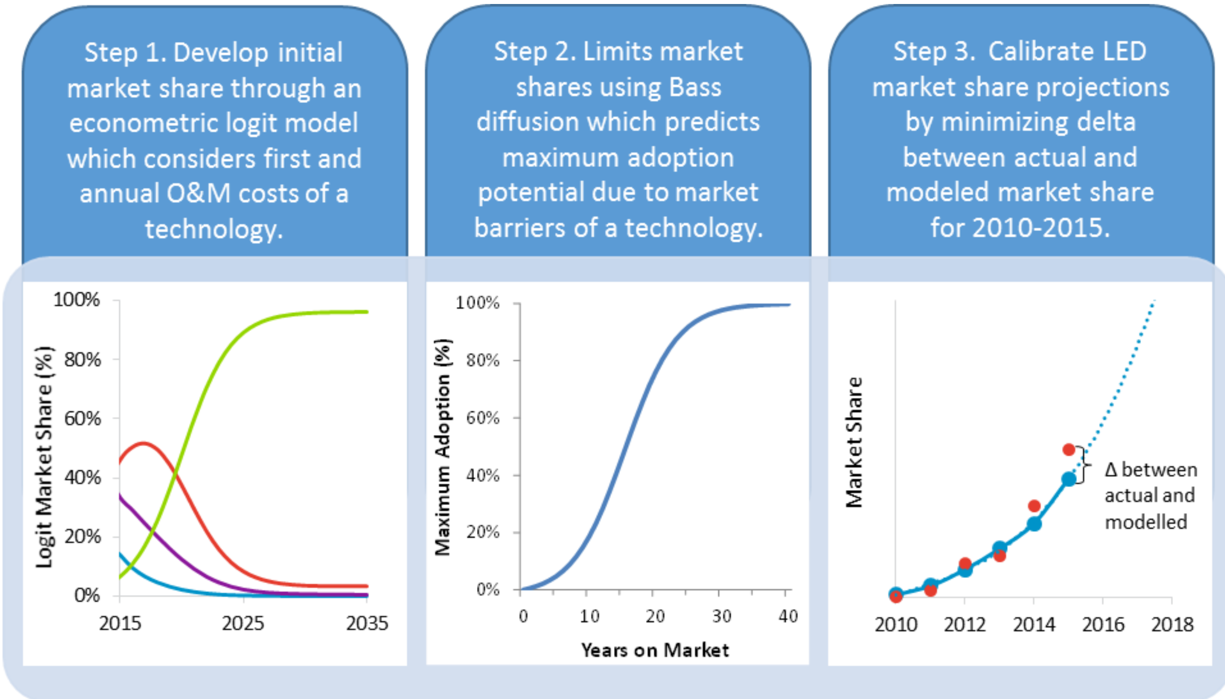

Figure 2.2 Market Share Modeling Approach

Step 7: Model the market share and energy savings of lighting controls.[11] The lighting market model calculates market share of connected lighting, as well as traditional lighting control systems, using an initial installed stock and calculated shipments in each analysis year. Additionally, 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.

Step 8: Calculate overall lighting market energy savings. Annual energy savings are then estimated by comparing the lighting energy consumption projected by the lighting market model to that of the hypothetical No-SSL scenario. 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, are unchanged.[12]

2.1 Lighting Market Model Enhancements

This iteration of the general illumination forecast improves upon past years' iterations in multiple ways. These enhancements are outlined below:

1. Updating the model to track lighting inventory on a unit basis. Past iterations of this model described the U.S. lighting inventory in terms of lighting service in units of teralumen-hours (i.e., the amount of light provided over time). This year's update converted the model to a

[11] Additional detail on the lighting controls methodology can be found in Appendix F.
[12] It has been hypothesized that certain standards would not have been implemented if not for the introduction of LEDs; however, such secondary effects are not accounted for in the energy savings calculation.

unit basis, where the model instead tracks the U.S. lighting inventory in terms of discrete lighting products, either as lamps, lamp – ballast systems, or entire lighting fixtures. Not only is this more intuitive, but it also allows for improved consistency with DOE's biennial Adoption Report. This is particularly important as the DOE SSL Program alternates between publishing a "snapshot" of the current LED installed base in the Adoption report and a forecast of the future U.S. lighting market in the Forecast Report, with each serving as an input for the other.

2. Calibration based on estimated LED market share for years 2010-2015. The last iteration of this model was calibrated using LED market share data for years 2010 through 2013. With two more years of complete LED market data available, this model offers improved calibration to historical data and trends, and thus effectively improves the accuracy of the model predictions.
3. Extend Model Forecast out to 2035. In the previous lighting market model, the forecast was limited to 2030. The updated model covers years 2015 through 2035.
4. Addition of LED lamps and luminaires into new and existing submarkets. In the updated lighting market model, LED lamps were added to the parking lot, area and roadway, and low and high bay submarkets to more accurately reflect the presence of high lumen output replacement lamp options that are recently gaining traction in market. These are seen as short term solutions due to ease of installation and lower first cost, and LED luminaires are expected to be stronger competitors in the long term. In addition, in previous iterations of the Forecast Report, decorative lamps were only analyzed in the residential sector. As a result of a finer granularity in the data used for the model update, decorative applications in the commercial sector are now assigned their own submarket. Additionally, fully integrated decorative luminaires are able to compete with lamps in decorative fixtures in both the residential and commercial sectors. Note that as a result of these enhancements, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses. (See Appendix A for more detail about the lighting technologies grouped in each submarket.)
5. Updated price and efficacy forecasts for LEDs. In the previous lighting market model, the anticipated LED price and efficacy values were derived from LED price and efficacy forecasts provided by Pacific Northwest National Laboratory (PNNL) in their SSL Pricing and Efficacy Trend Analysis for Utility Program Planning report. (10) However, this report has not yet been updated and the LED market has changed rapidly over the past three years. Therefore, new projections were developed through methods similar to those described in the PNNL report but using publicly available data through December 31, 2015. For more information on the development of LED price and efficacy projections, see Appendix D.
6. Updated lumen output and lamps per fixture assumptions for all products. The lumen output assumptions for LED products have also been updated using publicly available data to more accurately reflect real world products. Additionally, assumptions on the number of lamps used per fixture for many of the submarkets were revised. Note that as a result of these enhancements to lumen output and the number of lamps per fixture, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.
7. Lighting controls penetration and energy savings analysis, including connected lighting. In the previous lighting market model, controls were not explicitly modeled and the impacts of connected lighting were not included. Now, the lighting market model 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. See Appendix F for more information.

2.2 Simplifying Assumptions

In constructing the lighting market model, several simplifying assumptions were necessary to manage the analytical complexity of the U.S. lighting market. The assumptions are summarized below for convenience and clarity of presentation. The assumptions represent best estimates and were derived from inputs provided by DOE's SSL technical reports as well as industry experts; however, there is still significant uncertainty introduced with the assumptions. Each assumption is described below with a statement of whether it has a tendency to cause an overestimation or underestimation of the forecasted energy savings derived from the penetration of LED lighting. Due to the high level of uncertainty and lack of data in each area listed below, no attempt is made to quantify the magnitude of the effect.

1. Constant demand for lighting fixtures. It is assumed that the lumen output for each lighting technology is constant over the analysis period (2015–2035). This simplification may underestimate the forecasted energy savings from LEDs because it assumes that as conventional lighting systems fail they are replaced with LEDs of equivalent light output in all applications. However, due to the directionality of LEDs, many LED sources are able to emit better light distributions. Therefore, many spaces may be over-lit and LED technology may be able to achieve adequate illumination with fewer lumens and/or fixtures (e.g., due to improved uniformity, directionality, and/or color performance).

2. Renovations rate. The lighting market model assumes a constant 10% per year rate of lighting fixture replacements due to renovations of the installed base. This covers all upgrades/retrofits and renovations, regardless of their impetus, representing replacements that occur prior to the failure of the existing lighting fixture. This includes renovations undertaken for design or aesthetic preferences and "green" retrofits undertaken to reduce energy consumption. This renovation rate assumption has been increased from 5% to 10% compared to previous lighting market model iterations due to increasing concerns regarding energy consumption, as well as the growing prevalence of utility and government incentive programs that compensate consumers who retrofit using LED lighting products.[13] However, due to the high uncertainty in these inputs, the lighting market model may underestimate or overestimate the forecasted LED market penetration and energy savings.

3. LED and conventional technology price and performance improvement curves. The lighting market model is driven by price and performance improvement assumptions for LEDs and conventional technologies over the analysis period. Any deviations from these projections could cause the energy savings estimates to be higher or lower. Therefore, the lighting market model may underestimate or overestimate the forecasted LED market penetration and energy savings in the long term.

[13] Information on lighting incentives can be found at the Database of State Incentives for Renewables & Efficiency available at: www.dsireusa.org

4. Market share forecast. The economic portion of the lighting market model postulates that the lighting market responds primarily to first and annual costs and provides a probability of purchase for each technology under perfect competition. However, the lighting market model also recognizes that newer technologies are at a relative disadvantage compared with well-established incumbent technologies. The rate of market penetration is subject to certain market barriers, including, but not limited to, acceptance and availability of the technology. Typically, these barriers only apply to new market entrants, such as LED technologies, as it is these technologies that may initially be unknown to consumers or may not be readily available to purchase. As a product establishes itself on the market, however, benefits are communicated by word-of-mouth to the consumer base, manufacturers are able to ramp up production capacity, and stocking distribution channels emerge. To account for these factors, the lighting market model assumes a technology diffusion curve for both connected and non-connected LEDs based on the historical rate of penetration of other lighting and controls technologies. Depending on how connected and non-connected LEDs are marketed, this assumption may overestimate or underestimate the forecasted LED market penetration and energy savings.

5. Other future uncertainties. There are a wide array of potential developments that have been hypothesized that would greatly affect the lighting market. In short, the lighting market model does not address these developments as their likelihood is currently too speculative. Future studies should reassess these possible developments and address as needed.
   - Rebound effect – Users may increase their daily lighting usage because the operating cost is cheaper.
   - New technology – OLED lighting, laser lighting, or another unforeseen technology may be introduced or gain significant market share.
   - Government actions – Government actions, such as new efficiency standards or tax incentives could affect the future adoption of LED lighting products.

   Due to the great uncertainty surrounding each, the assumption to not include these possible market conditions may overestimate or underestimate the forecasted LED market penetration and energy savings.

3 Overview of the U.S. Lighting Market

3.1 Indoor

Residential, commercial, and industrial lighting employ many of the same lighting technologies in their indoor lighting applications. There are many similarities between the commercial and industrial sectors in terms of lighting technology and use trends, as lighting applications in these sectors are characterized by long operating hours (often greater than 10 hours per day) and higher lumen output requirements compared to the residential sector. Commercial and industrial lighting consumers are typically facility managers who are highly concerned with the lifetime costs of a lighting product. Therefore, technologies with high efficacy and long lifetime are more popular in these sectors, despite higher initial costs. Because of this distinct preference, both the commercial and industrial sectors are currently dominated by highly efficient and long lifetime linear fluorescent and HID technologies, which are primarily used in the linear fixture and low and high bay submarkets. Combined, the linear fixture and low and high bay submarkets represent 80% and 92% of the 2015 general illumination energy consumption in the commercial and industrial sectors, respectively. Lighting in the residential sector typically operates for less than 2 hours per day, and energy costs remain low. Therefore residential consumers place a high priority on low first cost when purchasing lighting products.

3.1.1 A-Type Submarket

The A-type submarket includes standard A-shape incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs), and LED replacement lamps used in omnidirectional indoor applications. These omnidirectional lamps are some of the most widely recognized on the market. While the vast majority of these lamps are used in omnidirectional indoor applications, some, due to their low cost and popularity, are also found in downlight and track lighting applications as discussed in Section 3.1.3, which covers the directional submarket. Additionally, a small number of these A-type lamps are used in outdoor submarkets, which is discussed in Section 3.2.

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 as well as EISA-compliant halogen lamps have begun to replace the traditional incandescent lamps in many applications.[14] A new rulemaking for general service lamps is currently underway that could cause both incandescent lamps and halogen lamps to exit the market earlier than forecasted.[15] However, these potential impacts are not considered in the lighting market model, as both compliance dates and standard

[14] 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

[15] For more information on DOEs General Service Lamps rulemaking, visit the docket at: http://www.regulations.gov/docket?D=EERE-2013-BT-STD-0051

levels are uncertain. This analysis considers only legislation and DOE regulations that are final (i.e., enacted in the *Code of Federal Regulations*[16]) and effective.

LED replacement lamps in the A-type submarket 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 2015, an LED-based dimmable A19 60 W-equivalent replacement lamp could be purchased for a price of less than $8 per bulb ($10/klm). While this is still more expensive than conventional incandescent or CFLs, rebates and incentives have and can further reduce the price to below $5. (2)

3.1.2 Decorative Submarket

Decorative is a fairly generic term that is used to cover a wide range of bulb shapes including bullet, globe, flame, and candle, among others. 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, LEDs 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 benefit 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.

The presence of decorative lamps and luminaires are most prevalent in the residential and commercial sectors, and are considered negligible in the industrial and outdoor sectors. Given their intended decorative function, these lamps typically require low lumen output and are not intended to independently illuminate a space or a task. However, they may have high color quality or dimming requirements depending on the use. Furthermore, as these products are primarily designed for their lighted as well as their unlighted appearance and aesthetic contribution to the space, an omnidirectional intensity distribution is generally preferable. At this time, energy efficiency standards have minimal restrictions on the majority of decorative incandescent lamp shapes.

3.1.3 Directional Submarket

Directional lighting is typically provided by either large reflector lamps (BR, R, PAR shapes) or smaller multifaceted reflector (MR) lamps, most commonly housed in track or downlight fixtures.

Downlights are widely used for ambient lighting in both residential and commercial buildings. These fixtures can be recessed or surface-mounted, and they have become popular because they are inexpensive and can provide inconspicuous ambient lighting for most room types. Track lights are also a popular fixture used for ambient lighting, but they are used for accent lighting in households, retail displays, restaurants, museums, and office buildings as well. These light fixtures are typically comprised of individual light fixtures, or track “heads”, attached to a continuous metal mounting

[16] For more information on the *Code of Federal Regulations* visit: http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR

device that is, in turn, attached to a ceiling or wall, or hung via suspension cables or rods. For both downlights and track lights, incandescent, halogen, and compact fluorescent reflector lamps (e.g., PAR, BR, and R lamps), pin-based CFLs, as well as LED lamps and luminaires are most commonly used. The model also considers that omnidirectional lamps can be installed in the residential sector, where consumers are most concerned with the initial bulb price as opposed to lighting quality and lifecycle costs.

While also installed in downlight or track fixtures, MR lamps do not compete directly with the large reflector lamps because they are most often operated at low voltage, and their design is constrained by a small form factor.[17] The most common MR lamp, the MR16, is particularly optimal for jewelry and other display applications due to their high CRI and well-controlled, high-intensity beam. (11) Halogen technology currently dominates the market for MR lamps, and, similar to the decorative lamp submarket, CFLs are not well suited for MR lamps due to size and form factor constraints.

The lighting market model assumes that both LED lamps and luminaires compete for market penetration in the directional submarket for downlights, track lights, and MR lamps. Because of the relatively low efficiency of incumbent technologies, downlight and track were among the earliest lighting applications where LED offered competitive performance. Consumers may put LED replacement lamps into existing downlight and track light fixtures or integrated directional LED luminaires may be used to replace these fixtures entirely.

For the commercial and residential sectors, the lighting market model separates the directional submarket into large (R, BR and PAR) and small (MR) reflector lamps. This is because consumer preference of incumbent technologies, which affects LED market penetration and resulting energy savings, differs for the two groups. For the industrial sector, small reflector lamps represent a negligible portion of the installed stock and are grouped with large reflectors into one singular directional submarket.

3.1.4 Linear Fixture Submarket

For the linear fixture submarket, the lighting market model considers T12, T8, and T5 linear and U-shaped fluorescent lamps that are less than, greater than, and equal to four feet in length. Both LED lamps and luminaires are assumed to compete in the linear fixture submarket. In the lighting market model, this submarket includes recessed troffers, surface-mounted fixtures, suspended fixtures, and other direct-lighting fixtures that customarily house a linear fluorescent or U-shaped fluorescent lamp and ballast system. Low and high bay fixtures are evaluated separately and the forecast results are presented in Section 3.1.5.

These fluorescent systems are widely utilized for commercial and industrial establishments because they offer a low cost, highly efficient, long lifetime lighting 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. (2)

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

3.1.5 Low and High Bay Submarket

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 LEDs to penetrate the market in significant quantities. Early generation high-bay LED luminaires lacked the lumen output to compete in this market. By 2013, the LED Lighting Facts database had 269 listed low and high bay luminaire products. Currently, there are over 4,000 listed low and high bay luminaire products, 55% of which emit over 15,000 lumens and 17% of which emit more than 25,000 lumens.[18] 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. To accommodate the increasing use of LED retrofit options for low and high bay applications, the lighting market model has been updated to forecast the potential for both LED luminaires and lamps in this submarket.

3.2 Outdoor

The general illumination submarkets in the outdoor sector consist of area and roadway, parking, and exterior building lighting. These lighting systems serve multiple purposes, such as providing proper illumination for pedestrian and automotive traffic, creating a sense of personal security, and attracting attention to business and spaces. HID and linear fluorescent lamps have historically been the predominant lighting technology used in the outdoor sector, but because of the importance of durability and lifetime, LEDs are a particularly attractive option.

3.2.1 Area and Roadway Submarket

Area 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.

LEDs are particularly advantageous in area and roadway lighting applications because they are excellent directional light sources, are durable, and exhibit long lifetimes. LED area 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. Because of these advantages, many local jurisdictions have initiated projects to completely transition their area and roadway lighting to LEDs. For example, the City of

[18] A full list of current LED Lighting Facts products can be found at: http://www.lightingfacts.com/

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. (12)

In addition to offering energy savings, LED area 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.

3.2.2 Parking Submarket

In this analysis, the parking lighting submarket has been divided into parking lots and covered garages, and does not consider street-side parking as those areas are covered in the area and roadway submarket discussed in Section 3.2.1.

The lighting technologies used for parking lots closely matches the technologies used for streetlighting, as these applications both have similar lighting requirements. Despite the similarities, penetration of LEDs in parking lot lighting lags behind that of area and roadway lighting, most likely because LED streetlighting adoption has come from local municipalities embarking on city-wide LED upgrades, while the majority of parking lot lighting is curated by private businesses. However, LEDs offer distinct advantages in parking lot applications and in particular can significantly improve light utilization.[19] 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. (13)

Parking garage structures, on the other hand, 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 LEDs in parking garage applications. LEDs are 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. (14) Due to this large energy savings potential of lighting controls, in the most recent Title 24 building code[20] 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.[21] While these building code requirements are only effective in California, this represents a significant opportunity for LEDs to help impact energy savings in parking garage applications across the U.S.

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[19] 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.

[20] For more information on Title 24 please see: http://www.dgs.ca.gov/dsa/Programs/progCodes/title24.aspx

[21] ANSI/ASHRAE/IES Standard 90.1-2013, Energy Standard for Buildings except Low-Rise Residential Buildings.

3.2.3 Building Exterior Submarket

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.

LEDs have 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 wallgrazing options for building façades through color tunability and better controllability, thus making them a top choice over incumbent sources. Due to the wide range of lumen requirements in this submarket, both LED lamps and luminaires compete for market share in building exterior lighting.

4 Lighting Market Model Results

In 2015, the total energy consumption in the United States was 97.8 quads of primary energy according to the EIA's AEO 2015. Roughly 39 quads, or 40%, of this energy was consumed for electricity use. (1) DOE estimated that in 2015, there were 6.9 billion lighting units[22] installed in the U.S., and that they consumed approximately 5.8 quads of energy annually.[23] Thus, lighting accounted for 6% of the total energy and 15% of the total electricity consumed in the U.S. in 2015.[24]

The results presented in this section covers years 2015 through 2035 for the following scenarios:

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 lamp and luminaire energy savings are calculated.

Current SSL Path The expected future path for LED lamps and luminaires given continuation of current levels of SSL investment and effort from DOE and industry stakeholders.

DOE SSL Program Goal The future path for SSL given DOE goals outlined in the annual SSL R&D Plan are met, representing the ultimate potential of what DOE has determined is technically feasible in the given time frame.

The Current SSL Path scenario estimates the expected future adoption of LEDs based on historical data and the current trajectory for the technology. The DOE SSL Program Goal scenario estimates the potential future adoption of LEDs based on what DOE has determined is technically feasible in the given time frame as outlined in the annual SSL R&D Plan, but additional efforts and funds would likely be required to meet these aggressive targets. (2) The hypothetical "No-SSL" scenario, as indicated above, is used as a reference condition from which SSL energy savings are calculated for both the Current SSL Path and DOE SSL Program Goal scenarios.

Figure 4.1 illustrates the increasing installed stock broken out by technology for the Current SSL Path scenario. In 2015, LEDs make up about 6% of the total installed stock, and it is projected that the penetration of LED lamps and luminaires will increase dramatically through 2035 to reach about 86%.

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[22] LED 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.

[23] Source energy consumption is calculated by multiplying electricity consumption by using a source-to-site conversion factor of 3.03. (1)

[24] Based on a total electricity consumption of 38.8 quads of source energy for residential, commercial, and industrial sectors from EIA's AEO 2015.

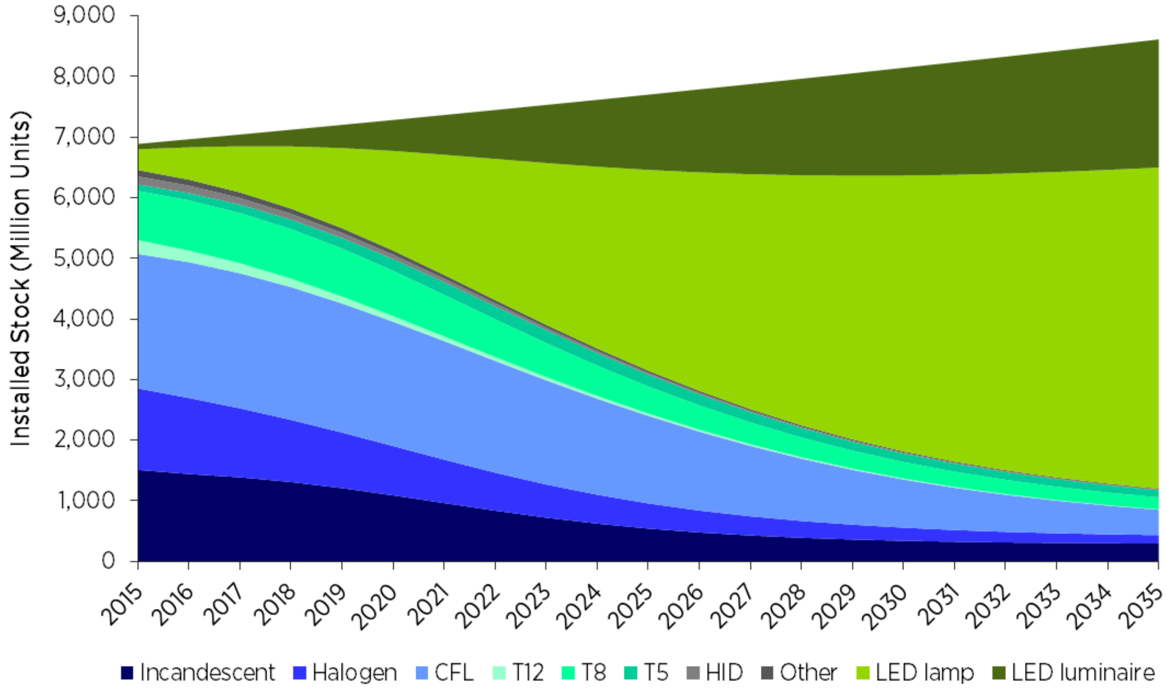

Figure 4.1 Installed Stock Projections for the Current SSL Path Scenario

Despite the increasing number of lighting products installed in the U.S. (up from 6.9 billion in 2015 to 8.6 billion in 2035), the lighting market model forecasts that LED adoption will lead to a continued reduction in energy use over time. Without SSL, the energy consumption of the U.S. lighting stock would continue to increase, up to 6.7 quads in 2035. As shown in Table 4.1, LEDs already offer 0.3 quads, or 280 trillion BTU (tBTU) of energy savings in 2015, but that is just the tip of the iceberg.[25]

Looking to the following Table 4.1, the results of the Current SSL Path scenario indicate that the LED lighting stock will experience rapid growth across all sectors. The residential sector is projected to dominate in terms of total LED lamps and luminaires installed, representing 61% of all LED installations in 2015 and growing to 76% by 2035. However, in terms of LED energy savings, due to low operating hours, the residential sector will provide roughly a quarter of the 2035 total. In contrast, the commercial, industrial and outdoor sectors make up a relatively smaller portion of the total LED installed stock, but the use of high lumen output lamps and long operating hours result in these sectors contributing greater shares of total LED energy savings. Despite representing only 16% of all LED installations in 2035, the commercial sector will provide half of all LED energy savings.

[25] Source energy savings are calculated by multiplying electricity savings by using a source-to-site conversion factor of 3.03. (1)

Table 4.1 U.S. LED Forecast Stock Results for the Current SSL Path Scenario

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**424**	**2,740**	**5,500**	**7,040**	**7,860**
	Commercial	136	436	826	1,080	1,220
	Residential	260	1,610	3,550	5,040	5,970
	Industrial	5	19	36	43	44
	Outdoor	30	93	137	160	177
	LED Installed Stock Penetration (%)	**6%**	**30%**	**59%**	**78%**	**86%**
	Commercial	12%	36%	64%	80%	86%
	Residential	5%	28%	57%	77%	86%
	Industrial	8%	32%	65%	78%	83%
	Outdoor	19%	57%	79%	88%	93%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. LED installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

Compared to the Current SSL Path, the DOE SSL Program Goal scenario offers a different view for the future of LED technology. Because adoption in the lighting market model is driven primarily by first as well as operation and maintenance costs, the total penetration of LED technology is similar in the two scenarios (LED penetration in the DOE SSL Program Goal scenario is slighting higher, reaching 88% by 2035). The primary difference between the two is the resulting energy savings due to penetration of lighting controls, particularly connected versus non-connected LEDs, and increased LED product efficacy.

The increase in connected lighting penetration[26] coupled with the more aggressive projections for LED lamp and luminaire efficacy result in a significant rise in forecasted energy savings for the DOE SSL Program Goal scenario. As shown below in Table 4.2, if the DOE targets are met, LEDs will enable an additional 1.4 quads in annual energy savings by 2035.

Table 4.2 U.S. LED Forecast Energy Savings Scenario Comparison

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Annual Energy Savings (tBTU)**	**280**	**998**	**2,110**	**2,990**	**3,720**
	Commercial	183	461	970	1,440	1,850
	Residential	35	287	643	875	1,020
	Industrial	22	49	100	131	155
	Outdoor	40	200	397	546	693
DOE SSL Program Goals	**Source Annual Energy Savings (tBTU)**	**280**	**1,510**	**3,260**	**4,420**	**5,070**
	Commercial	183	731	1,670	2,310	2,650
	Residential	35	324	717	972	1,140
	Industrial	22	76	158	195	209
	Outdoor	40	380	716	938	1,070

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

[26] A detailed discussion of the lighting control stock and energy savings impacts is provided in Section 4.1.

If LED lamps and luminaires continue to receive the current levels of SSL investment and effort from DOE and industry stakeholders, the U.S. lighting stock would consume 3.7 quads annually by 2035, representing a 55% reduction, compared to the hypothetical "No-SSL" scenario, which assumes LED technology never entered the lighting market. However, as seen in Figure 4.2, given that the more aggressive efficacy targets and connected lighting penetration goals laid out in the DOE SSL R&D Plan are met, LEDs would offer an additional annual energy savings of 1.4 quads in 2035. This results in a total energy reduction of 5.1 quads or a 75% reduction compared to the hypothetical "No-SSL" scenario, which is nearly equal to the energy consumed by 45 million U.S. homes.

This energy savings opportunity is driven largely by the linear fixture, outdoor, and low and high bay submarkets. These applications, characterized by high light output and long operating hours, are where increased controllability and networked capabilities will have the greatest value to customers. With these three submarkets leading the charge, LEDs installed with traditional control strategies as well as connected capabilities will contribute to a significant portion of the forecasted energy savings. Of the total 5.1 quads in annual energy savings by 2035, one-third is made possible by the penetration of connected-LEDs.

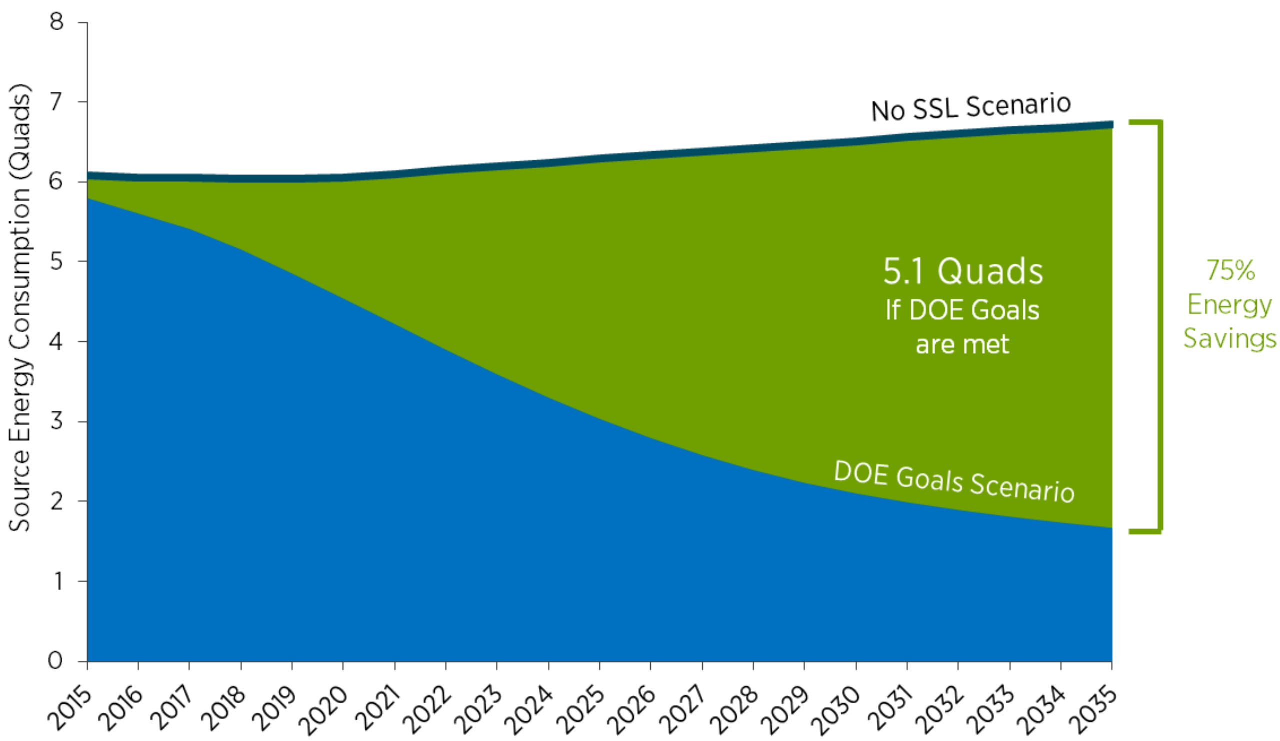

Figure 4.2 DOE SSL Program Goal Scenario Energy Savings Forecast, 2015-2035

While the decrease in energy consumption from 55% to 75% in 2035 may seem small, Figure 4.3 illustrated that the DOE SSL Program Goal scenario represents an additional cumulative energy saving of 20 quads – enough energy to power 90% of U.S. homes for one year. Therefore, the DOE SSL Program Goal scenario results in a massive increase in total energy savings from LED lighting.

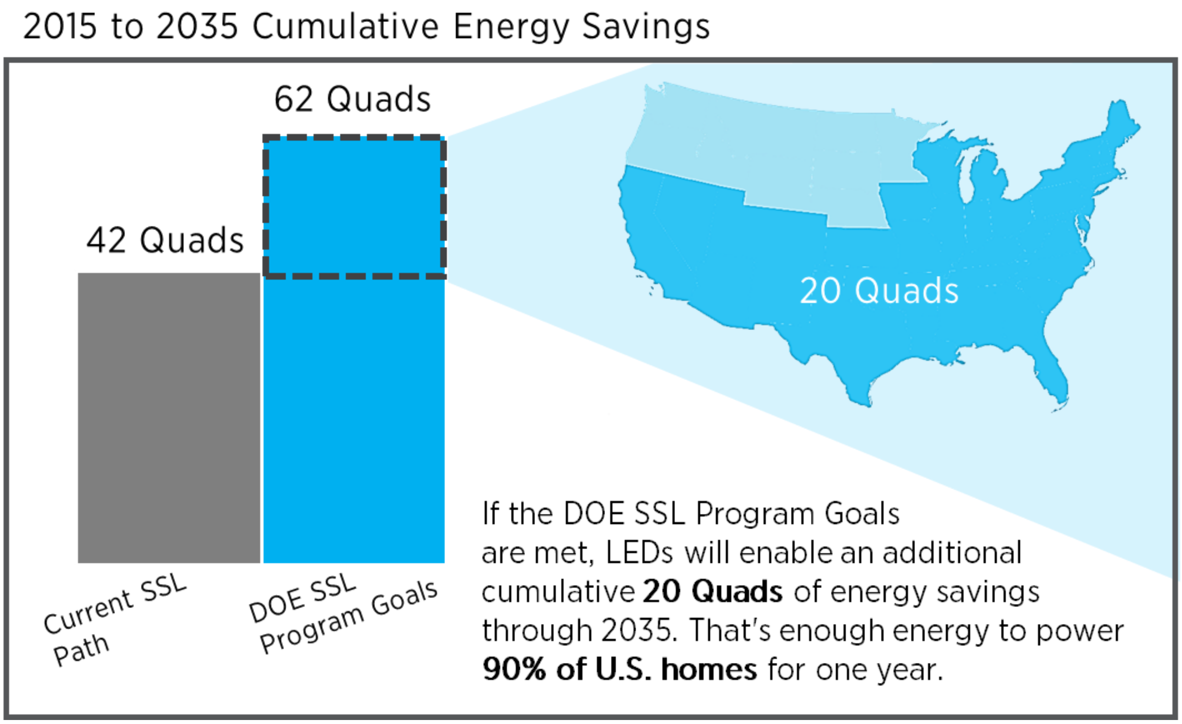

Figure 4.3 U.S. Cumulative Energy Savings Forecast from 2015 to 2035

4.1 Lighting Control Stock and Energy Savings Results

In recent years, lighting controls have garnered increased attention as a potential method of more intelligently operating lighting systems to save energy. Lighting controls, which include various dimming and sensor technologies used separately or in conjunction with other systems such as timers and daylighting, can, if used properly, yield significant energy savings, as they use feedback from the lit environment to provide adequate lighting levels only when needed. For this analysis, the lighting market model forecasts the impact from several types of control systems including traditional single-strategy controls (dimming, daylighting, occupancy sensing, and timing) as well as multi-strategy, energy management systems, and connected lighting.

In this Forecast Report, connected lighting is defined as 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.

Given the above definition, it is assumed that connected controls systems 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.

In the Current SSL Path and DOE SSL Program Goal scenarios, connected lighting is expected to have the greatest impact on LED luminaires. While connected LED lamps will certainly become increasingly utilized, connected LED linear fixtures (i.e., troffer, panel, strip, suspended, etc.), low and high bay, and outdoor luminaires target the applications where increased controllability and networked capabilities will have the greatest value to customers.

The major assumptions for connected lighting in each scenario are summarized below:

Connected Lighting Assumptions for Each Scenario:

- The **Current SSL Path** scenario assumes that the rate of market penetration of connected lighting is similar to that experienced for occupancy sensors, resulting in a slow adoption. This represents a scenario where the continued lack of performance reporting and verification, as well as the inability to address complexity and interoperability barriers, cause a lag in consumer adoption. *Within the 2035 timeframe, for the Current SSL Path scenario, the majority of luminaires installed are non-connected LEDs.*
- The **DOE SSL Program Goal** scenario, on the other hand, assumes that the rate of market penetration of connected lighting follows the same trajectory of LED lighting, resulting in an accelerated adoption. This represents a scenario in which industry and DOE efforts to demonstrate and verify energy savings benefits, as well as develop interoperable and user-friendly products accelerate consumer adoption. *Within the 2035 timeframe, the majority of luminaires installed in the SSL Program Goals scenario are connected LEDs.*

Table 4.3 summarizes the 2015 installed stock penetration for each control type analyzed in the lighting market model. These estimates are used as the baseline control stock for both the Current SSL Path and DOE SSL Program Goal scenarios.[27]

Table 4.3 2015 Installed Stock Penetration of Lighting Controls for Both Scenarios

Installed Stock Penetration (%)	Commercial	Residential	Industrial	Outdoor
None	68%	86%	94%	41%
Dimmer	3%	11%	4%	<1%
Daylighting	<1%	<1%	<1%	39%
Occupancy Sensor	6%	<1%	2%	<1%
Timer	4%	<1%	<1%	20%
Energy Management Systems	15%	<1%	<1%	<1%
Multi	4%	<1%	<1%	<1%
Connected	<1%	<1%	<1%	<1%

The light market model estimates that the use of traditional single and multi-strategy as well as energy management systems resulted in about 0.7 quads of energy savings in 2015 – or a roughly 10% reduction in overall lighting energy consumption. Currently, the vast majority of energy saving from controls is derived from energy management systems in the commercial sector, representing 0.34 quads or about half of the total. This is followed by commercial occupancy sensors at 0.1 quads or about 14% of all 2015 lighting control energy savings. Penetration of these more traditional

[27] Details on the lighting controls methodology can be found in Appendix F.

control strategies has been slow-moving, and many have only reached installed adoption of less than 5% despite being available for decades. Going forward, it is expected that the penetration of traditional single and multi-strategy controls as well as energy management systems will give way to connected lighting. While still emerging, connected lighting provides a large opportunity for energy savings in the U.S. The controllability of LED technology, as well as the low cost to integrate sensing, data processing, and network interface hardware will help overcome many of the existing barriers to utilizing lighting controls.

Table 4.4 presents the forecasted installed penetration of connected LED luminaires (as compared to non-connected) for each scenario. In the DOE SSL Program Goal scenario, connected LED luminaires reach an overall installed stock roughly double the size achieved in the Current SSL Path in 2035 (59% and 23%, respectively).

Table 4.4 Installed Penetration of Connected-LED Luminaires (Relative to Non-Connected)

	Sector	2015	2020	2025	2030	2035
Current SSL Path	**Connected LED Luminaires (%)**	**<1%**	**1%**	**4%**	**12%**	**23%**
	Commercial	<1%	2%	7%	17%	34%
	Residential	<1%	1%	3%	6%	12%
	Industrial	<1%	1%	4%	12%	27%
	Outdoor	<1%	<1%	3%	10%	25%
DOE SSL Program Goals	**Connected LED Luminaires (%)**	<1%	**15%**	**31%**	**43%**	**59%**
	Commercial	<1%	28%	52%	66%	73%
	Residential	<1%	1%	4%	13%	29%
	Industrial	<1%	16%	42%	60%	66%
	Outdoor	<1%	9%	37%	63%	77%

While the model also considers the impacts of connected LED lamps, these products are not expected to have similar impacts as LED luminaires. As seen in Table 4.5, due to the limiting form factor, relative high cost and lower potential for energy savings, in both scenarios connected LED lamps represent the minority of all LED lamps installed.

Table 4.5 Installed Penetration of Connected-LED Lamps (Relative to Non-Connected)

	Sector	2015	2020	2025	2030	2035
Current SSL Path	**Connected LED Lamps (%)**	**<1%**	**<1%**	**<1%**	**2%**	**4%**
	Commercial	<1%	<1%	<1%	3%	9%
	Residential	<1%	<1%	<1%	2%	4%
	Industrial	<1%	<1%	<1%	2%	8%
	Outdoor	<1%	<1%	<1%	1%	5%
DOE SSL Program Goals	**Connected LED Lamps (%)**	**<1%**	**<1%**	**1%**	**5%**	**16%**
	Commercial	<1%	<1%	1%	6%	18%
	Residential	<1%	<1%	1%	5%	16%
	Industrial	<1%	<1%	1%	5%	15%
	Outdoor	<1%	<1%	<1%	3%	10%

While the above Table 4.4 and Table 4.5 show the increase in connected LEDs relative to the total population of installed LED lamps and luminaires, Figure 4.4 illustrates the forecasted penetration of these connected-LED products by 2035 relative to the total installed lighting stock for each scenario. In the DOE SSL Program Goal scenario, where adoption of connected-LEDs is accelerated, this equates to an overall penetration of 24% (connected-LED lamps and luminaires combined) of the U.S. lighting stock while LED with traditional lighting controls represents 15%.

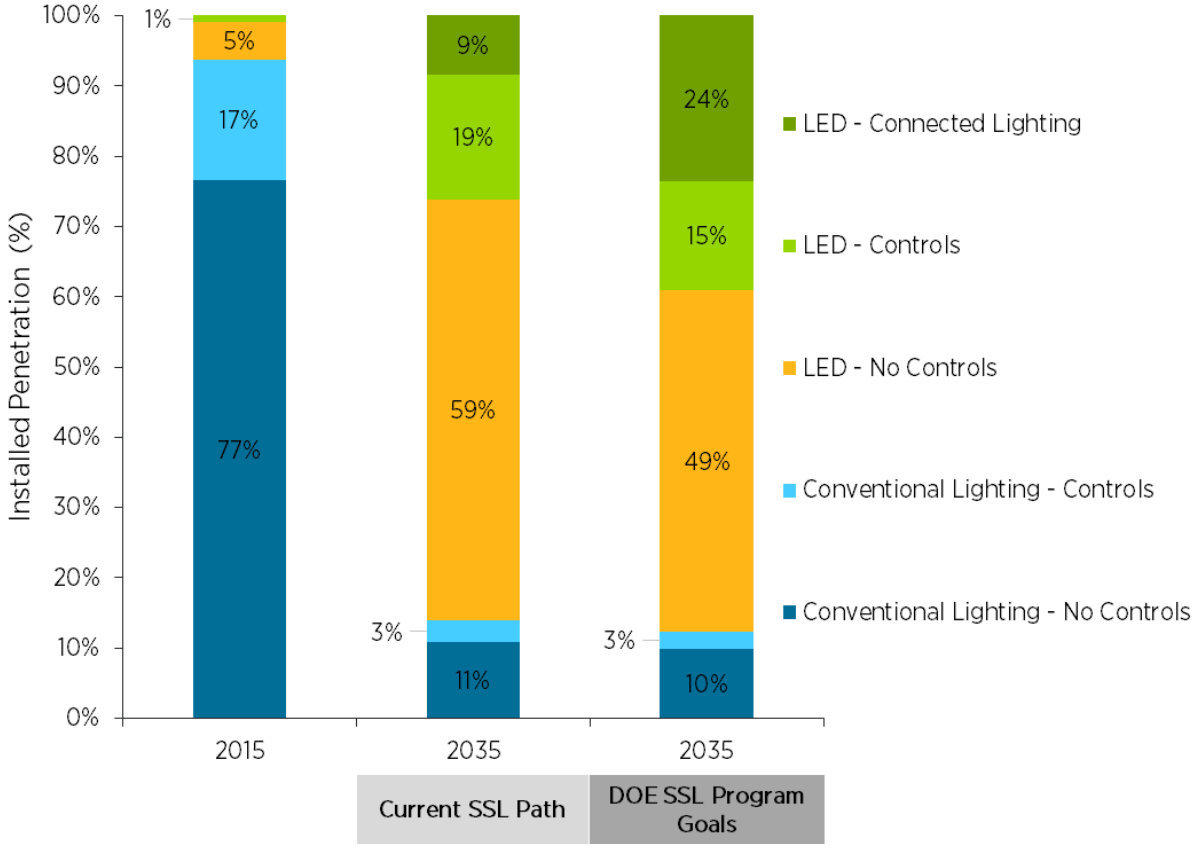

Figure 4.4 Lighting Controls Installed Penetration for LED vs. Conventional Lighting

As seen in Figure 4.4, both connected lighting and traditional control systems are expected to thrive due to their compatibility with LED lighting. However, in both scenarios connected lighting represents the majority of the future savings from lighting controls and is the source of nearly all growth. As shown in Table 4.6, for the Current SSL Path scenario, connected lighting penetration is lower, however, in total, lighting controls still results in an annual energy savings of 1,050 tBTU by 2035 – roughly half of this is attributed to connected-LEDs.

In the DOE SSL Program Goal scenario, the 2035 forecasted annual energy savings from lighting controls more than doubles to 2,280 tBTU or roughly 2.3 quads. Connected-LEDs in this scenario are responsible for about 75% of the 2035 lighting controls energy savings or 1,703 tBTU equivalent to 1.7 quads. By avoiding 1.7 quads of annual energy consumption, connected-LEDs would save the U.S. over $17 billion in energy costs.

Table 4.6 Annual Energy Savings from Lighting Controls by Sector for Each Scenario[1]

	Sector	2015	2020	2025	2030	2035
Current SSL Path	**Source Annual Energy Savings (tBTU)**	**658**	**695**	**700**	**807**	**1,050**
	Commercial	543	581	584	661	829
	Industrial	18	16	13	15	22
	Residential	5	8	12	19	30
	Outdoor	92	90	89	111	170
DOE SSL Program Goals	**Source Annual Energy Savings (tBTU)**	**658**	**1,400**	**1,610**	**1,910**	**2,280**
	Commercial	543	1,180	1,330	1,530	1,760
	Industrial	18	31	26	31	53
	Residential	5	20	42	61	75
	Outdoor	92	172	212	291	388

1. The energy savings presented in this Table 4.6 are not additive to those provided in Table 4.2 and represent the portion attributed to lighting control use.

4.2 Submarket Stock and Energy Savings Results

When considering the scenario results by submarket, several interesting trends emerge. In 2015, the majority of installations were omnidirectional A-type, followed by directional, linear fixture, and decorative. However, a large number of installations does not necessarily translate directly to the best opportunity for energy savings. As shown in Figure 4.5., the energy savings opportunity depends on the number of installations, the number of hours each installation is operated, and the energy efficiency improvement offered by LEDs compared to the incumbent technologies with which they are competing.

For example, in 2015, 46% 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 90 million low and high bay fixtures were installed in the U.S. in 2015, but they operate for an average of about 12 hours per day in the commercial and industrial sectors. Therefore, low and high bay fixtures contribute the same 2015 LED energy savings as A-type lamps despite the huge disparity in number of installations. Linear fixture applications are also characterized by long operating hours represent a significant portion of the 2015 LED energy savings at 20%, and are predicted to contribute the most (29% in the Current SSL Path and 32% in the DOE SSL Program Goal scenarios) to 2035 LED energy savings.

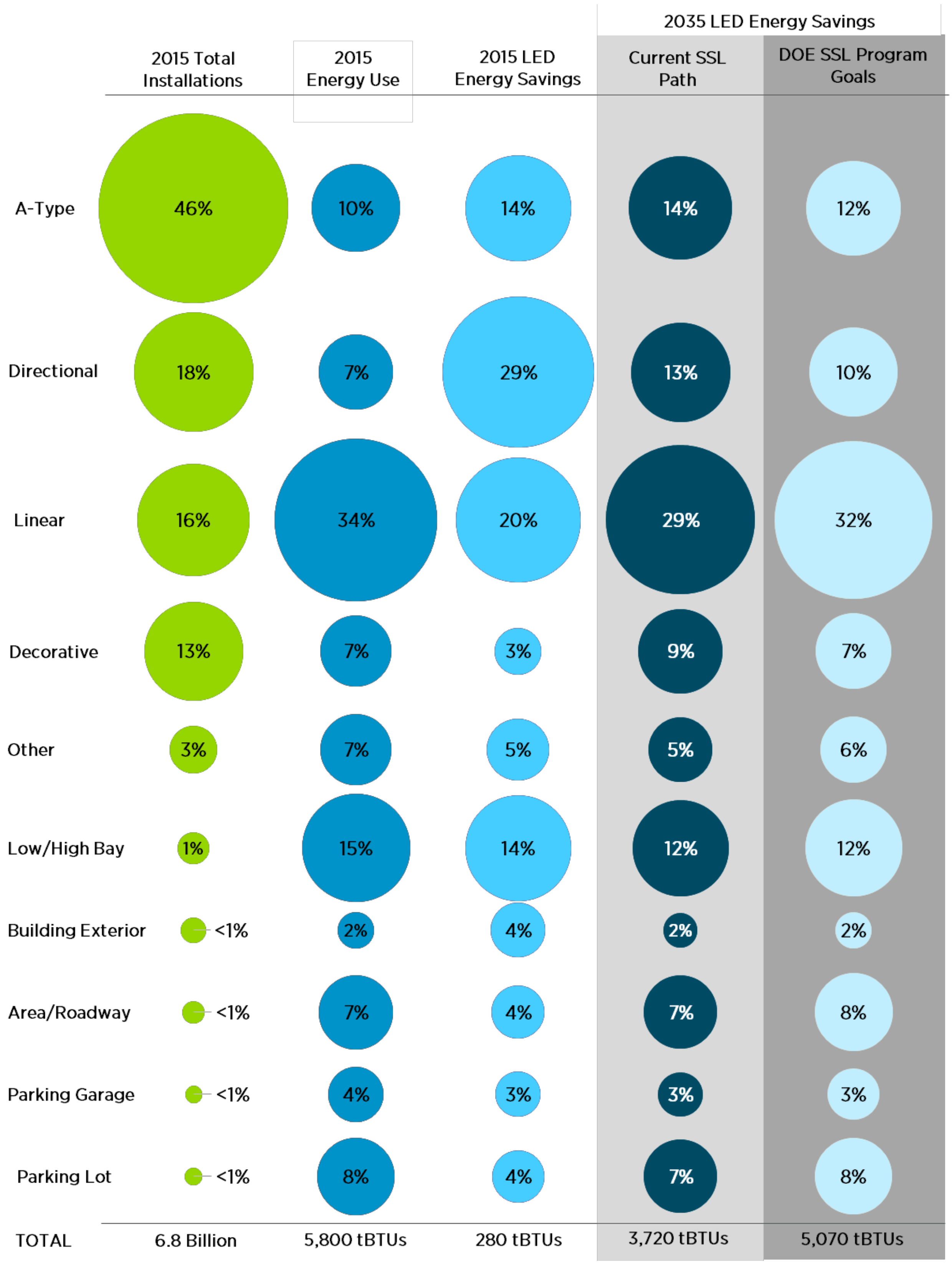

Figure 4.5 Total U.S. Lighting Installations, Energy Consumption, and LED Energy Savings

As shown in Table 4.7, of the submarkets examined, the lighting market model anticipates that LEDs will grow most rapidly in the area and roadway, low and high bay and A-type submarkets in terms of the percentage of total lighting installations. In the area and roadway submarket, already a popular application for LED upgrades, LEDs are predicted to comprise over 90% installed penetration by 2025 and nearly 100% by 2035. Low and high bay LEDs have seen recent growth in adoption – achieving an estimated 6% of all installations in 2015. This is expected to grow to 86% by the end of the analysis period. The A-type submarket will shift to LEDs a bit more slowly, with a projected 56% installed penetration by 2025, but will consist of 90% LEDs by 2035.

Table 4.7 LED Penetration by Submarket for the Current SSL Path Scenario

	2015[1]	2020	2025	2030	2035
A-Type	6%	29%	56%	78%	90%
Decorative	2%	27%	63%	77%	82%
Directional	11%	39%	69%	82%	86%
Linear Fixture	3%	16%	47%	68%	77%
Low and High Bay	6%	38%	68%	80%	86%
Parking	17%	48%	72%	84%	90%
Area and Roadway	21%	66%	91%	97%	99%
Building Exterior	21%	58%	77%	85%	91%
Other[2]	7%	39%	71%	87%	93%
Total LED Installed Stock Penetration	**6%**	**30%**	**59%**	**78%**	**86%**

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.
2. The "other" submarket is included to accommodate lighting products with unknown applications; however, it will not be explored in great detail in this report.

The following sections discuss the detailed results for each of the submarkets analyzed.

4.2.1 A-Type

Although the most familiar light bulb to consumers, the installed stock of incandescent A-type lamps has dropped significantly in recent years due to federal minimum energy efficiency standards (see Appendix C.1). As a result of EISA 2007, the A-type market has migrated away from incandescent towards the more efficient compact florescent and halogen technologies. Halogen lamps, while currently representing nearly half of all A-type sales because of their low cost and high consumer acceptance, are roughly one-third of the installed stock. As seen in Figure 4.6, by 2025, halogens are projected to drop below 10% of the installed stock yielding to the increasing adoption of LED lamps, and ultimately hold less than 2% of the installed stock in 2035. On the other hand, CFL are currently only about a quarter of sales but make-up 54% of the installed stock. CFL sales will continue to drop significantly over the next 20 years; however, due to their long life and low operating hours for A-type applications, CFL installations will remain throughout the analysis period.

In 2015, there were approximately 3.2 billion A-type lamps installed in omnidirectional applications. 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 continuous-decreasing price of LED lamps and greater consumer acceptance has enabled them to capture nearly 10% of sales in

2015. In terms of installations, by 2023, LEDs are projected to overtake CFLs as the most prevalent A-type technology, and by 2035 they will constitute nearly 90% of the 4 billion A-type lamp installations.

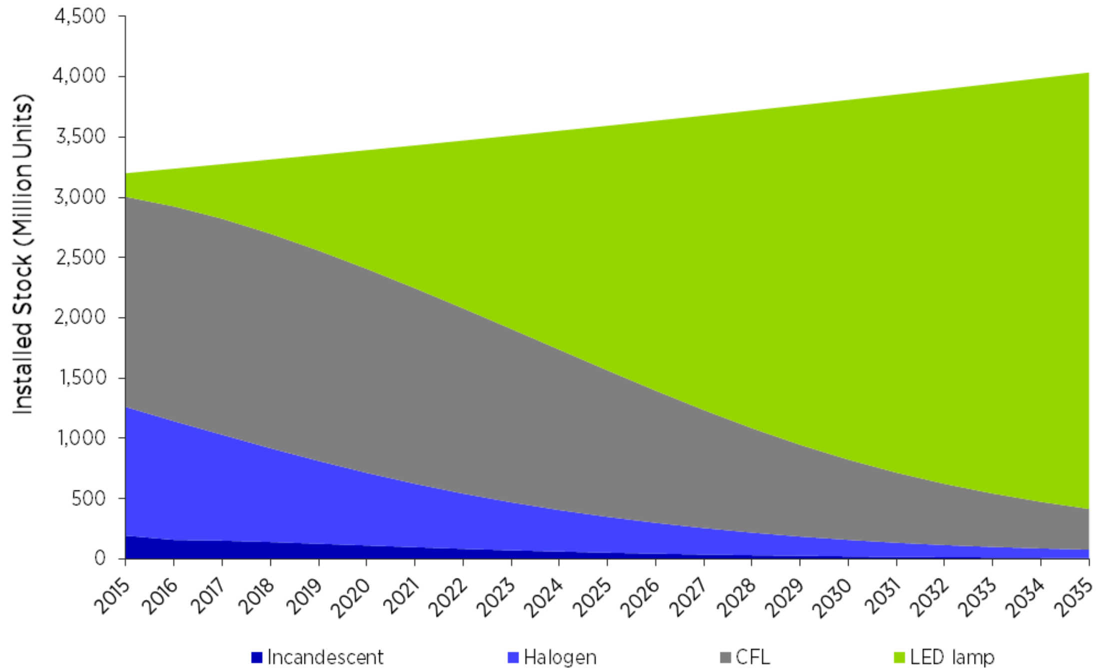

Figure 4.6 A-Type Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.8 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the A-type submarket.

Table 4.8 A-Type Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**196**	**985**	**2,030**	**2,980**	**3,620**
	Commercial	10	48	66	73	78
	Residential	186	936	1,960	2,910	3,540
	Industrial	<1	<1	<1	<1	<1
	LED Installed Stock Penetration (%)	**6%**	**29%**	**56%**	**78%**	**90%**
	Commercial	15%	70%	91%	96%	97%
	Residential	6%	28%	56%	78%	90%
	Industrial	13%	47%	74%	89%	95%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

When comparing the A-type submarket installed stock forecast results by sector, the commercial and industrial sectors shown in Figure 4.7 and Figure 4.8 are quite similar. Both show a quick uptake of LEDs following the final phase of EISA 2007, which kicked-in as of January of 2014 resulting in LEDs making up about 15% and 13% of the commercial and industrial installed stock, respectively.

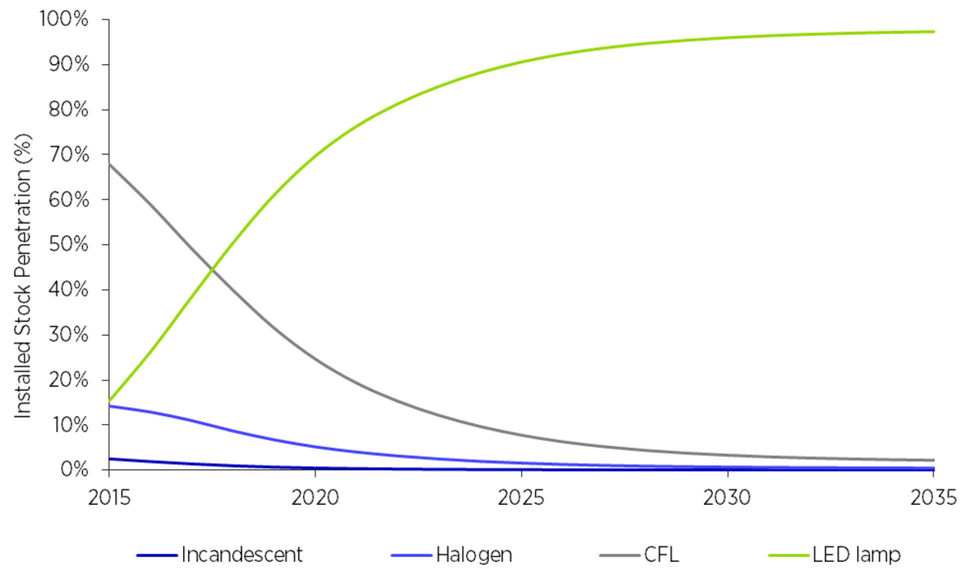

Figure 4.7 Commercial A-Type Submarket Stock Forecast for the Current SSL Path Scenario

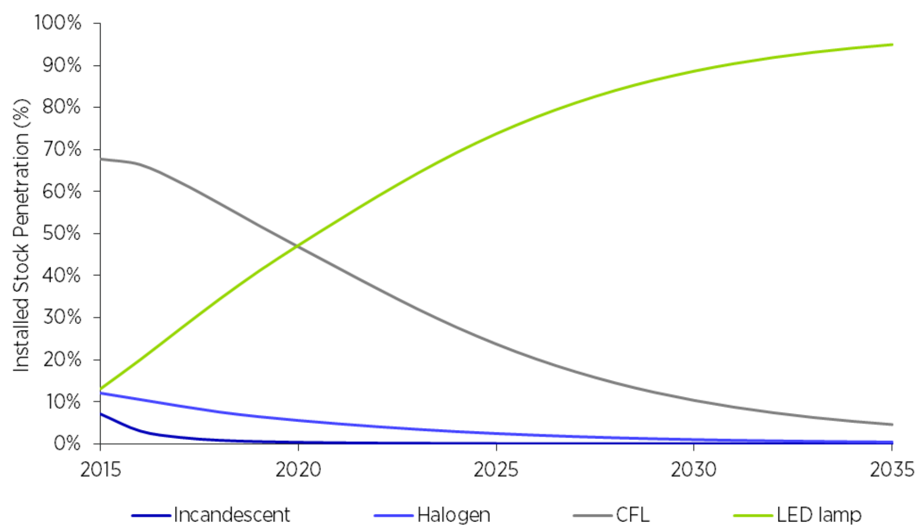

Figure 4.8 Industrial A-Type Submarket Stock Forecast for the Current SSL Path Scenario

However, due to shorter operating hours and emphasis on low first costs, incumbent technologies, including incandescent, maintain a foothold in the residential installed stock of A-type lamps for longer, and the LED installed penetration for the residential sector, shown in Figure 4.9, is more gradual and initially lags by about three years. However, by 2035, LED lamps are projected to make up over 90% of the installed stock in all three sectors.

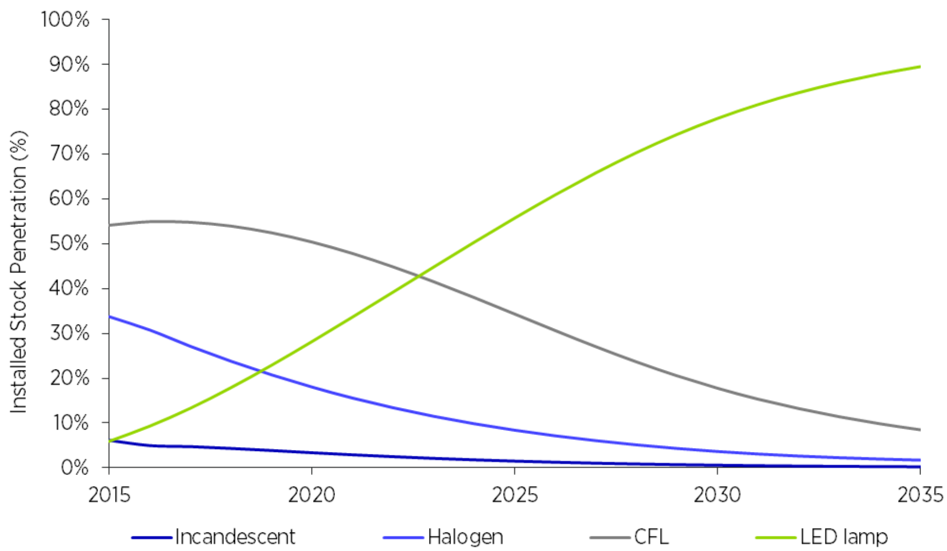

Figure 4.9 Residential A-Type Submarket Stock Forecast for the Current SSL Path Scenario

Figure 4.10 shows the transition from conventional lighting to LEDs. While connected-LED lamps are expected to penetrate into A-type applications, compared to other submarkets analyzed in this report, connected lighting will comprise a relatively small portion of the installed stock. The lighting market model forecasts that roughly 4% of all installations will be connected-LED lamps by 2035 if current levels of SSL investment and effort from DOE and industry stakeholders is maintained. An increase in connected-LED lamps is expected for the DOE SSL Program Goal scenario, with installed penetration reaching 15% by 2035.

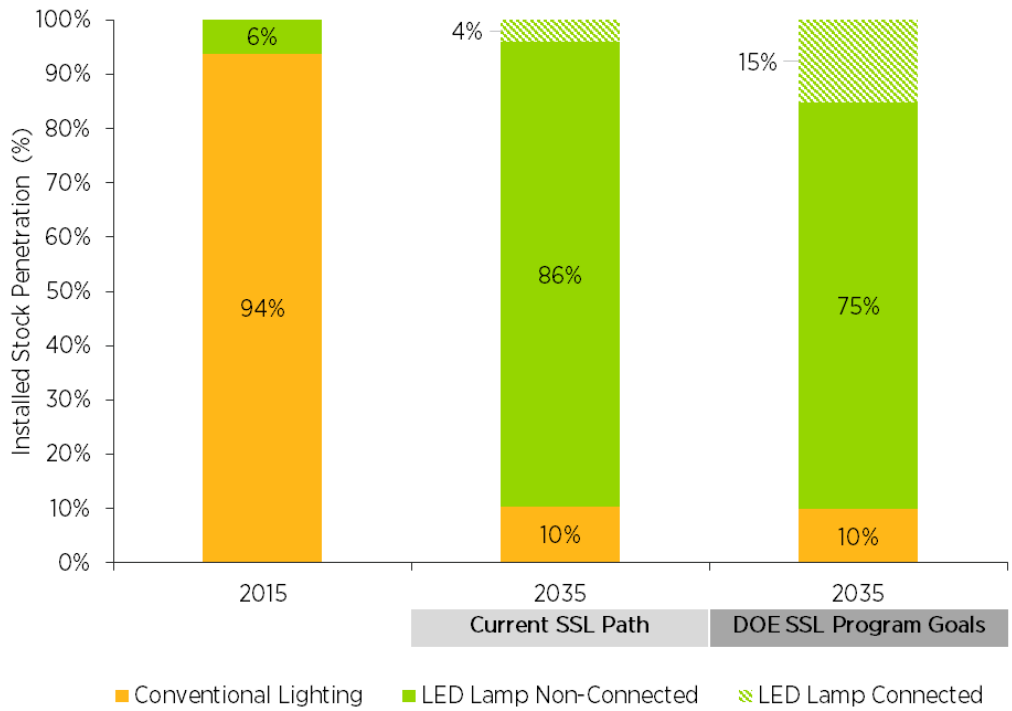

Figure 4.10 A-Type Submarket LED Installed Stock Penetration

Table 4.9 shows that the increasing adoption of LED lighting is expected to achieve 70% source energy savings in 2035 for the Current SSL Path scenario and 80% source energy savings in 2035 for the DOE SSL Program Goal scenario in the A-type lamp submarket across all sectors. This increase results in an additional 74 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by over 656 thousand U.S. homes.

Table 4.9 A-Type Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**42**	**180**	**328**	**451**	**533**
	Commercial	14	30	41	45	49
	Residential	28	150	287	406	484
	Industrial	<1	<1	<1	<1	<1
	Source Energy Savings (%)	**7%**	**28%**	**48%**	**62%**	**70%**
	Commercial	20%	46%	62%	68%	71%
	Residential	5%	26%	46%	62%	70%
	Industrial	11%	21%	35%	46%	52%
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**42**	**200**	**369**	**510**	**607**
	Commercial	14	34	47	53	56
	Residential	28	166	322	457	550
	Industrial	<1	<1	<1	<1	<1
	Source Energy Savings (%)	**7%**	**31%**	**54%**	**70%**	**80%**
	Commercial	20%	52%	72%	79%	82%
	Residential	5%	28%	52%	69%	80%
	Industrial	11%	29%	49%	63%	70%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.2 Decorative

As described in Section 3.1.2, the decorative submarket comprises a wide range of shapes including bullet, globe, flame, and candle, among others. Because of their relative low cost, aesthetic appeal, and absence of federal efficiency standards, incandescent lamps remain the dominate player in the decorative submarket, representing 86% of the 860 million decorative installations in 2015. Incandescent lamps are projected to gradually be replaced with an increasing number of LED lamps and luminaires as they become cheaper and consumers more energy conscious, but incandescent lamps are still expected to hold onto 15% of the 1.1 billion decorative installations in 2035.

LEDs, while available for all existing decorative lamp shapes, have only recently began offering replacements that meet the aesthetic criteria demanded by some consumers. As seen in Figure 4.11, by 2035, LED lamps are projected to hold 68% of the installed stock, while LED luminaires lag behind with roughly 13%.

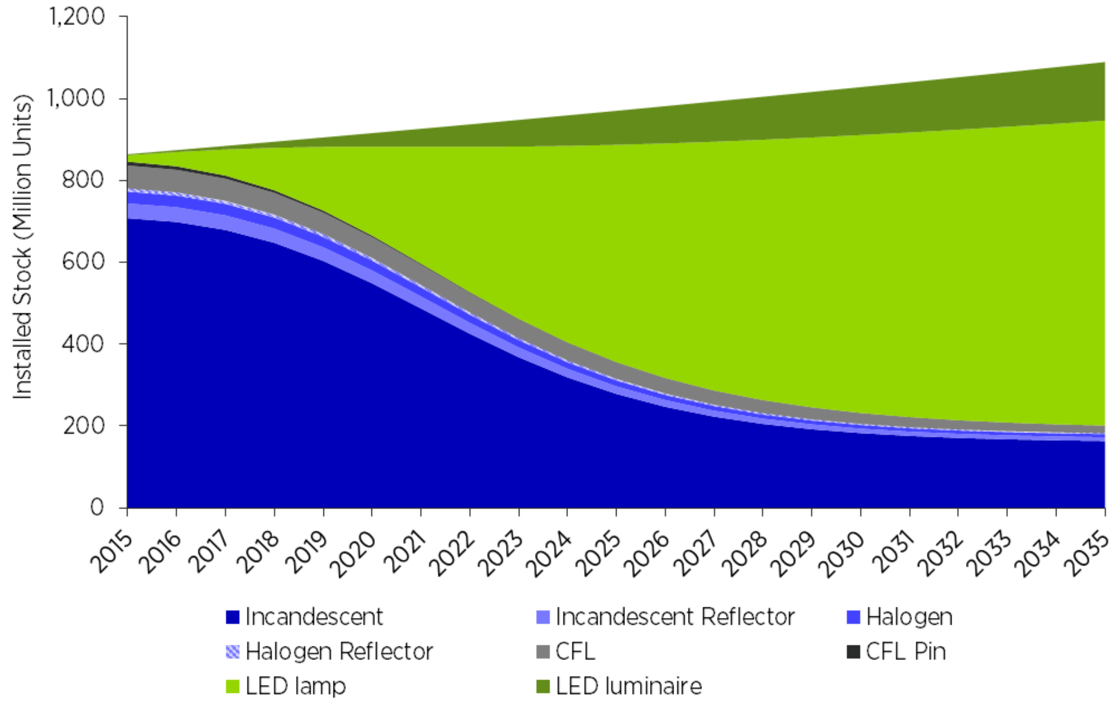

Figure 4.11 Decorative Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.10 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the decorative submarket.

Table 4.10 Decorative Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**18**	**250**	**614**	**796**	**888**
	Commercial	2	18	25	28	30
	Residential	16	232	589	768	859
	LED Installed Stock Penetration (%)	**2%**	**27%**	**63%**	**77%**	**82%**
	Commercial	8%	68%	89%	92%	93%
	Residential	2%	26%	63%	77%	81%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses..

Figure 4.12 and Figure 4.13 below show the different impact LEDs have on the commercial and residential sectors, respectively.

For the commercial sector, the lighting market model forecasts that LED lamps will overtake incandescent lamps in 2018 with 37% installed stock penetration. LED lamps continue to rise in popularity until they peak in 2023 at 67% installed stock. At this point, LED luminaires begin to see more aggressive growth mostly at the expense of LED lamps.

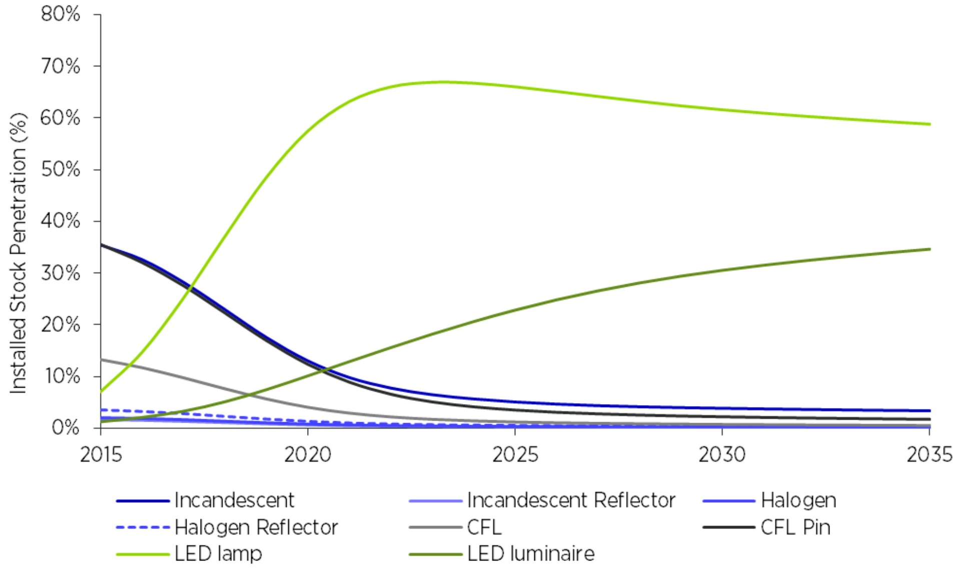

Figure 4.12 Commercial Decorative Submarket Stock Forecast for the Current SSL Path Scenario

In contrast, in the residential sector shown in Figure 4.13, incandescent lamps remain dominant until 2023, and, while projected to decline, will still make up 16% of the installed stock in 2035. Similar to the commercial sector, LED lamps are first to penetrate decorative applications followed by LED luminaires; however, residential consumers are more sensitive to higher first costs and difficulty of installation, causing LED lamps to continue to be favored out through 2035. By 2035, LED luminaires are projected to represent 13% of decorative installations in the residential sector.

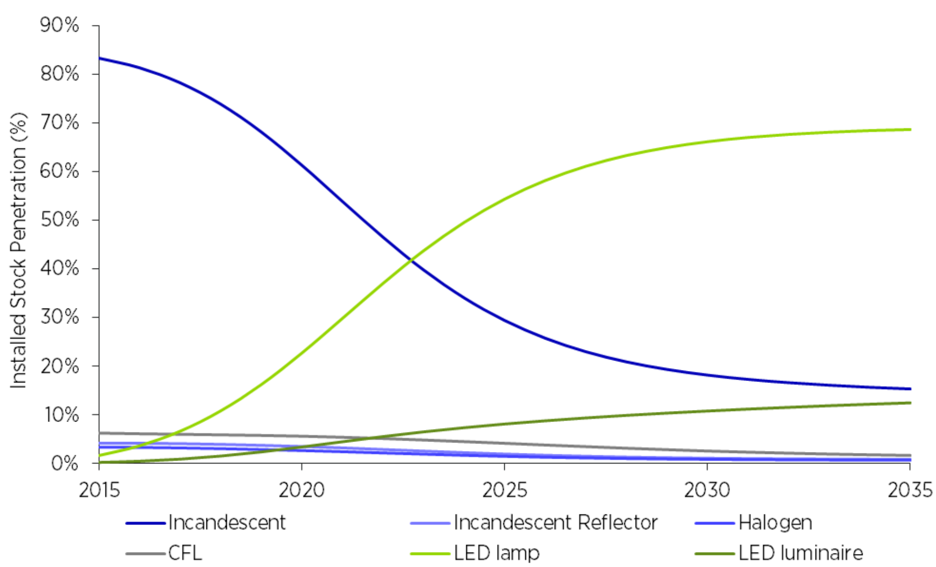

Figure 4.13 Residential Decorative Submarket Stock Forecast for the Current SSL Path Scenario

Figure 4.14 illustrates the transition to LEDs, as well as the persistence of conventional technology for decorative applications by 2035 (conventional lighting remains 18% and 16% of the installed stock for the Current SSL Path and DOE Program Goals scenarios, respectively).

In addition, compared to the A-type submarket, connected LED lamps are expected to penetrate an even smaller portion of decorative installations. Because the majority decorative installations are in the residential sector, these lighting products are characterized by low operating hours making it difficult for consumers to value the added features and energy savings that connected lighting offers. Across all sectors, the lighting market model forecasts that less than 4% of all installations will be connected products by 2035 if current levels of SSL investment and effort from DOE and industry stakeholders is maintained. A slight increase in connected LED luminaire is expected for the DOE SSL Program Goal scenario. Resulting in an overall connected penetration of 11% by 2035.

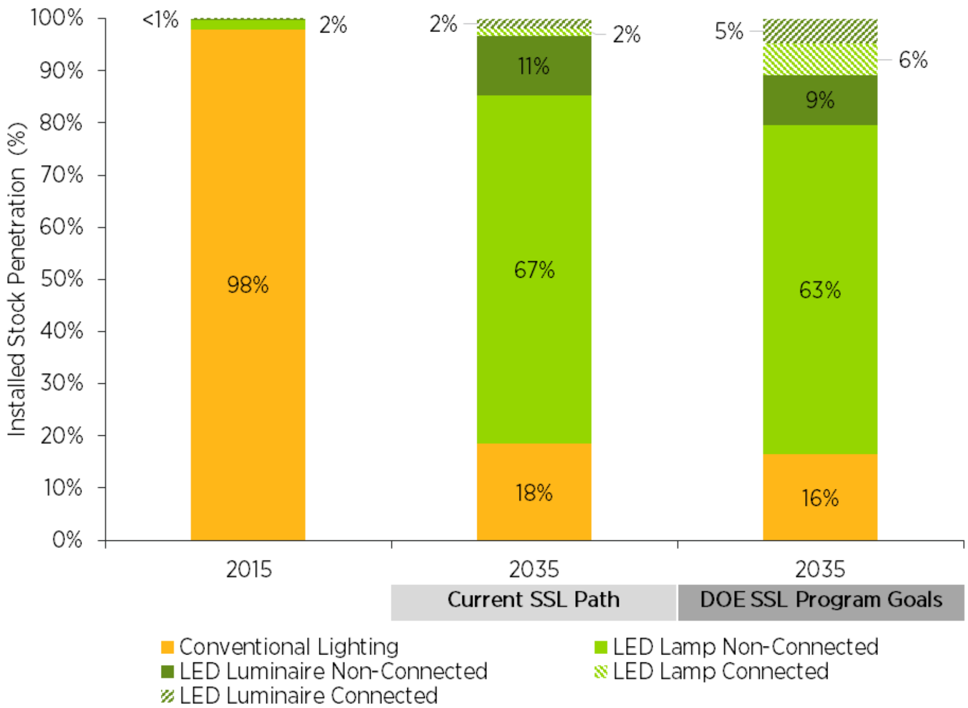

Figure 4.14 Decorative Submarket LED Installed Stock Penetration

Table 4.11 shows that the increasing adoption of LED lighting is expected to achieve 76% source energy savings in 2035 for the Current SSL Path scenario and 83% source energy savings in 2035 for the DOE SSL Program Goal scenario in the decorative submarket across all sectors. This increase results in an additional 30 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by nearly 265 thousand U.S. homes.

Table 4.11 Decorative Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**8**	**139**	**279**	**331**	**357**
	Commercial	11	81	115	126	133
	Residential	<1	57	164	205	224
	Source Energy Savings (%)	**2%**	**33%**	**64%**	**73%**	**76%**
	Commercial	7%	54%	74%	78%	81%
	Residential	<1%	21%	58%	70%	74%
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**8**	**161**	**311**	**362**	**387**
	Commercial	11	92	128	138	144
	Residential	<1	69	183	224	243
	Source Energy Savings (%)	**2%**	**38%**	**71%**	**80%**	**83%**
	Commercial	7%	61%	82%	86%	88%
	Residential	<1%	26%	65%	76%	80%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.3 Directional

LED directional luminaires were some of the earliest applications for SSL in general illumination, particularly LED downlights, and as of 2015 have already established themselves as a significant competitor in directional applications. Figure 4.15 and Figure 4.16 illustrate the forecasted installed stock for both large and small directional applications.

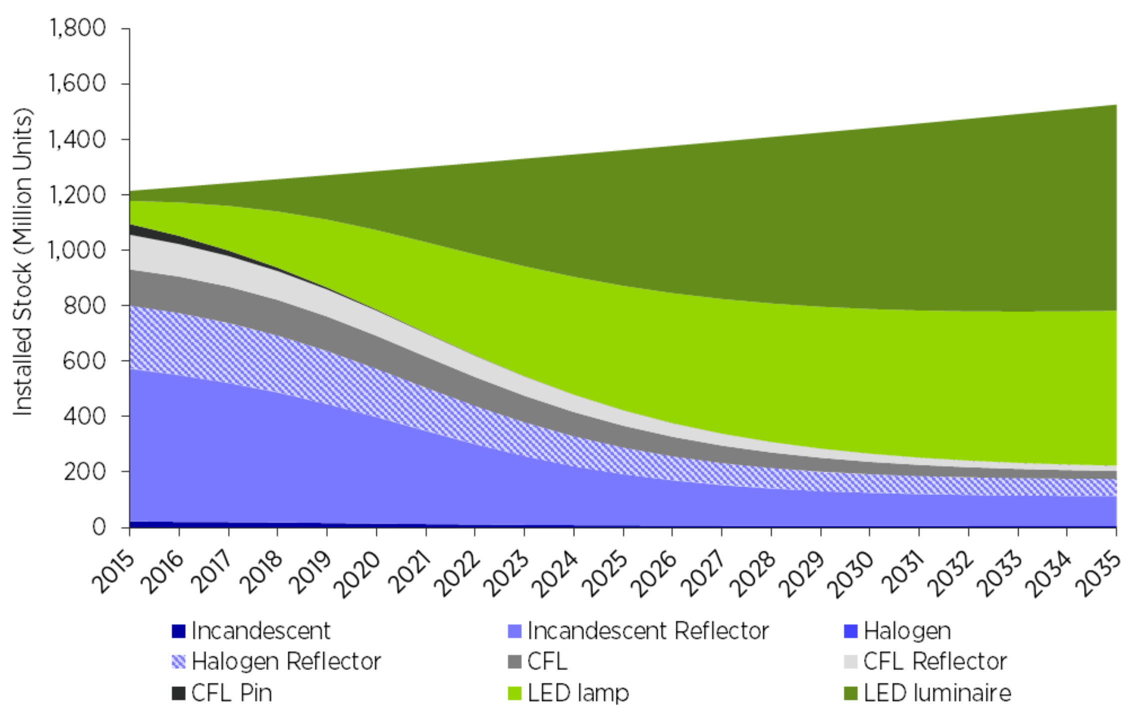

Figure 4.15 Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

By 2035, LED luminaires hold the majority over LED lamps in large directional applications, at 49% and 37% of the installed stock, respectively. As seen in Figure 4.16, a similar trend is expected in small directional applications. However, adoption of LED luminaires in small directional applications is delayed relative to those competing in large directional. LED luminaires not expected to represent the majority of installations until 2029, but then are expected to dominate installations reaching 60% by 2035.

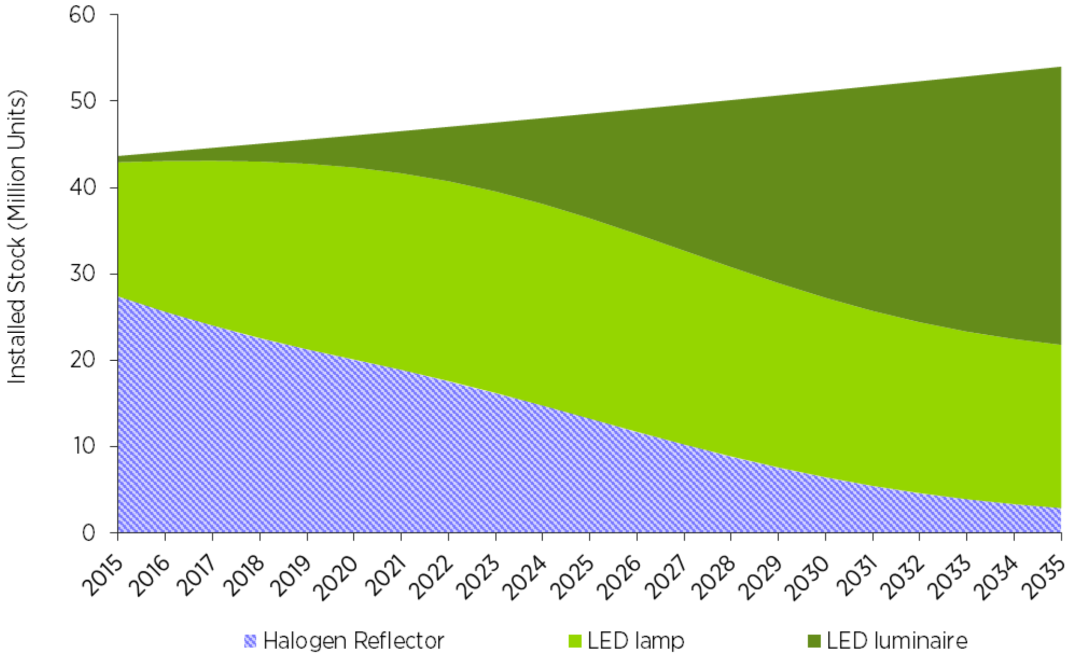

Figure 4.16 Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.12 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the large and small directional submarket combined.

Table 4.12 Directional Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**136**	**526**	**974**	**1,220**	**1,350**
	Commercial	87	168	187	199	209
	Residential	49	358	787	1,020	1,150
	Industrial	<1	<1	<1	<1	<1
	LED Installed Stock Penetration (%)	**11%**	**39%**	**69%**	**82%**	**86%**
	Commercial	50%	92%	97%	99%	99%
	Residential	5%	31%	65%	79%	84%
	Industrial	40%	94%	97%	98%	98%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

The early prevalence of LEDs in directional applications is particularly noticeable when considering the results by sector. Figure 4.17 and Figure 4.18 show the forecasted installed penetration in the commercial sector for large and small directional applications, respectively. In 2015, LEDs already represent 48% of large directional stock and 64% of small directional stock. This substantial early penetration is driven by LED replacement lamps. However, as mentioned above, replacement lamps are expected to reach their peak early, with LED luminaires becoming the majority of large directional installations by 2020 and small directional installations by 2030.

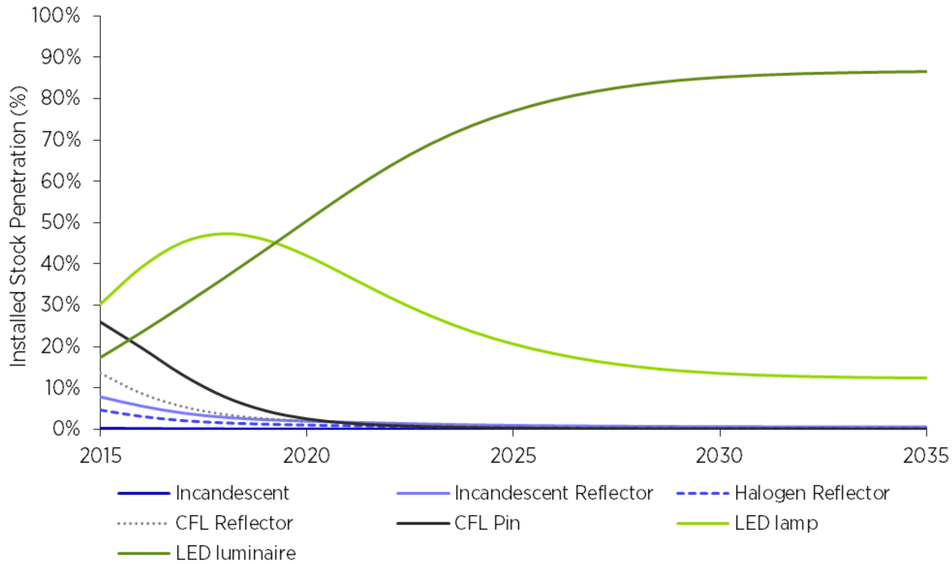

Figure 4.17 Commercial Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

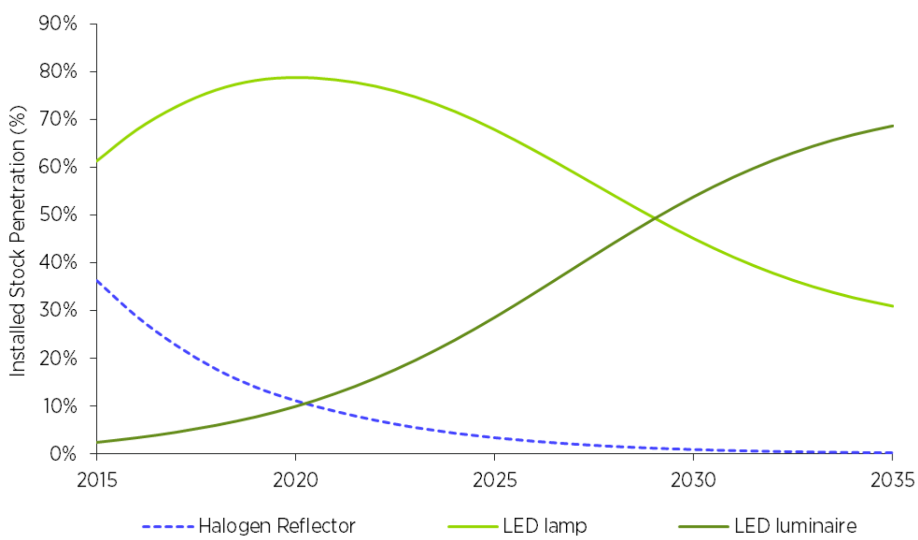

Figure 4.18 Commercial Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

As seen in Figure 4.19, LEDs also represented the majority of directional installations in the industrial sector in 2015,[28] with LED lamps and luminaires making up 18% and 22% of installations respectively. By 2025, LEDs are expected to make up 98% of industrial large directional installations.

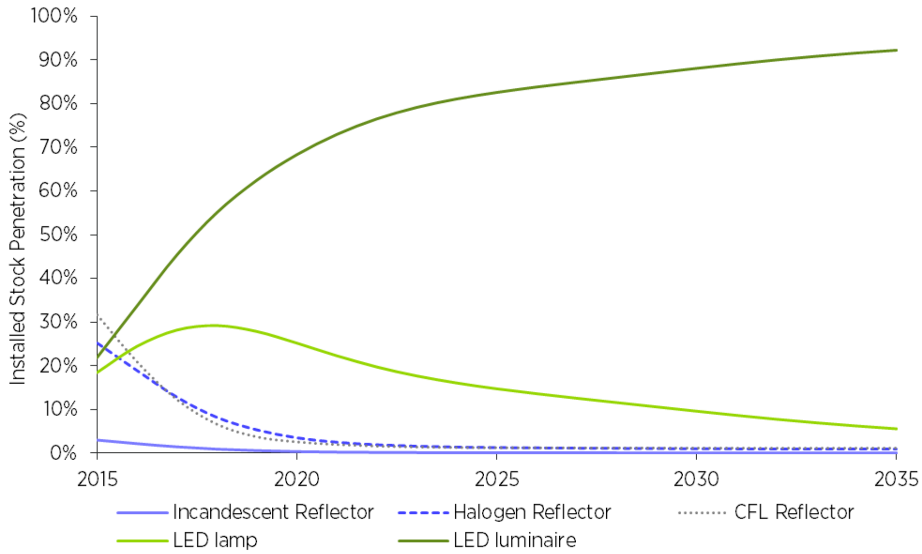

Figure 4.19 Industrial Directional Submarket Stock Forecast for the Current SSL Path Scenario

While progress has been slower in the residential sector, LED lamps and luminaires also achieved non-negligible penetration by 2015, as seen below in Figure 4.20 and Figure 4.21. In 2015, LEDs represent nearly 5% of large directional installation and over 2% of small directional installations in the residential sector. LEDs continue to gain traction, with LEDs becoming the majority in large directional applications in 2023 and small directional applications in 2027.

However, low cost and inefficient halogen and incandescent reflector lamps are expected to remain appealing to some first cost-conscious residential consumers. Compact fluorescent reflectors also linger within the residential sector for large directional lamps, however this is mainly due to the low operating hours typically seen in U.S. households and longer life of compact fluorescent technology. Ultimately conventional lighting technologies make up about 16% and 12% of the large and small directional residential installations in 2035, respectively.

[28] For the industrial sector, small reflector lamps represent a negligible portion of the installed stock and are grouped with large reflectors into one singular directional submarket.

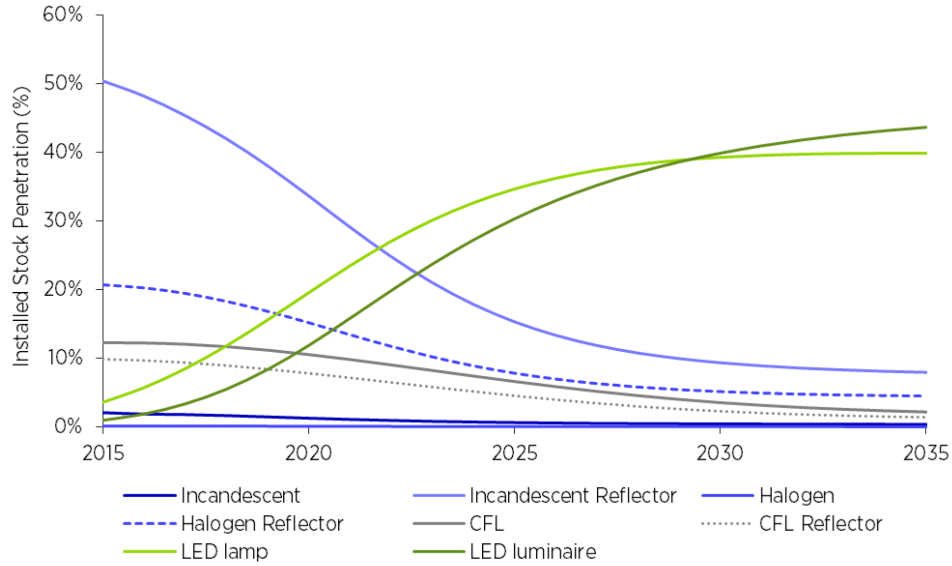

Figure 4.20 Residential Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

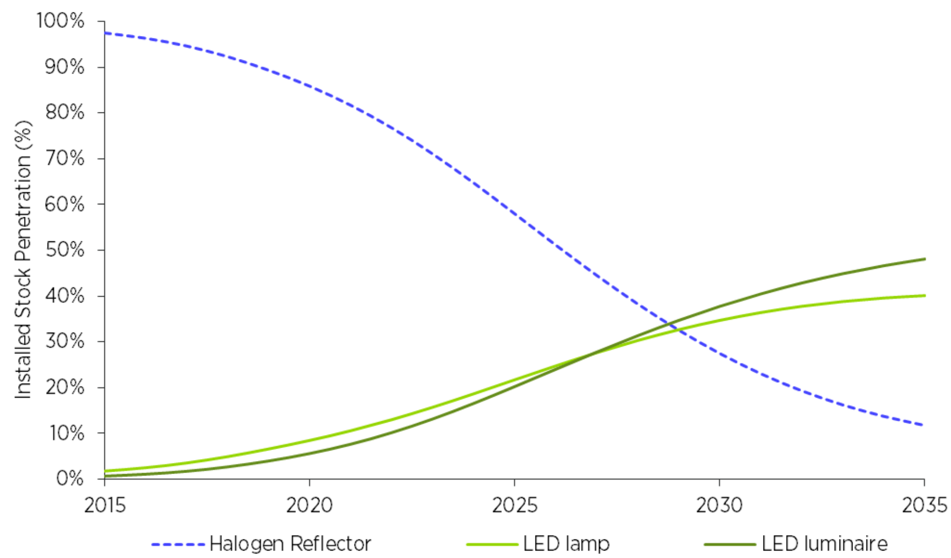

Figure 4.21 Residential Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

When comparing the entire directional submarket (including both small and large directional applications), Figure 4.22 shows that the by 2035 LED installed stock penetration is expected to reach approximately 86%. Non-connected LEDs are forecasted to be the majority in the Current SSL Path scenario, representing 76% of the directional installed base (10% connected-LED). While non-connected LEDs are also forecasted to be the majority in the DOE SSL Program Goal scenario, connected-LEDs penetration significantly increases. Therefore, if the DOE goals are met, connected-LED lamps and luminaires are projected to represent 24% of the installed base for directional applications.

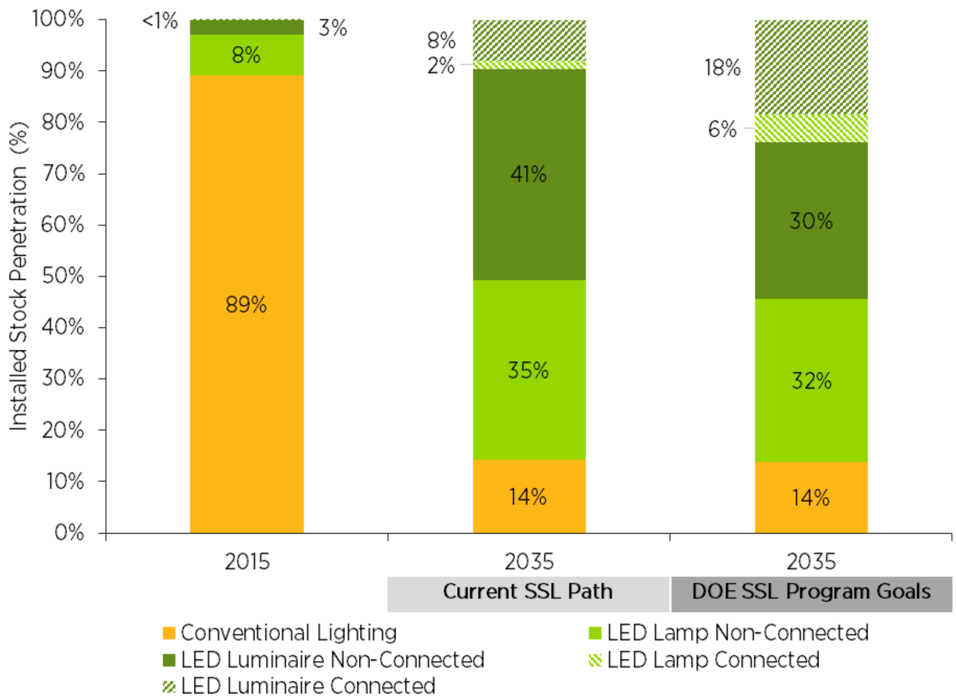

Figure 4.22 Directional Submarket LED Installed Stock Penetration

Table 4.13 shows that the increasing adoption of LED lighting is expected to achieve 77% source energy savings in 2035 for the Current SSL Path scenario and 85% source energy savings in 2035 for the DOE SSL Program Goal scenario in the directional submarket across all sectors. This increase results in an additional 46 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by nearly 408 thousand U.S. homes.

Table 4.13 Directional Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**86**	**230**	**366**	**444**	**492**
	Commercial	77	153	190	214	231
	Residential	8	77	176	230	260
	Industrial	<1	<1	<1	<1	<1
	Source Energy Savings (%)	**16%**	**43%**	**64%**	**73%**	**77%**
	Commercial	34%	63%	74%	80%	84%
	Residential	3%	26%	55%	68%	72%
	Industrial	22%	64%	71%	76%	81%
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**86**	**264**	**415**	**494**	**538**
	Commercial	77	179	221	243	255
	Residential	8	85	193	251	283
	Industrial	<1	<1	<1	<1	<1
	Source Energy Savings (%)	**16%**	**49%**	**72%**	**81%**	**85%**
	Commercial	34%	74%	86%	91%	93%
	Residential	3%	28%	61%	74%	78%
	Industrial	22%	75%	85%	90%	92%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses..

4.2.4 Linear Fixture

Historically, fluorescent lighting has dominated the linear fixture submarket to the point that it was basically the only lighting technology used. When considering the different fluorescent tube diameters (i.e., T12, T8 and T5), there has been a continuing trend away from T12 lamps due to the emergence of higher efficiency T8 and T5 lamp options. The transition to these higher efficiency fluorescent lamps has also been propelled by federal minimum energy efficiency standards (see Appendix C.1). For example, in 2001, T12 systems constituted approximately 72% of the linear fluorescent installed base in the commercial sector and 67% in the industrial sector, whereas in 2015, T12 systems constituted only 7% and 12%, respectively. (15) By 2032, T12 lamps are forecasted to drop to less than 1% of the total linear fixture submarket installed base. As seen in Figure 4.23, LED lamps and luminaires are predicted to absorb most of this decline, increasing to 16% and 61% by 2035, respectively.

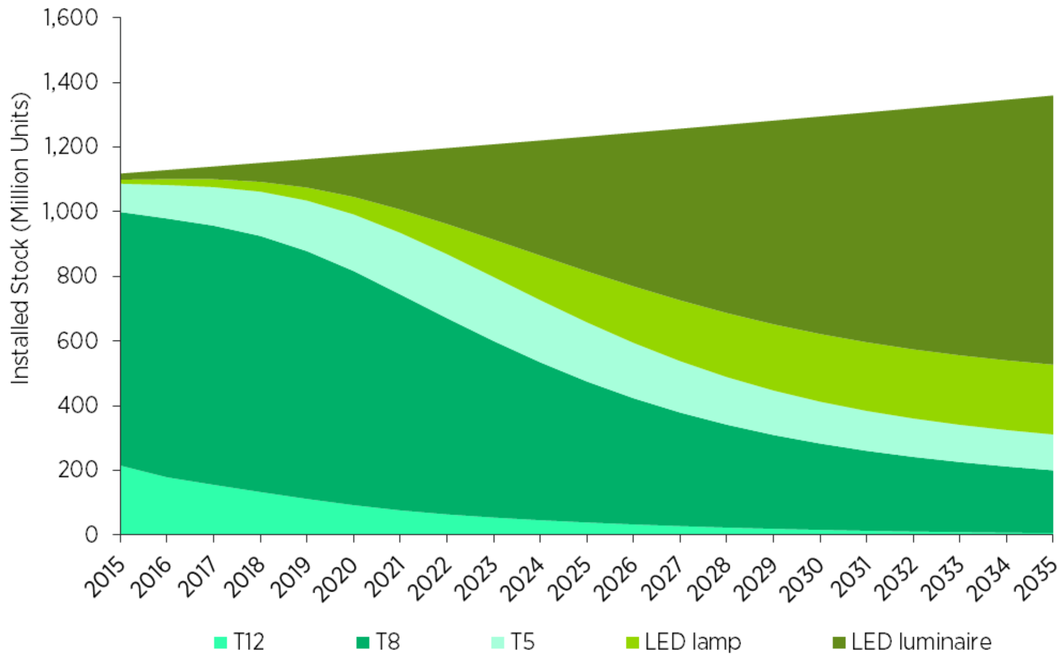

Figure 4.23 Linear Fixture Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.14 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the linear fixture submarket.

Table 4.14 Linear Fixture Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**31**	**182**	**575**	**882**	**1,050**
	Commercial	24	136	437	653	753
	Residential	4	33	110	195	262
	Industrial	4	14	28	33	34
	LED Installed Stock Penetration (%)	**3%**	**16%**	**47%**	**68%**	**77%**
	Commercial	3%	17%	52%	73%	80%
	Residential	1%	10%	32%	54%	68%
	Industrial	8%	30%	64%	78%	83%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

Figure 4.24, Figure 4.25 and Figure 4.26 show that the linear fixture submarket will be strongly affected by the availability of high-performance LED lighting products in all sectors. While fluorescent systems (lamp and ballast) currently have efficacies averaging between 40 and 90 lm/W, both LED lamps and luminaires consistently exceed all fluorescent lighting systems in efficacy. The forecasted takeover of LED technology in this submarket can largely be attributed to LED luminaires, which are expected to have a rapid increase in average efficacy to over 170 lm/W by

2035 – or about double that of an average fluorescent T5 lamp and ballast system. Consequently, as shown in Figure 4.24, the forecast model predicts that LED lamps and luminaires combined in the commercial sector will contribute 17% of the linear fixture stock by 2020. LED penetration is then expected to accelerate to 80% by 2035.

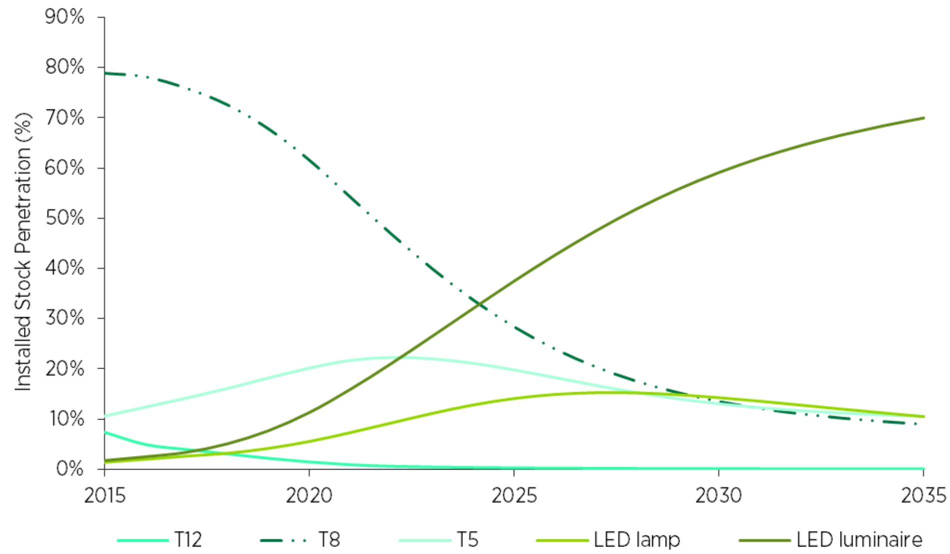

Figure 4.24 Commercial Linear Fixture Stock Forecast for the Current SSL Path Scenario

Although significantly smaller in terms of number of installations, the industrial sector, shown below in Figure 4.25, mimics the trends seen in the commercial sector. The lighting market model estimates that LED lamps and luminaires will represent 30% of industrial linear stock in 2020, and will grow quickly to 83% by 2035.

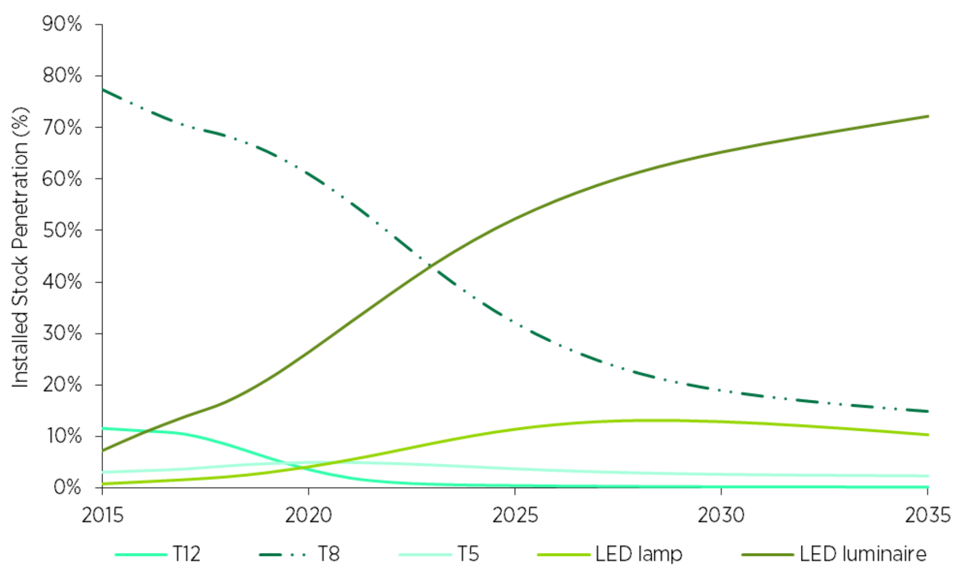

Figure 4.25 Industrial Linear Fixture Stock Forecast for the Current SSL Path Scenario

In the residential sector, the take-over of LED lamps and luminaires is slower than in the commercial and industrial sectors, where facilities managers place a higher value on lifecycle costs than the average residential consumer. Illustrated in Figure 4.26, LEDs make the slowest gains in the residential sector. Though LEDs are still successfully, capturing 68% of installed stock by 2035.

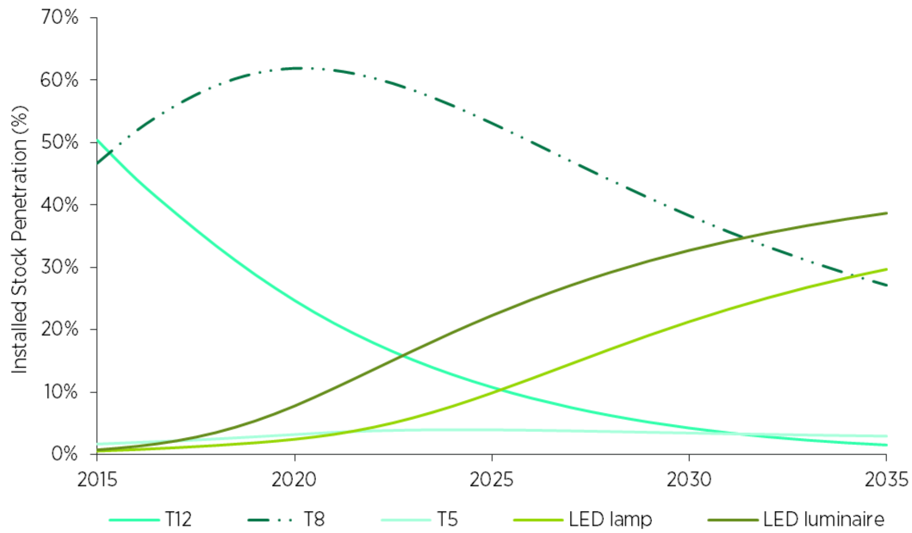

Figure 4.26 Residential Linear Fixture Stock Forecast for the Current SSL Path Scenario

Figure 4.27 provides a comparison of the total LED installed stock penetration in 2035 for both the Current SSL Path and DOE SSL Program Goal scenarios. Due to the magnitude of installations and high operating hours, the linear fixture submarket is posed to experience some of the greatest gains from connected lighting.

For the Current SSL Path scenario, while the majority of LEDs installed are non-connected LED luminaires, connected-LEDs in total comprise 20% of the linear fixture stock by 2035. If the DOE goals for connected lighting adoption are achieved, connected-LED penetration is projected to increase substantially. In the DOE SSL Program Goal scenario, connected-LED lamps and luminaires are forecasted to represent the vast majority of linear fixture installations at 48% by 2035.

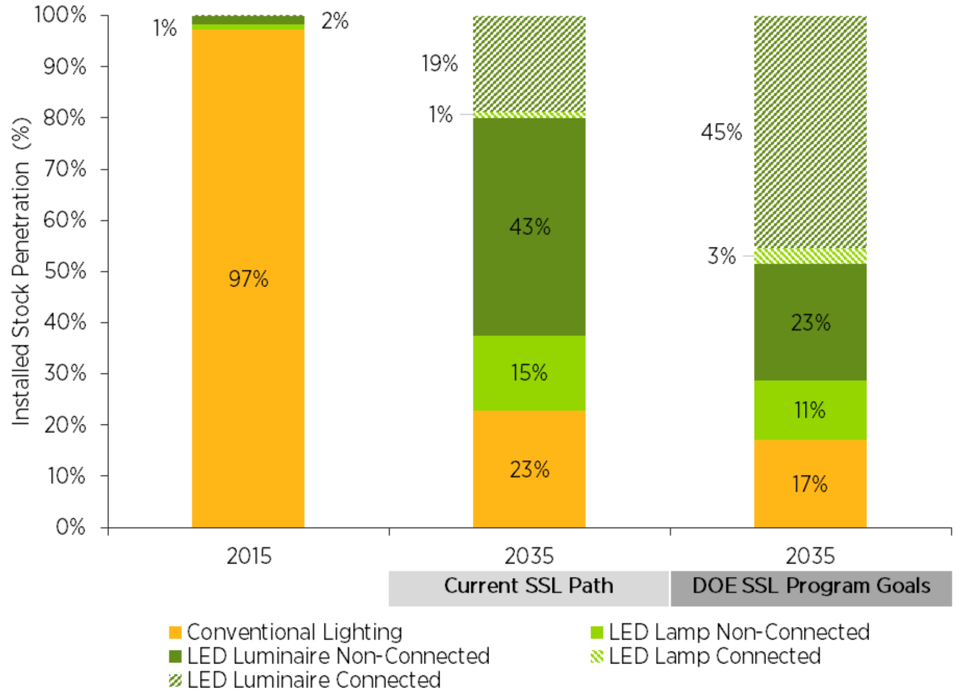

Figure 4.27 Linear Fixture Submarket LED Installed Stock Penetration

Table 4.15 shows that the increasing adoption of LED lighting is expected to achieve 46% source energy savings in 2035 for the Current SSL Path scenario and 70% source energy savings in 2035 for the DOE SSL Program Goal scenario in the linear fixture submarket across all sectors. This increase results in an additional 580 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by over 5.1 million U.S. homes.

Table 4.15 Linear Fixture Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**59**	**108**	**444**	**799**	**1,110**
	Commercial	45	87	382	697	976
	Residential	<1	7	27	51	70
	Industrial	13	13	35	52	65
	Source Energy Savings (%)	**3%**	**5%**	**20%**	**34%**	**46%**
	Commercial	2%	5%	19%	34%	45%
	Residential	<1%	6%	23%	41%	54%
	Industrial	8%	9%	25%	38%	48%
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**59**	**226**	**902**	**1,430**	**1,690**
	Commercial	46	190	803	1,290	1,520
	Residential	<1	8	29	55	77
	Industrial	13	28	70	90	97
	Source Energy Savings (%)	**3%**	**11%**	**40%**	**62%**	**70%**
	Commercial	2%	10%	41%	62%	71%
	Residential	<1%	7%	25%	44%	59%
	Industrial	8%	19%	49%	66%	73%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.5 Low and High Bay

Low and high bay lighting has become increasingly popular, likely due to the growth in large commercial retail facilities such as Home Depot, Costco, and other big-box retail stores. In 2015, the low and high bay submarket represents 15% of all lighting energy use – the second highest energy consumption of all the submarkets evaluated, making this a key application for LED impact on energy savings.

As seen in Figure 4.28, fluorescent lamps made up the majority of the 2015 low and high bay installations at 64%. Of this T8 systems dominate, followed by T5 and T12 respectively. Overall, LED luminaires held about 5% in 2015, while high wattage LED retrofit lamps represented less than one percent. While currently LED lamps and luminaires only in total represent about 6% of all low and high bay installations, this climbs to 38% by 2020 and 86% by 2035.

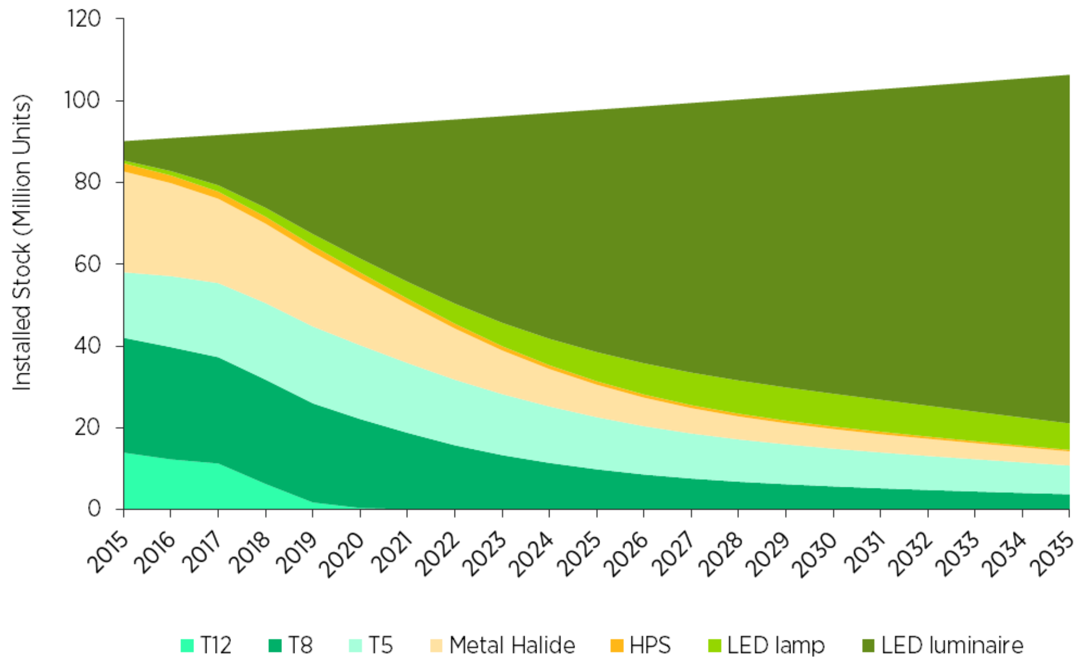

Figure 4.28 Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.16 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the low and high bay submarket.

Table 4.16 Low and High Bay Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)[1]**	**5**	**36**	**66**	**82**	**92**
	Commercial	5	32	60	74	84
	Industrial	<1	4	6	7	8
	LED Installed Stock Penetration (%)	**6%**	**38%**	**68%**	**80%**	**86%**
	Commercial	6%	39%	68%	80%	87%
	Industrial	5%	35%	64%	76%	83%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

As seen in Figure 4.29 and Figure 4.30, fluorescent lamps made up the majority of the 2015 low and high bay stock followed by metal halide and HPS for both the commercial and industrial sectors. However, by 2020, LEDs are projected to represent 39% of commercial low and high bay stock and about 35% of industrial, becoming the majority of installations in 2022 for the commercial sector and 2023 for the industrial sector. The LED share of installed stock continues to grow, and by 2035 reaches 87% and 83% in the commercial and industrial sectors, respectively.

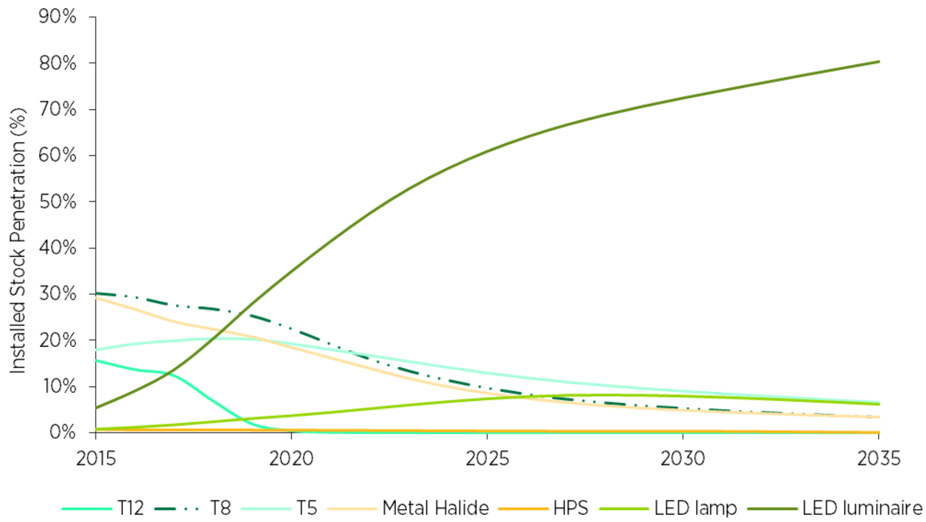

Figure 4.29 Commercial Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

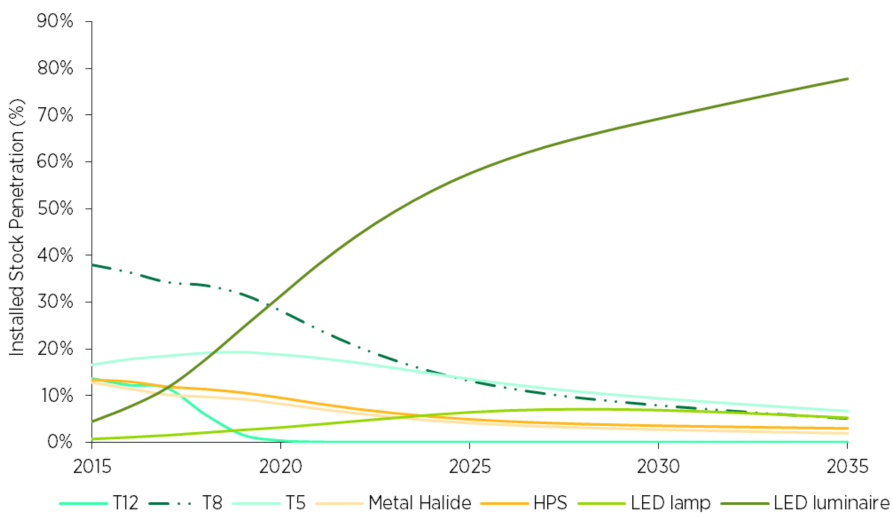

Figure 4.30 Industrial Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

Similar to linear fixtures, the low and high bay submarket is another key application where the benefits of connected-LEDs are predicted to have a significant impact. In the Current SSL Path scenario, the lighting market model predicts that connected-LED products will reach 27% by 2035.

On the other hand, in the DOE SSL Program Goal scenario, the portion of non-connected versus connected-LEDs is expected to flip, connected-LEDs holding the vast majority of low and high bay installations. As seen in Figure 4.31, this translates to connected-LED lamps and luminaires representing 59% of all low and high bay installations.

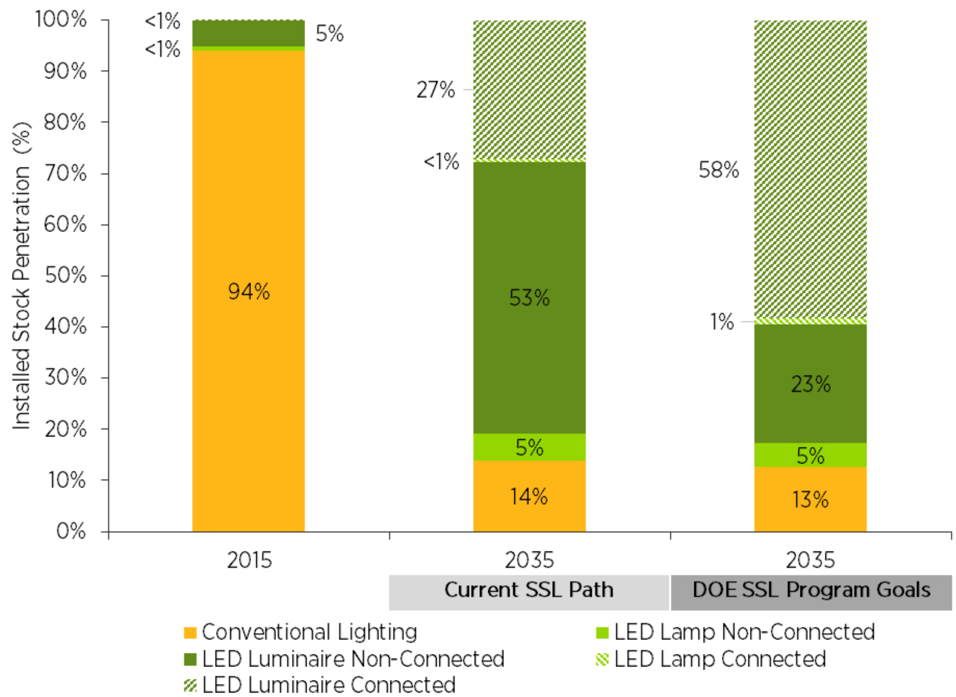

Figure 4.31 Low and High Bay Submarket LED Installed Stock Penetration

Table 4.17 shows that the increasing adoption of LED lighting is expected to achieve 53% source energy savings in 2035 for the Current SSL Path scenario and 72% source energy savings in 2035 for the DOE SSL Program Goal scenario in the low and high bay submarket across all sectors. This increase results in an additional 175 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by nearly 1.6 million U.S. homes.

Table 4.17 Low and High Bay Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**42**	**123**	**251**	**357**	**464**
	Commercial	38	100	204	297	391
	Industrial	4	23	47	61	73
	Source Energy Savings (%)	**4%**	**14%**	**29%**	**41%**	**53%**
	Commercial	5%	14%	28%	41%	52%
	Industrial	2%	15%	34%	45%	56%
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**43**	**207**	**432**	**555**	**639**
	Commercial	39	174	363	470	545
	Industrial	4	33	69	85	93
	Source Energy Savings (%)	**4%**	**24%**	**50%**	**64%**	**72%**
	Commercial	5%	24%	51%	64%	72%
	Industrial	2%	22%	49%	63%	72%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.6 Area and Roadway

LEDs are particularly advantageous in the street and roadway lighting submarket because they are excellent directional light sources, durable, and exhibit long lifetimes. Largely because of these advantages, LEDs already hold an impressive 21% of installations in 2015. Metal halide and HPS comprise about 16% and 62% of the 2015 area and roadway installations, respectively. However they quickly give way to LED lamps and luminaires, which are projected to represent the majority by 2019. While there are a few instances of incandescent, CFL, linear fluorescent, mercury vapor, low pressure sodium, and other miscellaneous lamps, combined they make up less than 0.1% of all area and roadway installations in 2015, and while included in the lighting market model are not show in Figure 4.32. The lighting market model projects LED market share to increase rapidly, reaching over 90% of area and roadway installation as early as 2025.

Like many other submarkets, we see an initial uptake of LED replacement lamps followed by their decline at the expense of LED luminaires. This is likely because the perceived low risk of trying LED replacement lamps because they offer a cheaper and (sometimes) simpler installation compared to LED luminaires. However, in the long run as LEDs become ubiquitous, it is expected that consumers will place more value in the performance and reliability of luminaires.

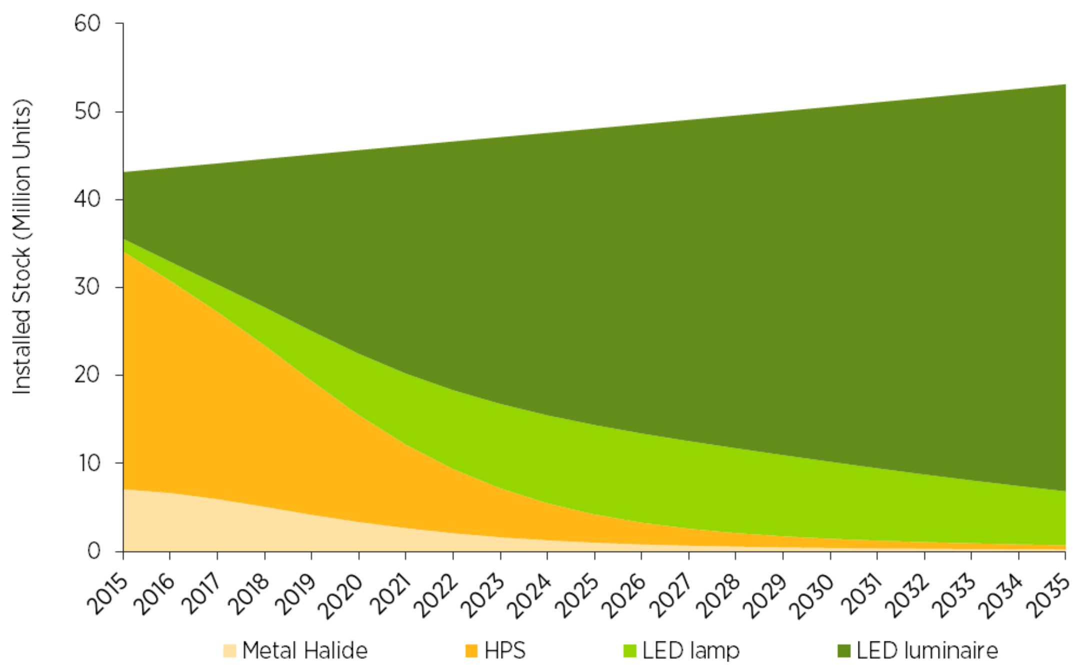

Figure 4.32 Area and Roadway Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.18 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the area and roadway submarket.

Table 4.18 Area and Roadway Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	LED Installed Stock (million units)[1]	9	30	44	49	52
	LED Installed Stock Penetration (%)	21%	66%	91%	97%	99%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

Of the LED lamps and luminaires installed in area and roadway applications, many are expected to be connected due to an increasingly attractive value proposition. The prospective capability to control and monitor each streetlight from one central location is highly appealing to municipalities and utilities alike. Figure 4.33 shows the forecast of connected versus non-connected LED lighting in both the Current SSL Path and DOE SSL Program Goal scenarios. In 2035, for the Current SSL Path scenario, the majority of LED lamp and luminaire installations are expected to be non-connected, with connected-LEDs reaching roughly 22%. However, for the DOE SSL Program Goal scenario, a staggering 72% of all LED area and roadway installations are projected to have connected capabilities.

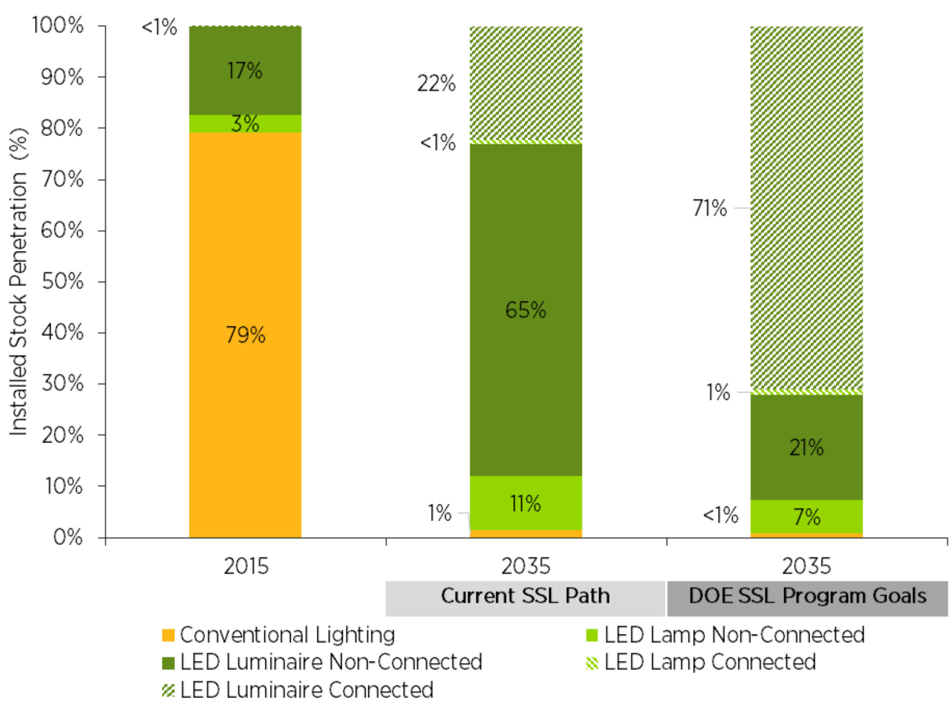

Figure 4.33 Area and Roadway Submarket LED Installed Stock Penetration

Table 4.19 shows that the increasing adoption of LED lighting is expected to achieve 52% source energy savings in 2035 for the Current SSL Path scenario and 80% source energy savings in 2035 for the DOE SSL Program Goal scenario in the area and roadway submarket. This increase results in an additional 145 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by nearly 1.3 million U.S. homes.

Table 4.19 Area and Roadway Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	Source Energy Savings (tBTU)	10	75	153	211	270
	Source Energy Savings (%)	2%	16%	32%	43%	52%
DOE SSL Program Goals	Source Energy Savings (tBTU)	10	158	277	358	415
	Source Energy Savings (%)	2%	34%	58%	71%	80%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.7 Parking

In 2015, there were over 52 million installations in the parking submarket, with nearly 27 million in parking lots and 26 million in parking garages. Similar to area and roadway applications, there are a few instances of incandescent, halogen, mercury vapor lamps and other miscellaneous lamps[29], combined they made up less than 0.01% of all parking installations in 2015. These technologies while included in the lighting market model are not show in Figure 4.34 or Figure 4.35.

As shown in Figure 4.34, metal halide and HPS made up 60% and 25% of the 2015 parking lot installations, respectively, and they prove to be strong competitors. LED lamps and luminaires do not take the majority until 2021, and in 2035, metal halide and HPS still make up over 10% of parking lot installations.

[29] These other miscellaneous lamps include lighting technologies such as plasma and induction lamps.

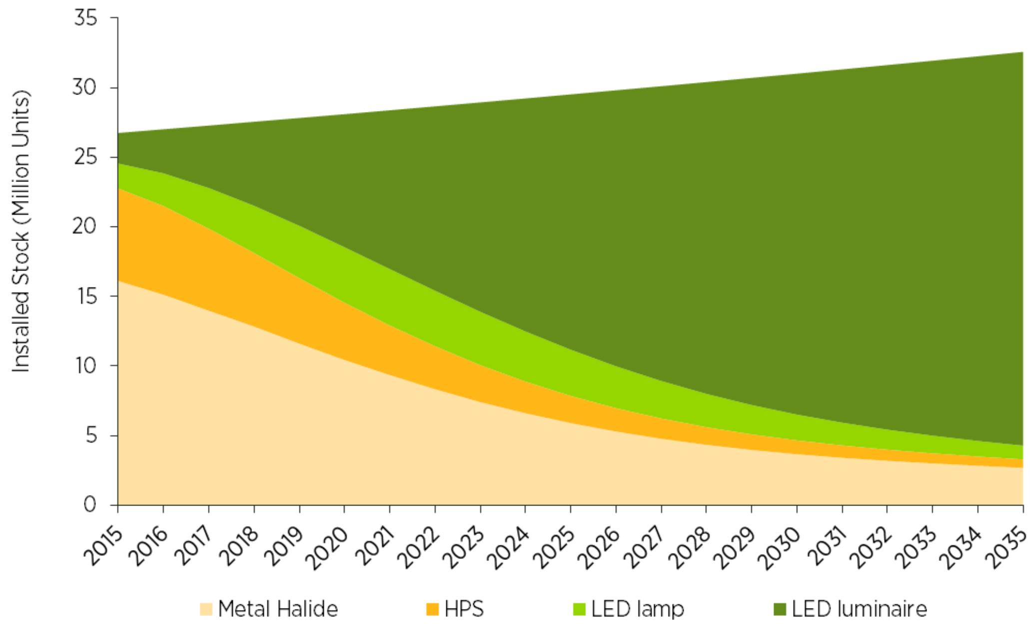

Figure 4.34 Parking Lot Submarket Stock Forecast for the Current SSL Path Scenario

As shown in Figure 4.35, parking garage has a unique mix of technologies for the outdoor sector because the fixtures are employed predominantly in covered garages with low mounting heights. In 2015, linear fluorescent, metal halide, and HPS made up 35%, 22%, and 23% of the 2015 parking garage installations, respectively. LED lamps and luminaires reach the majority of installations in 2021, and by 2035 represent 91% of all installations.

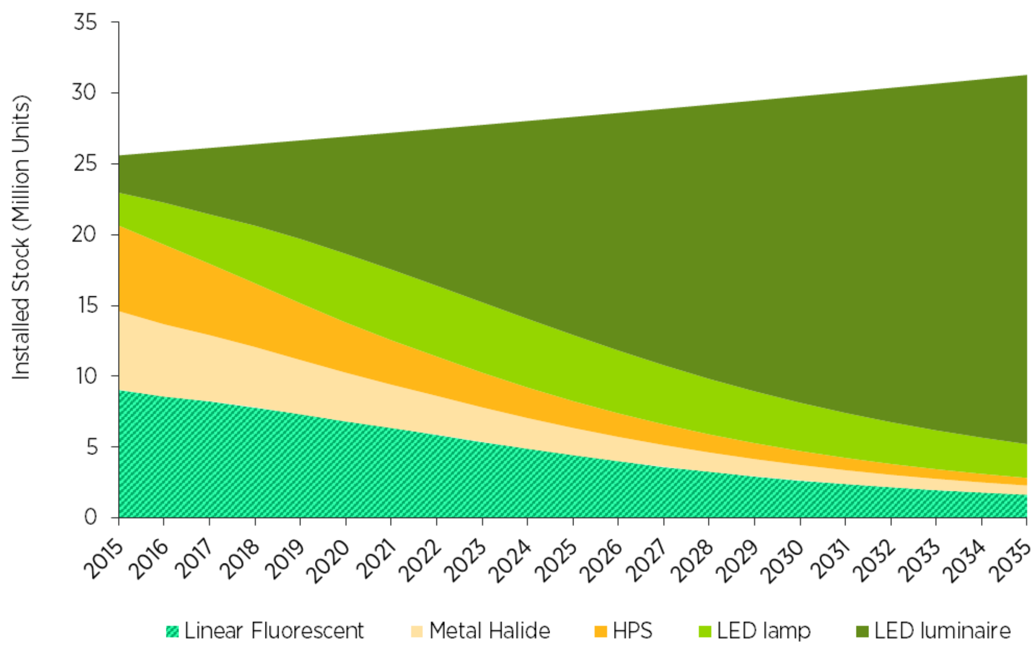

Figure 4.35 Parking Garage Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.20 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the parking lot and garage submarket combined.

Table 4.20 Parking Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	LED Installed Stock (million units)[1]	9	27	42	51	58
	LED Installed Stock Penetration (%)	17%	48%	72%	84%	90%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

Figure 4.36 shows the forecast of connected versus non-connected LED lighting in both the Current SSL Path and DOE Program Goals scenarios. Similar to the area and roadway submarket, parking applications are well-suited for connected capabilities. In 2035, for the Current SSL Path scenario, the majority of LED lamps and luminaires are expected to be non-connected, with connected products representing about 22% of all parking installations. If DOE's goals for connected adoption are met, by 2035, connected-LEDs are expected to represent the over-whelming majority of installations comprising 69% of all parking installations.

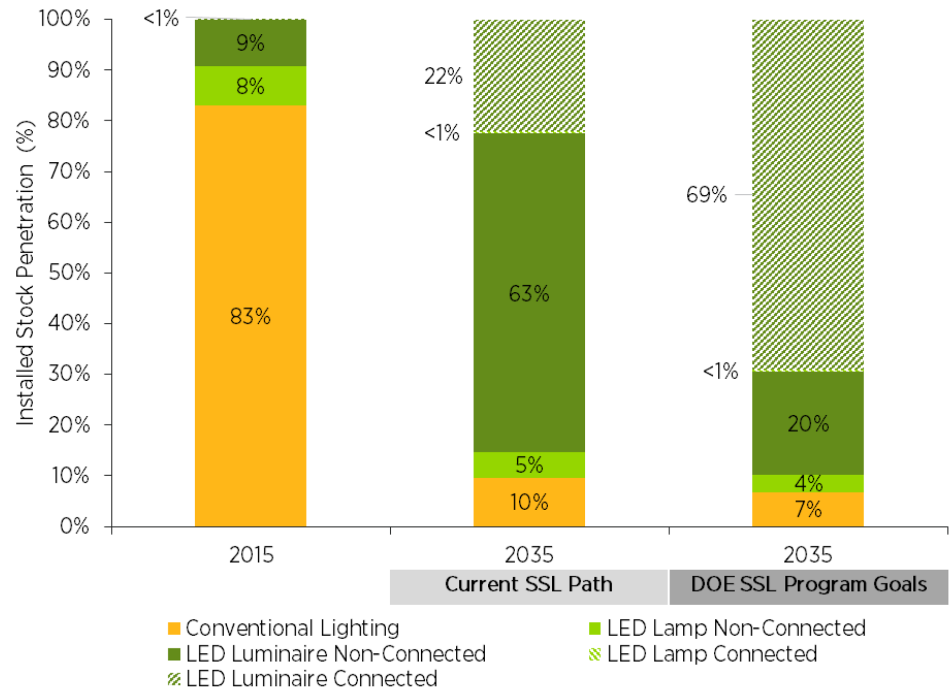

Figure 4.36 Parking Submarket LED Installed Stock Penetration

Table 4.21 shows that the increasing adoption of LED lighting is expected to achieve 46% source energy savings in 2035 for the Current SSL Path scenario and 73% source energy savings in 2035 for the DOE SSL Program Goal scenario in the parking submarket. This increase results in an additional

216 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by about 1.9 million U.S. homes.

Table 4.21 Parking Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	Source Energy Savings (tBTU)	18	95	200	284	366
	Source Energy Savings (%)	2%	13%	27%	37%	46%
DOE SSL Program Goals	Source Energy Savings (tBTU)	18	179	378	509	582
	Source Energy Savings (%)	2%	24%	50%	66%	73%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

4.2.8 Building Exterior

Due to the wide variety of applications considered in the building exterior submarket, several different technologies and lumen output levels are applicable to this submarket. Lower lumen technologies including incandescent, halogen, and compact fluorescent lamps – compete for illumination of walkways and porches. While higher lumen technologies such as HID lamps and high output pin-based CFLs are often used for flood and security lighting as well as wall packs. In 2015, together incandescent, halogen, and CFL lamps represent about 45% of installations, while higher output metal halide and HPS represent a combined 25% in the building exterior submarket.

As shown in Figure 4.37, much like the other outdoor submarkets, LED lighting products in the building exterior submarket are gaining significant market adoption. In 2015, LED lamps and luminaires in this submarket have reached a combined total of about 21% of the installed stock, or roughly 12 million total installations. LED lamps are competitive in the near term, yet LED luminaire prices are projected to continue to decrease, becoming cheaper on a system basis (lamp and ballast) than HPS in 2017 and metal halide in 2018 prompting a swift increase in the adoption of LEDs in this submarket. As shown in Figure 4.37, combined the penetration of LED lamps and luminaires is forecasted to grow near exponentially to 77% in 2025 and 91% by 2035.

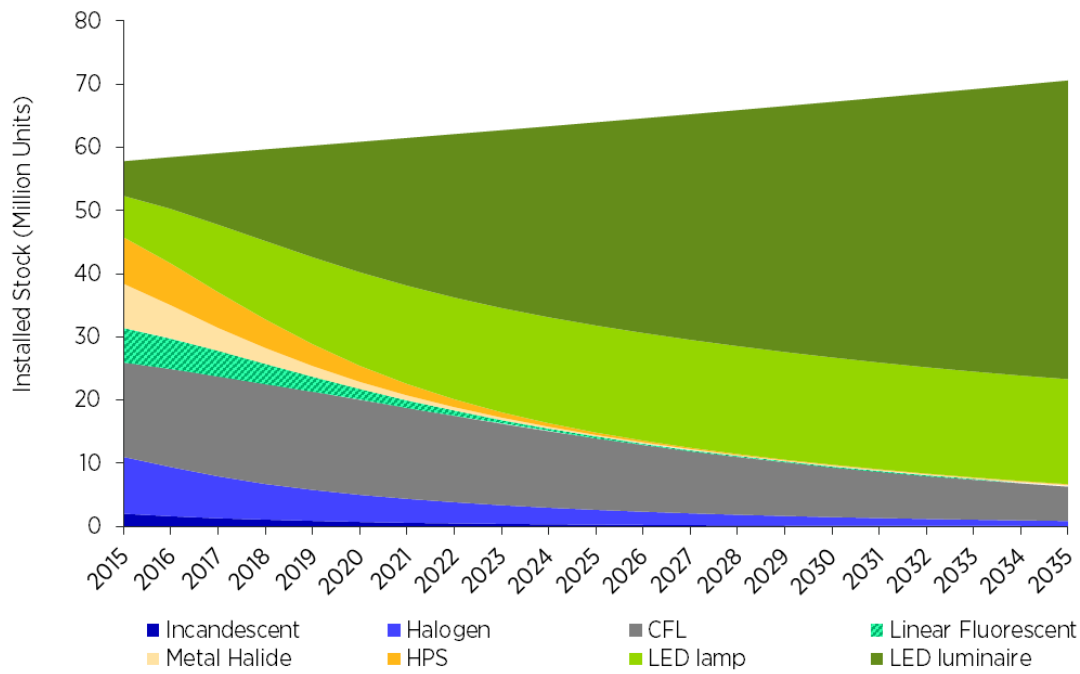

Figure 4.37 Building Exterior Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.22 provides the lighting market model forecast results for LED installed stock penetration over the 20 year analysis period for the building exterior submarket.

Table 4.22 Building Exterior Submarket LED Stock Forecast Results

		2015[2]	2020	2025	2030	2035
Current SSL Path	LED Installed Stock (million units)[1]	12	35	49	57	64
	LED Installed Stock Penetration (%)	21%	58%	77%	85%	91%

1. Installed stock for the DOE SSL Program Goal scenario is not provided as there are negligible differences between scenarios. In addition, LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).
2. As a result of the lighting market model improvements discussed in Section 2.1, the LED penetration results for 2015 have been updated compared to previous DOE SSL Program market analyses.

Figure 4.38 shows the forecast of connected versus non-connected LED lighting in both the Current SSL Path and DOE Program Goals scenarios. The building exterior submarket is not expected to value connected lighting as highly as the other outdoor submarkets, however is still expected to see significant penetration. For the Current SSL Path scenario, by 2035, connected-LEDs represent the minority at 17% of installations. However, for the DOE SSL Program Goal scenario, connected-LEDs are projected to become the majority at 51% of all building exterior installations by 2035.

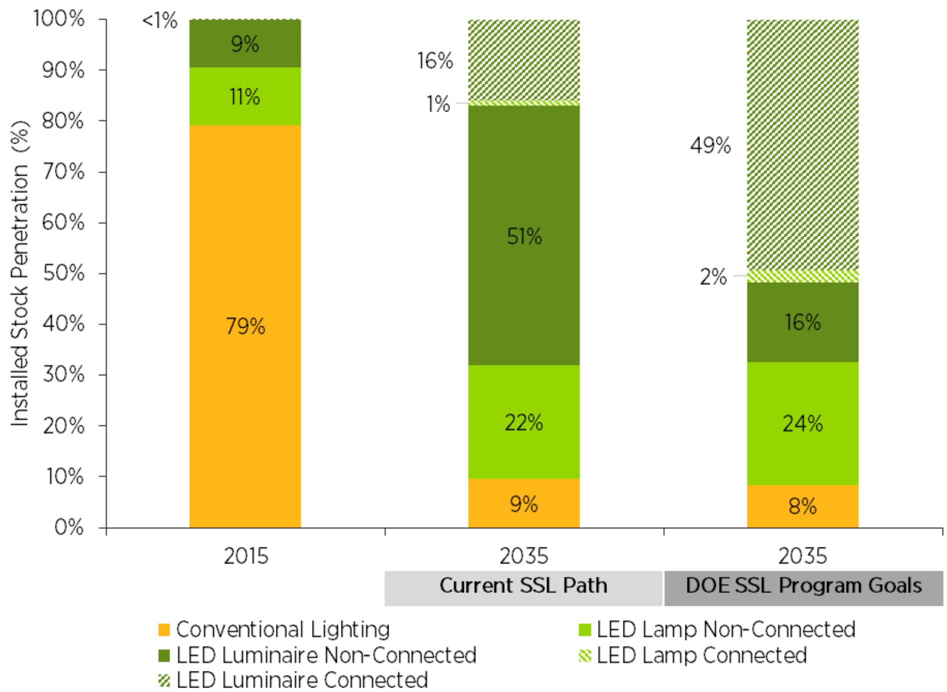

Figure 4.38 Building Exterior Submarket LED Installed Stock Penetration

Table 4.23 shows that the increasing adoption of LED lighting is expected to achieve 52% source energy savings in 2035 for the Current SSL Path scenario and 76% source energy savings in 2035 for the DOE SSL Program Goal scenario in the building exterior submarket. This increase results in an additional 29 tBTUs of annual energy savings by 2035 – equivalent to the energy consumed by about 257 thousand U.S. homes.

Table 4.23 Building Exterior Submarket LED Energy Savings Forecast Results

		2015[1]	2020	2025	2030	2035
Current SSL Path	Source Energy Savings (tBTU)	11	27	39	49	60
	Source Energy Savings (%)	10%	24%	34%	43%	52%
DOE SSL Program Goals	Source Energy Savings (tBTU)	11	43	64	79	89
	Source Energy Savings (%)	10%	39%	56%	68%	76%

1. As a result of the lighting market model improvements discussed in Section 2.1, the LED energy savings results for 2015 have been updated compared to previous DOE SSL Program market analyses.

5 LED Forecast Comparison

Below the results of this forecast are compared to seven other forecast analyses to provide greater context. In addition, included in the comparison set are the 2012 and 2014 iterations of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* forecast analyses. Table 5.1 below lists these forecasts in increasing order of projected LED market penetration in 2020. These forecasts vary in methodology, regions covered (i.e., U.S. market, global market), metric (i.e., sales, installations, and socket penetration), as well as the LEDs units considered (i.e., lamps, luminaires, systems). Nonetheless, each presents a calculated impression of the importance of LEDs to the general lighting market in 2020.

Table 5.1 Comparison of Multiple LED Forecast Analyses

	LED Metric	Region	2020 Value
IHS Research, May 2015	% Lamp Installations	World	25%
Strategies Unlimited, 2015	% Lamp Installations	North America	32%
DOE, 2016	**% Installations (Unit Systems)**[1]	**U.S.**	**30%**
Samsung Electronics, 2014	% Unit Sales	World	42%
Strategies Unlimited, 2015	% Luminaire Installations	North America	53%
McKinsey, 2012	% Unit Sales	World	57%
Goldman Sachs, 2016	% Unit Sales	U.S.	77%
Canaccord Genuity, 2013	% Socket Penetration	World	54% to 80%
DOE, 2014	% Installations (Teralumen Hours)	U.S.	39%
DOE, 2012	% Installations (Teralumen Hours)	U.S.	13%

1. LED installations and penetration values are calculated in terms of systems (lamp(s), ballast and fixture are counted as one unit).

The results of this forecast model are generally consistent with those of other studies. All of the analyses conclude that LED lighting will have tremendous growth over the remainder of this decade, and comprise anywhere from a quarter to upwards of 80% of lighting by 2020.

This report is the second of the DOE SSL Program's forecast analyses that have calibrated the U.S. lighting market model using LED sales and shipment data provided by manufacturers, distributors, retailers as well as industry associations. This track record makes it possible to calibrate the lighting market model outputs for future years based on the actual pattern by which LEDs have gained market share thus far, effectively improving the accuracy of the predictions. The calibration to LED sales and shipment data indicated that market penetration is roughly the same compared to what was estimated in the 2014. However, the lighting market model predicts a more rapid growth in LED adoption compared to the 2012 iteration, which was unable to utilizes LED sales and shipment data for calibration.

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Appendix A Submarket Classifications and Lighting Inventory

This study divides the U.S. lighting market into four primary lighting sectors: residential, commercial, industrial, and outdoor. The residential, commercial, and industrial sectors correspond to EIA's building category designations, while the outdoor sector contains major stationary lighting sources such as area and roadway lighting as well as those that are associated with building exterior applications (i.e., parking lot lights and exterior wall packs). The study models and reports results separately for each sector in order to capture major differences in inventory and patterns of usage arising from distinct lighting needs and decision-makers.

In order to model the competition between lighting technologies within the U.S. lighting market, the current model examines ten submarkets, which are based on common general illumination applications. The lighting market model is capable of processing a multi-dimensional analysis, where the submarkets are application-based. This enables a single lighting technology, such as linear fluorescent lamps, to compete in multiple submarkets (i.e., linear fixtures, low and high bay, and parking) compared to the previous model iteration, which grouped all linear fluorescent lamps into a single submarket regardless of application.

The lighting technologies competing within each submarket are derived from the U.S. Lighting Market Characterization (LMC) report (4), as well as the public data files provided by the Northwest Energy Efficiency Alliance (NEEA) 2014 Commercial Building Stock Assessment (6). A total of 29 conventional lighting technologies were considered:

- Incandescent: A-type, general decorative, reflector, miscellaneous
- Halogen: A-type, decorative, reflector, low voltage display, miscellaneous
- Compact fluorescent: screw-base, pin-base, reflector, miscellaneous
- Linear fluorescent: T5, T12 less than 4ft, T12 4ft, T12 greater than 4ft, T12 U-shaped, T8 less than 4ft, T8 4ft, T8 greater than 4ft, T8 U-shaped lamps, miscellaneous
- High-intensity discharge: mercury vapor, metal halide, high pressure sodium, low pressure sodium
- Other: LED, miscellaneous

This analysis reduces that count to 22 by combining linear fluorescent categories less than 4ft, 4ft, greater than 4ft, and U-shaped for both T8 and T12. Furthermore, the "other miscellaneous" category, and all lamps in that category, are excluded from this analysis due to great uncertainty regarding these lamp types and their characteristics. The excluded miscellaneous lamps account for less than 8 terawatt-hours of annual energy use, or less than one percent, of lighting energy consumption in 2010; thus, the impact of their exclusion is minimal. The LMC was used to develop the 2010 installed base for conventional technologies in the remaining product categories.

The LMC is used as the starting point for the lighting technologies examined in the U.S. lighting market model because it provides detailed lamp counts and provides the inventory foundation for this study. However, it is important to note that the base year for the LMC lighting inventory is 2010, while the base year for this study is 2015. In order to appropriately update the LMC inventory estimates to 2015, data was collected through interviews with manufacturers and retailers, as well as from the 2014 Commercial Building Stock Assessment.

However, because the LMC grouped all LEDs into a single category and included LED exit signs, which are not considered a general illumination white-light source, LMC data was not used to develop the 2010 installed base of LEDs. Instead the LED installed base was estimated from the Adoption Report[30], which collected LED sales data for the years 2010, 2012, 2013, 2014, and 2015 from manufacturers, retailers, industry experts, as well as the shipment data from National Electrical Manufacturers Association, ENERGY STAR®, and lighting distributors.

[30] The LED Adoption report analyses are available on the DOE SSL Program webpage: http://energy.gov/eere/ssl/market-studies.

Appendix B Annual Lumen Demand and Market Turnover

After calculating the installed lighting stock for 2015 by sector and submarket, the next step was to project forward the annual available lighting market for each year through 2035. This determines how much of the lighting market is replaced or added each year. This turnover and growth represents the available market opportunity for LED products to compete with conventional lighting technologies within each of the submarkets. To estimate this, the U.S. lighting market model evaluates three events that determine the new installations available each year:

New Construction. New fixtures installed each year due to floor space growth in each sector, determined by growth or retirement projections. The AEO 2015 provides annual average growth forecasts of floor space in the residential and commercial sectors. (1) Projections suggest that residential floor space will increase by an average of 1.17% per annum over the 20-year analysis period, and the commercial sector floor space will increase by an average of 0.99% per annum. AEO 2015 does not provide growth forecasts for the industrial or outdoor sectors. Because the outdoor sector includes buildings-related outdoor lighting, it was assumed that its growth rate would match that of the commercial sector. For the industrial sector, the AEO 2015 annual projections for manufacturing employment indicate an average decline of 0.59% per annum. This estimate was used as a proxy for the expected annual decline in industrial floor space.

In summary, the average annual floor space growth rates used in the analysis, representing the annual change in lighting demand between 2015 and 2035, are:

- Residential: 1.17% growth
- Commercial: 0.99% growth
- Industrial: -0.56% growth
- Outdoor: 0.99% growth

For the lighting stock demand in this category, the costs considered for conventional technologies include the costs of the lamp, fixture, and ballast (if appropriate). For LED lamp products, the costs considered include the costs of the lamp and fixture, while LED luminaire products include only the cost of the complete luminaire system. Luminaires are defined as fully integrated lighting products designed to replace an entire fixture (not just the lamp). An example of an LED luminaire would be a fully integrated 2' X 2' troffer replacement.

Renovations. Lamps (and ballasts, if appropriate) and fixtures being installed to replace existing lamps and fixtures during renovation, retrofit/upgrade, or remodeling. This replacement generally occurs before a lamp has burned out, providing an additional opportunity for the penetration of new technologies into the building stock. It is assumed that this occurs at a rate of 10% each year in each sector, for a mean renovation cycle of 10 years. The lighting market model assumes this constant rate of lighting fixture retrofits and renovations in the No-SSL, Current SSL Path and DOE SSL Program Goal scenarios. As with the new construction category, LED lamps in this market will compete with conventional lighting technologies on a basis that includes new fixture costs. It is important to note that this renovation rate assumption has been increased from 5% to 10% compared to previous lighting market model iterations due to increasing concerns regarding energy consumption, as well as the growing prevalence of utility and government incentive programs that compensate consumers who retrofit using LED lighting products.[31] However, due to the high uncertainty in these inputs, the lighting market model does not attempt to quantify these trends and, consequentially, may underestimate or overestimate the forecasted LED market penetration and energy savings.

Replacements. Lamps or lamp and ballast systems that burn out and are replaced during a calendar year. This calculation of the available lighting market is based on the operating hours and the lifetime (in hours) of the lamps and ballasts installed. For this analysis, the lighting market model assumes that manufacturers of LED technology produce either lamps that match conventional screw-base and pin-based technologies, which can be installed directly into existing lighting fixtures, or luminaires, which represent a fixture change-out.

These three components—new construction, replacements and renovations—together determine the total available market in each submarket and sector. With a projected lighting market demand for each year, the next step is to determine how the lighting technologies will develop and improve over time.

[31] Information on lighting incentives can be found at the Database of State Incentives for Renewables & Efficiency available at: www.dsireusa.org

Appendix C Conventional Technology Improvement Projection

Due to continued R&D investment, competition from LED lighting products, and general market demand for cost-effective lighting, the performance and cost characteristics of conventional lighting technologies are expected to improve over the analysis period. However, the ability of these conventional technologies to react rapidly (in terms of performance improvement) to the emergence of a new light source such as LED lighting is relatively small because these are mature technologies (particularly incandescent and fluorescent) and established market competitors. The following tables present performance characteristics in 2015. Lighting technologies that do not appear in the tables for a given sector indicate that the 2010 LMC did not record any lighting consumption by that technology in that sector. The efficacies presented in these tables represent mean system efficacies (including ballast losses, where appropriate), rather than initial efficacies. When comparing conventional technologies to LED luminaires, the model also incorporates additional assumptions related to conventional technology fixture efficiencies. However, these fixture efficiencies are not incorporated into the mean system efficacies presented in Table C-1, Table C-2, Table C-3 and Table C-4.

Table C-1 Commercial Sector Conventional Technology Performance 2015

Commercial Sector Submarkets	Mean Lamp Wattage (W)[1]	Lamp Life (1,000 hr)[2]	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
A-Type						
Incandescent Omni	62	2	16	$0.5	--	$15
Halogen Omni	53	2	15	$1.9	--	$15
CFL Omni	17	10	55	$3.0	--	$15
Decorative						
Incandescent Omni	69	2	12	$0.5	--	$23
Incandescent Directional	59	3	10	$3.1	--	$23
Halogen Omni	55	2	15	$1.9	--	$23
Halogen Directional	60	3	15	$4.6	--	$23
CFL Directional	27	10	46	$10	--	$23
CFL Pin	28	12	59	$5.4	$18	$23
Downlights						
Incandescent Omni	48	2	12	$0.5	--	$23
Incandescent Directional	65	3	10	$3.1	--	$23
Halogen Omni	46	2	15	$1.9	--	$23
Halogen Directional	77	3	15	$4.6	--	$23
CFL Directional	20	10	46	$10	--	$23
CFL Pin	19	12	59	$5.4	$18	$23

Track Lighting						
Incandescent Omni	34	2	16	$0.5	--	$23
Incandescent Directional	65	3	10	$3.1	--	$23
Halogen Omni	38	2	15	$1.9	--	$23
Halogen Directional	59	3	15	$4.6	--	$23
CFL Directional	20	10	46	$10	--	$23
Small Directional (MR16)						
Halogen	60	4	18	$4.5	--	$18
Linear Fixtures						
T12 <4ft	39	15	56	$3.0	$17	$70
T8 <4ft	25	20	73	$5.4	$18	$70
T5 <4ft	32	30	77	$6.2	$22	$75
T12 4ft	43	20	71	$2.5	$17	$70
T8 4ft	28	24	79	$4.4	$18	$70
T5 4ft	35	30	91	$6.2	$22	$75
T12 >4ft	78	12	77	$5.7	$19	$70
T8 >4ft	48	24	84	$7.0	$22	$70
Low and High Bay						
T12	75	12	71	$5.7	$19	$70
T8	49	18	79	$8.4	$22	$70
T5	66	30	91	$6.2	$25	$75
Metal Halide	524	20	74	$40	$205	$75
High Pressure Sodium	356	24	109	$51	$260	$80
Other						
CFL Pin	19	12	59	$5.4	$18	$15
Halogen	73	1	11	$0.5	--	$15
Metal Halide	341	20	74	$40	$205	$75
High Pressure Sodium	356	24	109	$51	$260	$80
Miscellaneous	11	4	67	$5.4	$18	$70

1. Ballast losses are accounted for in the lamp wattage assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).
2. The model also incorporates system lifetime assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).

Table C-2 Residential Sector Conventional Technology Performance 2015

Residential Sector Submarkets	Mean Lamp Wattage (W)[1]	Lamp Life (1,000 hr)[2]	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
A-Type						
Incandescent Omni	64	1	17	$0.5	--	$18
Halogen Omni	48	2	15	$1.9	--	$18
CFL Omni	16	10	54	$3.0	--	$18
Decorative						
Incandescent Omni	53	2	12	$0.5	--	$23
Incandescent Directional	46	3	10	$3.1	--	$23
Halogen Omni	42	2	15	$1.9	--	$23
Halogen Directional	46	3	15	$4.6	--	$23
CFL Omni	21	10	46	$10	--	$23
CFL Pin	17	12	59	$5.4	$18	$23
Downlights						
Incandescent Omni	42	1	17	$0.5	--	$23
Incandescent Directional	68	3	10	$3.1	--	$23
Halogen Omni	43	2	15	$1.9	--	$23
Halogen Directional	52	3	14	$4.6	--	$23
CFL Omni	17	10	55	$3.0	--	$23
CFL Directional	17	10	44	$10	--	$23
Track Lighting						
Incandescent Omni	42	1	17	$0.5	--	$23
Incandescent Directional	68	3	10	$3.1	--	$23
Halogen Omni	43	2	15	$1.9	--	$23
Halogen Directional	52	3	14	$4.6	--	$23
CFL Omni	17	10	54	$3.0	--	$23
CFL Directional	17	10	44	$10	--	$23
Small Directional (MR16)						
Halogen	43	4	17	$4.2	--	$23
Linear Fixtures						
T12 <4ft	16	15	52	$3.0	$20	$50
T8 <4ft	14	20	65	$5.4	$23	$45
T5 <4ft	18	30	73	$4.2	$26	$75
T12 4ft	24	15	67	$2.0	$20	$50
T8 4ft	20	21	76	$2.8	$23	$45
T5 4ft	29	30	85	$4.2	$26	$75
T12 >4ft	43	12	75	$5.7	$23	$50
T8 >4ft	33	18	88	$7.0	$27	$45

Other						
Halogen	78	4	14	$4.2	--	$18
CFL Pin	18	12	60	$5.4	$23	$18
Mercury Vapor	193	24	29	$37	--	$70
Metal Halide	77	12	50	$52	$160	$75
High Pressure Sodium	150	24	71	$50	$220	$80
Miscellaneous	54	4	38	$37	--	$18

1. Ballast losses are accounted for in the lamp wattage assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).
2. The model also incorporates system lifetime assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).

Table C-3 Industrial Sector Conventional Technology Performance 2015

Industrial Sector Submarkets	Mean Lamp Wattage (W)[1]	Lamp Life (1,000 hr)[2]	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
A-Type						
Incandescent Omni	46	2	16	$0.5	--	$15
Halogen Omni	29	2	15	$1.9	--	$15
CFL Omni	11	10	54	$3.0	--	$15
Directional						
Incandescent Directional	65	3	10	$1.3	--	$23
Halogen Directional	48	3	13	$3.7	--	$23
CFL Directional	16	10	43	$3.9	--	$23
Linear Fixtures						
T12 <4ft	41	15	49	$3.0	$17	$70
T8 <4ft	24	20	73	$5.4	$18	$70
T12 4ft	39	20	72	$2.0	$17	$70
T8 4ft	30	24	79	$2.8	$18	$70
T5 4ft	56	30	85	$4.2	$22	$75
T12 >4ft	84	12	78	$5.7	$19	$70
T8 >4ft	62	18	83	$7.0	$22	$70
Low and High Bay						
T12	75	12	72	$5.7	$19	$70
T8	57	18	79	$8.4	$22	$70
T5	68	30	85	$6.2	$25	$75
Metal Halide	424	20	77	$40	$210	$75
High Pressure Sodium	295	24	106	$51	$260	$80
Other						
CFL Pin	44	12	70	$5.4	$18	$15
Metal Halide	424	20	77	$53	$200	$75
High Pressure Sodium	295	24	106	$50	$250	$80

1. Ballast losses are accounted for in the lamp wattage assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).
2. The model also incorporates system lifetime assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).

Table C-4 Outdoor Sector Conventional Technology Performance 2015

Outdoor Sector Submarkets	Mean Lamp Wattage (W)[1]	Lamp Life (1,000 hr)[2]	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
Area and Roadway						
Incandescent	181	1	12	$0.5	--	$275
CFL	39	10	55	$6.6	--	$275
Linear Fluorescent	25	21	75	$2.8	$19	$70
Metal Halide	273	20	61	$40	$190	$330
High Pressure Sodium	230	24	85	$50	$260	$320
Low Pressure Sodium	78	25	90	$39	$110	$270
Other	62	18	76	$26	--	$300
Parking Lot						
Incandescent	130	1	12	$0.5	--	$275
Halogen	96	2	17	$3.3	--	$275
Metal Halide	341	20	61	$40	$160	$330
High Pressure Sodium	280	24	85	$50	$260	$320
Parking Garage						
Incandescent	172	1	12	$0.5	--	$275
Halogen	127	2	17	$3.3	--	$275
Linear Fluorescent	49	21	75	$2.8	$19	$70
Metal Halide	218	20	61	$40	$160	$330
High Pressure Sodium	201	24	85	$50	$260	$320
Other	97	13	76	$18	--	$300
Building Exterior						
Incandescent	90	1	12	$0.5	--	$15
Halogen	67	2	17	$3.3	--	$15
CFL	20	10	55	$6.7	--	$15
Linear Fluorescent	39	21	75	$2.8	$19	$70
Metal Halide	87	12	61	$38	$160	$360
High Pressure Sodium	78	24	85	$45	$195	$225
Low Pressure Sodium	74	25	89	$40	$100	$170
Other	52	15	76	$21	--	$230
Other						
Incandescent	86	1	12	$0.5	--	$15
Halogen	544	2	17	$3.3	--	$15
Linear Fluorescent	148	21	75	$2.8	$19	$70
Metal Halide	607	20	61	$98	$210	$525
High Pressure Sodium	522	24	85	$141	$260	$550

1. Ballast losses are accounted for in the lamp wattage assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).
2. The model also incorporates system lifetime assumptions for ballasted technologies (i.e., linear fluorescent and HID lamps).

The lighting market model introduces price and performance changes linearly as percentage improvements over the analysis period, 2015 to 2035. The lighting market model improves the lamp efficacy, ballast efficiency (if applicable), and equipment costs for each of the conventional lighting technologies. Labor costs are assumed to remain unchanged. These incremental performance improvements were developed in consultation with industry experts, with consideration given to the historical performance trajectory of each lighting technology. The percent improvement therefore varies depending on a particular lighting technology's seniority in the lighting market.

For nearly all technologies the lamp, ballast (if applicable), and fixture costs are expected to decrease at a rate of 0.5% per year. The lighting market model also assumes that CFLs as well as halogen directional, T5, metal halide lamps are expected to increase in efficacy at a rate of 0.5% per year. The exceptions are incandescent omnidirectional, T12, mercury vapor lamps, and low pressure sodium lamps, which are expected to show no improvement for any of the cost and performance parameters. These technologies are mature and there is little, if any, room for improvement. The market is moving away from mature technologies to more efficient options instead of trying to improve their performance. For all applicable technologies, ballast lifetime and costs are expected to improve, but not ballast efficiency. For all technologies, the only improvements expected to be made to fixtures are in reducing first cost. While manufacturing costs may decrease, the technology used in lighting fixtures themselves will remain largely unchanged.

Appendix C.1 Legislation and DOE Regulations

The lighting market model accounts for several regulatory measures on conventional light sources. Efficiency standards result in changes to both the performance and price of the affected conventional sources and force market trends to more efficient technologies. These include both standards prescribed via congressional action (e.g., general service incandescent lamp standards established in EISA 2007) as well as energy efficiency standards that are promulgated by DOE (e.g., the fluorescent lamp efficacy standard published in January 2015). The analysis considers only legislation and DOE regulations that are final (i.e., enacted in the *Code of Federal Regulations*[32]) and effective. The lighting market model does not take into account draft or pending legislation or regulations, as both the compliance dates and standard levels are uncertain. The lighting market model accounts for the new regulations by modifying the anticipated efficacy improvements and resulting price increases based on the performance criteria specified by the standard.

These regulatory measures force an improvement in the efficacy of conventional technologies, in some cases making it more difficult for LED technology to penetrate the general illumination market. This then requires that LEDs achieve higher efficacy levels and lower price points before the market starts to shift. The following list summarizes the existing regulatory measures that are taken into account in this iteration.

1. General service lamps. Section 321 of EISA 2007 prescribed maximum wattage standards for medium screw-base (MSB) general service incandescent lamps, which took effect between 2012 and 2014. The lighting market model assumes that covered non-halogen incandescent products are unlikely to meet the 2012–2014 maximum wattage standards. As such, this analysis models the EISA 2007 standards by manually removing covered

[32] For more information on the *Code of Federal Regulations* visit: http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR

incandescent MSB products from the modeled marketplace, with the standard becoming effective in each sector in the year corresponding to its mean incandescent MSB lamp wattage. This causes a market transition toward more efficient lamps, such as standard-compliant halogen and CFLs.[33] DOE is also required to conduct another rulemaking amending the standards for general service lamps, scheduled to be effective in 2020. If that rule does not produce energy savings equivalent to a minimum efficacy standard of 45 lumens per watt for GSLs, a backstop provision will prohibit the sale of any general service lamp that does not meet a minimum efficacy of 45 lumens per watt.

The current market share model predicts that even without the penetration of LED lighting products, the average marketplace efficacy of general service lamps will exceed 45 lumens per watt by 2020 through the increased sales of CFL products in both the commercial and residential sectors. Because it is not conclusive that the backstop requirement will be activated and due to the uncertainty in DOE's future actions, the lighting market model does not assume any change in the products sold in 2020. It is important to emphasize that the analysis and assumptions for this model regarding EISA 2007 have no implications for DOE's position or future actions. See Section 321 of EISA 2007.

2. Fluorescent lamps. The Energy Policy Act of 1992 (EPAct 1992) amendments to the Energy Policy and Conservation Act of 1975 (EPCA) established energy conservation standards for certain classes of general service fluorescent lamps (GSFLs). DOE published amendments to these standards in January 2015, which will become effective January 28, 2018. These amendments set 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. The lighting market model incorporates these standards by increasing the efficacy and price of linear fluorescent lamps accordingly. (10 CFR 430.32(n))

3. Fluorescent ballasts. This DOE regulation applies to covered fluorescent ballasts manufactured on or after November 14, 2014, and prescribes minimum ballast efficiency standards that will effectively shift the fluorescent market from T12 magnetic ballasts to T8 and T5 electronic ballast systems. Because covered magnetic ballasts are unlikely to meet the standards, this analysis manually removes T12 systems from the modeled marketplace over time. (10 CFR 430.32(m))

4. Incandescent reflector lamps. This DOE energy conservation regulation, which applies to lamps manufactured on or after July 14, 2012, amends EPCA to prescribe minimum efficacy standards for covered products in the 40-205 W range, determined by lamp spectrum, lamp diameter, and rated voltage. Certain small diameter, elliptical reflector, and bulged reflector incandescent reflector lamps (IRLs) are excluded. These standards promote the adoption of halogen infrared technologies. The lighting market model incorporates these standards by increasing the efficacy and price of halogen reflector lamps accordingly. (10 CFR 430.32(n))

[33] The Energy and Water Development and Related Agencies Appropriations Act, 2014, passed by the U.S. Congress on January 17, 2014, contains a provision that prohibits DOE from enforcing the GSIL, candelabra-base incandescent lamp, and intermediate- base incandescent lamp standards contained in Section 321 of EISA 2007 in fiscal year 2014. The standards, however, have not been repealed and remain in effect.

5. Mercury vapor ballasts. The Energy Policy Act of 2005 (EPAct 2005) banned the manufacture and importation of mercury vapor lamp ballasts (except specialty application mercury vapor lamp ballasts) after January 1, 2008. These ballasts are no longer available for purchase in the United States and were thus removed from the analysis of the commercial, industrial, and outdoor sectors. Mercury vapor lamps used in the residential sector, however, are assumed to be self-ballasted and not covered by this regulation. They were therefore retained in the residential analysis.

6. Metal Halide Fixtures. Section 324 of EISA 2007 prescribed minimum efficiency standards for metal halide fixtures to be applied to lamp fixtures manufactured on or after January 1, 2009. DOE published amendments to these standards in February 2014, which will become effective February 10, 2017. The standards set minimum efficiency requirements for metal halide fixtures between 50 W and 1000 W, determined by wattage and voltage. The lighting market model incorporates these standards by increasing the efficacy and price of metal halide fixtures accordingly. (10 CFR 431.326)

Appendix D LED Technology Improvement Projection

The lighting market model is largely driven by price and performance improvement assumptions for LEDs over the analysis period. These attributes are used as input data to the logit model in the form of two economic metrics: 1) first cost and 2) annual operation and maintenance cost. Previously, the forecast model leveraged price and efficacy projections developed in the 2013 SSL Pricing and Efficacy Trend Analysis for Utility Program Planning report. (10) However, this report has not been updated and SSL price and performance have experienced significant change and require a re-evaluation of their improvement trends. This appendix summarizes the method used to develop updated price and efficacy projections for the DOE lighting market model.

Appendix D.1 LED Price Projections

The LED price projections for the DOE lighting market model were derived based on the premise that cost of production for new technologies tends to fall with design and manufacturing learning, as well as production increases. To help determine the trend in LED price decline, automated web-scraping software was used to collect pricing data. 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 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 since 2010 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.

Web-Scrape Data Cleaning

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.

In order 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.

Methodology

To further organize this data into a structure compatible with the U.S. lighting market model, LED product types tracked in the web-pricing database were grouped into the model's application submarkets. 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 D-1, represent a simplification of possible lighting installations, and do not represent all LED product types used in practice for each application submarket.[34]

Table D-1 LED Product Type Groupings for Pricing Analysis

Application Submarkets		Description of Web-Based LED Product Types Groupings
LED Lamps	A-Type Lamps	A15, A19 and A21 lamp shapes
	Downlighting - Large	BR40, R30, BR40, R40, and 6 in. downlight retrofit lamps
	Downlight/Track - Small	MR16, PAR16 and R16 lamp shapes
	Track Lighting - Large	PAR20, PAR30 and PAR38 lamp shapes
	Linear Fixture - <4ft	2 ft. and 2 ft. U-shape linear lamps
	Linear Fixture - 4ft	4 ft. linear lamps
	Linear Fixture - >4ft	5 ft., 6 ft. and 8 ft. linear lamps
	Low and High Bay	High wattage retrofit and low and high bay lamps
	Decorative	Candle, flame, torpedo, and globe lamp shapes
	Area and Roadway	High wattage retrofit lamps
	Parking Lot	High wattage retrofit lamps
	Garage	High wattage retrofit and 4 ft. linear lamps
	Building Exterior	PAR30, PAR38 and high wattage retrofit lamps
LED Luminaires	Downlight/Track - Large	5 in., 6 in., 7 in. and 8 in. downlight fixtures
	Downlight/Track - Small	2 in., 3 in. and 4 in. downlight fixtures
	Linear Fixture - <4ft	2x2 ft. and 1x2 ft. panel, troffer, suspended and strip light fixtures
	Linear Fixture - 4ft	2x4 ft. and 1x4 ft. panel, troffer, suspended and strip light fixtures
	Linear Fixture - >4ft	1x8 ft. panel, troffer, suspended and strip light fixtures
	Low and High Bay	Low and high bay fixtures
	Decorative	Decorative surface, flush and wall mounted indoor fixtures
	Area and Roadway	Roadway, street and area fixtures
	Parking Lot	Canopy and area fixtures
	Garage	Garage, canopy and area fixtures
	Building Exterior	Porch, flood, wall pack and landscape fixtures

The price data for each application submarket were then aggregated for each collection period to produce measures of typical LED sales price over time. The aggregated time series for each application submarket was characterized by two distinct trends. Each experienced a slow rate of price decline, followed by rapid decline beginning at varying points after 2012. This noticeable change in the rate of LED price drop for all application submarkets could be due to a variety of factors such as increase in product offerings by online retailers, as well as new and mixing brands and pricing strategies resulting from increased competition and market activity.

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

To accommodate each decline region, a piece-wise trend was utilized – the 'slow' region characterized by linear declining price and the 'rapid' region by the mathematical model described in the LBNL report Recent Price Trends and Learning Curves for Household LED Lamps from a Regression Analysis of Internet Retail Data. (16) Figure D-1 illustrates this piece-wise trend for the LED lamps in the large downlight application submarket.

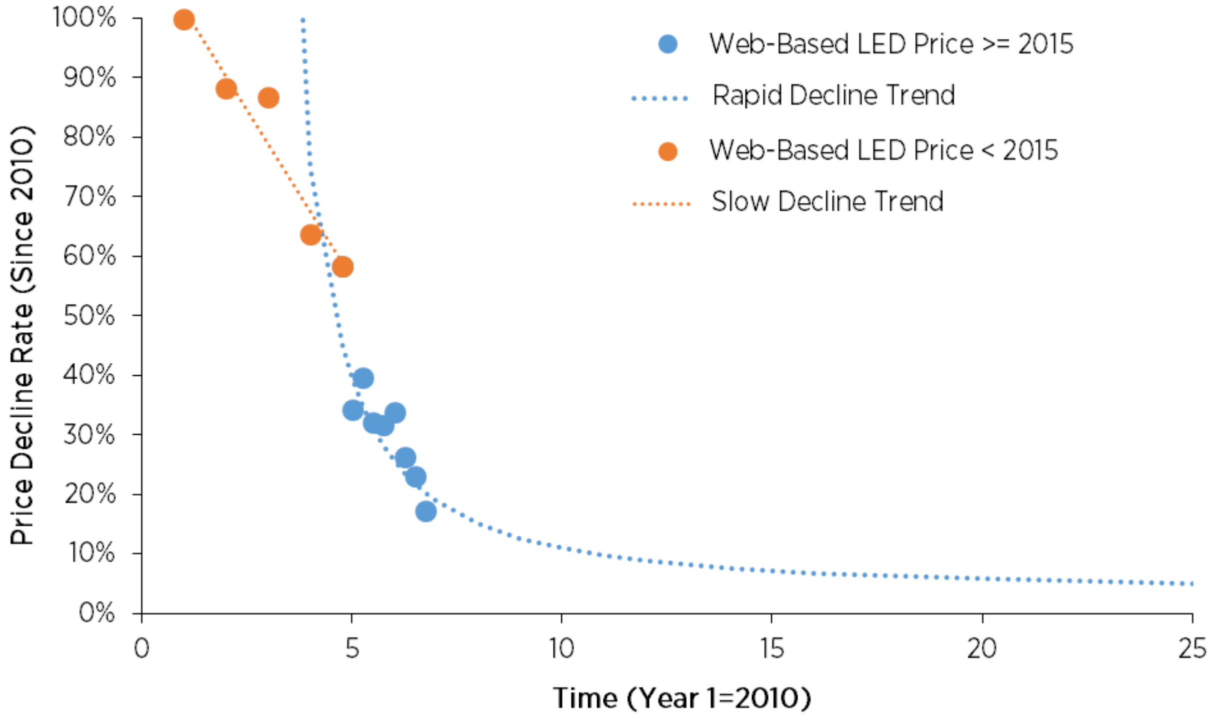


Figure D-1 LED Lamp Price Trends for the Large Downlight Application Submarket

As discussed in the LBNL report, the phenomenon of new technology price decline is often discussed in the context of experience curves, which characterize the cost of manufacturing for a given technology as a declining power law function of cumulative industry manufacturing experience. The experience curve function was fit to the time-series web data in the 'rapid' decline region and was used to derive future trends LED pricing for each submarket application.[35]

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 the projection method. Since the LED pricing data is aggregated for each collection period, it is not possible to accurately quantify the correlation or uncertainty in the fitted price trends. Also, as mentioned in the LBNL report, the typical consumer price may not be an ideal metric for projecting LED pricing, since the relation between manufacturing cost and typical market price may not be constant over time. (16) This is complicated by the availability of government and utility incentives, volume purchases, and sales negotiation, which can lower prices considerably. The price projection inputs for both LED

[35] Learning rate parameters for the experience curve model are provided in the LBNL report were adopted for all LED lamp and luminaire submarkets.

lamps and luminaires are not adjusted to account for any discounts that could be obtained through other sales channels.

The LED lamp and luminaire price projections shown in Table D-2 as well as in Figure D-2 are utilized as inputs for the lighting market model to describe the general projected trend in LED price decline.

Table D-2 LED Lamp and Luminaire Price Projections Application Submarket ($/klm)

Application Submarkets		2015	2020	2025	2030	2035
LED Lamps	A-Type Lamps	$16	$4	$3	$3	$3
	Downlighting - Large	$21	$12	$9	$8	$7
	Downlight/Track - Small	$47	$13	$10	$9	$9
	Track Lighting - Large	$28	$15	$12	$10	$8
	Linear Fixture - <4ft	$26	$8	$5	$4	$4
	Linear Fixture - 4ft	$20	$7	$5	$4	$3
	Linear Fixture - >4ft	$22	$9	$6	$5	$4
	Low and High Bay	$30	$17	$13	$11	$10
	Decorative	$28	$8	$6	$6	$5
	Area and Roadway	$23	$15	$12	$11	$10
	Parking Lot	$23	$15	$12	$11	$10
	Garage	$21	$13	$11	$10	$10
	Building Exterior	$24	$13	$10	$8	$7
LED Luminaires	Downlight/Track - Large	$71	$27	$19	$15	$14
	Downlight/Track - Small	$96	$36	$25	$21	$18
	Linear Fixture - <4ft	$47	$27	$22	$20	$18
	Linear Fixture - 4ft	$45	$25	$21	$18	$17
	Linear Fixture - >4ft	$81	$37	$25	$20	$17
	Low and High Bay	$36	$17	$13	$12	$11
	Decorative	$88	$50	$41	$37	$34
	Area and Roadway	$63	$25	$18	$15	$13
	Parking Lot	$59	$23	$16	$14	$12
	Garage	$70	$23	$15	$12	$10
	Building Exterior	$79	$25	$16	$13	$11

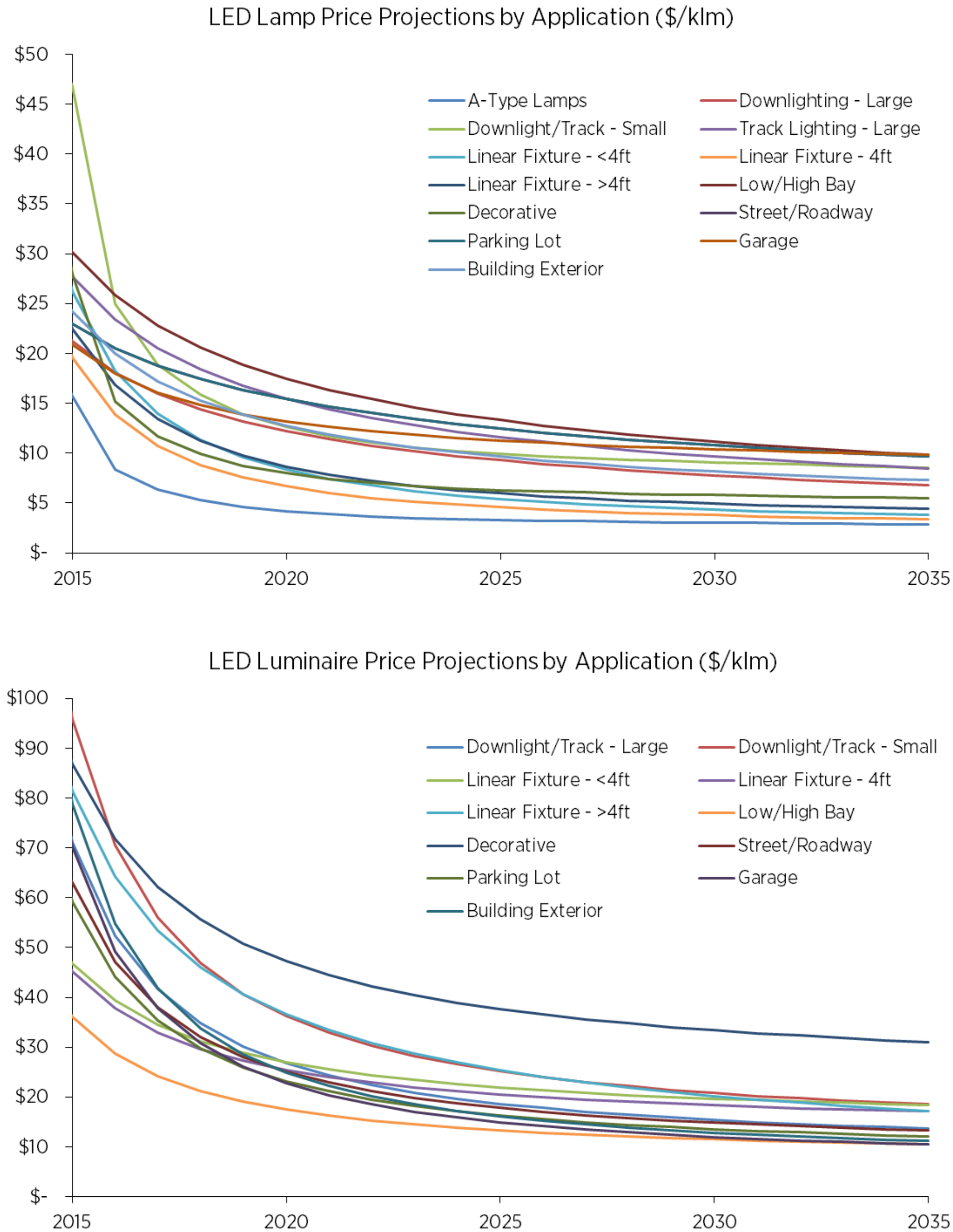


Figure D-2 LED Lamp and Luminaire Price Projections by Application Submarket ($/klm)

Appendix D.2 LED Efficacy Projections

The LED efficacy inputs for the lighting market model are derived using public databases to track LED product availability and performance. These updated inputs leverage three additional years of data using similar methods as described in the 2013 SSL Pricing and Efficacy Trend Analysis for Utility Program Planning report. (10) The following three programs have maintained public databases listing the performance of available (and/or qualified) LED products since 2009.

LED Lighting Facts® (http://www.lightingfacts.com/Products): DOE's voluntary LED Lighting Facts® program maintains a database of all LED products that have received the Lighting Facts® label, in order to showcase LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The product database, which began listing products in 2009, now contains nearly 40,000 lamp, luminaire, and retrofit products across all general illumination applications.

ENERGY STAR® (https://www.energystar.gov/products): ENERGY STAR® is a U.S. Environmental Protection Agency (EPA) voluntary program that identifies products with superior energy efficiency. ENERGY STAR® certifies lamps and fixtures for use in commercial and residential buildings based on a variety of performance criteria including, but not limited to, efficacy. The ENERGY STAR® label is widely recognized by American consumers as an indicator of a high efficiency product. Because the ENERGY STAR® criteria are applied to LED and incumbent technologies alike, many LED products are easily able to reach the minimum efficacy values required. The ENERGY STAR® Certified Light Bulb Database contains over 7,500 products and the ENERGY STAR® Certified Light Fixture Database contains over 11,000 products. Combined, they contain products for most general illumination applications in the commercial and residential sectors.

DesignLights Consortium™ (https://www.designlights.org/QPL): The DesignLights Consortium™ (DLC) is a collaboration among federal, regional, state, utility, and energy efficiency program members, luminaire manufacturers, lighting designers, and other industry stakeholders throughout the U.S. and Canada. The DLC maintains a public list of high quality, high efficiency LED products for the commercial sector. The DLC Qualified Products List has over 160,000 lamps and luminaires predominantly for use in commercial and industrial applications.

Each of these datasets record when an LED product was added as well as when the product is archived or no longer qualified. These data fields were used to identify which products were available for purchase in each year, and are assumed to represent the LED products available in the U.S. lighting market. To organize this data into a structure compatible with the lighting market model, LED product types were grouped into the model's application submarkets. These groupings are based on assumptions of how that product is most commonly used. For example, similar to the groupings used for the LED price inputs, it is assumed that MR16, PAR16 and R16 lamps are the most common lamp products used in small downlighting and track applications, while 2 in., 3 in. and 4 in. downlight and track fixtures are the most common luminaires. The product type groupings, shown in Table D-3, represent a simplification of possible lighting installations, and do not represent all LED product types used in practice for each application submarket.[36] In addition, these groupings

[36] Grouping assumptions were limited by the data fields provided in the LED Lighting Facts®, ENERGY STAR® and DLC databases.

are slightly different from those used to develop the LED pricing inputs. The data fields provided in the LED Lighting Facts®, ENERGY STAR® and DLC databases are limited compared to the web-pricing database, therefore, it was infeasible to disaggregate LED efficacy to the same level of granularity as LED price.

Table D-3 LED Product Type Groupings for Efficacy Analysis

Application Submarkets		Description of LED Product Types Groupings
LED Lamps	A-Type Lamps	A15, A19 and A21 lamp shapes
	Downlight/Track - Large	BR40, R30, BR40, R40, PAR20, PAR30, PAR38 and 6 in. downlight retrofit lamps
	Downlight/Track - Small	MR16, PAR16 and R16 lamp shapes
	Linear Fixture	All linear lamps
	Low and High Bay	High wattage retrofit and low and high bay lamps
	Decorative	Candle, flame, torpedo, and globe lamp shapes
	Area and Roadway	High wattage retrofit lamps
	Parking Lot	High wattage retrofit lamps
	Garage	High wattage retrofit and 4 ft. linear lamps
	Building Exterior	PAR30, PAR38 and high wattage retrofit lamps
LED Luminaires	Decorative	Decorative surface, flush and wall mounted indoor fixtures
	Downlight/Track - Large	5 in., 6 in., 7 in. and 8 in. downlight fixtures
	Downlight/Track - Small	2 in., 3 in. and 4 in. downlight fixtures
	Linear Fixture	Panel, troffer, suspended and strip light fixtures
	Low and High Bay	Low and high bay fixtures
	Area and Roadway	Roadway, street and area fixtures
	Parking Lot	Canopy and area fixtures
	Garage	Garage, canopy and area fixtures
	Building Exterior	Porch, flood, wall pack and landscape fixtures

Similar to the method used to develop the LED price projection inputs, this time series of LED efficacy data was aggregated for each of the above shown application submarkets to produce measures of market average efficacy over time. To accommodate the data provided in each of the three datasets, a weighted market-average efficacy[37] in each year was calculated. Projections were then developed by fitting a logarithmic curve to the historical time series of weighted market-average efficacy. Figure D-3 illustrates the market average efficacy calculated from each database for LED luminaires in the large downlight application submarket, as well as the weighted market-average efficacy, which is used as the efficacy projection input for the lighting market model.

[37] The weighted average efficacy in each year was calculated using product counts in each of the three public LED product databases.

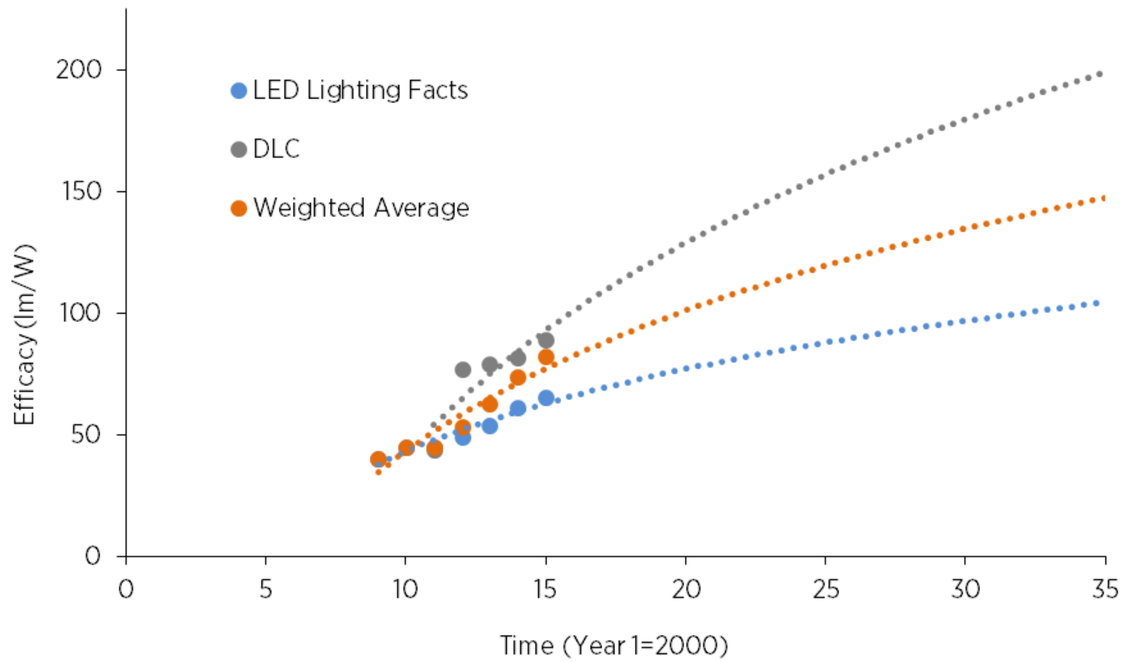
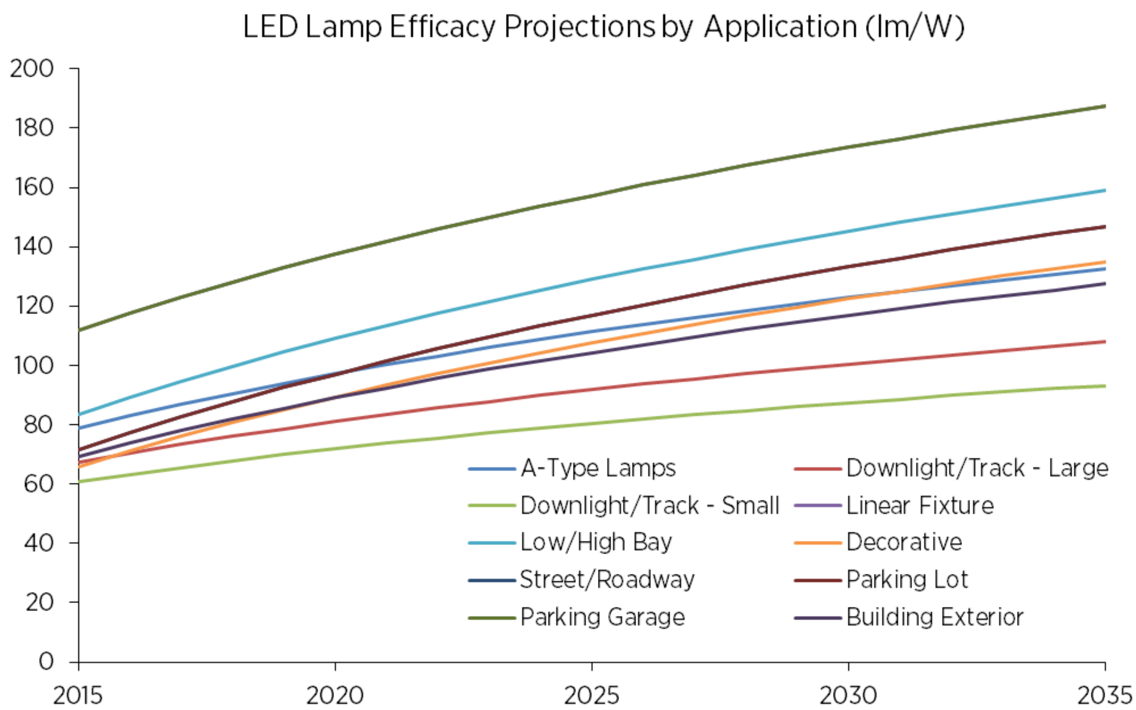


Figure D-3 LED Luminaire Efficacy Trends for the Large Downlight Application Submarket

The LED lamp and luminaire efficacy projections shown in Table D-4, as well as in Figure D-4, are utilized as inputs for the lighting market model to describe the general projected increasing trend in LED efficacy.

Table D-4 LED Lamp and Luminaire Efficacy Projections and Descriptions by Application (lm/W)

Application Submarkets		2015	2020	2025	2030	2035
LED Lamps	A-Type Lamps	79	97	111	123	133
	Downlight/Track - Large	67	81	92	101	108
	Downlight/Track - Small	61	72	80	87	93
	Linear Fixture	112	137	157	174	187
	Low and High Bay	83	109	129	145	159
	Decorative	66	89	108	122	135
	Area and Roadway	71	97	117	133	147
	Parking Lot	71	97	117	133	147
	Garage	112	137	157	174	187
	Building Exterior	69	89	104	117	127
LED Luminaires	Decorative	72	90	105	116	126
	Downlight/Track - Large	77	101	120	135	148
	Downlight/Track - Small	77	101	120	135	148
	Linear Fixture	99	123	142	158	171
	Low and High Bay	100	121	138	152	164
	Area and Roadway	86	105	120	132	142
	Parking Lot	86	105	120	132	142
	Garage	89	105	118	128	136
	Building Exterior	89	115	136	153	167



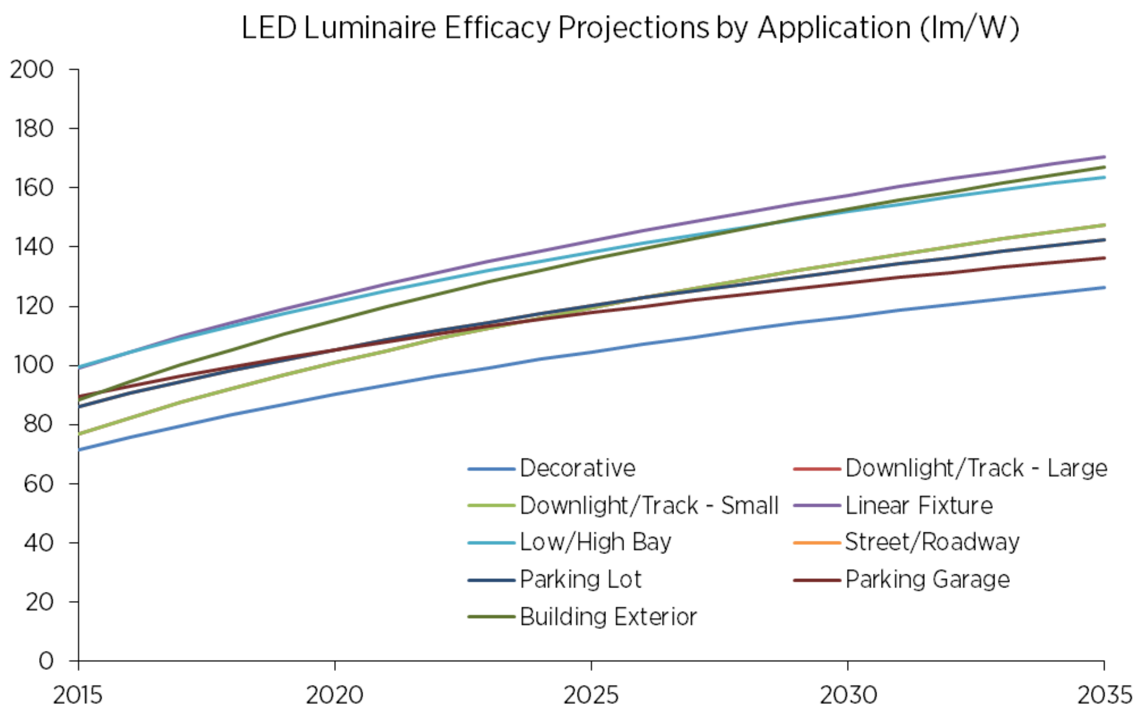


Figure D-4 LED Lamp and Luminaire Efficacy Projections by Application Submarket (lm/W)

Appendix E Lighting Market Penetration Model

Each year, new lamps and luminaires are sold, as old lamps are replaced or fixtures are installed or upgraded. This creates an annual lighting market demand, which may be satisfied by a suite of technologies, and represents an opportunity for a consumer to switch or adopt a new lighting technology. The lighting market model predicts market share as an aggregate of many individual purchasing decisions by way of three components: an econometric logit model that considers economic factors, a technology diffusion curve that considers existing marketplace presence, and an acceptance factor that considers non-economic biases. This approach of using a logit model and a technology diffusion model in concert has been previously used in several analyses. (8; 9)

Appendix E.1 Econometric Logit Model

The current forecast model uses a conditional logit model to award available market to multiple competing lighting technologies, similar to the model used in the National Residential Sector Demand Module of NEMS 2013 (3) for the lighting technology choice component.

The conditional logit model is a widely recognized method of forecasting a product's market penetration based on several quantitative or categorical explanatory variables. The result of the conditional logit is a probability of purchase, which represents an aggregation of a large number of individual consumer purchasing decisions. The logit model is predicated on the assumption that these individual decisions are governed by consumer utility (i.e., the relative value) that consumers place on the various technology attributes of an alternative. For example, consumers may be strongly influenced by a product's first cost, but may also place some lesser value on a product's efficacy. In the lighting market model, it is assumed that lighting purchasing decisions are primarily governed by two economic parameters, both of which are expressed in dollars per kilolumen, for comparison among technologies:

- *First Cost* includes the lamp price, ballast price (if applicable), and, in the case of the new and retrofit market segments, the fixture price. For LED luminaires, first cost indicates the price of the complete luminaire. This also includes a labor charge, where applicable.

- *Annual Operation and Maintenance (O&M) Cost* includes annual energy cost and annual replacement cost. It is a function of the mean lamp or ballast life, annual operating hours, lamp price, ballast price (if applicable), and a labor charge (if applicable).

These parameters, which collectively determine the life-cycle cost of a lighting product, were chosen to help characterize two types of lighting consumers:

- Those who prefer low retail price. These consumers place less importance on annual cost savings, which is derived from the efficacy and lifetime performance of a lighting product.
- Those who make purchasing decisions based primarily on the life-cycle or annual cost of a lighting product. These consumers place less importance on the upfront product cost.

The market penetration model bases market share calculations in each lighting application on one of these two characteristic consumers. In order to estimate how purchasing decisions are made for each application (i.e., to determine the characteristic relationship between the two cost variables), logistic regressions of historical price and performance data were performed for several lighting applications.

The econometric model used to forecast market share relies entirely on economic metrics and is therefore a simplification of consumer rationale. In reality, consumers consider other factors, such as color quality, dimmability, or aesthetics in their lighting decisions, in addition to economic factors. To account for these qualities, the lighting market model applies acceptance factors to particular technologies to moderate that technology's value to a consumer. For example, the lighting market model assumes acceptance factors less than one for CFL and HPS technologies in indoor applications, which, despite competitive price and performance with other technologies, have low market share largely due to their color quality and dimmability.

Appendix E.2 Technical Discussion of the Conditional Logit Model

Logistic regression is a statistical method of predicting the probability of the occurrence of an event by fitting data to a logistic curve, which takes the form:

$$p_j(z) = \frac{e^{z_j}}{\sum_{j=1}^{n} e^{z_j}}$$

Where:

- $p_j(z)$ is the probability of an individual choosing product j, and
- z is a linear relationship between the independent variables called the logit.

The logit, which represents the natural logarithm of the odds of an event occurrence, is defined as such:

$$z = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

Where:

- x_i represent the independent variables, and
- β_i represent the regression coefficients.

The conditional logistic regression model is a form of logistic regression that is commonly used in marketing to model consumer choices. It predicts the probability of multiple discrete, categorical (i.e., unable to be ordered in any meaningful way) outcomes, such as occurs in a marketplace with several competitive products. By defining a relationship between a response variable and several independent, explanatory variables, which can be ordinal (ordered) or categorical, the conditional logit model is able to predict the expected market shares of various products.

Appendix E.3 Logit Model Input Data

Appendix C and Appendix D discuss how the lighting market model tracks the evolution of price and performance attributes for conventional lighting technologies and LEDs, respectively. These attributes are used as input data to the logit model in the form of two economic metrics: first cost and annual operation and maintenance cost. First cost is a straightforward measure of the purchase price that the consumer pays. Annual O&M cost includes annual energy, replacement and labor costs. Annual replacement cost is an annualized estimate of the cost of replacing burned out lighting equipment, distributed over the average lifetime of the lighting product in years. It is calculated from average lamp or ballast lifetime in hours, average operating hours per year, and the cost of the replacement unit. Annual energy cost is based on average efficacy values and average operating hours per year by application, which is also discussed in Appendix C and Appendix D, and average electricity prices by sector. Electricity prices used for the operating cost evaluation are taken from the EIA's AEO 2015 reference scenario. Because the majority of outdoor lighting is used on and around commercial buildings, we assumed that commercial electricity prices apply to the outdoor sector. The AEO 2015 also provides several alternative electricity price scenarios, but variation is minor such that their effect on the logit model was negligible. The electricity prices used in the analysis are shown in Table E-1.

Table E-1 Electricity Price Projections in 2015 Dollars per Kilowatt-Hour

	Average Electricity Price ($/kWh)				
Sector	2015	2020	2025	2030	2035
Residential	$0.125	$0.146	$0.166	$0.183	0.205
Commercial	$0.105	$0.120	$0.136	$0.149	0.166
Industrial	$0.073	$0.082	$0.094	$0.103	0.117
Outdoor	$0.105	$0.120	$0.136	$0.149	0.166

Source: EIA, 2015

Appendix E.4 Technology Diffusion Curve

While the conditional logit model provides a probability of purchase for each technology under perfect competition, the lighting market model also recognizes that newer technologies are at a relative disadvantage compared with well-established incumbent technologies. The rate of market penetration is subject to certain market barriers, including, but not limited to, acceptance and availability of the technology. Typically these barriers only apply to new market entrants, such as LED technologies, as technologies may initially be unknown to consumers or may not be readily available to purchase. However, as a product establishes itself on the market, benefits are communicated by word-of-mouth to the consumer base, manufacturers are able to ramp up production capacity, and stocking distribution channels emerge. To simulate this lag effect on newer technologies, the lighting market model applies a Bass technology diffusion model to the logit model market share predictions. The Bass diffusion model is a widely recognized marketing tool used in technology forecasting that effectively slows the rate of technology adoption based on the time necessary for consumers to become aware of and adopt a new lighting technology. In today's lighting market, the effect of technology diffusion is primarily limited to LED lighting (both connected and non-connected products) as it is the only significant emerging technology on the market. Therefore, the lighting market model tends to delay the adoption of LED products despite rapid gains in efficacy improvement and cost reduction.

In this analysis, the Bass curve used for conventional (non-LED) technologies is based on a PNNL report, which uses historical market penetration data for electronic ballasts, T8 fluorescent lamps, and CFLs to create a lighting-specific diffusion curve. (17) Considering the historical diffusion of CFLs into the marketplace to be atypical due to various early performance issues such as poor light levels and color rendition, discussed at length in a 2006 DOE report (18), this analysis modified the PNNL diffusion curve to be based only on electronic ballasts and T8 fluorescent lamps. These technologies are common in the commercial and industrial sectors, which causes the curve to be more representative of these sectors than the residential and outdoor sectors.

Additionally, LEDs are a versatile, promising technology that has begun to demonstrate significant benefits over incumbent competitors. LED adoption estimates for several lighting applications indicate that the diffusion of LED technology is occurring at a faster rate compared to incumbent lighting technologies. Figure E-1 below shows the average estimated LED market share for all general illumination applications as compared to incumbent technologies. To account for this difference, this updated analysis assigns to LED products a faster diffusion rate compared to the incumbent competitors.

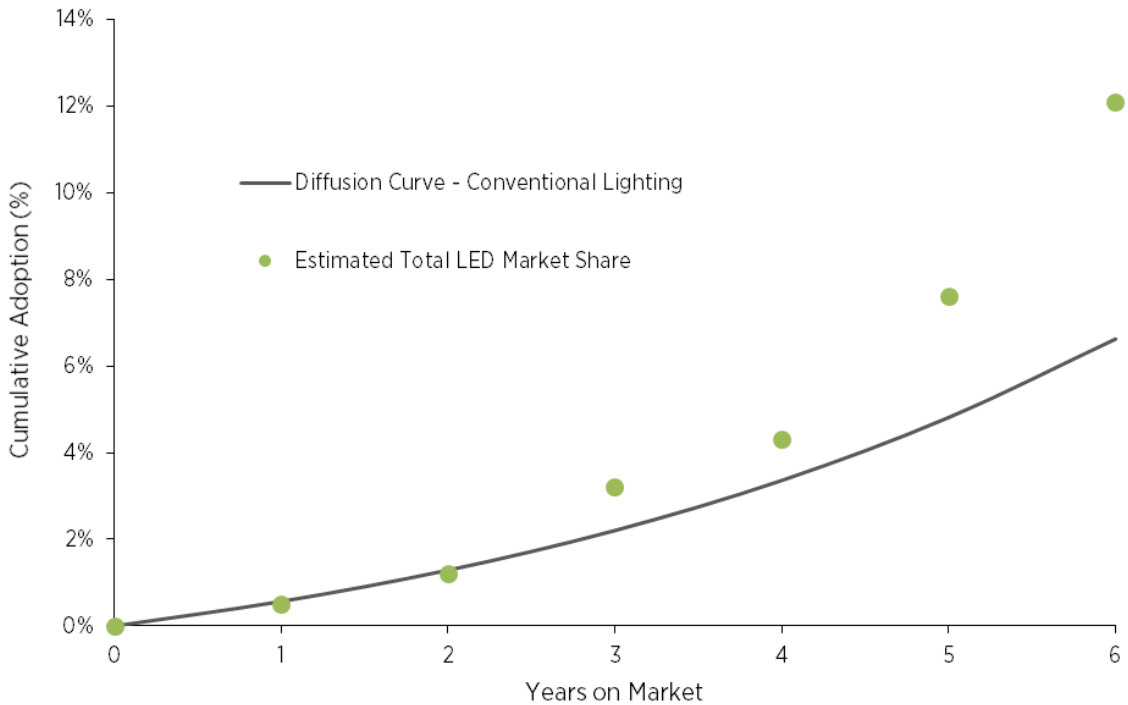


Figure E-1 LED Market Share vs. Conventional Lighting Technology Diffusion

Appendix F Lighting Controls Analysis

Installation and use of lighting controls, particularly connected lighting, provides a large opportunity for energy savings in the U.S. The inherent properties of SSL provide an opportunity to integrate controls and increase the energy savings potential of lighting systems. The controllability of LED technology, as well as the low cost to integrate sensing, data processing, and network interface hardware will help overcome many of the existing hurdles to utilizing lighting controls.

For the updated lighting market model, a new module was developed to determine the forecasted installed penetration as well as the additional energy savings from connected SSL products. To implement the lighting controls component of the model, traditional lighting controls as well as connected systems were researched and analyzed to determine the lighting applications for which they are well-suited. These control systems were then assessed for their compatibility with various lighting technologies as well as their potential for energy savings. The installed penetration was then calculated based on building stock assessment data, which involved analysis of the prevalence of various lighting control systems in conjunction with technology diffusion estimates. Using this methodology, estimates were developed for the current and projected energy savings achieved by connected SSL products under the No-SSL, Current SSL Path and DOE SSL Program Goal scenarios.

Appendix F.1 Data Collection

The first step in determining the additional energy savings from lighting controls and connected lighting was a literature review. Over 140 sources[38] were collected and reviewed including case studies, journal articles, reports, manufacturer literature, websites, DOE rulemaking analyses, and presentations.

The goal of the literature review was to collect data on the following inputs for the lighting controls energy savings analysis:

1. Market penetration of various lighting control systems, including connected lighting products, which involved research and collection of shipment and installed stock data as well as any trends or barriers that may affect adoption.
2. Change in wattage due to traditional controls and connected lighting, which included wattage decreases from traditional control strategies, such as dimming, or wattage increases due to standby[39] energy consumption.
3. Reduction in operating hours due to traditional controls and connected lighting, which result from controls that have the capability of turning lights off, such as occupancy sensors.
4. Percent of time traditional controls and connected lighting are used once they are installed. This input is essential because even when controls are installed, they are often only used part

[38] A list of all sources collected and reviewed for the literature review are provided in Appendix G. Please note that not all sources were referenced for this lighting controls analysis.

[39] Standby energy consumption refers to the condition in which the control is connected to a main power source and facilitates activation of active mode by remote switch (including remote control), internal sensor, or timer.

of the time. For example, occupancy sensors are only activated when there are no occupants in the room.

Data collection also involved interviews with various stakeholders, including manufacturers, utilities, and local governments. Once preliminary results were developed, a meeting was held with DOE and these stakeholders to discuss the methodology and results for the controls analysis. During the stakeholder meeting, invaluable insight was collected regarding the use and market for traditional controls and connected lighting, as well as how these products will improve going forward and their potential for energy savings. This vital feedback has been incorporated into the control analysis and the team is greatly appreciative of the time and effort given by the participating organizations.[40]

Appendix F.2 Scope and Assumptions

After data collection was completed, the first step of the controls analysis involved determining which lighting control strategies and systems to include, and the establishing a definition and scope for each. The main traditional lighting control strategies - dimming, daylighting, occupancy sensing, and timing - were grouped into "control systems" and align with what is available on the market based on research and stakeholder feedback. While this analysis focuses on connected lighting, it was important that the model also consider the impacts of non-connected lighting controls so as not to exaggerate the forecasted energy savings.

The following Table F-1 provides a summary of the assumptions for each traditional control strategy, as well as examples of control products that are included in each strategy.

Table F-1 Traditional Control Strategies Scope

Control Strategies	Wattage Reduction Effect	On/Off Effect	Lamp Technologies Included	Categories Included
Dimmer	✓		All	Personal Tuning Task Tuning Institutional Tuning High-End Trim Demand Response Bi-Level/Multi-Level Switching Lumen Maintenance
Daylighting	✓		All	Photosensors Daylight Harvesting
Occupancy Sensor		✓	All	Occupancy Sensors Vacancy Sensors
Timer		✓	All	Scheduling

The lighting market model assumed that each traditional control strategy would have the effect of reducing wattage or turning the light off. This analysis assumed that dimmers and daylighting reduce wattage, while occupancy sensors and timers turn the lights off. For this forecast analysis, connected

[40] Please see the Acknowledgements section at the beginning of this report for a list of all participating organizations.

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. In addition, the analysis assumed that all of the non-connected control systems (e.g., Single, Multi and EMS) can be applied to all lighting technologies, but their prevalence varies and is determined by market share, the calculation methodology for which is described in the following section.

The assumptions provided in Table F-2 explain how these control systems were implemented in the lighting market model.

Table F-2 Summary of Control Systems and Assumptions

Control System	Communication Between Lighting Products?	Description
Single	No	Any of the traditional control strategies implemented by themselves (i.e., without any other control strategies)
Multi	No	Any combination of two, three, or four of the traditional control strategies implemented together on the same lamp or luminaire. There is no communication between different lamps and luminaires.
Energy Management System (EMS)	No	A building energy management system that allows control of lamps and luminaires within a single building. All four traditional control strategies are implemented. There is no communication between different lamps and luminaires.
Connected	Yes	All four traditional control strategies are implemented. Additional energy savings based on communication between connected lamps and luminaires, as well as use optimization through machine learning algorithms.

The analysis uses the assumption that EMS and connected lighting would include all four traditional control strategies and thus would have the capability of both reducing wattage and turning the light off. The analysis also uses the assumption that EMS can be applied to all lighting technologies; however, connected lighting is only feasible for LED technology. The following Table F-3 provides a summary of the assumptions for EMS and connected lighting, as well as examples of control products that are included in each system.

Table F-3 EMS and Connected Lighting Scope

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

While the model control system groupings, definitions, and scope simplify the range and complexity of products available, these assumptions are reasonable given the current limited penetration of all lighting control systems.[41] Even though many products for controlling light have been commercially available for decades, deployment and energy savings have been limited due to their complexity, high cost, limited interoperability, low use, and a lack of knowledge on how to install, commission, and operate them. This model focuses on the potential for connected SSL lighting products to reverse this paradigm going forward.

Appendix F.3 Lighting Controls Methodology

The calculation for total energy savings from each lighting control system consists of two separate components that are multiplied together to obtain the total energy savings. The first component is market share, which is the percent of lamps or luminaires that have each control system in each year. The second component is the savings per control system, which is the energy saved for lamps and luminaires that have controls installed. The following steps illustrate at a high level the methodology used to calculate total energy savings from each control system.

Step 1: Forecast the market share of lamps and luminaires with each lighting control system through 2035.

Step 2: Determine the energy savings per individual lamp or luminaire from each lighting control system through 2035.

Step 3: Multiply the installed stock of controls by the individual savings per control system to determine market-wide energy savings.

Inputs for each component were developed using the data collected from the literature review and stakeholder feedback. Each component is discussed in more detail in the following sections. The resulting energy savings are included in the results discussed earlier in this report.

Market Share

Calculating market share required two sets of input data: the current installed base of each control system and the forecasted shipments of each control system in each year through 2035.

For non-connected control systems, the analysis first determined the current installed base of each control system for each lamp technology. As described earlier in this report, the lighting market model assumes that the market share of each lamp technology changes over time. The controls analysis assumes that controls remain installed and the market share of lamp technologies they control follows the same trajectory as the forecast model.

For connected lighting, two scenarios were evaluated, the Current SSL Path and DOE SSL Program Goal. In both scenarios connected lighting is expected to have the greatest impact on LED luminaires. While connected LED lamps will certainly become increasingly utilized, connected LED

[41] "Figure 4.1 Percentage of Commercial Buildings with Controls Strategy according to the 2012 Commercial Buildings Energy Consumption Survey by the U.S. Energy Information Administration," SSL R&D Plan, DOE, June 2016. http://energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_%20jun2016_2.pdf

linear fixtures (i.e., troffer, panel, strip, suspended, etc.), low and high bay, and outdoor luminaires target the applications where increased controllability and networked capabilities will have the greatest value to customers.

The major assumptions for the Current SSL Path and DOE SSL Program Goal scenarios are summarized below:

Connected Lighting Assumptions for Each Scenario:

- The **Current SSL Path** scenario assumes that the rate of market penetration of connected lighting is similar to that experienced for occupancy sensors, resulting in a slow adoption. This represents a scenario where the continued lack of performance reporting and verification, as well as the inability to address complexity and interoperability barriers, cause a lag in consumer adoption. *Within the 2035 timeframe, for the Current SSL Path scenario, the majority of luminaires installed are non-connected LEDs.*

- The **DOE SSL Program Goal** scenario, on the other hand, assumes that the rate of market penetration of connected lighting follows the same trajectory of LED lighting, resulting in an accelerated adoption. This represents a scenario in which industry and DOE efforts to demonstrate and verify energy savings benefits, as well as develop interoperable and user-friendly products accelerate consumer adoption. *Within the 2035 timeframe, the majority of luminaires installed in the SSL Program Goals scenario are connected LEDs.*

These assumptions for each scenario feed into the market share calculation which consists of two parts: the payback acceptance which considers first and operating costs and technology diffusion curve that considers existing marketplace presence.

The economic portion of the model assumes that the lighting market responds to simple payback, which focuses on a comparison of first cost and operating cost savings across all sectors. The payback acceptance curve component awards available market share to connected lighting based on consumer aversion to payback, as developed by Arthur D. Little, Inc. Based on interviews and data collected during the literature review process, payback period for connected lighting products was assumed to vary by sector and building type ranging from one to roughly eight years. These acceptance curves then relate the payback to the fraction of the ultimate market captured by sector. The curves are presented below in Figure F-1.

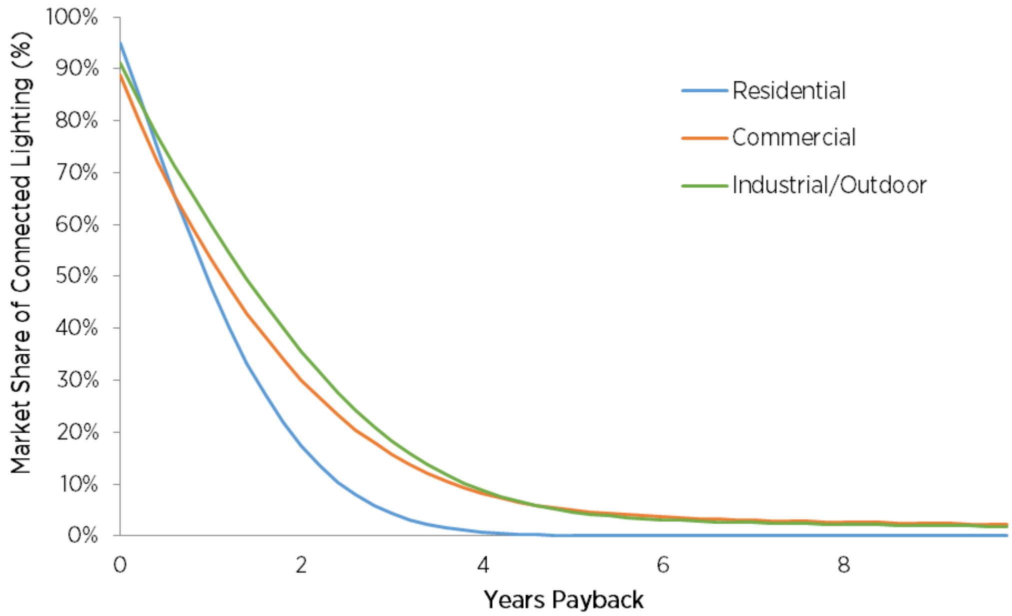


Figure F-1 Market Response Curves Used to Determine Payback Acceptance

Source: Arthur D. Little internal draft, 2001

While the payback acceptance provides a probability of purchase for connected lighting under perfect competition, the lighting market model also recognizes that newer technologies are at a relative disadvantage compared with well-established incumbent technologies. Therefore, newer technologies, such as connected lighting, are at a relative disadvantage and subject to certain market barriers. Connected lighting represents a new market entrant that may initially be unknown to consumers or may not be readily available to purchase. To simulate the maximum adoption potential of connected lighting over time, the lighting market model applies a Bass technology diffusion model.[42]

Two separate diffusion curves were developed to describe the adoption potential for connected lighting in each scenario. The Current SSL Path scenario applies the diffusion curve for occupancy sensors, while the DOE SSL Program Goal scenario applies the same diffusion curve used for LED lighting. Penetration data collected from historical sales, as well as from the U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options (19), 2010 U.S. Lighting Market Characterization (4) and the LED Adoption (20) reports, were used to derive diffusion curves for occupancy sensors and LED lighting. Figure F-2 below illustrates the diffusion curves applied for each scenario.

[42] See Appendix E for a discussion of the Lighting Market Penetration Model.

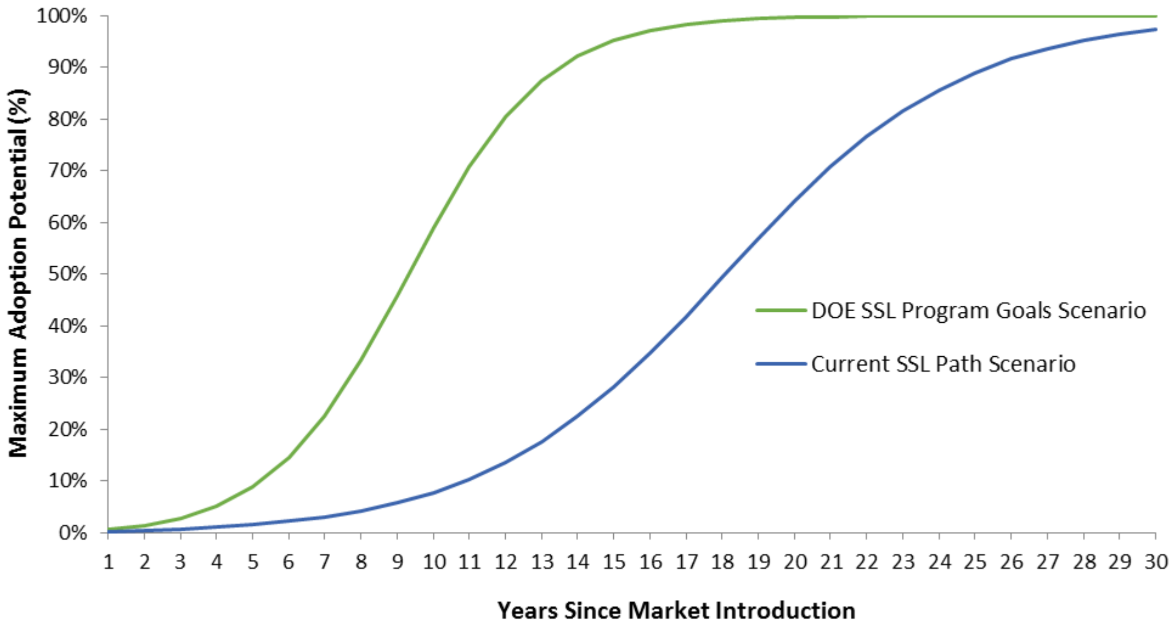


Figure F-2 Bass Diffusion Curves Applied to Connected Lighting for each Scenario

Per Control Savings

Calculating the energy savings for each control strategy required three sets of input data: a baseline lighting load profile, the energy reduction of each control strategy, and the percent of time that the control is actually used.

For each lighting control application, 24-hour lighting load profiles were developed for three day types: weekday, weekend, and holiday. The baseline lighting load profiles account for the probability that a lamp or luminaire would be turned on, and thus could achieve energy savings from lighting controls. The analysis assumed that manual on/off switches are not lighting controls; thus, the baseline lighting load profiles were used as a starting point from which to calculate energy savings from controls.

Based on research and stakeholder input, the analysis assumed that the energy reduction from controls that have a wattage reduction effect is 50% and that the energy reduction from controls that have an on/off effect is 100% when the light is turned off. During times when the controls are not used, the model assumes there is no energy reduction.

The use percentages are based on the amount of time that controls are used once installed. For example, if an occupancy sensor turns a light off for 15 minutes in a given hour, its use effect is 25% in that hour.

The following equations show how the three inputs described above are combined to calculate the total energy savings per control strategy.

$$Control\ Strategy\ Energy\ Savings =$$

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

Where:

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

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

For control systems that use multiple traditional control strategies (i.e., Multi, EMS, and Connected), the control effects from each strategy are summed in each hour. 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). The following equation shows how the energy savings per control system are calculated in those cases.

$$Control\ System\ Energy\ Savings =$$

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

As an example, Figure F-3 illustrates the baseline load profile and the load profile with dimmers for a commercial office on a weekday. The energy savings for dimmers are calculated by taking the ratio of the load profile with dimmers to the baseline load profile.

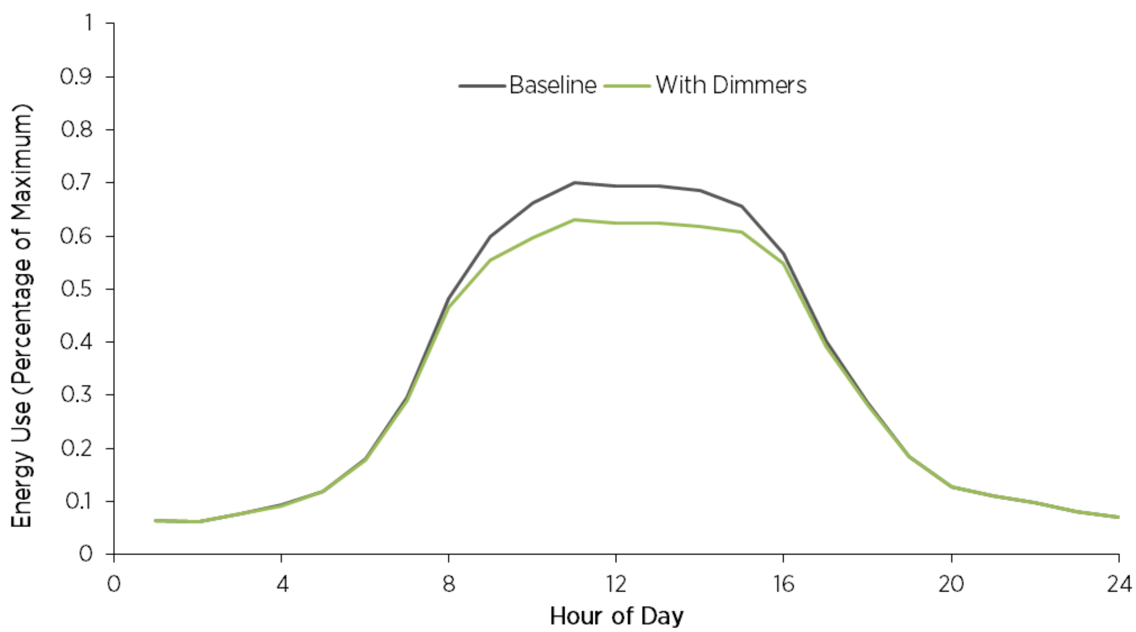


Figure F-3 Example Load Profiles for a Commercial Weekday

Based on the literature review as well as stakeholder feedback, lighting control installations were assumed to have varying savings impacts by application or building type.

Within the outdoor sector, lighting control savings were evaluated separately for each of the lighting market model application submarkets (e.g., lighting control use and energy savings in area and roadway applications is different than those for in parking garage applications) because data and feedback indicated that lighting controls would have different use patterns in the different outdoor submarkets.

For the commercial sector, differences in lighting control impacts are largely governed by building type rather than application submarkets due to differences in baseline lighting load profiles and lighting control use patterns. Therefore, separate use and energy savings effects were modeled for the listed building types shown below:

- Office
- Retail
- Lodging
- Health
- Education
- Warehouse

Because differences in lighting control impacts are modeled by building type rather than application submarkets in the commercial sector, these impacts are weighted by the prevalence of each building type in the U.S. based on data provided in the 2012 Commercial Building Energy Consumption Survey to develop a commercial sector average. (21) The lighting control use and energy savings effects are not assumed to differ by application submarket in the commercial sector (e.g., a connected LED luminaire has the same impact in the Directional and Linear Fixture submarkets).

Lighting controls impacts within the industrial and residential sectors are not assumed to differ by application or building type because energy savings potential from controls is small and because there is less variation in baseline lighting load profiles, lighting control use, and energy savings between different applications or building types in these sectors.

The following table shows the energy savings assumptions for each control system by application. For connected lighting, the savings are calculated by layering all four traditional control strategies and then applying an adjustment factor to account for the fact that connected systems offer more energy savings potential due to their ability to communicate and the opportunity for use optimization through machine learning, which is assumed to improve over time.

Table F-4 Energy Savings for each Control Type by Application

Applications	Dimmer	Daylighting	Occupancy	Timer	Multi	EMS	Connected Lighting 2015	Connected Lighting 2035
Commercial - Office	6%	15%	56%	10%	40%	67%	68%	81%
Com/Ind - Warehouse	3%	14%	83%	13%	52%	70%	71%	85%
Commercial - Retail	7%	15%	21%	19%	22%	36%	36%	43%
Commercial - Lodging	4%	9%	75%	47%	53%	70%	71%	85%
Commercial - Health	10%	13%	20%	9%	25%	42%	43%	51%
Commercial - Education	5%	14%	57%	10%	40%	67%	68%	81%
Residential	4%	10%	70%	41%	50%	70%	71%	85%
Industrial	25%	5%	50%	50%	49%	70%	71%	85%
Street/Roadway	14%	11%	20%	17%	30%	50%	50%	60%
Parking Lot	14%	11%	20%	17%	30%	50%	50%	60%
Garage	11%	2%	21%	6%	20%	33%	34%	40%
Building Exterior	14%	9%	20%	17%	29%	49%	50%	59%

The calculation for total energy savings from each lighting control system consists of multiplying the market share of each control system by the savings per individual control system. The following equation illustrates the total energy savings calculation.

$$Total\ Controls\ Energy\ Savings = \sum_{Control\ Systems} (Market\ Share_{Control\ System} \times Energy\ Savings_{Control\ System})$$

Appendix G Lighting Controls Literature Review Sources

Source Title	Author	Year
Middlesex Community College	Acuity Brands	2013
Product and Application Guide	Acuity Brands	2015
Philips Hue: Automated Home Lighting Gets Colorful	AnandTech	2013
Modeling the Market Penetration of Advanced Lighting Controls in the U.S Commercial Sector	Andrew Sturges	2012
An Analysis of Energy-Efficient Light Fittings and Lighting Controls	Applied Energy	2009
Energy Efficient Lighting Control	Auralight	2012
Dual-Loop Photosensor Control Systems: Reliable, Cost-Effective Lighting Control for Skylight Applications	Benjamin Koyle and Konstantinos Papamichael	2010
BPA Easily Commissioned Lighting Controls Phase 2 Report	Bonneville Power Administration	2015
A Simplified Method to Estimate Energy Savings of Artificial Lighting Use From Daylighting	Building and Environment	2004
Determination of the Energy Saving by Daylight Responsive Lighting Control Systems with an Example From Istanbul	Building and Environment	2003
Achieving Energy-Efficient Lighting in California	California Energy Commission	2015
Dual-Loop Photosensor Control System for Daylight Harvesting	California Energy Commission	2013
Lighting California's Future: Integration of Lighting Controls with Utility Demand Response Signals	California Energy Commission	2011
Pleasanton Library Cuts Lighting Energy Use 46% with Wireless Lighting Controls and Fixture Retrofits	California Energy Commission	2012
Saving Energy in Buildings with Adaptive Lighting Systems	California Energy Commission	2015
Staff Analysis of M. Niels Engineering Report, Submitted with IBEW Lighting Alteration Comments.	California Energy Commission	2016
2010 Lighting Technology Overview and Best-Practice Solutions	California Public Utilities Commission	2010
Final Report: Baseline Characterization Market Effects Study of Investor-Owned Utility Programs to Support LED Lighting in California	California Public Utilities Commission	2014
Luminaire Level Lighting Control	California Public Utilities Commission	2014
Outdoor Lighting Controls	California Public Utilities Commission	2014
Experimental and Simulation Study on the Performance of Daylighting in an Industrial Building and its Energy Saving Potential	Chen et al	2014
Energy Efficiency Potential Study for Consolidated Edison Company of New York, Inc. Volume 2: Electric Potential Report	Con Edison of New York	2010
Residential Lighting Controls Market Characterization	Consortium for Energy Efficiency	2014
Control Systems & LEED	Cooperman et al	2012

Lighting and the Living Lab	Cordell et al	2014
A Life Cycle Cost Evaluation of Multiple Lighting Control Strategies	Daintree	2014
The Value of Wireless Lighting Control	Daintree	2014
Advanced Lighting Controls for Reducing Energy Use and Cost in DoD Installations	Department of Defense	2013
2010 U.S. Lighting Market Characterization	Department of Energy	2010
DOE Connected Lighting Systems Presentations	Department of Energy	2015
DOE GSL Preliminary Analysis TSD, Appendix 10C	Department of Energy	2014
Lighting Development, Adoption, and Compliance Guide	Department of Energy	2012
Department of Energy Appliance Standards - Lighting	Department of Energy	Various
Use of Occupancy Sensors in LED Parking Lot and Garage Applications: Early Experiences	Department of Energy	2012
Commercial Lighting Controls Metering Study	DTE Energy	2013
Achieving Energy Efficiency Through Integrated Lighting Controls	Eaton	2015
Beyond the Source: Integrated Controls and Other Technologies that are Advancing LEDs	Eaton	2015
Dimming According to Daylight – Effect on Lamp Life	Eino Tetri and Virorel Gligor	2002
Lighting Energy Savings in Offices Using Different Control Systems and Their Real Consumption	Energy and Buildings	2007
Smart Occupancy Sensors to Reduce Energy Consumption	Energy and Buildings	1999
Study of Daylight Data and Lighting Energy Savings for Atrium Corridors with Lighting Dimming Controls	Energy and Buildings	2013
Commissioning for Optimal Savings from Daylight Controls	Energy Center of Wisconsin	2013
Energy Savings from Daylighting: A Controlled Experiment	Energy Center of Wisconsin	2006
Performance of an LED Lighting System in a Parking Application	Energy Center of Wisconsin	2013
Design Brief Lighting Controls	Energy Design Resources	Unknown
CBECS Database	Energy Information Administration	2012
RECS Database	Energy Information Administration	2009
Shedding Light on the Commercial Lighting Market in Wisconsin	Environmental and Economic Research and Development Program	2013
Monitored Lighting Energy Savings From Dimmable Lighting Controls in The New York Times Headquarters Building	Fernandes et al.	2013
Rogers Centre a Project by Encelium Technologies	Frost & Sullivan	Unknown
Luminaire Efficiency: What Mandatory and Voluntary Labels Achieve, and What They Should Achieve in the Future	Geilinger et al.	2012
Integrated Daylight Systems	General Service Administration	2014
LED Fixtures with Integrated Controls	General Service Administration	2015

Occupant Responsive Lighting	General Service Administration	2012
Occupancy Sensors, Efficient Lighting, and More Reduce Costs at Senior Living Facility	Green Generation Solutions	Unknown
An Old Idea Made New: It's Daylight and It's Saving Energy and Dollars	Greenfleet	2010
Harvesting Daylight	Hastbacka et al.	2013
Automatic Street Lighting System for Energy Efficiency Based on Low Cost Microcontroller	Husin et al.	2012
Energy Efficient Lighting Control System Design for Corridor illumination	Jayashri A.Bangali and Arvind D.Shaligram	2012
A Sensor-Less LED Dimming System Based on Daylight Harvesting with BIPV Systems	Korean Institute of Energy Research	2013
A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings	Lawrence Berkeley National Laboratory	2011
Adapting Wireless Technology to Lighting Control and Environmental Sensing	Lawrence Berkeley National Laboratory	2005
Responsive Lighting Solutions	Lawrence Berkeley National Laboratory	2012
Evaluation of Lighting Performance in Office Buildings with Daylighting Controls	Li et al.	2001
Lighting and Energy Performance for an Office Using High Frequency Dimming Controls	Li et al.	2006
Bi-level Switching Study Demonstrates Energy Savings	Lighting Controls Association	2007
Estimating Energy Savings with Lighting Controls	Lighting Controls Association	2013
Market Research Suggests High Degree of Confidence with LED Lighting and Controls	Lighting Controls Association	2014
Task Tuning Promises Significant Energy Savings	Lighting Controls Association	2016
Exploratory Analysis of Operational Parameter of Controls	Lighting Research Center	2001
Part 1: Automatic Shut-off Controls	Lighting Research Center	2002
Light Control for Energy Savings	Lutron	2014
High Performance Lighting Controls in Private Offices: A Field Study Of User Behavior And Preference	Marrow et al.	1998
Lighting the way: Perspectives on the Global Lighting Market	McKinsey & Company	2012
Michigan Statewide Commercial and Industrial Lighting Hours-of-Use Study	Michigan Public Service Commission	2014
Adjusting Lighting Levels in Commercial Buildings	Minnesota Department of Commerce	2015
Demand Reduction and Energy Savings Using Occupancy Sensors	National Electrical Manufacturers Association	2001
Energy Savings with Fluorescent and LED Dimming	National Electrical Manufacturers Association	2015
Lighting Controls Terminology	National Electrical Manufacturers Association	2014
Integrated Design Team Guide to Realizing Over 75% Lighting Energy Savings in High-Performance Office Buildings	National Renewable Energy Laboratory	2013
Adding Advanced Behavioural Models in Whole Building Energy Simulation: A Study on the Total Energy Impact of Manual and Automated Lighting Control	National Research Council Canada	2006
Demand-Responsive Lighting : A Field Study	National Research Council Canada	2010
Energy Performance of Daylight-Linked Automatic Lighting Control Systems in Large Atrium	National Research Council Canada	2003

Spaces: Report on Two Field-Monitored Case Studies		
Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study	National Research Council Canada	2007
Advanced Sensors for Intelligent Buildings	Navigant Research	2016
Building Energy Management Systems	Navigant Research	2015
Commercial Building Automation Systems	Navigant Research	2014
Energy Efficient Lighting for Commercial Markets	Navigant Research	2014
High-Bay Lighting	Navigant Research	2014
Industrial and High-Bay Lighting	Navigant Research	2016
Industrial Energy Management Systems	Navigant Research	2015
Intelligent Buildings 10 Trends	Navigant Research	2015
Intelligent Lighting Controls for Commercial Buildings	Navigant Research	2015
Leaderboard Report: Building Energy Management Systems	Navigant Research	2014
LED Lighting: Global Outlook	Navigant Research	2015
Outdoor and Parking Lighting Systems	Navigant Research	2014
Residential Energy Efficient Lighting and Lighting Controls	Navigant Research	2014
Smart Buildings Networking and Communications	Navigant Research	2014
Smart Street Lighting	Navigant Research	2014
Wireless Control Systems for Smart Buildings	Navigant Research	2014
Wireless Power	Navigant Research	2015
Summary Paper on Lighting Controls	New Buildings Institute	Unknown
2014 Commercial Building Stock Assessment: Final Report	Northeast Energy Efficiency Alliance	2014
Luminaire Level Lighting Controls Market Baseline	Northeast Energy Efficiency Alliance	2014
NEEA Study: Technology and Market Assessment of Networked Outdoor Lighting Controls	Northeast Energy Efficiency Alliance	2011
Optimum Lighting Energy Savings with Addressable Dimming Controls	Osram Sylvania	Unknown
Advanced Lighting Control System in an Office Building	Pacific Gas and Electric Company	2013
Hardwired Standby Loads: Lighting Controls	Pacific Gas and Electric Company	2008
Integrated Lighting System Product for Existing Buildings - Market and Economic Analysis for Offices Phase 1	Pacific Gas and Electric Company	2010
Street Lighting Network Controls - Market Assessment Report	Pacific Gas and Electric Company	2010
Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways	Pacific Northwest National Laboratory	2005
Cost-Effectiveness Analysis of Expanding use of Occupancy Sensors	Pacific Northwest National Laboratory	2015

Energy Savings for OccupancyBased Control (OBC) of VariableAir-Volume (VAV) Systems	Pacific Northwest National Laboratory	2013
Exterior Lighting Scoping Study	Pacific Northwest National Laboratory	2011
Retail Lamps Study 3.1: Dimming, Flicker, and Power Quality Characteristics of LED A Lamps	Pacific Northwest National Laboratory	2014
Energy-Efficient Control of Solid-State Lighting	Paradiso et al.	2011
Prevalence and Penetration of Lighting Control Systems in Dubai Buildings: A pointer to Future Measures	R. Gomathi Bhavani and M.A. Khan	2008
Citywide Retrofit Project, Arlington, VA	Revolution Lighting Technologies	2014
Ambient Light Sensor (ALS) Applications in Portable Electronics	Rohm Semiconductor	2009
Tri Tool Advanced Lighting Controls Project	Sacramento Municipal Utility District	2014
High Bay Occupancy Sensors: Delivering Energy Savings and Fast Return on Investment	Sensor Switch	2013
U.S. Energy Savings Potential from Dynamic Daylighting Control Glazings	Shehabi et al.	2013
Getting Plug Loads in Check	Smart Building Center	2015
Measure Information Template – Office Task Lighting Controls	Southern California Edison	2013
Statewide Lighting Market Transformation Program Report	Southern California Edison	2015
Energy Efficient Lighting	State of Michigan	Unknown
Commercial and Industrial Building Lighting Efficiency	Sustainable Energy Association of Australia	2012
Boosting Energy Savings through Lighting Occupancy Control Settings in Multifamily Buildings	Taitem	2012
PIR-Sensor-Based Lighting Device with Ultra-low Standby Power Consumption	Tsai et al.	2011
Daylight Harvesting	United National Development Program	2012
Adaptive Corridor Lighting	University of California, Davis	2013
California's Advanced Lighting Controls Training Program: Building a Skilled Workforce in the Energy Efficiency Market	University of California, Davis	2012
Network Adaptive Exterior Lighting for the Health Care Sector	University of California, Davis	2014
An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems	VonNeida et al.	2000
WattStopper Wireless Exterior Lighting Controls Combined with LED Upgrades Cut Energy Use by 86%	Wattstopper	2015
Lighting Controls (Energy Engineering)	what-when-how.com	Unknown
Quantifying National Energy Savings Potential of Lighting Controls in Commercial Buildings	Williams et al.	2012
Lighting: Occupancy Sensors / Energy Saving Sensors	www.energysavingsensors.com	2010
Effects of Occupancy and Lighting Use Patterns on Lighting Energy Consumption	Yun et al.	2010
Integrated Lighting and Plug Load Controls	Zhang et al.	2012

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