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RENEWABLE ENERGY

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

December 2019

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# Disclaimer

# Comments

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

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# List of Acronyms and Abbreviations

| | |
|---|---|
| AEO | Annual Energy Outlook |
| BR | Bulged Reflector |
| BTU | British Thermal Unit |
| CCT | Correlated Color Temperature |
| CFL | Compact Fluorescent Lamp |
| CFR | Code of Federal Regulations |
| Com | Commercial |
| DALI | Digital Addressable Lighting Interface |
| DLC | DesignLights Consortium |
| DOE | U.S. Department of Energy |
| EIA | U.S. Energy Information Administration |
| EISA | Energy Independence and Security Act |
| EMS | Energy Management Systems |
| EPAct | Energy Policy Act |
| EPCA | Energy Policy and Conservation Act of 1975 |
| GSFL | General Service Fluorescent Lamp |
| HID | High Intensity Discharge |
| HPS | High Pressure Sodium |
| Ind | Industrial |
| IRL | Incandescent Reflector Lamp |
| kWh | Kilowatt-hour |
| LBNL | Lawrence Berkeley National Laboratory |
| LED | Lighting-Emitting Diode |
| LLLC | Luminaire Level Lighting Controls |
| lm | Lumen |
| LMC | Lighting Market Characterization |
| LPS | Low Pressure Sodium |
| MH | Metal Halide |
| MSB | Medium Screw Base |
| MR | Multifaceted Reflector |
| MV | Mercury Vapor |
| NEMS | National Energy Modeling System |
| NEEA | Northwest Energy Efficiency Alliance |
| O&M | Operation and Maintenance |
| Out | Outdoor |
| PAR | Parabolic Aluminized Reflector |
| Quad | Quadrillion British Thermal Units |
| R | Reflector |
| Res | Residential |
| SSL | Solid-State Lighting |
| tBTU | Trillion British Thermal Units |
| TWh | Terrawatt-hour |
| U.S. | United States |
| W | Watt |

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# Executive Summary

In 2017, the total energy consumption in the United States (U.S.) was 96.8 quadrillion British thermal units (BTU), or quads, of primary energy according to the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2018. (1) Roughly 38% of this energy was consumed for electricity use. (1) The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program estimated that in 2017, lighting consumed approximately 6 quads of energy[1] and accounted for 6% of the total energy and 16% of the total electricity consumed in the U.S. in 2017.[2] Light-emitting diodes (LEDs), a type of SSL, are revolutionizing the lighting market. LEDs have surpassed, or matched, all conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and, due to their increasing cost competitiveness, LEDs are successfully competing in a wide variety of lighting applications. Going forward, LED technology is expected to continue to improve, with increasing efficacy and decreasing prices while enabling new opportunities for lighting design and energy savings.

Among its various activities, DOE has supported studies forecasting the market penetration of 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 eighth iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* report, presents the results of the 2018 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 Goals** The future path for SSL given the 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 LED lighting based on historical data and the current trajectory for the technology. The DOE SSL Program Goals scenario estimates the potential future adoption of LED lighting based on what DOE has determined is technically feasible in the given time frame, but would require additional efforts and funds to meet these goals. 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 Goals scenarios.

The model created for this report, the lighting market model, assumes the market adoption of LED lighting technology is driven primarily by projected improvements in product efficacy and price, as well as established technology diffusion rates. In 2017, the lighting market model estimates that LED penetration reached about 19% of all lighting installations, enabling 1.1 quadrillion British thermal units (quads) in energy savings.[1] By the end of the analysis period, LEDs are anticipated to hold the majority of lighting installations in each of the submarkets examined, comprising 84% of all unit installations. Of the submarkets examined, the lighting market model anticipates that the LED penetration will grow the most in low and high bay and linear fixture submarkets between 2017 and 2035. These are submarkets where the LED penetration is currently low but there is significant potential for growth due to potential savings. While those applications experience the largest growth, the area and roadway, parking, and building exterior submarkets are anticipated to have the

[1] Source energy consumption is calculated by multiplying electricity consumption by a source-to-site conversion factor of 3.14. Note: this reference was accessed in July 2018 and reflects the electricity system efficiency at the time of the analysis. (14)

[2] Based on a total electricity consumption of 37.3 quads of source energy for residential, commercial, and industrial sectors from the EIA AEO 2018. (1)

highest LED penetration by 2035. These applications tend to already have high LED penetration, which is expected to grow to near full saturation by 2035. In addition, they are typically high-lumen applications, allowing significant opportunity for energy savings.

If LED lamps and luminaires continue to receive the current levels of SSL investment and effort from DOE and industry stakeholders, LEDs would offer a total annual energy reduction of 4.8 quads. However, given that the more aggressive efficacy targets and connected lighting penetration goals laid out in the DOE SSL R&D Plan are met, an additional annual energy savings reduction of 1.3 quads could be achieved in 2035. The reduced consumption in the residential sector alone would save an average household approximately $15 annually in 2017 and $117 annually in 2035 – a cumulative savings of $1,420 over the 18-year forecast period.[3]

The difference in cumulative energy savings over time between the Current SSL Path and DOE Program Goals is substantial. From 2017 to 2035, a total cumulative energy savings of 78 quads is possible if the DOE SSL Program Goals for LED efficacy and connected lighting are achieved – equivalent to approximately $890 billion in avoided energy costs.[4] Figure ES.1 illustrates that the DOE SSL Program Goals scenario represents additional cumulative energy savings of 16 quads. Therefore, the DOE SSL Program Goals scenario results in a massive increase in total energy savings from LED lighting.

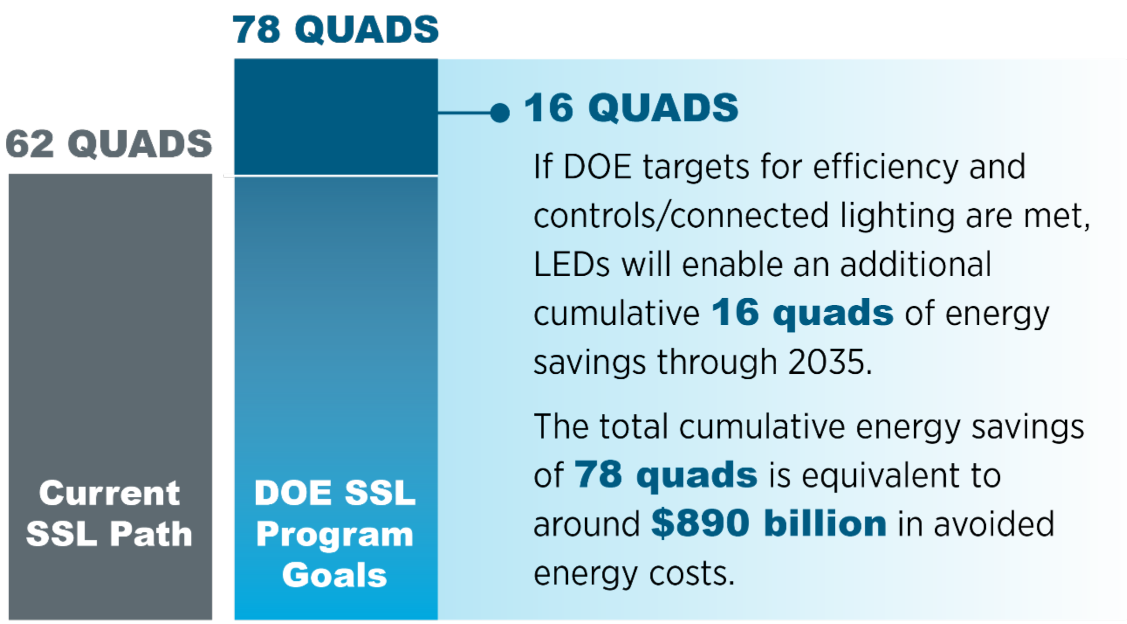


Figure ES.1 U.S. Cumulative Energy Savings Forecast from 2017 to 2035.[5]

Though all forecasts lack certainty, the findings present a plausible outcome of what can be achieved with advanced lighting technology, and will be of use to manufacturers, suppliers, and other stakeholders in the lighting industry as the transition to LED technology moves forward.

[3] This savings calculation is represented in 2017 dollars. The calculation uses the forecasted cost of residential electricity provided by EIA in the Annual Energy Outlook (AEO) 2018. (1) The number of homes nationwide in 2016 is estimated by the U.S. Census to be 131.1 million. The number of homes is assumed to grow at the same rate as residential floorspace, an average of 1.2% per year over the forecast period. (1)

[4] The avoided energy costs are represented in 2017 dollars based on the forecasted cost of electricity provided in the EIA AEO 2018. (1)

[5] All estimates that depend on commercial building electricity consumption are based on the assumption that each commercial building consumes 6,143 kWh of electricity per month in 2017, as estimated by 2018 EIA. (44)

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# 1. Introduction

In 2017, the total energy consumption in the United States (U.S.) was 96.8 quadrillion British thermal units (BTU), or quads, of primary energy according to the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2018. (1) Roughly 38% of this energy was consumed for electricity use. (1) The U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program estimated that in 2017, lighting consumed approximately 6.0 quads of energy[6] and accounted for 6% of the total energy and 16% of the total electricity consumed in the U.S. in 2017.[7] Light-emitting diodes (LEDs), a type of SSL, are revolutionizing the lighting market. LEDs have surpassed, or matched, all conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and, due to their increasing cost competitiveness, LEDs are successfully competing in a wide variety of lighting applications. Going forward, LED technology is expected to continue to improve, with increasing efficacy and decreasing prices while enabling new opportunities for lighting design and energy savings.

This study is the eighth iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* report, hereafter referred to as the "Forecast Report", a 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.[8] 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 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.

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The Current SSL Path scenario estimates the expected future adoption of LED lighting based on historical data and the current trajectory for the technology. The DOE SSL Program Goals scenario estimates the potential future adoption of LED lighting 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 Goals 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 nine steps starting with the development of 2017 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 National

[6] Source energy consumption is calculated by multiplying electricity consumption by a source-to-site conversion factor of 3.14. Note: this reference was accessed in July 2018 and reflects the electricity system efficiency at the time of the analysis. (14)
[7] Based on a total electricity consumption of 37.3 quads of source energy for residential, commercial, and industrial sectors from the EIA AEO 2018. (1)
[8] Past iterations of the Forecast Report are available at: http://energy.gov/eere/ssl/market-studies.

Energy Modeling Systems (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 lighting market 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 Goals 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. 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 and exchange data with other devices.

Additionally, a set of Appendices provide a much deeper dive into the different elements of the analytical approach. An Excel spreadsheet[9] is also provided as a supplement to this report and includes all the report tables, as well as site energy savings results in terms of TWh.

[9] The 2018 Forecast Report Excel Tables can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

# 2. Analytical Approach

The methodology followed in developing the 2018 U.S. lighting market model, hereafter referred to as the "lighting market model", and forecasting aggregate consumer lighting purchases consists of a nine-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), 2015 Lighting Market Characterization (5), the Residential Lighting End-Use Consumption Study (6),[10] Northwest Energy Efficiency Alliance (NEEA) 2014 Commercial Building Stock Assessment (7), and the Adoption of Light Emitting Diodes in Common Lighting Applications referred to hereafter as the "LED Adoption Report" (8), 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 2017.

Step 2: Develop arenas for competition.[11] As depicted in Figure 2.1, the current lighting market model examines eight submarkets across four sectors where a total of 15 lighting technology categories may compete. An "other" technology category was also considered in some submarkets and includes technologies such as plasma and induction lighting. The "other" technology is also included where there is uncertainty in the existing inventory. Additionally, an "other" submarket in each sector accommodates 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). The lighting market model also allows lighting systems to include controls. Within the lighting market model, controls can be single strategy (e.g., dimmers, daylighting, occupancy sensors, and timers), multi-strategy (which combines two or more single control strategies), energy management systems (EMS), or connected lighting.

[10] 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 and 2015 Lighting Market Characterization are used for the operating hour estimates for lighting installed in the commercial, industrial, and outdoor sectors.
[11] Additional detail on how the arenas for competition were developed is included in Appendix A.

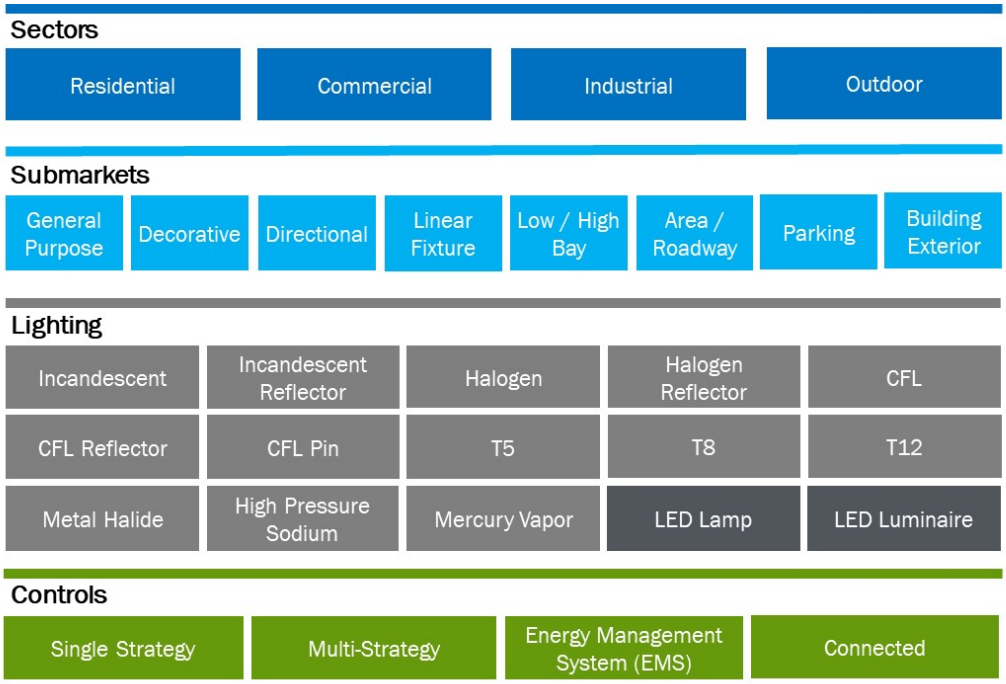


Figure 2.1 Lighting Market Competition Arenas

Step 3: Project annual lighting demand forecast.[12] The EIA AEO 2018 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 specific to each year were used in the lighting market model. Projections suggest that residential floor space will increase by an average of 1.2% per annum over the 18-year analysis period, and the commercial sector floor space will increase by an average of 1.1% per annum. The AEO 2018 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 2018 annual projections for manufacturing employment were used as a proxy for the annual increase in industrial floor space. The data were fit to a best fit curve to smooth out yearly variations. The data indicate an average increase of 0.8% per annum over the 18-year analysis period.

Step 4: Calculate the available market.[13] 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 probability distribution,[14] 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. (9)

Step 5: Project conventional and LED lighting technology improvement.[15] 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

[12] Additional detail on how the annual lighting demands were calculated can be found in Appendix B.
[13] Additional detail on how the market turnovers were calculated can be found in Appendix B.
[14] 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. (44)
[15] Additional detail on how the cost and efficacy improvements were determined can be found in Appendix C and Appendix D.

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 DesignLights Consortium Qualified Products) and prices of LED products available for purchase that have systematically been collected regularly 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.[16] 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 lighting market 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. (10; 11)

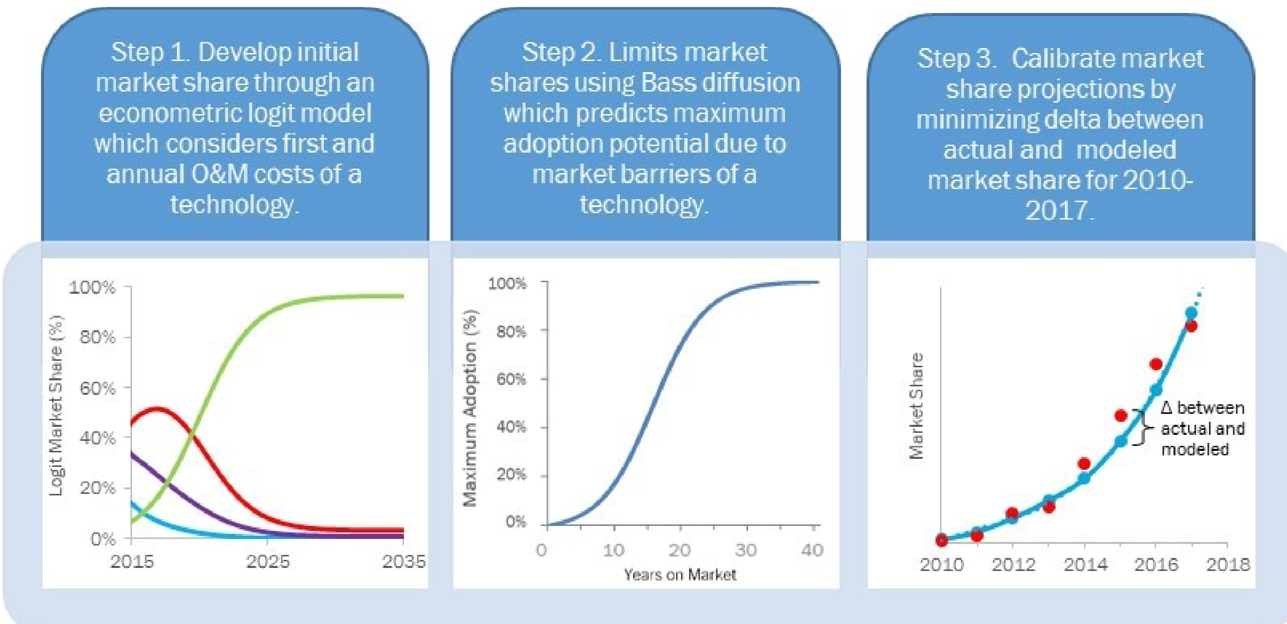


Figure 2.2 Market Share Modeling Approach

Step 7: Model the market share and energy savings of lighting controls.[17] 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.[18]

[16] Additional detail on the logit model, the diffusion curve, and the calibration can be found in Appendix E.
[17] Additional detail on the lighting controls methodology can be found in Appendix F.
[18] 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.

## 2.1. Lighting Market Model Enhancements

Input data was updated for most model inputs based on increased data availability. In addition to these updated input data, this iteration of the general illumination forecast improves upon the methodology used in past years' iterations in multiple ways. These enhancements are outlined below:

1. Calibration based on estimated LED market share for years 2010-2017. The last iteration of this lighting market model was calibrated using LED market share data for years 2010 through 2015. With two more years of complete LED market data available, this lighting market model offers improved calibration to historical data and trends, and thus effectively improves the accuracy of model predictions.

2. Calibration based on 2015 LMC Stock. In this Forecast Report and in past years, the lighting market model used the 2010 LMC as its basis for initial stock in 2010. Additionally, for this Forecast Report, the 2015 LMC stock values for all technologies were used during the calibration process to inform growth trends by technology and adjust 2010 stock as needed.

3. Added supplemental spreadsheet of tables. This year's report includes a supplemental spreadsheet with all the tables included in the report. [19]

4. Changed LED lumen output over time. It was previously assumed that the lumen output for each lighting technology is constant over the analysis period (2017-2035). This assumes that, as conventional lighting systems fail, they are replaced with LED lamps or luminaires of equivalent light output in all applications. However, historical data have shown an increase in per-unit LED lighting output, thought to be due to the increasing ability of LED technology to cost-effectively reach higher lumen output applications. The lighting market model assumes LED lumen output will continue to increase over time until it reaches the average of the conventional technologies it competes against within a given submarket.

5. Addition of LED luminaires into general purpose submarkets. In past iterations of this report, it was assumed that LED luminaires would not be used in general purpose applications. Based on increased data availability, this assumption was updated with the understanding that LED luminaires are viable options for general purpose applications and will penetrate these submarkets.

## 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. Each assumption may 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. Renovations rate. The lighting market model assumes a constant 10% per year rate of lighting fixture replacements due to renovations of the installed base. (9) 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 is based on increasing concerns regarding energy consumption, as well as the growing prevalence of utility and

[19] The 2018 Forecast Report Excel Tables can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

government incentive programs that compensate consumers who retrofit using LED lighting products.[20] (12)

2. 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.

3. 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 newer market entrants, such as LED technologies, as it is these technologies that may have initially been unknown to consumers or may have not been 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 can 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 LED lighting based on the historical rate of penetration of other lighting and controls technologies.

4. Lighting controls assumptions. There is wide variation in the types of lighting controls available and the ways in which they operate. Therefore, the lighting market model makes its best attempt to capture the major strategies and control effects that are currently employed. For example, each traditional control strategy is limited to either having the effect of reducing wattage or turning lights off, whereas in practice some traditional control types, such as daylighting, may have either or both capabilities. Additionally, each control strategy encompasses a range of subcategories and attempts to estimate the average use for all subcategories in aggregate.

5. Changes in lumen output assumptions. The average light output of LED lighting products has increased significantly and consistently since LED products were first introduced. The lighting market model attempts to quantify these trends using logarithmic growth models based on historical product specification data provided by the DesignLights Consortium™ (DLC), ENERGY STAR® and LED Lighting Facts program. While there have been studies published showing the physiological effects of lighting on humans (13), including potential to influence sleep patterns and productivity, the lighting market model does not attempt to quantify these aspects. Furthermore, it is important to recognize that these recent human physiological discoveries have not yet influenced the light levels of products entering the lighting market. Rather, the increase in per-unit light output seen in the historical data is thought to be due to the increasing ability of LED technology to cost-effectively reach higher lumen output applications. In addition, while the lighting market model assumes LED light output has historically increased via a logarithmic growth trend, it is not certain whether the average per-unit light output will continue to increase. Therefore, the model only projects future increases in LED light output if, as of 2017, it is below the average of the conventional technologies it competes against within a given submarket.

6. Conversion of source energy to site electricity. Source-to-site conversion efficiency, which represents the efficiency of electricity production and delivery, is assumed to remain at a constant value of 3.14 throughout the forecast period. (14) Since the metric describes efficiency of electricity generation, it is

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

plausible that the efficiency could increase due to new or improved technologies. However, given the level of uncertainty, no attempt is made to quantify these changes in the lighting market model.

7. Other future uncertainties. There is 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.

    a. Rebound effect – Users may increase their daily lighting usage because the operating cost is cheaper.

    b. New technology – OLED lighting, laser lighting, or another unforeseen technology may be introduced or gain significant market share.

    c. Government actions – Government actions, such as new efficiency standards or tax incentives could affect the future adoption of LED lighting products.

# 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 84% and 91% of the 2017 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 lighting energy costs remain low. Therefore, residential consumers place a high priority on low first cost when purchasing lighting products.

### 3.1.1. General Purpose Submarket

The general purpose submarket includes standard A-shape incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs), LED luminaires, 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 general purpose 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.[21]

LED replacement lamps in the general purpose 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 2017, the average LED-based dimmable A19 60 W-equivalent replacement lamp price was $5.90 per bulb ($7.74/klm). While this is still more expensive than conventional incandescent or CFLs, rebates and incentives have and can further reduce the price to below $2 or $3 per lamp.

### 3.1.2. Decorative Submarket

Decorative is a generic term 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. Manufactures have developed 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 increasingly popular as they offer an aesthetic appearance as well as a significant energy savings benefit compared to

[21] 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 40 W, 60 W, 75 W, and 100 W medium screw based incandescent light bulbs. More information can be found at: http://energy.gov/eere/buildings/appliance-and-equipment-standards-program

incandescent products. Additionally, fully integrated decorative LED luminaires, which typically 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 not prevalent 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 appearance 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, and 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 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., parabolic aluminized reflector (PAR), bulged reflector (BR), and reflector (R) lamps), pin-based CFLs, as well as LED lamps and luminaires are most commonly used. The lighting market 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 life-cycle 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.[22] 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. (15) 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

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

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 approximately 31% 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 life-cycle costs, with efficacies as high as 108 lm/W and prices as low as $4/klm. (2)

### 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 T8 lamps, have become a major player due to their superior lumen maintenance and enhanced control options.

Only recently have technological and cost improvements allowed LEDs to significantly penetrate the market. 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 10,000 listed low and high bay luminaire products, 56% of which emit over 15,000 lumens and 21% of which emit more than 25,000 lumens.[23] In addition, while less efficient than LED luminaire options, LED retrofit lamps designed for direct replacement for HID and fluorescent lamps are 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 forecasts 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 building exterior 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, lifetime, and reducing energy use, as well as the growing interest in connected and smart city infrastructure, LED lighting is a particularly attractive option.

### 3.2.1. Area and Roadway Submarket

Area and roadway luminaires serve to illuminate outdoor areas 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. In addition, 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. Because of these advantages, many local

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

jurisdictions have initiated projects to completely transition their area and roadway lighting to LEDs. For example, the City of Los Angeles has completed a citywide street lighting replacement program and has installed over 170,000 LED street lights, reducing energy usage by 64%, and saving $9 million in annual energy costs. (16) Similarly, the City of Chicago announced in December 2016 its plans to convert over 270,000 street lights to LEDs by 2021, with over 18,000 already installed as of July 2018. (17) In addition, both Los Angeles and Chicago have been installing "smart" LED lighting with advanced lighting controls and connective features which have led to several non-energy benefits such as reduced 311 calls, reduced street light outage response time, improved asset management, and increased cellphone coverage.

### 3.2.2. Parking Submarket

In this analysis, the parking lighting submarket has been divided into parking lots and covered garages. It 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 street lighting, as these applications 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 street lighting 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.[24] For example, a 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. (18)

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 many 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. LED lighting is well suited for use with control systems and have been shown to provide additional energy savings of 20% to 60% depending on the application and use-case. (19) Due to this large energy savings potential of lighting controls, in the most recent Title 24 building code[25] the state of California expanded its requirements for the use of advanced dimming controls, along with occupancy and daylight sensors. As a result, lighting in parking garages in California must have occupancy controls, with power required to reduce by a minimum of 30% when there is no activity detected within a lighting zone for 20 minutes. (20) While these building code requirements are currently only in California, if additional local and state governments adopt similar building code requirements this represents an opportunity for LEDs to help impact energy savings in parking garage applications across the U.S.

### 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 energy performance have made them increasingly viable options. Since LED products can also offer low-profile lighting, this has made installation easier in areas with tight clearance and

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

offers building managers and specifiers more effective options for lighting narrow areas, such as under benches or accent planters. These small form-factors and the ability to precisely place light sources can result in less light pollution in building exterior applications. LED products may also offer better wall-washing or wall grazing options for building façades through color tunability and better controllability, thus making them a top choice over incumbent sources. 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 2017, the total energy consumption in the United States was 96.8 quads of primary energy according to the EIA AEO 2018. (1) Roughly 37.3 quads, or 38%, of this energy was consumed for electricity use. (1) DOE estimated that in 2017, there were 7.6 billion lighting units[26] installed in the U.S., and that they consumed approximately 6 quads of energy annually.[27] Thus, lighting accounted for 6% of the total energy and 16% of the total electricity consumed in the U.S. in 2017.[28]

The results presented in this section cover years 2017 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 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 Goals** The future path for SSL given the 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 LED lighting based on historical data and the current trajectory for the technology. The DOE SSL Program Goals scenario estimates the potential future adoption of LED lighting 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 Goals scenarios.

Figure 4.1 illustrates the increasing installed stock broken out by technology for the Current SSL Path scenario. In 2017, LED lighting makes up about 19% of the total installed stock, and it is projected that the installed penetration of LED lamps and luminaires will increase dramatically through 2035 to reach about 84%.

[26] 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.
[27] Source energy consumption is calculated by multiplying electricity consumption by using a source-to-site conversion factor of 3.14. (14)
[28] Based on a total electricity consumption of 37.3 quads of source energy for residential, commercial, and industrial sectors from the EIA AEO 2018. (1)

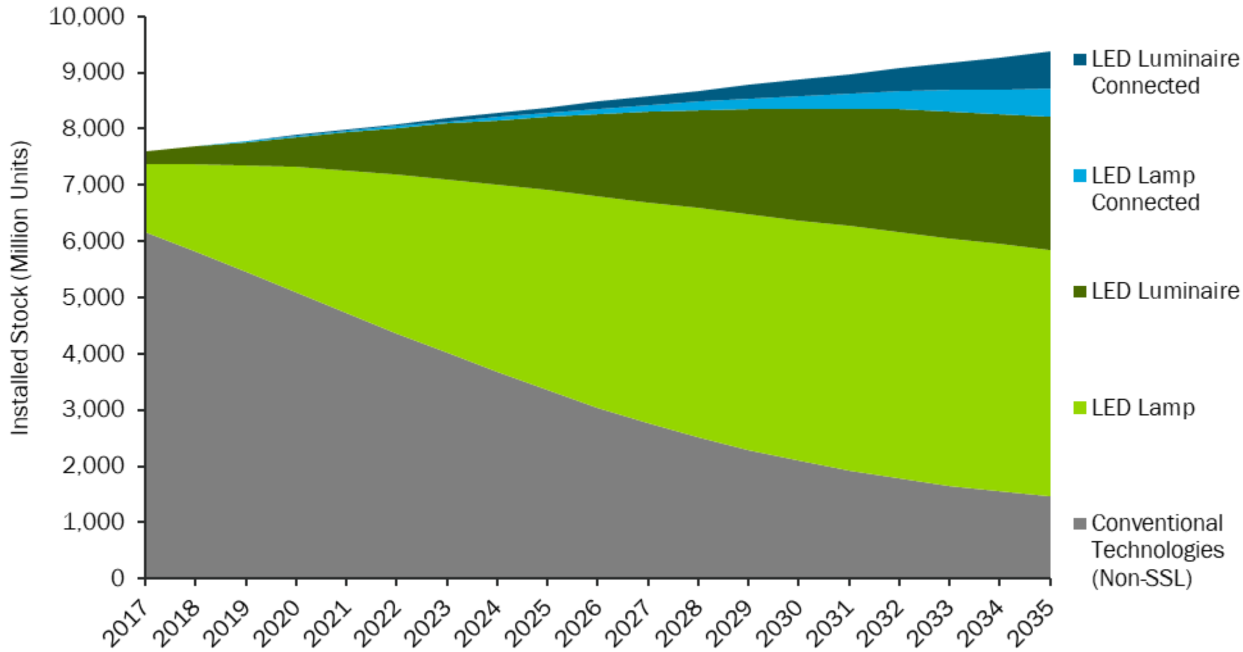


**Figure 4.1 Total U.S. Installed Stock Projections for the Current SSL Path Scenario. In 2017, LED lighting makes up about 19% of the overall installed stock, and it is projected that the installed penetration of LED lamps and luminaires will increase dramatically through 2035 to reach about 84%.**

Below, Figure 4.2 through Figure 4.5 provide a more detailed breakdown of the data underlying Figure 4.1. Specifically, the plots show how installed stock by technology changes over time in each sector.

Following the residential sector, the commercial sector has the second largest installed lighting stock, which is represented in Figure 4.2. The commercial sector accounts for 16% of all lighting installations nationwide in 2017. The most common conventional technologies used in the commercial sector are linear fluorescent, CFL, incandescent, metal halide, and halogen. However, because of the increasing prevalence of LEDs, the installed stock of conventional technologies consistently declines throughout the forecast period. When looking at the growth of connected lighting, the stock of non-connected LED lighting peaks in 2029, at which point connected lighting increases in prevalence through the end of the forecast period to 28% by 2035.

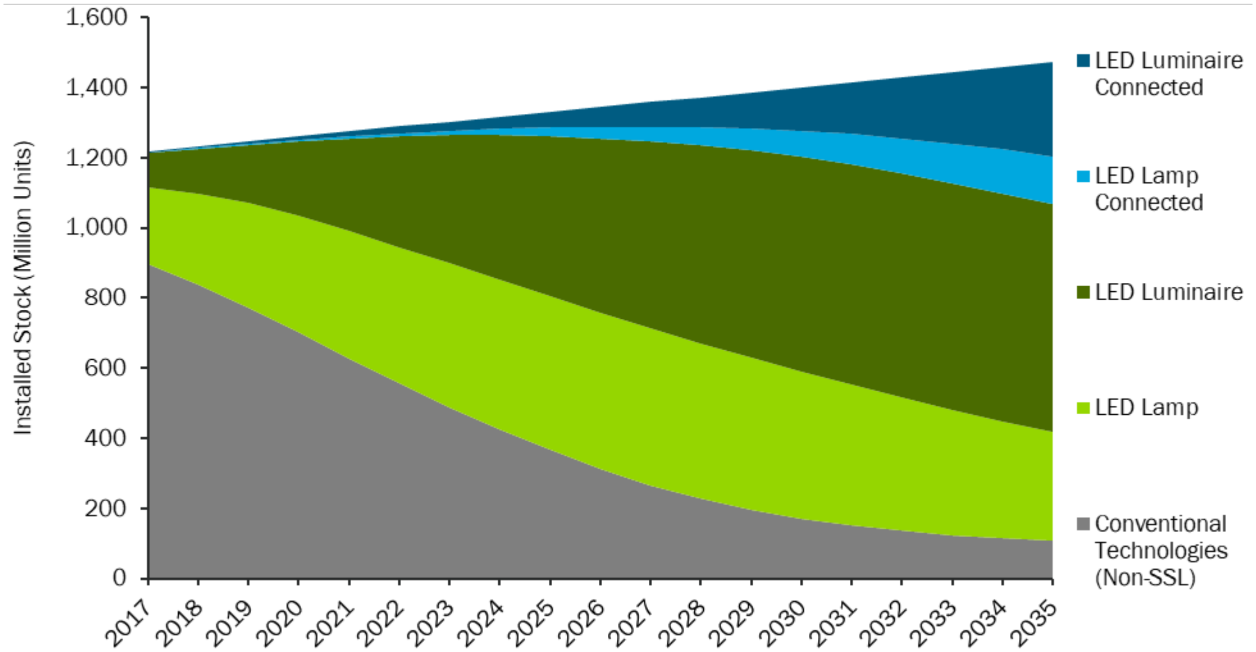


**Figure 4.2 Commercial Building Sector Installed Stock Projections for the Current SSL Path Scenario. In this sector, the stock of non-connected LED lighting peaks in 2029, at which point connected lighting increases in prevalence through the end of the forecast period to 28% by 2035.**

The installed stock data shown in Figure 4.2 is further disaggregated in Table 4.1 below.

**Table 4.1 Commercial Building Sector Installed Stock Projections for the Current SSL Path Scenario (Million Lamp Systems)**

| Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Incandescent | 28 | 11 | 5 | 4 | 3 |
| Halogen | 9 | 3 | 1 | 1 | 1 |
| CFL | 96 | 43 | 16 | 10 | 8 |
| Linear Fluorescent | 736 | 626 | 336 | 152 | 94 |
| Other | 3 | 2 | <1 | <1 | <1 |
| Metal Halide | 24 | 16 | 7 | 3 | 2 |
| LED Lamp | 219 | 334 | 438 | 419 | 309 |
| LED Luminaire | 101 | 211 | 457 | 612 | 649 |
| LED Lamp Connected | <1 | 5 | 25 | 75 | 136 |
| LED Luminaire Connected | 2 | 8 | 44 | 125 | 272 |
| Total | 1,218 | 1,260 | 1,331 | 1,401 | 1,474 |

As shown in Figure 4.3, residential has, by far, the largest stock of any sector – over 80% of all installations nationwide. Despite consistent growth in stock, a steady, nearly linear decline in conventional technologies is expected between 2017 and 2035. The most common conventional technologies used in the residential sector are CFL, incandescent, halogen, and linear fluorescent. Growth is expected in both connected and non-connected LED lighting, though non-connected LED lamps increasingly become the most significant contributors to installed stock. By 2035, non-connected LED lamps are expected to make up 54% of the residential sector stock while conventional technologies will remain notably more dominant than in other sectors, maintaining 18% installed penetration with over 1.34 billion units.

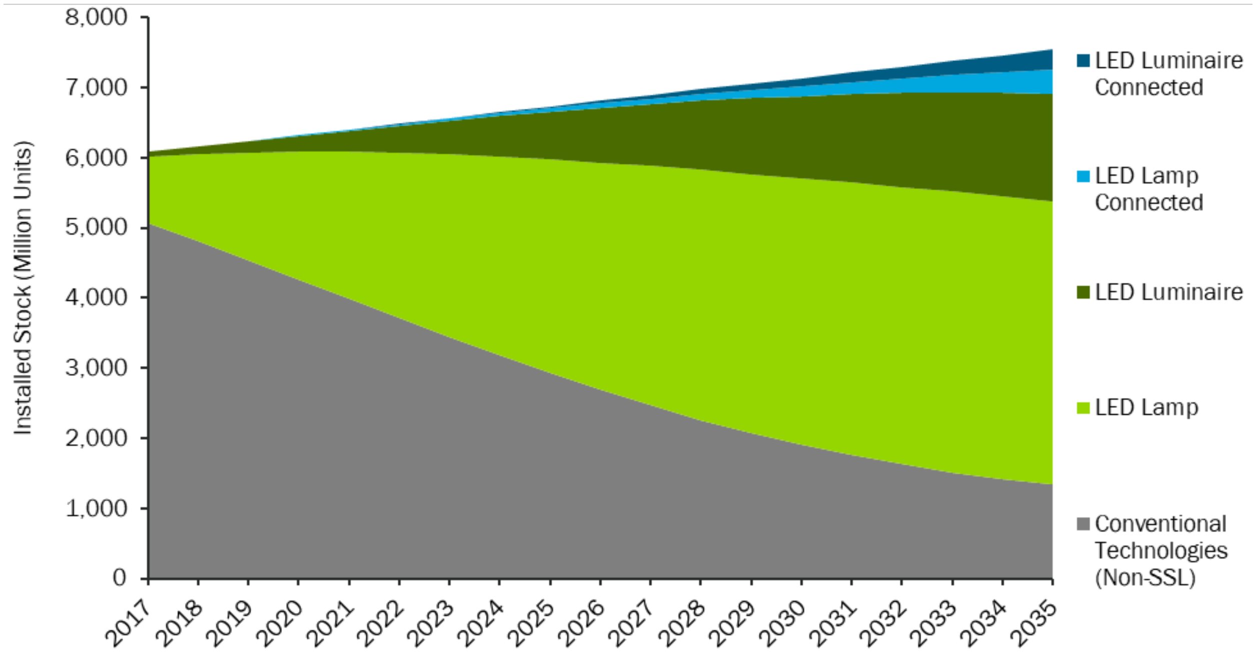


**Figure 4.3 Residential Building Sector Installed Stock Projections for the Current SSL Path Scenario. It is expected that a constant decline in conventional technologies will occur throughout the forecast period, with non-connected LED lamps expected to reach 54% by 2035.**

The installed stock data shown in Figure 4.3 is further disaggregated in Table 4.2 below.

**Table 4.2 Residential Building Sector Installed Stock Projections for the Current SSL Path Scenario (Million Lamp Systems)**

| Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Incandescent | 1,876 | 1,579 | 1,102 | 718 | 483 |
| Halogen | 897 | 626 | 416 | 315 | 263 |
| CFL | 1,995 | 1,784 | 1,219 | 750 | 510 |
| Linear Fluorescent | 250 | 229 | 168 | 109 | 72 |
| Other | 42 | 39 | 28 | 16 | 9 |
| Mercury Vapor | <1 | <1 | <1 | <1 | <1 |
| Metal Halide | <1 | <1 | <1 | <1 | <1 |
| HPS | <1 | <1 | <1 | <1 | <1 |
| LED Lamp | 949 | 1,828 | 3,046 | 3,800 | 4,038 |
| LED Luminaire | 78 | 221 | 677 | 1,175 | 1,535 |
| LED Lamp Connected | 2 | 10 | 49 | 144 | 344 |
| LED Luminaire Connected | <1 | 4 | 29 | 109 | 290 |
| Total | 6,090 | 6,321 | 6,734 | 7,135 | 7,544 |

Trends in the industrial sector installed stock are shown in Figure 4.4. The most common conventional technologies used in the industrial sector are linear fluorescent, metal halide, and HPS. Changes in technology mix are similar to those in the commercial sector, though the industrial sector has a far less significant impact on energy consumption due to the relatively small stock. There are nearly 15 times more lighting products installed in the commercial sector than the industrial sector.

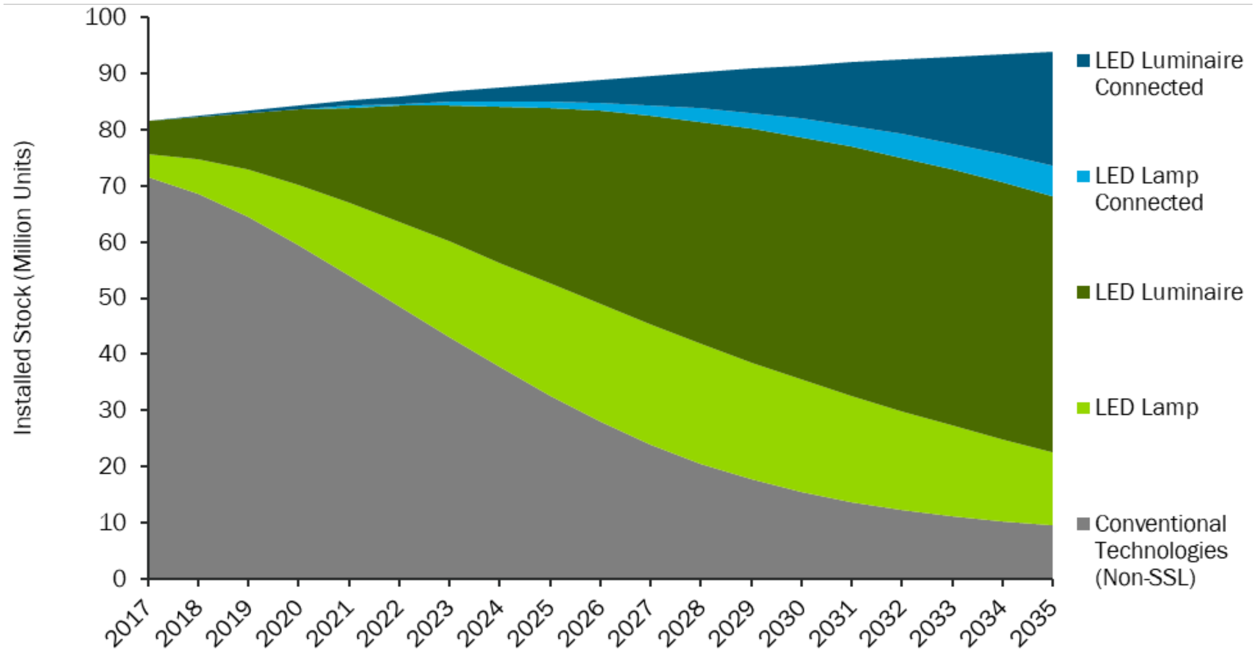


**Figure 4.4 Industrial Building Sector Installed Stock Projections for the Current SSL Path Scenario. Changes in technology mix are similar to those in the commercial sector, though the industrial sector has a far less significant impact on energy consumption due to the relatively small stock.**

The installed stock data shown in Figure 4.4 is further disaggregated in Table 4.3 below.

**Table 4.3 Industrial Building Sector Installed Stock Projections for the Current SSL Path Scenario (Million Lamp Systems)**

| Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Linear Fluorescent | 62 | 52 | 29 | 13 | 8 |
| Metal Halide | 7 | 6 | 3 | 2 | <1 |
| HPS | 2 | 2 | <1 | <1 | <1 |
| LED Lamp | 4 | 11 | 20 | 20 | 13 |
| LED Luminaire | 6 | 13 | 31 | 43 | 46 |
| LED Lamp Connected | <1 | <1 | 1 | 3 | 5 |
| LED Luminaire Connected | <1 | <1 | 3 | 9 | 20 |
| Total | 82 | 84 | 88 | 91 | 94 |

Figure 4.5 shows changes in the outdoor sector installed stock of lighting. The most common conventional technologies used in the outdoor sector are HPS, metal halide, CFL, halogen, incandescent, and mercury vapor. However, LED lighting quickly becomes the most prevalent technology with conventional lighting technologies – mainly metal halide and HPS – predicted to comprise less than 10% of all installations by 2025. The outdoor sector is also unique because it has the highest installed penetration of connected lighting throughout the entire forecast period, totaling 33% by 2035. Similarly, the outdoor sector has the highest installed penetration of LED lighting for all years between 2017 and 2035.

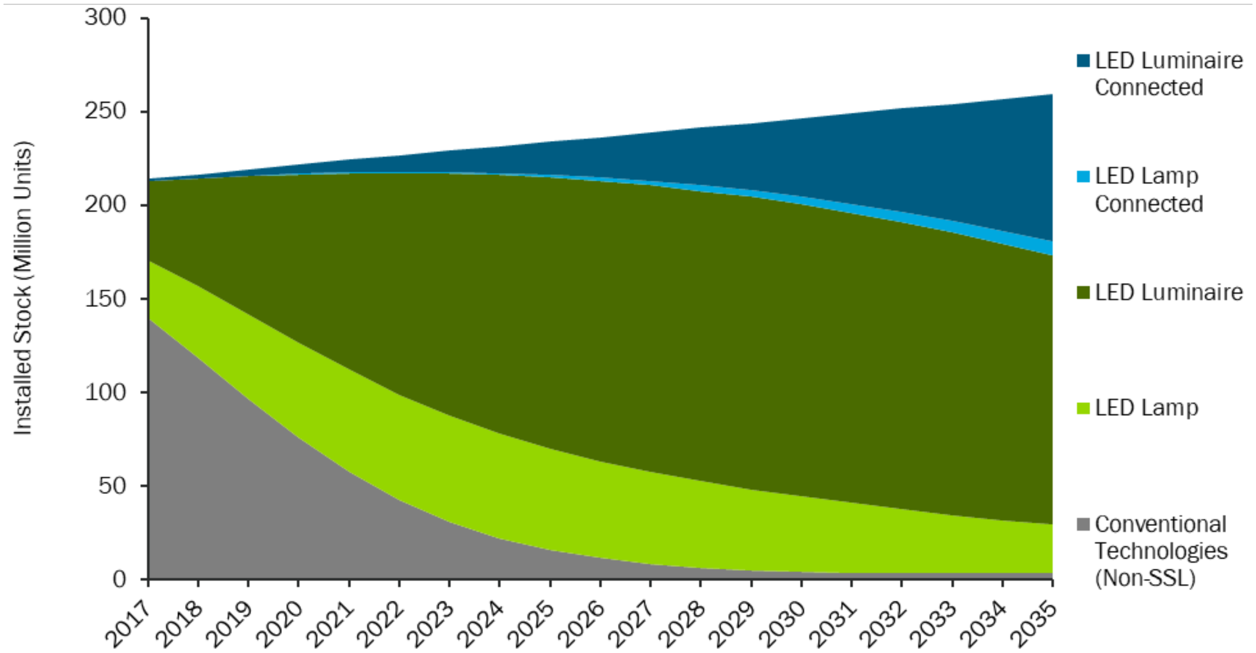


**Figure 4.5 Outdoor Sector Installed Stock Projections for the Current SSL Path Scenario. The outdoor sector has the highest installed percentage of LED and connected lighting of the four sectors analyzed.**

The installed stock data shown in Figure 4.5 is further disaggregated in Table 4.4 below.

**Table 4.4 Outdoor Sector Installed Stock Projections for the Current SSL Path Scenario (Million Lamp Systems)**

| Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Incandescent | 3 | <1 | <1 | <1 | <1 |
| Halogen | 4 | 1 | <1 | <1 | <1 |
| CFL | 9 | 4 | <1 | <1 | <1 |
| Other | 10 | 5 | <1 | <1 | <1 |
| Mercury Vapor | 1 | <1 | <1 | <1 | <1 |
| Metal Halide | 43 | 24 | 5 | 2 | 1.8 |
| HPS | 46 | 26 | 5 | <1 | <1 |
| LPS | <1 | <1 | <1 | <1 | <1 |
| LED Lamp | 31 | 50 | 54 | 40 | 26 |
| LED Luminaire | 42 | 90 | 145 | 156 | 144 |
| LED Lamp Connected | <1 | <1 | 2 | 4 | 8 |
| LED Luminaire Connected | 1 | 5 | 18 | 42 | 78 |
| Total | 214 | 222 | 234 | 246 | 259 |

When considering all sectors – commercial, residential, industrial and outdoor – combined, lighting installations increase by about 1.3% annually (up from 7.6 billion in 2017 to 9.4 billion in 2035). Looking to the following Table 4.5, 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 72% of LED installations in all sectors in 2017 and growing to 79% by 2035. However, in terms of forecasted 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 forecasted LED energy savings. Despite representing only 17% of LED installations in all sectors in 2035, the commercial sector will provide 39% of all LED energy savings.

Table 4.5 U.S. LED Forecast Stock Results for the Current SSL Path Scenario

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)** | **1,440** | **2,790** | **5,040** | **6,780** | **7,910** |
| | Commercial | 322 | 558 | 964 | 1,230 | 1,370 |
| | Residential | 1,030 | 2,060 | 3,800 | 5,230 | 6,210 |
| | Industrial | 10 | 25 | 56 | 76 | 84 |
| | Outdoor | 75 | 146 | 218 | 242 | 256 |
| | **LED Installed Stock Penetration (%)** | **19%** | **35%** | **60%** | **76%** | **84%** |
| | Commercial | 26% | 44% | 72% | 88% | 93% |
| | Residential | 17% | 33% | 56% | 73% | 82% |
| | Industrial | 12% | 29% | 63% | 83% | 90% |
| | Outdoor | 35% | 66% | 93% | 98% | 99% |

1. Installed stock for the DOE SSL Program Goals 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).

Despite the growing installed stock, the lighting market model forecasts that LED adoption will lead to a continued reduction in energy use over time. As shown by the Current SSL Path scenario in Table 4.6, LED lighting already offers 1.1 quads, or 1,110 trillion BTU (tBTU) of energy savings in 2017. If the lighting market continues along the Current SSL Path scenario, a total annual energy savings of 4.8 quads is possible by 2035, of which 12% is made possible by the penetration of connected LED lighting.

Compared to the Current SSL Path scenario, the DOE SSL Program Goals scenario offers a different view for the future of LED technology. Because adoption in the lighting market model is driven primarily by first cost 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 Goals scenario is slightly higher, reaching 87% by 2035). The primary difference between the two is the resulting energy savings due to penetration of lighting controls, particularly connected versus non-connected LED lighting, and increased LED product efficacy.

The increase in connected lighting penetration[29] 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 Goals scenario. As can be calculated using Table 4.6, if the DOE targets are met, LED lighting will enable an additional 1.3 quads in annual energy savings in 2035.

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

Table 4.6 U.S. LED Forecast Energy Savings Scenario Comparison

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)[30]** | **1,110** | **1,980** | **3,260** | **4,130** | **4,820** |
| | Commercial | 457 | 716 | 1,190 | 1,570 | 1,900 |
| | Residential | 171 | 371 | 719 | 1,030 | 1,270 |
| | Industrial | 36 | 94 | 216 | 309 | 372 |
| | Outdoor | 444 | 802 | 1,130 | 1,220 | 1,270 |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **1,140** | **2,310** | **4,160** | **5,380** | **6,130** |
| | Commercial | 468 | 872 | 1,670 | 2,250 | 2,590 |
| | Residential | 171 | 426 | 844 | 1,200 | 1,460 |
| | Industrial | 39 | 120 | 291 | 412 | 488 |
| | Outdoor | 462 | 896 | 1,350 | 1,510 | 1,580 |

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 only 3.4 quads annually by 2035. However, 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 1.3 quads in 2035.

The total energy savings opportunity across all sectors 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 consumers. With these three submarkets leading the charge, LED lighting installed with traditional control strategies or connected capabilities will contribute to a significant portion of the forecasted energy savings. In 2017, the total energy savings opportunity from the DOE SSL Program Goals scenario is 1.1 quads. Of the total 6.1 quads in annual energy savings in 2035, 16% is made possible by the penetration of connected LED lighting.

The difference in cumulative energy savings over time between the Current SSL Path and DOE Program Goals is substantial, and Figure 4.6 illustrates that the DOE SSL Program Goals scenario represents additional cumulative energy savings of 16 quads. Therefore, the DOE SSL Program Goals scenario results in a massive increase in total energy savings from LED lighting.

[30] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

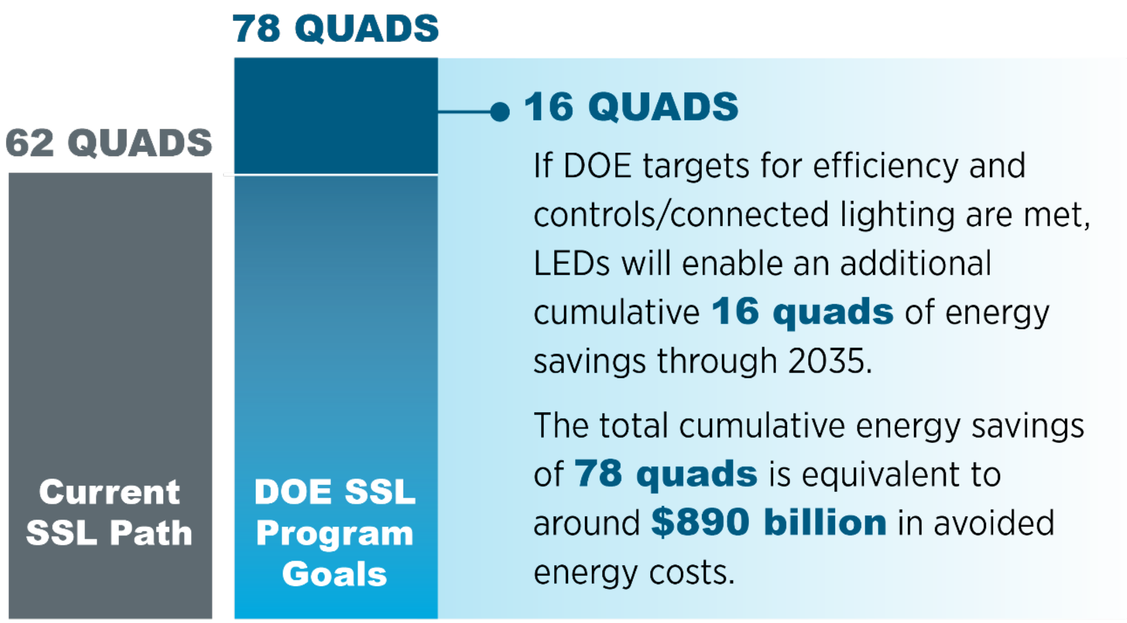


Figure 4.6 U.S. Cumulative Energy Savings Forecast from 2017 to 2035

## 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 (EMS), 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 and exchange data with other devices.

Given the above definition, it is assumed that connected control systems are exclusive to LED lighting and are not available with conventional lighting technologies (i.e., incandescent, halogen, fluorescent and HID). However, for all other control systems including single-strategy, multi-strategy, and EMS, any lighting technology can be employed.

In the Current SSL Path and DOE SSL Program Goals 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 dimmable linear fluorescent ballasts and DALI (Digital Addressable Lighting Interface) systems, resulting in a slower 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 LED luminaires.*

- The **DOE SSL Program Goals** 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 LED luminaires.*

Table 4.7 summarizes the 2017 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 Goals scenarios.[31]

Table 4.7 2017 Installed Stock Penetration of Lighting Controls for Both Scenarios

| Installed Stock Penetration (%) | Commercial | Residential | Industrial | Outdoor |
|---|---|---|---|---|
| None | 66% | 86% | 93% | 13% |
| Dimmer | 3% | 11% | 4% | 4% |
| Daylighting | <1% | <1% | <1% | 53% |
| Occupancy Sensor | 6% | <1% | 2% | 17% |
| Timer | 4% | <1% | <1% | 12% |
| Multi | 4% | <1% | <1% | <1% |
| EMS | 16% | <1% | <1% | <1% |
| Connected | <1% | <1% | <1% | <1% |

The lighting market model estimates that the use of traditional single, multi-strategy, and EMS resulted in about 0.6 quads of energy savings in 2017 – or a roughly 9% reduction in overall lighting energy consumption. Currently, the largest portion of energy savings from controls is derived from EMS in the commercial sector, representing 0.28 quads or about half of the total. This is followed by commercial occupancy sensors at 0.06 quads or about 11% of all 2017 lighting control energy savings. Penetration of these more traditional 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 EMS 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.

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

**Progress Towards the DOE SSL Program Goals Scenario**

As shown in subsequent tables and figures, there is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of energy savings as well as connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.

Table 4.8 presents the forecasted installed penetration of connected LED luminaires (as compared to non-connected) for each scenario. In the DOE SSL Program Goals scenario, connected LED luminaires reach an overall installed stock more than double the size achieved in the Current SSL Path scenario in 2035 (56% and 22%, respectively).

Table 4.8 Installed Penetration of Connected LED Luminaires (Relative to Non-Connected)

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Installed Stock Penetration (%)** | **2%** | **3%** | **7%** | **13%** | **22%** |
| | Commercial | 2% | 4% | 9% | 17% | 30% |
| | Residential | <1% | 2% | 4% | 9% | 16% |
| | Industrial | 2% | 4% | 9% | 18% | 31% |
| | Outdoor | 3% | 5% | 11% | 21% | 35% |
| DOE SSL Program Goals | **Installed Stock Penetration (%)** | **13%** | **21%** | **31%** | **42%** | **56%** |
| | Commercial | 16% | 32% | 54% | 70% | 79% |
| | Residential | <1% | 2% | 7% | 20% | 41% |
| | Industrial | 20% | 35% | 55% | 70% | 78% |
| | Outdoor | 26% | 39% | 60% | 75% | 82% |

While the lighting market 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 4.9, 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 4.9 Installed Penetration of Connected LED Lamps (Relative to Non-Connected)

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Installed Stock Penetration (%)** | **<1%** | **<1%** | **2%** | **5%** | **10%** |
| | Commercial | <1% | 1% | 5% | 15% | 31% |
| | Residential | <1% | <1% | 2% | 4% | 8% |
| | Industrial | <1% | 2% | 5% | 14% | 29% |
| | Outdoor | <1% | <1% | 3% | 10% | 23% |
| DOE SSL Program Goals | **Installed Stock Penetration (%)** | **<1%** | **<1%** | **3%** | **8%** | **21%** |
| | Commercial | <1% | 1% | 6% | 16% | 33% |
| | Residential | <1% | <1% | 2% | 7% | 20% |
| | Industrial | <1% | 2% | 6% | 15% | 31% |
| | Outdoor | <1% | <1% | 3% | 10% | 25% |

While the above Table 4.8 and Table 4.9 show the increase in connected LED lighting relative to the total population of installed LED lamps and luminaires, Figure 4.7 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 Goals scenario, where adoption of connected LED lighting is accelerated, this equates to an overall penetration of 30% (connected LED lamps and luminaires combined) of the U.S. lighting stock while LED lighting with traditional lighting controls represents 14%.

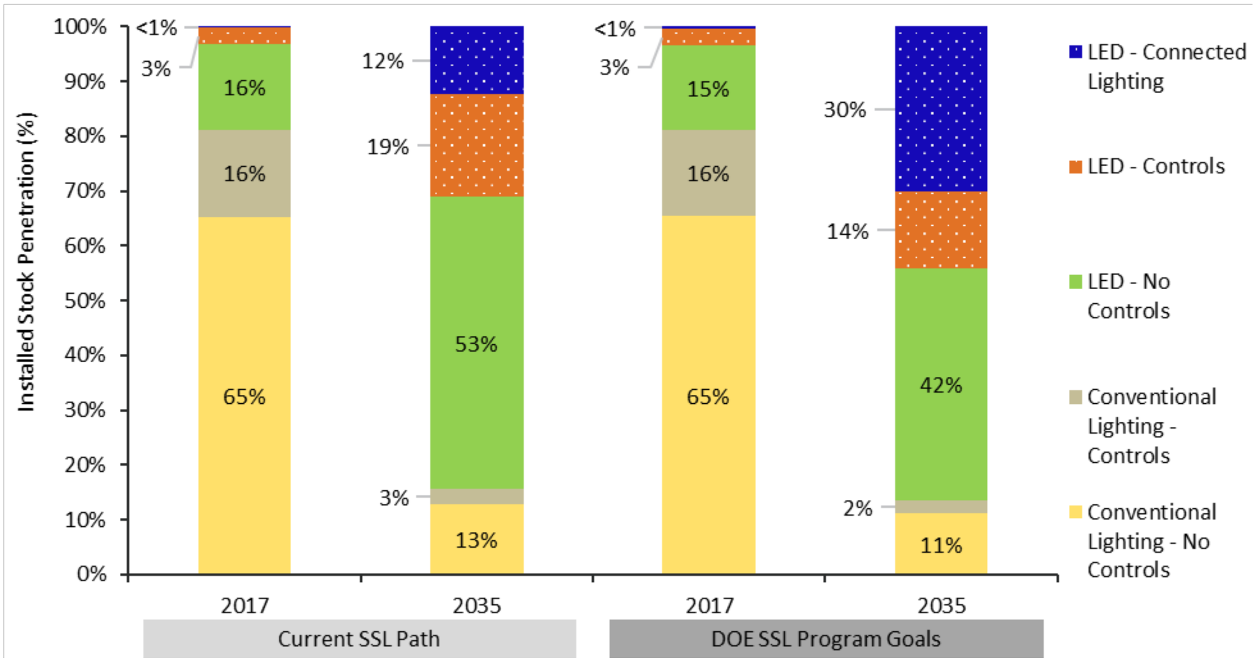


Figure 4.7 Lighting Controls Installed Penetration for LED Lighting vs. Conventional Lighting

As seen in Figure 4.7, 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 4.10, for the Current SSL Path scenario, connected lighting penetration is lower. However, in total, lighting controls still result in an annual energy savings of 1,050 tBTU, or 98 TWh, by 2035 – roughly half of this is attributed to connected LED lighting.

In the DOE SSL Program Goals scenario, the 2035 forecasted annual energy savings from lighting controls increases to 1,350 tBTU (126 TWh) or roughly 1.3 quads. Connected LED lighting in this scenario is responsible for about 74% of the 2035 lighting controls energy savings, or 1,004 tBTU, equivalent to 1 quad. By avoiding 1 quad of annual energy consumption, connected LED lighting would save the U.S. over $10 billion in energy costs.

Table 4.10 Annual Energy Savings from Lighting Controls by Sector for Each Scenario[1]

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Annual Energy Savings (tBTU)[32]** | **555** | **548** | **575** | **741** | **1,050** |
| | Commercial | 425 | 430 | 431 | 522 | 711 |
| | Residential | 10 | 9 | 10 | 14 | 24 |
| | Industrial | 8 | 11 | 25 | 49 | 77 |
| | Outdoor | 112 | 98 | 109 | 156 | 238 |
| DOE SSL Program Goals | **Source Annual Energy Savings (tBTU)** | **584** | **632** | **831** | **1,100** | **1,350** |
| | Commercial | 436 | 464 | 574 | 727 | 867 |
| | Residential | 10 | 9 | 9 | 16 | 34 |
| | Industrial | 10 | 21 | 54 | 92 | 127 |
| | Outdoor | 128 | 138 | 194 | 262 | 326 |

1. The energy savings presented in Table 4.10 are not additive to those provided in Table 4.6 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 2017, the majority of installations were general purpose, followed by directional, decorative, and linear fixture. However, a large number of installations does not necessarily translate directly to the best opportunity for energy savings. As shown in Figure 4.8, 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 2017, 45% of U.S. lighting installations were general purpose lamps with over 3.4 billion units in use. However, the majority of general purpose lamps are used in the residential sector and operate an average of less than two hours per day. Meanwhile, only 50 million parking lot fixtures were installed in the U.S. in 2017, but they operate for over 12 hours per day on average. Therefore, parking lot fixtures contribute approximately the same 2017 LED energy savings as general purpose lamps despite the huge disparity in number of installations. Linear fixture applications, which are also characterized by long operating hours, represent a small portion of the 2017 LED energy savings at 7%, yet are predicted to contribute the most (21% in the Current SSL Path scenario and 26% in the DOE SSL Program Goals scenario) to 2035 LED energy savings.

Figure 4.8 provides a breakdown of installed stock and energy use by lighting application. It also shows how the 2035 forecasted energy use changes between the Current SSL Path and the DOE SSL Program Goals scenarios. Note that the size of the circles in the figure represent the energy use distribution among the submarkets for each column and not the magnitude. The total magnitude is provided as a total in the bottom row. In every lighting application, the total energy use is lower in the DOE SSL Program Goals scenario than the Current SSL Path scenario. This is due to the increased efficacy of LED products as well as penetration of connected lighting enabled within the DOE SSL Program Goals scenario. As seen in Figure 4.8, this effect is most noticeable for the linear fixtures submarket, as troffers and other existing linear fluorescent fixtures represent the greatest opportunity for connected lighting systems. These trends are discussed further in Section 4.2.4. The corresponding energy savings are 1,110 tBTU in 2017, 4,820 tBTU in 2035 for the Current SSL Path scenario, and 6,130 tBTU in 2035 for the DOE SSL Program Goals scenario.

[32] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

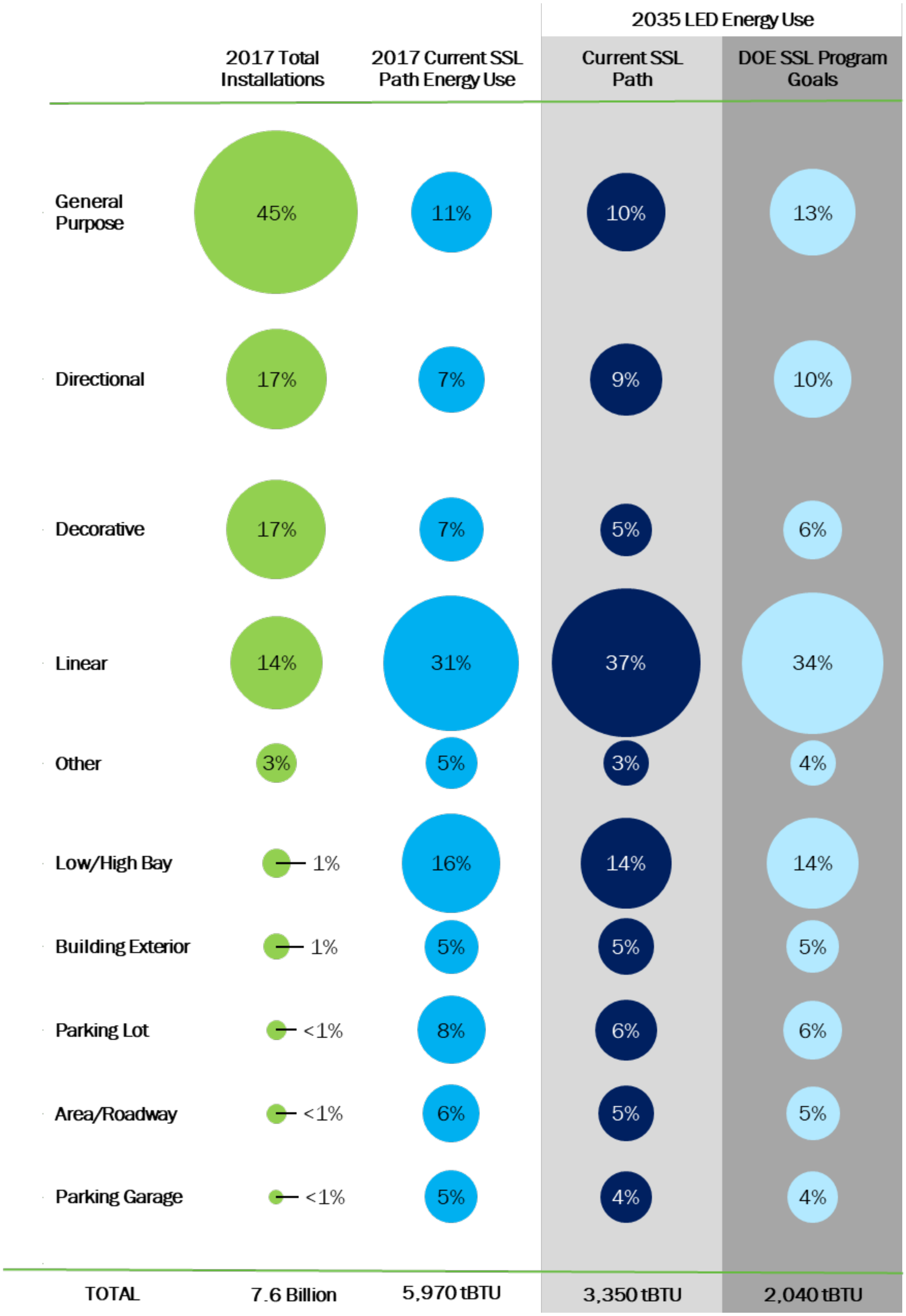


Figure 4.8 Total U.S. Lighting Installations, Energy Consumption, and LED Lighting Energy Use

As shown in Table 4.11, of the submarkets examined, the lighting market model anticipates that the LED penetration will grow the most in low and high bay and linear fixture submarkets between 2017 and 2035.

These are submarkets where the LED penetration is currently low but there is significant potential for growth due to potential savings. While those applications experience the largest growth, the area and roadway, parking, and building exterior submarkets are anticipated to have the highest LED penetration by 2035. These applications tend to already have high LED penetration, which is expected to grow to near full saturation by 2035. In addition, they are typically high-lumen applications, leaving significant opportunity for energy savings.

Table 4.11 LED Penetration by Submarket for the Current SSL Path Scenario

| Submarket | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| General Purpose | 21% | 39% | 62% | 77% | 85% |
| Decorative | 8% | 20% | 46% | 70% | 85% |
| Directional | 28% | 44% | 63% | 73% | 77% |
| Linear Fixture | 11% | 25% | 59% | 80% | 88% |
| Low/High Bay | 12% | 28% | 61% | 82% | 90% |
| Parking | 36% | 69% | 95% | 98% | 98% |
| Area/Roadway | 37% | 64% | 92% | 99% | 100% |
| Building Exterior | 31% | 63% | 92% | 98% | 98% |
| Other[1] | 22% | 41% | 68% | 84% | 91% |
| TOTAL LED Installed Stock Penetration | 19% | 35% | 60% | 76% | 84% |

1. 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. General Purpose

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 general purpose submarket has migrated away from incandescent lamps towards the more efficient LED technology. It is expected that both incandescent and halogen technologies will decline from their 2017 levels of roughly 17% and 15% market penetration, respectively, to 3% each by 2035.

As seen in Figure 4.9, CFLs are expected to see the most drastic decline in stock. Initially, CFLs made up 48% of the general purpose submarket, but the stock in 2035 is expected to decrease to less than a quarter of 2017 levels. CFL stock will continue to drop significantly over the next 18 years; however, due to their long life and low operating hours for general purpose applications, CFL installations will remain throughout the analysis period.

In 2017, there were approximately 3.4 billion general purpose lamps installed in omnidirectional applications. While much of the phased-out incandescent lamp stock has historically been replaced by CFL and halogen lamps, LED lamps and luminaires are currently on the rise. The continuously decreasing price of LED lamps and luminaires and greater consumer acceptance enables their stock to increase rapidly. In terms of installations, LED lamps and luminaires are projected to overtake CFLs as the most prevalent general purpose lighting technology by 2021. By 2035, they are expected to constitute 85% of the 4.2 billion general purpose lamp installations.

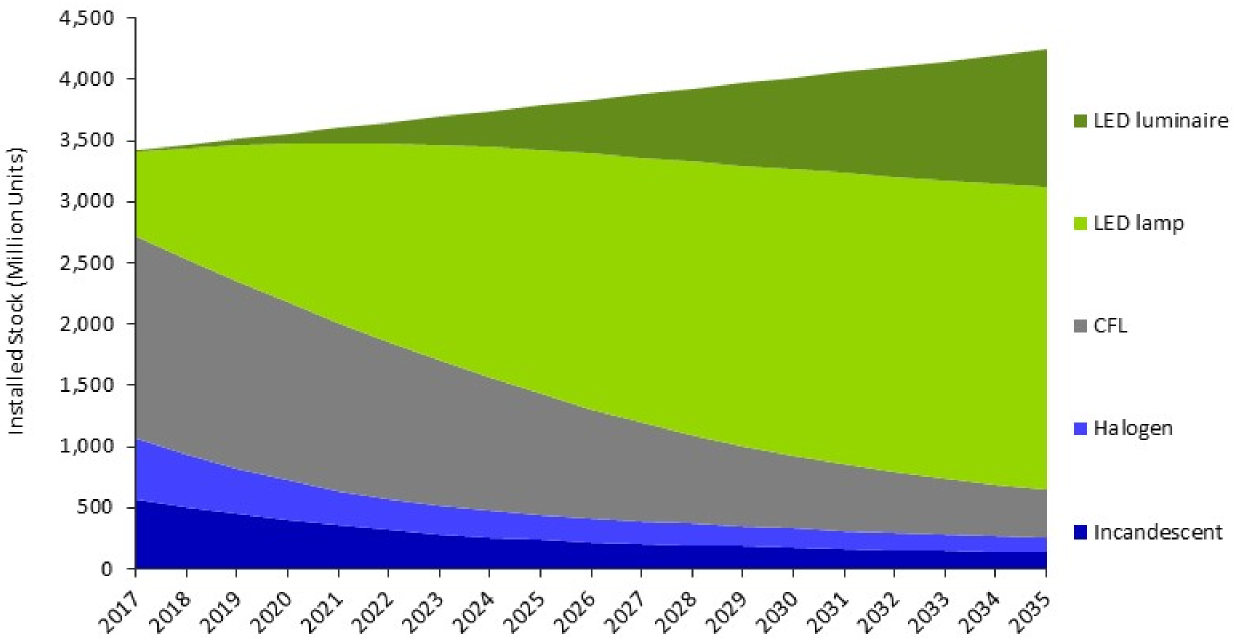


**Figure 4.9 General Purpose Submarket Stock Forecast for the Current SSL Path Scenario**

Table 4.12 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the general purpose submarket.

**Table 4.12 General Purpose Submarket LED Stock Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)[1]** | **713** | **1,380** | **2,360** | **3,090** | **3,590** |
| | Commercial | 47 | 64 | 78 | 86 | 92 |
| | Residential | 666 | 1,320 | 2,280 | 3,000 | 3,500 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **LED Installed Stock Penetration (%)** | **21%** | **39%** | **62%** | **77%** | **85%** |
| | Commercial | 59% | 78% | 90% | 94% | 96% |
| | Residential | 20% | 38% | 62% | 77% | 84% |
| | Industrial | 65% | 83% | 92% | 95% | 96% |

1. Installed stock for the DOE SSL Program Goals 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).

When comparing the general purpose submarket installed stock forecast results by sector, the commercial and industrial sectors shown in Figure 4.10 and Figure 4.11 are quite similar. Both show a steady decline of conventional technologies, largely due to the final phase of EISA 2007, which kicked in as of January 2014. The resulting growth in LED lamps and luminaires is expected to increase their penetration in the general purpose submarket drastically. By 2035, LED penetration is expected to be 96% of both the commercial and industrial installed stock. At the same time, connected LED lighting is expected to account for roughly one quarter of both commercial and industrial general purpose lighting.

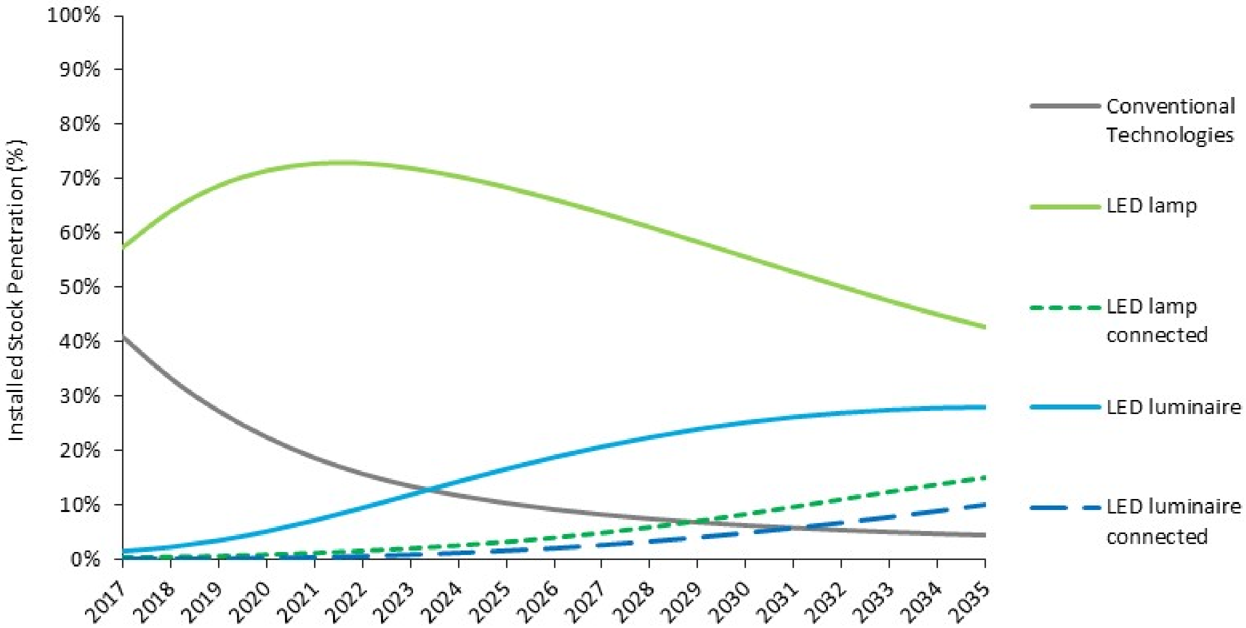


Figure 4.10 Commercial General Purpose Submarket Stock Forecast for the Current SSL Path Scenario

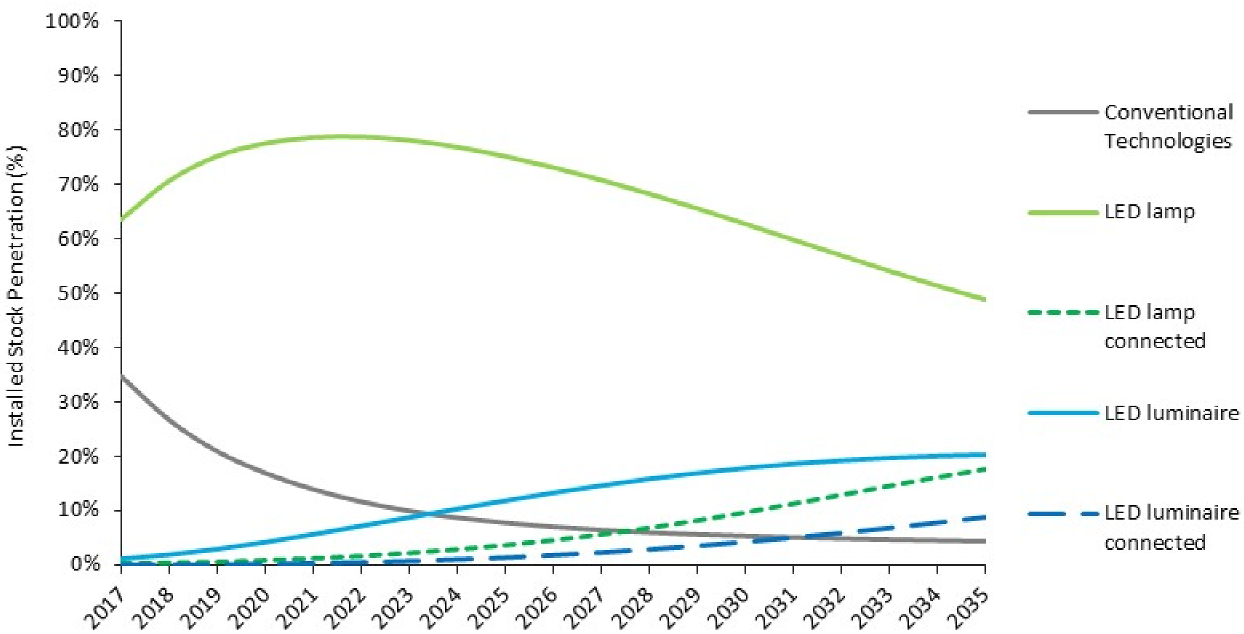


Figure 4.11 Industrial General Purpose Submarket Stock Forecast for the Current SSL Path Scenario

However, due to shorter operating hours and emphasis on low first costs, incumbent technologies (incandescent, halogen, and CFL) maintain a foothold longer in residential general purpose lighting. The LED installed penetration for the residential sector, shown in Figure 4.12 is more gradual than other sectors. It initially lags the commercial sector penetration by about seven years. By 2035, LED lamps and luminaires are projected to make up 58% and 26%, respectively, of the general purpose installed stock in the residential sector. However, connected LED lighting is expected to make up less than 10% of general purpose residential lighting by 2035.

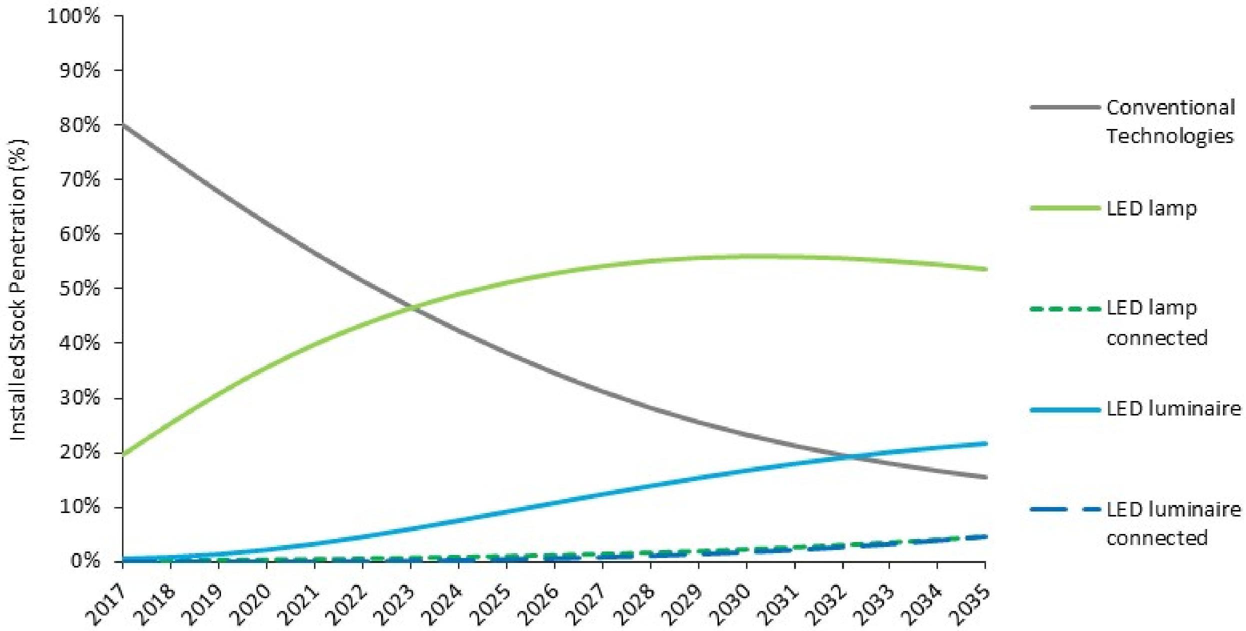


Figure 4.12 Residential General Purpose Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.13 provides further breakdown of the data underlying the above figures. It shows how the installed penetration of each relevant technology evolves throughout the forecast period.

Table 4.13 General Purpose Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | Incandescent | 2% | <1% | <1% | <1% | <1% |
| | Halogen | 2% | <1% | <1% | <1% | <1% |
| | CFL | 37% | 21% | 10% | 6% | 4% |
| | LED lamp | 57% | 72% | 69% | 56% | 43% |
| | LED lamp connected | <1% | <1% | 3% | 8% | 15% |
| | LED luminaire | 1% | 5% | 17% | 25% | 28% |
| | LED luminaire connected | <1% | <1% | 2% | 5% | 10% |
| Residential | Incandescent | 17% | 12% | 6% | 4% | 3% |
| | Halogen | 15% | 9% | 6% | 4% | 3% |
| | CFL | 48% | 41% | 26% | 15% | 9% |
| | LED lamp | 19% | 36% | 51% | 56% | 54% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 5% |
| | LED luminaire | <1% | 2% | 9% | 17% | 22% |
| | LED luminaire connected | <1% | <1% | <1% | 2% | 4% |
| Industrial | Incandescent | 3% | <1% | <1% | <1% | <1% |
| | Halogen | 5% | 2% | <1% | <1% | <1% |
| | CFL | 28% | 15% | 7% | 5% | 4% |
| | LED lamp | 64% | 78% | 75% | 63% | 49% |
| | LED lamp connected | <1% | <1% | 4% | 10% | 18% |
| | LED luminaire | 1% | 4% | 12% | 18% | 20% |
| | LED luminaire connected | <1% | <1% | 1% | 4% | 9% |

Figure 4.13 shows the transition from conventional lighting to LED lighting. While connected LED lighting is expected to penetrate general purpose applications, connected lighting will comprise a relatively small portion of the installed stock, as compared to other submarkets analyzed in this report. The lighting market model forecasts that roughly 10% of all installations will be connected LED lamps or luminaires by 2035 if current levels of SSL investment and effort from DOE and industry stakeholders are maintained. An increase in connected LED lighting is expected for the DOE SSL Program Goals scenario, with installed penetration reaching 24% by 2035.

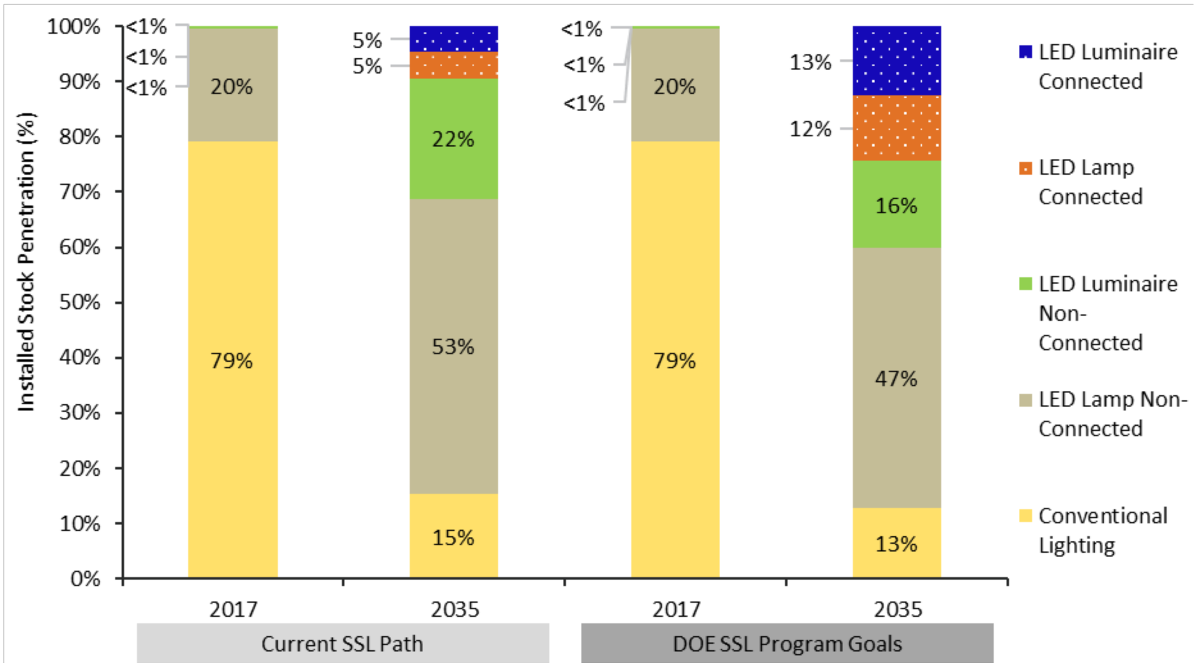


**Figure 4.13 General Purpose Submarket LED Installed Stock Penetration**

Table 4.14 shows that the increasing adoption of LED lighting is expected to achieve 66% source energy savings in 2035 for the Current SSL Path scenario and 75% source energy savings in 2035 for the DOE SSL Program Goals scenario in the general purpose submarket across all sectors. This increase results in an additional 90 tBTU of annual energy savings by 2035.

Table 4.14 General Purpose Submarket LED Energy Savings Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)[33]** | **110** | **230** | **405** | **549** | **670** |
| | Commercial | 26 | 36 | 46 | 54 | 62 |
| | Residential | 84 | 194 | 358 | 495 | 608 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **Source Energy Savings (%)** | **14%** | **30%** | **48%** | **59%** | **66%** |
| | Commercial | 32% | 44% | 55% | 62% | 68% |
| | Residential | 12% | 28% | 47% | 58% | 66% |
| | Industrial | 36% | 46% | 56% | 63% | 69% |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **110** | **266** | **474** | **633** | **760** |
| | Commercial | 26 | 42 | 57 | 66 | 72 |
| | Residential | 84 | 224 | 417 | 568 | 688 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **Source Energy Savings (%)** | **14%** | **34%** | **56%** | **68%** | **75%** |
| | Commercial | 32% | 52% | 68% | 75% | 80% |
| | Residential | 12% | 32% | 54% | 67% | 74% |
| | Industrial | 37% | 54% | 69% | 76% | 81% |

### 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 are the dominant player in the decorative submarket, representing 79% of the 1,269 million decorative installations in 2017. Incandescent lamps are projected to gradually be replaced with an increasing number of LED lamps and luminaires as they become cheaper and consumers become more energy conscious, but incandescent lamps are still expected to hold onto 13% of the 1,570 million decorative installations in 2035.

LED lamps, while available for all existing decorative lamp shapes, have only recently begun offering replacements that meet the aesthetic criteria demanded by some consumers. As seen in Figure 4.14, by 2035, LED lamps are projected to hold 74% of the installed stock, while LED luminaire stock is expected to be 11%.

[33] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

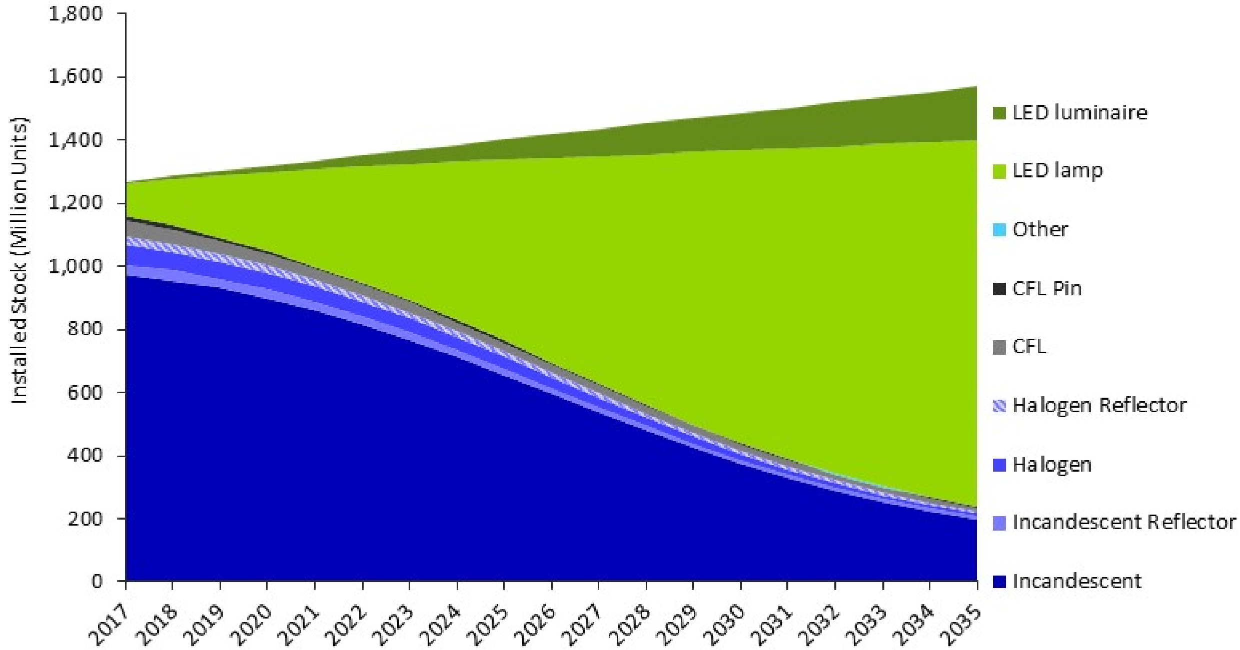


**Figure 4.14 Decorative Submarket Stock Forecast for the Current SSL Path Scenario**

Table 4.15 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the decorative submarket.

**Table 4.15 Decorative Submarket LED Stock Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)[1]** | **107** | **269** | **639** | **1,040** | **1,330** |
| | Commercial | 33 | 68 | 86 | 94 | 99 |
| | Residential | 74 | 201 | 553 | 951 | 1,230 |
| | **LED Installed Stock Penetration (%)** | **8%** | **20%** | **46%** | **70%** | **85%** |
| | Commercial | 38% | 76% | 90% | 93% | 94% |
| | Residential | 6% | 16% | 42% | 69% | 84% |

1. Installed stock for the DOE SSL Program Goals 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).

Figure 4.15 and Figure 4.16 show commercial and residential forecasted penetration of conventional technologies, as well as connected and non-connected LED lamps and luminaires. Table 4.16 also provides a more detailed tabular breakdown of the data.

The commercial sector decorative submarket is dominated by conventional technologies in 2017, with approximately 62% of installations. However, these conventional technologies quickly lose market share, amounting to less than 6% market share by 2035. Throughout the forecast period, conventional technologies are comprised of almost solely CFL and incandescent lamps. Despite near-zero penetration of connected lighting in 2017, connected LED lamps and luminaires achieve a cumulative 25% market share by 2035. The penetration of non-connected LED lamps peaks in 2023 and subsequently declines due to growth in LED luminaires and connected lighting.

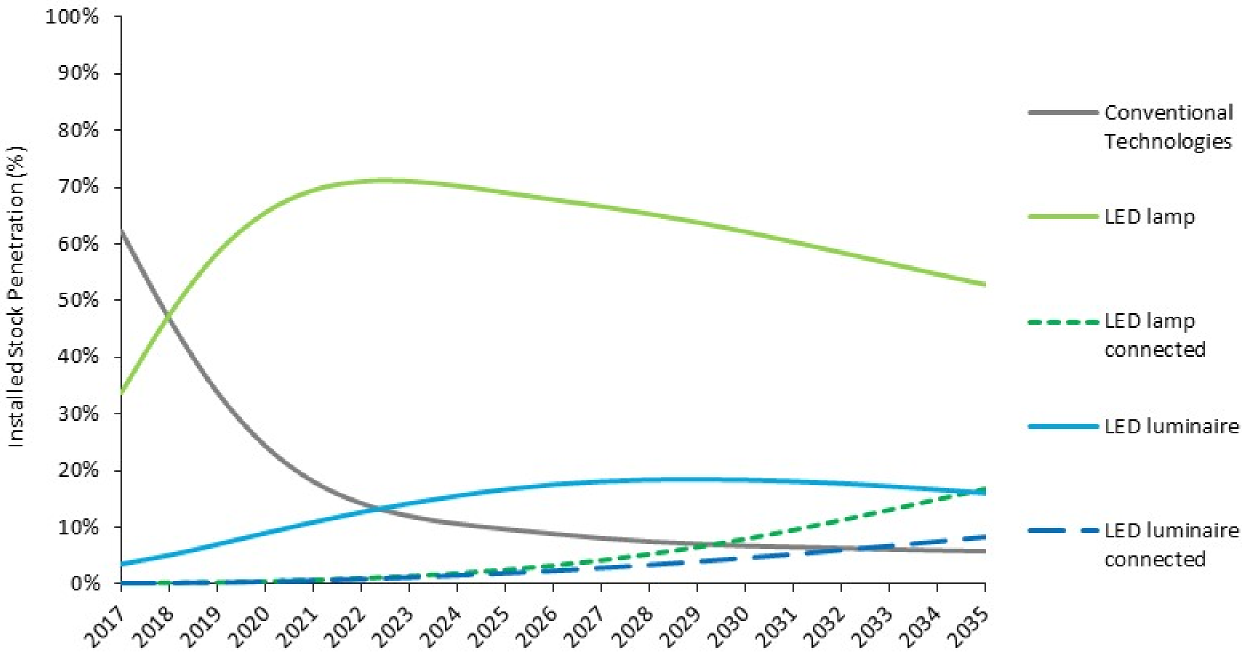


Figure 4.15 Commercial Decorative Submarket Stock Forecast for the Current SSL Path Scenario

Conventional technologies are expected to dominate the residential sector much longer than the commercial sector. Similar to the commercial sector, LED lamps penetrate decorative applications before LED luminaires; however, in contrast to the commercial sector, residential consumers are more sensitive to higher first costs and difficulty of installation, causing LED lamp penetration to continue to increase through 2035. Figure 4.16 shows that the penetration of LED technologies does not surpass conventional technologies, which are almost entirely incandescent, until 2027. By 2035, connected lighting installed penetration will be less than 8%, though LED in total will be 84% of the installed stock.

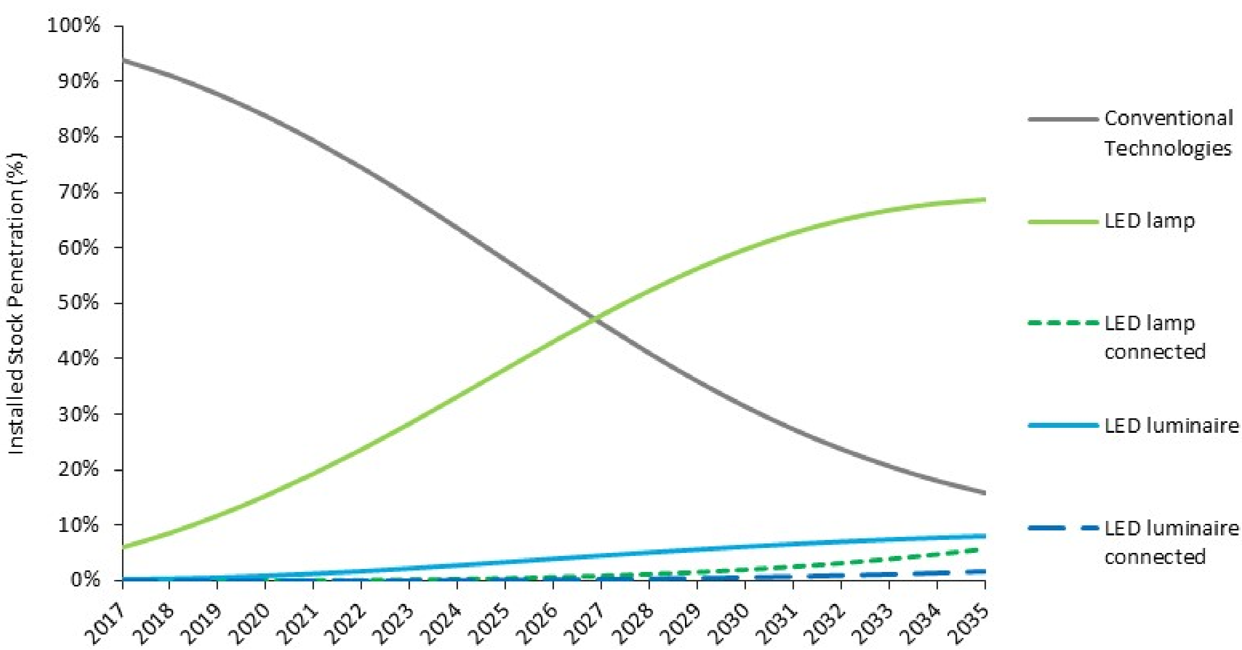


Figure 4.16 Residential Decorative Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.16 provides further breakdown of the data underlying the above figures. It shows how the installed penetration of each relevant technology changes over the forecast period.

Table 4.16 Decorative Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | Incandescent | 26% | 10% | 4% | 3% | 2% |
| | Incandescent Reflector | 2% | <1% | <1% | <1% | <1% |
| | Halogen Reflector | 3% | 1% | <1% | <1% | <1% |
| | CFL | 14% | 6% | 2% | 1% | 1% |
| | CFL Pin | 17% | 6% | 2% | 2% | 1% |
| | Other | <1% | <1% | <1% | <1% | <1% |
| | LED lamp | 34% | 66% | 69% | 62% | 53% |
| | LED lamp connected | <1% | <1% | 2% | 8% | 17% |
| | LED luminaire | 4% | 9% | 17% | 18% | 16% |
| | LED luminaire connected | <1% | <1% | 2% | 5% | 8% |
| Residential | Incandescent | 80% | 72% | 50% | 27% | 13% |
| | Incandescent Reflector | 3% | 2% | 2% | <1% | <1% |
| | Halogen Reflector | 2% | 2% | 1% | <1% | <1% |
| | CFL | 3% | 3% | 2% | 1% | <1% |
| | CFL Pin | <1% | <1% | <1% | <1% | <1% |
| | Other | <1% | <1% | <1% | <1% | <1% |
| | LED lamp | 6% | 15% | 38% | 60% | 69% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 6% |
| | LED luminaire | <1% | <1% | 3% | 6% | 8% |
| | LED luminaire connected | <1% | <1% | <1% | <1% | 2% |

Figure 4.17 illustrates the transition to LED lamps and luminaires, as well as the persistence of conventional technology for decorative applications by 2035 (conventional lighting remains 15% and 14% of the installed stock for the Current SSL Path and DOE SSL Program Goals scenarios, respectively).

By 2035, connected LED lamp penetration is expected to be similar in the decorative and general purpose submarkets. Because the majority of 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 9% of all decorative installations will be connected products by 2035 if current levels of SSL investment and effort from DOE and industry stakeholders are maintained. The penetration of connected lighting in the DOE SSL Program Goals scenario is expected to increase more than twofold over the Current SSL Path scenario, resulting in an overall connected installed penetration of 20% by 2035.

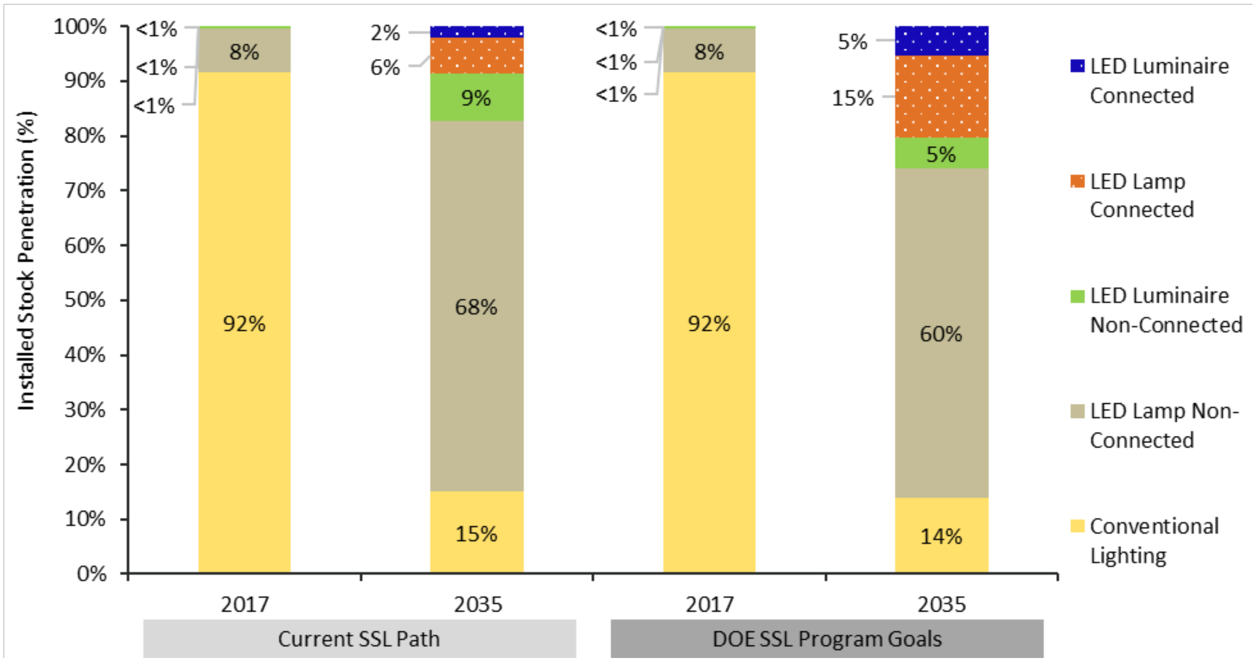


**Figure 4.17 Decorative Submarket LED Lighting Installed Stock Penetration**

Table 4.17 shows that the increasing adoption of LED lighting is expected to achieve 72% source energy savings in 2035 for the Current SSL Path scenario and 78% source energy savings in 2035 for the DOE SSL Program Goals scenario in the decorative submarket across all sectors. This increase results in an additional 37 tBTU of annual energy savings by 2035.

**Table 4.17 Decorative Submarket LED Lighting Energy Savings Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)**[34] | **47** | **113** | **216** | **319** | **396** |
| | Commercial | 36 | 75 | 100 | 113 | 123 |
| | Residential | 11 | 38 | 115 | 206 | 273 |
| | **Source Energy Savings (%)** | **10%** | **24%** | **43%** | **60%** | **72%** |
| | Commercial | 26% | 52% | 67% | 73% | 77% |
| | Residential | <1% | 11% | 33% | 55% | 69% |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **47** | **127** | **244** | **354** | **433** |
| | Commercial | 36 | 84 | 114 | 127 | 135 |
| | Residential | 11 | 42 | 130 | 228 | 298 |
| | **Source Energy Savings (%)** | **10%** | **27%** | **49%** | **67%** | **78%** |
| | Commercial | 26% | 59% | 76% | 82% | 85% |
| | Residential | <1% | 13% | 37% | 61% | 76% |

### 4.2.3. Directional

As described in Section 3.1.3, directional lighting is typically provided by either large reflector lamps (BR, R, PAR shapes) or smaller MR lamps, most commonly housed in track or downlight fixtures. The lighting market

[34] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

model assumes that both LED lamps and luminaires compete for installations in the directional submarket for downlights, track lights, and MR lamps. While LED lamps installed in downlight and track fixtures represent the majority of LED technology that is employed in directional applications, LED directional luminaires were some of the earliest applications for luminaires in general illumination, particularly LED downlights. Due to the early adoption of LED downlights, as of 2017, they have established themselves as a significant competitor in directional applications. Figure 4.18 and Figure 4.19 illustrate the forecasted installed stock for both large and small directional applications.

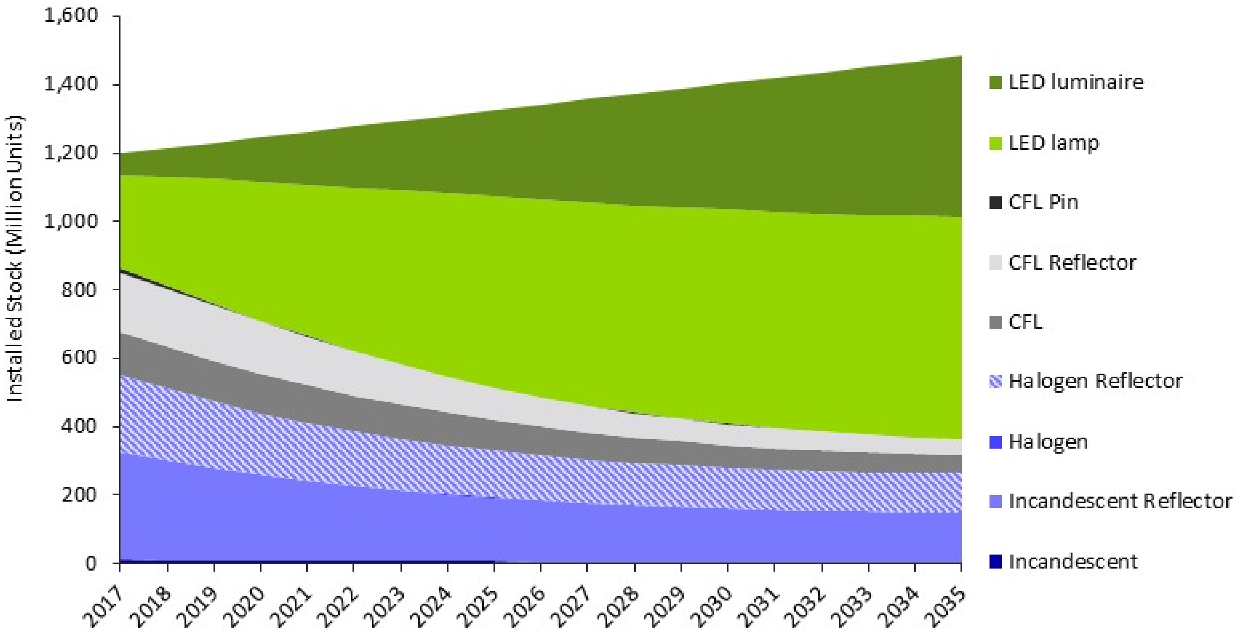


Figure 4.18 Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

Throughout the forecast period, LED lamps hold the majority over LED luminaires in large directional applications, though they are both significant competitors. In 2035, LED lamps and LED luminaires make up 44% and 32% of the installed stock, respectively. As seen in Figure 4.19, the same relationship is expected in 2017 in small directional applications; however, starting in 2034, LED luminaires hold greater market share than LED lamps – 50% and 47%, respectively, in 2035.

Adoption of LED lighting in large directional applications is delayed relative to those competing in small directional applications. LED lighting in small directional applications represents the majority of installations in 2019, whereas this does not occur until 2022 in large directional applications.

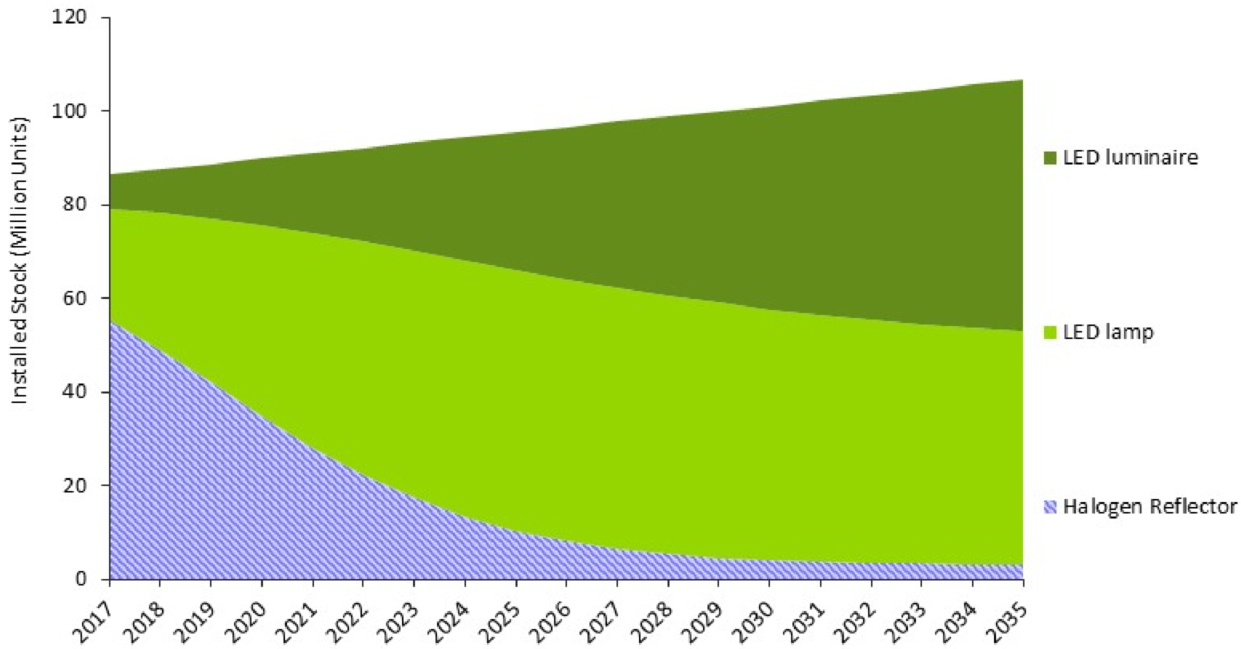


Figure 4.19 Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.18 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the large and small directional submarkets combined.

Table 4.18 Directional Submarket LED Lighting Stock Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)[1]** | **367** | **589** | **896** | **1,090** | **1,220** |
| | Commercial | 120 | 142 | 155 | 163 | 172 |
| | Residential | 247 | 447 | 741 | 929 | 1,050 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **LED Installed Stock Penetration (%)** | **28%** | **44%** | **63%** | **73%** | **77%** |
| | Commercial | 83% | 96% | 99% | 99% | 99% |
| | Residential | 22% | 38% | 59% | 69% | 74% |
| | Industrial | 60% | 80% | 88% | 90% | 91% |

1. Installed stock for the DOE SSL Program Goals 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).

The early prevalence of LEDs in directional applications is particularly noticeable when considering the results by sector. Figure 4.20 and Figure 4.21 show the forecasted installed penetration in the commercial sector for large and small directional applications, respectively. In 2017, LED lighting represents 83% of commercial LED stock in both large directional and small directional submarkets. This substantial early penetration is driven by non-connected LED lamps. However, since these non-connected LED lamps are expected to reach their peak early, they are surpassed in 2025 by non-connected LED luminaires for large directional applications and in 2027 for small directional applications. In both applications, connected lighting does not play a major role until later years in the forecast. By 2035, the total connected lighting installed penetration in large directional and small directional applications is 29% and 30%, respectively.

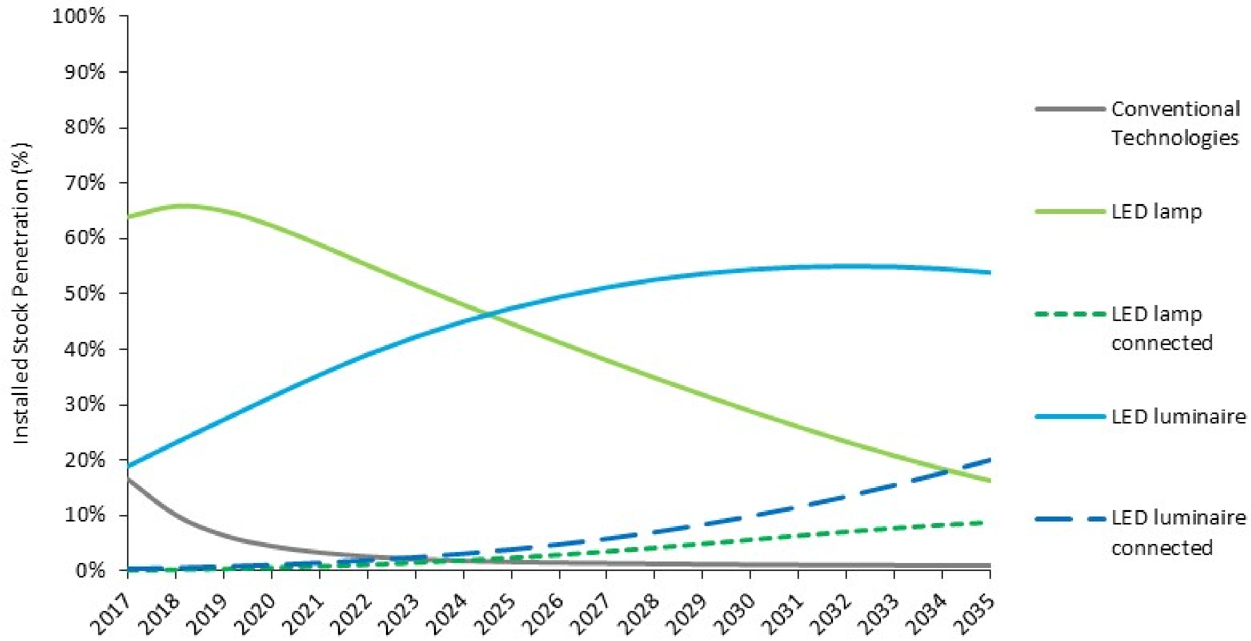


Figure 4.20 Commercial Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

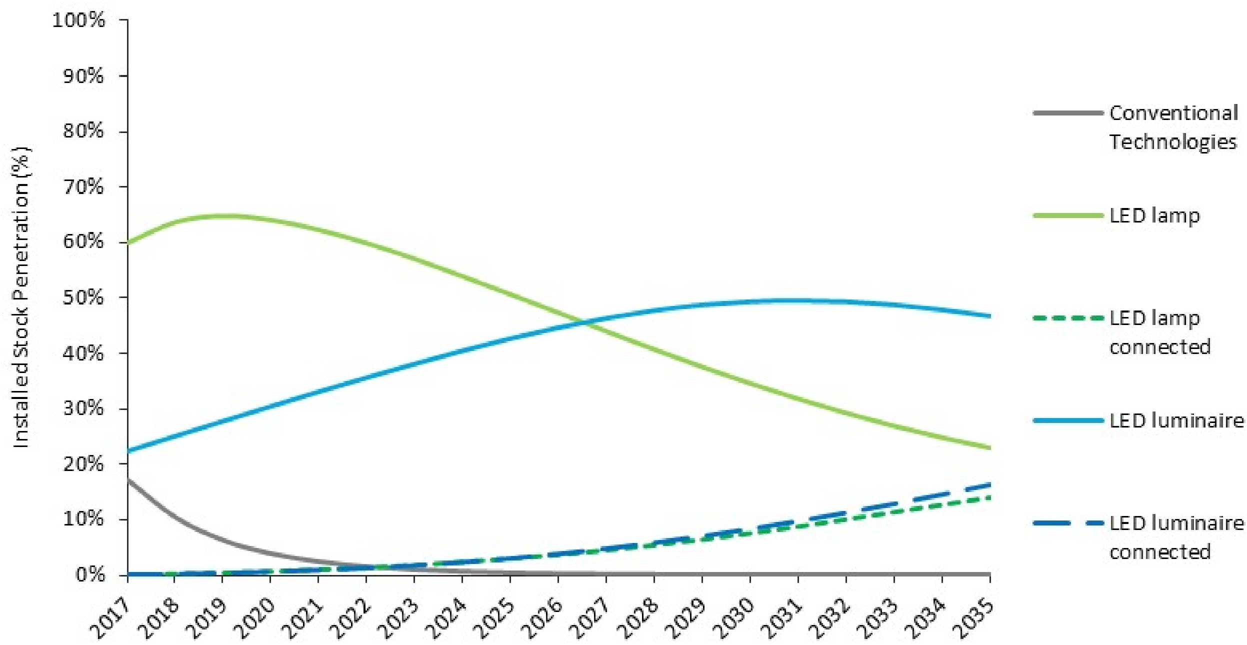


Figure 4.21 Commercial Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

As seen in Figure 4.22, LED lighting also represents the majority of directional installations in the industrial sector in 2017,[35] with non-connected LED lamps and luminaires making up 48% and 12% of installations respectively. Connected lighting is expected to achieve over 10% installed penetration by 2029, and, by 2035,

[35] 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.

it will compose 24% of the industrial directional submarket. By 2035, LED lighting is expected to make up 91% of industrial directional installations.

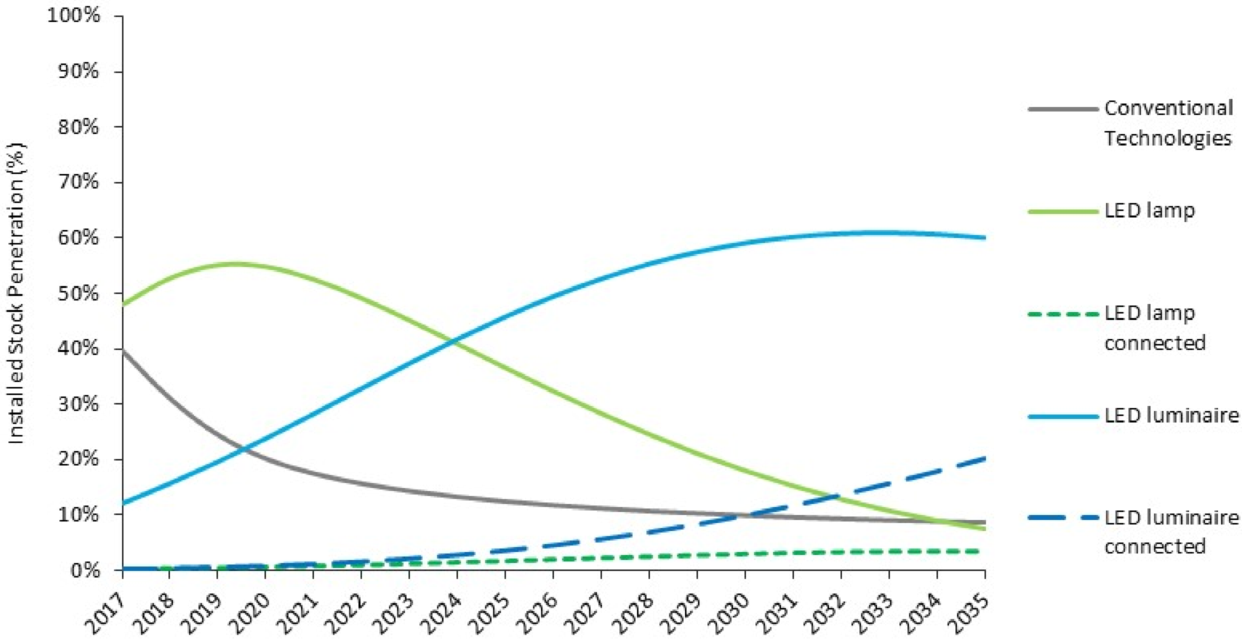


Figure 4.22 Industrial Directional Submarket Stock Forecast for the Current SSL Path Scenario

While progress has been slower in the residential sector, LED lamps and luminaires also achieved notable installed penetration in 2017, as seen below in Figure 4.23 and Figure 4.24. In 2017, LED lighting represents approximately 22% of both large directional and small directional installations in the residential sector. LED lighting continue to gain traction and become the majority in large directional applications in 2023 and in small directional applications in 2020.

However, halogen and incandescent reflector lamps are expected to remain appealing to some residential consumers. Compact fluorescent reflectors also linger within the residential sector for large directional lamps. This is mainly due to the low operating hours typically seen in U.S. households and the longer life of compact fluorescent technology. Ultimately, conventional lighting technologies make up about 27% and 4% of the large and small directional residential installations in 2035, respectively.

Similar to other submarkets, connected lighting experiences notably slower growth in the residential sector than in other sectors. In 2035, connected lighting accounts for only 7% and 11% of the large and small directional installations, respectively, in the residential sector.

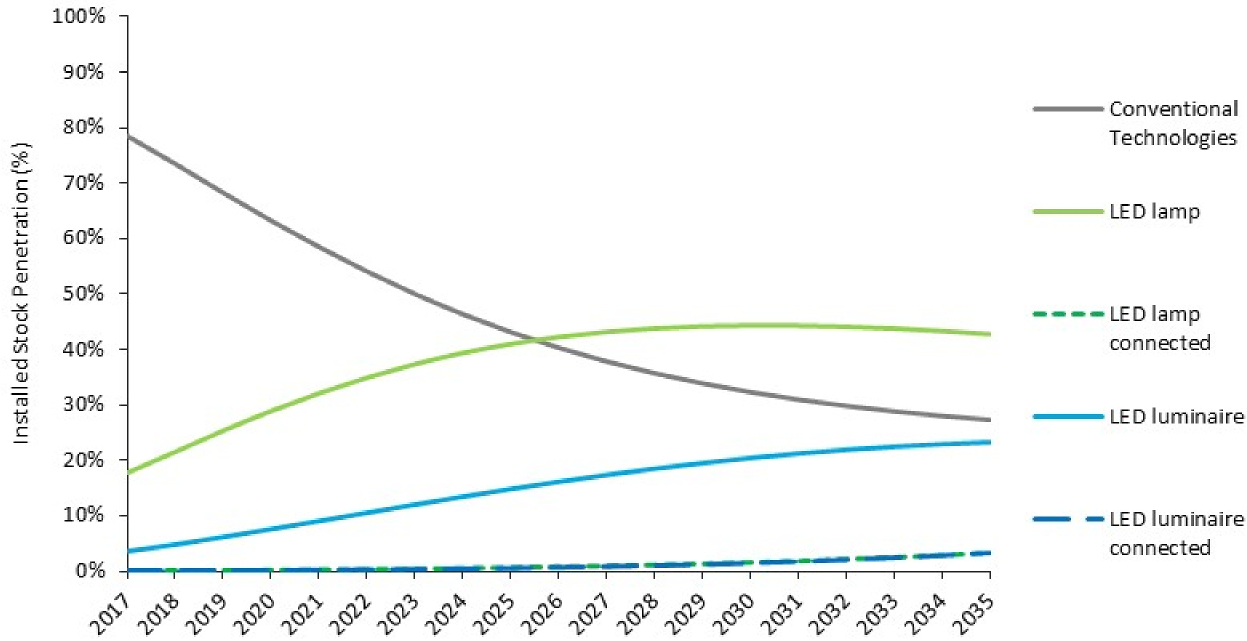


Figure 4.23 Residential Large Directional Submarket Stock Forecast for the Current SSL Path Scenario

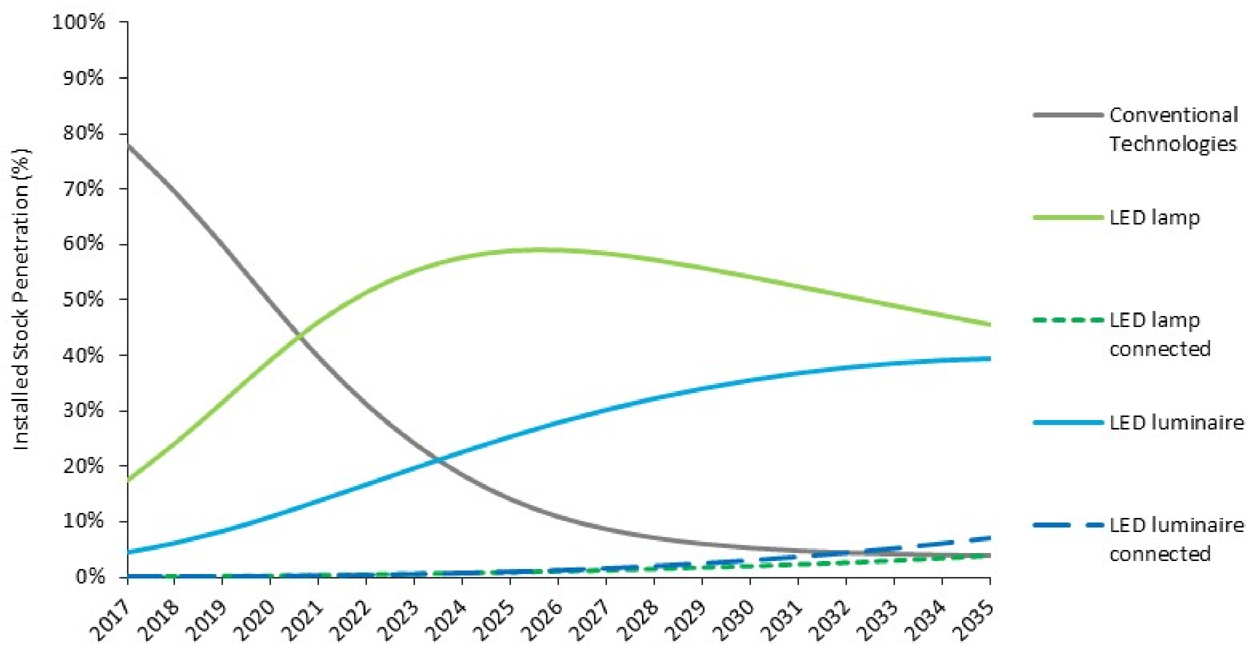


Figure 4.24 Residential Small Directional Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.19, Table 4.20, and Table 4.21 provide further breakdown of the data underlying the above figures. They show how the installed penetration of each relevant technology evolves throughout the forecast period.

Table 4.19 Large Directional Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | Incandescent Reflector | 1% | <1% | <1% | <1% | <1% |
| | Halogen Reflector | <1% | <1% | <1% | <1% | <1% |
| | CFL Reflector | 2% | <1% | <1% | <1% | <1% |
| | CFL Pin | 13% | 3% | <1% | <1% | <1% |
| | LED lamp | 64% | 62% | 45% | 29% | 16% |
| | LED lamp connected | <1% | <1% | 3% | 6% | 9% |
| | LED luminaire | 19% | 32% | 48% | 55% | 54% |
| | LED luminaire connected | <1% | 1% | 4% | 10% | 20% |
| Residential | Incandescent Reflector | 29% | 22% | 16% | 12% | 11% |
| | Halogen Reflector | 21% | 16% | 11% | 9% | 9% |
| | CFL | 11% | 10% | 8% | 5% | 4% |
| | CFL Reflector | 16% | 14% | 8% | 5% | 4% |
| | LED lamp | 18% | 29% | 41% | 44% | 43% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 3% |
| | LED luminaire | 4% | 8% | 15% | 21% | 23% |
| | LED luminaire connected | <1% | <1% | <1% | 1% | 3% |

Table 4.20 Small Directional Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | Halogen Reflector | 17% | 4% | <1% | <1% | <1% |
| | LED lamp | 60% | 64% | 51% | 35% | 23% |
| | LED lamp connected | <1% | <1% | 3% | 8% | 14% |
| | LED luminaire | 22% | 31% | 43% | 49% | 47% |
| | LED luminaire connected | <1% | <1% | 3% | 8% | 16% |
| Residential | Halogen Reflector | 78% | 49% | 14% | 5% | 4% |
| | LED lamp | 18% | 39% | 59% | 54% | 46% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 4% |
| | LED luminaire | 4% | 11% | 25% | 36% | 40% |
| | LED luminaire connected | <1% | <1% | <1% | 3% | 7% |

Table 4.21 Industrial Sector Directional Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Industrial | Incandescent Reflector | 2% | 1% | <1% | <1% | <1% |
| | Halogen Reflector | 2% | 1% | <1% | <1% | <1% |
| | CFL Reflector | 36% | 18% | 12% | 9% | 8% |
| | LED lamp | 48% | 55% | 36% | 18% | 7% |
| | LED lamp connected | <1% | <1% | 2% | 3% | 4% |
| | LED luminaire | 12% | 24% | 46% | 59% | 60% |
| | LED luminaire connected | <1% | <1% | 4% | 10% | 20% |

When comparing the entire directional submarket (small directional and large directional applications in all relevant sectors), Figure 4.25 shows that the total LED installed stock penetration is expected to reach approximately 77% by 2035. Non-connected LED lighting is forecasted to be the majority in the Current SSL Path scenario, representing 68% of the directional installed base (with 9% connected). While non-connected

LED lighting is also forecasted to be the majority in the DOE SSL Program Goals scenario, connected LED penetration significantly increases. Therefore, if the DOE goals are met, connected LED lamps and luminaires are projected to increase an additional 14% over the Current SSL Path scenario, resulting in a total of 23% installed penetration of connected lighting in directional applications.

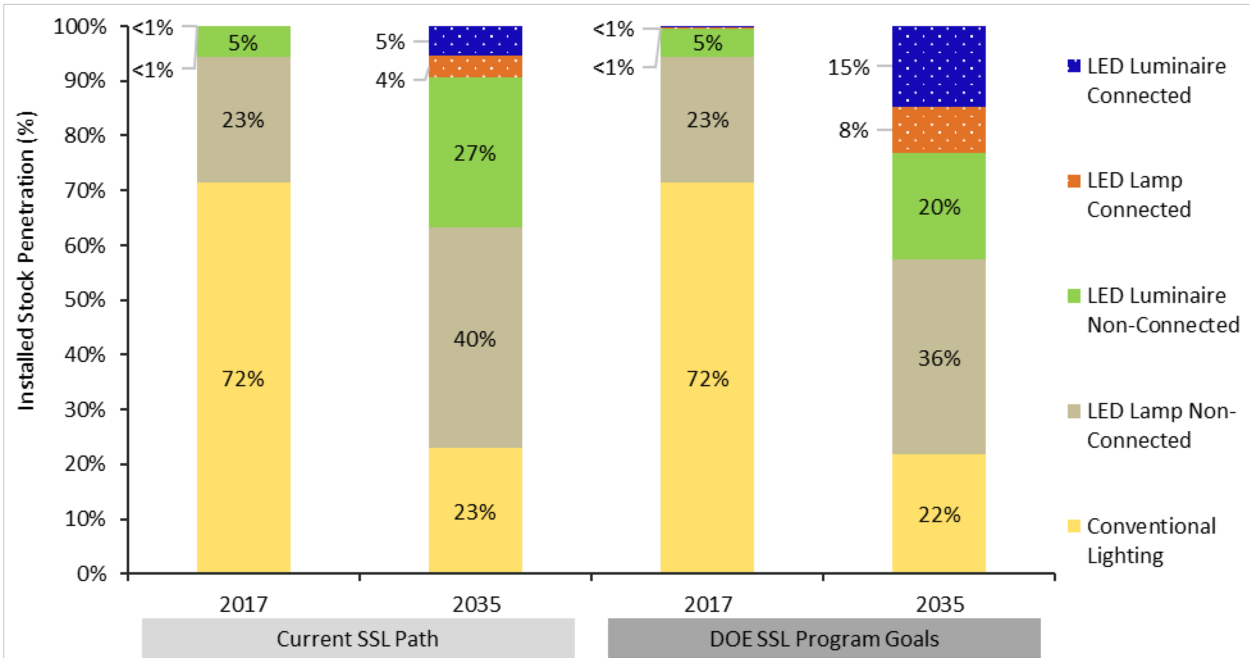


Figure 4.25 Directional Submarket LED Lighting Installed Stock Penetration

Table 4.22 shows that the increasing adoption of LED lighting is expected to achieve 62% source energy savings in 2035 for the Current SSL Path scenario and 74% source energy savings in 2035 for the DOE SSL Program Goals scenario in the directional submarket across all sectors. This 12% increase in savings results in an additional 95 tBTU of annual energy savings by 2035.

Table 4.22 Directional Submarket LED Lighting Energy Savings Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)[36]** | **210** | **284** | **372** | **435** | **486** |
| | Commercial | 143 | 167 | 186 | 200 | 215 |
| | Residential | 67 | 116 | 187 | 235 | 271 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **Source Energy Savings (%)** | **32%** | **43%** | **53%** | **58%** | **62%** |
| | Commercial | 57% | 66% | 70% | 73% | 77% |
| | Residential | 17% | 28% | 42% | 49% | 54% |
| | Industrial | 14% | 17% | 13% | 16% | 22% |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **211** | **320** | **447** | **525** | **581** |
| | Commercial | 145 | 189 | 225 | 243 | 256 |
| | Residential | 67 | 131 | 222 | 282 | 326 |
| | Industrial | < 1 | < 1 | < 1 | < 1 | < 1 |
| | **Source Energy Savings (%)** | **33%** | **48%** | **63%** | **70%** | **74%** |
| | Commercial | 57% | 74% | 85% | 89% | 91% |
| | Residential | 17% | 32% | 50% | 60% | 64% |
| | Industrial | 16% | 37% | 54% | 65% | 72% |

### 4.2.4. Linear Fixture

In 2017, the linear fixture submarket consumed more energy than any other submarket – nearly twice as much as the second highest consuming submarket (low and high bay). 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 2017, T12 systems constituted only 9% and 13%, respectively. (21) By 2026, T12 lamps are forecasted to drop to less than 5% of the total linear fixture submarket installed base. However, the more efficient T8 and T5 technologies maintain over 50% installed penetration until 2023. As seen in Figure 4.26, LED lamps and luminaires are predicted to absorb most of this decline, increasing to 28% and 59%, respectively, by 2035.

[36] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

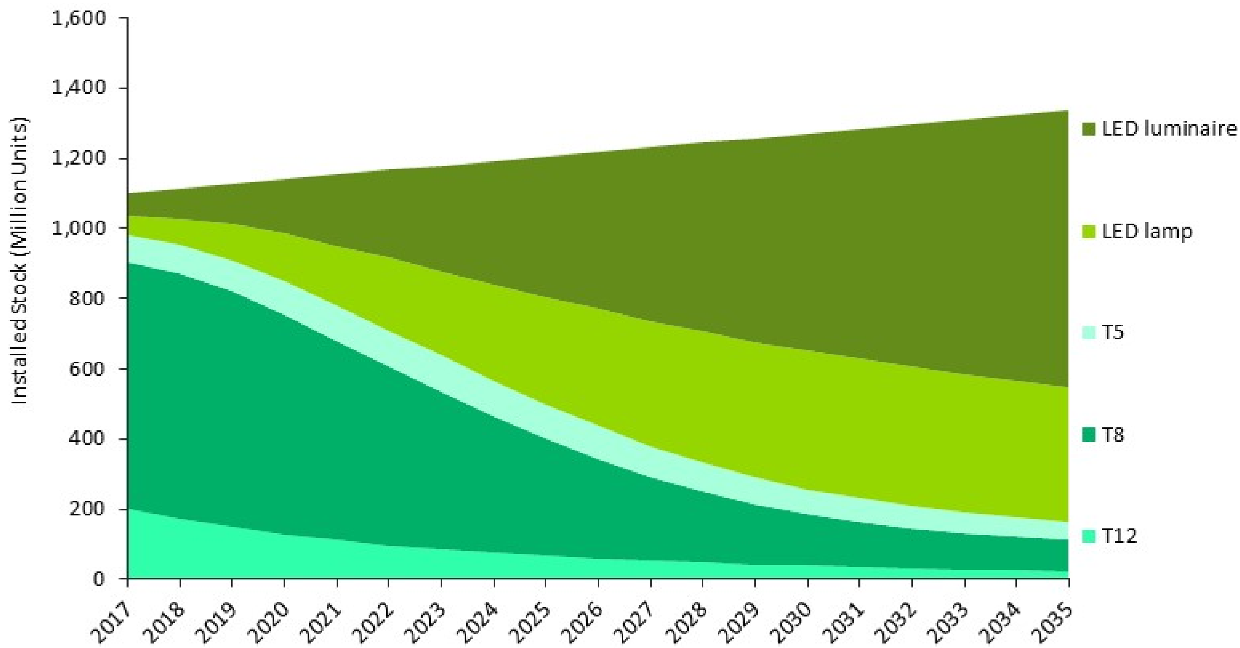


**Figure 4.26 Linear Fixture Submarket Stock Forecast for the Current SSL Path Scenario**

Table 4.23 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the linear fixture submarket.

**Table 4.23 Linear Fixture Submarket LED Lighting Stock Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)**[1] | **119** | **291** | **707** | **1,010** | **1,170** |
| | Commercial | 91 | 221 | 536 | 752 | 851 |
| | Residential | 22 | 53 | 132 | 210 | 265 |
| | Industrial | 7 | 17 | 38 | 52 | 57 |
| | **LED Installed Stock Penetration (%)** | **11%** | **25%** | **59%** | **80%** | **88%** |
| | Commercial | 12% | 28% | 63% | 84% | 91% |
| | Residential | 8% | 19% | 44% | 66% | 79% |
| | Industrial | 12% | 29% | 64% | 84% | 91% |

1. Installed stock for the DOE SSL Program Goals 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).

Figure 4.27, Figure 4.28, and Figure 4.29 show that the linear fixture submarket will be strongly affected by the availability of high-performance LED lighting products in all sectors. Linear fluorescent systems (lamp and ballast) currently have efficacies averaging between 75 and 98 lm/W, while LED lamps and LED luminaires have efficacies of 104 lm/W and 96 lm/W, respectively, in 2017. 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 152 lm/W by 2035 – over 150% greater than the most efficient fluorescent T5 lamp and ballast system. Consequently, as shown in Figure 4.27 the lighting market model predicts that LED lamps and luminaires in the commercial sector will contribute 28% of the linear fixture stock by 2020 but increase to 91% installed penetration by 2035. Due to the relatively high potential for energy savings, connected lighting is expected to make up 28% of the commercial linear fixture submarket by 2035.

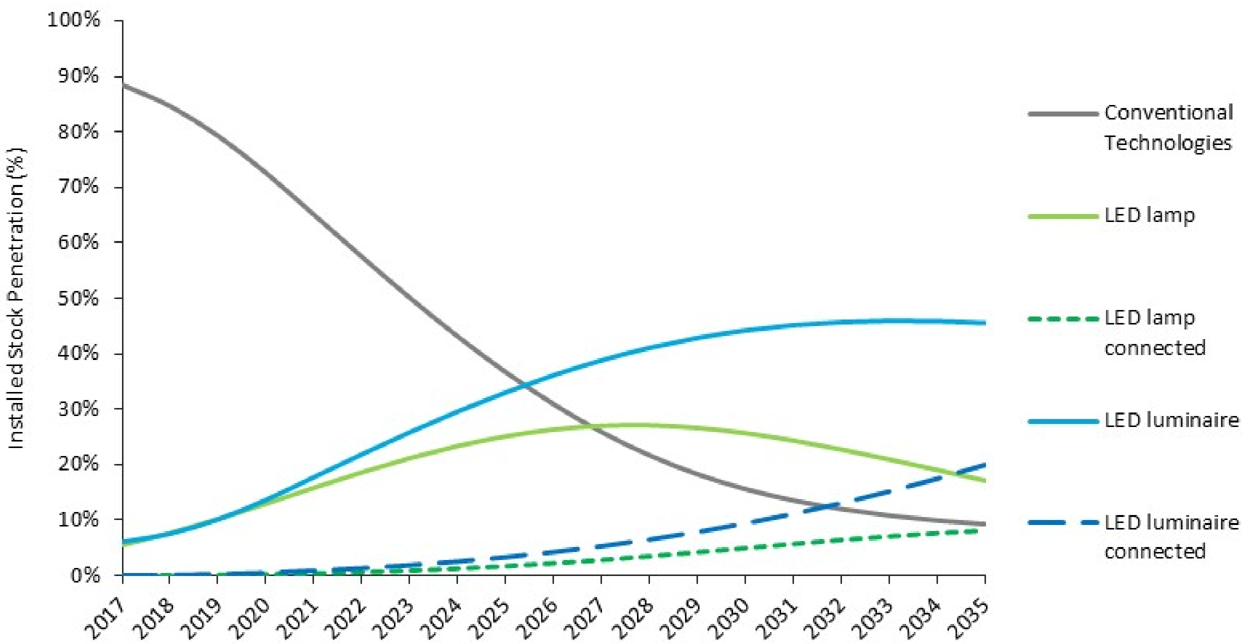


Figure 4.27 Commercial Linear Fixture Stock Forecast for the Current SSL Path Scenario

Although significantly smaller in terms of number of installations, the industrial sector mimics the trends seen in the commercial sector, as shown in Figure 4.28. The lighting market model estimates that LED lamps and luminaires will represent 29% of industrial linear stock in 2020 and will grow quickly to 91% by 2035. For the same reasons seen in the commercial sector, connected lighting will make up a notable portion of the industrial linear fixture submarket, a total of 28% by 2035.

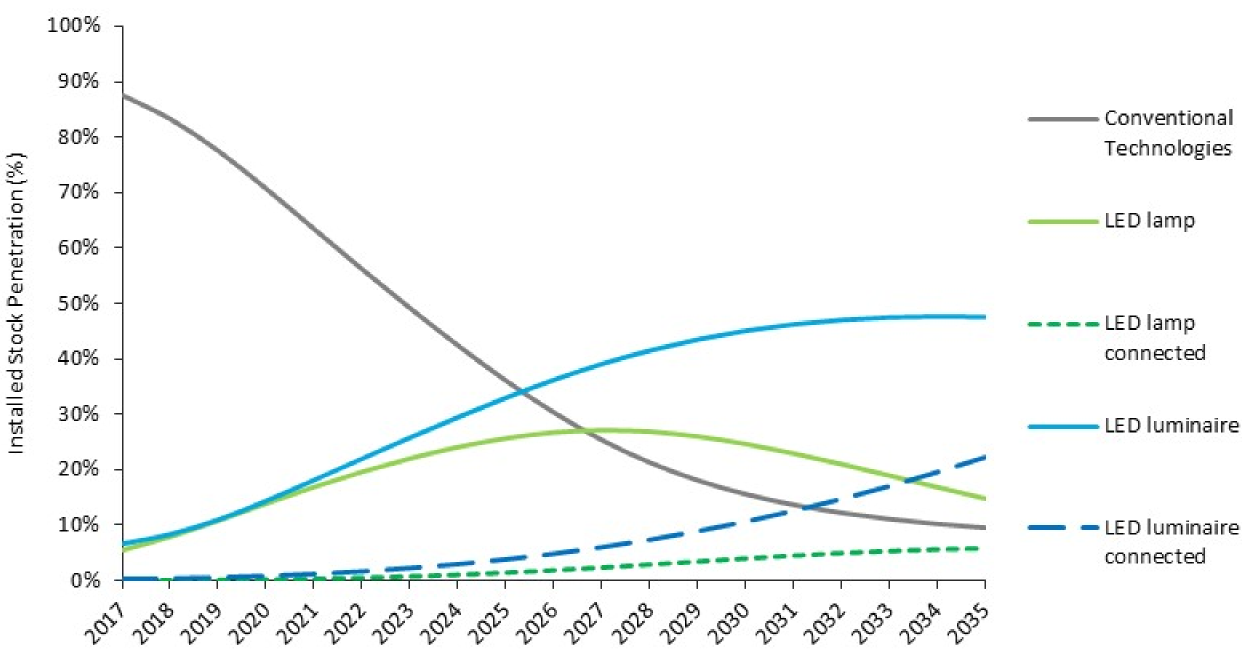


Figure 4.28 Industrial Linear Fixture Stock Forecast for the Current SSL Path Scenario

In the residential sector, the takeover of LED lamps and luminaires is slower than in the commercial and industrial sectors, where facilities managers place a higher value on life-cycle costs than the average residential consumer. Illustrated in Figure 4.29, LED lighting makes slower gains in the residential sector than other sectors. Regardless, adoption of LED lighting is still expected to increase, capturing 79% of installed stock by 2035. Similarly, the residential sector experiences the slowest adoption of connected lighting. Despite energy savings opportunities, connected lighting is expected to make up only 10% of the installed stock by 2035.

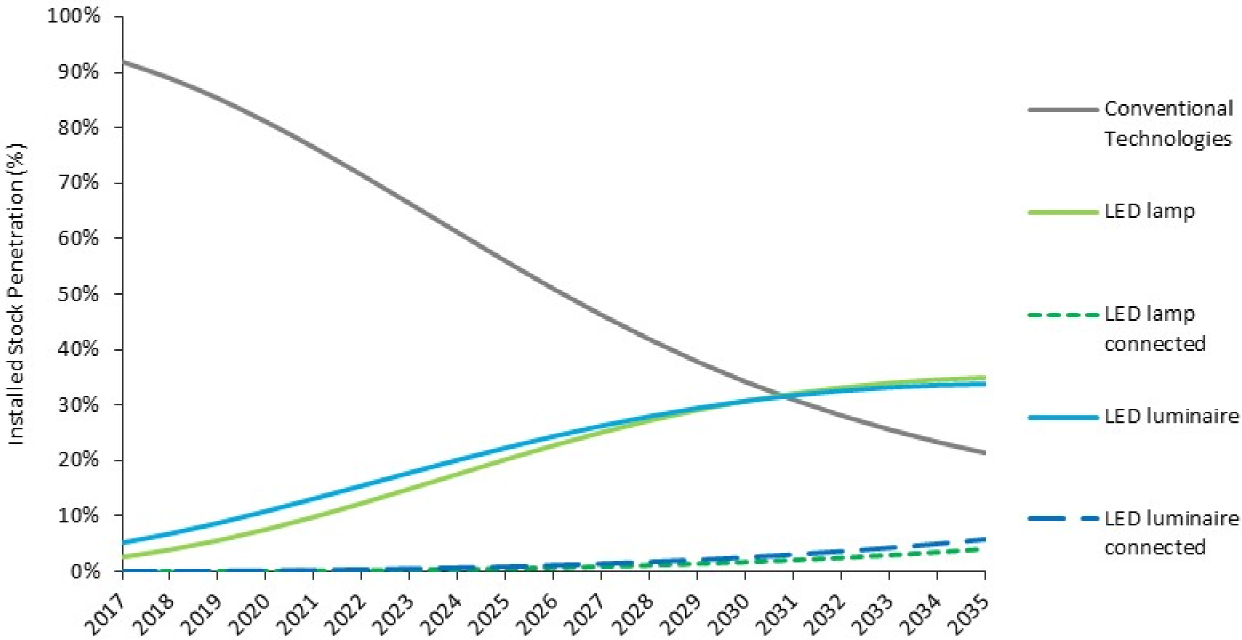


Figure 4.29 Residential Linear Fixture Stock Forecast for the Current SSL Path Scenario

Table 4.24 provides further breakdown of the data underlying the above figures. It shows how the installed penetration of each relevant technology evolves throughout the forecast period.

Table 4.24 Linear Fixture Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | T12 | 9% | 4% | <1% | <1% | <1% |
| | T8 | 72% | 60% | 27% | 9% | 5% |
| | T5 | 7% | 9% | 9% | 6% | 4% |
| | LED lamp | 6% | 13% | 25% | 26% | 17% |
| | LED lamp connected | <1% | <1% | 2% | 5% | 8% |
| | LED luminaire | 6% | 14% | 33% | 44% | 46% |
| | LED luminaire connected | <1% | <1% | 3% | 9% | 20% |
| Residential | T12 | 45% | 35% | 21% | 11% | 7% |
| | T8 | 44% | 42% | 31% | 19% | 12% |
| | T5 | 4% | 4% | 4% | 3% | 3% |
| | LED lamp | 3% | 8% | 20% | 31% | 35% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 4% |
| | LED luminaire | 5% | 11% | 22% | 31% | 34% |
| | LED luminaire connected | <1% | <1% | <1% | 3% | 6% |
| Industrial | T12 | 13% | 5% | <1% | <1% | <1% |
| | T8 | 52% | 43% | 20% | 7% | 4% |
| | T5 | 23% | 23% | 15% | 8% | 6% |
| | LED lamp | 5% | 14% | 26% | 25% | 15% |
| | LED lamp connected | <1% | <1% | 1% | 4% | 6% |
| | LED luminaire | 7% | 14% | 33% | 45% | 48% |
| | LED luminaire connected | <1% | <1% | 4% | 11% | 22% |

Figure 4.30 provides a comparison of the total LED installed stock penetration in 2035 for both the Current SSL Path and DOE SSL Program Goals scenarios. Due to the magnitude of installations and high operating hours, the linear fixture submarket is poised to experience some of the greatest growth in connected lighting.

For the Current SSL Path scenario, the majority of LEDs installed are non-connected LED luminaires, yet connected LED lighting comprises 23% of the linear fixture stock by 2035. If the DOE goals for connected lighting adoption are achieved, connected LED installed penetration is projected to increase substantially. In the DOE SSL Program Goals scenario, connected LED lamps and luminaires are forecasted to represent the vast majority, approximately 56%, of linear fixture installations by 2035.

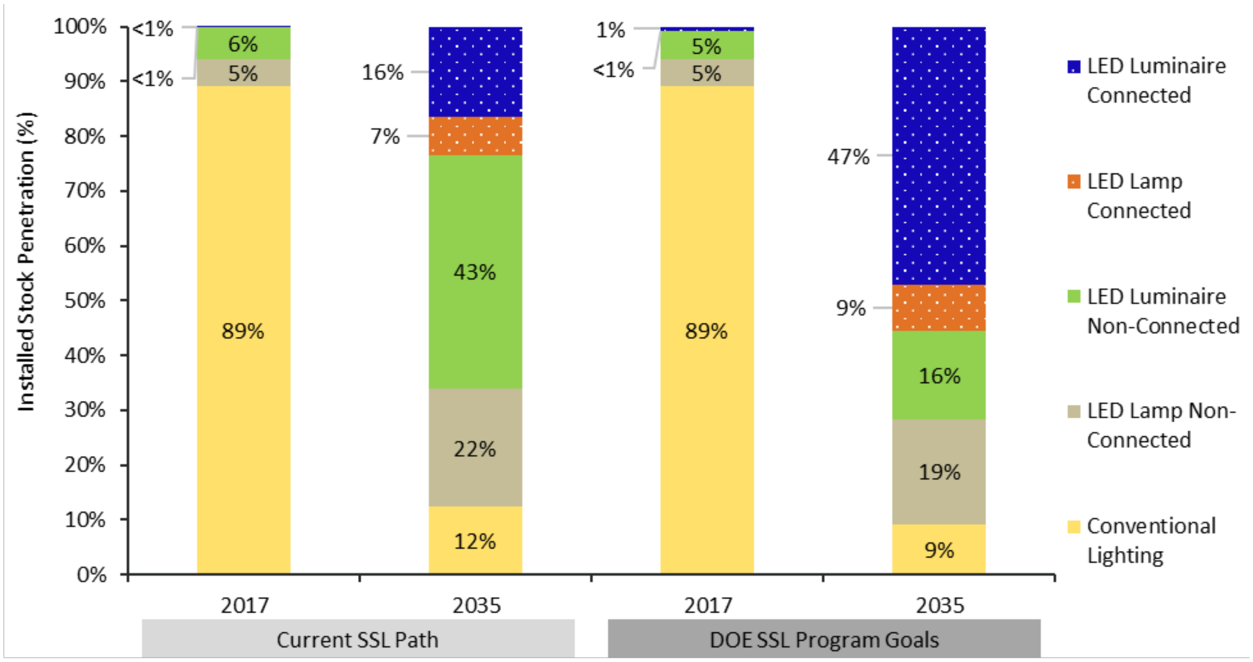


Figure 4.30 Linear Fixture Submarket LED Lighting Installed Stock Penetration[37]

Table 4.25 shows that the increasing adoption of LED lighting is expected to achieve 45% source energy savings in 2035 for the Current SSL Path scenario and 70% source energy savings in 2035 for the DOE SSL Program Goals scenario in the linear fixture submarket across all sectors. This increase results in an additional 570 tBTU of annual energy savings by 2035.

[37] There is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.

**Table 4.25 Linear Fixture Submarket LED Lighting Energy Savings Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)[38]** | **75** | **157** | **435** | **736** | **1,020** |
| | Commercial | 61 | 122 | 338 | 577 | 814 |
| | Residential | 6 | 14 | 36 | 60 | 77 |
| | Industrial | 8 | 22 | 61 | 99 | 132 |
| | **Source Energy Savings (%)** | **4%** | **8%** | **21%** | **34%** | **45%** |
| | Commercial | 4% | 8% | 20% | 32% | 44% |
| | Residential | <1% | 8% | 22% | 35% | 44% |
| | Industrial | 4% | 11% | 29% | 45% | 56% |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **82** | **268** | **825** | **1,290** | **1,590** |
| | Commercial | 67 | 217 | 680 | 1,070 | 1,300 |
| | Residential | 6 | 16 | 45 | 74 | 96 |
| | Industrial | 9 | 35 | 100 | 151 | 186 |
| | **Source Energy Savings (%)** | **4%** | **14%** | **40%** | **59%** | **70%** |
| | Commercial | 4% | 14% | 40% | 60% | 70% |
| | Residential | <1% | 10% | 27% | 43% | 55% |
| | Industrial | 5% | 18% | 48% | 69% | 79% |

### 4.2.5. Low and High Bay

Low and high bay lighting has become increasingly popular, likely due in part to the growth in large commercial retail facilities such as Home Depot, Costco, and other big-box retail stores. In 2017, the low and high bay submarket represents 16% 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 4.31, fluorescent lamps made up the majority of the 2017 low and high bay installations, approximately 64%. Of this, T8 systems dominate, followed by T5 and T12, respectively. Overall, LED luminaires held about 10% of the installed stock in 2017, while LED lamps represented 2%. Despite the low initial stock, LED products quickly dominate the submarket, making up 61% of the installed stock in 2025. By 2035, LED luminaire penetration climbs rapidly to 79% and LED lamps make up 11% of the low and high bay submarket.

[38] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

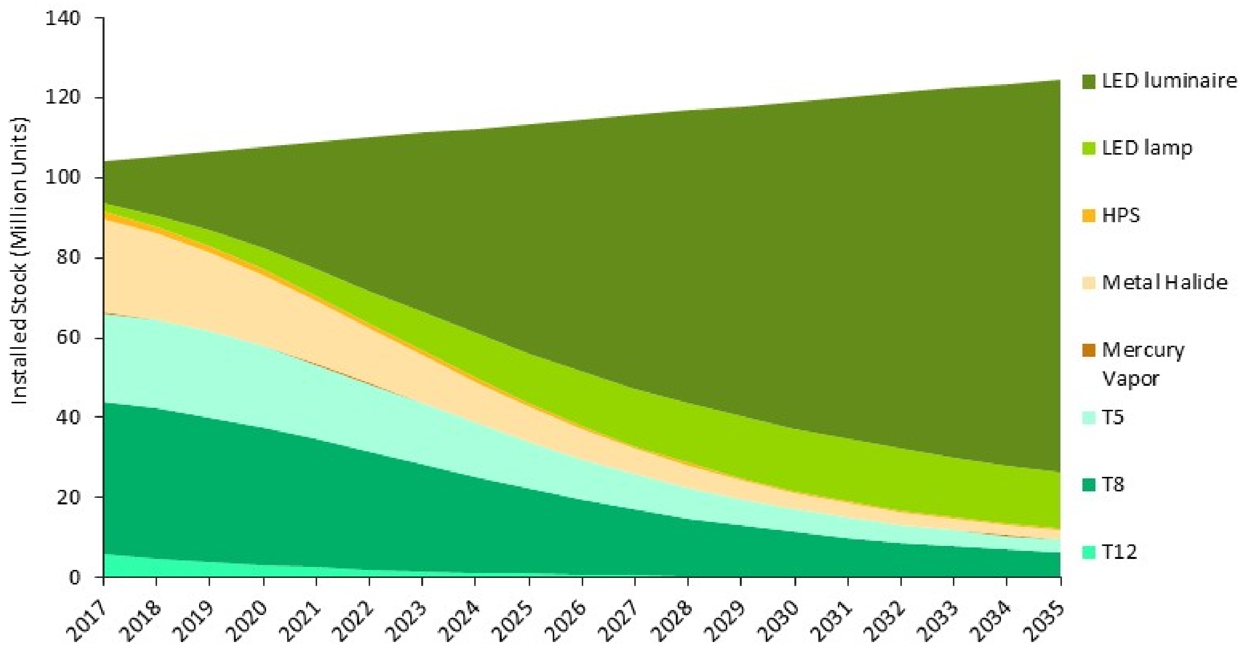


Figure 4.31 Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.26 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the low and high bay submarket.

Table 4.26 Low and High Bay Submarket LED Lighting Stock Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **LED Installed Stock (million units)[1]** | **13** | **30** | **70** | **97** | **112** |
| | Commercial | 10 | 24 | 55 | 76 | 88 |
| | Industrial | 2 | 6 | 15 | 21 | 24 |
| | **LED Installed Stock Penetration (%)** | **12%** | **28%** | **61%** | **82%** | **90%** |
| | Commercial | 13% | 29% | 63% | 83% | 91% |
| | Industrial | 10% | 24% | 57% | 78% | 88% |

1. Installed stock for the DOE SSL Program Goals 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).

As seen in Figure 4.32 and Figure 4.33, LED luminaire installed penetration grows significantly in both the commercial and industrial sectors. In the commercial sector, the stock of non-connected LED lamps and non-connected LED luminaires peaks in 2028 and 2032, respectively. After these years, connected lighting begins to take over the loss of installations. By 2035, connected lighting makes up 26% of the low and high bay submarket in the commercial sector and 25% in the industrial sector.

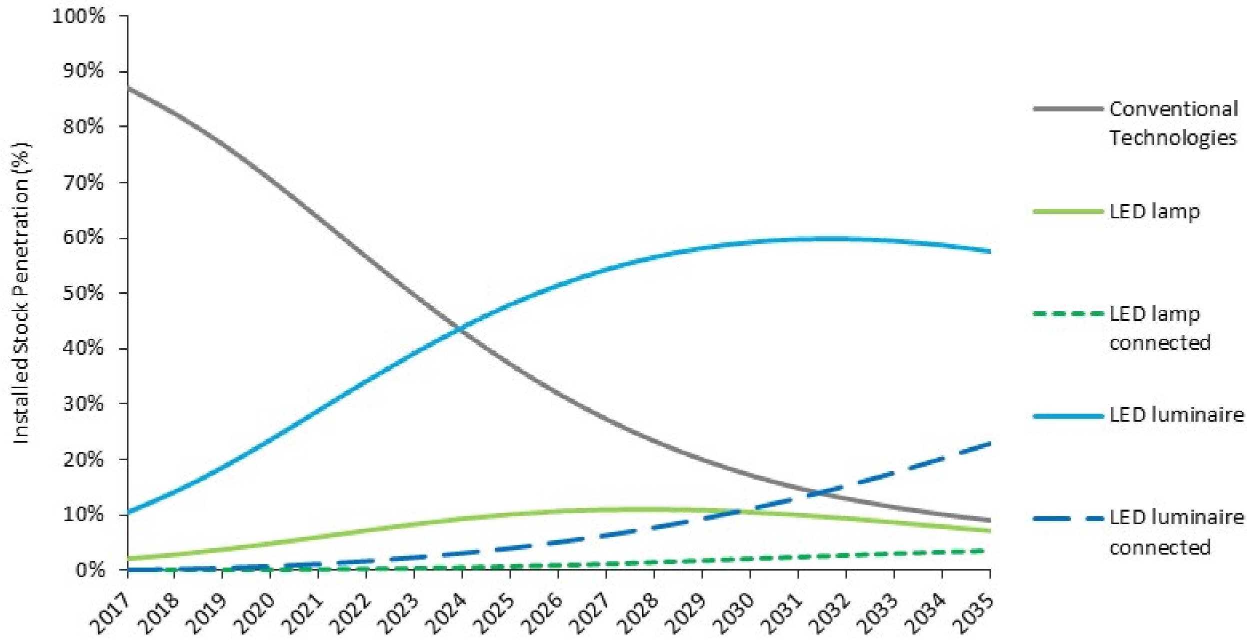


Figure 4.32 Commercial Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

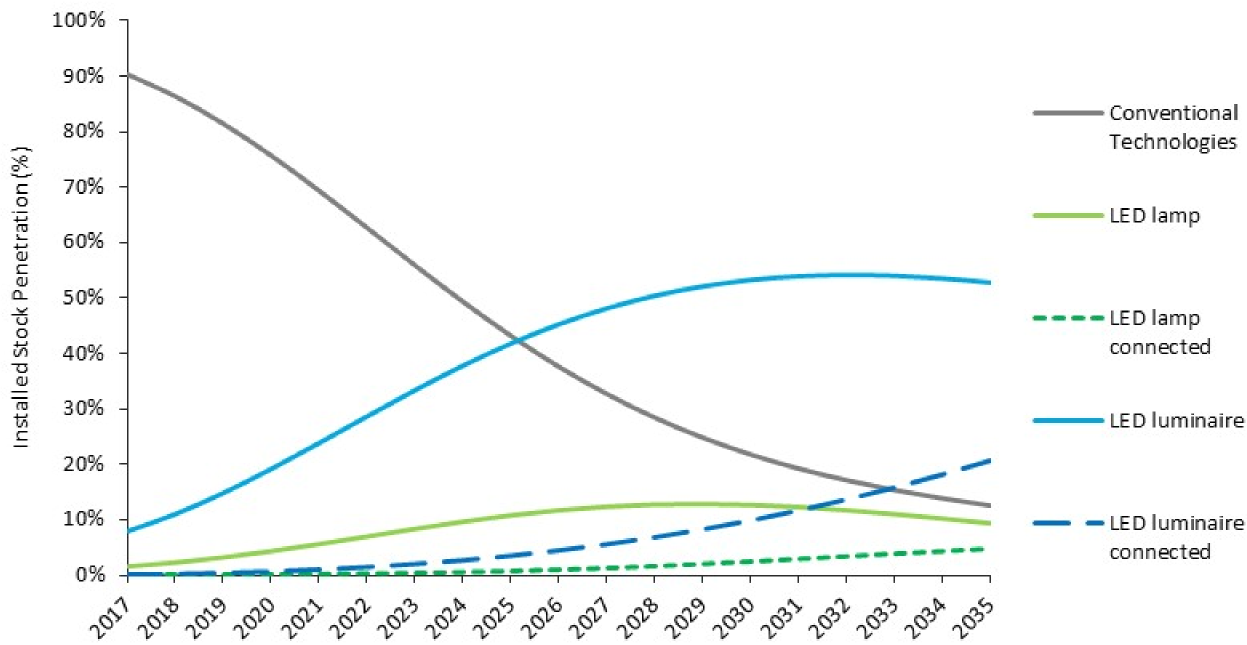


Figure 4.33 Industrial Low and High Bay Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.27 provides further breakdown of the data underlying the above figures. It shows how the installed penetration of each relevant technology evolves throughout the forecast period.

Table 4.27 Low and High Bay Submarket Installed Penetration for the Current SSL Path Scenario

| | Technology | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Commercial | T12 | 6% | 3% | <1% | <1% | <1% |
| | T8 | 35% | 31% | 18% | 9% | 5% |
| | T5 | 24% | 21% | 12% | 5% | 2% |
| | Metal Halide | 21% | 15% | 7% | 3% | 2% |
| | LED lamp | 2% | 5% | 10% | 10% | 7% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 3% |
| | LED luminaire | 11% | 24% | 48% | 59% | 58% |
| | LED luminaire connected | <1% | <1% | 4% | 11% | 23% |
| Industrial | T12 | 3% | 2% | 1% | <1% | <1% |
| | T8 | 42% | 36% | 21% | 10% | 5% |
| | T5 | 12% | 10% | 7% | 4% | 3% |
| | Metal Halide | 26% | 21% | 12% | 6% | 4% |
| | HPS | 7% | 6% | 3% | 2% | <1% |
| | LED lamp | 2% | 4% | 11% | 13% | 9% |
| | LED lamp connected | <1% | <1% | <1% | 2% | 5% |
| | LED luminaire | 8% | 19% | 42% | 53% | 53% |
| | LED luminaire connected | <1% | <1% | 4% | 10% | 21% |

Similar to linear fixtures, the low and high bay submarket is another key application where the benefits of connected LED lighting are predicted to have a significant impact. In the Current SSL Path scenario, the lighting market model predicts that connected LED products will reach 26% by 2035.

On the other hand, in the DOE SSL Program Goals scenario, the portion of non-connected versus connected LED lighting is expected to flip, with connected lamps and luminaires holding the vast majority of low and high bay installations. As seen in Figure 4.34, this translates to connected LED lamps and luminaires representing 65% of all low and high bay installations.

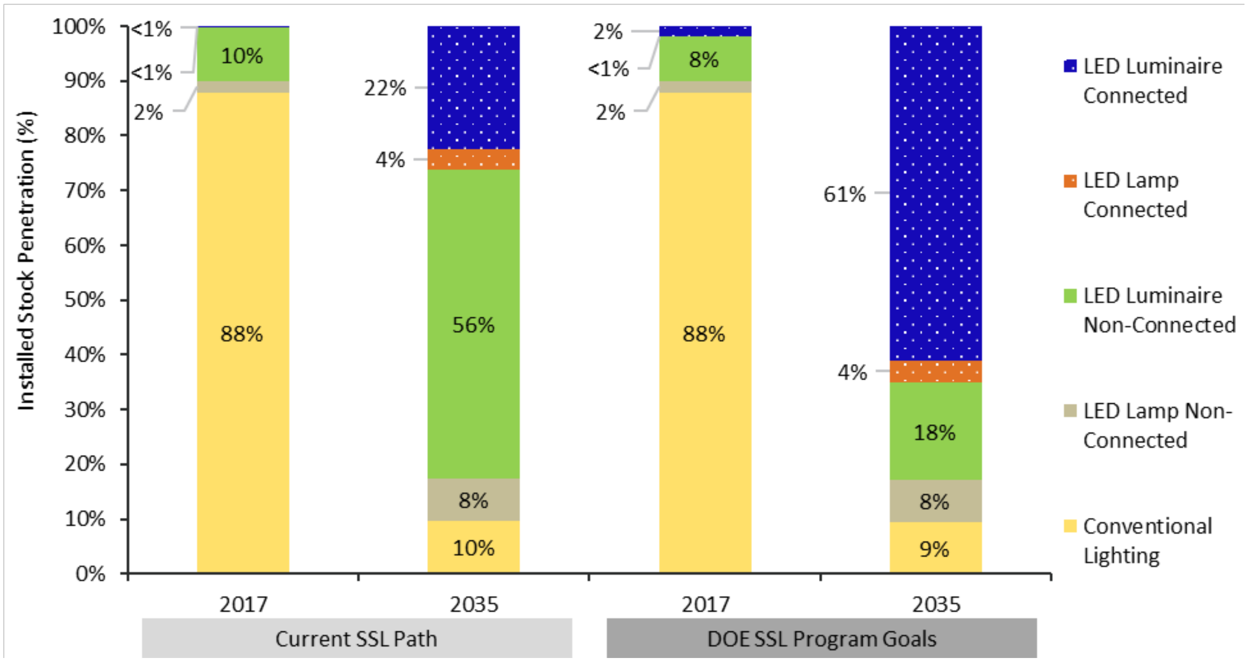


Figure 4.34 Low and High Bay Submarket LED Lighting Installed Stock Penetration[39]

Table 4.28 shows that the increasing adoption of LED lighting is expected to achieve 62% source energy savings in 2035 for the Current SSL Path scenario and 76% source energy savings in 2035 for the DOE SSL Program Goals scenario in the low and high bay submarket across all sectors. This increase results in an additional 168 tBTU of annual energy savings by 2035.

[39] There is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.

**Table 4.28 Low and High Bay Submarket LED Lighting Energy Savings Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | **Source Energy Savings (tBTU)[40]** | **185** | **303** | **536** | **679** | **760** |
| | Commercial | 161 | 245 | 406 | 501 | 556 |
| | Industrial | 24 | 57 | 129 | 178 | 204 |
| | **Source Energy Savings (%)** | **16%** | **26%** | **45%** | **57%** | **62%** |
| | Commercial | 19% | 30% | 48% | 58% | 63% |
| | Industrial | 8% | 18% | 39% | 53% | 60% |
| DOE SSL Program Goals | **Source Energy Savings (tBTU)** | **189** | **325** | **625** | **823** | **928** |
| | Commercial | 164 | 261 | 470 | 604 | 673 |
| | Industrial | 25 | 64 | 154 | 219 | 255 |
| | **Source Energy Savings (%)** | **16%** | **28%** | **53%** | **69%** | **76%** |
| | Commercial | 19% | 32% | 56% | 70% | 77% |
| | Industrial | 8% | 20% | 46% | 65% | 75% |

### 4.2.6. Area and Roadway

LED lighting is particularly advantageous in the area and roadway lighting submarket because they are excellent directional light sources, durable, and exhibit long lifetimes. Largely because of these advantages, LED lamps and luminaires already hold an impressive 37% of installations in 2017. HPS lamps comprise about 57% of the 2017 area and roadway installations. The installed stock of metal halide, LPS, and "other" technology lamps has historically been non-negligible, but, as of 2017, they each account for 2% or less of the stock. In area and roadway applications, the "other" technology category is almost entirely induction lighting. In total, non-HPS conventional technologies make up less than 6% of installations in 2017. Going forward, the large stock of HPS lamps quickly gives way to LED lamps and luminaires, which are projected to collectively represent the majority by 2019. The lighting market model projects LED installed stock to increase rapidly, reaching over 90% of area and roadway installation as early as 2025. By 2035, nearly all installations will be LED lamps or luminaires.

Like many other submarkets, we see an initial uptake of LED replacement lamps. However, by 2026, the installed penetration of LED lamps begins to decrease 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.

[40] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

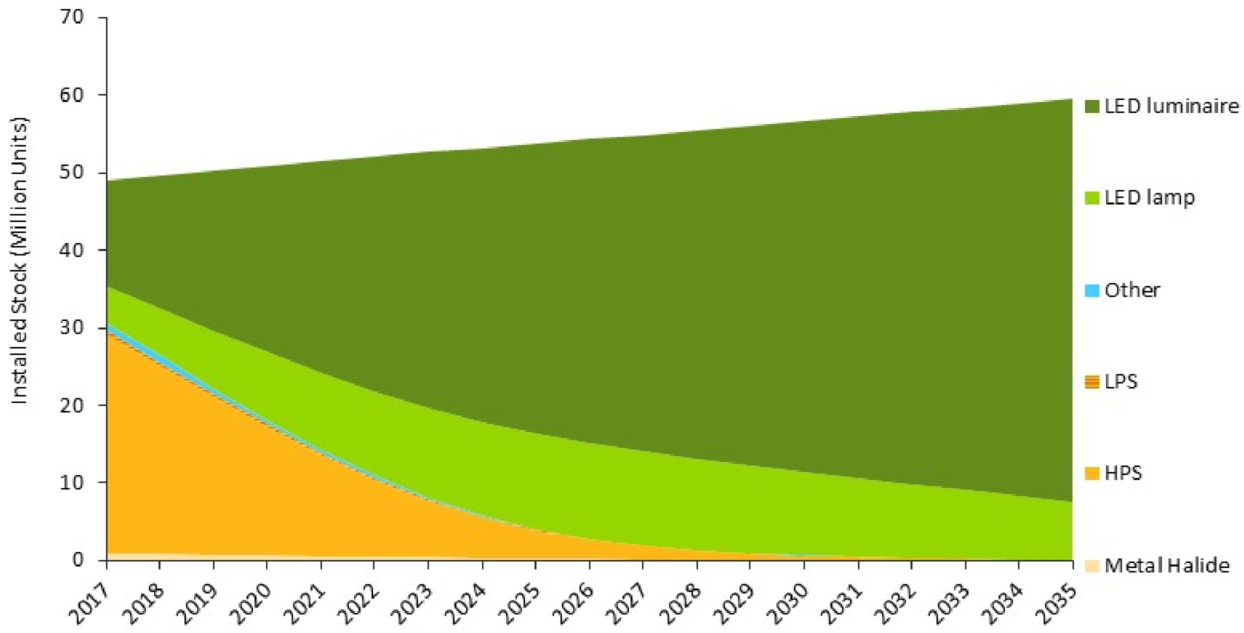


Figure 4.35 Area and Roadway Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.29 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the area and roadway submarket.

Table 4.29 Area and Roadway Submarket LED Lighting Stock Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | LED Installed Stock (million units)[1] | 18 | 33 | 50 | 56 | 59 |
| | LED Installed Stock Penetration (%) | 37% | 64% | 92% | 99% | 100% |

1. Installed stock for the DOE SSL Program Goals 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).

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 street light from one central location is highly appealing to municipalities and utilities alike.

Figure 4.36 shows the forecast of connected versus non-connected LED lighting in both the Current SSL Path and DOE SSL Program Goals 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 LED lighting reaching roughly 33%. However, for the DOE SSL Program Goals scenario, a staggering 76% of all LED area and roadway installations are projected to have connected capabilities.

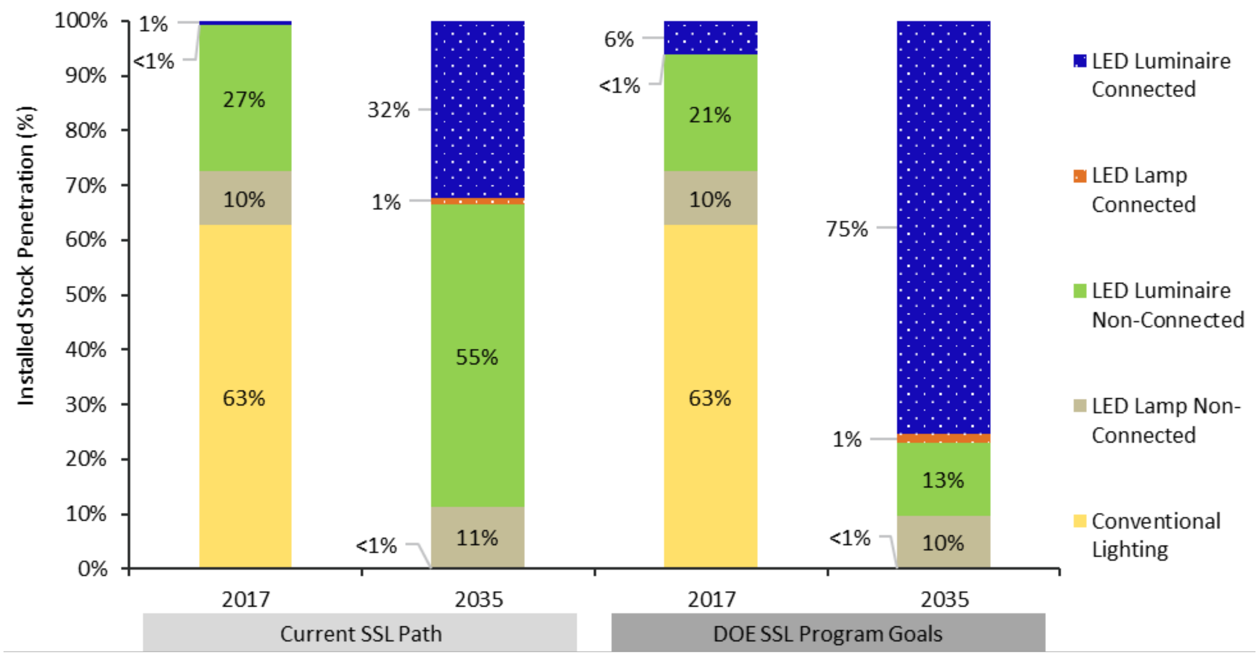


**Figure 4.36 Area and Roadway Submarket LED Lighting Installed Stock Penetration[41]**

Table 4.30 shows that the increasing adoption of LED lighting is expected to achieve 63% source energy savings in 2035 for the Current SSL Path scenario and 79% source energy savings in 2035 for the DOE SSL Program Goals scenario in the area and roadway submarket. This increase results in an additional 77 tBTU of annual energy savings by 2035.

**Table 4.30 Area and Roadway Submarket LED Lighting Energy Savings Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | Source Energy Savings (tBTU)[42] | 89 | 161 | 248 | 283 | 303 |
| | Source Energy Savings (%) | 21% | 37% | 55% | 61% | 63% |
| DOE SSL Program Goals | Source Energy Savings (tBTU) | 94 | 182 | 302 | 356 | 380 |
| | Source Energy Savings (%) | 22% | 42% | 67% | 76% | 79% |

### 4.2.7. Parking

In 2017, there were over 76 million installations in the parking submarket, with nearly 50 million in parking lots and 26 million in parking garages. Similar to building exterior applications, there are some instances of incandescent, halogen, and linear fluorescent lamps and other miscellaneous lamps[43]; combined, they make up 15% of all parking installations in 2017.

As shown in Figure 4.37, metal halide and HPS made up 47% and 13% of the 2017 parking lot installations, respectively, and they prove to be strong competitors. Collectively, LED lamps and luminaires are expected to

[41] There is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.
[42] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report
[43] These other miscellaneous lamps include lighting technologies such as plasma and induction lamps.

represent the majority of installations by 2019. As with many outdoor submarkets, LED luminaires dominate the installed stock by 2035, comprising over 94% of parking light installations.

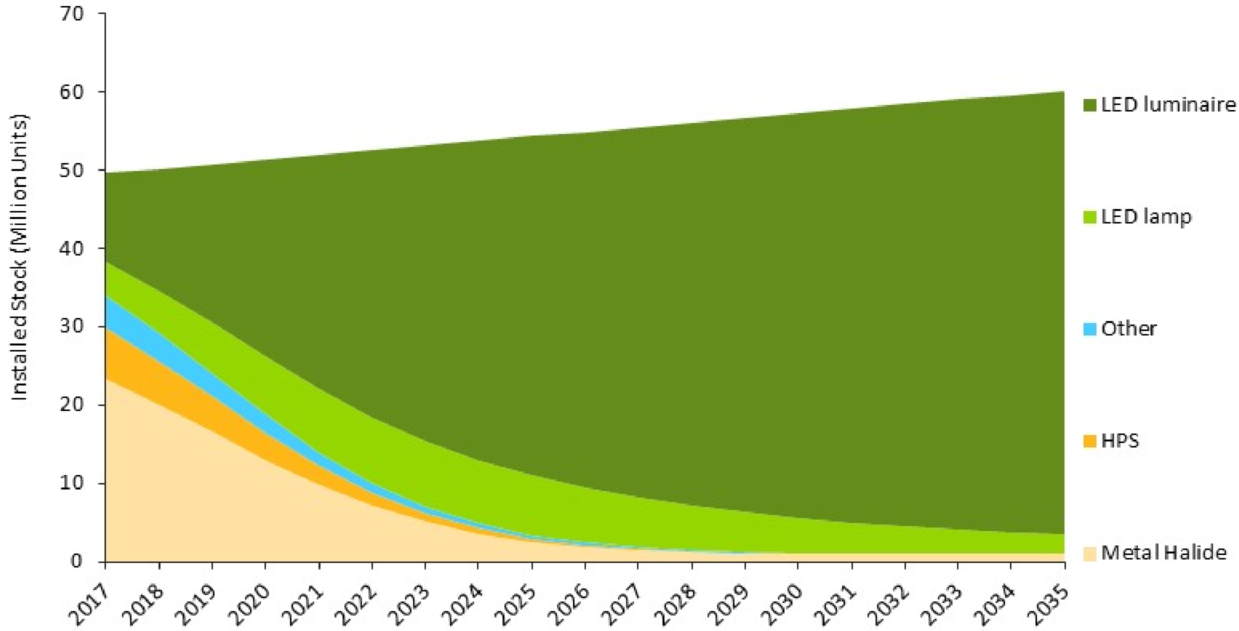


Figure 4.37 Parking Lot Submarket Stock Forecast for the Current SSL Path Scenario

As shown in Figure 4.38, the parking garage submarket has a unique mix of technologies at the beginning of the forecast period. Because the fixtures in parking garage applications are employed predominantly in covered garages with low mounting heights, many technologies prove effective. In 2017, the most prevalent conventional technology is HPS, making up 17% of the submarket. The "other" technology category, which is almost entirely induction lighting, plays a significant role in both parking garage and parking lot applications. Metal halide, halogen, and linear fluorescent make up 10%, 7%, and 4% of the 2017 parking garage installations, respectively. LED lamps and luminaires collectively reach the majority of installations in 2018, and by 2035 represent nearly all installations.

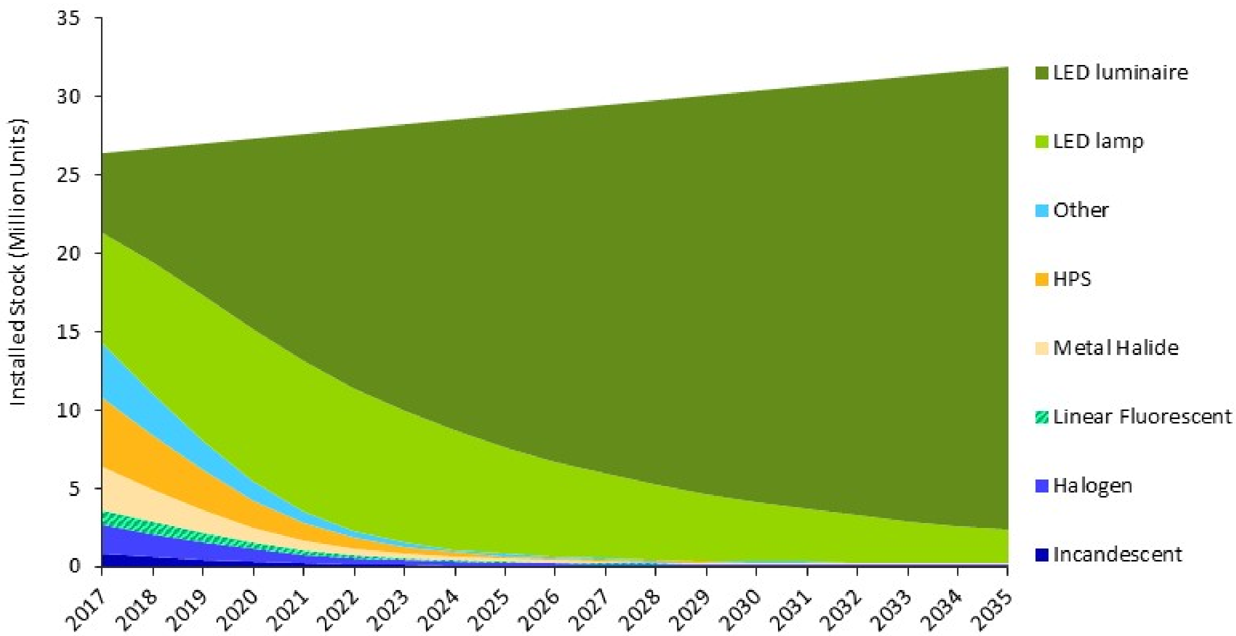


**Figure 4.38 Parking Garage Submarket Stock Forecast for the Current SSL Path Scenario**

Table 4.31 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the parking lot and garage submarkets combined.

**Table 4.31 Parking Submarket LED Lighting Stock Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | LED Installed Stock (million units)[1] | 28 | 55 | 79 | 86 | 91 |
| | LED Installed Stock Penetration (%) | 36% | 69% | 95% | 98% | 98% |

1. Installed stock for the DOE SSL Program Goals 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).

Figure 4.39 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 33% of all parking installations. If the DOE goals for connected adoption are met, by 2035, connected LED lighting is expected to represent the overwhelming majority, comprising 75% of all parking installations.

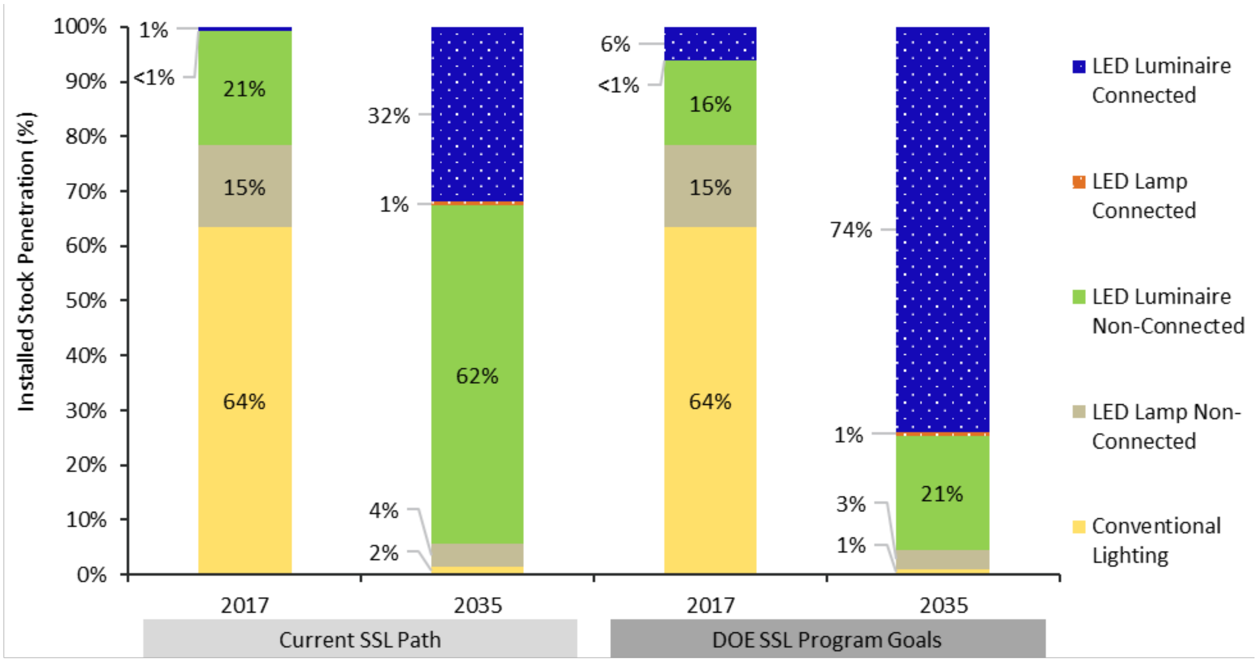


Figure 4.39 Parking Submarket LED Lighting Installed Stock Penetration[44]

Table 4.32 shows that the increasing adoption of LED lighting is expected to achieve 66% source energy savings in 2035 for the Current SSL Path scenario and 80% source energy savings in 2035 for the DOE SSL Program Goals scenario in the parking submarket. This increase results in an additional 150 tBTU of annual energy savings by 2035.

Table 4.32 Parking Submarket LED Lighting Energy Savings Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | Source Energy Savings (tBTU)[45] | 259 | 483 | 660 | 692 | 710 |
| | Source Energy Savings (%) | 26% | 47% | 64% | 66% | 66% |
| DOE SSL Program Goals | Source Energy Savings (tBTU) | 268 | 531 | 770 | 835 | 860 |
| | Source Energy Savings (%) | 26% | 52% | 74% | 79% | 80% |

### 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. 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 2017, incandescent, halogen, and compact fluorescent lamps together represent about 15% of installations, while higher output metal halide and HPS represent a combined 25% in the building exterior submarket. Linear fluorescent lamps comprise 27% of the submarket.

[44] There is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.

[45] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

As shown in Figure 4.40, much like the other outdoor submarkets, LED lighting products in the building exterior submarket are gaining significant ground. In 2017, LED lamps and luminaires in this submarket have reached a combined total of about 31% of the installed stock, or roughly 27 million total installations. LED lamps are competitive in the near term, yet LED luminaire prices, which are already cheaper on a system basis (lamp and ballast) than HPS and metal halide, are projected to continue to decrease, prompting a swift increase in the adoption of LEDs in this submarket. As shown in Figure 4.40, the installations of LED lamps and luminaires combined are forecasted to grow to 92% in 2025 and 98% by 2035.

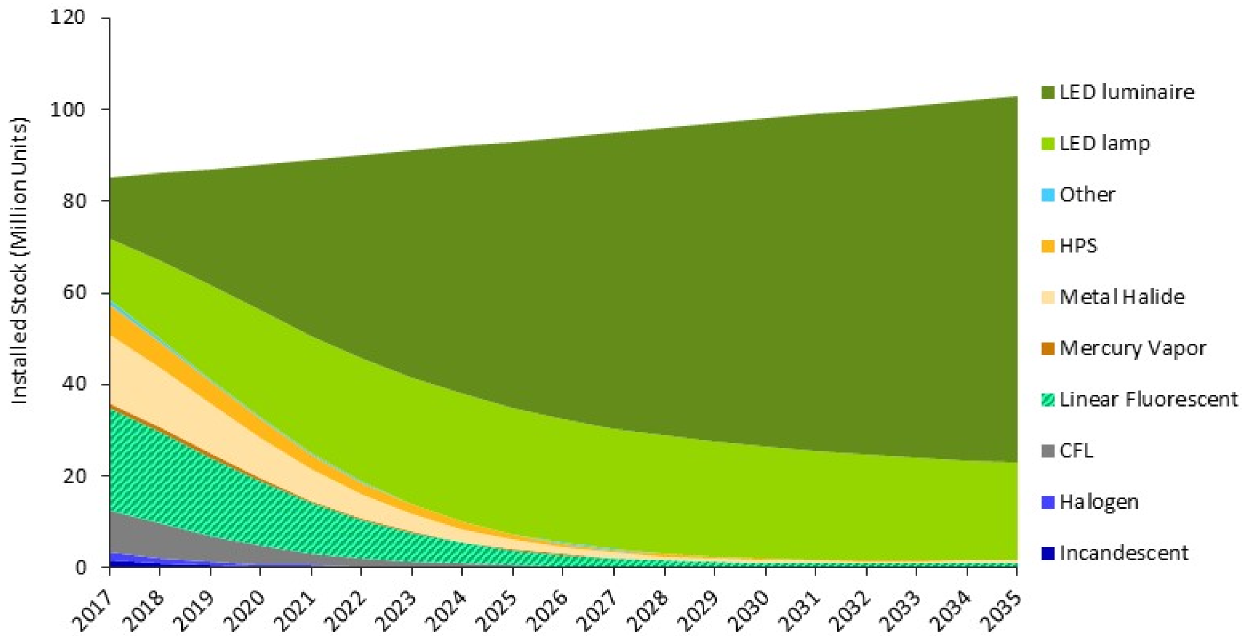


Figure 4.40 Building Exterior Submarket Stock Forecast for the Current SSL Path Scenario

Table 4.33 provides the lighting market model forecast results for LED installed stock penetration over the 18-year analysis period for the building exterior submarket.

Table 4.33 Building Exterior Submarket LED Lighting Stock Forecast Results

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | LED Installed Stock (million units)[1] | 27 | 55 | 86 | 96 | 101 |
| | LED Installed Stock Penetration (%) | 31% | 63% | 92% | 98% | 98% |

1. Installed stock for the DOE SSL Program Goals 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).

Figure 4.41 shows the forecast of connected versus non-connected LED lighting in both the Current SSL Path and DOE SSL Program Goals scenarios. The building exterior submarket is not expected to value connected lighting as highly as the other outdoor submarkets. However, it is still expected to see significant installation growth. For the Current SSL Path scenario, by 2035, connected LED lighting represents the minority at 34% of installations. However, for the DOE SSL Program Goals scenario, connected LED lighting is projected to become the majority at 74% of all building exterior installations by 2035.

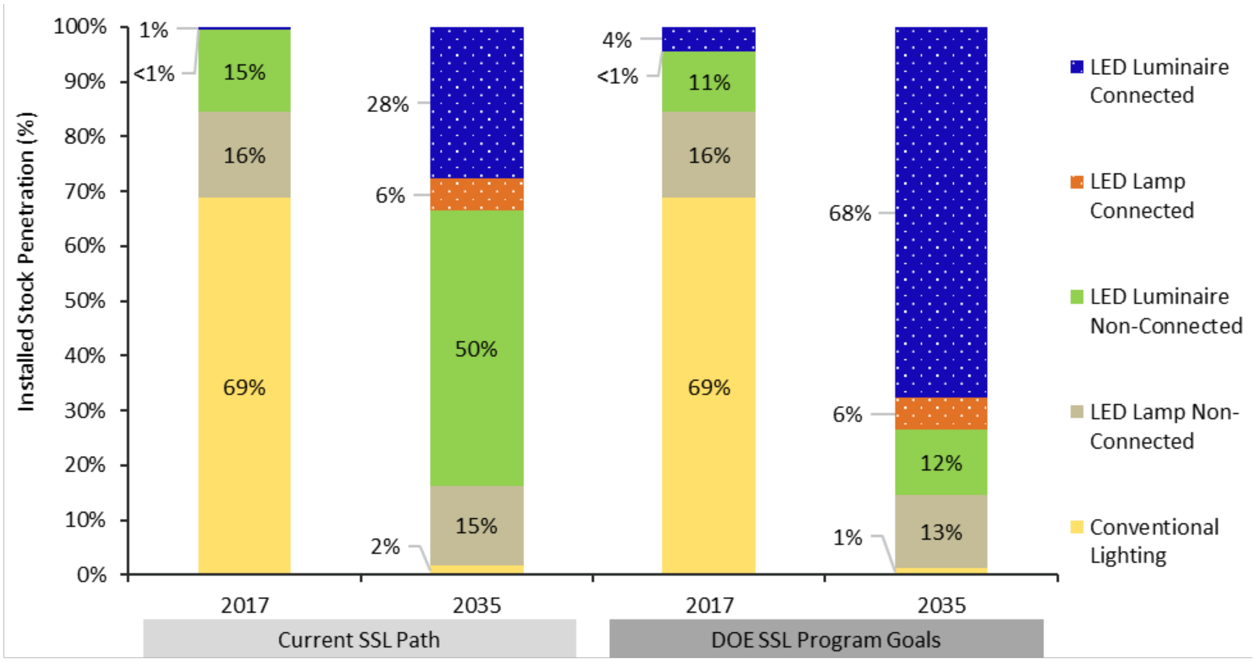


**Figure 4.41 Building Exterior Submarket LED Lighting Installed Stock Penetration[46]**

Table 4.34 shows that the increasing adoption of LED lighting is expected to achieve 59% source energy savings in 2035 for the Current SSL Path scenario and 77% source energy savings in 2035 for the DOE SSL Program Goals scenario in the building exterior submarket. This increase results in an additional 82 tBTU of annual energy savings by 2035.

**Table 4.34 Building Exterior Submarket LED Lighting Energy Savings Forecast Results**

| | | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Current SSL Path | Source Energy Savings (tBTU)[47] | 96 | 157 | 220 | 242 | 254 |
| | Source Energy Savings (%) | 25% | 40% | 54% | 58% | 59% |
| DOE SSL Program Goals | Source Energy Savings (tBTU) | 100 | 180 | 275 | 316 | 336 |
| | Source Energy Savings (%) | 26% | 46% | 67% | 75% | 77% |

[46] There is already a measurable difference between the Current SSL Path and the DOE SSL Program Goals scenarios in terms of connected lighting penetration. The 2016 Forecast Report showed that the variation between the two scenarios was relatively small in 2015, the beginning of the forecast period for the 2016 lighting market model. However, in this Forecast Report, in the 2017 model start year there is already a noticeable difference between the scenarios. This energy savings differential is expected to continue to grow in the future, emphasizing the missed opportunity for potential savings if the goals of the DOE SSL program are not met.

[47] The source energy savings values are also provided in TWh units in the 2018 Forecast Report Excel Tables, which can be found at: https://www.energy.gov/eere/ssl/downloads/2018-ssl-forecast-report

# 5. LED Forecast Comparison

Below the results of this Forecast Report are compared to nine other forecast analyses to provide greater context. In addition, included in the comparison set are the 2012, 2014, and 2016 iterations of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* report. (22; 23; 24) Table 5.1 below lists these forecasts. It is important to note that each varies in methodology, regions covered (e.g., U.S. market, global market), metric (e.g., sales, installations, and socket penetration), as well as the LED units considered (e.g., 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 Lighting Forecast Analyses

| Source | LED Metric | Region | 2020 Value |
|---|---|---|---|
| Strategies Unlimited, 2018 | % Lamp & Luminaire Installations | World | 44% |
| Bonneville Power Administration, 2017 | % Lamp Installations – Residential | U.S. Pacific Northwest | 53% |
| Goldman Sachs, 2016 | % Unit Sales | U.S. | 77% |
| Strategies Unlimited, 2015 | % Luminaire Installations | North America | 53% |
| Strategies Unlimited, 2015 | % Lamp Installations | North America | 32% |
| IHS Research, May 2015 | % Lamp Installations | World | 25% |
| Samsung Electronics, 2014 | % Unit Sales | World | 42% |
| Canaccord Genuity, 2013 | % Socket Penetration | World | 54% to 80% |
| McKinsey, 2012 | % Unit Sales | World | 57% |
| DOE, 2018 | % Installations (Unit Systems)[1] | U.S. | 35% |
| DOE, 2016 | % Installations (Unit Systems)[1] | U.S. | 30% |
| DOE, 2014 | % Installations (Teralumen Hours)[2] | U.S. | 39% |
| DOE, 2012 | % Installations (Teralumen Hours)[2] | 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).
2. The 2012 and 2014 iterations of the Forecast Report 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). The 2016 Forecast Report and this Forecast Report have converted the model to a 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.

The results of these studies vary significantly. However, all of the analyses conclude that LED lighting will have tremendous growth over the remainder of this decade and comprise anywhere from 25% to upwards of 80% of all lighting installations (new and existing) by 2020. Note that since the region analyzed in these reports varies, many of them are not directly comparable.

This report is the third DOE SSL Program Forecast Report that has calibrated the lighting market model using LED sales and shipment data provided by manufacturers, distributors, retailers, and industry associations. This track record makes it possible to calibrate the lighting market model outputs for future years based on the actual pattern of LED market share changes thus far, effectively improving the accuracy of the predictions. This calibration to LED sales and shipment data indicated that expected installations are similar to DOE estimates from 2016 and 2014. However, the lighting market model estimates a higher LED installed stock in 2017 and predicts a more rapid growth in LED lighting compared to the 2016 DOE SSL Forecast.

The results published in this Forecast Report are, in general, comparable to those published in the 2016 DOE SSL Forecast. Table 5.2 shows the national-level results of the 2016 DOE SSL Forecast compared to the results of this Forecast Report. The most significant changes are due to updated data from the 2015 LMC. (5) Some results from the 2015 LMC are used as inputs to the lighting market model, whereas others are used to aid in calibrating the lighting market model. In both cases, previous versions of the DOE SSL Forecast used data from the 2010 LMC. (4) Since the 2015 LMC became available in November 2017, it has offered increased accuracy and new data for this lighting market model update.

As can be seen in Table 5.2, the total installed stock was increased. In particular, the total 2017 stock was revised from 7.0 billion to 7.6 billion, and the 2035 stock was revised from 8.6 billion to 9.4 billion. (5) This change is driven mostly by the recently published 2015 LMC. In the 2015 LMC, total stock was estimated to be proportionally higher than the total stock estimates in the 2010 LMC, thus changing inputs to, and calibration of, this lighting market model. (4; 5)

Table 5.2 also shows that, in addition to the increased stock, the estimated total number of LED lighting units installed in 2017 was increased from 14% of total stock in the 2016 Forecast Report to 18% in this Forecast Report. This revision was based on new data from the 2015 LMC and the 2017 LED Adoption Report. The estimated 2017 installed penetration of connected LED lighting has remained nearly the same, while the final 2035 connected installed penetration was revised upward from 10% to 15%. This change is also due to updated data from the 2017 LED Adoption Report. (25)

Lastly, Table 5.2 shows that the total 2035 energy consumption across all sectors is now estimated to be slightly higher. This difference is rooted in the increased stock estimates. However, although the total energy consumption increased, the per-unit energy consumption decreased due in part to the higher estimated initial LED installed penetration. These revisions to total stock, LED installed penetration, and energy consumption are the most notable national-level changes compared to the previous 2016 DOE SSL Forecast.

Table 5.2 Comparison of DOE SSL Forecast 2016 and 2018

| Metric | Year | 2016 Forecast Report | 2018 Forecast Report | Main Cause of Revision |
|---|---|---|---|---|
| Total Stock | 2017 | 7.0 billion | 7.6 billion | Increased stock due to updated input data from LMC 2015. |
| | 2035 | 8.6 billion | 9.4 billion | Difference is caused by increased 2017 stock (growth rate from 2017 to 2035 is very similar in both forecasts). |
| LED Installed Penetration | 2017 | 14% | 19% | Updated input data from LMC 2015 and additional data from 2017 LED Adoption Report. |
| | 2035 | 86% | 84% | Minor change. |
| Connected Installed Penetration (Within LEDs) | 2017 | <1% | <1% | Minor change. |
| | 2035 | 10% | 15% | Updated data from 2017 LED Adoption Report. |
| Total Energy Consumption | 2017 | 5,784 tBTU | 5,966 tBTU | Updated input data from LMC 2015 and additional data from 2017 LED Adoption Report. |
| | 2035 | 3,112 tBTU | 3,350 tBTU | This difference is largely due to increased stock. On a per-unit basis, the energy consumption decreased – in part due to quicker LED penetration. |

# 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 the EIA 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 to capture major differences in inventory and patterns of usage arising from distinct lighting needs and decision-makers.

To model the competition between lighting technologies within the U.S. lighting market, the current lighting market 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).

The lighting technologies competing within each submarket are derived from the 2010 U.S. Lighting Market Characterization (LMC) report (4), 2015 LMC report (5), and the public data files provided by the Northwest Energy Efficiency Alliance (NEEA) 2014 Commercial Building Stock Assessment. (4; 5; 7) A total of 31 conventional lighting technologies were considered:

- Incandescent: general purpose, decorative, reflector, miscellaneous
- Halogen: general purpose, 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
- Light-emitting diode: LED lamps and luminaires
- Other: induction, miscellaneous

This analysis reduces that count to 23 by combining linear fluorescent categories less than 4ft, 4ft, greater than 4ft, and U-shaped for both T8 and T12. Furthermore, the “other” category and all lamps in that category are excluded from this analysis due to great uncertainty regarding these lamp types and their characteristics. These excluded 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 2010 LMC was used to develop the 2010 installed base for conventional technologies in the remaining product categories.

The 2010 LMC is used as the starting point for the lighting technologies examined in the 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 2017. In order to appropriately update the LMC inventory estimates to 2017, data was collected through interviews with manufacturers and retailers, as well as from the 2014 Commercial Building Stock Assessment. Additionally, the 2015 LMC was used to calibrate the stock for all technologies, and in some instances resulted in stock shifts that impacted the base year lighting inventory. The directional and low and high bay submarkets experienced the biggest shift. In addition, the 2015 LMC release included a revision to the 2010 outdoor sector stock values due to enhanced data availability. As a result, the 2010 and 2015 stock values that were used for calibration experienced modifications that, in some instances, were significant. This led to an increase in initial stock for all submarkets within the outdoor sector. The most significant revision was a 42% stock increase in the parking submarket.

However, because the 2010 LMC grouped all LED lighting into a single category and included LED exit signs, which are not considered a general illumination white-light source, the 2010 LMC data was not used to develop the 2010 installed base of LED lamps and luminaires. Instead, the LED installed base was estimated using a combination of data sources including the 2015 LMC, which provides LED stock estimates for the following product categories: general purpose, integrated, linear, reflector, reflector – low voltage, and miscellaneous. Additionally, the LED Adoption Report[48], which collected LED sales data for the years 2010, 2012, 2013, 2014, 2015, 2016, and 2017 from manufacturers, retailers, industry experts, as well as the shipment data from National Electrical Manufacturers Association, ENERGY STAR®, and lighting distributors.

[48] 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 2017 by sector and submarket, the next step was projecting 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. This is estimated by the lighting market model, which evaluates three events that determine the new installations available each year:

**New Construction**. New construction includes new fixtures installed each year due to floor space growth in each sector, determined by growth or retirement projections. The AEO 2018 provides annual average growth forecasts of floor space in the residential and commercial sectors. (1) Projections specific to each year were used in the lighting market model. Projections suggest that residential floor space will increase by an average of 1.2% per annum over the 18-year analysis period, and the commercial sector floor space will increase by an average of 1.1% per annum. The AEO 2018 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 2018 annual projections for manufacturing employment were used as a proxy for the annual increase in industrial floor space. The data were fit to a best fit curve to smooth out yearly variations. The data indicate an average increase of 0.8% per annum over the 18-year analysis period.

In summary, the average annual floor space growth rates used in the analysis, representing the annual change in lighting demand between 2017 and 2035, are:

- Residential: 1.2% growth
- Commercial: 1.1% growth
- Industrial: 0.8% growth
- Outdoor: 1.1% growth

For the lighting stock demand in this category, the costs considered for conventional technologies include the costs of the lamp, fixture, and ballast (where relevant). 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.** Renovations include lamps (and ballasts, where relevant) 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 Goals scenarios. As with the new construction category, LED lamps in this market compete with conventional lighting technologies on a basis that includes new fixture costs. It is important to note that this renovation rate is 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.[49] (12) 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.** Replacements include 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

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

lifetime (in hours) of the lamps and ballasts installed. For this analysis, the lighting market model assumes that manufacturers of LED lighting products produce either 1) lamps that match conventional screw-base and pin-based technologies, which can be installed directly into existing lighting fixtures, or 2) 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 develop and improve over time.

# 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 2017. The efficacies presented in these tables represent mean system efficacies (including ballast losses, where appropriate), rather than initial efficacies.

The lighting market model improves the lamp efficacy, ballast efficiency (if applicable), and equipment costs for some conventional lighting technologies, as described below. 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.

The costs of CFL, linear fluorescent, mercury vapor, metal halide, high presume sodium, low pressure sodium, and directional lamps, ballasts (if applicable), and fixtures are expected to decrease at a rate of between 0.1% and 0.6% per year. The magnitude of cost changes is highest at the beginning of the forecast period and decreases through the end.

The lighting market model also assumes that efficacy is expected to increase at a rate of 0.5% per year for halogen directional, T5, metal halide, and CFL pin lamps. The remaining conventional technologies are expected to show no efficacy improvements. 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 is expected to improve, but not ballast efficiency. For all technologies, the only improvements expected to be made to fixtures are in reducing first cost. This is because manufacturing costs may decrease, but the technology used in lighting fixtures themselves is expected to remain largely unchanged.

**Table C.1 Commercial Sector Conventional Technology Performance 2017**

| Commercial Sector Submarkets | Mean Lamp Wattage (W)[1] | Lamp Life (1,000 hr)[2] | Mean Efficacy (lm/W) | Lamp Price ($) | Ballast Price ($) | Fixture Price ($) |
|---|---|---|---|---|---|---|
| General Purpose | | | | | | |
| Incandescent Omni | 40 | 2.7 | 17 | 4.7 | - | 15 |
| Halogen Omni | 60 | 1.4 | 17 | 4.5 | - | 15 |
| CFL Omni | 21 | 11 | 65 | 12 | - | 14 |
| Decorative | | | | | | |
| Incandescent Omni | 43 | 2.5 | 7.9 | 1.3 | - | 19 |
| Incandescent Directional | 43 | 2.5 | 7.9 | 3.1 | - | 18 |
| Halogen Omni | 43 | 2.3 | 17 | 3.8 | - | 19 |
| Halogen Directional | 43 | 2.3 | 17 | 4.7 | - | 18 |
| CFL Omni | 33 | 10 | 52 | 3.6 | - | 17 |
| CFL Pin | 35 | 10 | 52 | 6.8 | 17 | 14 |
| Downlights | | | | | | |
| Incandescent Omni | 63 | 2.7 | 11 | 0.5 | - | 23 |
| Incandescent Directional | 97 | 2.7 | 9.2 | 3.1 | - | 23 |
| Halogen Omni | 64 | 1.4 | 16 | 1.9 | - | 23 |
| Halogen Directional | 67 | 3.2 | 14 | 4.7 | - | 23 |
| CFL Directional | 21 | 9.2 | 45 | 17 | - | 21 |
| CFL Pin | 40 | 9.3 | 45 | 17 | 17 | 14 |
| Track Lighting | | | | | | |
| Incandescent Omni | 40 | 2.7 | 17 | 0.5 | - | 24 |
| Incandescent Directional | 97 | 2.7 | 9.2 | 3.1 | - | 23 |
| Halogen Omni | 60 | 1.4 | 17 | 1.9 | - | 23 |
| Halogen Directional | 67 | 3.2 | 14 | 4.7 | - | 23 |
| CFL Directional | 21 | 9.2 | 45 | 9.3 | - | 21 |
| Small Directional (MR16) | | | | | | |
| Halogen | 41 | 3.2 | 14 | 4.6 | - | 23 |
| General Service Linear Fixtures | | | | | | |
| T12 <4ft | 40 | 11 | 88 | 2.9 | 15 | 68 |
| T8 <4ft | 43 | 22 | 79 | 5.3 | 17 | 68 |
| T5 <4ft | 84 | 20 | 87 | 6.1 | 20 | 73 |
| T12 4ft | 65 | 16 | 88 | 2.4 | 15 | 68 |
| T8 4ft | 69 | 32 | 85 | 4.4 | 17 | 68 |
| T5 4ft | 75 | 34 | 98 | 6.1 | 20 | 73 |
| T12 >4ft | 150 | 12 | 88 | 5.6 | 17 | 68 |
| T8 >4ft | 132 | 26 | 92 | 6.9 | 20 | 68 |
| T5 >4ft | 75 | 23 | 98 | 6.1 | 20 | 73 |
| Low/High Bay | | | | | | |
| T12 | 284 | 12 | 88 | 5.6 | 17 | 68 |
| T8 | 283 | 27 | 89 | 8.2 | 20 | 68 |
| T5 | 164 | 22 | 89 | 6.1 | 23 | 73 |
| Mercury Vapor | 374 | 17 | 33 | 31 | - | 67 |
| Metal Halide | 498 | 15 | 67 | 39 | 195 | 72 |

| | | | | | | |
|---|---|---|---|---|---|---|
| High Pressure Sodium | 441 | 26 | 90 | 49 | 248 | 78 |
| Low Pressure Sodium | 177 | 20 | 76 | 38 | 103 | 67 |
| **Other** | | | | | | |
| CFL Pin | 28 | 12 | 67 | 5.0 | 17 | 14 |
| Halogen | 89 | 1.5 | 23 | 4.6 | - | 15 |
| Mercury Vapor | 374 | 17 | 33 | 31 | - | 67 |
| Metal Halide | 437 | 15 | 77 | 39 | 195 | 72 |
| High Pressure Sodium | 441 | 26 | 90 | 49 | 248 | 78 |
| Miscellaneous | 22 | 11 | 51 | 5.5 | - | 70 |

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

**Table C.2 Residential Sector Conventional Technology Performance 2017**

| Residential Sector Submarkets | Mean Lamp Wattage (W)[1] | Lamp Life (1,000 hr)[2] | Mean Efficacy (lm/W) | Lamp Price ($) | Ballast Price ($) | Fixture Price ($) |
|---|---|---|---|---|---|---|
| General Purpose | | | | | | |
| Incandescent Omni | 58 | 2.7 | 11 | 0.5 | - | 19 |
| Halogen Omni | 51 | 1.4 | 18 | 1.9 | - | 19 |
| CFL Omni | 15 | 11 | 65 | 2.7 | - | 17 |
| Decorative | | | | | | |
| Incandescent Omni | 46 | 2.5 | 7.9 | 1.3 | - | 19 |
| Incandescent Directional | 46 | 2.5 | 7.9 | 3.1 | - | 18 |
| Halogen Omni | 40 | 2.3 | 17 | 3.8 | - | 19 |
| Halogen Directional | 40 | 2.3 | 17 | 4.7 | - | 18 |
| CFL Omni | 20 | 10 | 52 | 3.6 | - | 17 |
| CFL Pin | 29 | 10 | 52 | 5.0 | 17 | 14 |
| Downlights | | | | | | |
| Incandescent Omni | 36 | 2.7 | 17 | 0.5 | - | 23 |
| Incandescent Directional | 61 | 2.7 | 9.2 | 3.1 | - | 23 |
| Halogen Omni | 52 | 1.4 | 17 | 1.9 | - | 23 |
| Halogen Directional | 55 | 3.2 | 19 | 4.7 | - | 23 |
| CFL Omni | 15 | 11 | 65 | 13 | - | 21 |
| CFL Directional | 16 | 9.2 | 45 | 21 | - | 21 |
| Track Lighting | | | | | | |
| Incandescent Omni | 36 | 2.7 | 17 | 0.5 | - | 24 |
| Incandescent Directional | 61 | 2.7 | 9.2 | 3.1 | - | 23 |
| Halogen Omni | 52 | 1.4 | 17 | 1.9 | - | 24 |
| Halogen Directional | 55 | 3.2 | 19 | 4.7 | - | 23 |
| CFL Omni | 15 | 11 | 65 | 6.7 | - | 21 |
| CFL Directional | 16 | 9.2 | 45 | 15 | - | 21 |
| Small Directional (MR16) | | | | | | |
| Halogen | 32 | 3.2 | 14 | 4.3 | - | 23 |
| General Service Linear Fixtures | | | | | | |
| T12 <4ft | 34 | 11 | 88 | 2.9 | 19 | 48 |
| T8 <4ft | 40 | 22 | 75 | 5.3 | 21 | 44 |
| T5 <4ft | 35 | 20 | 87 | 4.2 | 24 | 73 |
| T12 4ft | 67 | 16 | 88 | 1.9 | 19 | 48 |
| T8 4ft | 71 | 32 | 85 | 2.7 | 21 | 44 |
| T5 4ft | 31 | 34 | 98 | 4.2 | 24 | 73 |
| T12 >4ft | 133 | 12 | 88 | 5.6 | 21 | 48 |
| T8 >4ft | 123 | 26 | 92 | 6.9 | 25 | 44 |
| Other | | | | | | |
| CFL Pin | 23 | 12 | 67 | 3.3 | 20 | 17 |
| Halogen | 90 | 1.5 | 23 | 4.3 | - | 19 |
| Mercury Vapor | 271 | 17 | 33 | 36 | - | 67 |
| Metal Halide | 105 | 15 | 67 | 51 | 151 | 72 |
| High Pressure Sodium | 221 | 26 | 90 | 48 | 206 | 78 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Miscellaneous | 71 | 11 | 51 | 38 | - | 19 |

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

Table C.3 Industrial Sector Conventional Technology Performance 2017

| Industrial Sector Submarkets | Mean Lamp Wattage (W)[1] | Lamp Life (1,000 hr)[2] | Mean Efficacy (lm/W) | Lamp Price ($) | Ballast Price ($) | Fixture Price ($) |
|---|---|---|---|---|---|---|
| General Purpose | | | | | | |
| Incandescent Omni | 31 | 2.7 | 19 | 7.6 | - | 15 |
| Halogen Omni | 32 | 1.4 | 21 | 4.5 | - | 15 |
| CFL Omni | 17 | 11 | 65 | 4.5 | - | 14 |
| Directional | | | | | | |
| Incandescent Directional | 62 | 2.7 | 9.2 | 3.1 | - | 23 |
| Halogen Directional | 69 | 3.2 | 19 | 4.7 | - | 23 |
| CFL Directional | 15 | 9.2 | 45 | 19 | - | 21 |
| General Service Linear Fixtures | | | | | | |
| T12 <4ft | 42 | 11 | 88 | 2.9 | 15 | 68 |
| T8 <4ft | 32 | 22 | 79 | 5.3 | 17 | 68 |
| T12 4ft | 68 | 16 | 88 | 2.4 | 15 | 68 |
| T8 4ft | 62 | 32 | 95 | 4.4 | 17 | 68 |
| T5 4ft | 103 | 34 | 98 | 6.1 | 20 | 73 |
| T12 >4ft | 146 | 12 | 88 | 5.6 | 17 | 68 |
| T8 >4ft | 137 | 26 | 92 | 8.2 | 20 | 68 |
| T5 >4ft | 104 | 23 | 98 | 6.1 | 20 | 73 |
| Low/High Bay | | | | | | |
| T12 | 175 | 12 | 88 | 5.6 | 17 | 68 |
| T8 | 175 | 27 | 89 | 8.2 | 20 | 68 |
| T5 | 227 | 22 | 89 | 6.1 | 23 | 73 |
| Mercury Vapor | 613 | 17 | 33 | 31 | - | 67 |
| Metal Halide | 312 | 15 | 67 | 39 | 201 | 72 |
| High Pressure Sodium | 547 | 26 | 90 | 48 | 248 | 78 |
| Other | | | | | | |
| CFL Pin | 80 | 12 | 67 | 6.6 | 17 | 14 |
| Mercury Vapor | 613 | 17 | 33 | 56 | - | 67 |
| Metal Halide | 312 | 15 | 67 | 39 | 201 | 72 |
| High Pressure Sodium | 547 | 26 | 90 | 48 | 248 | 78 |
| Miscellaneous | 143 | 11 | 51 | 14 | - | 76 |

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

**Table C.4 Outdoor Sector Conventional Technology Performance 2017**

| 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/Roadway | | | | | | |
| Incandescent | 211 | 3.7 | 8.6 | 0.5 | - | 275 |
| Mercury Vapor | 341 | 17 | 33 | 39 | - | 261 |
| Metal Halide | 165 | 15 | 67 | 39 | 178 | 312 |
| High Pressure Sodium | 191 | 26 | 90 | 48 | 248 | 303 |
| Low Pressure Sodium | 225 | 20 | 76 | 38 | 103 | 261 |
| Miscellaneous | 225 | 20 | 76 | 26 | 176 | 299 |
| Parking Lot | | | | | | |
| Incandescent | 168 | 3.7 | 8.6 | 0.5 | - | 275 |
| Halogen | 81 | 2.7 | 23 | 1.3 | - | 275 |
| Mercury Vapor | 389 | 17 | 33 | 31 | - | 311 |
| Metal Halide | 269 | 15 | 67 | 39 | 155 | 312 |
| High Pressure Sodium | 274 | 26 | 90 | 62 | 248 | 303 |
| Miscellaneous | 238 | 20 | 76 | 19 | 201 | 324 |
| Parking Garage | | | | | | |
| Incandescent | 168 | 3.7 | 8.6 | 0.5 | - | 275 |
| Halogen | 81 | 2.7 | 23 | 1.3 | - | 275 |
| Linear Fluorescent | 76 | 15 | 77 | 2.7 | 17 | 68 |
| Mercury Vapor | 389 | 17 | 33 | 31 | - | 311 |
| Metal Halide | 269 | 15 | 67 | 39 | 155 | 312 |
| High Pressure Sodium | 274 | 26 | 90 | 48 | 248 | 303 |
| Miscellaneous | 238 | 20 | 76 | 19 | 201 | 324 |
| Building Exterior | | | | | | |
| Incandescent | 89 | 3.7 | 8.6 | 0.5 | - | 15 |
| Halogen | 62 | 2.7 | 23 | 1.3 | - | 15 |
| CFL | 24 | 12 | 67 | 6.1 | - | 14 |
| Linear Fluorescent | 85 | 15 | 75 | 2.7 | 17 | 68 |
| Mercury Vapor | 254 | 17 | 33 | 29 | - | 164 |
| Metal Halide | 220 | 15 | 67 | 36 | 151 | 341 |
| High Pressure Sodium | 233 | 26 | 90 | 42 | 186 | 213 |
| Low Pressure Sodium | 225 | 20 | 76 | 38 | 103 | 164 |
| Miscellaneous | 16 | 17 | 80 | 21 | - | 232 |
| Other | | | | | | |
| Incandescent | 138 | 3.7 | 8.6 | 0.5 | - | 15 |
| Halogen | 81 | 2.7 | 23 | 1.3 | - | 15 |
| Linear Fluorescent | 127 | 15 | 75 | 2.7 | 17 | 68 |
| Mercury Vapor | 393 | 17 | 33 | 74 | - | 311 |
| Metal Halide | 252 | 15 | 67 | 94 | 201 | 499 |
| High Pressure Sodium | 339 | 26 | 90 | 136 | 248 | 523 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Miscellaneous | 123 | 11 | 51 | 21 | 224 | 467 |

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

## 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*[50]) 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 LED lighting 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 maximum wattage standards 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.[51] 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 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.

   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 lighting market 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. 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

[50] For more information on the *Code of Federal Regulations* visit: http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR
[51] 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 40 W, 60 W, 75 W, and 100 W medium screw based incandescent light bulbs. More information can be found at: http://energy.gov/eere/buildings/appliance-and-equipment-standards-program

general service fluorescent lamps (GSFLs). DOE published amendments to these standards in 2009, which became effective in 2012. DOE published amendments to those standards in January 2015, which became effective January 26, 2018. These amendments set some 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 luminous efficiency standards that will effectively shift the fluorescent market from T12 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, prescribes 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))

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 became 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 standards also prohibit probe start ballasts in metal halide lamp fixtures greater than 500 W and less than or equal to 1,000 W. 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 LED lighting 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. This appendix summarizes the method used to develop updated price and efficacy projections for the lighting market model.

## Appendix D.1. LED Price Projections

The LED price projections for the 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 (general purpose, globe, decorative, BR, PAR, R, MR, etc.) to luminaires (general purpose downlights, track fixtures, surface mounted/recessed troffers, panels, high/low bay, etc.) and outdoor fixtures.

It is also important to recognize the limitations of this web-scraped dataset, namely by relying on a singular sales channel source of LED product pricing information, there is inherent bias introduced within the analysis. The methodology utilized for this Forecast Report makes no effort to investigate the correlations between volume purchasing or product performance and the influence these may have on pricing. However, recent work by California's electric investor owned utilities concluded that performance, and in particular efficacy, has a negligible influence on LED product pricing. (26)

### Web-Scrape Data Cleaning

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

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

### Methodology

To further organize this data into a structure compatible with the 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 in this submarket. 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.[52]

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

**Table D.1 LED Product Type Groupings for Pricing Analysis**

| Application Submarkets | | Description of Web-Based LED Product Types Groupings |
|---|---|---|
| LED Lamps | General Purpose Lamps | A19, and A21 lamp shapes |
| | Decorative | Candle and flame 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 | 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 |
| | Area and Roadway | High wattage retrofit lamps |
| | Parking Lot | High wattage retrofit and low and high bay lamps |
| | Garage | PAR38 and 4 ft. linear lamps |
| | Building Exterior | PAR30 and PAR38 |
| LED Luminaires | General Purpose Luminaire | Wall and ceiling mounted ambient fixtures |
| | Decorative | Decorative surface, flush, and wall mounted indoor fixtures |
| | Downlight/Track - Large | 6 in., 7 in., and 8 in. downlight fixtures |
| | Downlight/Track - Small | 3 in., 4 in., and 5 in. downlight fixtures |
| | Linear Fixture - <4ft | 2x2 ft. and 1x2 ft. panels, troffers, and strip light fixtures |
| | Linear Fixture - 4ft | 2x4 ft. and 1x4 ft. panels and troffers |
| | Linear Fixture - >4ft | 1x8 ft. 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 | 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 relatively linear rate of price decline, followed by a non-linear decline beginning at varying points near 2015. 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.

To accommodate each decline region, a piece-wise trend was utilized – the 'linear' region and the 'experience curve' region characterized by the mathematical model described in the Lawrence Berkeley National Laboratory (LBNL) report Recent Price Trends and Learning Curves for Household LED Lamps from a Regression Analysis of Internet Retail Data. (27)

Figure D.1 illustrates this piece-wise trend for the LED lamps in the large downlight application submarket and compares the 2016 projection to the current projection. The linear decline region was not updated, as this region is reflective of years 2010 to 2015.

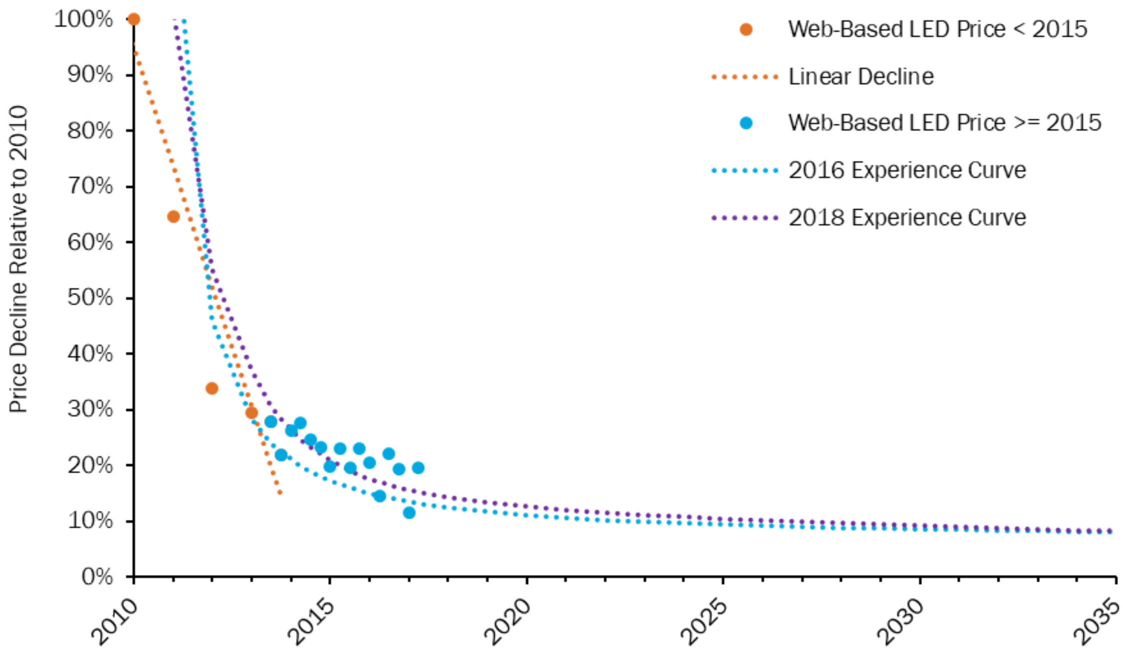


**Figure D.1 LED Lamp Price Trends for the Large Downlight Application Submarket**

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. An experience curve takes the form:

$$P_i = A * Q_i^{-b} + C$$

where $\boldsymbol{P_i}$ represents price relative to the initial price, $\boldsymbol{Q_i}$ represents cumulative product shipments relative to market introduction, and ***A***, ***b*** and **C** are constants. ***A*** is a price scaler relative to shipments, ***b*** is the regression coefficient for the experience curve, and ***C*** represents the final relative price at t∞. For this analysis, it is assumed that the market introduction year was 2010, since at this time LED lighting represented less than 1% of the lighting market. (4) Future LED prices for each model submarket were then determined by multiplying the projected $\boldsymbol{P_i}$ for years from 2017 to 2035 by the initial 2010 price. The usage of experience curves takes into account Haitz's Law[53] as well as the general observation that cost of production for new technologies tends to fall by a fixed fraction each time their cumulative production doubles. This is a common phenomenon for many electrical products and is used by DOE to estimate future price decline for all appliance standards (including LED covered lighting products). (28) The experience curve is an empirical model based on historical fits of price data to cumulative production.

The experience curve function was fit to the time-series web data and was used to derive future trends LED pricing for each submarket application. Unique experience curve parameters were derived for each individual submarket. As seen in Figure D.1, the updated experience curve projections slightly differ from the projections provided in the 2016 Forecast Report. One clear trend is that in many submarkets, the web-prices of LED

[53] Haitz's law is an observation and forecast about the steady improvement, over many years, of LED lighting. It states that every decade, the cost per lumen (unit of useful light emitted) falls by a factor of 10, and the amount of light generated increases by a factor of 20.

lamps and luminaires have not declined as rapidly as previously expected. The new projected experience curves account for additional observed price data collected through 2017, and as such provide a more accurate rate of price decline for each submarket.

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. (27) 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 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)[54]

| | Application Submarkets | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| LED Lamps | General Purpose Lamps | 12 | 4 | 3 | 3 | 3 |
| | Downlighting - Large | 19 | 15 | 14 | 13 | 13 |
| | Downlight/Track - Small | 35 | 13 | 10 | 9 | 9 |
| | Track Lighting - Large | 20 | 15 | 14 | 13 | 13 |
| | Linear Fixture - <4ft | 13 | 7 | 4 | 4 | 4 |
| | Linear Fixture - 4ft | 9 | 5 | 4 | 4 | 4 |
| | Linear Fixture - >4ft | 11 | 6 | 4 | 4 | 4 |
| | Low and High Bay | 24 | 19 | 15 | 14 | 14 |
| | Decorative | 27 | 8 | 6 | 6 | 5 |
| | Area and Roadway | 18 | 14 | 12 | 11 | 11 |
| | Parking Lot | 18 | 16 | 15 | 14 | 14 |
| | Garage | 16 | 13 | 12 | 11 | 11 |
| | Building Exterior | 22 | 17 | 14 | 13 | 11 |
| LED Luminaires | General Purpose Luminaires | 59 | 40 | 26 | 20 | 16 |
| | Downlight/Track - Large | 59 | 40 | 26 | 20 | 16 |
| | Downlight/Track - Small | 75 | 50 | 29 | 20 | 16 |
| | Linear Fixture - <4ft | 36 | 28 | 24 | 23 | 22 |
| | Linear Fixture - 4ft | 39 | 27 | 21 | 20 | 19 |
| | Linear Fixture - >4ft | 52 | 30 | 22 | 20 | 18 |
| | Low and High Bay | 26 | 21 | 17 | 16 | 15 |
| | Decorative | 254 | 175 | 132 | 114 | 103 |
| | Area and Roadway | 44 | 31 | 22 | 17 | 14 |
| | Parking Lot | 45 | 28 | 17 | 13 | 10 |
| | Garage | 49 | 30 | 17 | 12 | 10 |
| | Building Exterior | 52 | 33 | 23 | 19 | 16 |

[54] Prices are represented as nominal dollars.

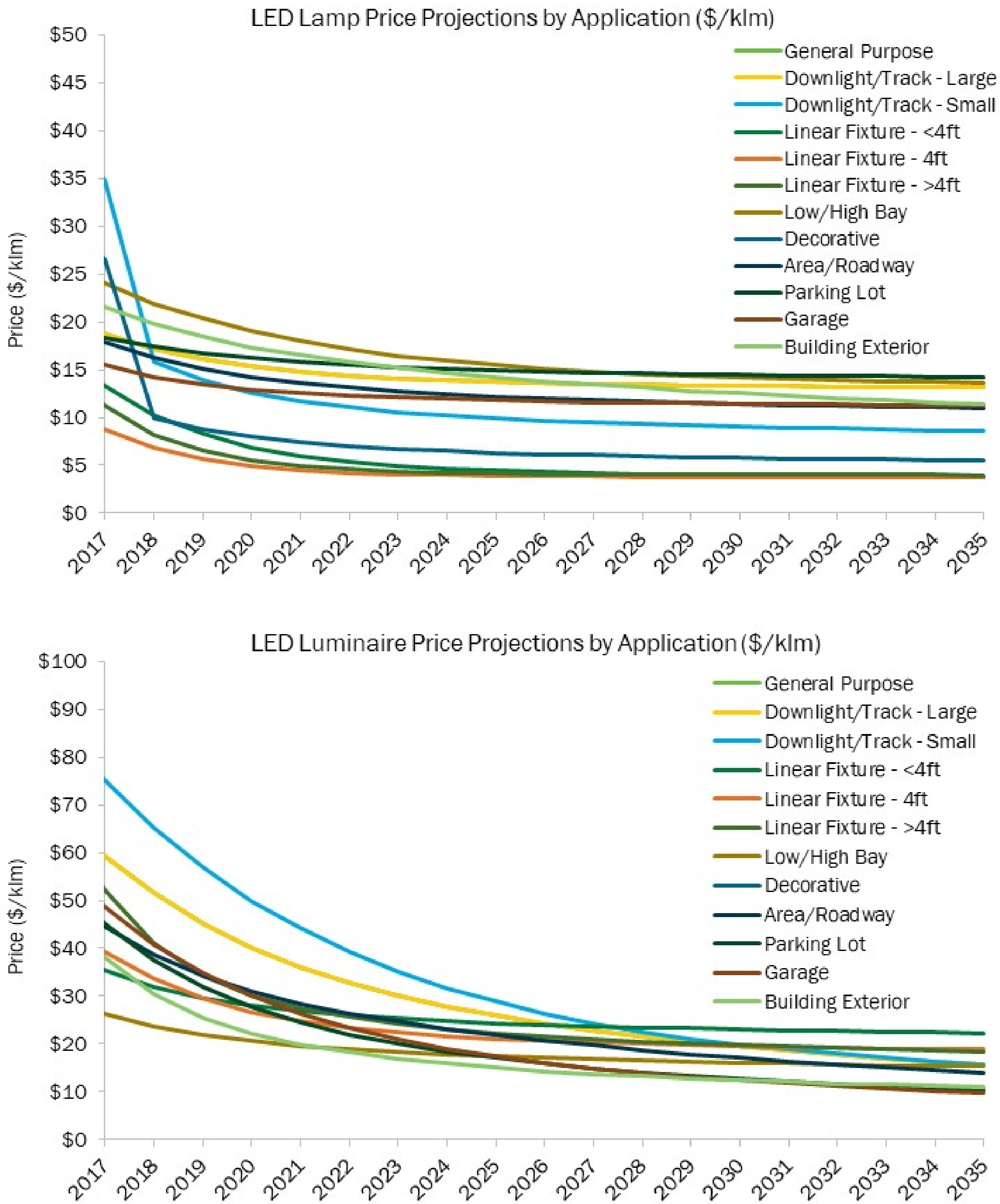


**Figure D.2 LED Lamp and Luminaire Price Projections by Application Submarket ($/klm)[55]**

[55] Prices are represented as nominal dollars.

## 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. 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): The voluntary LED Lighting Facts program maintains a database of all LED products that have received the LED Lighting Facts label, in order to showcase LED products for general illumination applications from manufacturers who commit to testing products and reporting performance results according to industry standards. From the program's inception in 2009 through April 2018, the product database was funded by DOE and maintained by D+R International. Since May 2018, the program and database management have continued by D+R International without DOE funding. This analysis uses specifications from the over 73,000 lamp, luminaire, and retrofit products that were listed as of March 2018.
- **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. As of January 2018, the ENERGY STAR® Certified Light Bulb Database contained over 9,000 products and the ENERGY STAR® Certified Light Fixture Database contained over 16,000 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. In January 2018, the DLC Qualified Products List had nearly 470,000 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.[56] In addition, these groupings 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.

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

**Table D.3 LED Lighting Product Type Groupings for Efficacy Analysis**

| Application Submarkets | | Description of LED Product Types Groupings |
|---|---|---|
| LED Lamps | General Purpose Lamps | A19 and A21 lamp shapes |
| | Decorative | Candle and flame lamp shapes |
| | Downlight/Track - Large | BR40, R30, BR40, R40, 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 |
| | Area and Roadway | High wattage retrofit lamps |
| | Parking Lot | High wattage retrofit and low and high bay lamps |
| | Garage | PAR38 and 4 ft. linear lamps |
| | Building Exterior | PAR30, PAR38 and high wattage retrofit lamps |
| LED Luminaires | General Purpose Luminaires | Wall and ceiling mounted ambient fixtures |
| | Decorative | Decorative surface, flush, and wall mounted indoor fixtures |
| | Downlight/Track - Large | 4 in., 5 in., 6 in., 7 in., and 8 in. downlight fixtures |
| | Downlight/Track - Small | 2 in. and 3 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[57] 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.

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

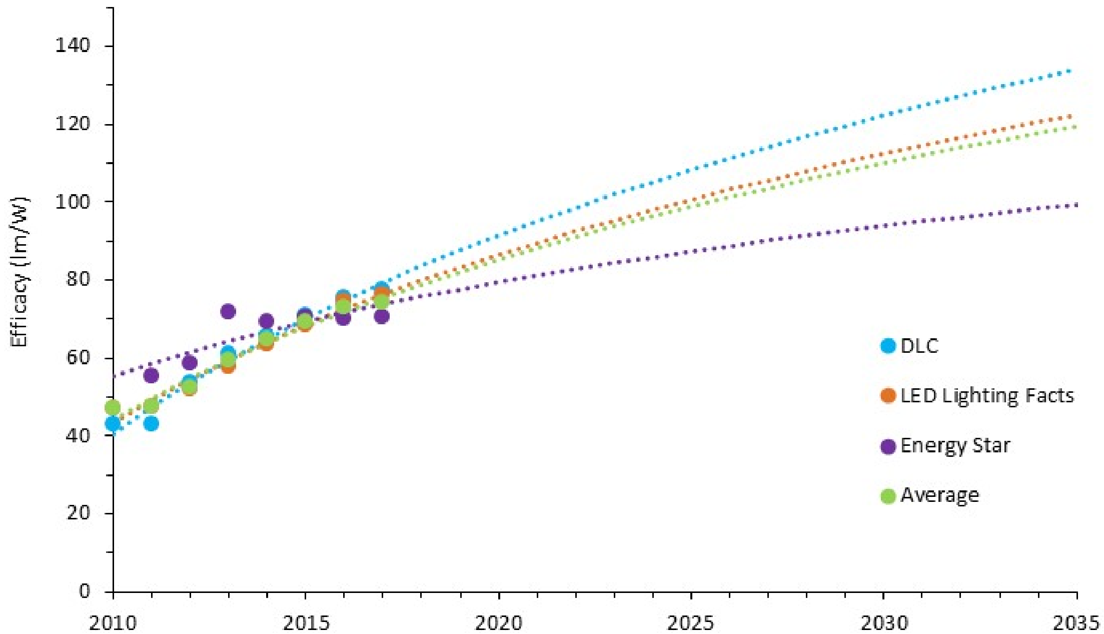


Figure D.3 LED Luminaire Efficacy Trends for the Large Downlight Application Submarket

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)[58]

| | Application Submarkets | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| LED Lamps | General Purpose | 93 | 105 | 122 | 136 | 147 |
| | Decorative | 83 | 95 | 112 | 125 | 137 |
| | Downlight/Track - Large | 76 | 84 | 95 | 103 | 111 |
| | Downlight/Track - Small | 67 | 73 | 83 | 91 | 97 |
| | Linear Fixture | 104 | 116 | 132 | 145 | 157 |
| | Low/High Bay | 95 | 109 | 129 | 145 | 159 |
| | Area/Roadway | 107 | 120 | 138 | 152 | 165 |
| | Parking Lot | 107 | 120 | 138 | 152 | 165 |
| | Garage | 123 | 137 | 157 | 174 | 187 |
| | Building Exterior | 93 | 110 | 132 | 150 | 167 |
| LED Luminaires | General Purpose | 93 | 105 | 122 | 136 | 147 |
| | Decorative | 87 | 97 | 111 | 123 | 133 |
| | Downlight/Track - Large | 74 | 83 | 95 | 105 | 113 |
| | Downlight/Track - Small | 51 | 57 | 64 | 71 | 76 |
| | Linear Fixture | 96 | 109 | 126 | 140 | 152 |
| | Low/High Bay | 118 | 132 | 152 | 167 | 181 |
| | Area/Roadway | 107 | 120 | 138 | 152 | 165 |
| | Parking Lot | 107 | 120 | 138 | 152 | 165 |
| | Garage | 103 | 114 | 129 | 141 | 151 |
| | Building Exterior | 106 | 115 | 130 | 142 | 152 |

[58] Ballast losses are accounted for in the lamp wattage assumptions where relevant.

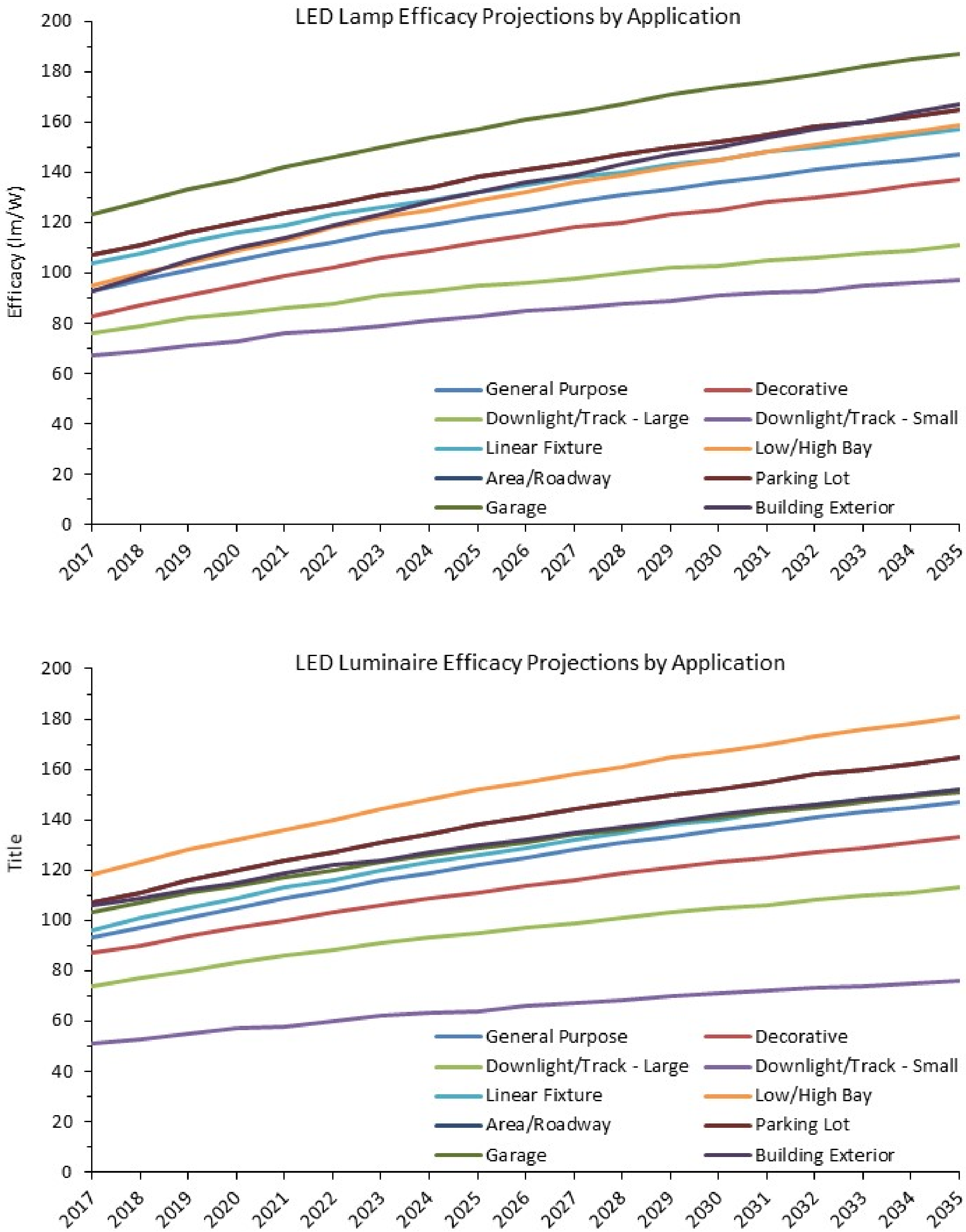


Figure D.4 LED Lamp and Luminaire Efficacy Projections by Application Submarket (lm/W)[59]

[59] Ballast losses are accounted for in the lamp wattage assumptions where relevant.

# 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. (10; 11)

## Appendix E.1. Econometric Logit Model

The lighting market 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 lamp system, 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. 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 in some cases 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
- $\beta_i$ 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 LED lighting, 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 AEO 2018 reference scenario. Because the majority of outdoor lighting is used on and around commercial buildings, it was assumed that commercial electricity prices apply to the outdoor sector. The AEO 2018 also provides several alternative electricity price scenarios, but variation is minor such that their effect on the logit model was negligible. (1) The electricity prices used in the analysis are shown in Table E.1.

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

| | Average Electricity Price ($/kWh) | | | | |
|---|---|---|---|---|---|
| Sector | 2017 | 2020 | 2025 | 2030 | 2035 |
| Commercial | $0.11 | $0.12 | $0.14 | $0.15 | $0.17 |
| Residential | $0.13 | $0.14 | $0.17 | $0.19 | $0.21 |
| Industrial | $0.07 | $0.08 | $0.09 | $0.10 | $0.11 |
| Outdoor | $0.11 | $0.12 | $0.14 | $0.15 | $0.17 |

Source: EIA AEO 2018 (1)

## 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 newer 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. (29) 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 (30), 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 demonstrated 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 installed saturation for all general illumination applications as compared to several incumbent lighting and control technologies. To account for this difference, the analysis assigns a faster diffusion rate to LED products compared to the incumbent competitors.

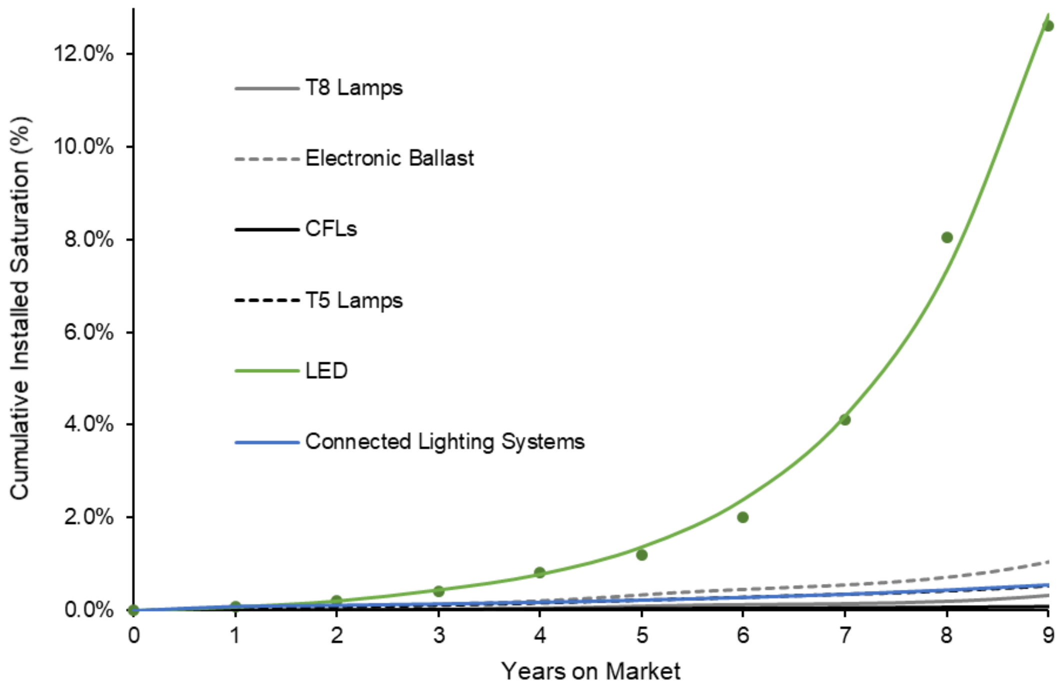


**Figure E.1 LED Lighting vs. Conventional Lighting Technology Saturation**[60]

[60] Data points in green shown in Figure E.1 represent LED adoption estimates derived from the 2017 LED Adoption report. (31)

# 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 lighting market model, a 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 lighting market 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 Goals 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 were collected and reviewed including case studies, journal articles, reports, manufacturer literature, websites, DOE rulemaking analyses, and presentations in the 2016 iteration of *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* report. An additional 111 sources[61] were collected and reviewed for this 2018 iteration.

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[62] 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 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 during the 2016 DOE SSL Forecast analysis. For both the 2016 and 2018 Forecast Reports, once preliminary results were developed, meetings were held with DOE and these stakeholders to discuss the methodology and results for the controls analysis. During the stakeholder meetings, 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

[61] A list of all new 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.
[62] 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.

incorporated into the control analysis and the team is greatly appreciative of the time and effort given by the participating organizations.[63]

## 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 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 lighting market model also consider the impacts of non-connected lighting controls so as not to exaggerate the forecasted energy savings.

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. 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. One exception is that daylighting is assumed to turn lights off in the outdoor sector only.

**Table F.1 Traditional Control Strategies Scope**

| Control Strategies | Wattage Reduction Effect | On/Off Effect | Lamp Technologies Included | Categories Included |
|---|---|---|---|---|
| **Dimmer** | ✓ | | All | Personal Tuning |
| **Daylighting** | ✓ | ✓<br>(Outdoor Sector) | All | Photosensors<br>Daylight Harvesting |
| **Occupancy Sensor** | | ✓ | All | Occupancy Sensors<br>Vacancy Sensors |
| **Timer** | | ✓ | All | Scheduling |

For this forecast analysis, connected lighting is assumed to be an LED-based lighting system with integrated sensors and controllers that are networked (either wired or wireless), enabling lighting products within the system to communicate and exchange data with other devices. 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.

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

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 EMS that allows control of lamps and luminaires within a single building. A combination of traditional control strategies are implemented. There is no communication between different lamps and luminaires. |
| **Connected** | Yes | A combination of 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 a combination of traditional control strategies and thus would have the capability of both reducing wattage and turning the light off. For the residential sector, it was assumed that EMS and connected lighting include the use of dimming and timers only. In contrast, for all other sectors, the use of all four traditional control strategies was assumed. EMS and connected lighting also offer additional capabilities over traditional control strategies, such as high-end trim. 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 Strategies | Control Strategies | | | | Lamp Technologies Included | Categories Included |
|---|---|---|---|---|---|---|
| | Dimmer[1] | Daylighting | Occupancy Sensor | Timer | | |
| **EMS** | ✓ | ✓ | ✓ | ✓ | All | Energy Management System<br>Building Management System<br>Building Energy Management System<br>Building Automation System |
| **Connected Lighting (COM, IND, OUT)** | ✓ | ✓ | ✓ | ✓ | LED Lamps and Luminaires Only | Luminaire Level Lighting Controls<br>“Smart” Lamps<br>Advanced<br>Networked |
| **Connected Lighting (RES)** | ✓ | | | ✓ | | |

1. For EMS and connected lighting only, the dimmer control strategy includes the impacts of leveraging high-end trim.

While the lighting market 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.[64] (2) 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. The lighting market 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 the methodology used to calculate total energy savings from each control system at a high level.

**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 reviews 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 lighting market model.

For connected lighting, two scenarios were evaluated, the Current SSL Path and DOE SSL Program Goals scenarios. 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 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 Goals scenarios are summarized below:

[64] See "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," in the DOE SSL R&D Plan, found at: http://energy.gov/sites/prod/files/2016/06/f32/ssl_rd-plan_%20jun2016_2.pdf

**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 dimmable linear fluorescent ballasts and DALI (Digital Addressable Lighting Interface) systems, resulting in a slower 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 LED luminaires.

The **DOE SSL Program Goals** 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 LED luminaires.

These assumptions for each scenario feed into the market share calculation, which consists of two parts: 1) the payback acceptance that considers first and operating costs and 2) technology diffusion curve that considers existing marketplace presence.

The economic portion of the lighting market 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 five 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

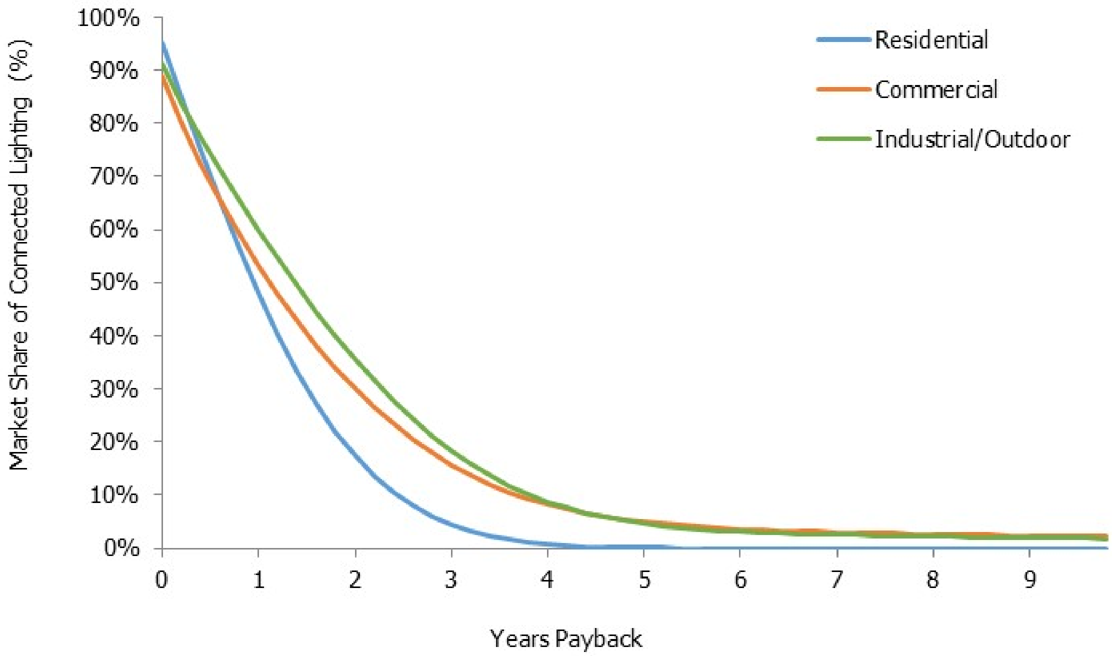


**Figure F.1 Market Response Curves Used to Determine Payback Acceptance**

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.[65]

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 dimmable linear fluorescent ballasts and Digital Addressable Lighting Interface (DALI) systems, while the DOE SSL Program Goals 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 (31), Dimming Fluorescent Lamp Ballasts (32), Luminaire Level Lighting Controls (LLLC) Market Characterization and Baseline Report (33), 2010 U.S. Lighting Market Characterization (4) and the LED Adoption Reports (34) were used to derive diffusion curves for dimmable linear fluorescent ballasts, DALI systems, and LED lighting. Figure F.2 below illustrates the diffusion curves applied for each scenario.

[65] See Appendix E for a discussion of the lighting market penetration model.

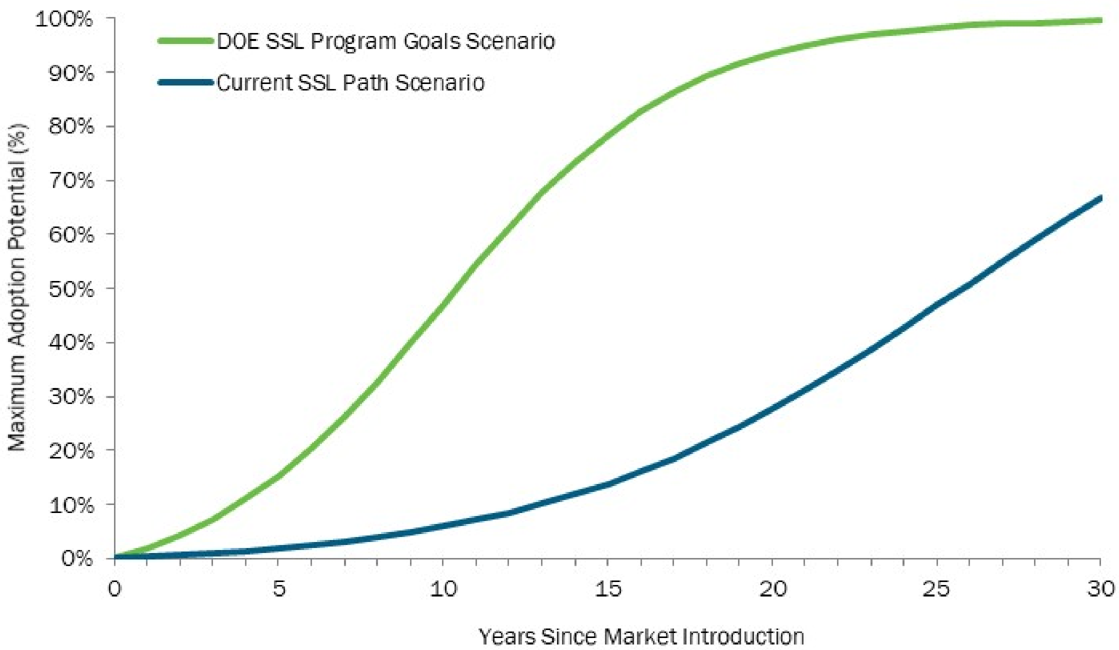


Figure F.2 Bass Diffusion Curves Applied to Connected Lighting for Each Scenario

**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 four day types: weekday, Saturday, Sunday, 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. For each single strategy, the analysis assumes that only that strategy is implemented. For example, for occupancy sensors, the per control savings value assumes that occupancy sensors are the only control type implemented over the 24-hour period (i.e., occupancy sensors cause lights to turn off overnight, as opposed to another single strategy such as timers).

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 lighting market 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. Additional adjustments were included to account for users not utilizing controls to their full capability (e.g., due to controls not working properly or users overriding their functionality). These adjustments were estimated using 2014 Commercial Building Stock Assessment data. (7)

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:

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

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.

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

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 baseline load profiles are for lighting only. For the area and roadway submarket, data was provided by National Grid. For the other outdoor submarkets, baseline load profiles were estimated based on expert assumptions and stakeholder feedback. For all other submarkets, they are derived from data provided by the California Public Utilities Commission. (35) The energy savings percent for dimmers is calculated by taking the ratio of the load profile with dimmers to the baseline load profile.

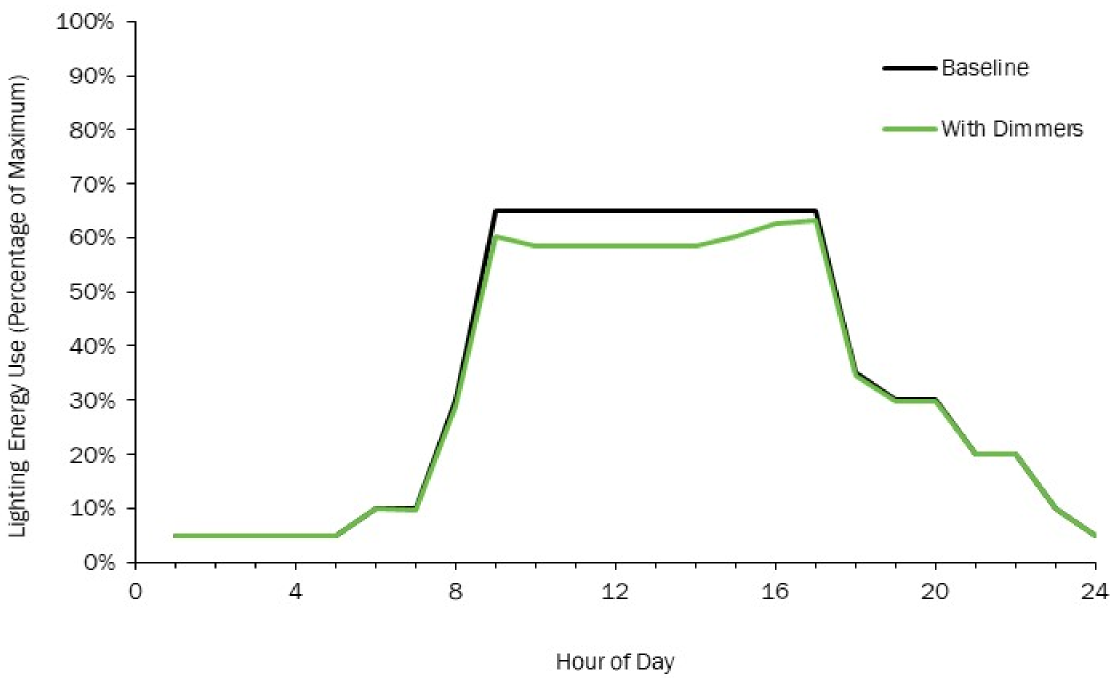


**Figure F.3 Example Lighting Load Profiles for a National Average Commercial Office Weekday**

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. (36) 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 traditional control strategies and then applying an adjustment factor to account for the fact that connected systems offer more energy savings potential due to and additional control strategies, such as high-end trim, their ability to communicate, and the opportunity for use optimization through machine learning, which is assumed to improve over time. It is possible that because connected lighting makes controlling and turning lights on easier it would use more energy than non-connected lighting. However, it was assumed that the factors contributing to energy savings potential outweighed this possibility.

**Table F.4 Energy Savings for each Control Type by Application**

| Applications | Dimmer Only | Daylighting Only | Occupancy Sensor Only | Timer Only | Multi | EMS | Connected Lighting | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | 2017 | 2035 |
| Commercial - Office | 5% | 14% | 26% | 4% | 37% | 46% | 53% | 63% |
| Com/Ind - Warehouse | 2% | 15% | 37% | 9% | 44% | 55% | 57% | 67% |
| Commercial - Retail | 6% | 14% | 38% | 12% | 49% | 59% | 60% | 71% |
| Commercial - Lodging | 3% | 8% | 40% | 36% | 63% | 70% | 72% | 85% |
| Commercial - Health | 7% | 14% | 37% | 6% | 46% | 57% | 59% | 69% |
| Commercial - Education | 5% | 14% | 42% | 12% | 52% | 62% | 64% | 75% |
| Residential | 2% | 8% | 17% | 18% | 27% | 28% | 29% | 34% |
| Industrial | 23% | 9% | 27% | 49% | 65% | 69% | 71% | 83% |
| Area/Roadway | 14% | 4% | 19% | 17% | 35% | 46% | 47% | 55% |
| Parking Lot | 20% | 4% | 17% | 17% | 35% | 48% | 50% | 58% |
| Garage | 20% | 4% | 15% | 5% | 22% | 40% | 41% | 48% |
| Building Exterior | 14% | 4% | 19% | 17% | 35% | 46% | 48% | 57% |

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

This appendix contains new literature review sources collected for the 2018 Forecast Report. The literature review sources collected for the 2016 Forecast Report were also used for this report's analysis. See the 2016 Forecast Report for the list of additional literature review sources. (22)

| Source Title | Author | Year |
|---|---|---|
| Lighting the Way to Savings | Ameresco | Unknown |
| Intelligent Efficiency: Opportunities, Barriers, and Solutions | American Council for an Energy-Efficient Economy | 2013 |
| Smart Buildings: A Deeper Dive into Market Segments | American Council for an Energy-Efficient Economy | 2017 |
| Smart Buildings: Using Smart Technology to Save Energy in Existing Buildings | American Council for an Energy-Efficient Economy | 2017 |
| Calculation Methodology for the Advanced Lighting Control Systems (ALCS) | American Society of Heating, Refrigerating and Air-Conditioning Engineers | 2016 |
| Global Intelligent Lighting Controls Market - Analysis and Forecast | BIS Research | 2017 |
| Advanced Lighting Controls | Bonneville Power Administration | 2016 |
| Easily Commissioned Lighting Control Phase 3 Report | Bonneville Power Administration | 2016 |
| What is a Smart Building | Building Efficiency Initiative | 2011 |
| Let There Be Daylight | Building Energy Exchange | 2012 |
| Living Lab NYC | Building Energy Exchange | 2015 |
| Living Lab: Lighting the Future | Building Energy Exchange | Unknown |
| Office Lighting Retrofit Case Study | Building Energy Exchange | 2014 |
| Occupancy-based Lighting Control in Open-plan Office Spaces: A State-of-the-art Review | C. Bakker, M. Aries, H. Kort, A. Rosemann | 2016 |
| Occupancy-based Lighting Control in Open-plan Office Spaces: The Influence of Occupancy Patterns | C. Bakker, T. Voort, A. Rosemann | 2017 |
| Office Daylighting Potential | California Energy Commission | 2011 |
| Outdoor Lighting Energy Savings Potential | California Lighting Technology Center | Unknown |
| Guest Room Occupancy Controls | California Public Utilities Commission | 2011 |
| California Statewide Codes and Standards Program Impact Evaluation Report | California Public Utilities Commission | 2017 |
| The Ultimate Guide to Building Automation | Control Solutions | 2015 |
| 2015 U.S. Lighting Market Characterization | Department of Energy | 2017 |
| Commercial Advanced Lighting Control Demonstration and Deployment | Department of Energy | 2016 |
| Connected Lighting System Interoperability Study Part 1: Application Programming Interfaces | Department of Energy | 2017 |
| PoE Lighting System Energy Reporting Study Part 1 | Department of Energy | 2017 |
| Results from the Field: Highlights from Technology Demonstration Projects | Department of Energy | 2016 |
| Wireless Occupancy Sensors for Lighting Controls | Department of Energy | Unknown |
| DLC Advanced Lighting Technology Demonstration: Cree SmartCast | DesignLights Consortium | 2017 |
| DLC Advanced Lighting Technology Demonstration: Daintree ConstrolScope | DesignLights Consortium | 2017 |

| | | |
|---|---|---|
| DLC Advanced Lighting Technology Demonstration: Digital Lumens | DesignLights Consortium | 2017 |
| DLC Advanced Lighting Technology Demonstration: Enlighted | DesignLights Consortium | 2018 |
| DLC Advanced Lighting Technology Demonstration: Philips SpaceWise | DesignLights Consortium | 2017 |
| Energy Savings from Networked Lighting Control Systems | DesignLights Consortium | 2017 |
| Networked Lighting Control System Technical Requirements v2.0 | DesignLights Consortium | 2017 |
| Industrial LED Lighting Network as Wireless Access Infrastructure | Dialight | Unknown |
| Distributed Low-Voltage Power System Case Study | Eaton | 2018 |
| Making Outdoor Lighting More Efficient, Safe, and Affordable with Open-standard Control Networking Technology | Echelon | Unknown |
| Monitored Outdoor Lighting: Market Challenges, Solutions, and Next Steps | Echelon | 2007 |
| Shining a Light on Energy Savings | Echelon | Unknown |
| Smart Lighting & Smart Hub | Efficiency Vermont | 2016 |
| Commercial Buildings Energy Consumption Survey: Trends in Lighting In Commercial Buildings | Energy Information Administration | 2017 |
| Today in Energy: Large commercial buildings are more likely to use lighting control strategies | Energy Information Administration | 2017 |
| The Light Bulb Revolution | Environmental Protection Agency | 2017 |
| Building Controls Technical Brief | Florida Power & Light | Unknown |
| Energy Savings from Five Home Automation Technologies: A Scoping Study of Technical Potential | Fraunhofer USA | 2016 |
| July 2015 Press Release: Smart Lighting Has the Potential to Reduce Energy Costs by 90 Percent | Gartner | 2015 |
| November 2015 Press Release: 6.4 Billion Connected "Things" Will Be in Use in 2016, Up 30 Percent From 2015 | Gartner | 2015 |
| Integrated Daylighting Systems | General Services Administration | 2014 |
| Retrofit Demonstration of LED Fixtures with Integrated Controls | General Services Administration | 2015 |
| Wireless Advanced Lighting Controls | General Services Administration | 2015 |
| The Internet of Things: Making sense of the next mega-trend | Goldman Sachs | 2014 |
| WinLight: A WiFi-based Occupancy-drive Lighting Control System for Smart Building | H. Zou, Y. Zhou, H. Jiang, S. Chien, L. Xie, C. J. Spanos | 2017 |
| A New Way to Think About Office Lighting | Harvard Business Review | 2017 |
| 2017 Connected Lighting Workshop Presentations | https://www.energy.gov/eere/ssl/solid-state-lighting | 2017 |
| Wireless Control: Lighting Raised to a New Power | International Parking Institute | 2009 |
| Machine-to-Machine connections to hit 18 billion in 2022, generating USD1.2 trillion revenue | https://iotbusinessnews.com | 2012 |
| 2016 Energy Efficiency Indicator Survey | Johnson Controls | 2016 |
| Intelligent Efficiency | Johnson Controls | 2014 |
| Lighting Control Systems: Factors Affecting Energy Savings Evaluation | L. Bellia, F. Fragliasso, A. Pedace | 2015 |

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