U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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

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Prepared by Navigant Consulting, Inc.

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Disclaimer

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COMMENTS

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Executive Summary

The United States Department of Energy (DOE) has been at the forefront of the solid-state lighting revolution. Among its various activities, DOE has supported studies forecasting the market penetration of light-emitting diodes (LEDs) in general illumination applications since 2002. These forecasts provide a comprehensive overview of the expected path of LED adoption within the United States and estimate the energy savings offered by LED products out to year 2030. This, the sixth iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*, presents the results of the United States lighting market model, which leverages updated data sources and provides a more detailed breakdown of general lighting applications than presented in past forecasts. This study estimates the expected future adoption of LEDs based on the current trajectory for the technology and does not necessarily represent the maximum potential—both in terms of market penetration and energy savings—of LED technology.

The lighting market model assumes the market adoption of LED lighting technology is driven primarily by projected improvements in LED product efficacy and price, as well as established technology diffusion rates. At the end of the analysis period, LEDs are anticipated to dominate lighting sales in each of the submarkets examined, comprising 84% of all sales by lumen-hours. This will dramatically lower national energy consumption. Without LEDs, the model projects that the energy consumption of the lighting sector would grow to approximately eight quadrillion Btu (quads). The market penetration of LEDs is projected to drive a 40% reduction in energy consumption, or a total energy savings of 3.0 quads, in 2030 alone, which is nearly the total energy consumed by 24 million United States homes today.

Of the eight submarkets examined, the lighting market model anticipates that LEDs will grow most rapidly in the street and roadway and general service submarkets in terms of the percentage of total lumen-hour sales. In the street and roadway submarket, already a popular area for LED upgrades, LEDs are predicted to reach 83% market share of sales by 2020 and nearly 100% by 2030. The general service submarket will shift to LEDs a bit more slowly, with a projected 55% market share of sales in 2020, but will also almost entirely consist of LEDs by 2030.

Though all forecasts lack certainty, the findings present a thorough overview of where the lighting market is currently headed and will be of use to manufacturers, suppliers, and other stakeholders in the lighting industry as the transition to LED technology moves forward. Additionally, this study is accompanied by an online interactive model, which allows users to adjust key inputs, including price and efficacy trends, to better understand how these adjustments affect the forecasted LED penetration and energy savings. The online interactive model is available at be http://energy.gov/eere/ssl/led-lighting-forecast.

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1 Introduction

According to a recent U.S. Department of Energy (DOE) report, lighting consumed approximately 18% of the total U.S. electricity use in 2013 (Navigant, 2014). At that time, light-emitting diode (LED) lamp and luminaire products were costly, and very few were installed in general illumination applications; however, predictions suggested that they would soon greatly transform the market. In the subsequent four years, LED technology has improved considerably and early energy-savings predictions have begun to materialize.

This study is the sixth iteration of the *Energy Savings Forecast of Solid-State Lighting (SSL) in General Illumination Applications* forecast analysis. As in past iterations, this study provides updated predictions of LED market penetration and energy savings compared to conventional lighting sources (i.e., incandescent, halogen, fluorescent, and high-intensity discharge) in all general illumination applications from present-day through 2030.[1] An econometric lighting market model forecasts the expected annual lighting energy consumption which assumes the continued and increasing penetration of LED technology and a counter-factual scenario where LEDs never existed. LEDs energy savings can be derived by comparing these forecasts. This study estimates the expected future adoption of LEDs based on the current trajectory for the technology. Therefore, the results of the light market model do not necessarily represent the maximum potential, both in terms of market penetration and energy savings, of LED technology.

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

Section 2 which provides a high level overview of the analytical approach used to forecast LED energy savings. The approach consists of seven steps starting with developing 2013 lighting inventories and ending with calculating the energy savings due to LED penetration. The lighting market model utilizes a econometric logit model to award available market share to multiple competing lighting technologies, similar to the model used in the National Residential Sector Demand Module of NEMS 2013 (U.S. EIA, 2013) for the lighting technology choice component, and is discussed in detail in Appendix F.

Section 3 which provides a detailed look at the results of the econometric model. Discussion concerning the predicted market share of each lighting technology and resulting energy consumption is provided for the entire lighting market as well as each submarket that is examined.

Section 4 which provides an abridged sensitivity analysis that looks at the effects of variations in price and efficacy trends. Readers are invited to visit http://energy.gov/eere/ssl/led-lighting-forecast, where they can manipulate an interactive version of the lighting market model, and further investigate the model sensitivities.

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

[1] Past iterations of the *Energy Savings Forecast of Solid-State Lighting (SSL) in General Illumination Applications* reports are available at: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

2 Analytical Approach

The methodology followed in developing the U.S. lighting market model and forecasting aggregate consumer lighting purchases, consists of a seven-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 (Navigant, 2012), the Residential Lighting End-Use Consumption Study (PNNL, 2013(a)),[2] and the Adoption of Light Emitting Diodes in Common Lighting Applications: Snapshot of 2013 Trends (Navigant, 2014), the lighting market model uses the lamp installations, average efficacies, wattages, and operating hours to estimate a national lighting inventory in lumen-hours of lighting service for each sector (i.e. residential, commercial, industrial, and outdoor). The base year for the inventory considered in this analysis is 2013.

Step 2, Develop arenas for competition.[3] As depicted in Figure 2.1, the current lighting market model examines eight submarkets across four sectors where a total of 15 technology categories may compete (not including an "other" technology category used when there is uncertainty in the existing inventory). An "other" submarket was also included in each sector to accommodate lighting products with unknown applications. It is assumed that LEDs will compete with these products separately.

Establishing submarket categories based on common general illumination applications is a significant improvement from the previous model iteration, where competition between lighting technologies was simplified by only examining five technology-based submarkets: medium screw-base general service lamps (GSL–MSB), reflector–screw-base, linear fluorescent, high-intensity discharge (HID), and miscellaneous. This improvement to the lighting market model enables a single lighting technology, such as linear fluorescent lamps, to compete in multiple submarkets (i.e. linear fixtures, low/high bay, and parking) compared to the previous model iteration which grouped all linear fluorescent lamps into a single submarket regardless of application.

[2] The *Residential Lighting End-Use Consumption Study* is used for the operating hour estimates for lighting installed in the residential sector, while the *2010 Lighting Market Characterization* is used for the operating hour estimates for lighting installed in the commercial, industrial and outdoor sectors.

[3] Additional detail on how the arenas for competition were developed is included in Appendix A.

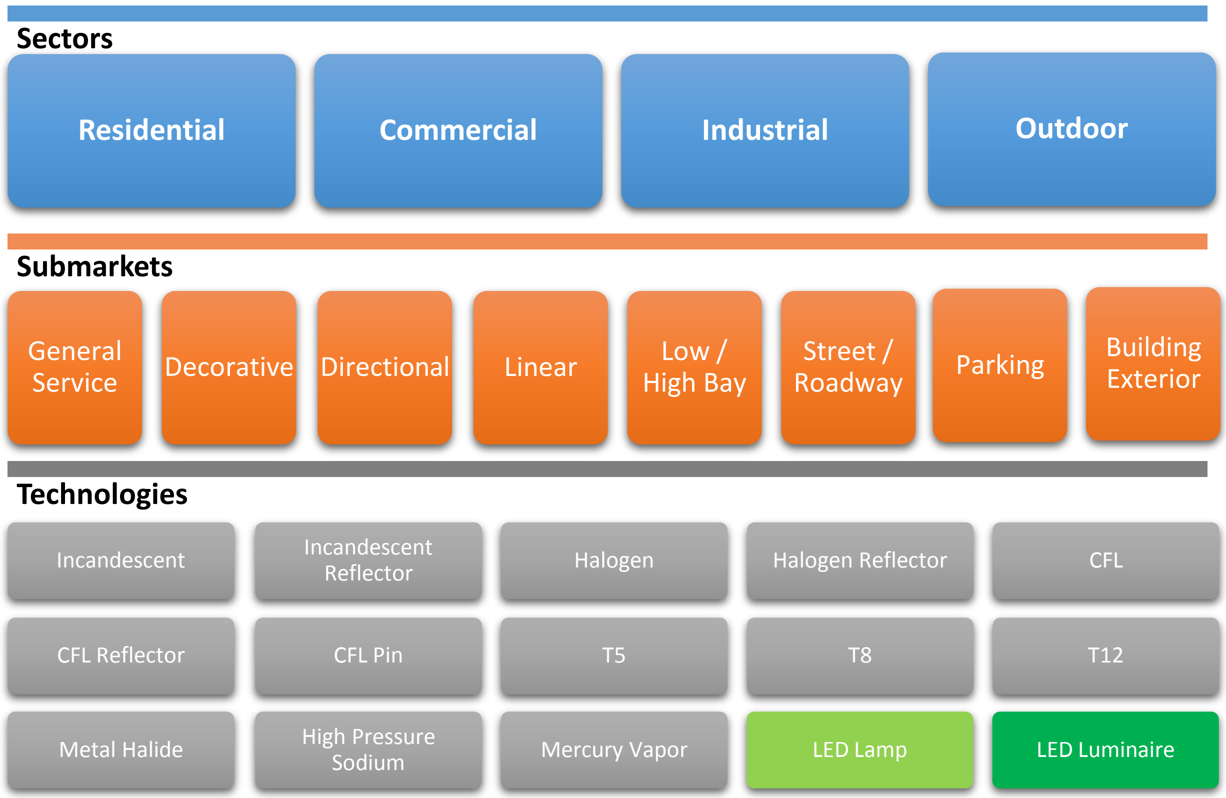

Figure 2.1 Lighting Market Arenas

Step 3, Project annual lumen demand forecast.[4] Assuming constant lumen demand per square foot of floor space in each sector, the lighting market model forecasts U.S. lumen demand from 2013 to 2030. The Annual Energy Outlook (AEO) 2014 provides annual average growth forecasts of floor space in the residential and commercial sectors, which are used to project increases in lumen demand moving forward (U.S. EIA, 2014). Projections suggest that residential floor space will increase by an average of 1.31% per annum over the 20-year analysis period, and the commercial sector floor space will increase by an average of 1.00% per annum. AEO 2014 does not provide a 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 2014 annual projections for manufacturing employment growth were used as a proxy for annual average floor space growth estimates of floor space.

Step 4, Calculate the available market.[5] Each year, new lamps enter the market as old lamps are replaced or fixtures are installed or retrofitted. This creates an annual lumen market turnover, which may be satisfied by a suite of lighting technologies. The lighting market model considers three possible events that create lumen 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 lumen turnover due to new installations is

[4] Additional detail on how the annual lumen demands were calculated can be found in Appendix C.
[5] Additional detail on how the lumen market turnovers were calculated can be found in Appendix C.

derived from maintaining lighting density per unit area for the projected new building floor space in the various sectors as discussed in Step 3. The quantity of lumen turnover due to replacements is based on the lumens that fail in a calendar year, which is calculated using a Weibull probability distribution,[6] typical lighting operating hours and lifetimes. The quantity of lumen turnover due to renovation is assumed to be a constant 5% of all lumen-hours per year, or a mean renovations cycle of 20 years.

Step 5, Project conventional and LED lighting technology improvement.[7] Recognizing that the incumbent conventional lighting technologies will compete with new LED lighting products, the lighting market model allows for both cost reductions and performance improvements in efficacy and lifetime for conventional lighting technologies (i.e., incandescent, halogen, fluorescent, and HID) and LEDs. Technology performance improvements are also adjusted to account for existing legislative and regulatory energy conservation standards that take effect in future years. The lighting market model primarily uses adjusted price and performance curves for LED lighting based on data published in the *2013 SSL Pricing and Efficacy Trend Analysis for Utility Program Planning* (PNNL, 2013(b)).

Step 6, Model the market share of all lighting technologies.[8] The lighting market model predicts market share as an aggregate of many individual purchase decisions using two analytic components: an econometric logit model that considers cost factors influencing each decision, and a technology diffusion curve that considers time dependent market factors influencing each decision. Additionally, LED penetration is calibrated through a reverse engineering process comparing past LED market share values predicted by the model to actual historical values. Figure 2.2 summarizes this approach. This approach of using a logit model and a technology diffusion model in concert is well tested and has been previously used in many forecast models (Cao, 2004; Paidipati, Frantzis, Sawyer, & Kurrasch, 2008).

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

[7] Additional detail on how the cost and efficacy improvements were determined can be found in Appendix E.

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

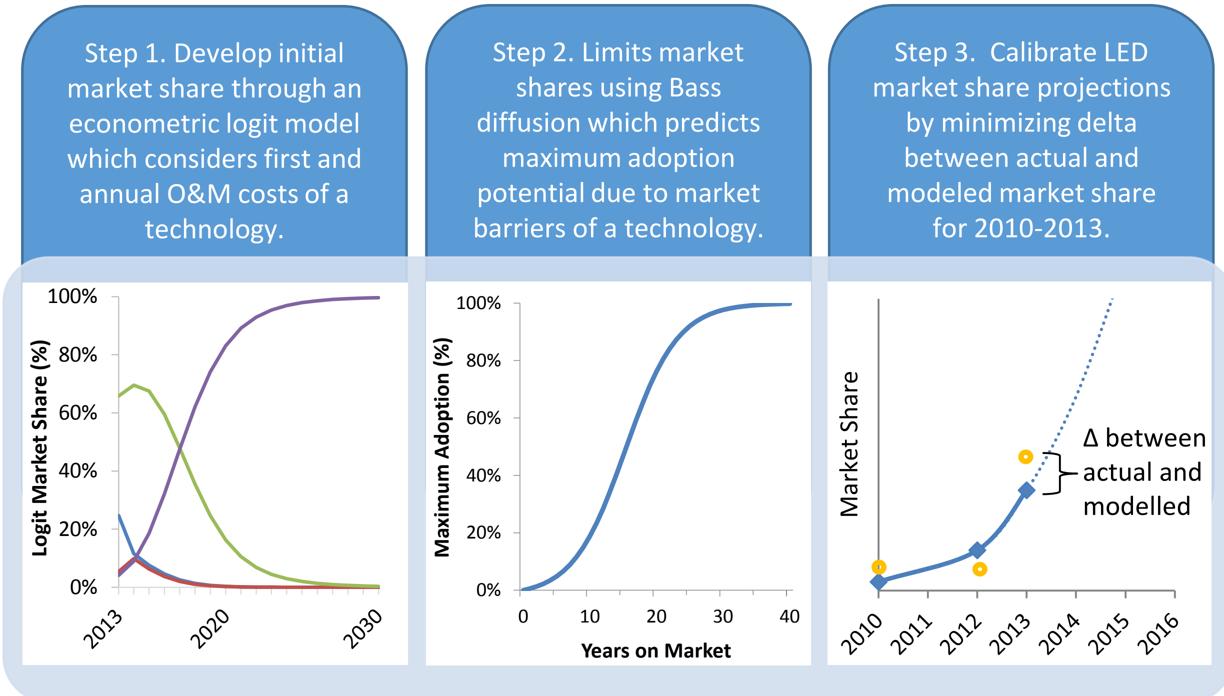

Figure 2.2 Market Share Modeling Approach

Step 7, Calculate energy savings. Annual energy savings are then estimated by comparing the lighting energy consumption projected by the lighting market model to that of a counter-factual LED-absent scenario. In the no-LED scenario, LED products are assumed to have never entered the general illumination market, but all other market conditions, such as energy conservation standards for conventional technologies, are unchanged.[9]

2.1 Lighting Market Model Enhancements

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

1. Calibration based on estimated LED market share. Past iterations of this model used hypothetical market penetration rates based on how similar products historically gained market share. Market-share data for LED lamp and luminaire products are now available for several past years. This track record makes it possible to calibrate the lighting market model outputs for future years based on the actual pattern by which LEDs have gained market share thus far, effectively improving the accuracy of the predictions.
2. Moving the lighting market model to an advanced quantitative decision-support software tool. Previous iterations of the lighting market model were limited by the two-dimensional nature of spreadsheet calculations. For this iteration, the lighting market

[9] 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.

model was moved to a new software package[10] that allows for complex multi-dimensional analysis, minimizing the need for many over-simplified assumptions and improving the overall characterization of the U.S. lighting market.

3. A deeper disaggregation of LED products and applications. In this study, the lighting market model tracks the penetration of LED lamp and luminaire products separately to more accurately describe competition with incumbent technologies. This also allows LED lamp and luminaire products to compete within the same submarket, which was not considered in the previous lighting market model iterations.

4. Reorganization of submarkets. Thanks in part to a transition to the new software package[10], the U.S. lighting market model is now capable of processing a more complex multi-dimensional analysis as well as more sophisticated market share calculations where the submarkets are application-based rather than grouped by lighting technology. As mentioned in the Section 2, the submarkets in the previous lighting market model included: GSL–MSB, screw-base reflector, linear fluorescent, HID and miscellaneous. The technologies that competed for market share were limited within each of these submarkets. In the updated lighting market model, submarkets are defined by applications within each sector and allow for competition among all available technologies. For example, the new model considers the use of omnidirectional lamps in directional applications in acknowledgement that residential consumers use general service lamps (GSLs) as a common "fix" for several home-based applications. Also, in the updated lighting market model, HID and linear fluorescent fixtures are able to compete within low/high bay applications, whereas in the previous model this was not considered. (See Appendix A for more detail about the lighting technologies grouped in each submarket.)

5. Advanced failure-rate calculations. In the previous lighting market model, failure rates were calculated assuming a constant annual failure rate based solely on a product's expected lifetime and operating hours. In this updated model iteration, lamp and ballast failures are predicted using the Weibull probability distribution,[6] which predicts the proportion of remaining units that are expected to fail each year. Using the Weibull distribution allows the lighting market model to track the vintage or installation year of all products within the installed stock, and, with this knowledge, predict the number of failures.

6. Updated price and efficacy forecasts for LEDs. In past iterations the anticipated LED price and efficacy values for out-years were derived from the DOE SSL Program's Multi-year Program Plan (MYPP).[11] The MYPP indicates performance goals that the market believes are achievable with DOE support. As mentioned in step 5 of Section 2, this year's lighting market model relies primarily on LED price and efficacy forecasts provided by PNNL. While the MYPP indicates expectations for the best available product, the PNNL forecast indicates expectations for average products, which is a better representation of the entire LED market.

[10] Analytica® is a quantitative decision-support environment that facilitates problem visualization. More information can be found at: http://www.lumina.com/
[11] The DOE SSL Program's MYPP is updated annually and is available at: http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html

2.2 Simplifying Assumptions

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

1. Constant demand for lighting intensity. It is assumed that the level of lighting intensity (lumens per square foot) in buildings remains constant over the analysis period (2013–2030). This simplification may underestimate the forecasted energy savings from LEDs because it requires LEDs match the source lumen output levels of conventional sources in all applications. However, many spaces may be over-lit and LED technology may be able to achieve adequate illumination with fewer lumens (e.g., due to improved uniformity, directionality, and/or color performance).

2. Prevalence of lighting controls. One of LEDs' strengths is their compatibility with lighting controls. Higher LED adoption is likely to be accompanied with higher control usage. The use of networked lighting controls, such as motion sensors or occupancy sensors, will allow for instantaneous response to the demand for lighting and save energy by providing artificial light only when and where it is needed. The lighting market model assumes the prevalence and use of controls does not change drastically during the analysis period. This assumption likely underestimates the forecasted energy savings of LEDs, as controls are becoming increasingly popular in lighting upgrades/retrofits and new construction, particularly where they can be easily integrated into LED luminaries themselves.

3. Renovations rate. The lighting market model assumes a constant, 5% per year, rate of lighting fixture replacements due to renovations of the installed base. This covers all upgrades/retrofits and renovations, regardless of their impetus, and includes renovations undertaken for design or aesthetic preferences and "green" retrofits undertaken to reduce energy consumption. With concerns over climate change mounting, energy-efficiency retrofits are likely to increase in frequency over time. In addition, utility and government incentive programs are starting to compensate consumers who retrofit using LED lighting products.[12] 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.

4. LED and conventional technology price and performance improvement curves. The lighting market model is driven by price and performance improvement assumptions for

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

LEDs and conventional technologies over the analysis period. Any deviations from these projections could cause the energy savings estimates to be higher or lower. Because the price and performance projections in the *2013 SSL Pricing and Efficacy Trend Analysis for Utility Program Planning* the lighting market model may underestimate or overestimate the forecasted LED market penetration and energy savings in the long term.

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

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

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

3 Lighting Market Model Results

DOE estimates that in 2013 lighting technologies were responsible for 17% of total U.S. electricity consumption, using approximately 609 terawatt-hours of site electricity, or about 6.9 quads of source energy. As seen in Figure 3.1, which presents the lighting energy consumption forecast as predicted by the lighting market model, LED lighting is projected to reduce lighting energy consumption by 15% in 2020 and 40% in 2030, which, in absolute terms, is 261 terawatt-hours or 3.0 quads saved in 2030.

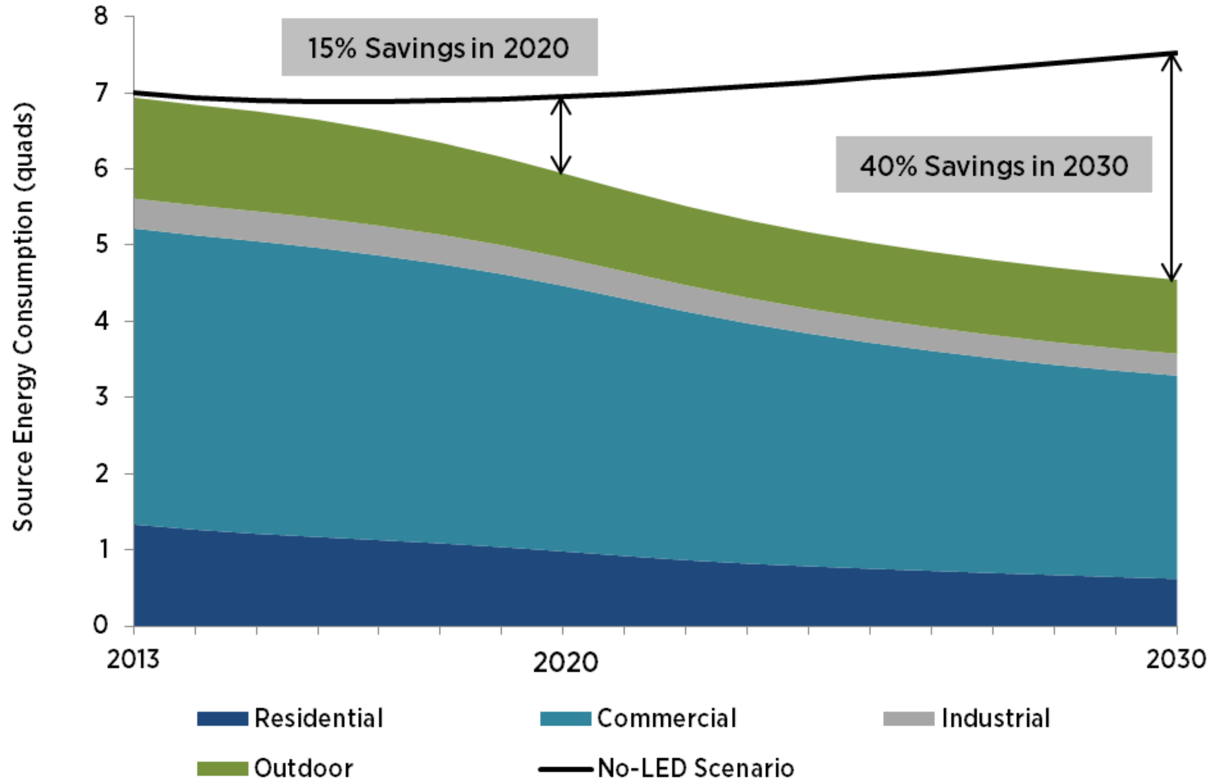

Figure 3.1 Total U.S. Lighting Energy Consumption Forecast, 2013 to 2030

As presented in Table 3.1, the results of this forecast indicate that LED lighting sales (based on lumen-hours) will increase from approximately 3% in 2013 to about 48% in 2020, and 84% in 2030. The rapid growth of LED products between today and 2020 is largely due to LEDs costs reaching highly-competitive levels and newly enacted efficiency standards. Much of this growth will occur first in the outdoor sector, with nearly the entire sector shifting to LEDs by 2025. This sector's conventional outdoor lighting technologies have relatively high first costs and thus LED luminaires will rapidly become cost-competitive.

Table 3.1 U.S. LED Forecast Results by Sector

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	**3%**	**11%**	**48%**	**72%**	**84%**	–
Residential	< 1%	3%	33%	71%	83%	–
Commercial	2%	8%	42%	69%	82%	–
Industrial	< 1%	3%	26%	58%	87%	–
Outdoor	9%	22%	75%	97%	99%	–
Site Electricity Savings (TWh)	**5**	**12**	**89**	**190**	**261**	**2,216**
Residential	< 1	2	18	42	61	487
Commercial	2	5	41	97	139	1,122
Industrial	< 1	< 1	4	9	14	106
Outdoor	2	5	27	41	48	502
Source Energy Savings (TBtu)	**56**	**141**	**1,010**	**2,166**	**2,980**	**25,266**
Residential	7	28	200	483	696	5,554
Commercial	26	60	467	1,109	1,580	12,788
Industrial	< 1	2	41	108	157	1,206
Outdoor	22	52	303	467	547	5,718
Site Electricity Savings (%)	**< 1%**	**2%**	**15%**	**30%**	**40%**	**20%**
Residential	< 1%	2%	17%	39%	53%	25%
Commercial	< 1%	2%	12%	27%	37%	18%
Industrial	< 1%	< 1%	10%	25%	35%	16%
Outdoor	2%	4%	21%	32%	36%	22%

As seen in Figure 3.2 below, in 2013 the installed base in lumen-hours was dominated by linear fluorescent and HID lighting, both of which have high operating hours, high lumen output per lamp, and large number of installations. However, in terms of installed base, LED lighting is predicted to account for a majority of installations by 2022 and 88% of all lumen-hours being produced for general illumination in 2030.

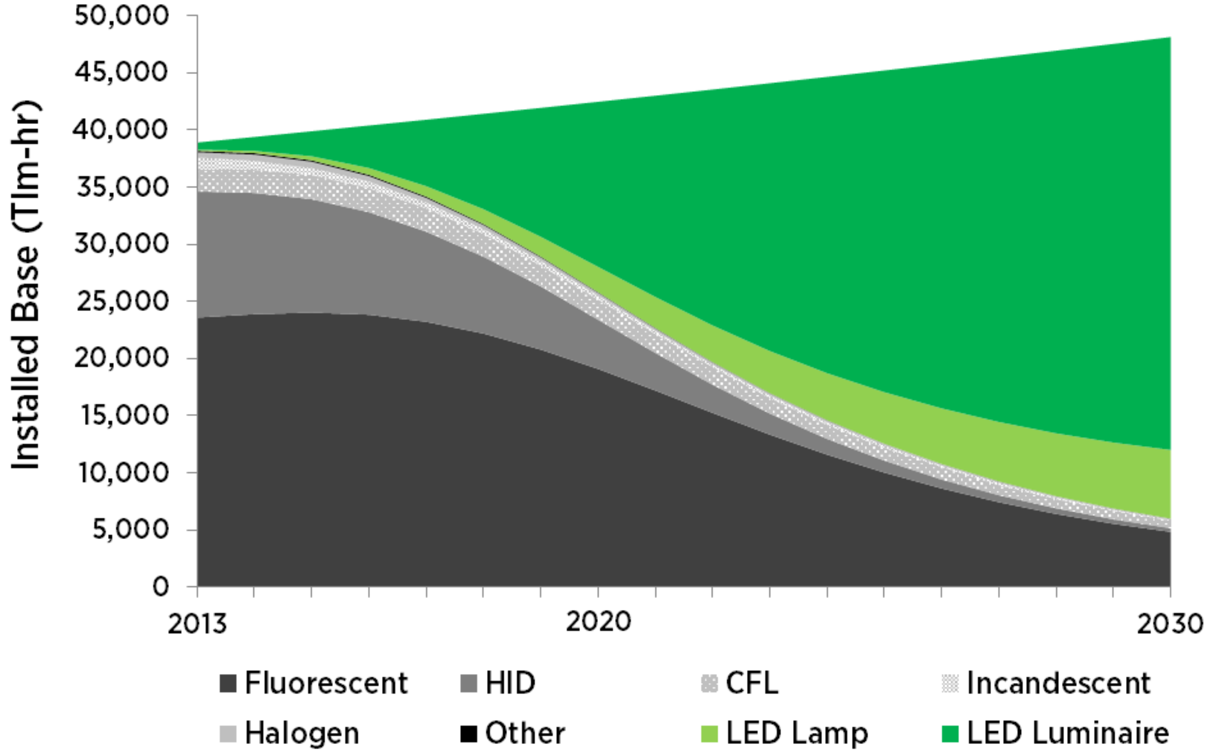

Figure 3.2 U.S. Lighting Service Forecast, 2013 to 2030

The following sections describe the major results of the forecast model for each of the lighting submarkets.

3.1 Indoor Lighting

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/high bay submarkets. Combined, the linear fixture and low/high bay submarkets represent 85% and 88% of the 2013 general illumination energy consumption in the commercial and industrial sectors, respectively.

LEDs are projected to only offer incremental improvement over linear fluorescent and HID technologies in the near-term; however, with expected performance and price improvements, LEDs hold great promise in the long-run for cutting energy consumption in the commercial and industrial sectors. Therefore, energy savings in the commercial sector, shown in Figure 3.3, is projected to reach only 12% in 2020, but grow to 37% in 2030. Energy savings projections for the industrial sector, shown in Figure 3.4, are similar.

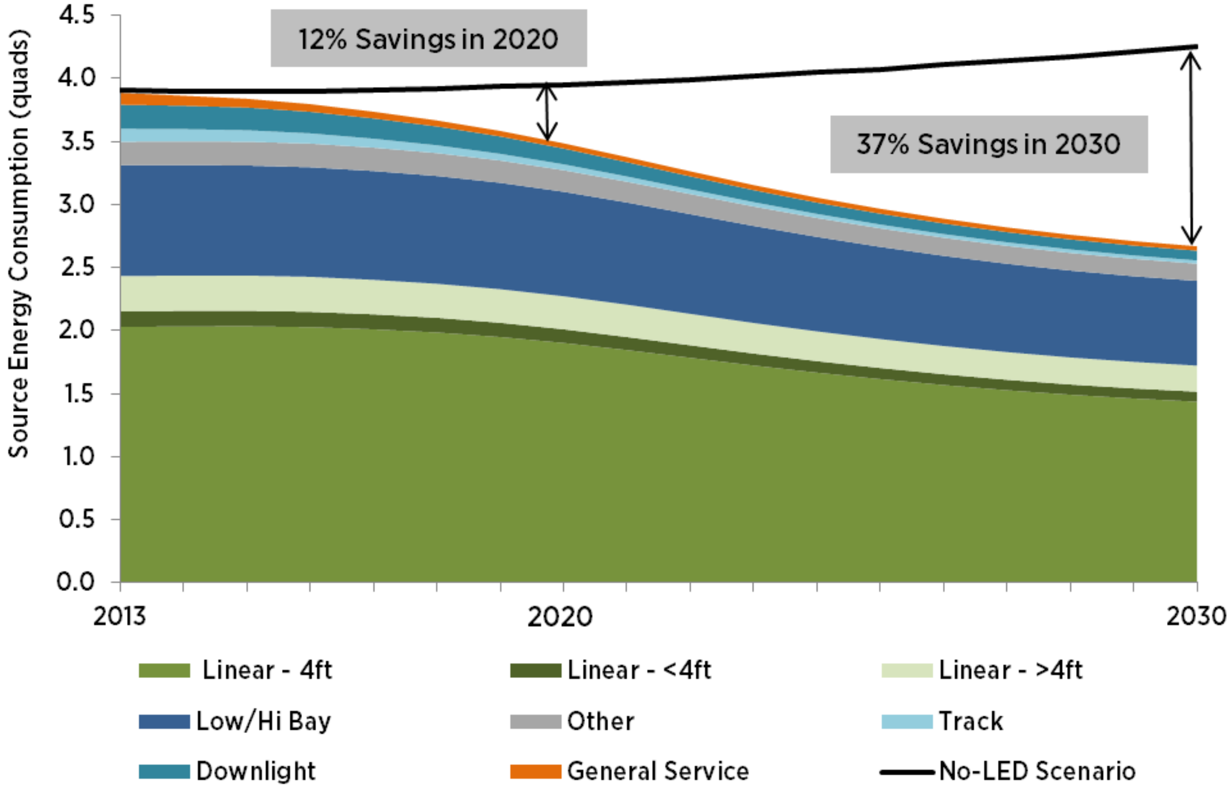

Figure 3.3 Commercial Lighting Energy Consumption Forecast, 2013 to 2030

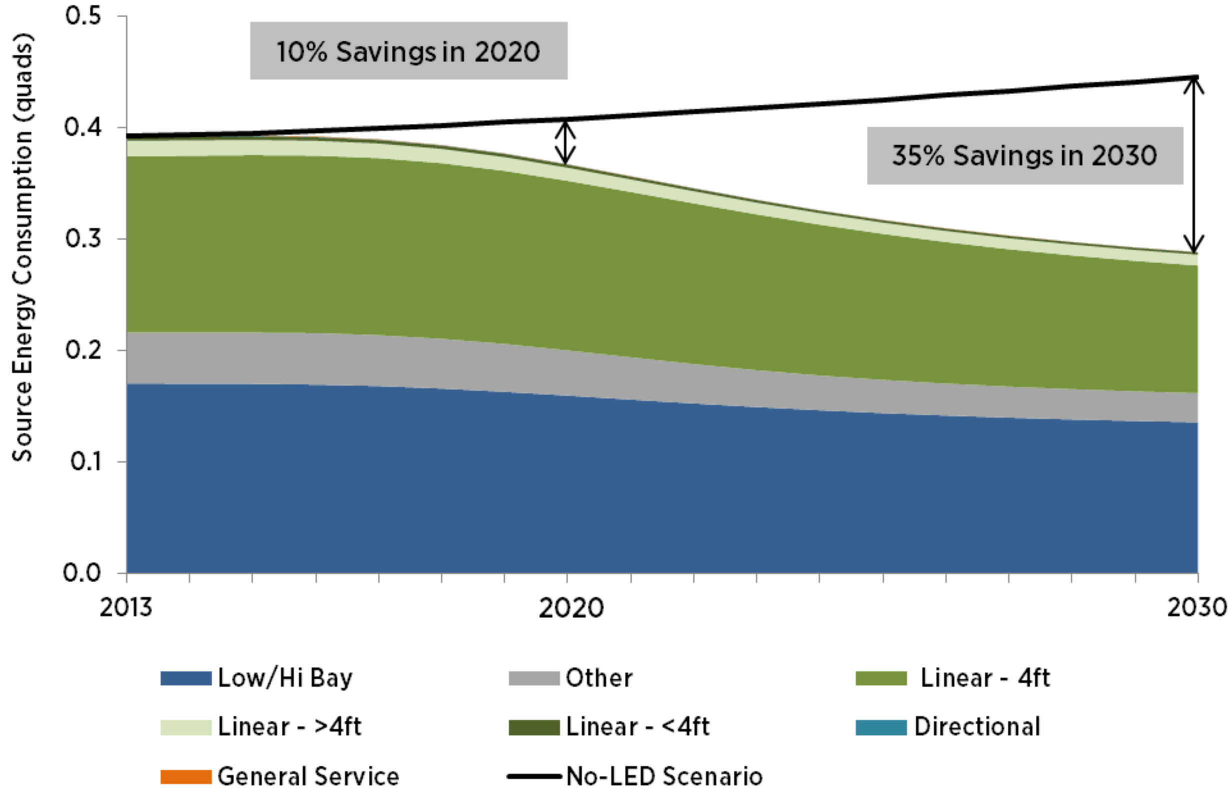

Figure 3.4 Industrial Lighting Energy Consumption Forecast, 2013 to 2030

Residential lighting is used in single-family, multi-family, and mobile households, with the majority provided by lamps and/or luminaires in the general service and directional submarkets. Although residential lighting represents the largest number of installed lamps at approximately 5.8 billion in 2013, lamps in this sector are used for relatively few operating hours, averaging less than two hours per day and providing roughly 3,400 teralumen-hours of lighting service annually. Due to low lamp usage and limited lighting education, consumers in the residential sector place a higher value on the price of a lighting product rather than its annual costs. The residential sector as a whole is therefore less concerned with the efficacy and lifetime performance of lighting products. Due to the high efficacy and increasing penetration of LED products, as seen in Figure 3.5, the lighting market model predicts significant energy savings in the residential sector, estimating a 53% decrease in energy consumption compared to the no-LED scenario by 2030.

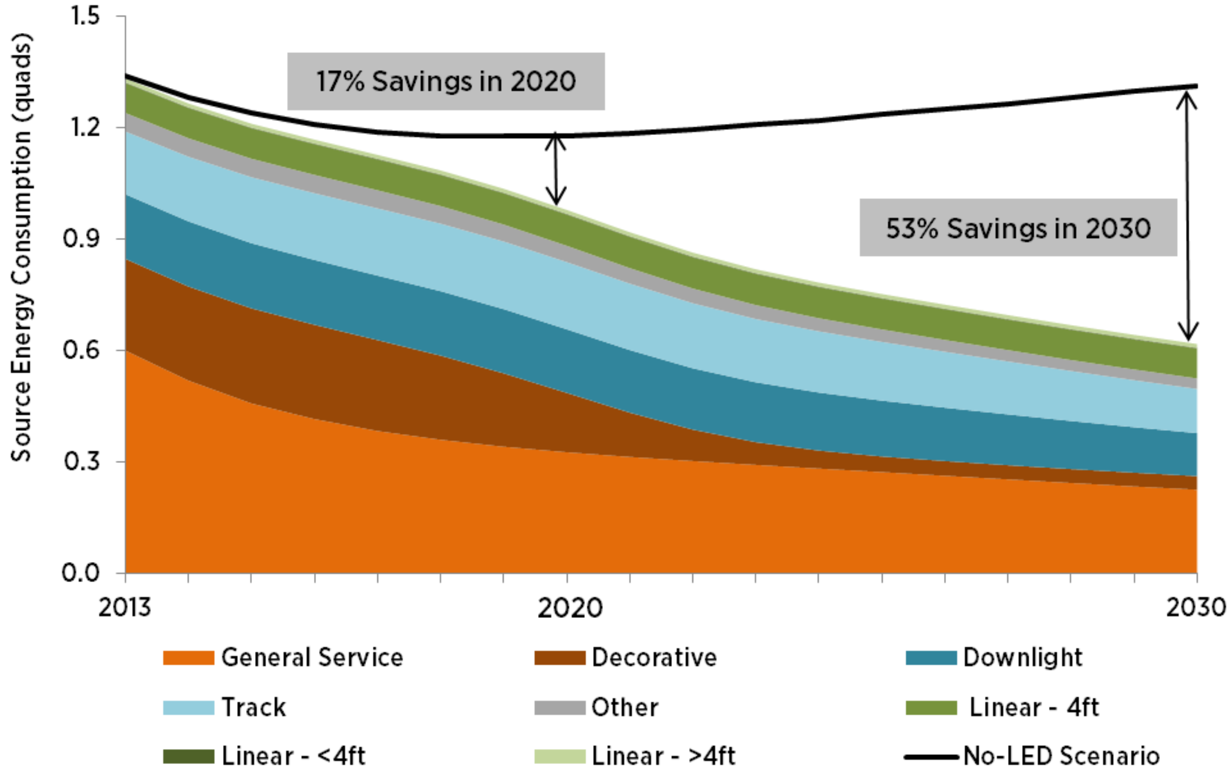

Figure 3.5 Residential Lighting Energy Consumption Forecast, 2013 to 2030

3.1.1 General Service Submarket

The general service submarket includes standard incandescent A-type lamps, incandescent halogen, CFLs, and LED replacement lamps. These omnidirectional lamps, are some of the most widely recognized and, while the vast majority of these lamps are used in general service 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 GSLs are used in outdoor submarkets, discussed in Section 3.2.

Incandescent A-type lamps are still the most familiar to consumers, and in 2013 constitute the majority of this submarket, however, their market share has dropped significantly in recent years. This shift is largely due to the implementation of Energy Independence and Security Act of 2007 (EISA 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 halogen lamps have begun to replace the traditional incandescent lamps in many applications.[13]

[13] EISA 2007 does not ban incandescent light bulbs, but its minimum efficiency standards are high enough that incandescent lamps most commonly used by consumers today will not meet the requirements. This Act essentially eliminates 40W, 60W, 75W, and 100W medium screw based incandescent light bulbs. More information can be found at: http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/eisa_2007.pdf

LED replacement lamps in the general service submarket became available to consumers between 2007 and 2009 at a typical cost over $50 per lamp, and struggled to match the efficiency of incumbent CFLs. The high first cost and limited energy savings over CFLs has limited the uptake of LED lighting in general service applications, but significant improvements have been made in recent years. As a result, the lighting market model predicts that LEDs will be the dominant technology in general service applications by 2020, having an overall market share, shown in Table 3.2, of 55% across the three indoor sectors.

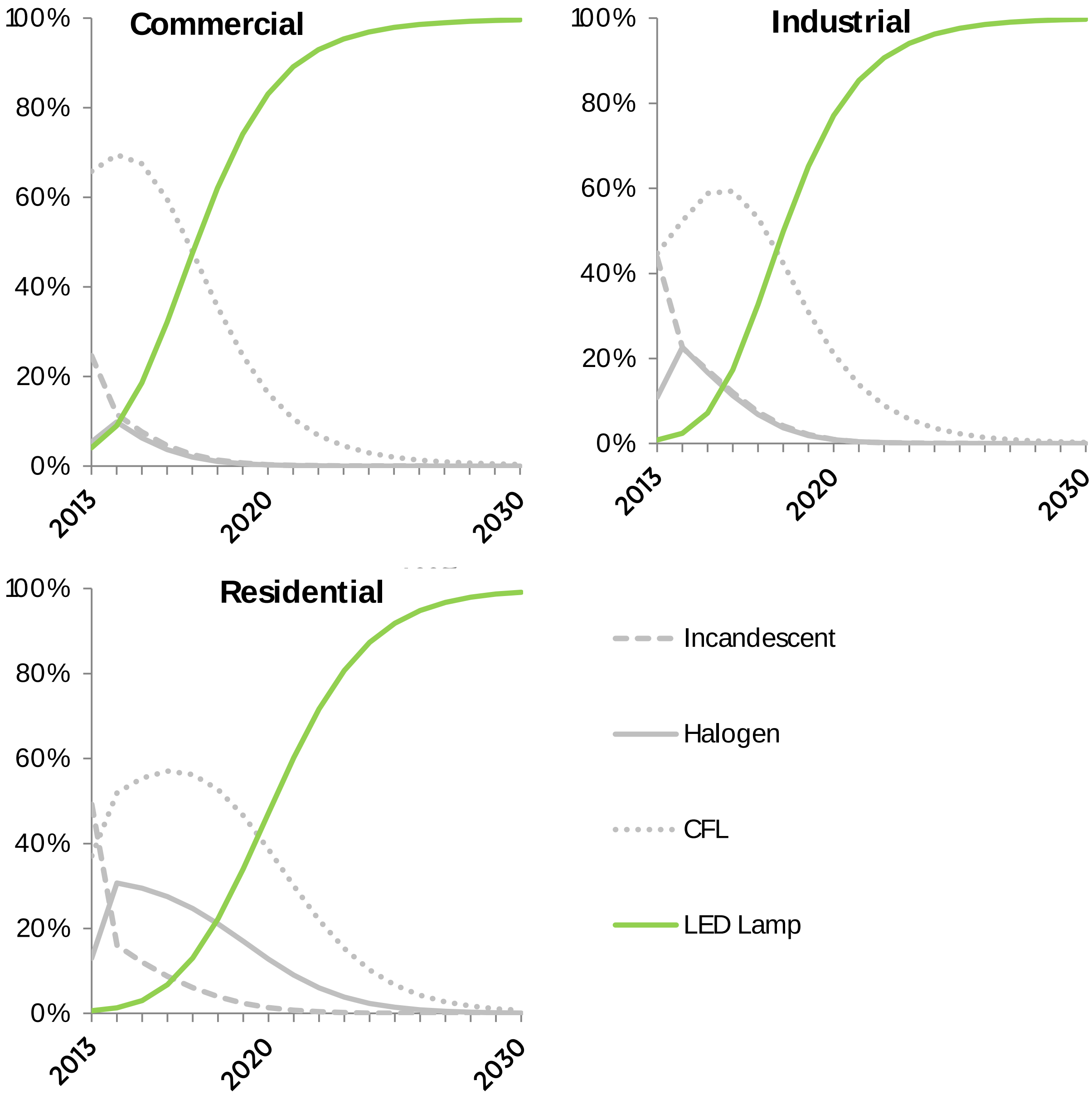

Figure 3.6 General Service Market Share (% of lm-hr sales) Forecast, 2013 to 2030

While the market share forecasts for the commercial and industrial sectors are quite similar, with a quick uptake of LEDs following the final phase of EISA 2007 which kicked-in as of January of

2014, the LED market share for the residential sector lags by about three years. In 2020, it is forecasted that LED lamps will have 83% and 77% of the market share in the commercial and industrial sectors respectively, while the residential market share is predicted to be 47% LED. When looking for alternatives to incandescent lamps, many first cost-conscious residential consumers will switch to halogen or CFL lamp options until the price of LED lamps becomes more comparable. Despite this slower uptake of LEDs, over 80% of the expected energy savings for general service applications is from the residential sector due to the sheer number of lamps installed.

Table 3.2 General Service Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	**2%**	**8%**	**55%**	**93%**	**> 99%**	**-**
Residential	< 1%	3%	47%	92%	> 99%	-
Commercial	4%	19%	83%	98%	> 99%	-
Industrial	< 1%	7%	77%	98%	> 99%	-
Site Electricity Savings (TWh)	< 1	**3**	**6**	**11**	**17**	**149**
Residential	< 1	2	4	9	14	114
Commercial	< 1	< 1	2	2	3	35
Industrial	< 1	< 1	< 1	< 1	< 1	< 1
Site Electricity Savings (%)	**2%**	**5%**	**16%**	**29%**	**43%**	**20%**
Residential	< 1%	4%	12%	27%	42%	18%
Commercial	7%	12%	37%	41%	48%	32%
Industrial	2%	6%	45%	45%	51%	31%

3.1.2 Decorative Lamp Submarket

Decorative is a fairly generic term that is used to cover a wide range of bulb shapes including bullet, globe, flame, and candle, among others. These lamps are most common in the residential sector and are intended for use in decorative fixtures, including chandeliers, pendants, wall sconces and lanterns, and nightlights. The presence of decorative lamps in the commercial, industrial, and outdoor sectors is considered to be negligible in the lighting market model. Given their intended decorative function, these lamps typically require low lumen output and are not intended to independently illuminate a space or a task, but may have high color quality requirements depending on the use. Furthermore, as these bulbs 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, and, in the absence of LED alternatives, the no-LED scenario market composition is expected to remain largely unchanged from the current 2013 stock which is over 95% incandescent. 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. In the

LED scenario, as the cost of LED lamps continue to fall, their share increases, becoming the majority of decorative lamps sales by 2022, and reaching 94% by 2030. LED replacement lamps penetrate this submarket, where the majority of competition comes from short-lived incandescent lamps, much faster than in other submarkets, such as general service, where CFLs are a more prominent competitor. The forecasted market share for the decorative lamp submarket is shown in Figure 3.7.

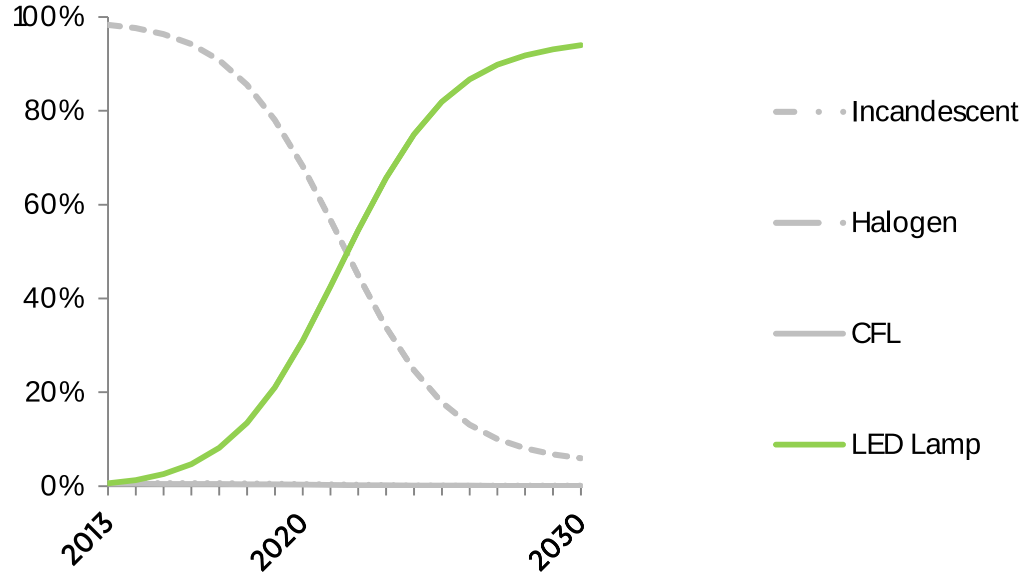

Figure 3.7 Decorative Lamp Market Share (% of lm-hr sales) Forecast, 2013 to 2030

Furthermore, because, in the absence of LEDs, inefficient incandescent lamps would continue to hold the majority of the residential decorative lamp market, there is a large opportunity for relative energy savings. The projected energy savings for residential decorative applications is shown in Table 3.3 below. As LEDs replace incandescent lamps and reach 94% of the market share in 2030, energy savings of up to 89% is expected. However, due to low lumen output, short operating hours, and a small installed base, residential decorative lamps in general will have a small impact on the overall projected energy savings for the United States lighting market.

Table 3.3 Decorative Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	< 1%	3%	31%	82%	94%	–
Site Electricity Savings (TWh)	< 1	< 1	11	24	26	255
Site Electricity Savings (%)	< 1%	1%	44%	86%	89%	55%

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 have become popular because they are inexpensive and can provide inconspicuous ambient lighting for most room types. Track lights are also a popular fixture used for ambient lighting, but they are used for accent lighting in households, retail displays, restaurants, museums, and office buildings as well. These light fixtures are typically comprised of individual light fixtures, or track "heads", attached to a continuous metal mounting device that is, in turn, attached to a ceiling or wall, or hung via suspension cables or rods. For both downlights and track lights using incandescent, halogen, and compact fluorescent reflector lamps (e.g., PAR, BR, and R lamps), pin-based CFLs, as well as LED lamps and luminaires are most commonly used. The model also considers omnidirectional lamps that can be installed in the residential sector where consumers are most concerned with the initial bulb price as opposed to lighting quality and lifecycle costs. While also installed in downlight or track fixtures, MR lamps do not compete directly with the large reflector lamps because they are most often operated at low voltage and their design is constrained by a small form factor.[14] 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 (Rensselaer Polytechnic Institute, 2002). 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. 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 settings, where directional applications make-up about 3% and 16%, respectively, of the total lighting service, the lighting market model separates directional submarket into large reflector downlights, large reflector track lights, and MR lamps. This is because consumer preference of incumbent technologies, which affects LED market penetration and resulting energy savings, used in downlighting and track lighting differs. However, due to limited incumbent technology options for MR lamps, the differences between market share projections for MR lamps in track and downlighting are negligible. The market share projections for large reflector downlights, large reflector track lights, and MR lamps are shown in Figure 3.8, Figure 3.9, and Figure 3.10, respectively.

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

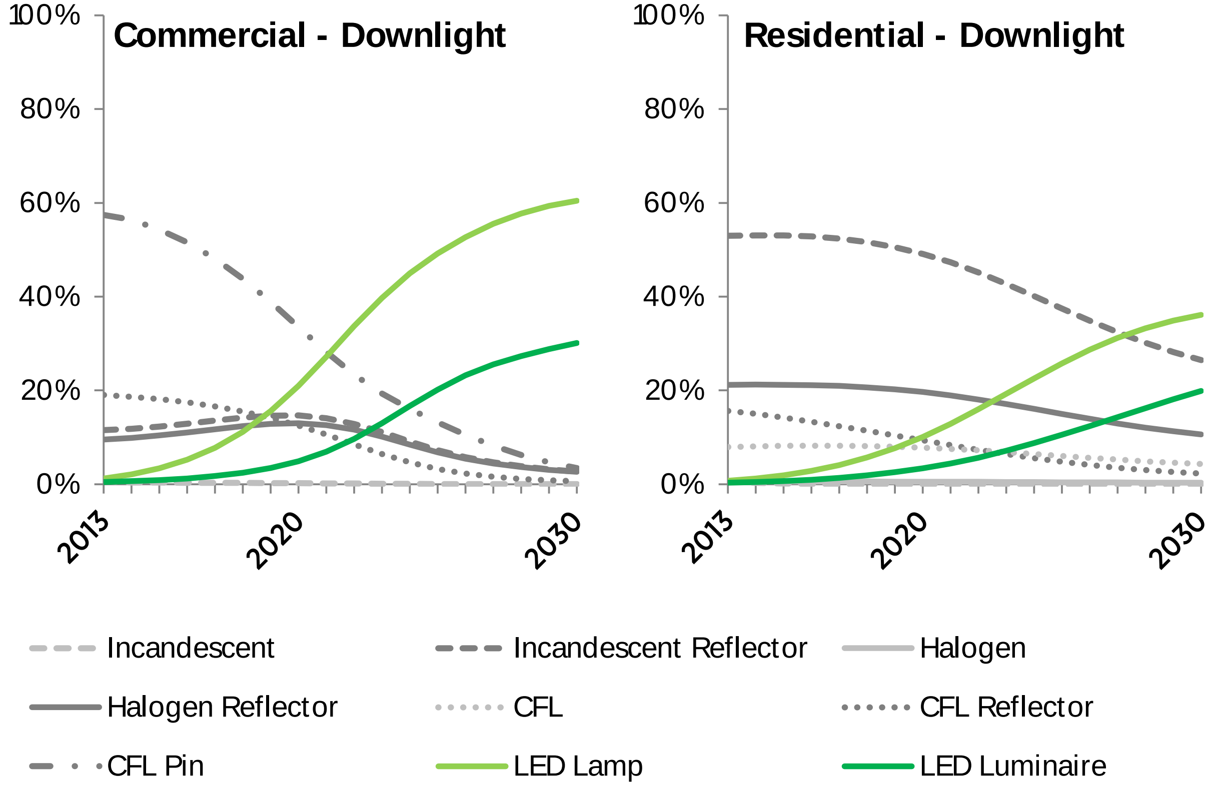

Figure 3.8 Downlight Applications Market Share (% of lm-hr sales) Forecast, 2013 to 2030

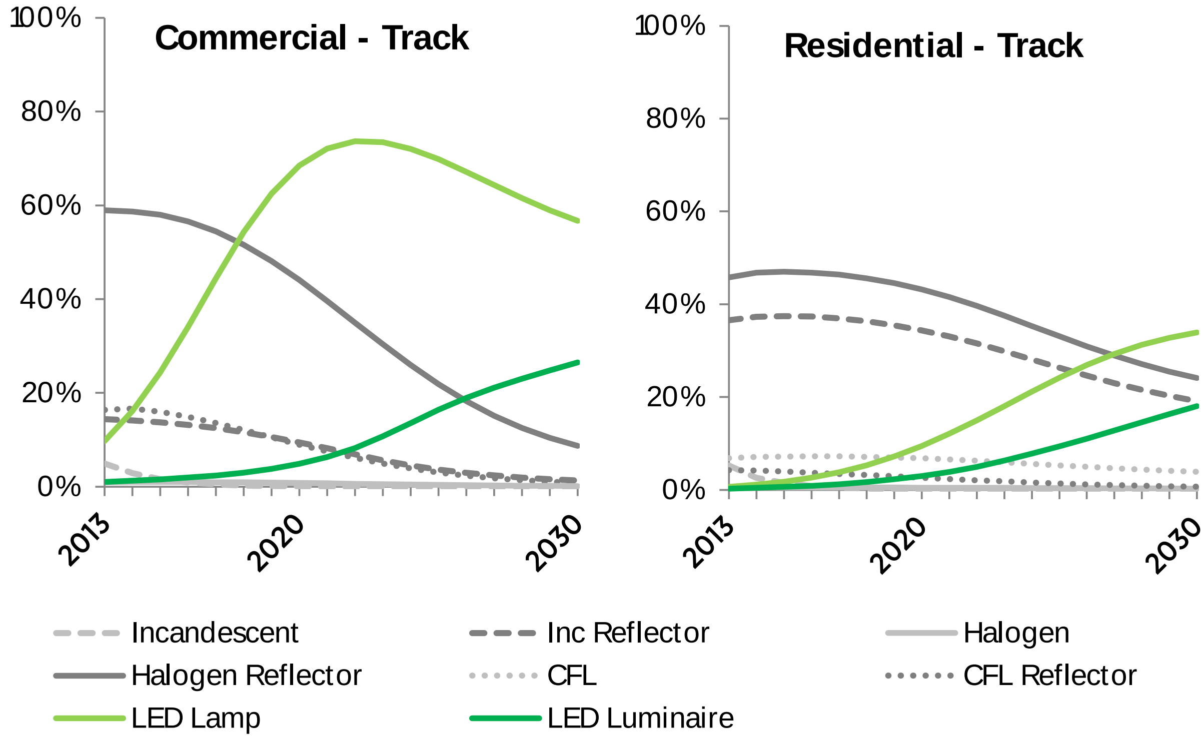

Figure 3.9 Track Applications Market Share (% of lm-hr sales) Forecast, 2013 to 2030

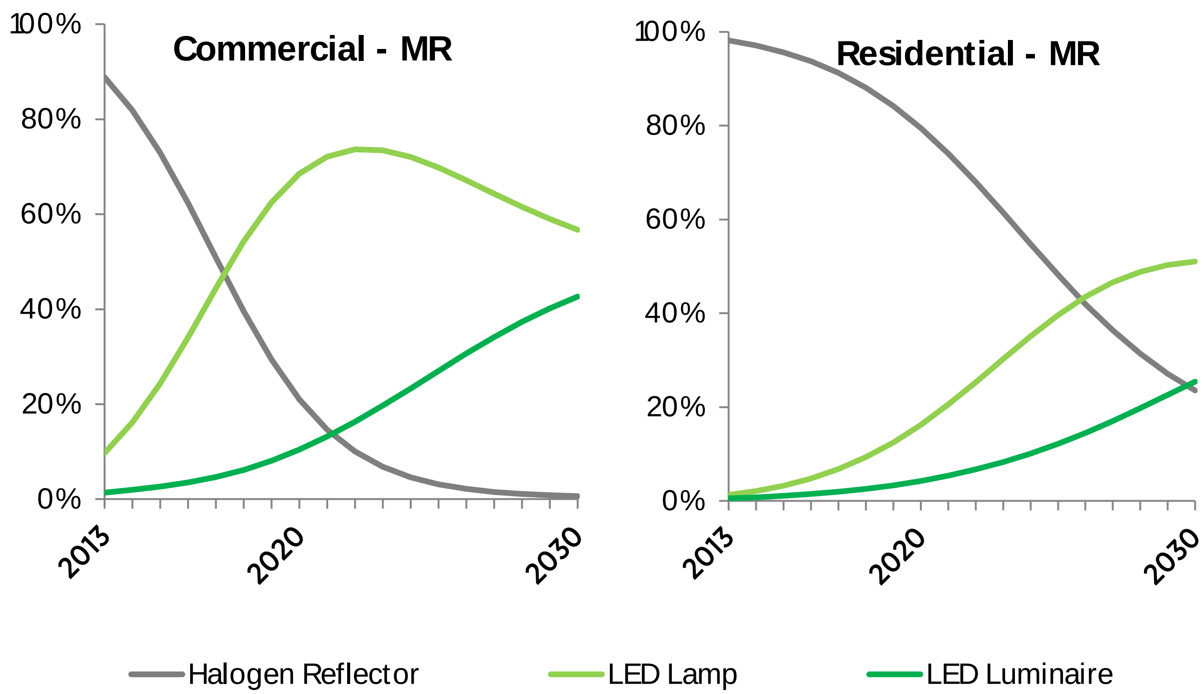

Figure 3.10 MR16 Applications Market Share (% of lm-hr sales) Forecast, 2013 to 2030

In the industrial sector, due to the limited use of directional lighting (less than 1% of industrial lighting service), directional lighting is not subdivided. The market share projection for industrial directional lighting is shown in Figure 3.11.

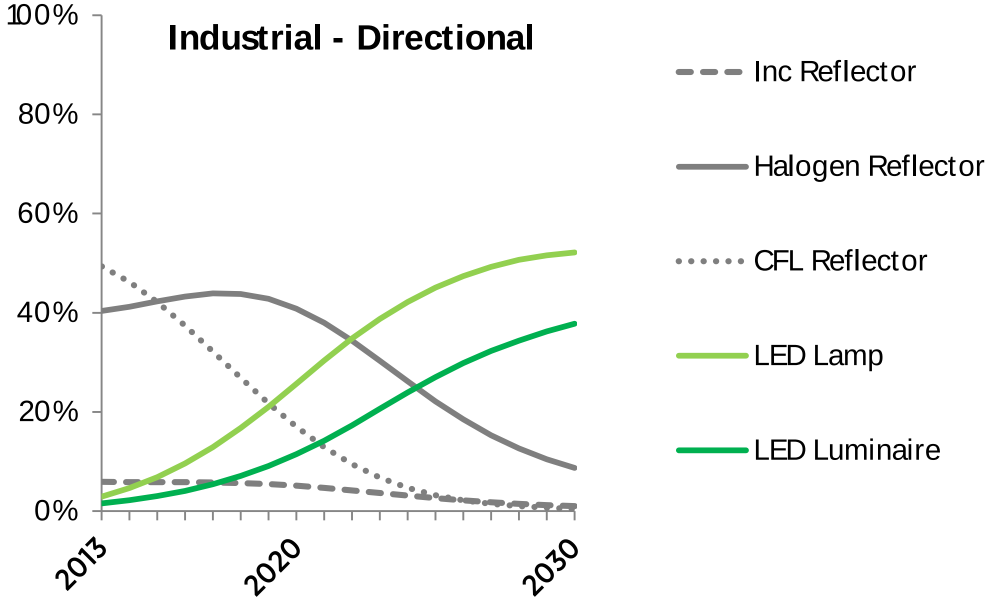

Figure 3.11 Industrial Directional Applications Market Share (% of lm-hr sales) Forecast, 2013 to 2030

LEDs have already established themselves as a significant competitor in directional applications, particularly in the industrial and commercial sectors. In the commercial sector, for 2013, LEDs represent nearly 2% of downlight lumen-hour sales, over 4% of track lighting, and 12% of MR16 lamps. Similarly in the industrial sector, LEDs in the directional submarket reach nearly over 4% of 2013 lumen-hour sales. While somewhat slower, in the residential sector, LED lamps and luminaires also achieve non-negligible penetration. In 2013, LEDs lumen-hour sales represent 1% of downlights, 1% of track lights, and nearly 2% of all MR16 lamps in the residential sector.

As seen in Table 3.4, due to the high efficacy and increasing penetration of LED lighting products, energy savings are already occurring in 2013 and result in a 3% reduction in energy consumption compared to the no-LED scenario. The lighting market model predicts substantial energy savings in all sectors, with an estimated 23% decrease from the no-LED scenario by 2020 and 55% by 2030. The cumulative savings amount to 321 terawatt-hours of electricity over the entire analysis period from 2013 to 2030.

Table 3.4 Directional Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	**4%**	**8%**	**26%**	**55%**	**74%**	**-**
Residential	1%	3%	13%	35%	54%	-
Commercial	5%	13%	44%	77%	92%	-
Industrial	4%	10%	37%	72%	90%	-
Site Electricity Savings (TWh)	**2**	**4**	**14**	**25**	**36**	**321**
Residential	< 1	< 1	2	7	16	90
Commercial	2	3	12	18	20	231
Industrial	< 1	< 1	< 1	< 1	< 1	< 1
Site Electricity Savings (%)	**3%**	**6%**	**23%**	**40%**	**55%**	**29%**
Residential	< 1%	1%	5%	21%	44%	15%
Commercial	6%	13%	45%	64%	69%	46%
Industrial	< 1%	< 1%	39%	64%	70%	40%

3.1.4 Linear Fixture Submarket

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

These fluorescent fixture systems are widely utilized for commercial and industrial establishments because they offer a low cost, highly efficient and long lifetime lighting source. As a result, these fluorescent fixture systems represent nearly half of all lighting service in the United States across all sectors. Because of the significant lighting service required by these applications, the penetration of LED lighting has the potential to greatly reduce total energy consumption. However, because modern linear fluorescent systems are such tough competitors in terms of efficacy and initial and lifecycle costs, the penetration of LEDs, and hence the forecasted energy savings, are much lower compared to other applications.

Currently, fluorescent lighting dominates these applications to the point that it is 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 energy efficiency standards (see Appendix D.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 (Navigant, 2002), whereas in 2013, T12 systems constituted only 7% and 6%, respectively. By 2017, T12 lamps sold on a lumen-hour basis is forecasted to drop to less than one percent of the total linear fixture submarket. T5 lamps and LED luminaires are predicted to absorb most of this decline, increasing to 22% and 24% of total sales respectively. In the no-LED scenario, commercial T5 lamp systems would be expected to continue gaining market share, surpassing that of T8 lamp and ballast systems by 2024. Figure 3.12 shows that the linear fixture submarket will be strongly affected by the availability of high-performance LED lighting products in all sectors.

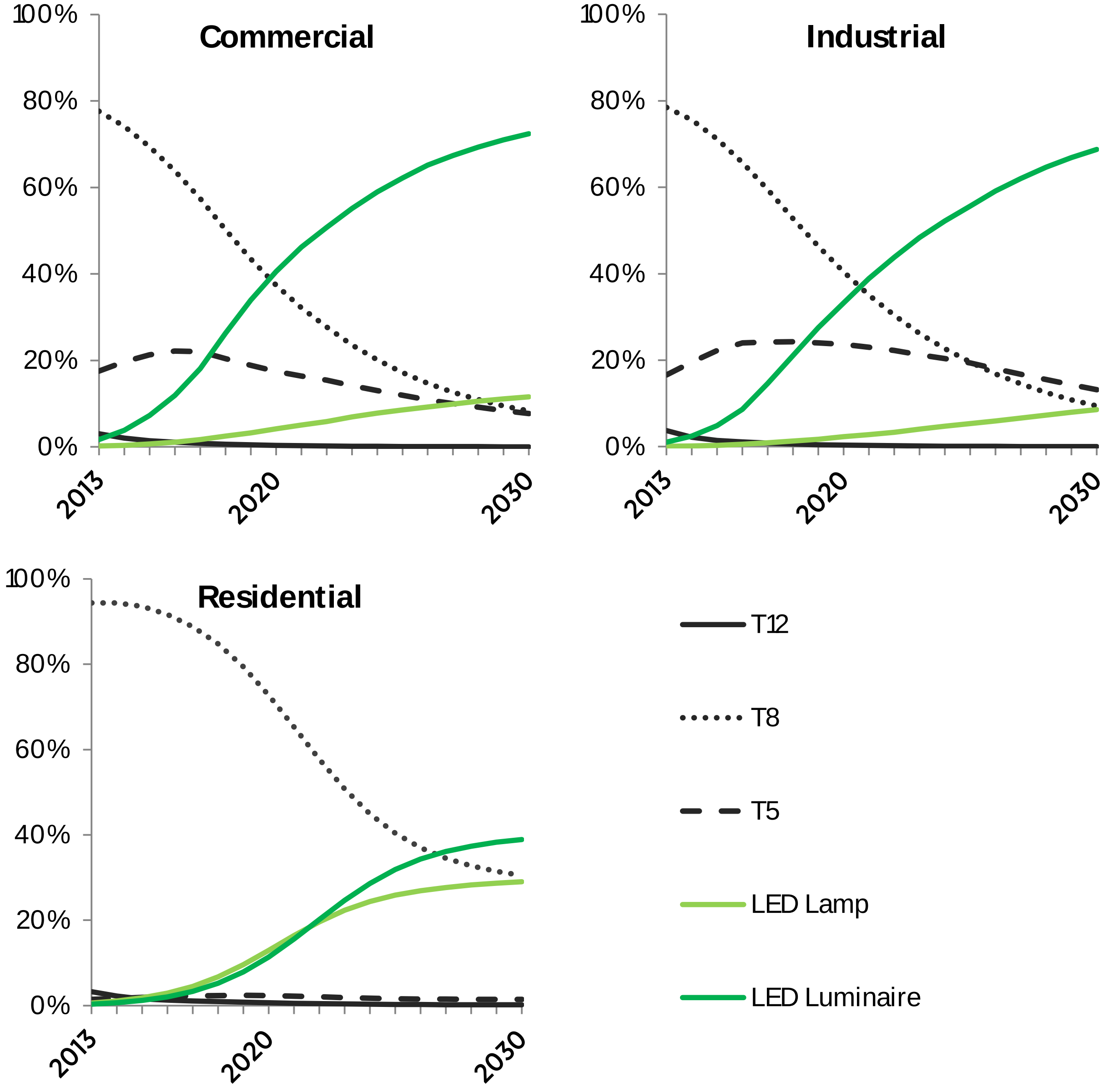

Figure 3.12 Linear Fixture Market Share (% of lm-hr sales) Forecast, 2013 to 2030

While fluorescent systems (lamp and ballast) currently have efficacies averaging between 40 and 90 lm/W, by 2016, both LED lamps and luminaires are expected to consistently exceed all fluorescent lighting systems in efficacy. The forecasted takeover of LED technology in this submarket can largely be attributed to LED luminaires which are expected to have a rapid increase in average efficacy to over 180 lumens per watt by 2030 – or about double that of currently available fluorescent T5 lamp and ballast systems. Consequently, the forecast model predicts LEDs will contribute 45% of commercial linear fixture sales by 2020 and will accelerate to 84% market share by 2030. The industrial sector, although significantly smaller, mimics the trends seen in the commercial sector. The lighting market model estimates that LED lamps and luminaires will represent 35% of industrial linear fixture sales in 2020, and will grow quickly to 78% by 2030. In the residential sector the take-over of LED lamps and luminaires is slower compared to the commercial and industrial sectors which place a higher value on lifecycle costs. Though still successfully capturing 68% of the market by 2030, LEDs make the slowest market share gains in the residential sector. Table 3.5 shows that the increasing adoption of LED lighting should achieve 36% site electricity savings in 2030 in the linear fixture submarket across all sectors.

Table 3.5 Linear Fixture Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	**2%**	**8%**	**44%**	**70%**	**83%**	**-**
Residential	< 1%	3%	24%	58%	68%	-
Commercial	2%	8%	45%	71%	84%	-
Industrial	1%	5%	35%	62%	78%	-
Site Electricity Savings (TWh)	**< 1**	**< 1**	**22**	**62**	**94**	**696**
Residential	< 1	< 1	< 1	< 1	1	8
Commercial	< 1	< 1	20	58	86	642
Industrial	< 1	< 1	1	4	6	46
Site Electricity Savings (%)	**< 1%**	**< 1%**	**9%**	**25%**	**36%**	**16%**
Residential	< 1%	< 1%	1%	7%	15%	5%
Commercial	< 1%	< 1%	9%	25%	36%	16%
Industrial	< 1%	< 1%	9%	25%	37%	16%

3.1.5 Low/High Bay Submarket

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

Only in the past few years have technological and cost improvements allowed LEDs to penetrate the market in significant quantities. Early generation high-bay LED luminaires lacked the lumen output to compete in this market. By 2013, the DOE's LED Lighting Facts had over 100 listed high-bay luminaire products that emitted over 15,000 lumens, and manufacturers now offer products with output exceeding 25,000 lumens at efficacies over 100 lm/W.[15]

Low and high bay lighting has become increasingly popular, likely due to the growth in large commercial retail facilities such as Home Depot, Costco, and other big-box retail stores. In 2013 the low/high bay submarket represents a quarter of all lighting service provided to the commercial sector and about half for the industrial sector, making this a key application for LED impact on energy savings. As seen in Figure 3.13, fluorescent lamps made up the majority of the 2013 low/high bay sales for both the commercial and industrial sectors, at 56% and 85% fluorescent respectively. Overall in both the commercial and industrial sector, LED luminaires held less than 1% of the 2013 market share with the remainder being HID.

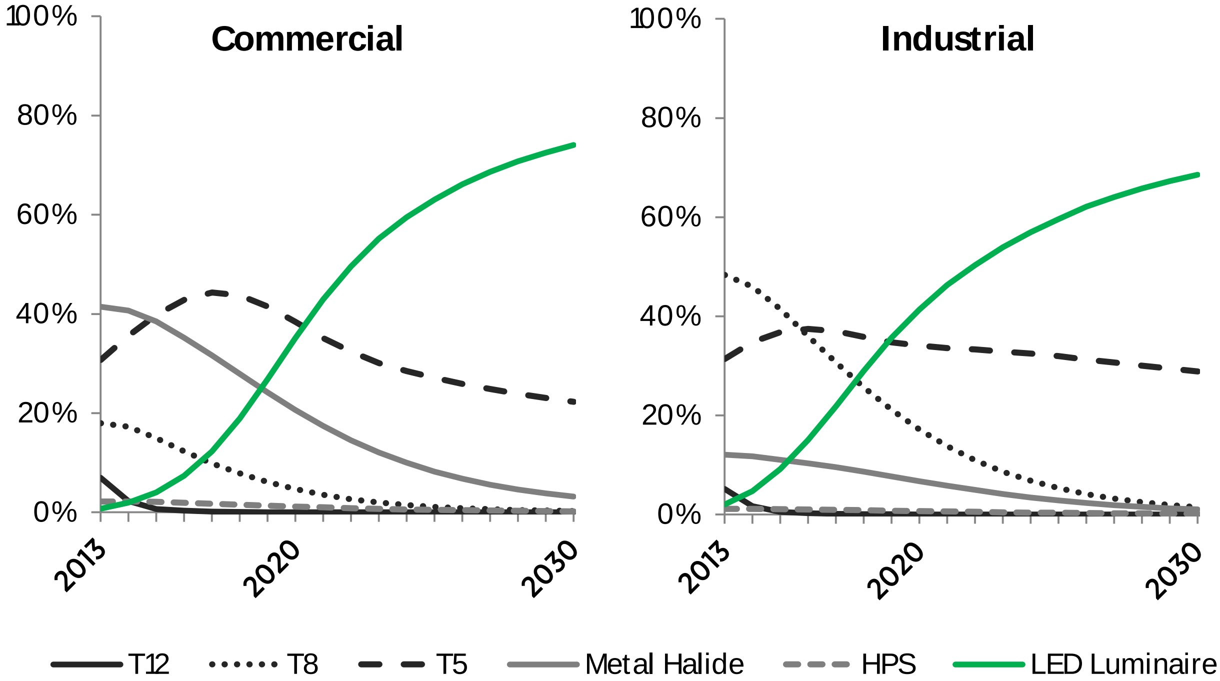

Figure 3.13 Low/High Bay Market Share (% of lm-hr sales) Forecast, 2013 to 2030

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

Table 3.6 shows that LED luminaires are projected to represent 4% of commercial low/high bay sales and about 9% in industrial markets in 2015. This climbs to 35% and 41% in the commercial and industrial sectors respectively by 2020. This penetration of LED luminaires will result in nearly a 6% reduction in annual energy consumption from the no-LED scenario in 2020 and 28% in 2030.

Table 3.6 Low/High Bay Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	**< 1%**	**5%**	**36%**	**63%**	**73%**	**-**
Commercial	< 1%	4%	35%	63%	74%	-
Industrial	2%	9%	41%	60%	69%	-
Site Electricity Savings (TWh)	**< 1**	**< 1**	**5**	**18**	**27**	**194**
Commercial	< 1	< 1	4	14	23	155
Industrial	< 1	< 1	1	3	5	39
Site Electricity Savings (%)	**< 1%**	**< 1%**	**6%**	**19%**	**28%**	**12%**
Commercial	< 1%	< 1%	5%	18%	28%	11%
Industrial	< 1%	< 1%	9%	21%	29%	14%

3.2 Outdoor Lighting Submarkets

The general illumination submarkets in the outdoor sector consist of street and roadway, parking, and exterior building lighting. These lighting systems serve multiple purposes, such as providing proper illumination for pedestrian and automotive traffic, creating a sense of personal security, and attracting attention to business and spaces. HID and linear fluorescent lamps have historically been the predominant lighting technology used in the outdoor sector, but because of the importance of durability and lifetime, LEDs are a particularly attractive option. As presented in Figure 3.14, the lighting market model predicts that LEDs will reduce the sector's energy consumption by 21% in 2020 and 36% in 2030 compared to the no-LED scenario.

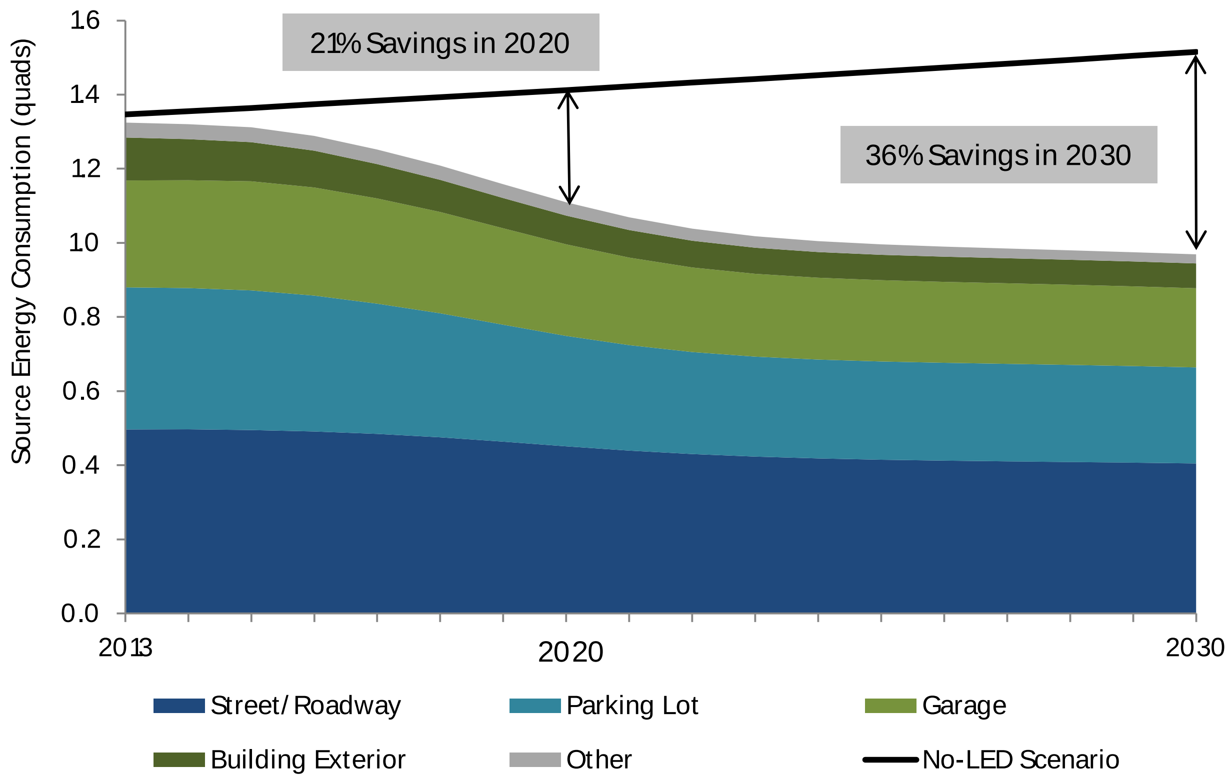

Figure 3.14 Outdoor Lighting Energy Consumption Forecast, 2013 to 2030

3.2.1 Street/Roadway Submarket

LEDs are particularly advantageous in the street and roadway lighting submarket because they are excellent directional light sources, durable, and exhibit long lifetimes. Because of these advantages, many local jurisdictions have initiated projects to completely transition their lighting in these applications to LEDs. For example, the City of Los Angeles has completed a four-year, citywide street lighting replacement program and has installed over 140,000 LED streetlights (U.S. DOE, 2014). By the end of 2013, the total installed base of U.S. outdoor area and roadway LEDs exceeded 3.3 million (Navigant, 2014).

In 2013, in this submarket LEDs already held an impressive 14% market share, while high pressure sodium (HPS) and metal halide made up the majority of the remainder. The lighting market model projects LED market share to increase rapidly, reaching 50% of all lumen-hour sales as early as 2017, as shown in Figure 3.15.

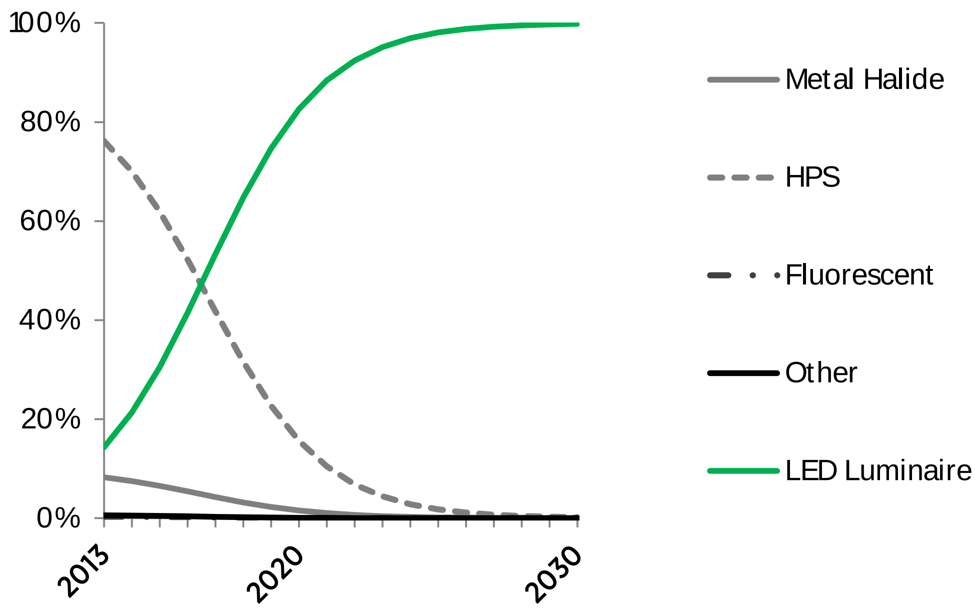

Figure 3.15 Street and Roadway Market Share (% of lm-hr sales) Forecast, 2013 to 2030

The lighting market model projects that nearly 100% of the street and roadway lighting installed base in 2030 will be LED. This almost complete saturation with LED technologies will offer nearly 30% site electricity savings, which is impressive considering efficient HID technologies are being displaced by LEDs. Detail on the predictions for street and roadway submarket are shown below in Table 3.7

Table 3.7 Street and Roadway Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	14%	31%	83%	98%	99%	–
Site Electricity Savings (TWh)	< 1	1	7	11	14	137
Site Electricity Savings (%)	1%	2%	14%	24%	28%	16%

3.2.2 Parking Submarket

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

The lighting technologies used for parking lots closely matches the technologies used for streetlighting, as these applications both have similar lighting requirements. Despite having similar application requirements, adoption of LED luminaires in lot applications lags behind the adoption of LED streetlights, holding 7% of the lot market share in 2013 (compared to 14% for street/roadway). This difference is likely because LED streetlight momentum has come from municipalities embarking on city-wide LED upgrades. Sales in the parking lot submarket are currently dominated by metal halide, which represents 81% of the market share in 2013, while HPS were approximately 12% of the total market.

Parking garage structures, on the other hand, are unique in the outdoor sector because lighting fixtures are well protected from the elements and mounting height is generally limited by low ceilings. While HID lamps are used for lighting parking garage structures, the low-mounting heights of lighting fixtures require a large number of fixtures in order to meet desired illumination distributions. These conditions favor linear fluorescent fixtures, which held 43% market share of lumen-hours sales in 2013, although metal halide and HPS are also prominent contenders.

By comparing the market share forecasts for lot and garage, shown in Figure 3.16, these differences in incumbent technology preferences become clear. Additionally, LED lamps compete for market share in garage lighting, but not lot lighting. This is a result of the opportunity to replace linear fluorescent lamps, however the lighting market model projects that it is more likely that these linear fluorescent fixtures in parking garage structures will be replaced with LED luminaires.

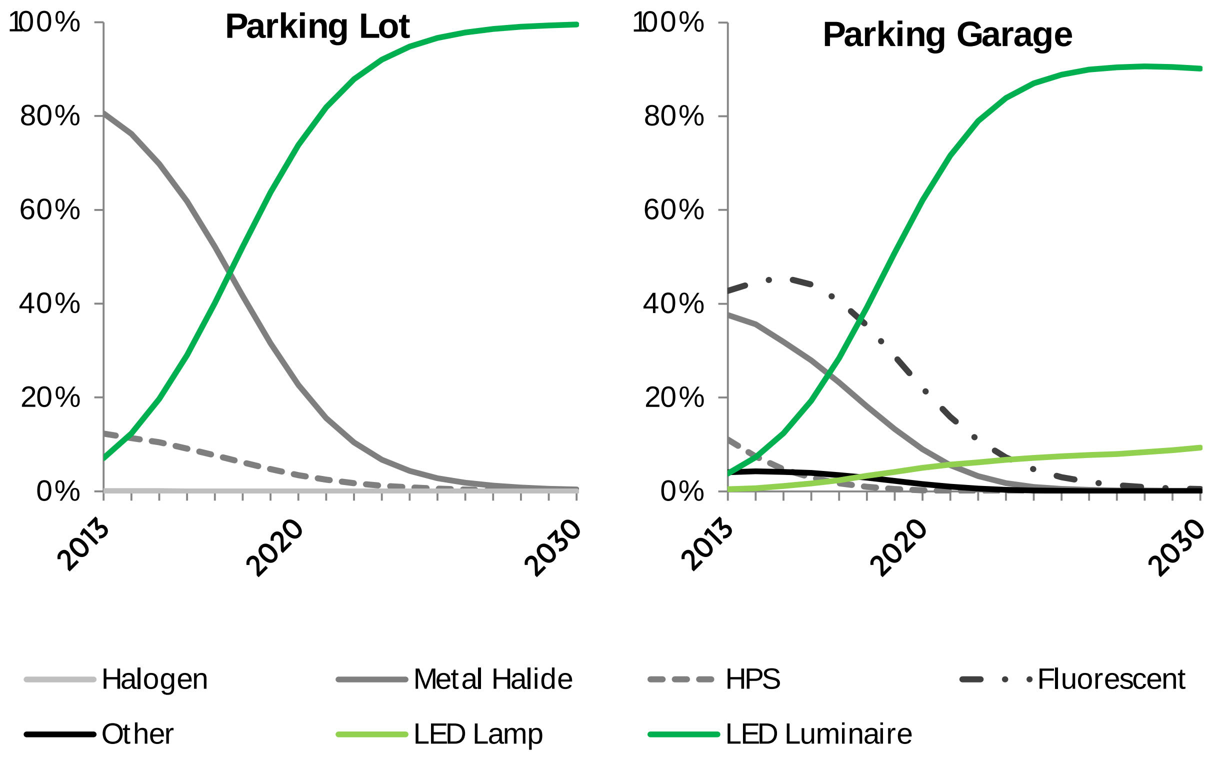

Figure 3.16 Parking Market Share (% of lm-hr sales) Forecast, 2013 to 2030

In Table 3.8 we see that LEDs penetrate parking lot applications slightly faster than parking garage applications. As we saw in the linear fixture and low/high bay submarkets, LEDs have difficulty displacing relatively low-cost linear fluorescent fixtures, but are more competitive with HID fixtures. LED luminaire prices are projected to continue to decrease, becoming cheaper than HPS, on a dollar per kilolumen basis, in 2015 and metal halide in 2016. LEDs therefore penetrate parking lot applications faster than parking garage applications where the majority of lamps to be displaced are linear fluorescent. The lighting market model projects that by 2030, LEDs will offer 41% and 36% energy savings for parking lots and garage structures, respectively, for a total cumulative energy savings of 274 TWh.

Table 3.8 Parking Submarket Forecast

		2013	2015	2020	2025	2030	Cumulative (2013-2030)
Lot	LED Market Share (% of lm-hr sales)	7%	20%	74%	97%	99%	-
	Site Electricity Savings (TWh)	< 1	2	10	14	16	172
	Site Electricity Savings (%)	1%	5%	27%	37%	41%	26%
Garage	LED Market Share (% of lm-hr sales)	4%	13%	67%	96%	> 99%	-
	Site Electricity Savings (TWh)	< 1	< 1	5	9	10	102
	Site Electricity Savings (%)	< 1%	<1%	20%	31%	36%	21%
Total	LED Market Share (% of lm-hr sales)	6%	17%	71%	97%	> 99%	-
	Site Electricity Savings (TWh)	< 1	2	15	23	26	274
	Site Electricity Savings (%)	< 1%	3%	24%	35%	39%	24%

3.2.3 Building Exterior Submarket

In this analysis, the building exterior submarket is defined as lighting designed to illuminate walkways, steps, driveways, porches, decks, building architecture, or the landscape areas and can be used to provide security outside of residential, commercial, and industrial buildings. Floodlights are a common choice for these applications, with metal halide and high pressure sodium technologies historically being the most commonly used, especially where a high lumen output is required. Together, metal halide and high pressure sodium lamps represent over half of the lumen-hour sales to the building exterior submarket. The remaining majority of this submarket is comprised of low lumen output CFLs, which represent about 27% of building exterior lights. Due to the wide range of lumen requirements in this submarket, both LED lamps and luminaires compete for market share in building exterior lighting.

As seen in Figure 3.17 below, much like the other outdoor submarkets, LED lighting products in the building exterior submarket are gaining significant market adoption. In 2013, LED lamps and luminaires in this submarket have reached a combined total of about seven percent of lumen-hour sales. LED luminaire prices are projected to continue to decrease, becoming cheaper than HPS in 2015 and metal halide in 2017 prompting a swift increase in the adoption of LEDs in this submarket. Combined the penetration of LED lamps and luminaires is forecasted to grow near exponentially to 71% in 2020 and 99% by 2030.

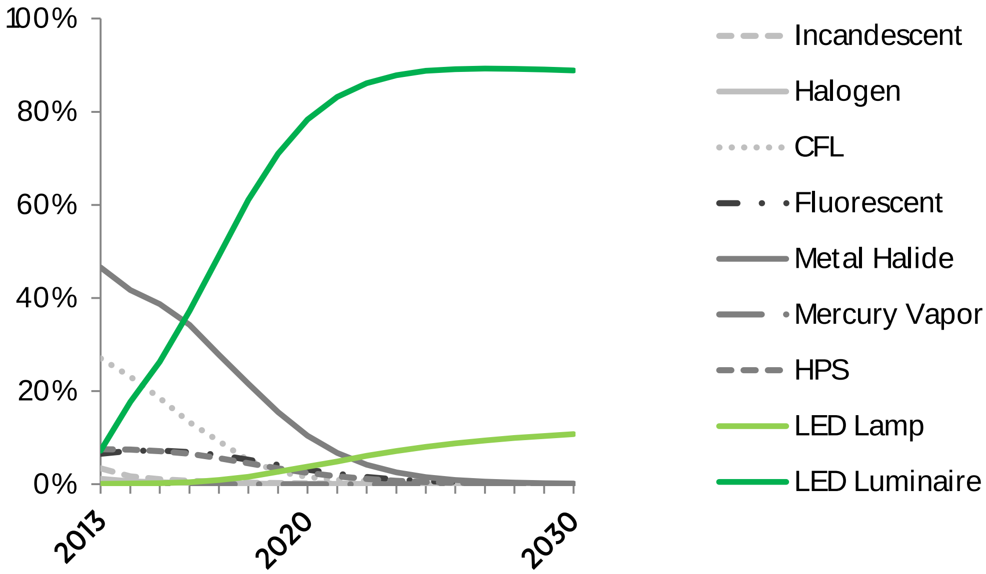

Figure 3.17 Building Exterior Market Share (% of lm-hr sales) Forecast, 2013 to 2030

Table 3.9 conveys how the projected rapid adoption of LED lighting products will result in significant energy savings for the building exterior submarket. The lighting market model forecasts that by 2030, LED lamps and luminaires combined will achieve a 50% energy savings for this submarket compared to the no-LED scenario. The cumulative savings amount to 74 terawatt-hours of electricity over the entire analysis period from 2013 to 2030.

Table 3.9 Building Exterior Submarket Forecast

	2013	2015	2020	2025	2030	Cumulative (2013-2030)
LED Market Share (% of lm-hr sales)	7%	17%	71%	97%	99%	-
Site Electricity Savings (TWh)	1	2	4	5	6	74
Site Electricity Savings (%)	9%	17%	39%	47%	50%	37%

3.3 Forecast Model Comparison

Below the results of this forecast are compared to six other forecast analyses to provide greater context. Included in the comparison set are the 2010 and 2012 iterations of the *Energy Savings Forecast of Solid-State Lighting (SSL) in General Illumination Applications* forecast analyses. Table 3.10 below lists these forecasts in decreasing order of projected LED market penetration in

2020. These forecasts vary in methodology, regions covered (i.e. U.S. market, global market), and units (i.e. sales by units, sales by value). Nonetheless, each presents a calculated impression of the importance of LEDs to the general lighting market in 2020.

Table 3.10 Forecast Model – LED Market Share Comparison

	Metric	Region	2020
McKinsey, 2012	%units	World	57%
IHS Research, 2011	%value	World	50%
DOE, 2014	**%lumen-hours**	**United States**	**48%**
McKinsey, 2011	%units	World	46%
Samsung Electronics, 2014	%units	World	42%
DOE, 2012	%lumen-hours	**United States**	36%
DOE, 2010	%lumen-hours	**United States**	21%

The results of this forecast model are generally consistent with those of other studies. All of the analyses conclude that LED lighting will have tremendous growth over the remainder of this decade, and roughly comprise 50% of all lighting sales by 2020. Though it is not presented in the above Table 3.10, most studies expect LEDs to continue their growth, with some models predicting 2030 market share as high as 90%.

An interesting observation that can be gleaned from Table 3.10 is that all other things being equal, generally the more recent a forecast is, the more optimistic its anticipated market share. This is witnessed in the DOE reports as well as the McKinsey analyses. This report is the first of the DOE SSL Program's forecast analyses that have calibrated the U.S. lighting market model using LED sales and shipment data provided by manufacturers, distributors, retailers as well as industry associations. This track record makes it possible to calibrate the lighting market model outputs for future years based on the actual pattern by which LEDs have gained market share thus far, effectively improving the accuracy of the predictions. The calibration to LED sales and shipment data indicated that market penetration is higher and moving more rapid than was estimated in past iterations of the U.S. lighting market model, and thus this is properly reflected in this 2014 report.

4 Sensitivity Analysis

Readers are invited to test the DOE SSL Program's lighting market model for themselves. An online version is provided at http://energy.gov/eere/ssl/led-lighting-forecast. At this site one can examine a number of sensitivity scenarios to better understand how changes in inputs affect the forecasted LED penetration and energy savings. The following section of this report provides a brief snapshot of this sensitivity analysis.

There are multiple projections – price and efficacy being among the most influential – that were used as inputs in the lighting market model. For each of these projections the best-available resources in concert with manufacturer and industry expertise were utilized to help ensure the results discussed in **Section 3** represent the best estimate for expected future LED penetration and energy savings. However, as with any forward-looking analysis, there are always elements of uncertainty.

The sensitivity analysis provided online allows users to examine how variations in the model's inputs affect the energy savings results presented in this study. Four inputs may be adjusted, as depicted in Table 4.1, allowing users to examine a wide variety of scenarios. Control over these inputs is provided as they were found to be the most influential on results. Many other inputs with inherent uncertainties, such as the projected price of electricity, are used in the lighting market model, but varying these inputs (within a reasonable range) did not greatly affect the results and thus they may not be manipulated in the online model.

Table 4.1 Adjustable Sensitivity Inputs for Online Lighting Market Model Tool

LED Efficacy Improvement	**Controls Growth Due to LEDs**
Low: LED efficacy improves 30% slower than current projection. Reference: LED efficacy improves based on current projection. High: LED efficacy improves 30% faster than current projection. DOE Goal: LED efficacy improves such that it meets 2014 MYPP goals (U.S. DOE, 2014).	Reference: Operating hours for all lighting does not change. Medium: Operating hours for LEDs linearly decrease to a level that is 15% less than reference operating hours by 2030. High: Operating hours for LEDs linearly decrease to a level that is 30% less than reference operating hours by 2030.
LED Price Decline	**Renovation Rate**
Low: LED price decline quickens by 30% compared to current projection. Reference: LED price declines based on current projection. High: LED price decline slows by 30% compared to current projection. DOE Goal: LED price declines such that it meets 2014 MYPP goals (U.S. DOE, 2014).	Low: 0% lighting turnover per year due to renovation, upgrades or retrofit. Reference: 5% lighting turnover per year due to renovation, upgrades or retrofit. High: 15% lighting turnover per year due to renovation, upgrades or retrofit.

One scenario, that is particularly important to the DOE SSL Program, is highlighted below in Figure 4.1. This scenario examines the energy savings impact if DOE's goals for LED price and efficacy, provided in the 2014 MYPP, are realized. This scenario is intentionally ambitious as it illustrates a case where the DOE SSL Program's goals are representative of all LED lighting products entering the United State light market. However, it indicates how aggressive investment in LED technology has the potential to greatly impact our nation's energy footprint. If the DOE's goals are realized, LEDs will reach a market share of 68% of lumen-hour sales in 2020 and over 90% in 2030. The total annual general illumination lighting sector energy consumption in 2030 would decrease by 60% to 265 TWh – this equates to over an additional 130 TWh in energy savings compare to the model's reference scenario. While the cumulative energy savings during the analysis period, from 2013 to 2030, over the no-LED scenario would increase to nearly 3900 TWh or 40 quads – equal to over $380 billion in avoided electricity costs. This DOE goal's scenario shows the significant increase in energy savings that could be captured through increased investment of SSL technology.

DOE SSL Program Goals	2013	2015	2020	2030[1]
LED Efficacy (lm/W)	96	130	200	230
LED Lamp Price ($/klm)	$ 17	$ 10	$ 5	$ 2
LED Luminaires Price ($/klm)	$ 44	$ 34	$ 20	$ 10

1. 2030 values for LED lamp and luminaire price ($/klm) are not provided in the 2014 MYPP and have been projected to 2030 base on prior year goals.

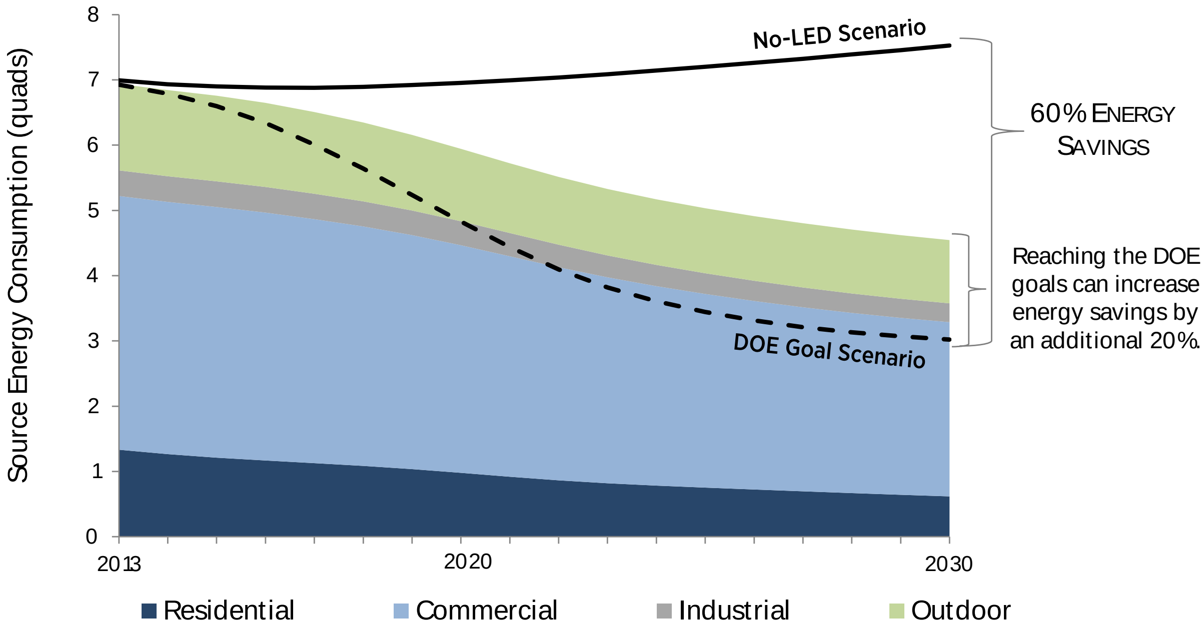

Figure 4.1 Forecasted LED Energy Savings if DOE SSL Program Goals are Realized

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Appendix A Submarket Classifications and Lighting Inventory

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

In order to model the competition between lighting technologies within U.S. lighting market, the current model examines eight submarkets, which are based on common general illumination applications. This is a significant improvement from the previous model iteration, where competition between lighting technologies was simplified by only examining five technology-based submarkets: GSL–MSB, reflector–screw-base, linear fluorescent, HID, and miscellaneous. Thanks in part to a transition to the Analytica® software package, the U.S. lighting market model is now capable of processing a more complex multi-dimensional analysis, as well as a more sophisticated market share calculations, where the submarkets are application-based rather than grouped by lighting technology. This improvement to the lighting market model enables a single lighting technology, such as linear fluorescent lamps, to compete in multiple submarkets (i.e. linear fixtures, low/high bay, and parking) compared to the previous model iteration which grouped all linear fluorescent lamps into a single submarket regardless of application.

As in the previous model iteration, the lighting technologies competing within each submarket are derived from the U.S. Lighting Market Characterization (LMC) report (Navigant, 2012). In the LMC, 28 lighting technologies were considered:

- <u>Incandescent:</u> general service–A-type, general service–decorative, reflector, miscellaneous
- <u>Halogen:</u> general service, reflector, low voltage display, miscellaneous
- <u>Compact fluorescent:</u> general service–screw-base, general service–pin-base, reflector, miscellaneous
- <u>Linear fluorescent:</u> 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
- <u>High-intensity discharge:</u> mercury vapor, metal halide, high pressure sodium, low pressure sodium
- <u>Other:</u> LED lamp, miscellaneous

This analysis reduces that count to 21 by combining linear fluorescent categories, less than 4ft, 4ft, greater than 4ft, and U-shaped, for both T8 and T12. Furthermore, the "other miscellaneous" category in the LMC, and all lamps in this category, are excluded from this analysis due to great uncertainty regarding these lamp types and their characteristics. The excluded miscellaneous lamps account for less than 6 terawatt-hours of annual energy use, or less than one percent, of lighting energy consumption in 2013; thus, the impact of their exclusion is minimal. The LMC was used to develop the 2010 installed base for conventional technologies in the remaining product categories.

The LMC is used as the starting point for the lighting technologies examined in the U.S. lighting market model because it provides detailed lamp counts and provides the inventory foundation for this study. However, it is important to note that the base year for the LMC lighting inventory is 2010, while the base year for this study is 2013. In order to appropriately update the LMC inventory estimates to 2013, new data was collected through interviews with manufacturers, distributor, retailers, as well as industry associations.

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

Appendix B LED Lamps and Luminaires Product Descriptions

Table B.1 Description of the LED Lamp and Luminaire Groupings in Each Submarket

SUBMARKET	LIGHTING PRODUCT	DESCRIPTION
A-type	Lamps	All A-type lamp shapes with a medium-screw base.
Decorative	Lamps	All bullet, candle, flare, globe, and any other decorative lamp shapes.
Directional	Lamps and Luminaires	Includes reflector, BR, MR, and PAR lamps as well as recessed and surfaced mounted downlights and indoor accent, track, and spot light luminaires.
Linear Fixtures	Lamps and Luminaires	All troffer, panel, suspended, and pendant luminaires, as well as, LED linear replacement lamps.
Low/High Bay	Luminaires	Includes LED low and high bay luminaires.
Parking	Lamps and Luminaires	Includes LED lamps and luminaires for attached and stand-alone parking garages, as well as parking lot applications. LED lamps are only considered viable in parking garage applications.
Streetlights/Roadway	Luminaires	Includes LED luminaires installed in street and roadway applications.
Building Exterior	Lamps and Luminaires	Includes all lamps fixtures installed in façade, spot, architectural, flood, wallpack, step/path applications.
Other	Lamps and Luminaires	Includes all other special use lighting applications such as tunnel, signage, wall-wash, and cove.

Appendix C Annual Lumen Demand and Market Turnover

Appendix C.1 National Lumen Demand Projection

After calculating the lighting service, or lumen-hour, demand in 2013 by sector and submarket, the next step was to project forward the lighting demand for each year through 2030. To do this, the 2013 lumen-hour demand was divided by the cumulative national floor space for each sector to determine a lighting demand density in lumen-hours per square foot of building space. Then, assumed floor space growth rates were applied to these densities to project total lighting demand for each sector from 2013 to 2030, holding lighting demand density (kilolumen-hours per square foot) constant. In the residential sector, the average lighting demand density in 2013 was approximately 16.3 kilolumen-hours per square foot, while density in the commercial sector was more than fifteen times higher, at 304 kilolumen-hours per square foot. The commercial lighting service was higher due to the longer operating hours and higher levels of illumination in commercial floor space.

Annual Energy Outlook (AEO) 2014 provides annual average growth forecasts of floor space in the residential and commercial sectors, which are used to project increases in lumen demand moving forward (U.S. EIA, 2014). Projections suggest that residential floor space will increase by an average of 1.31% per annum over the 20-year analysis period, and the commercial sector floor space will increase by an average of 1.00% per annum. AEO 2014 does not provide a 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 2014 annual projections for manufacturing employment growth were used as a proxy for annual average floor space growth estimates of floor space.

In summary, the average annual floor space growth rates used in the analysis, representing the annual change in lumen-hour demand between 2013 and 2030, are:

- Residential: 1.31% growth
- Commercial: 1.00% growth
- Industrial: 0.24% growth
- Outdoor: 1.00% growth

Appendix C.2 Annual Available Market

After estimating the national annual lumen-hour demand, the next step is to determine how much of the lighting market is replaced or added each year. This turnover and growth represents the available market opportunity for LED products to compete with conventional lighting technologies within each of the submarkets. To estimate this, the lighting market model evaluates three events that determine the available lumen-hours on the lighting market each year:

- <u>New construction</u>. New fixtures installed each year due to floor space growth in each sector, determined by growth or retirement projections and the apportionment of lighting intensity per unit floor space. For the lumen-hours of service in this category, the costs considered for conventional technologies include the costs of the lamp, fixture, and ballast (if appropriate). For LED lamp products, the costs considered include the costs of lamp and fixture, while LED luminaire products include only the cost of the complete luminaire system. Luminaires are defined as fully integrated lighting products designed to replace an entire fixture (not just the lamp). An example of an LED luminaire would be a fully integrated 2' X 2' troffer replacement.

- Renovations. Lamps (and ballasts, if appropriate) and fixtures being installed to replace existing lamps and fixtures during renovation, retrofit/upgrade, or remodeling. This replacement generally occurs before a lamp has burned out, providing an additional opportunity for the penetration of new technologies into the building stock. It is assumed that this occurs at a rate of 5% each year in each sector, for a mean renovation cycle of 20 years. The lighting market model assumes a constant rate of lighting fixture retrofits and renovations of five percent of the installed base in both the no LED and LED scenarios. As with the new construction category, LED lamps in this market will compete with conventional lighting technologies on a basis that includes new fixture costs. It is important to note however that utility and government incentive programs are starting to compensate consumers who retrofit using LED lighting products, potentially causing a future increase in the rate of retrofits due to the presence of LEDs. Due to the high uncertainty in these inputs, the lighting market model does not attempt to quantify these trends and, consequentially, likely underestimates the turnover rate of the installed base of LED lamps and luminaires, and thus also underestimates the forecasted LED market penetration and energy savings.

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

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

Appendix D 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 2013. Lighting technologies that do not appear in the tables for a given sector indicate that the 2010 LMC did not record any lighting consumption by that technology in that sector. The efficacies presented in these tables represent mean system efficacies (including ballast losses, where appropriate), rather than initial efficacies. When comparing conventional technologies to LED luminaires, the model also incorporates additional assumptions related to conventional technology fixture efficiencies. However, these fixture efficiencies are not incorporated into the mean system efficacies presented in the following tables.

Table D.2 Commercial Sector Conventional Technology Performance 2013

Commercial Sector Submarkets	Mean System Wattage (W)	Lamp Life (1,000 hr)*	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
General Service						
Incandescent Omni	16	1.8	16	$ 0.5	$ –	$ 16
Halogen Omni	15	1.5	15	$ 1.9	$ –	$ 15
CFL Omni	55	10	55	$ 3.0	$ –	$ 55
Downlights						
Incandescent Omni	12	1.8	12	$ 0.5	$ –	$ 12
Incandescent Directional	10	2.5	10	$ 3.1	$ –	$ 10
Halogen Omni	15	1.5	15	$ 1.9	$ –	$ 15
Halogen Directional	15	3.0	15	$ 4.6	$ –	$ 15
CFL Directional	46	10	46	$ 10	$ –	$ 46
CFL Pin	59	12	59	$ 5.4	$ 18	$ 59
Track Lighting						
Incandescent Omni	16	1.8	16	$ 0.5	$ –	$ 16
Incandescent Directional	10	2.5	10	$ 3.1	$ –	$ 10
Halogen Omni	15	1.5	15	$ 1.9	$ –	$ 15
Halogen Directional	15	3.0	15	$ 4.6	$ –	$ 15
CFL Directional	46	10	46	$ 10	$ –	$ 46
Small Directional (MR16)						
Halogen	18	4.1	18	$ 4.5	$ –	$ 18
General Service Linear Fixtures						
T12 <4ft	56	15	56	$ 3.0	$ 17	$ 56
T8 <4ft	73	20	73	$ 5.4	$ 18	$ 73
T5 <4ft	77	30	77	$ 6.2	$ 22	$ 77
T12 4ft	71	20	71	$ 2.5	$ 17	$ 71
T8 4ft	79	24	79	$ 4.4	$ 18	$ 79
T5 4ft	91	30	91	$ 6.2	$ 22	$ 91
T12 >4ft	77	12	77	$ 5.7	$ 19	$ 77
T8 >4ft	84	24	84	$ 7.0	$ 22	$ 84
Low/High Bay						
T12	71	12	71	$ 5.7	$ 19	$ 71
T8	79	18	79	$ 8.4	$ 22	$ 79
T5	91	30	91	$ 6.2	$ 25	$ 91
Metal Halide	74	20	74	$ 40	$ 205	$ 74
High Pressure Sodium	109	24	109	$ 51	$ 260	$ 109
Other						
CFL Pin	59	12	59	$ 5.4	$ 18	$ 59
Halogen	11	1.0	11	$ 0.5	$ –	$ 11
CFL	16	4.1	16	$ 4.5	$ –	$ 16
Metal Halide	74	20	74	$ 40	$ 205	$ 74
High Pressure Sodium	109	24	109	$ 51	$ 260	$ 109
Miscellaneous	67	4.1	67	$ 5.4	$ 18	$ 67

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps).

Table D.3 Residential Sector Conventional Technology Performance 2013

Residential Sector Submarkets	Mean System Wattage (W)	Lamp Life (1,000 hr)*	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
General Service						
Incandescent Omni	64	1.4	17	$ 0.5	$ –	$ 18
Halogen Omni	51	1.5	15	$ 1.9	$ –	$ 18
CFL Omni	17	10	54	$ 3.0	$ –	$ 18
Decorative						
Incandescent Omni	44	1.0	11	$ 1.3	$ –	$ 18
Halogen Omni	51	1.2	14	$ 3.7	$ –	$ 18
CFL Omni	17	10	53	$ 3.9	$ –	$ 18
Downlights						
Incandescent Omni	57	1.4	17	$ 0.5	$ –	$ 23
Incandescent Directional	68	2.5	10	$ 3.1	$ –	$ 23
Halogen Omni	51	1.5	15	$ 1.9	$ –	$ 23
Halogen Directional	68	3.0	14	$ 4.6	$ –	$ 23
CFL Omni	17	10	55	$ 3.0	$ –	$ 23
CFL Directional	17	10	44	$ 10.1	$ –	$ 23
Track Lighting						
Incandescent Omni	57	1.4	17	$ 0.5	$ –	$ 23
Incandescent Directional	68	2.5	10	$ 3.1	$ –	$ 23
Halogen Omni	51	1.5	15	$ 1.9	$ –	$ 23
Halogen Directional	68	3.0	14	$ 4.6	$ –	$ 23
CFL Omni	17	10	54	$ 3.0	$ –	$ 23
CFL Directional	17	10	44	$ 10	$ –	$ –
Small Directional (MR16)						
Halogen	44	4.1	17	$ 4.2	$ –	$ 23
General Service Linear Fixtures						
T12 <4ft	17	15	52	$ 3.0	$ 20	$ 49
T8 <4ft	18	20	65	$ 5.4	$ 23	$ 44
T5 <4ft	13	30	73	$ 4.2	$ 26	$ 74
T12 4ft	24	15	67	$ 2.0	$ 20	$ 49
T8 4ft	24	21	76	$ 2.8	$ 23	$ 44
T5 4ft	19	30	85	$ 4.2	$ 26	$ 74
T12 >4ft	43	12	75	$ 5.7	$ 23	$ 49
T8 >4ft	35	18	88	$ 7.0	$ 27	$ 44
Other						
Halogen	82	4.1	14	$ 4.2	$ –	$ 18
CFL Pin	18	12	60	$ 5.4	$ 23	$ 18
Mercury Vapor	193	24	29	$ 37	$ –	$ 178
Metal Halide	79	12	50	$ 53	$ 159	$ 210
High Pressure Sodium	150	24	71	$ 50	$ 217	$ 215
Miscellaneous	54	4.1	38	$ 37	$ –	$ 18

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps).

Table D.4 Industrial Sector Conventional Technology Performance 2013

Industrial Sector Submarkets	Mean System Wattage (W)	Lamp Life (1,000 hr)*	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
General Service						
Incandescent Omni	46	2	16	$ 0.5	$ -	$ 15
Halogen Omni	44	2	15	$ 1.9	$ -	$ 15
CFL Omni	17	10	54	$ 3.0	$ -	$ 15
Directional						
Incandescent Directional	65	3	10	$ 1.3	$ -	$ 23
Halogen Directional	70	3	13	$ 3.7	$ -	$ 23
CFL Directional	16	10	43	$ 3.9	$ -	$ 23
General Service Linear Fixtures						
T12 <4ft	41	15	49	$ 3.0	$ 17	$ 44
T8 <4ft	26	20	73	$ 5.4	$ 18	$ 44
T12 4ft	39	20	72	$ 2.0	$ 17	$ 44
T8 4ft	30	24	79	$ 2.8	$ 18	$ 44
T5 4ft	58	30	85	$ 4.2	$ 22	$ 49
T12 >4ft	84	12	78	$ 5.7	$ 19	$ 44
T8 >4ft	73	18	83	$ 7.0	$ 22	$ 44
Low/High Bay						
T12	62	12	72	$ 5.7	$ 19	$ 44
T8	52	18	79	$ 8.4	$ 22	$ 44
T5	58	30	85	$ 6.2	$ 25	$ 49
Metal Halide	435	20	77	$ 40	$ 211	$ 306
High Pressure Sodium	295	24	106	$ 51	$ 260	$ 224
Other						
CFL Pin	45	12	70	$ 5.4	$ 18	$ 15
Metal Halide	435	20	77	$ 53	$ 208	$ 306
High Pressure Sodium	295	24	106	$ 50	$ 256	$ 224

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps).

Table D.5 Outdoor Sector Conventional Technology Performance 2013

Outdoor Sector Submarkets	Mean System Wattage (W)	Lamp Life (1,000 hr)*	Mean Efficacy (lm/W)	Lamp Price ($)	Ballast Price ($)	Fixture Price ($)
Street/Roadway						
Incandescent	181	1.4	12	$ 0.5	$ -	$ 15
CFL	44	10	55	$ 6.6	$ -	$ 15
Linear Fluorescent	50	21	75	$ 2.8	$ 19	$ 70
Metal Halide	233	20	61	$ 40	$ 187	$ 323
High Pressure Sodium	230	24	85	$ 50	$ 260	$ 314
Low Pressure Sodium	78	25	90	$ 39	$ 109	$ 271
Other	62	18	76	$ 26	$ -	$ 295
Parking Lot						
Incandescent	112	1.4	12	$ 0.5	$ -	$ 15
Halogen	108	1.5	17	$ 3.3	$ -	$ 15
Metal Halide	449	20	61	$ 40	$ 163	$ 323
High Pressure Sodium	280	24	85	$ 50	$ 260	$ 314
Parking Garage						
Incandescent	79	1.4	12	$ 0.5	$ -	$ 15
Halogen	75	1.5	17	$ 3.3	$ -	$ 15
Linear Fluorescent	73	21	75	$ 2.8	$ 19	$ 70
Metal Halide	203	20	61	$ 40	$ 163	$ 323
High Pressure Sodium	160	24	85	$ 50	$ 260	$ 314
Other	97	13	76	$ 18	$ -	$ 320
Building Exterior						
Incandescent	61	1.4	12	$ 0.5	$ -	$ 15
Halogen	74	1.5	17	$ 3.3	$ -	$ 15
CFL	22	10	55	$ 6.7	$ -	$ 15
Linear Fluorescent	43	21	75	$ 2.8	$ 19	$ 70
Metal Halide	72	12	61	$ 38	$ 159	$ 358
High Pressure Sodium	78	24	85	$ 45	$ 195	$ 224
Low Pressure Sodium	74	25	89	$ 40	$ 106	$ 172
Other	68	15	76	$ 21	$ -	$ 232
Other						
Incandescent	86	1.4	12	$ 0.5	$ -	$ 15
Halogen	544	1.5	17	$ 3.3	$ -	$ 15
Linear Fluorescent	148	21	75	$ 2.8	$ 19	$ 70
Metal Halide	1,122	20	61	$ 98	$ 211	$ 517
High Pressure Sodium	1,000	24	85	$ 141	$ 260	$ 542

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps).

The lighting market model introduces price and performance changes linearly as percentage improvements over the analysis period, 2013 to 2030. The lighting market model improves the lamp efficacy, ballast efficiency (if applicable), lifetime, and equipment costs for each of the conventional lighting technologies. Labor costs are assumed to remain unchanged. These incremental performance improvements were developed in consultation with industry experts, with consideration given to the historical performance trajectory of each lighting technology.

The percent improvement therefore varies depending on a particular lighting technology's seniority in the lighting market.

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

Appendix D.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 July 2009). The analysis considers only legislation and DOE regulations that are final (i.e., enacted in the *Code of Federal Regulations*[16]) and effective. The lighting market model does not take into account draft or pending legislation or regulations, as both the compliance dates and standard levels are uncertain. The lighting market model accounts for the new regulations by modifying the anticipated efficacy improvements and resulting price increases based on the performance criteria specified by the standard.

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

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

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

compliant halogen and CFLs.[17] DOE is also required to conduct another rulemaking amending the standards for general service incandescent lamps, scheduled to be effective in 2020. If that rule does not produce energy savings equivalent to a minimum efficacy standard of 45 lumens per watt for GSLs, a backstop provision will prohibit the sale of any general service lamp that does not meet a minimum efficacy of 45 lumens per watt.

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

2. Candelabra-base and intermediate-base incandescent lamps. Section 321 of EISA 2007 also prescribed maximum wattage standards for candelabra-base incandescent lamps (60W) and intermediate-base incandescent lamps (40W), which became effective immediately on December 19, 2007. Due to lack of installed base data as presented in the LMC, it was not possible to disaggregate the installed inventory of candelabra and intermediate base incandescent lamps. Thus, this analysis assumes that currently available covered products already meet the EISA 2007 standards.

3. Fluorescent lamps. The Energy Policy Act of 1992 (EPAct 1992) amendments to the Energy Policy and Conservation Act of 1975 (EPCA) established energy conservation standards for certain classes of general service fluorescent lamps (GSFLs). DOE published amendments to these standards in July 2009, which became effective July 14, 2012. These amendments set new efficacy requirements for 4-foot medium bipin, 2-foot U-shaped, 8-foot slimline, 8-foot high output, 4-foot miniature bipin standard output, and 4-foot miniature bipin high output GSFLs by specific correlated color temperature (CCT) ranges. The lighting market model incorporates these standards by increasing the efficacy and price of linear fluorescent lamps accordingly. (10 CFR 430.32(n)).

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

5. Incandescent reflector lamps. This DOE energy conservation regulation, which applies to lamps manufactured on or after July 14, 2012, amends EPCA to prescribe minimum

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

efficacy standards for covered products in the 40-205W 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)).

6. 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.

Appendix E LED Technology Improvement Projection

Pacific Northwest National Laboratory (PNNL) prepared the *SSL Pricing and Efficacy Trend Analysis for Utility Program Planning* report for the U.S. DOE in October of 2013 (PNNL, 2013(b)). This work yielded price and efficacy projection curves that served as the basis for the lighting market model's LED improvement projections. For complete transparency on the inputs, LED price and performance improvement projections used in this analysis are found in Table E.6, Table E.8, and Table E.9.

In the previous model, to simplify the analysis, either LED lamps or LED luminaires could compete within the same submarket, but not both. While this restriction allowed the lighting market model to assign separate performance and costs to LED lamps and luminaires, it did not allow for competition between lamps and luminaires for the same application. In the updated lighting market model, both LED lamps and luminaires may compete for market share in the same application. For example LED linear replacement lamps and LED luminaires, such as troffers, can both compete in the linear fixture submarket. The updated model also allows for variation in price and performance parameters for LED lamps and luminaires across the different submarkets. This feature vastly improves the sophistication of the lighting market model and allows for a more accurate analysis.

Table E.6 provides the efficacy improvement curves for various LED lamps and luminaires. For comparison purposes, Table E.7 contains the performance parameters used in the 2012 model, which were derived from the 2011 DOE MYPP projections. We see that using the PNNL projections results in lower projected efficacies, and also a larger difference in performance between LED lamps and luminaires.

Table E.6 Average LED Lamp and Luminaire Efficacy Projections by Sector and Submarket

Sector Submarkets	LED Lamp Efficacy				LED Luminaire Efficacy			
	2013	2015	2020	2030	2013	2015	2020	2030
Commercial								
General Service	70	81	102	131	–	–	–	–
Directional	62	72	91	117	57	66	82	113
Small Directional (MR16)	58	66	81	103	57	66	82	113
General Service Linear Fixtures	86	91	109	132	98	106	131	181
Low/High Bay	–	–	–	–	95	101	121	160
Other	62	72	91	117	98	106	131	181
Residential								
General Service	70	81	102	131	–	–	–	–
Decorative	58	73	100	148	–	–	–	–
Directional	62	72	91	117	57	66	82	113
Small Directional (MR16)	58	66	81	103	57	66	82	113
General Service Linear Fixtures	86	91	109	132	98	106	131	181
Other	70	81	102	131	57	66	82	113
Industrial								
General Service	70	81	102	131	–	–	–	–
Directional	62	72	91	117	57	66	82	113
General Service Linear Fixtures	86	91	109	132	98	106	131	181
Low/High Bay	–	–	–	–	95	101	121	160
Other	62	72	91	117	98	106	131	181
Outdoor								
Street/Roadway	–	–	–	–	80	92	111	150
Parking Lot	–	–	–	–	80	92	111	150
Parking Garage	86	72	91	132	81	91	106	136
Building Exterior	86	72	91	132	81	91	106	136
Other	86	72	91	132	80	92	111	150

Table E.7 Previous 2012 Lighting Market Model Best-in-Class LED Efficacy Projections

LED Product Type	Efficacy (lm/W)			
	2015	2020	2025	2030
LED Lamp	113	182	199	203
LED Luminaire	145	193	202	203

The MYPP identifies a target lifetime of 50,000 hours for LED lamps and 100,000 hours for LED luminaires. In 2010, LED lamps typically had reported lifetimes of approximately 25,000 hours, while early LED luminaires had longer lifetimes of approximately 50,000 hours. The lifetime projections for LED lamps and luminaires use the same logistic curve (i.e. an S-curve) from the previous model iteration. Lifetime is logistically interpolated for each year of the analysis period assuming lifetimes of 50,000 hours and 100,000 hours for LED lamps and luminaires respectively in 2030. Table E.8 and Figure E.1 present the LED operating life projections used in this analysis.

Table E.8 LED Lamp and Luminaire Lifetime Projections

LED Product Type	Lifetime (1,000 hours)			
	2015	2020	2025	2030
LED Lamp	44	49	50	50
LED Luminaire	84	97	99	100

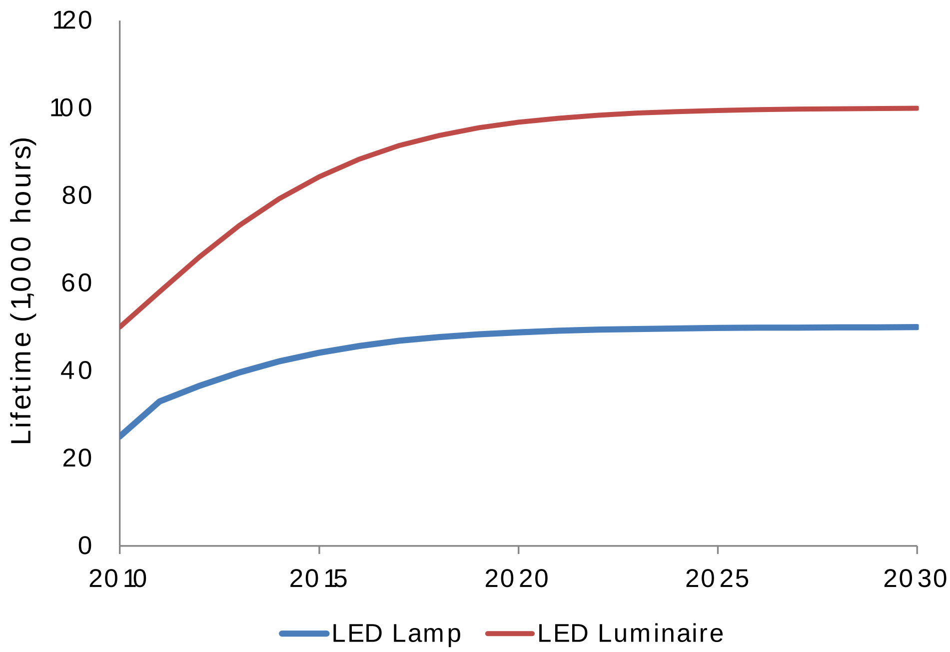

Figure E.1 LED Lamp and Luminaire Lifetime Projections

Table E.9 present the price improvement forecasts for LED products. These curves depict the price reduction from a high initial equipment cost to a lower projected first cost. For early LED products, the small form factors of replacement presented manufacturing challenges which led to very high first costs. Over time however, LED lamp prices are expected to decrease significantly, and much more so than luminaire products because luminaires are more material-intensive and therefore more expensive on a first cost per kilolumen basis. For comparison purposes, Table E.10 contains the price projections used in the 2012 model, which were derived from MYPP projections. These projected faster price reductions in the near term, but the old projections for 2030 were comparable to the updated projections for general service and directional lamps and outdoor luminaires.

Table E.9 Average LED Lamp and Luminaire Price Projections by Sector and Submarket

Sector Submarkets	LED Lamp Price ($/klm)				LED Luminaire Price ($/klm)			
	2013	2015	2020	2030	2013	2015	2020	2030
Commercial								
General Service	$ 43	$ 24	$ 8.7	$ 1.3	-	-	-	-
Directional	$ 61	$ 36	$ 15	$ 2.7	$ 96	$ 82	$ 59	$ 24
Small Directional (MR16)	$ 99	$ 59	$ 25	$ 4.9	$ 96	$ 82	$ 59	$ 24
General Service Linear Fixtures	$ 104	$ 89	$ 60	$ 28	$ 112	$ 89	$ 62	$ 30
Low/High Bay	-	-	-	-	$ 112	$ 89	$ 62	$ 30
Other	$ 61	$ 36	$ 15	$ 3	$ 112	$ 89	$ 62	$ 30
Residential								
General Service	$ 43	$ 24	$ 8.7	$ 1.3	-	-	-	-
Decorative	$ 70	$ 39	$ 12	$ 2.2	-	-	-	-
Directional	$ 61	$ 36	$ 15	$ 2.7	$ 96	$ 82	$ 59	$ 24
Small Directional (MR16)	$ 99	$ 59	$ 25	$ 4.9	$ 96	$ 82	$ 59	$ 24
General Service Linear Fixtures	$ 104	$ 89	$ 60	$ 28	$ 112	$ 89	$ 62	$ 30
Other	$ 43	$ 24	$ 8.7	$ 1.3	$ 96	$ 82	$ 59	$ 24
Industrial								
General Service	$ 43	$ 24	$ 8.7	$ 1.3	-	-	-	-
Directional	$ 61	$ 36	$ 15	$ 3	$ 96	$ 82	$ 59	$ 24
General Service Linear Fixtures	$ 104	$ 89	$ 60	$ 28	$ 112	$ 89	$ 62	$ 30
Low/High Bay	-	-	-	-	$ 112	$ 89	$ 62	$ 30
Other	$ 61	$ 36	$ 15	$ 2.7	$ 112	$ 89	$ 62	$ 30
Outdoor								
Street/Roadway	-	-	-	-	$ 55	$ 42	$ 27	$ 11
Parking Lot	-	-	-	-	$ 55	$ 42	$ 27	$ 11
Parking Garage	$ 104	$ 89	$ 60	$ 28	$ 55	$ 42	$ 27	$ 11
Building Exterior	$ 104	$ 89	$ 60	$ 28	$ 55	$ 42	$ 27	$ 11
Other	$ 104	$ 89	$ 60	$ 28	$ 55	$ 42	$ 27	$ 11

Table E.10 Previous 2012 Lighting Market Model LED Price Projections

LED Product Type	Price ($/klm)			
	2015	2020	2025	2030
LED Lamp	$11	$6.3	$4.4	$3.34
LED Luminaire	$42	$24	$16	$12

Appendix F 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 lumen market demand, which may be satisfied by a suite of lighting technologies, and represents an opportunity for a consumer to switch or adopt a new lighting technology. The lighting market penetration 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 (Cao, 2004; Paidipati, Frantzis, Sawyer, & Kurrasch, 2008).

Appendix F.1 Econometric Logit Model

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

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

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

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

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

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

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

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

Appendix F.2 Technical Discussion of the Conditional Logit Model

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

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

Where:

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

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

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

Where:

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

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

Appendix F.3 Logit Model Input Data

Appendix D and Appendix E discuss how the lighting market model tracks the evolution of price and performance attributes for conventional lighting technologies and LEDs, respectively. These attributes are used as input data to the logit model in the form of two economic metrics: first cost and annual operation and maintenance cost. First cost is a straightforward measure of the purchase price that the consumer pays. Annual O&M cost includes annual energy, replacement and labor costs. Annual replacement cost is an annualized estimate of the cost of replacing burned out lighting equipment, distributed over the average lifetime of the lighting product in years. It is calculated from average lamp or ballast lifetime in hours, average operating hours per year, and the cost of the replacement unit. Annual energy cost is based on average efficacy values and average operating hours per year by application, which is also discussed in Appendix D and Appendix E, and average electricity prices by sector. Electricity prices used for the operating cost evaluation are taken from the EIA's AEO 2014 reference scenario, and then converted from 2012 to 2014 dollars. Because the majority of outdoor lighting is used on and around commercial buildings, we assumed that commercial electricity prices apply to the outdoor sector. The AEO 2014 also provides several alternative electricity price scenarios, but variation is minor such that their effect on the logit model was negligible. The electricity prices used in the analysis are shown in Table F.11.

Table F.11 Electricity Price Projections in 2014 Dollars per Kilowatt-Hour

Sector	Average Electricity Price ($/kWh)				
	2013	2015	2020	2025	2030
Residential	$0.116	$0.119	$0.123	$0.123	$0.126
Commercial	$0.101	$0.102	$0.105	$0.104	$0.107
Industrial	$0.069	$0.069	$0.071	$0.072	$0.075
Outdoor	$0.101	$0.102	$0.105	$0.104	$0.107

Source: EIA, 2014

Appendix F.4 Technology Diffusion Curve

While the conditional logit model provides a probability of purchase for each technology under perfect competition, the lighting market model also recognizes that newer technologies are at a relative disadvantage compared with well-established incumbent technologies. The rate of market penetration is subject to certain market barriers, including, but not limited to, acceptance and availability of the technology. Typically, these barriers only apply to new market entrants, such as LED technologies, as technologies may initially be unknown to consumers or may not be readily available to purchase. However, as a product establishes itself on the market, benefits are communicated by word-of-mouth to the consumer base, manufacturers are able to ramp up production capacity, and stocking distribution channels emerge. To simulate this lag effect on newer technologies, the lighting market model applies a Bass technology diffusion model to the logit model market share predictions. The Bass diffusion model is a widely recognized marketing tool used in technology forecasting that effectively slows the rate of technology adoption based on the time necessary for consumers to become aware of and adopt a new lighting technology. In today's lighting market, the effect of technology diffusion is primarily limited to LED lighting 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 (PNNL, 2004). 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 (PNNL, 2006), this analysis modified the PNNL diffusion curve to be based only on electronic ballasts and T8 fluorescent lamps. These technologies are common in the commercial and industrial sectors, which causes the curve to be more representative of these sectors than the residential and outdoor sectors.

Additionally, LEDs are a versatile, promising technology that has begun to demonstrate significant benefits over incumbent competitors. The previous iteration of the DOE forecast model assumed that LED technology would diffuse at the same rate as conventional technology; however, LED adoption estimates for several lighting applications indicate that the diffusion of LED technology is occurring at a faster rate. Figure F.1 below shows the average estimated LED market share for all general illumination applications as compared to incumbent technologies. To account for this difference, this updated analysis assigns to LED products a faster diffusion rate compared to the incumbent competitors.

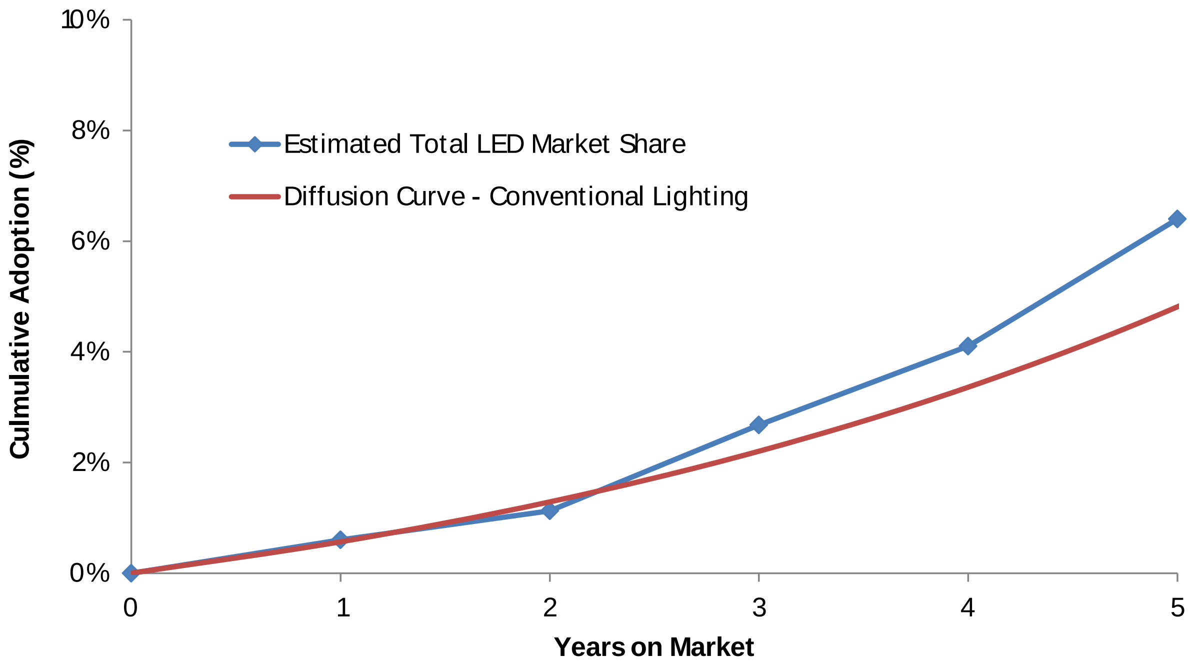

Figure F.1 LED Market Share vs. Conventional Lighting Technology Diffusion

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