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

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DISCLAIMER

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COMMENTS

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ABBREVIATIONS

AEO	Annual Energy Outlook
CCT	Correlated color temperature
CFL	Compact fluorescent lamp
CRI	Color rendering index
DOE	Department of Energy
EIA	Energy Information Administration
EISA 2007	Energy Independence and Security Act of 2007
EPAct 1992	Energy Policy Act of 1992
EPAct 2005	Energy Policy Act of 2005
EPCA	Energy Policy and Conservation Act of 1975
FR	Federal Register
GSFL	General service fluorescent lamp
GSL	General service lamp
HID	High-intensity discharge
HPS	High pressure sodium
IRL	Incandescent reflector lamp
klm	Kilolumen
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light-emitting diode
LFL	Linear fluorescent
lm/W	Lumens per watt
LMC	Lighting Market Characterization
LPS	Low pressure sodium
MECS	Manufacturing Energy Consumption Survey
MSB	Medium screw-base
MYPP	Multi Year Program Plan
NAICS	North American Industry Classification System
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NGLIA	Next General Lighting Industry Alliance
O&M	Operation and maintenance
OLED	Organic light-emitting diode
PNNL	Pacific Northwest National Laboratory
R&D	Research and development
SSL	Solid-state lighting
Tlm-hr	Teralumen-hour
TWh	Terawatt-hour
U.S.	United States
W	Watt

Executive Summary

Light-emitting diodes (LEDs), a type of solid-state lighting (SSL), offer the electric lighting market a new and revolutionary light source that saves energy and improves light quality, performance, and service. Today, white-light LEDs are competing or are poised to compete successfully with conventional lighting sources across a variety of general illumination applications due to their ability to offer high quality and cost-effective performance.

This U.S. Department of Energy (DOE) report forecasts the energy savings potential of light-emitting diode (LED) white-light sources compared to conventional white-light sources (i.e., incandescent, halogen, fluorescent, and high intensity discharge). Using an econometric model of the U.S. lighting market through the year 2030, the annual lighting energy consumption under a scenario considering the growing market presence of LEDs is compared to energy consumption under a baseline scenario, which hypothesizes no additional market penetration of LEDs in general illumination applications. This analysis finds that the energy savings potential, represented by the difference in energy consumption between the two scenarios, is significant.

The lighting market model separately analyzes four sectors of the U.S. lighting market: residential, commercial, industrial, and outdoor stationary. Within each sector, lamp types are classified and grouped according to their primary lighting application into one of five submarkets: medium screw-base general service lamps (GSL–MSB), screw-base reflector lamps, linear fluorescent lamps, high-intensity discharge lamps, and miscellaneous lamps. Lighting products vie simultaneously for available market within the first four submarkets. The miscellaneous submarket is a catchall for several applications that are dominated by a single technology, and lighting products in this submarket compete only with LED lighting and not with one another.

The econometric lighting market model relies on assumptions of projected LED and conventional technology efficacy, retail price, and operating life. These projected inputs for LED performance are based on work conducted collaboratively between DOE and the Next Generation Lighting Industry Alliance (NGLIA), a solid-state lighting technical working group managed by the National Electrical Manufacturers Association (NEMA). Price and performance metrics for conventional lighting technologies were estimated via a survey of market data and conversations with industry experts. The forecast model also utilizes a national inventory of lamps, as presented in DOE's 2010 U.S. Lighting Market Characterization (LMC) report, to determine annual demand for light in the analysis base year, 2010, to which floorspace growth projections are applied.

The econometric model uses a type of consumer choice model, known as a conditional logit model, which is commonly used in marketing to relate consumer preferences to market share. This analysis presumes that lighting purchasing decisions are primarily governed by two economic parameters, first cost and annual operating and maintenance costs to the consumer, both of which are expressed in dollars per kilolumen. A logistic regression on historical cost and market share data in the lighting market provided the model parameters. To simulate the delay in consumer uptake that affects new market entrants due to product unfamiliarity and unavailability, a Bass technology diffusion curve was also applied to effectively slow the rate of adoption of LED lighting products. The market shares forecasted by the lighting market model for each technology are applied to the annual demand for lighting, determined by the rate of lamp or ballast burnout and typical operating hours from the 2010 LMC, to forecast electricity consumption per annum. As described above, this yields an estimation of electricity savings each year, highlighted below:

- Assuming LED lamps and luminaires meet their expected efficacy, lifetime, and price targets, LED lighting will gain significant market penetration. By 2020, LED lighting is expected to represent 36 percent of lumen-hour sales on the general illumination market. By 2030, it is expected to grow to 74 percent of lumen-hour sales.
- In 2030, the annual energy savings due to the increased market penetration of LED lighting is estimated to be approximately 300 terawatt-hours, or the equivalent annual electrical output of about fifty 1,000-megawatt power plants. At today's energy prices, that would equate to approximately $30 billion in energy savings in 2030 alone. Assuming the current mix of generating power stations, these energy savings would reduce greenhouse gas emissions by 210 million metric tons of carbon. The total electricity consumption for lighting would decrease by roughly 46 percent relative to a scenario with no additional penetration of LED lighting in the market—enough electricity to completely power nearly 24 million homes in the U.S. today.
- Over the 20-year analysis period, spanning 2010–2030, the cumulative site energy savings are estimated to total approximately 2,700 terawatt-hours, representing approximately $250 billion at today's energy prices. Assuming the electric power plant generating mix is held constant over the next two decades, these savings would reduce greenhouse gas emissions by 1,800 million metric tons of carbon.

Figure ES. 1 summarizes the forecasted annual electricity consumption of lighting technologies and the electricity savings resulting from the increased use of LEDs in general illumination applications, disaggregated by building sector.

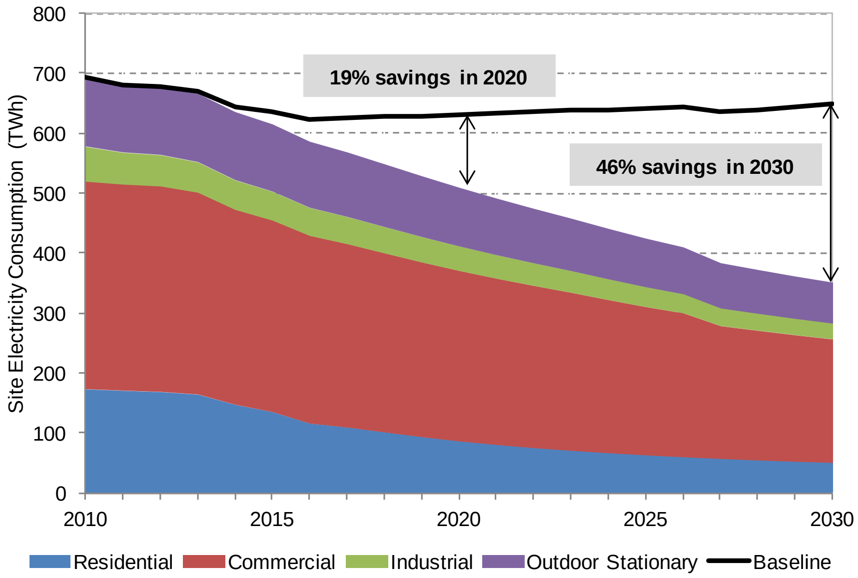

Figure ES. 1 Forecasted U.S. Lighting Energy Consumption and Savings, 2010 to 2030

Table ES. 1 presents baseline electricity consumption, LED market share, and electricity savings in each sector for five-year intervals throughout the analysis period. In absolute terms, the residential and commercial sectors provide the greatest opportunity for energy savings. The former is primarily composed of inefficient incandescent lamps, to which LEDs provide a cost-effective (on a life-cycle basis) alternative. The commercial sector contributed 60 percent of lighting service in the U.S. in 2010 and, by virtue of its size, presents an opportunity for significant energy savings. By 2030, the commercial sector energy savings potential will be 35 percent of the baseline energy consumption.

Table ES. 1 Total U.S. LED Forecast Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	**694**	**635**	**631**	**641**	**648**	**13,535**
Residential	173	142	138	146	153	3,105
Commercial	346	325	321	320	316	6,806
Industrial	58	49	44	41	38	947
Outdoor Stationary	116	119	128	135	141	2,676
LED market share (% of lm-hr)	**-**	**9.5%**	**35.8%**	**59.0%**	**73.7%**	**-**
Residential	-	8.1%	37.6%	60.7%	72.3%	-
Commercial	-	5.0%	27.8%	52.5%	70.4%	-
Industrial	-	8.8%	36.0%	59.2%	72.3%	-
Outdoor Stationary	-	29.0%	64.2%	81.6%	87.2%	-
Site electricity savings (TWh)	**-**	**21**	**122**	**217**	**297**	**2,672**
Residential	-	7	51	82	102	1,009
Commercial	-	6	38	73	111	902
Industrial	-	0	3	8	11	88
Outdoor Stationary	-	7	30	54	73	673
Site electricity savings (%)	**-**	**3.3%**	**19.4%**	**33.9%**	**45.8%**	**19.7%**
Residential	-	5.1%	37.3%	56.7%	66.9%	32.5%
Commercial	-	1.9%	11.7%	22.9%	35.0%	13.3%
Industrial	-	0.8%	7.4%	18.3%	29.4%	9.3%
Outdoor Stationary	-	6.2%	23.7%	40.2%	51.7%	25.2%

1 Introduction

Light-emitting diodes (LEDs) are on the verge of revolutionizing the lighting market. As a general illumination lighting source, LED products surpass many conventional lighting technologies (including incandescent and fluorescent light sources) in energy efficiency, lifetime, and versatility and rival them in color and light quality. Having already significantly penetrated several colored light applications, such as traffic signals and exit signs, white-light LED products have recently been commercialized. As of 2011, LEDs can be found in directional lamp fittings such as downlights, display, accent, under-cabinet lighting, as well as in area light fittings such as parking, roadway, and troffer lighting applications.

In recent years, retail costs have rapidly declined and are expected to continue this trend as manufacturing improvements, government investment, and economies of scale reduce manufacturing costs, which will be passed along to the consumer. As consumer prices drop, LEDs will become more cost-competitive with conventional lighting sources and will capture increasing shares of the general illumination market. This report details an analysis to forecast the energy savings due to the increasing market penetration of energy-efficient LED lighting.

The major progress in development and commercialization of LED lighting has been catalyzed by collaboration between the U.S. Department of Energy (DOE) and the National Electrical Manufacturers Association (NEMA) on a Next Generation Lighting Initiative. The Energy Policy Act of 2005 (P.L. 109-58) formally established this Initiative in Section 912 and allocated substantial funding for this critical work. LED lighting has also been included in the Energy Independence and Security Act of 2007 (EISA 2007) and the American Recovery and Reinvestment Act of 2009. Both of these laws expanded DOE's LED work supporting research and programs to accelerate market adoption and save energy.

This is the fourth iteration of this report, updating DOE's previous estimates of energy savings potential from LED lighting in general illumination applications published in 2010, 2006, 2003, and 2001. Using the recently published 2010 U.S. Lighting Market Characterization (LMC) inventory results, a forecast model of the U.S. national lighting market was developed, considering various lighting technologies, building sectors, and end-use applications. The model defines 2010 as the base year with projections beginning in 2011. This report presents input assumptions, the methodology, and the findings of this analysis and details several methodological changes and improvements from the previous forecast analysis, most recently published in 2010. The major changes for the new forecast model include:

1. A focus on LED lighting products rather than all solid-state lighting (SSL) products. Despite the potential for organic light-emitting diode (OLED) lighting, research and development (R&D) progress has been slower than expected, and thus the expected applications, efficacy projections, and price forecasts are highly speculative. Although previous versions have evaluated the potential for OLED lighting technologies, the current report only considers LED lighting for the forecast analysis.
2. A reorganization of similar technologies into groups for competition. Due to the complexity of the U.S. lighting market, it is useful to organize the different lighting

technologies into independent competition groups, or bins. Within these bins, lighting technologies are free to vie with one another for market share. The previous analysis grouped technologies using the color rendering index (CRI) of each light source as an indicator of light quality and assumed that low-CRI lighting technologies will not compete with high-CRI lighting technologies and vice versa. However, consumers have begun to demand high-CRI lighting products across many applications, and rather are now making purchase decisions based on correlated color temperature (CCT) (i.e., whether a lighting product provides cool or warm light). Because lighting applications can no longer be accurately characterized by distinct CRI bins, they were eliminated from the current analysis. Instead, the new model identifies known technology competitors and establishes groups based on common lighting applications. Each application group, or submarket, was developed considering like characteristics, such as color temperature, lumen output, or light distribution. The new forecast model groups technologies into these submarkets: medium screw-base general service lamps (GSL–MSB), screw-base reflector, linear fluorescent, high-intensity discharge (HID) and a miscellaneous group. (See Chapter 2 for more detail about these lighting groups.)

3. <u>A new econometric model to simulate the competition between incumbent and LED lighting products.</u> The previous lighting market model predicted the market share of LED lighting based on calculation of the simple payback period between LED technology and the average incumbent base. Due to the nature of the simple payback period calculation, this method was only capable of modeling market penetration between two characteristic technologies. However, in reality, the lighting market comprises several technologies simultaneously competing for the same applications. For example, in the residential sector, incandescent, halogen, CFL, and LED medium screw-base lamps compete with each other for the same sockets. The market share of each technology will depend not only on that technology's cost and performance characteristics, but also the characteristics of all of the competing technologies. In order to capture these market dynamics, the updated lighting market model predicts market share of each technology by utilizing a logistic regression dependent on first cost and annual operation and maintenance costs (see Section 6.1 for more details on the econometric model). This new model now forecasts the market trends that currently exist between conventional technologies, in addition to the penetration of LED lighting products. For instance, the model is used to project the penetration of T5 fluorescent lamp and ballast systems into T8 and T12 linear fluorescent systems.

1.1 Analytical Approach

The methodology followed in developing a model of the U.S. lighting market and forecasting aggregate consumer lighting decisions is outlined below:

1. <u>National lighting inventory and service</u>. Utilizing the estimated 2010 lamp inventory as published in the 2010 LMC, the lighting market model applies the average efficacies, wattages, and operating hours to convert the national lighting inventory into lumen-hours of lighting service in each sector (i.e., residential, commercial, industrial, and outdoor stationary).

2. Submarkets for competition. Using the lighting technology categories in the 2010 LMC report, the analysis defines five groups of technologies that directly compete with each other for available installations. These groups, or application submarkets, include: GSL–MSB, screw-base reflector, linear fluorescent, HID, and a group for miscellaneous products. The lighting types within each submarket (see Chapter 2 for complete list) compete for available market share only within their defined submarket. For example, an incandescent lamp in the GSL–MSB submarket cannot compete with a metal halide lamp in the HID submarket. The miscellaneous submarket was added for lighting products that have no clear incumbent competitors; thus, it is assumed that LEDs will penetrate all such products separately. These include lamp types such as pin-base CFLs, candelabra base incandescent lamps, MR16 lamps, etc.
3. Lumen demand forecast. Holding constant the lumen demand per square foot of floorspace in each sector, the model forecasts lumen demand from 2011 to 2030 by applying the building construction projection forecasts provided by Annual Energy Outlook 2011 (AEO 2011) for the residential and commercial sectors (EIA, 2011). Using the 2006 Manufacturing Energy Consumption Survey (MECS) floorspace estimate as a base, industrial floorspace was projected using annual construction costs of industrial buildings in conjunction with estimated floorspace costs per square foot (DCD Magazine, 2011; U.S. Census Bureau, 2011). The floorspace in the outdoor stationary sector is assumed to growth at the same rate as the commercial sector.
4. Market turnover. The lighting market model estimates the lumen "turnover" (i.e., annual available lumen market) in the U.S. based on new installations (new construction), replacement lamps, and retrofit fixtures. The calculated lumen turnover, which constitutes the available lighting market for which LED lamps and luminaires compete, is calculated based on the published lamp or ballast lifetimes of the conventional technologies and the estimated operating hours in the various end-use applications. New construction is derived from maintaining lighting density per unit area for the projected new building floorspace in the various sectors.
5. Conventional lighting technology improvement. 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 operating life for conventional lighting technologies (i.e., incandescent, halogen, fluorescent, and HID). These forecasted improvements are introduced linearly over the 20-year analysis period. Technology performance improvements are also adjusted to account for existing legislative and regulatory energy conservation standards (see Chapter 4).
6. LED lighting technology improvement. The model uses adjusted price and performance curves for LED lighting based on those published in the 2011 DOE SSL R&D Multi Year Program Plan (MYPP). The improvement trends are then extrapolated to 2030. (For details on how these curves were adjusted see Chapter 5.)
7. Market share of conventional technologies and LEDs. This analysis conjointly uses a logistic regression of historical data and a technology diffusion curve to forecast the market penetration of the different lighting technologies within the residential, commercial, industrial, and outdoor stationary sectors. The model assumes that the

market penetration of a product is determined by consumer preference for specific attributes of a product, as well as the existing presence of a technology on the marketplace. For lighting, consumers highly value first and annual costs (including energy, labor, and replacement costs), and the relative weight of these attributes will determine which lighting technology a consumer purchases. In addition, a Bass diffusion model was incorporated to determine the rate at which a specific technology will penetrate the lighting market based upon the length of time since its commercialization. The Bass technology diffusion model stipulates that technologies are gradually adopted over time and that consumer adoption of a product is proportional to the installed base. This market share modeling method is described further in Chapter 6.

8. Calculate energy savings. The model uses its market penetration and technology improvement projections for each lighting technology to forecast the energy consumption attributable to national lighting. Annual energy savings are then estimated by comparing the lighting energy consumption projected by the model to that of a baseline scenario, in which it is assumed that the U.S. market share of LED products does not grow beyond current levels.

The eight step approach outlined above describes the process and calculation steps behind the energy savings estimates presented in this report. The U.S. lighting market model, the numerical engine behind these energy savings estimates, is constructed and divided into six major sections, which are discussed separately in this report:

- Lighting inventory and submarket classifications (Chapter 2)
- Lumen demand forecast and market turnover (Chapter 3)
- Conventional technology improvement projection from 2011 to 2030 (Chapter 4)
- LED technology improvement projection from 2011 to 2030 based on the 2011 MYPP (Chapter 5)
- Forecasted market shares with econometric and technology diffusion models (Chapter 6)
- Installed stock model and resultant energy savings estimates (Chapter 7)
- Conclusions (Chapter 8)

1.2 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 discussed in detail in the relevant sections of this report, but are summarized here for convenience and clarity of presentation.

Some of these assumptions will have the effect of increasing the forecasted energy savings from LED lighting and others have the effect of reducing it. Each of the assumptions described below includes analysis of whether it has a tendency to increase or decrease the resulting estimate of energy savings potential derived from the penetration of LED lighting. The assumptions used for the analysis represent best estimates and were derived using inputs provided by DOE SSL technical reports as well as industry experts; however, there is still significant uncertainty in these inputs. To address this uncertainty, sensitivity analyses were conducted for several of the assumptions and are discussed in Appendix B.

1. <u>Competition within submarkets.</u> The analysis divides the national lighting inventory into application submarkets (defined in Chapter 2) by sector. Competition for both the substitution of replacement lamps and the installation of new and retrofit fixtures occurs within those submarkets. During the analysis period, end-users cannot substitute for a lighting product that is outside of a specific submarket. Although the submarkets have been designed to model the vast majority of current technological trends in the marketplace (such as the migration from incandescent to CFL or from T12 to T8 to T5 linear fluorescent lamps), they do not capture every trend. For example, in high-bay applications, there has been evidence of a movement from HID systems to high lumen output fluorescent systems, which is not captured by the submarket structure. While the impact of these simplifying assumptions are likely small, they could either decrease or increase energy savings relative to that which is predicted by the model.

2. <u>Constant demand for lighting intensity.</u> It is assumed that the level of lighting intensity (lumens per square foot) in buildings remains constant over the analysis period (2010–2030). This simplification will tend to decrease the estimate of energy savings from LEDs because it will require that LEDs match the source lumen output levels of conventional sources in all applications. However, in reality, LED technology may be able to achieve equivalent levels of area illumination with fewer source lumens because they are a more compact and directional light emission source.

3. <u>Retrofit rate.</u> The lighting market model assumes a constant rate of lighting fixture retrofits and renovations of five percent of the installed base in both the baseline and LED scenarios. This covers all retrofits and renovations, regardless of their impetus, and includes renovations untaken for design or aesthetic preferences and “green” retrofits undertaken in an effort to reduce energy consumption. With concerns over climate change mounting, energy-efficiency retrofits are increasingly common and 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. 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 in the LED scenario, and thus also underestimates the forecasted LED market penetration and energy savings. However, in order to assess how additional retrofits due to the presence of LEDs on the market could affect energy savings, a sensitivity analysis was performed in which the retrofit rate was increased to 15 percent only in the LED scenario. For a more detailed discussion, see Appendix B.

4. <u>LED and conventional technology price and performance improvement curves.</u> The lighting market model is driven by assumptions of price and performance improvement of 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 for LEDs and conventional technologies can have a significant impact on the resulting energy saving estimates, this report includes several sensitivity analyses designed to capture the variance in savings that could result from a deviation from predicted performance (see Appendix B for sensitivity analysis discussion and results).

In addition, the model assumes that the price (in $/klm) and performance (efficacy and lifetime) of LED lamps will not vary across lighting applications. The model also makes similar assumptions for LED luminaires. While this assumption seems to be relatively consistent with the price and performance of currently-available, high-volume LED products, this may not be the case with niche products (such as decorative LED lamps) that may have design constraints that limit the performance or require additional cost. Assuming constant price and performance could tend to overestimate the penetration of LEDs in these applications and result in an overestimate of energy savings.

5. <u>LED luminaire retrofits for linear fluorescent and HID systems.</u> The model assumes that consumers opting to replace their linear fluorescent and HID systems with LED technology will retrofit their conventional technology with new LED luminaires (rather than LED retrofit lamps) and gives consumers the option to convert to an LED luminaire only when they replace their ballasts or when they retrofit their fixtures. While LED T8 fluorescent replacements lamps are currently commercially available, thus far many do not appear to provide equivalent light output, color quality, distribution, or cost-effectiveness, compared to four-foot linear fluorescent lamps. Interviews with LED lighting manufacturers indicate a growing interest toward luminaire replacements for the HID and linear fluorescent markets, as luminaires more efficiently manage heat and control light distribution. Assuming that fluorescent and HID systems are replaced only with LED luminaires tends to decrease the energy savings estimate as it eliminates a large portion of available market (i.e., the fluorescent and HID lamp replacement market) for which LEDs can compete and creates a larger cost barrier to LED adoption.

6. <u>Market share forecast.</u> The economic portion of the model postulates that the lighting market responds primarily to first and annual costs. This modeling simplification neglects other factors that affect a lighting equipment purchasing decision, including aesthetics and environmental considerations, among others. In addition, market adoption can be hindered by the time it takes for the benefits of the technology to be communicated to members of society. The market share forecast accounts for such communication delays by incorporating the Bass technology diffusion model, which effectively slows the rate of technology adoption based on the time necessary for consumers to become aware of, accept, and adopt a new lighting technology. As discussed in Section 6.2, the model assumes a technology diffusion curve based on the historical rate of penetration of other lighting technologies. However, due to the uncertainty of the diffusion rate of LEDs, two sensitivities to this technology diffusion curve are presented in Appendix B.

2 Lighting Inventory and Submarket Classifications

This analysis divides the U.S. lighting market into four primary lighting sectors: residential, commercial, industrial, and outdoor stationary. The residential, commercial, and industrial sectors correspond to Energy Information Administration (EIA) building category designations, while the outdoor stationary 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 analysis 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. The lighting sectors are characterized by the following parameters from the 2010 U.S. Lighting Market Characterization report and the 2006 MECS.

Table 2.1 Description of 2010 Lighting Sector Parameters

Sector	Description	Lamp Inventory (millions)	Electricity Consumption (TWh/yr)	Typical Lamp Operating Hours (hr/day)	Floorspace (billion sq. ft.)
Residential	Living quarters and outdoor applications (e.g., porch, walkways) for private households.	5,812	173	1.8–2.5	193.4
Commercial	Interior service-providing facilities and equipment of businesses, governments, and other organizations.	2,063	346	9.8–12.4	81.2
Industrial	Interior facilities and equipment engaged in manufacturing, agriculture, forestry, fishing, construction, and mining.	144	58	11.7–17.9	9.7
Outdoor Stationary	Exterior commercial or industrial, such as parking lot lights or exterior wall packs. Also includes stationary lighting sources that are not associated with buildings.	178	116	9.0–14.0	N/A

The LMC estimates the installed base of lighting in the U.S. considering 28 different lamp types:

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

Existing LED lamps installed in the commercial and industrial sectors in 2010 were excluded from this analysis. This is because the existing installed base of LED lamps in these sectors comprises almost exclusively LED exit signs, which are not considered a general illumination white-light source. Likewise, the "other miscellaneous" category in the LMC is excluded from this analysis due to great uncertainty regarding the types of lamps included in that category and their characteristics. Combined, these excluded categories of lamps account for only 6 terawatt-hours of annual energy use, or less than one percent, of lighting energy consumption in 2010; thus, the impact of their exclusion is minimal.

In order to model the competition between lighting technologies within lighting applications, this analysis classifies each of the remaining LMC lamp types into one of five independent submarkets:[1]

- General service lighting–medium screw-base (GSL–MSB)
- Reflector–screw-base
- Linear fluorescent
- High-intensity discharge (HID)
- Miscellaneous

These application submarkets are used to classify the lumen-hours of lighting service from a particular lamp type and sector. Using historical lighting sales trends, the submarkets were created to group together the annual lighting demand by similar application. (However, in some cases these applications correspond to a particular technology.) For instance, a GSL–MSB lamp is designed to provide ambient light and is used for low lumen output applications such as a table lamp or ceiling fan, whereas a reflector lamp is a directional lighting source and is designed for track and downlighting applications. Because these types of lamps provide two distinctly different services, they are generally not direct competitors and can be classified in separate submarkets. Furthermore, the miscellaneous submarket was developed to include several applications that are dominated by a single technology. The lighting technologies within this submarket do not compete with one another; however, it is projected that LED lighting will

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[1] This approach is similar to that used in the lighting choice module of the NEMS Residential Sector Demand Module (EIA, 2010).

penetrate these individual applications. The miscellaneous submarket includes lighting types such as MR16s, which are becoming a common lighting option for display lighting in museums, art galleries, retail stores and entertainment venues, as well as pin-base CFLs, which are now prevalent in commercial office settings, among others.

One of the modeling assumptions regarding the application submarkets was that the demand for lumens in any given submarket will not shift out of that submarket during the analysis period. In other words, only the lamp types within a submarket compete for market share; therefore, an incandescent lamp in the GSL–MSB submarket may only compete against medium screw-base CFL and halogen lamps. Under this modeling assumption, an incandescent MSB lamp cannot lose market share to a CFL reflector lamp because these lamp types are classified in different submarkets. Although this assumption may not perfectly reflect the marketplace (e.g., where a consumer may substitute lamps types across submarkets because it is less expensive or offers some other desirable feature), it is a reasonable simplification.

The five submarkets and the lamp types within each are shown in Table 2.2.

Table 2.2 Conventional Lamp Types in Each Application Submarket

<table>
<tr><th>General Service Lamps - Medium Screw-Base</th><th>HID</th><th>Linear Fluorescent</th></tr>
<tr><td>Incandescent MSB
Halogen MSB
CFL MSB</td><td>Mercury Vapor
Metal Halide
High Pressure Sodium
Low Pressure Sodium</td><td rowspan="3">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
T5*</td></tr>
<tr><th>Reflectors (Screw-Base)</th><th>Miscellaneous</th></tr>
<tr><td>Incandescent Reflector
Halogen Reflector
CFL Reflector</td><td>Incandescent Other
Halogen Reflector Other
CFL Other
Linear Fluorescent Other
T5 Less than 4 ft*</td></tr>
</table>

*In the residential sector, T5 Less than 4 ft is included in the miscellaneous submarket because of their popularity for use in space-constrained residential applications, for which T8 and T12 do not compete. T5 lamps 4 ft and greater remain in the linear fluorescent submarket. In all other sectors, all T5 lamps are considered in the linear fluorescent submarket.

Based on average wattage, system efficacy, operating hours, and lamp inventory characteristics from the 2010 LMC in conjunction with average fixture efficiencies, the national demand for lighting service (in teralumen-hours[2]) in 2010 was estimated. For example, if an incandescent MSB lamp within the residential sector consumes 100 kWh in a year, this would be converted into 1,300 kilolumen-hours of lighting service. This result is found by multiplying 100 kWh of electricity consumption by 13 lumens per watt (lm/W), the estimated efficacy of a residential incandescent MSB lamp.

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[2] Due to the magnitude of calculated national lumen demand, the notation “tera-” is used, meaning 10E+12 (1,000,000,000,000) lumen-hours of annual lighting service. One thousand lumen-hours are approximately equal to the light output of a standard 75 watt incandescent lamp for one hour.

Using the aforementioned sectors and submarkets, the model segments the projected annual lighting demand into twenty unique bins defined by the four sectors and five submarkets, as shown in Table 2.3. As seen below, the commercial linear fluorescent submarket is estimated to be the submarket which provides the greatest lighting service to the nation, largely due to the size of its installed base and long operating hours. The second largest submarket (in terms of lighting service) is the outdoor stationary HID submarket, which similarly has relatively long operating hours and also comprises high lumen output lamps. Note that several submarkets (e.g., industrial and outdoor stationary GSL–MSB and reflector, and outdoor stationary linear fluorescent) show zero lighting service for 2010. For these categories the LMC did not provide a sufficient degree of technology disaggregation to model trends between lamp types in these submarkets. Thus, these lamps are accounted for in the miscellaneous submarket. For example, the majority of the miscellaneous submarket in the outdoor stationary sector comprises "miscellaneous linear fluorescent lamps," as classified by the LMC.

Table 2.3 National Lighting Service by Sector and Submarket, 2010

Submarket	Lighting Service (Tlm-hr)				
	Residential	Commercial	Industrial	Outdoor	Total
GSL-MSB	1,770	300	0	0	**2,060**
Reflector	360	290	0	0	**650**
Linear Fluorescent	390	13,570	1,290	0	**15,250**
HID	10	2,410	1,740	4,760	**8,920**
Miscellaneous	540	810	10	760	**2,120**
Total	**3,070**	**17,370**	**3,040**	**5,520**	**29,000**

3 Annual Lumen Demand and Market Turnover

3.1 National Lumen Demand Projection

After calculating the lighting service, or lumen-hour, demand in 2010 by sector and submarket, the next step was to projected forward growth in lighting demand between 2010 and 2030. To do this, the 2010 lumen-hour demand (presented in Table 2.3) was divided by the cumulative national floorspace for each sector to determine a lighting demand density in lumen-hours per square foot of building space. Then, assumed floorspace growth rates were applied to these densities to project total lighting demand for each sector from 2010 to 2030, holding lighting demand density constant. In the residential sector, the average lighting demand density in 2010 was approximately 15.9 kilolumen-hours per square foot, while density in the commercial sector was more than ten times higher, at 214 kilolumen-hours per square foot. The commercial lighting service was higher due to the longer operating hours and higher levels of illumination in commercial floorspace.

AEO 2011 provides annual average growth estimates of floorspace in the residential and commercial sectors, which are used to project increases in lumen demand moving forward. The residential floorspace increases by an average of 1.75 percent per annum over the 20-year analysis period, and the commercial sector floorspace increases by an average of 1.22 percent per annum. Unfortunately, AEO 2011 does not provide a growth estimate for the industrial or outdoor stationary sectors. Because the outdoor sector includes buildings-related outdoor lighting, it was assumed that the growth rate would mimic that of the commercial sector. For the industrial sector, an historical rate of construction of manufacturing facilities was estimated using historical annual construction costs for manufacturing buildings (U.S. Census Bureau, 2011) in conjunction with an estimated industrial floorspace cost per square foot (DCD Magazine, 2011). From historical MECS industrial floorspace data from several years and this annual construction rate, an historical net floorspace retirement rate was found and projected forward to 2030.

In summary, the average annual floorspace growth or retirement rates used in the analysis, representing the annual change in lumen demand between 2010 and 2030, are as follows:

- Residential: 1.75 percent growth
- Commercial: 1.22 percent growth
- Industrial: 0.94 percent decline
- Outdoor Stationary: 1.22 percent growth

This methodology of projecting lighting service demand is predicated on the assumption that future occupants of a lighted space will continue to expect today's illuminance levels and duration of service. Because light emission from LEDs is highly directional, a scenario where task lighting becomes more common in the future could be envisioned. If this were the case, task lighting would likely replace some of the area lighting and the lumen intensity per square foot would be lower than it is today. However, any such assumption and subsequent downward adjustment of lumen intensity due to anticipated performance of fixtures and/or consumer preference would be highly speculative. Holding the lighting density estimate constant in each sector leads to a conservative (i.e., not overstating) estimate of energy savings for two reasons: 1) any reduction in lighting density would equate to even greater energy savings because fewer lumens would be used in that installation than would be required to illuminate the same task with area lighting in the reference case; and 2) requiring equivalent lumen output on a source basis makes it harder for LEDs to compete.

In addition, the lighting market is beginning to transition towards smart design in response to increasing energy prices and mounting concern over environmental and climate change. For example, taking advantage of lighting control regimens (e.g., occupancy sensors or daylighting) to create responsive, localized lighting designs would enable a reduction in the overall lighting service (and thus associated energy consumption and savings due to LED penetration). However, LED luminaires could potentially enable easier and lower cost integration of lighting into smart building controls, thus facilitating the penetration of LED technology and the use of smart controls and potentially increasing energy savings.

3.2 Annual Available Market

Building on the national estimate of the projected annual lumen-hour service, 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 calculate this estimate, the model evaluates three events that determine the available lumen-hours on the lighting market each year:

- New construction. New fixtures installed each year due to floorspace growth in each sector, determined by growth or retirement projections (see Section 3.1 of this report) and the apportionment of lighting intensity per unit floorspace. For the lumen-hours of service in this category, the costs considered for conventional technologies include the cost of the lamp, fixture, and ballast (if appropriate). For LED technology, the costs considered include the cost of LED lamp and fixture (for the GSL–MSB and reflector submarkets) or LED luminaire (for the linear fluorescent and HID submarket).

- Retrofits. Lamps (and ballasts, if appropriate) and fixtures being installed to replace existing lamps and fixtures during renovation 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 five percent each year in each sector, for a mean retrofit cycle of 20 years. As with the new construction category, LED systems in this retrofit market will compete with conventional lighting technologies on a basis that includes new fixture costs.

- 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 model assumes that manufacturers of LED technology will produce lamps that match conventional screw-base technologies and can be installed directly into existing GSL–MSB and screw-base reflector lighting fixtures. Thus, in the replacement market, LED lamps compete with conventional lighting technologies (including the initial cost of the lamp). LED luminaires compete with incumbent technologies in the linear fluorescent and HID submarkets when a ballast burns out and must be replaced.

The lighting market model assumes a constant rate of lighting fixture retrofits and renovations of five percent of the installed base in both the baseline and LED scenarios. However, 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 in the LED scenario, and thus also underestimates the forecasted LED market penetration and energy savings. However, in order to assess how additional retrofits due to the presence of LEDs on the market could affect energy savings, a sensitivity analysis was performed, in which the retrofit rate was increased to 15 percent in the LED scenario. For a more detailed discussion, see Appendix B.

These three components—new construction, replacements and retrofits—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.

4 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 20-year analysis period. However, the ability of these conventional technology light sources 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 lighting market model introduces price and performance changes linearly as percentage improvements over the analysis period, 2010 to 2030. The model improves the lamp efficacy, operating life, and first cost for the four primary groups of conventional lighting technologies: incandescent, halogen, CFL, linear fluorescent, and HID. These incremental performance improvements were developed in consultation with industry experts, with consideration given to the historical performance trajectory of each lighting technology (Bardsley, et. al., 2011b). The percent improvement therefore varies depending on a particular lighting technology's seniority in the lighting market. The following tables present current and projected performance characteristics in 2010 and 2030, respectively, absent any new future standards.[3] 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.

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[3] Note that although the following tables present values for projected efficacy and lifetime improvements for all lamp types and technologies analyzed in 2010, several of these lamp types (e.g., T12 linear fluorescent lamps, incandescent MSB lamps, mercury vapor lamps) are projected to eventually be eliminated from the market due to Federal energy conservation standards. The model's implementation of these standards is discussed further in Section 4.1.

Table 4.1 Residential Sector Conventional Technology Performance, 2010 and 2030

	Baseline Technology in 2010				Percent Improvement by 2030	
Submarkets and Lamp Types	**Mean System Wattage (W)**	**Lamp Life (1,000 hr)***	**Mean System Efficacy (lm/W)**	**Fixture Efficiency (%)**	**Mean System Efficacy**	**Lamp Life**
General Service Lamps - Medium Screw Base						
Incandescent MSB	64	1.4	13	100%	0%	0%
Halogen MSB	50	1.5	15	100%	10%	10%
CFL MSB	17	10	53	100%	10%	10%
Reflectors						
Incandescent Reflector	69	2.5	10	100%	0%	0%
Halogen Reflector	14	3.0	14	100%	10%	10%
CFL Reflector	43	10	43	100%	10%	10%
Linear Fluorescent						
T12 Less than 4ft	16	20	52	70%	0%	0%
T12 4ft	27	20	67	70%	0%	0%
T12 Greater than 4ft	50	20	75	70%	0%	0%
T12 U-Shaped	27	20	63	70%	0%	0%
T8 Less than 4ft	16	20	55	70%	10%	10%
T8 4ft	26	20	73	70%	10%	10%
T8 Greater than 4ft	41	20	87	70%	10%	10%
T8 U-Shaped	27	20	77	70%	10%	10%
T5 4ft and Greater	36	20	90	90%	10%	10%
HID						
Mercury Vapor	193	20	29	65%	0%	0%
Metal Halide	79	18	49	65%	15%	15%
High Pressure Sodium	150	28	70	65%	5%	5%
Low Pressure Sodium	-	-	-	-	-	-
Miscellaneous						
Incandescent Other	44	1.0	11	100%	5%	10%
Halogen Reflector Other	70	4.0	15	100%	5%	10%
CFL Other	18	12	52	100%	5%	10%
Linear Fluorescent Other	16	20	63	70%	5%	10%
T5 less than 4 feet	19	20	53	90%	5%	10%

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps). Fluorescent ballasts are assumed to have a lifetime of 50,000 hours, while HID ballasts are assumed to last 75,000 hours.

Table 4.2 Commercial Sector Conventional Technology Performance, 2010 and 2030

	Baseline Technology in 2010				Percent Improvement by 2030	
Submarkets and Lamp Types	**Mean System Wattage (W)**	**Lamp Life (1,000 hr)***	**Mean System Efficacy (lm/W)**	**Fixture Efficiency (%)**	**Mean System Efficacy**	**Lamp Life**
General Service Lamps - Medium Screw Base						
Incandescent MSB	58	1.8	12	100%	0%	0%
Halogen MSB	46	1.5	15	100%	10%	10%
CFL MSB	20	10	54	100%	10%	10%
Reflectors						
Incandescent Reflector	79	2.5	10	100%	0%	0%
Halogen Reflector	15	3.0	15	100%	10%	10%
CFL Reflector	45	10	45	100%	10%	10%
Linear Fluorescent						
T12 Less than 4ft	35	20	56	70%	0%	0%
T12 4ft	43	20	71	70%	0%	0%
T12 Greater than 4ft	78	20	77	70%	0%	0%
T12 U-Shaped	42	20	65	70%	0%	0%
T8 Less than 4ft	20	20	71	70%	10%	10%
T8 4ft	30	20	78	70%	10%	10%
T8 Greater than 4ft	54	20	81	70%	10%	10%
T8 U-Shaped	31	20	76	70%	10%	10%
T5	36	20	90	90%	10%	10%
HID						
Mercury Vapor	362	20	38	65%	0%	0%
Metal Halide	349	18	73	65%	15%	15%
High Pressure Sodium	356	28	107	65%	5%	5%
Low Pressure Sodium	185	25	143	65%	5%	5%
Miscellaneous						
Incandescent Other	7	1.0	11	100%	5%	10%
Halogen Reflector Other	64	4.0	17	100%	5%	10%
CFL Other	19	12	55	100%	5%	10%
Linear Fluorescent Other	31	20	74	70%	5%	10%

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps). Fluorescent ballasts are assumed to have a lifetime of 50,000 hours, while HID ballasts are assumed to last 75,000 hours.

Table 4.3 Industrial Sector Conventional Technology Performance, 2010 and 2030

	Baseline Technology in 2010				Percent Improvement by 2030	
Submarkets and Lamp Types	**Mean System Wattage (W)**	**Lamp Life (1,000 hr)***	**Mean System Efficacy (lm/W)**	**Fixture Efficiency (%)**	**Mean System Efficacy**	**Lamp Life**
General Service Lamps - Medium Screw Base						
Incandescent MSB	46	1.8	12	100%	0%	0%
Halogen MSB	36	1.5	14	100%	10%	10%
CFL MSB	17	10	53	100%	10%	10%
Reflectors						
Incandescent Reflector	65	2.5	10	100%	0%	0%
Halogen Reflector	13	3.0	13	100%	10%	10%
CFL Reflector	42	10	42	100%	10%	10%
Linear Fluorescent						
T12 Less than 4ft	33	20	48	70%	0%	0%
T12 4ft	39	20	71	70%	0%	0%
T12 Greater than 4ft	84	20	78	70%	0%	0%
T12 U-Shaped	41	20	64	70%	0%	0%
T8 Less than 4ft	23	20	71	70%	10%	10%
T8 4ft	30	20	79	70%	10%	10%
T8 Greater than 4ft	73	20	78	70%	10%	10%
T8 U-Shaped	30	20	77	70%	10%	10%
T5	58	20	85	90%	10%	10%
HID						
Mercury Vapor	451	20	39	65%	0%	0%
Metal Halide	434	18	75	65%	15%	15%
High Pressure Sodium	295	28	105	65%	5%	5%
Low Pressure Sodium	-	-	-	-	-	-
Miscellaneous						
Incandescent Other	-	-	-	-	-	-
Halogen Reflector Other	145	4.0	13	100%	5%	10%
CFL Other	45	12	69	100%	5%	10%
Linear Fluorescent Other	42	20	80	70%	5%	10%

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps). Fluorescent ballasts are assumed to have a lifetime of 50,000 hours, while HID ballasts are assumed to last 75,000 hours.

Table 4.4 Outdoor Stationary Sector Conventional Technology Performance, 2010 and 2030

	Baseline Technology in 2010				Percent Improvement by 2030	
Submarkets and Lamp Types	**Mean System Wattage (W)**	**Lamp Life (1,000 hr)***	**Mean System Efficacy (lm/W)**	**Fixture Efficiency (%)**	**Mean System Efficacy**	**Lamp Life**
HID						
Mercury Vapor	219	20	30	65%	0%	0%
Metal Halide	247	18	60	65%	15%	15%
High Pressure Sodium	241	28	84	65%	5%	5%
Low Pressure Sodium	107	25	89	65%	5%	5%
Miscellaneous						
Incandescent Other	68	1.0	12	100%	5%	10%
Halogen Reflector Other	149	4.0	17	100%	5%	10%
CFL Other	22	12	55	100%	5%	10%
Linear Fluorescent Other	63	20	74	70%	5%	10%

*The model also incorporates system lifetime assumptions for technologies that use a ballast (i.e., linear fluorescent and HID lamps). Fluorescent ballasts are assumed to have a lifetime of 50,000 hours, while HID ballasts are assumed to last 75,000 hours.

Table 4.5 All Sector Conventional Technology Equipment Costs, 2010

Submarkets and Lamp Types	Residential			Commercial			Industrial			Outdoor Stationary		
	Lamp Price ($)†	Ballast Price ($)	Fixture Price ($)	Lamp Price ($)†	Ballast Price ($)	Fixture Price ($)	Lamp Price ($)†	Ballast Price ($)	Fixture Price ($)	Lamp Price ($)†	Ballast Price ($)	Fixture Price ($)
General Service Lamps - Medium Screw Base												
Incandescent MSB	$0.50	-	$18.50	$0.50	-	$15.00	$0.50	-	$15.00	-	-	-
Halogen MSB	$1.90	-	$18.50	$1.90	-	$15.00	$1.90	-	$15.00	-	-	-
CFL MSB	$3.00	-	$18.50	$3.00	-	$15.00	$3.00	-	$15.00	-	-	-
Reflectors												
Incandescent Reflector	$3.10	-	$18.50	$3.10	-	$15.00	$3.10	-	$15.00	-	-	-
Halogen Reflector	$4.70	-	$18.50	$4.70	-	$15.00	$4.70	-	$15.00	-	-	-
CFL Reflector	$10.30	-	$18.50	$10.30	-	$15.00	$10.30	-	$15.00	-	-	-
Linear Fluorescent												
T12 Less than 4ft	$3.30	$16.00	$50.00	$3.40	$16.00	$70.00	$3.40	$16.00	$45.00	-	-	-
T12 4ft	$3.30	$16.00	$50.00	$3.40	$16.00	$70.00	$3.40	$16.00	$45.00	-	-	-
T12 Greater than 4ft	$3.30	$16.00	$50.00	$3.40	$16.00	$70.00	$3.40	$16.00	$45.00	-	-	-
T12 U-Shaped	$3.30	$16.00	$50.00	$3.40	$16.00	$70.00	$3.40	$16.00	$45.00	-	-	-
T8 Less than 4ft	$4.30	$16.00	$45.00	$3.10	$16.00	$70.00	$3.10	$16.00	$45.00	-	-	-
T8 4ft	$4.30	$16.00	$45.00	$3.10	$16.00	$70.00	$3.10	$16.00	$45.00	-	-	-
T8 Greater than 4ft	$4.30	$16.00	$45.00	$3.10	$16.00	$70.00	$3.10	$16.00	$45.00	-	-	-
T8 U-Shaped	$4.30	$16.00	$45.00	$3.10	$16.00	$70.00	$3.10	$16.00	$45.00	-	-	-
T5*	$4.40	$20.00	$50.00	$4.40	$20.00	$75.00	$5.30	$20.00	$50.00	-	-	-
HID												
Mercury Vapor	$18.40	-	$60.00	$25.00	-	$70.00	$25.00	-	$70.00	$25.00	-	$70.00
Metal Halide	$29.00	$95.00	$100.00	$22.00	$110.00	$85.00	$22.00	$110.00	$85.00	$22.00	$90.00	$130.00
High Pressure Sodium	$21.00	$85.00	$60.00	$17.00	$90.00	$70.00	$17.00	$90.00	$70.00	$17.00	$80.00	$70.00
Low Pressure Sodium	$18.40	$175.00	$60.00	$40.00	$195.00	$155.00	$40.00	$195.00	$155.00	$40.00	$160.00	$240.00
Miscellaneous												
Incandescent Other	$1.00	-	$18.50	-	-	-	-	-	-	-	-	-
Halogen Reflector Other	$4.30	-	$18.50	$4.60	-	$15.00	$4.60	-	$15.00	$3.30	-	$15.00
CFL Other	$3.70	$30.00	$18.50	$5.50	$18.00	$15.00	$7.30	$18.00	$15.00	$6.70	$18.00	$15.00
Linear Fluorescent Other	$3.50	$15.00	$70.00	$3.30	$15.00	$70.00	$3.40	$15.00	$45.00	$3.60	$15.00	$70.00
T5 less than 4 feet	$3.30	$16.00	$50.00	-	-	-	-	-	-	-	-	-

*In the residential sector, this lamp type includes only T5 lamps that are 4 feet long or greater. In other sectors, this lamp type includes all T5 fluorescent lamps.

†Lamp costs are assumed to decrease by 10 percent by the end of the analysis period

4.1 Legislation and DOE Regulations

The lighting market model makes adjustments to the performance and price characteristics to account for several regulatory measures on conventional light sources. 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., published in the *Federal Register*) and effective. The model does not take into account draft or pending legislation or regulations, as both the compliance dates and standard levels are uncertain. The 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 are important to consider in the context of this analysis because they 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 revised analysis.

1. General service lamps. Section 321 of EISA 2007 prescribed maximum wattage standards for medium screw-base general service incandescent lamps, which take effect between 2012 and 2014. The model assumes that covered non-halogen incandescent products are unlikely to meet the 2012–2014 maximum wattage standards. As such, this analysis models the EISA 2007 standards by manually removing covered incandescent MSB products from the modeled marketplace, with the standard becoming effective in each sector in the year corresponding to its mean incandescent MSB lamp wattage. This causes a market transition toward more efficient lamps, such as standard-compliant halogen and CFLs.[4] 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 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.

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[4] The Energy and Water Development and Related Agencies Appropriations Act, 2012, passed by the U.S. Congress on December 16, 2011, 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 2012. The standards, however, have not been repealed and remain in effect.

2. <u>Candelabra-base and intermediate-base incandescent lamps.</u> 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. <u>Fluorescent lamps.</u> 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 will become 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 model incorporates these standards by increasing the efficacy and price of linear fluorescent lamps accordingly. (74 FR 34080).

4. <u>Fluorescent ballasts.</u> 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. (76 FR 70548)

5. <u>Incandescent reflector lamps.</u> This DOE energy conservation regulation, which applies to lamps manufactured on or after July 14, 2012, amends EPCA to prescribe minimum efficacy standards for covered products in the 40-205W 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 model incorporates these standards by increasing the efficacy and price of halogen reflector lamps accordingly. (74 FR 34080).

6. <u>Mercury vapor ballasts.</u> 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 U.S. and were thus removed from the analysis of the commercial, industrial, and outdoor stationary 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.

5 LED Technology Improvement Projection

The U.S. Department of Energy works with the Next Generation Lighting Industry Alliance (NGLIA), NEMA, several national laboratories, and numerous researchers to develop technology and manufacturing roadmaps for both LEDs and OLEDs. These roadmaps are contained in DOE's SSL R&D MYPP, which was last published in March 2011, and DOE's SSL R&D Manufacturing Roadmap, which was last published in July 2011. The MYPP provides the basis for the LED performance curves analyzed and presented in this report. The MYPP projects LED performance through 2020, and these trends were then extrapolated to 2030 for the purposes of this analysis. For complete transparency on the inputs, tables providing the price and performance improvement targets used in this analysis are found in Appendix A.

As mentioned in Chapter 1, only LED lighting technologies are considered in this analysis due the current lack of available OLED lighting products and to the great uncertainty in the potential for the OLED lighting market. Therefore, all energy savings are assumed to result from the market penetration of LED lighting.

The lighting market model makes several assumptions to simplify the analysis. Firstly, the model assumes that LED lighting products can be manufactured as an integrated replacement lamp or luminaire system.[5] Based on lighting market trends, it is assumed that either LED lamps or LED luminaires compete in each of the five submarkets. Consider the GSL–MSB submarket as an example: because all of the conventional lighting technologies competing within this submarket are lamps designed to fit a medium screw-base socket, the lighting market model allows only LED lamps to compete against conventional technologies. This distinction between the markets for LED lamps and luminaires allows the model to assign separate performance and costs to these products, based on current market research. For example, LED luminaire products generally offer higher efficacies than LED lamp products. This is likely because LED luminaire products, with optimized form factors, are able to better utilize the inherent benefits of LED technology and better manage thermal and optical losses. In addition, due to the additional material associated with the luminaire housing, current market pricing indicates that on a dollars per kilolumen basis, LED luminaires have slightly higher prices than replacement lamps. The applicable submarkets and basic characteristics of LED lamps and luminaires are shown in Table 5.1. The derived efficacies and costs are discussed further in the following sections.

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[5] See Chapter 5.0 of the 2011 MYPP for definitions of an integrated LED lamp and LED luminaire: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf

Table 5.1 Average LED Price and Performance Values in 2010

LED Product	Applicable Submarket	Color Temperature	Efficacy (lm/W)*	Price ($/klm)*	Life (1,000 hr)*
Lamp	GSL–MSB, Reflector, Miscellaneous	Warm-white	37	$55	25
Luminaire	Linear Fluorescent, Indoor HID, Miscellaneous	Cool-white	70	$181	25
	Outdoor HID	Cool-white	70	$181	50

*The values presented in this table represent average achieved levels of commercially available product by 2010 (Bardsley, et. al., 2011b). Efficacy values and prices presented in this table include the losses from and costs of electronic controls and drivers.
1. Cool White: CRI 70–80; CCT 4746–7040 K
2.Warm White: CRI 80–90; CCT 2580–3710 K

Due to the distinct differences between LED lamps and luminaires, separate technology improvement curves were adapted from DOE's MYPP and Manufacturing Roadmap for 2011, analyzing three critical performance metrics:

- Efficacy (lm/W)
- Lamp or luminaire price (dollars per kilolumen, including LED device and operating electronics)
- Lamp or luminaire life (hours of useful operational life)

DOE's MYPP projections of price and performance are developed through a collaborative effort between industry, academia, research laboratories, and the U.S. government.[6] The MYPP does not project LED price and performance to 2030, nor does it provide differentiation of LED technologies and performance product type. Rather, the MYPP provides a projection for a defined quality of light (e.g., warm-white luminaires are represented by a CRI between 80 and 90 and a CCT of 2580–3710 K, while cool-white luminaires are represented by a CRI between 70 and 80 and a CCT of 4746–7040 K) over a specific time period. For this forecast, the LED package performance curves were adjusted to account for the efficacy and lifetime losses associated with commercial LED lamp products. Lamp costs were projected from those presented in the MYPP, then normalized to 2010 market prices. Luminaire costs, too, are based on 2010 market prices, to which the cost reduction trends from DOE's SSL Manufacturing Roadmap were applied. The MYPP and Manufacturing Roadmap project LED lighting product cost improvement through 2020, and this analysis extrapolates the costs to 2030.

LED technology improves logistically (i.e., along an S-curve), although LED luminaire products improve earlier than LED lamps. In addition, higher color temperature (i.e., cool-white)

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[6] An SSL Partnership between DOE and NGLIA was created in February 2005. Administered by the National Electrical Manufacturers Association, NGLIA is a consortium of manufacturers working to accelerate SSL development and commercialization. For more information including a copy of the Memorandum of Understanding, visit: http://www1.eere.energy.gov/buildings/ssl/partnership_nglia.html

luminaires are typically used in the commercial, industrial, and outdoor stationary sectors, which typically demand higher efficacies. The performance of LED lamp products has lagged behind that of LED luminaire products because of higher efficiency losses attributable to their compact architecture, power supply complexity, and the demand for warm-white color temperatures. However, it is assumed that the challenges associated with the development of LED lamp products will eventually be resolved, allowing the performance of both LED lamp and luminaire products to converge over time.

In addition, because the MYPP only provides performance projections for best in class LED products, a delay factor of one year is incorporated in the analysis to represent the average market performance of an LED luminaire (i.e., the average market LED luminaire performance is one year behind that of best in class LED luminaire products), while a delay of two years is used to represent the losses associated with the less efficient LED lamp products.

Figure 5.1 and Table 5.2 provide the efficacy improvement curves for LED lamps and luminaires. LED lamps slightly lag behind LED luminaires in the near term, but they converge around 2025. DOE's MYPP indicates that LED efficacy levels will not exceed 268 lumens per watt due to efficiency limits.

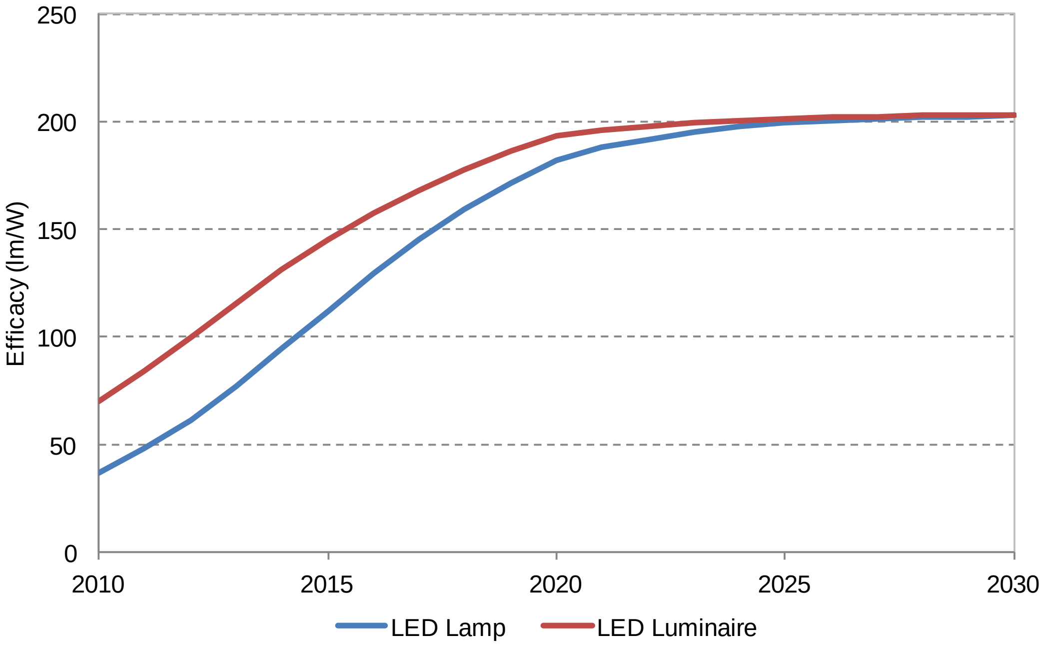

Figure 5.1 LED Efficacy Improvement

Table 5.2 LED Efficacy Improvement

LED Product	Efficacy (lm/W)				
	2010	2015	2020	2025	2030
Lamp	37	113	182	199	203
Luminaire	70	145	193	202	203

With respect to lifetime, the MYPP identifies a target lifetime of 50,000 hours for LED lamps and luminaires. Market research shows that LED lamps and indoor luminaires on today's market typically have a lifetime of approximately 25,000 hours. Using a logistic curve similar to that used to project efficacy, lifetime was logistically interpolated for each year of the analysis period. Luminaires for outdoor use typically have longer lifetimes (50,000 hours in 2011), such that their improvement in parallel with indoor luminaires should result in an average lifetime of 75,000 years by 2030. Figure 5.2 and Table 5.3 present the LED operating life projections used in this analysis.

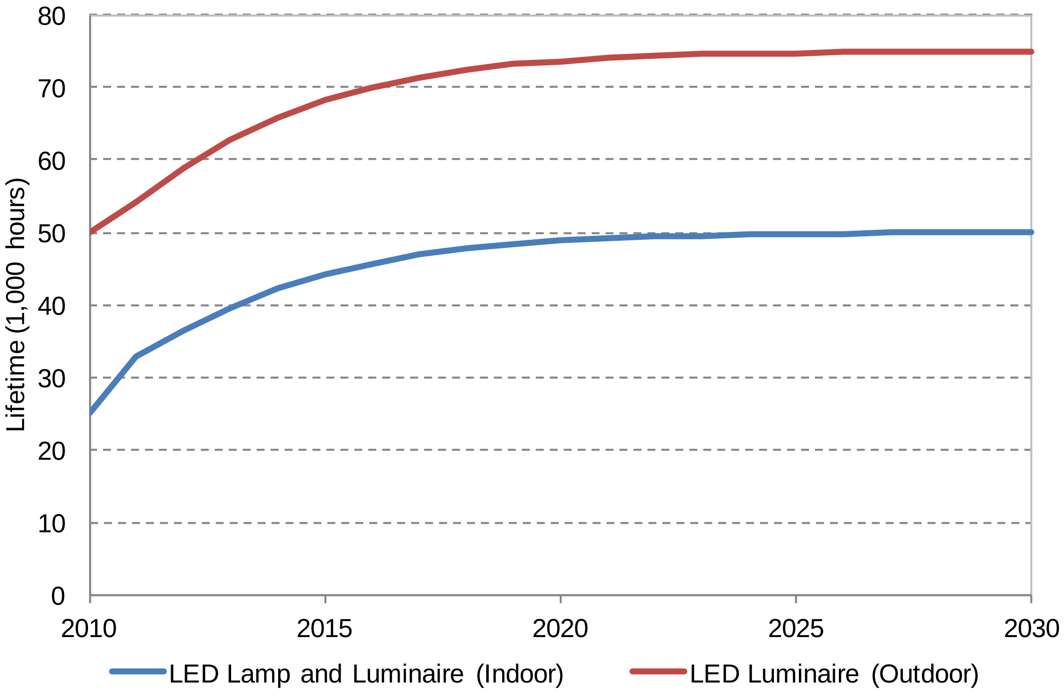

Figure 5.2 LED Lifetime Improvement

Table 5.3 LED Lifetime Improvement

LED Product	Lifetime (1,000 hours)				
	2010	2015	2020	2025	2030
Lamp & Luminaire (Indoor)	25.0	44.1	48.8	49.8	50.0
Luminaire (Outdoor)	50.0	68.2	73.7	74.7	75.0

Figure 5.3 and Table 5.2 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. The MYPP only provides first cost ($/klm) projections for LED lamp products. For this analysis, a separate reduction curve was developed for LED luminaire products because they are more material-intensive and therefore more expensive on a first cost per kilolumen basis. Using industry, DOE, and manufacturer pricing data, it was determined that the average cost of LED luminaires was about $181 per kilolumen in 2010. Thereafter, this analysis predicts that LED luminaire price will decrease at the same rate as the MYPP LED lamp forecast. Due to the comparative adolescence of the LED technology and marketplace, the LED price projection decreases exponentially between now and 2030 and then is projected to plateau at about $3 per kilolumen for LED lamps and $13 per kilolumen for luminaires.

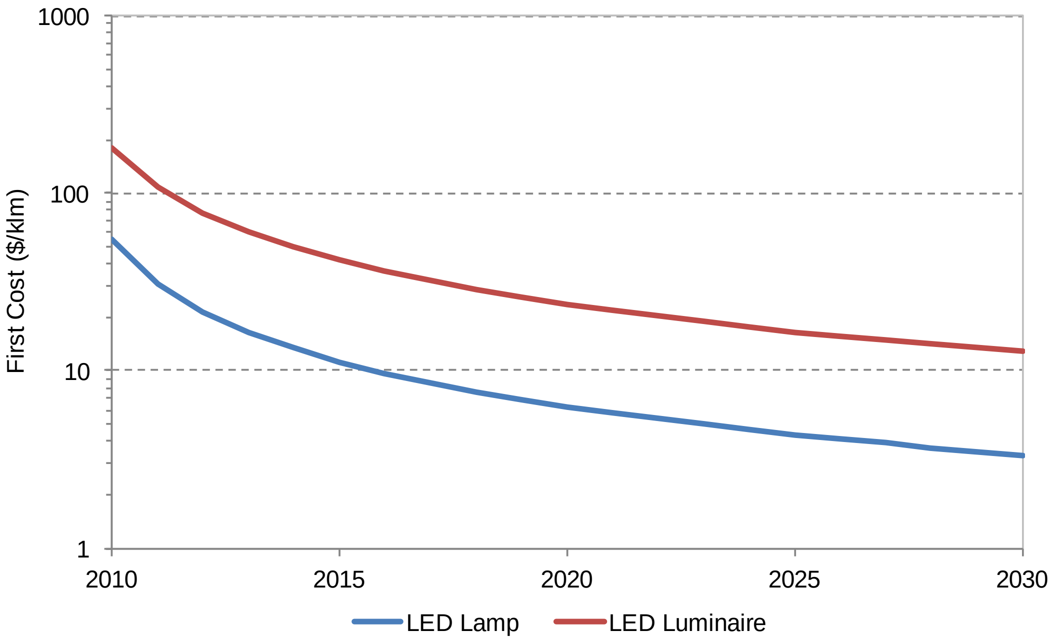

Figure 5.3 LED Price ($/klm) Improvement

Table 5.4 LED Price Improvement

LED Product	Price ($/klm)				
	2010	2015	2020	2025	2030
Lamp	$55.16	$11.25	$6.28	$4.36	$3.34
Luminaire	$180.88	$41.81	$23.69	$16.55	$12.73

For complete transparency of the inputs used in this study, detailed versions of the above figures and tables providing yearly results are provided in Appendix A.

6 Lighting Market Penetration Model

Each year, new lamps enter the market as old lamps are replaced or fixtures are installed or retrofitted. This creates an annual lumen market demand, which may be satisfied by a suite of lighting technologies, and 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 calibrates market share projections to historical data. This approach of using a logit model and a technology diffusion model in concert has been previously used by several reports (Cao, 2004; Paidipati, Frantzis, Sawyer, & Kurrasch, 2008).

6.1 Econometric Logit Model

The previous analysis awarded available market share to competing technologies based on simple payback, or the ratio of first year incremental purchase price to first year incremental savings. The primary drawback of the payback acceptance curve is that this method only allows for the competition between two technology options (i.e., the incumbent and the emerging technology). This method of determining market share worked well for the previous analysis, which compared a hypothetical, representative average incumbent technology (with price and performance parameters derived by averaging across all conventional technologies) to LEDs; however, this is not suitable for multiple technology comparison. To improve upon the simple payback method, the current analysis 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 2010 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 efficiency. 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 between 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 LEDs in certain submarkets, first cost indicates the price of the 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 constitute the life-cycle cost of a lighting product, were chosen to help characterize two types of lighting consumers:

- Those that 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 that 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 market sector (residential, commercial, industrial, and outdoor stationary) on one of these two characteristic consumers. In order to estimate how each sector makes purchasing decisions (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 technologies within each sector. Historical data for one specific submarket for each sector was chosen to represent consumer decisions. GSL–MSB data, linear fluorescent data, and HID data were considered representative of the residential sector, commercial and industrial sectors, and outdoor stationary sector, respectively.

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 derate that technology's value to a consumer. For example, the 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 (for CFLs only).

6.1.1 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 potential market shares of various products.

6.1.2 Logit Model Input Data

Chapters 4 and 5 discuss how the 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 and is discussed in Chapters 4 and 5. Annual O&M cost includes annual energy, replacement and labor costs. Annual replacement cost is an annualized measure 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 sector, which are also discussed in Chapters 4 and 5, and average electricity prices by sector. Electricity prices used for the operating cost evaluation are taken from the EIA's AEO 2011 reference scenario, then inflated from 2009 to 2011 dollars. In the absence of an electricity price for the outdoor stationary sector, it was assumed that these customers experienced the same electricity prices as the commercial sector. The AEO 2011 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 6.1.

Table 6.1 Electricity Price Projections in 2011 Dollars per Kilowatt-Hour

LED Product	Average Electricity Price ($/kWh)				
	2010	2015	2020	2025	2030
Residential	$0.118	$0.112	$0.110	$0.110	$0.110
Commercial	$0.100	$0.094	$0.093	$0.094	$0.094
Industrial	$0.067	$0.062	$0.062	$0.063	$0.064
Outdoor Stationary	$0.100	$0.094	$0.093	$0.094	$0.094

Source: EIA, 2011

6.2 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 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 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 which 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 emerging technology on the market. Therefore, the model tends to delay the adoption of LED products despite rapid gains in efficacy improvement and cost reduction.

The Bass curve used in this analysis, shown in Figure 6.1 on the next page, is based on a Pacific Northwest National Laboratory (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 stationary sectors. An average lighting diffusion curve including the historical penetration rate of CFLs is considered as a sensitivity analysis, further discussed in Appendix B.

Additionally, LEDs are a versatile, promising technology that has the potential to be significantly different from incumbent competitors, and therefore market adoption may occur at a faster rate than prior lighting technologies. To account for the uncertainty in the rate of technological diffusion, this analysis includes a sensitivity analysis in Appendix B that uses a rapid technology diffusion curve in addition to the lighting industry-specific curve.

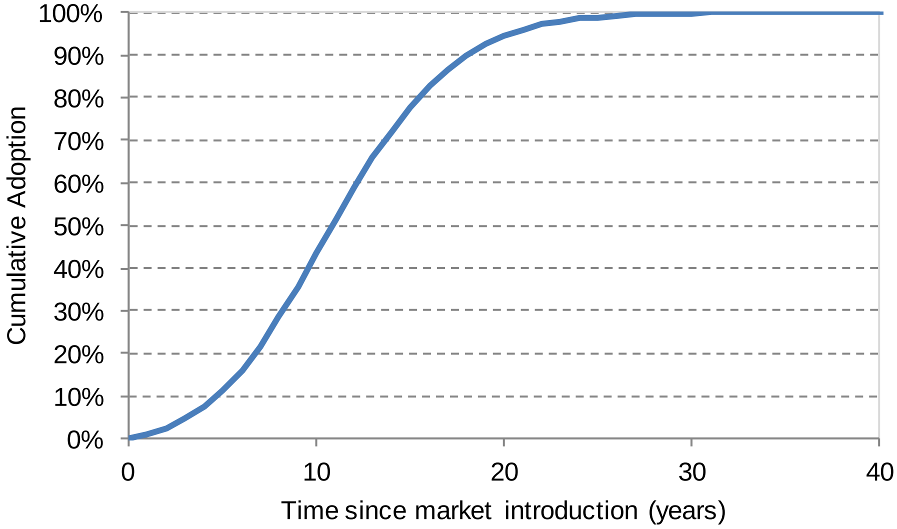

Figure 6.1 Reference Bass Lighting Technology Diffusion Curve

7 Forecast Model Results

The EIA estimates total U.S. site electricity consumption to be over 3,500 terawatt-hours (TWh), or 40 quadrillion Btu (quads) of primary energy in 2010 (EIA, 2011). DOE's forecast analysis estimates that lighting technologies are responsible for 18 percent of this electricity use with approximately 694 terawatt-hours of site electricity and 7.9 quads of primary energy consumption in 2010. In residential and commercial buildings, lighting is the second largest end-use of energy, representing approximately 16 percent of residential and 20 percent of commercial building electricity (D&R, 2011). As seen in Figure 7.1, which presents the lighting energy consumption forecast, the analysis indicates that LED lighting has tremendous potential to reduce energy consumption by nearly 20 percent in 2020 and nearly one half in 2030.

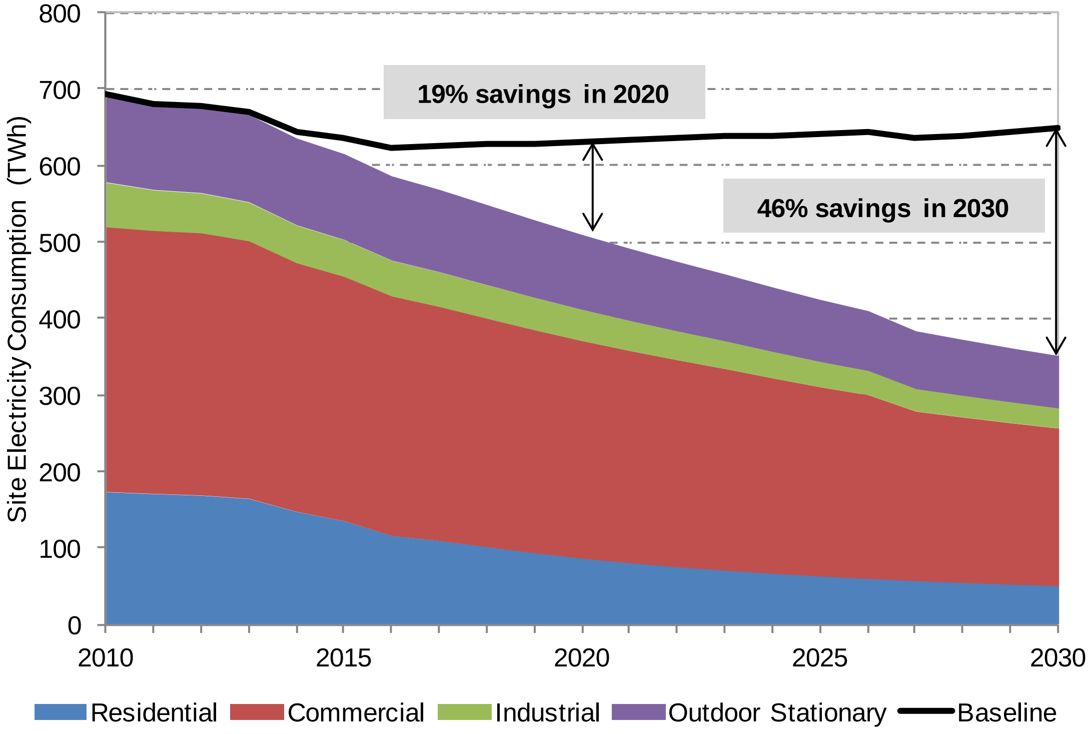

Figure 7.1 Total U.S. Lighting Energy Consumption Forecast, 2010 to 2030

As presented in Table 7.1, the results of this forecast study indicate that LED lighting sales (based on lumen-hours) will increase to 36 percent by 2020. The majority of this increase in market penetration comes from the commercial and outdoor stationary sectors, in which LED sales are forecasted to be approximately 800 and 500 teralumen-hours (Tlm-hr). In the commercial sector, this near-term increase from the 2010 baseline year is largely due to the size of the sector, which contributed 60 percent of lighting service (Tlm-hr) in 2010, and the cognizance of commercial consumers of low operating costs. Similarly, LED luminaires become increasingly cost-competitive in the outdoor stationary sector because of the comparatively high first costs associated with most conventional outdoor lighting options. By 2030, the model predicts that LED lighting will reach a market share of 74 percent, with large growth seen in all sectors and resulting in 46 percent site electricity savings, amounting to 297 terawatt-hours saved from baseline consumption.

Table 7.1 Total U.S. LED Forecast Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	**694**	**635**	**631**	**641**	**648**	**13,535**
Residential	173	142	138	146	153	3,105
Commercial	346	325	321	320	316	6,806
Industrial	58	49	44	41	38	947
Outdoor Stationary	116	119	128	135	141	2,676
LED market share (% of lm-hr)	**-**	**9.5%**	**35.8%**	**59.0%**	**73.7%**	**-**
Residential	-	8.1%	37.6%	60.7%	72.3%	-
Commercial	-	5.0%	27.8%	52.5%	70.4%	-
Industrial	-	8.8%	36.0%	59.2%	72.3%	-
Outdoor Stationary	-	29.0%	64.2%	81.6%	87.2%	-
Site electricity savings (TWh)	**-**	**21**	**122**	**217**	**297**	**2,672**
Residential	-	7	51	82	102	1,009
Commercial	-	6	38	73	111	902
Industrial	-	0	3	8	11	88
Outdoor Stationary	-	7	30	54	73	673
Site electricity savings (%)	**-**	**3.3%**	**19.4%**	**33.9%**	**45.8%**	**19.7%**
Residential	-	5.1%	37.3%	56.7%	66.9%	32.5%
Commercial	-	1.9%	11.7%	22.9%	35.0%	13.3%
Industrial	-	0.8%	7.4%	18.3%	29.4%	9.3%
Outdoor Stationary	-	6.2%	23.7%	40.2%	51.7%	25.2%

Although LED lighting is projected to achieve 74 percent of lumen-hour sales in 2030, as seen in Figure 7.2, its penetration into the installed base of lighting lags at approximately 50 percent of lumen-hours being serviced. In 2010, the installed lighting service in lumen-hours is dominated by linear fluorescent and HID lighting, both of which have high operating hours, high lumen output per lamp, and large number of installed lamps. These products have system lifetimes ranging from 50,000 hours to 75,000 hours, which limits the available market into which LEDs can penetrate.

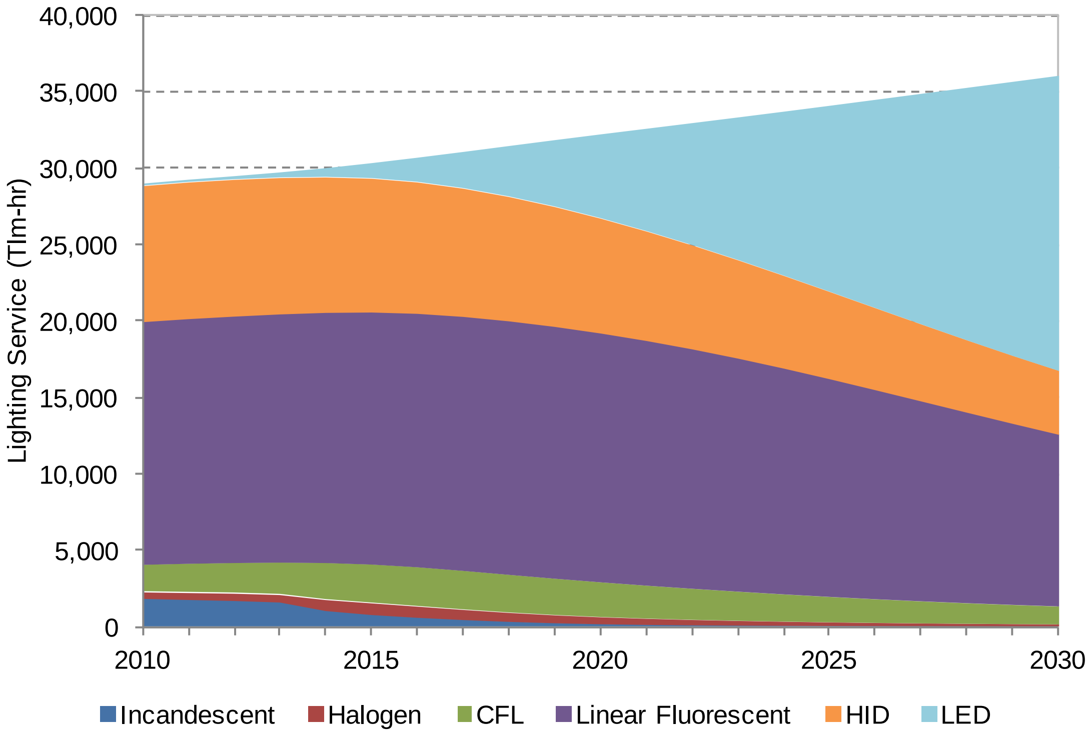

Figure 7.2 Total U.S. Lighting Service Forecast, 2010 to 2030

The following sections describe the major results of the forecast model for each of the lighting sectors: residential, commercial, industrial, and outdoor stationary.

7.1 Residential

Residential lighting is used in single-family, multi-family, and mobile households for a variety of applications, including both ambient and directional lighting. Although residential lighting represents the largest number of installed lamps at approximately 5.8 billion, lamps in this sector are used for relatively few operating hours, averaging less than two hours per day and providing roughly 3,000 teralumen-hours of lighting service annually. Due to low lamp usage and limited lighting education, residential consumers 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 lighting products, as seen in Figure 7.3, the lighting market model predicts significant energy savings in the residential sector, estimating a 37 percent decrease from the baseline energy consumption by 2020 and 67 percent by 2030. Across the entire residential sector, as seen in Figure 7.4, LEDs are expected to represent over 25 percent of the installed base of lumen-hours by 2020 and 62 percent by 2030. The cumulative savings amount to 1,010 terawatt-hours of electricity over the entire analysis period from 2010 to 2030, equivalent to the electricity consumed by more than 81 million households in one year.

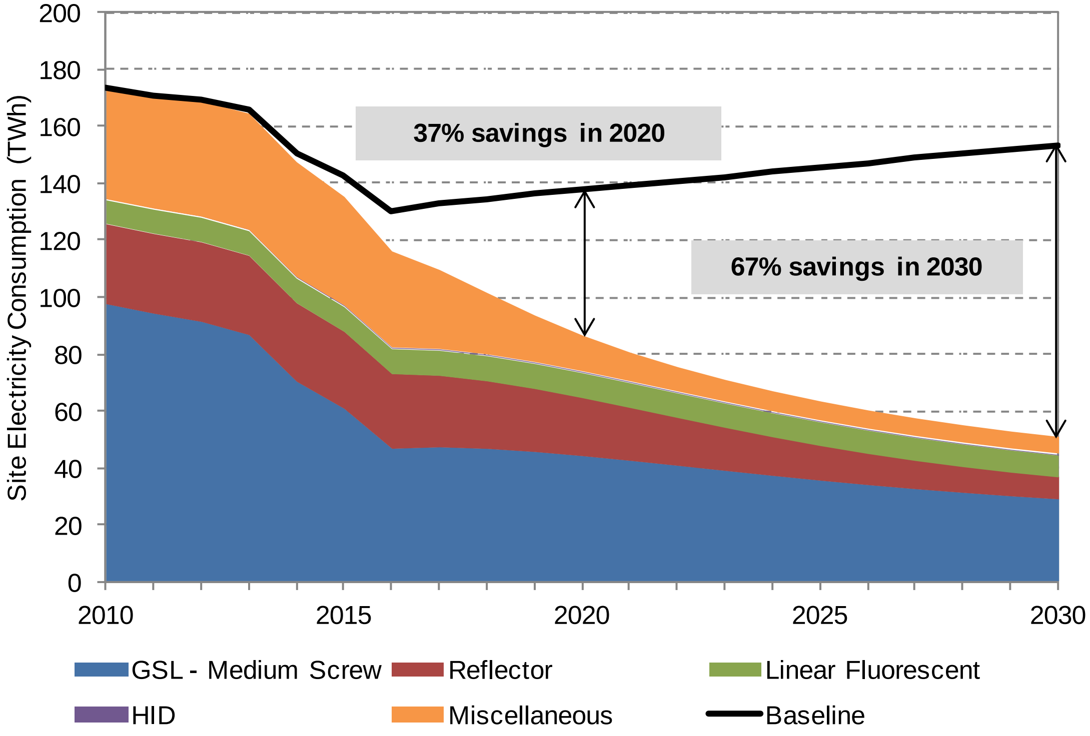

Figure 7.3 Residential Lighting Energy Consumption Forecast, 2010 to 2030

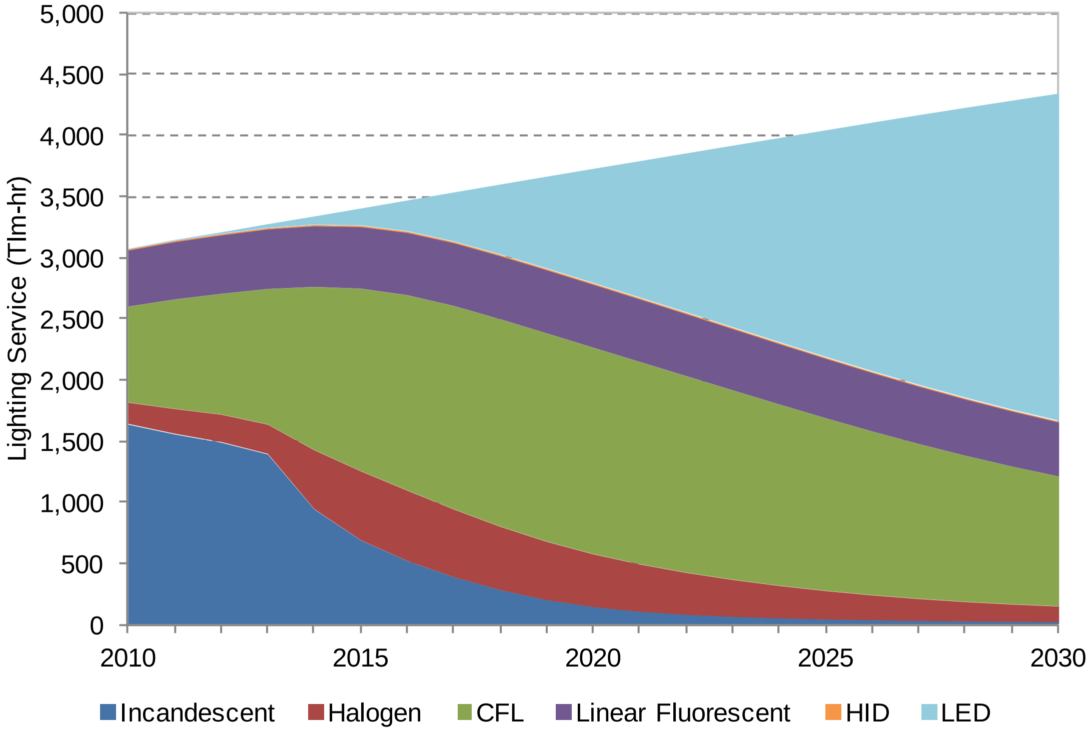

Figure 7.4 Residential Lighting Service Forecast, 2010 to 2030

Figure 7.3 shows that the GSL–MSB lamp submarket consumes the vast majority of residential lighting energy. In 2010, nearly 3.2 billion GSL–MSB lamps were installed in U.S. residences, making this submarket the largest in terms of lamp installations, but due to low operating hours it only provided about 1,800 teralumen-hours of lighting service per annum.

Incandescent and CFL lamps primarily constitute the GSL–MSB lamps used in residential applications. These lamps are extremely versatile and popular for a variety of applications in U.S. residences due to their widely-prevalent medium screw-base socket. They are typically used in ambient lighting applications, in which light is designed to diffuse in all directions, such as in a table lamp, chandelier, or ceiling fan fixture.

Reflector lamps also represent a significant portion of the residential lamps, providing over 360 teralumen-hours of lighting service via nearly 720 million lamp installations in 2010. Unlike GSL–MSB lamps, reflector lamps are used in directional lighting applications in which a more concentrated light beam is desired, such as accent and general area downlighting. The reflector submarket currently consists of mainly incandescent and halogen reflector lamps.

Linear fluorescent fixtures are also used in residential applications, with nearly 440 million lamps installed, providing approximately 390 teralumen-hours of lighting service in 2010. These systems are less versatile than GSL–MSB and reflector lamps in the residential sector because they require a ballast and fixture configuration. T12 lamps and ballasts are the least efficient and most common fluorescent lighting system, with more efficient and more costly T8 and T5 lamp and ballast systems constituting the remainder of the residential installed base.

In 2010, miscellaneous residential lamps represented about 1.4 billion installed lamps and 540 teralumen-hours of lighting service. These lamps are primarily incandescent lamps that utilize candelabra and intermediate screw-base sockets, which are smaller than the more common medium screw base. Incandescent candelabra lamps are most often used for decorative or table lamp applications that require very low levels of lumen output. In the residential sector only, fluorescent T5 lamps that are shorter than four feet in length are included in the miscellaneous submarket. This is because these specialty lamps are commonly used in some space-constrained residential lighting applications, such as under-cabinet lighting, for which T8 and T12 do not generally compete.

Lastly, as seen in Figure 7.3, the HID submarket represents an extremely small portion of installed residential lamps, providing only eight teralumen-hours of lighting service in 2010, with only 1.4 million lamps installed. Because HID lamps are primarily designed for outdoor applications that require high lighting output and low lighting quality, residential HID lamps are limited to garage lighting applications and mainly consist of HPS lamps.

7.1.1 GSL–MSB

GSL–MSB lamps represent the largest submarket within the residential sector. Incandescent lamps still constitute the majority of this submarket due to their low price and wide recognition; however, they have suffered significant loss of market share to CFLs in recent years. When CFLs were initially introduced to the market, there was much resistance from residential consumers because of their high initial cost and performance issues, including slow turn-on time, poor color quality, and problems with dimmability. However, this resistance to adopt CFL technology is beginning to dissipate due to significant price reduction, performance improvements, recognition of energy and cost savings, and the prevalence of utility subsidies. CFLs are now a major market player, with CFLs markedly increasing from approximately 2 percent (by lumen-hours) of the MSB installed base in residences in 2001 to 38 percent in 2010. However, incandescent lighting still dominates the installed base, accounting for 61 percent of all residential GSL–MSB lumen-hours in 2010.

This trend is expected to accelerate with the implementation of EISA 2007 general service incandescent lamp standards. The maximum wattage standards, which began to take effect on January 1, 2012, will effectively require the efficacy of general service incandescent lamps to improve by approximately 25 percent. Halogen incandescent lamps that meet these standards are currently commercially available and are expected to replace traditional incandescent lamps in many applications. The model predicts that a significant portion of residential consumers will switch to halogen incandescent lamps over CFLs due to the relatively higher price of CFLs and the dwindling, yet still present, stigma of CFLs. Absent the presence of LED lamps, halogen lighting would represent approximately one-third of MSB lumen-hour sales in 2020, while CFL would constitute all remaining lumen-hour sales.

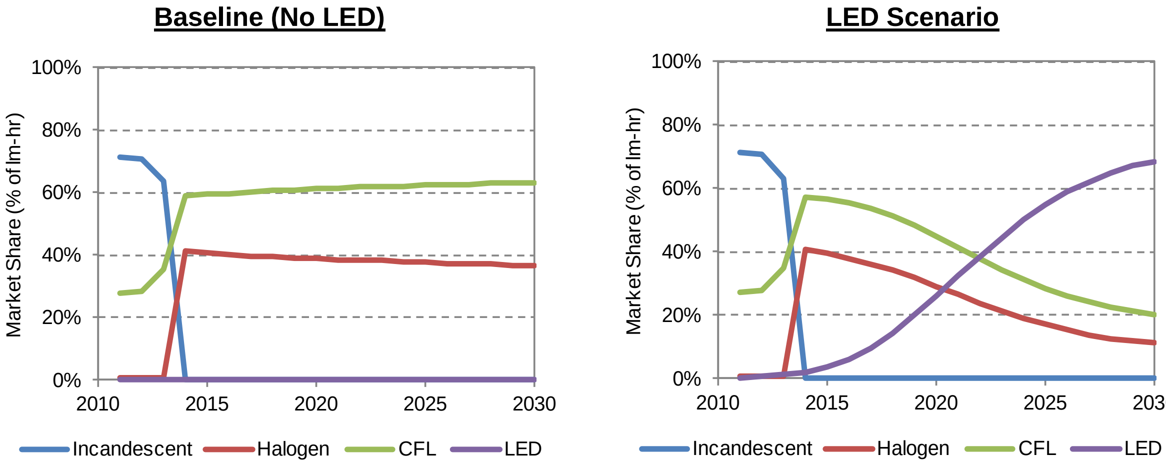

Figure 7.5 Residential GSL–MSB Market Share Forecast, 2010 to 2030

The lighting market model forecasts that LED lamps will begin to rapidly gain market share in the residential GSL–MSB submarket after 2014 as the retail prices approach those of halogen and CFL products, which will cost between $2.50 and $3.30 per kilolumen in the same year. Despite an average efficacy that greatly exceeds the capability of halogen and CFL technology, the forecast model predicts that sales of LED lamps will remain slow until prices fall low enough to compete with other technologies after 2014, but will subsequently ramp up to 26 percent market share by 2020 and 69 percent in 2030. As shown in Table 7.2, the steady transition to LED lighting is expected to save 47 percent of baseline energy consumption by 2030.

Table 7.2 Residential GSL–MSB Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	98	62	50	52	54	1,278
LED market share (% of lm-hr)	-	3.8%	26.0%	54.7%	68.6%	-
Site electricity savings (TWh)	-	1	6	17	26	195
Site electricity savings (%)	-	1.3%	12.6%	32.4%	47.0%	15.3%

7.1.2 Reflector

Like the GSL–MSB submarket, the screw-base reflector submarket currently consists of incandescent, halogen and CFL lighting technologies; however, the market shares of each technology vary greatly. CFL products are less prevalent in this submarket because adopting fluorescent technology for reflector lamp applications presents several barriers. CFL reflector lamps are typically bulky and emit light from a larger area than an incandescent reflector, making it difficult to create an effective directional lighting source. Due to these major issues, CFL reflectors represented 15 percent of installed reflector lamps in the residential sector in 2010, while the remainder is split between incandescent and halogen reflector lamp lumen-hours at approximately 53 percent and 31 percent, respectively. As seen in Figure 7.6 , in the absence of LED reflector lamps, DOE expects that incandescent reflectors, which are exempt from EISA 2007, will maintain a strong market presence, with only minor market share losses to halogen and CFL reflector lamps.

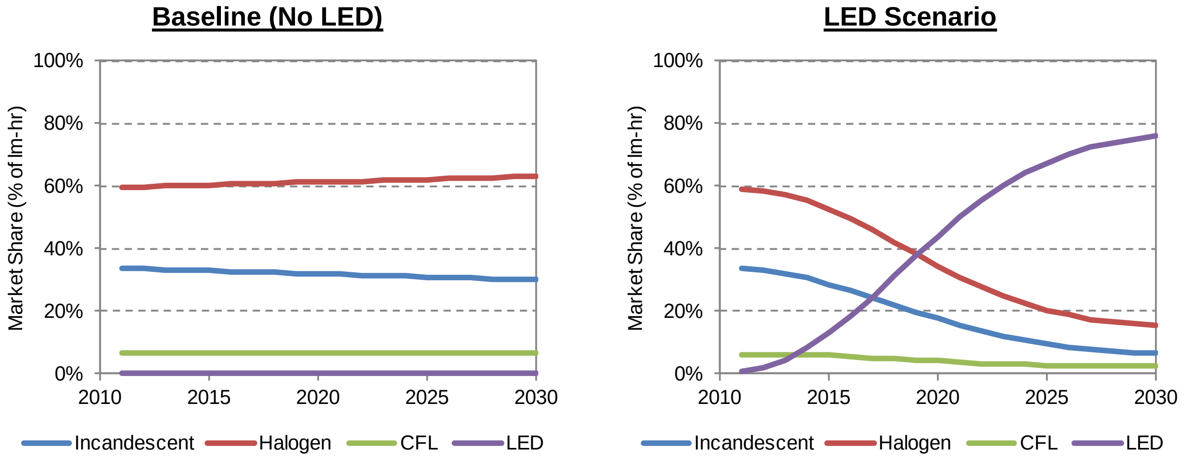

Figure 7.6 Residential Reflector Market Share Forecast, 2010 to 2030

The LED scenario, shown in the right-hand panel of Figure 7.6 , indicates that even though reflector lamps are exempt from the EISA 2007 standards, LED technology will nonetheless have a major impact on the reflector submarket. LED reflector lamps will soar to 76 percent of lumen-hour sales by 2030. The faster penetration in this submarket, as compared to the GSL–MSB submarket, can be attributed to the added complexity of the reflector lamp design, which raises the average retail price, resulting in a smaller price differential with LED lamps. In 2010, incandescent, halogen and CFL reflectors sold for approximately $4.40, $4.70, and $14.00 per kilolumen, respectively. From 2015 to 2020, the price of LED lamps is expected to drop from about $11 per kilolumen to $6 per kilolumen, while average efficacy is forecasted to increase from 129 lumens per watt to 182 lumens per watt.

The high market penetration of LED lamps will result in large energy savings for the reflector submarket. The potential for energy savings from LED lamps will be even further augmented by the prevalence of inefficient incandescent and halogen lamps, which compose the majority of installed lamps in the baseline scenario. As shown in Table 7.3, the lighting market model forecasts a 34 percent reduction of baseline energy consumption by 2020 and 77 percent by 2030.

Table 7.3 Residential Reflector Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	28	29	31	33	34	649
LED market share (% of lm-hr)	-	12.9%	44.0%	67.5%	75.8%	-
Site electricity savings (TWh)	-	2	10	20	26	239
Site electricity savings (%)	-	6.0%	33.1%	62.0%	76.8%	36.8%

7.1.3 Linear Fluorescent

T12 lamp and ballast systems are the least efficient linear fluorescent option considered in this analysis and represent the majority of the linear fluorescent installed base, followed by more efficient T8 and T5 systems. In 2010, T12 lamps formed 84 percent of the residential linear fluorescent installed base (by lumen-hours), followed by T8 at 16 percent and high efficiency T5 lamps 4 feet or longer at zero percent. The model’s baseline scenario predicts that T8 lamp and ballast systems will be the dominant market share holder until around 2023 in the absence of LED luminaires; however, T5 penetration is expected to increase significantly due to price decline and performance gains until it overtakes T8 lamp and ballast systems in market share.

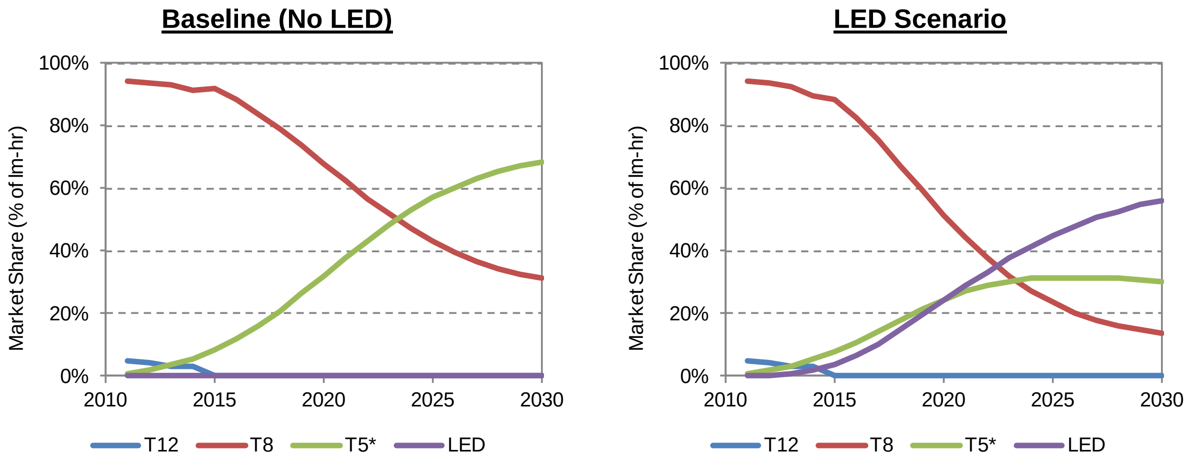

Figure 7.7 Residential Linear Fluorescent Market Share Forecast, 2010 to 2030

Though still successfully capturing over half the market by 2030, LEDs make the slowest market share gains in this residential submarket. By 2020, LED luminaires will be the most economical lighting option for fixture installations in this submarket, with the price falling to $24 per kilolumen and annual costs dropping to about $0.70 per kilolumen. However, despite a clear economic advantage, LED luminaires achieve only 24 percent market share (by lumen-hours) due to the dampening effect of the technology diffusion curve. This 32 percent increase in LED penetration in this residential submarket between 2020 and 2030 will be driven almost entirely by the new construction and fixture retrofit segment of the market. In contrast to the fixture market, penetration into the replacement market is negligible until after 2018 because LED luminaires are not as cost-competitive in the lamp and ballast replacement market. Because linear fluorescent systems are highly efficient, ranging from around 45 lumens per watt for T12 systems and nearly 80 lumens per watt for T5 (including ballast and fixture inefficiencies), the potential energy savings due to the penetration of LEDs is much lower than that of the GSL–MSB and reflector submarkets. Table 7.4 shows that the increasing adoption of LED lighting should achieve 15 percent site electricity savings by 2030.

Table 7.4 Residential Linear Fluorescent Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	8	9	9	9	9	187
LED market share (% of lm-hr)	-	3.8%	24.2%	45.0%	56.1%	-
Site electricity savings (TWh)	-	0	0	1	1	10
Site electricity savings (%)	-	0.3%	3.4%	9.6%	16.2%	5.5%

7.1.4 Miscellaneous and HID

The miscellaneous submarket for the residential sector consists almost entirely of candelabra and other decorative incandescent lamps. Due to the relatively high initial cost and low efficacy of these specialty incandescent lamps, LEDs are expected to penetrate this submarket rapidly. The lighting market model forecasts that LED lamps will exceed 72 percent of the miscellaneous lamp submarket by 2020 and will reach 96 percent by 2030.

LED luminaires also penetrate the HID submarket quite quickly because HID prices are high and LED luminaires become cost-competitive relatively sooner than in other submarkets. Once the first cost and efficacy of LED luminaires reach $60 per kilolumen and 115 lumens per watt in 2013, LED luminaires will begin to penetrate the HID market at 3 percent and are expected to increase to 74 percent by 2030. However, because this submarket is so small in the residential sector, the potential for energy savings is miniscule at 2.2 terawatt-hours cumulatively saved over the entire forecast period.

7.2 Commercial and Industrial

Due to the great similarities between the commercial and industrial sectors in terms of lighting technology and use trends, this section describes the forecast model results for them jointly. Commercial and industrial lighting consumers are typically facility managers who are highly concerned with lifetime costs of a product. Therefore, lighting products 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 dominated by the linear fluorescent and HID submarkets, which offer the most efficient and longest lifetime lighting technologies currently available. Together, the linear fluorescent and HID submarkets represent 83 percent and 99 percent of the installed lumen-hour base of the commercial and industrial markets, respectively.

In these sectors, there has been a distinct trend in favor of more energy-efficient lighting systems. For example, in 2001, T12 systems constituted approximately 72 percent of the commercial sector linear fluorescent installed lamp base and 67 percent of the industrial, whereas in 2010, T12 systems constituted only 33 percent and 28 percent, respectively. Likewise, metal halide lamps have been gaining ground as replacements for higher wattage halogen lamps in applications such as commercial track- and downlighting and industrial high bay fixtures.

The GSL–MSB, reflector, and miscellaneous submarkets represent far smaller segments of the industrial sector, collectively comprising 0.9 percent of the industrial installed base of lamps and roughly 17 percent of the commercial installed base of lamps. In the commercial sector, the majority of these are provided by screw-base incandescent and CFL lamps, which are primarily utilized by smaller commercial spaces and businesses, and pin-base CFLs, which have started to replace U-shaped T12 and T8 lamps in 2-ft by 2-ft troffer applications.

Both the commercial and industrial sectors have long operating hour requirements and together provide the majority of lighting service with 17,400 and 3,000 teralumen-hours, respectively. Because of the significant lighting service required by these sectors, the penetration of LED lighting is central to greatly reducing energy consumption. Efficacy projections indicate that, by 2025, LED lighting products will have reached efficacies exceeding 200 lumens per watt—a performance far superior to the most efficient fluorescent and HID lighting products available today. Because commercial and industrial consumers place a high value on the annual costs of a lighting product, LED lighting holds even greater promise in cutting energy consumption in these two sectors.

Energy savings in the commercial sector are projected to reach 12 percent in 2020 and 35 percent in 2030, relative to the baseline. This energy reduction is the result of a forecasted increase in LED lighting penetration of 28 percent in 2020 to 70 percent in 2030. Although this is a smaller percentage of electricity savings than the residential sector, the commercial sector provides so much lighting service that the total electricity savings are much greater, cumulatively saving more than 900 terawatt-hours of electricity between 2010 and 2030. This is equal to the electricity consumed by over 72 million households for one year.

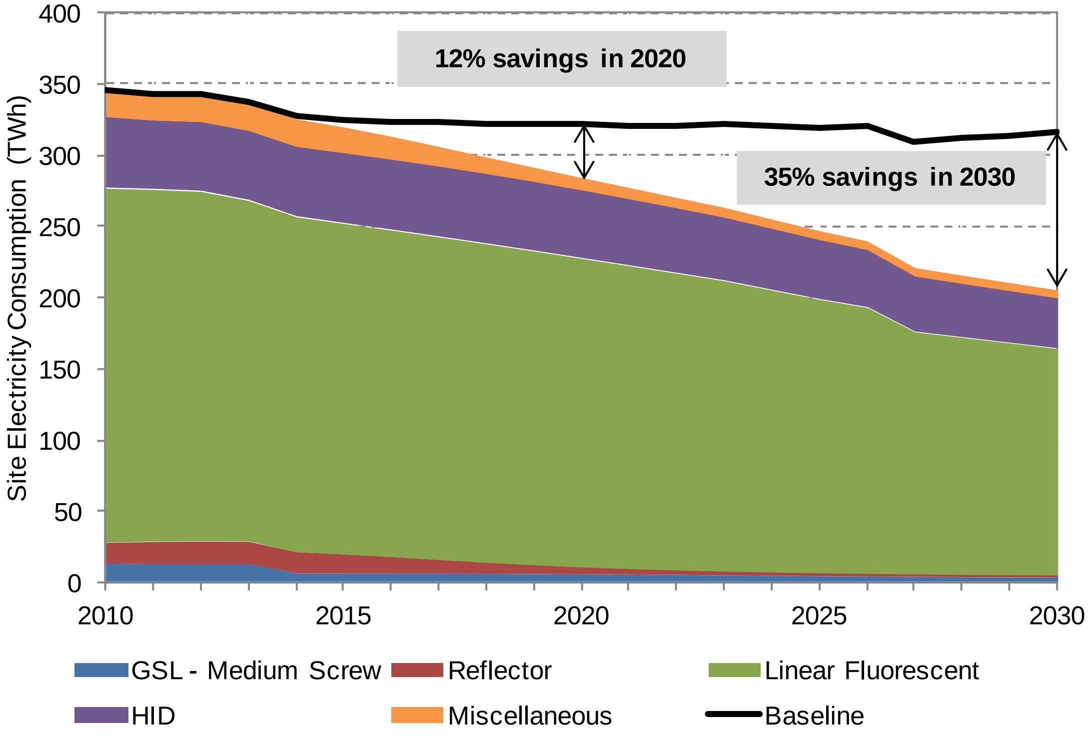

Figure 7.8 Commercial Lighting Energy Consumption Forecast, 2010 to 2030

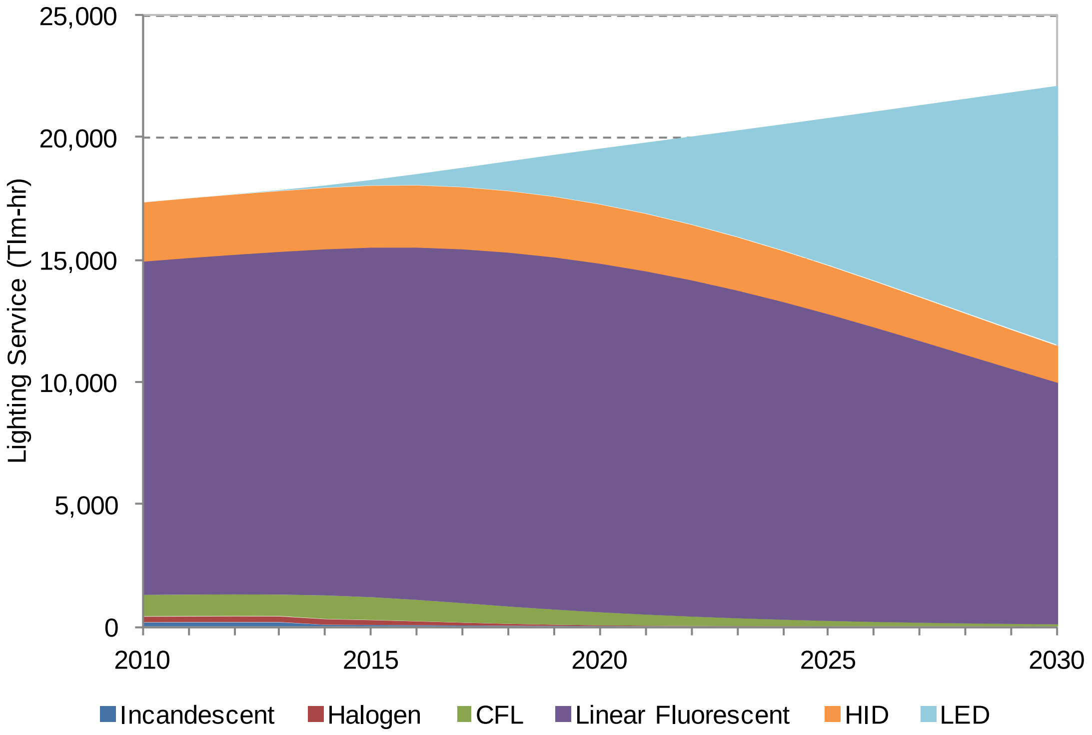

Figure 7.9 Commercial Lighting Service Forecast, 2010 to 2030

LED lighting penetrates the industrial sector slightly more slowly than the commercial sector. The industrial market has traditionally been more sluggish in the transition to more efficient lighting sources (e.g., the transition from T12 to T8). Nevertheless, a 29 percent decrease from the baseline energy consumption is expected by 2030. This energy reduction is the result of a forecasted increase in LED lighting penetration to 36 percent in 2020 and 72 percent in 2030. The penetration of LED lighting into the industrial sector is projected to cumulatively save 88 terawatt-hours of electricity from 2010 to 2030, equal to the amount needed to power 7 million households for one year.

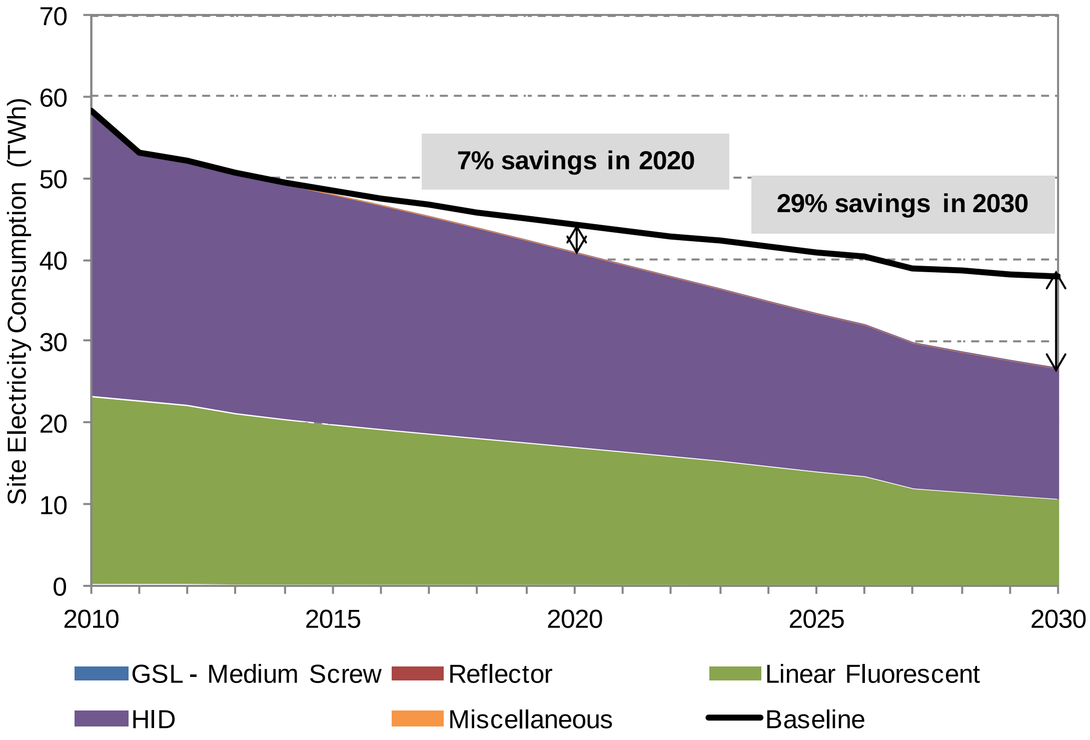

Figure 7.10 Industrial Lighting Energy Consumption Forecast, 2010 to 2030

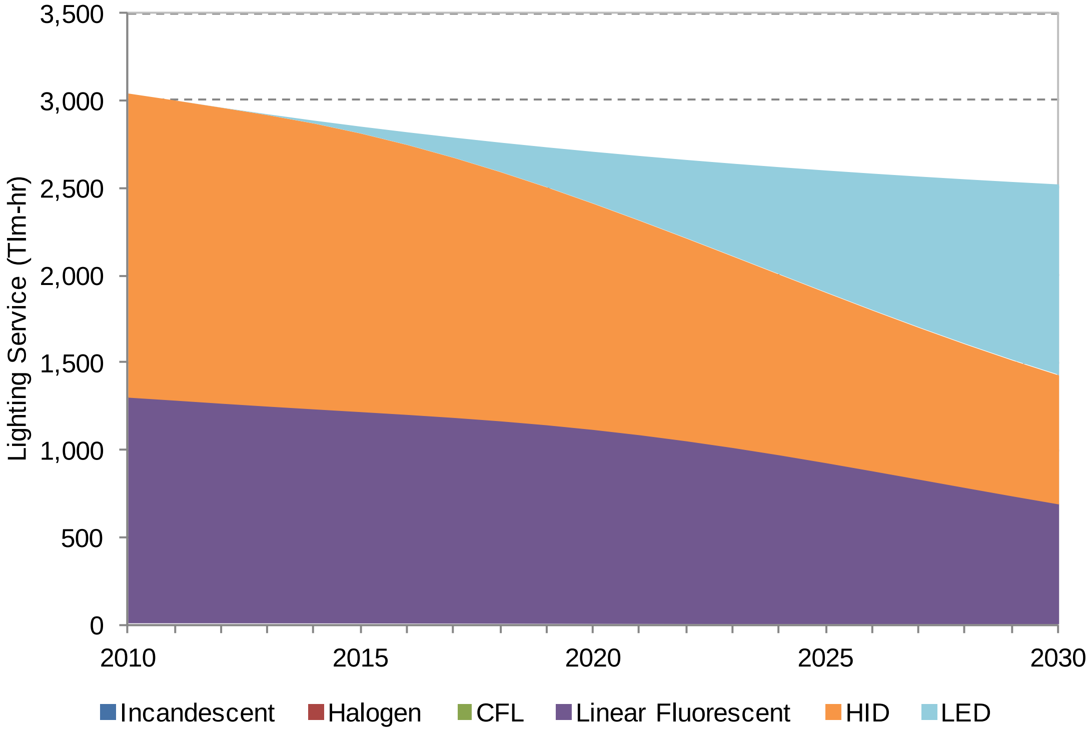

Figure 7.11 Industrial Lighting Service Forecast, 2010 to 2030

7.2.1 Linear Fluorescent

The linear fluorescent submarket of the commercial sector provides more lighting service than any other submarket in any sector, supplying over 13,500 teralumen-hours in 2010, and consequently it also presents the largest potential for energy savings. As previously stated, the commercial sector is more sensitive to a lighting product's annual cost than to its price, and this preference has been historically demonstrated by relatively rapid movements toward more efficient lighting products. For example, prior to the development of the electronically-ballasted T8 lamp system in the 1980s, the linear fluorescent submarket was dominated by magnetically-ballasted T12 lamp systems; in less than 20 years, T8 lamps captured over half of the linear fluorescent submarket (DOE, 2011). More recently, the linear fluorescent submarket has begun to shift toward even more efficient T5 lamp and ballast systems, which in 2011 represented an estimated 28 percent of lumen-hours sold in the commercial linear fluorescent submarket. Absent of LED luminaire penetration, commercial T5 lamp and ballast systems are expected to continue gaining market share, surpassing that of T8 lamp and ballast systems by 2016.

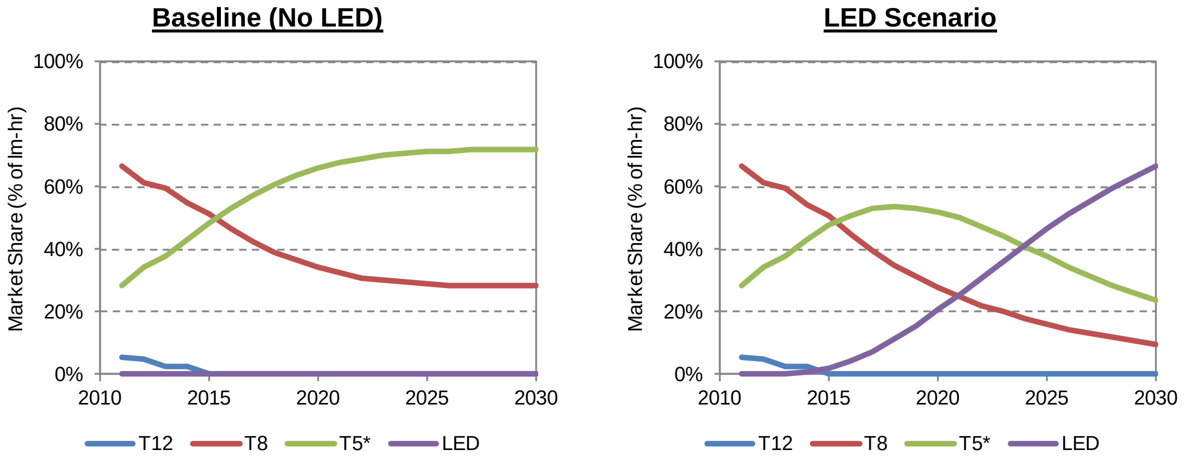

Figure 7.12 Commercial Linear Fluorescent Market Share Forecast, 2010 to 2030

Figure 7.12 shows that the commercial linear fluorescent submarket will be strongly affected by the availability of high-performance LED lighting products. LED luminaires exceed all fluorescent lighting systems in system efficacy and are expected to surpass 200 lumens per watt by 2025. Consequently, the forecast model predicts LED luminaires will contribute 21 percent of commercial linear fluorescent lighting sales by 2020 and will accelerate to 67 percent market share by 2030. The swift takeover by LED luminaires can largely be attributed to a rapid increase in average efficacy to over 200 lumens per watt by 2030—more than double that of currently available fluorescent T5 lamp and ballast systems.

Table 7.5 Commercial Linear Fluorescent Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	249	233	225	220	213	4,761
LED market share (% of lm-hr)	-	1.8%	20.5%	46.3%	66.5%	-
Site electricity savings (TWh)	-	0	8	28	54	334
Site electricity savings (%)	-	0.1%	3.6%	12.7%	25.4%	7.0%

The industrial sector, although significantly smaller, is very similar to the commercial linear fluorescent submarket in technology choice and usage patterns. In 2010, linear fluorescent systems represented 42 percent of the entire lighting service for the industrial sector, emitting nearly 1,300 teralumen-hours, mostly from efficient T8 lamp and ballast systems. The industrial sector, though to a lesser degree than the commercial sector, is also more sensitive to a lighting product's annual cost than to its price. In recent years, T8 lamp and ballast systems have represented the vast majority of lamp installations as they replace less efficient T12 lamp and ballast systems (DOE, 2011). More recently, the linear fluorescent submarket has begun to shift toward even more efficient T5 lamp and ballast systems, which currently represent about 7 percent of installed industrial linear fluorescent lamps, or 15 percent of industrial linear fluorescent lighting service. The baseline forecast indicates that T5 lamp and ballast systems will continue to gain market share from both T12 and T8 systems.

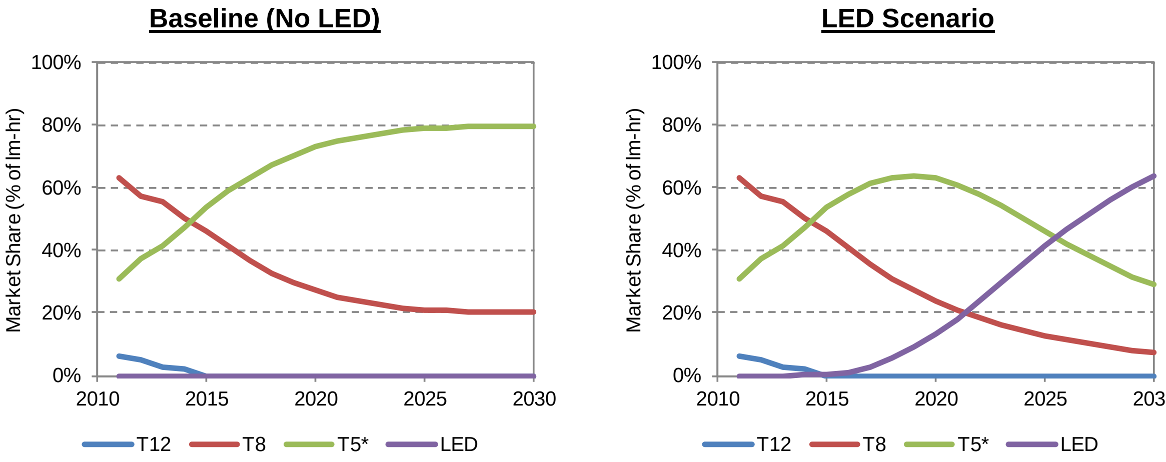

Figure 7.13 Industrial Linear Fluorescent Market Share Forecast, 2010 to 2030

Figure 7.13 indicates that the market penetration of LED luminaires will have a significant impact on the industrial linear fluorescent submarket. The lighting market model estimates that LED luminaires will only represent 0.4 percent of submarket sales in 2015, but will grow quickly to over 13 percent by 2020 and 64 percent by 2030. The penetration of LED luminaires will also result in energy savings, with a forecasted 22 percent reduction from the submarket's baseline consumption by 2030.

Table 7.6 Industrial Linear Fluorescent Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	23	20	17	15	13	369
LED market share (% of lm-hr)	-	0.4%	13.3%	41.2%	63.8%	-
Site electricity savings (TWh)	-	0	0	1	3	17
Site electricity savings (%)	-	0.0%	1.8%	9.2%	21.6%	4.5%

7.2.2 HID

The HID submarket is the second largest in the commercial sector; however, at approximately 2,400 teralumen-hours in 2010, it trails the linear fluorescent submarket by a wide margin. The primary reason for HID’s lack of popularity is the low color rendering index (CRI) of HPS, mercury vapor, and non-ceramic metal halide lamps. Other limitations include long warm-up and re-strike times, ballast noise, lamp size, and limited compatibility with lighting controls. Recent improvements in metal halide technology have incorporated pulse-start systems and ceramic arc tube variants, making these lamps more attractive than incandescent and fluorescent sources in certain applications, including accent, track and downlighting. However, the large size of most metal halide lamps still greatly limits their potential for many commercial lighting applications. The lighting market model estimates that metal halide lamps represented about 84 percent of the lighting service provided by commercial HID sources in 2010, while HPS composed approximately 14 percent and mercury vapor lamps, due to ballast standards, are disappearing from the marketplace and contributed only 1.5 percent of lighting service in this submarket in 2010. Without the penetration of LED luminaires, this submarket would likely remain rather stagnant, with metal halide slowly gaining market share from HPS systems to reach 94 percent of unit sales by 2030.

Figure 7.14 also shows the LED luminaires are forecasted to penetrate the HID submarket earlier and more rapidly than other submarkets. This is because HID lamp and ballast systems are the most expensive lighting submarket on a first-cost ($/klm) basis, allowing LED luminaires to compete earlier than in other submarkets. Even though annual costs are a strong indicator of the success of a particular lighting technology in the commercial sector, LED luminaires are predicted to have a slight advantage in the HID submarket because they are more competitive on a first-cost basis.

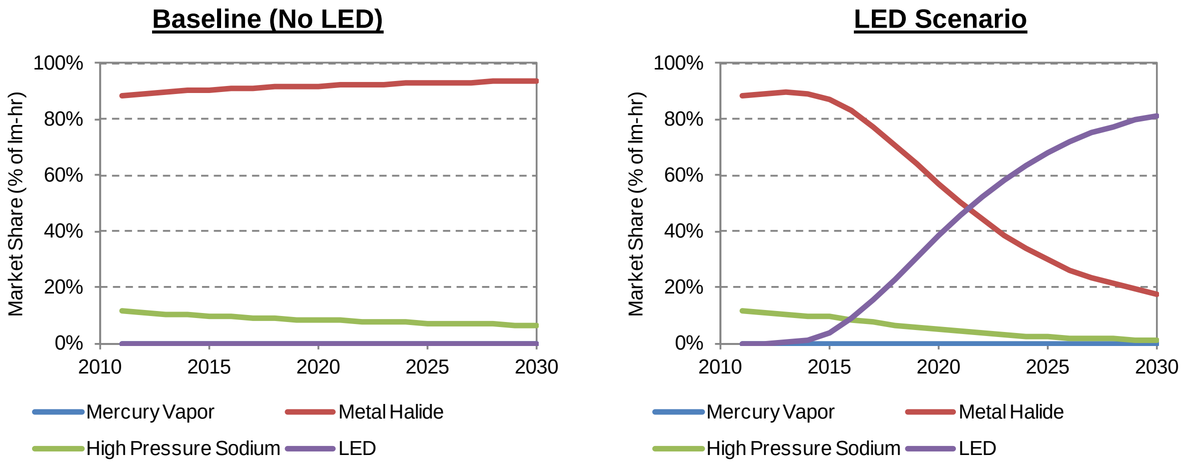

Figure 7.14 Commercial HID Market Share Forecast, 2010 to 2030

Table 7.7 shows that LED luminaires are projected to represent 4 percent of commercial HID lumen-hour sales by 2015, climbing to 38 percent by 2020. This penetration of LED luminaires will result in an 8 percent reduction from baseline energy consumption by 2020 and 36 percent by 2030.

Table 7.7 Commercial HID Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	0	233	51	53	55	1,080
LED market share (% of lm-hr)	-	3.9%	38.2%	68.1%	81.1%	-
Site electricity savings (TWh)	-	0	4	12	20	135
Site electricity savings (%)	-	0.3%	7.6%	21.9%	35.6%	12.5%

In the industrial sector, HID sources supply 57 percent of all lighting service—approximately 1,700 teralumen-hours in 2010. The majority of HID sources are metal halide lamps, followed by HPS and mercury vapor, in descending order. HID lamps are "point sources" and enable the development of luminaires with good optical control, which can more efficiently deliver light to a work area from large mounting heights. HID sources are best operated on long operating cycles of 12 hours per day or more, which is typical for the industrial sector. The market breakdown for industrial HID lamps is slightly different than the commercial sector due to differing application requirements and smaller relative preference for annual costs over first costs. The majority of industrial lighting is used for high bay applications that require high light output, making HPS (estimated to be about 30 percent of lumen-hours in the industrial HID submarket in 2011) a favorable option. However, like the commercial sector, metal halide systems still represent the majority of lighting purchases because they are able to economically provide high efficiencies for a large range of lighting outputs. Metal halide lamp and ballast sales are estimated to account for approximately 70 percent of all industrial HID lighting sales in 2011.

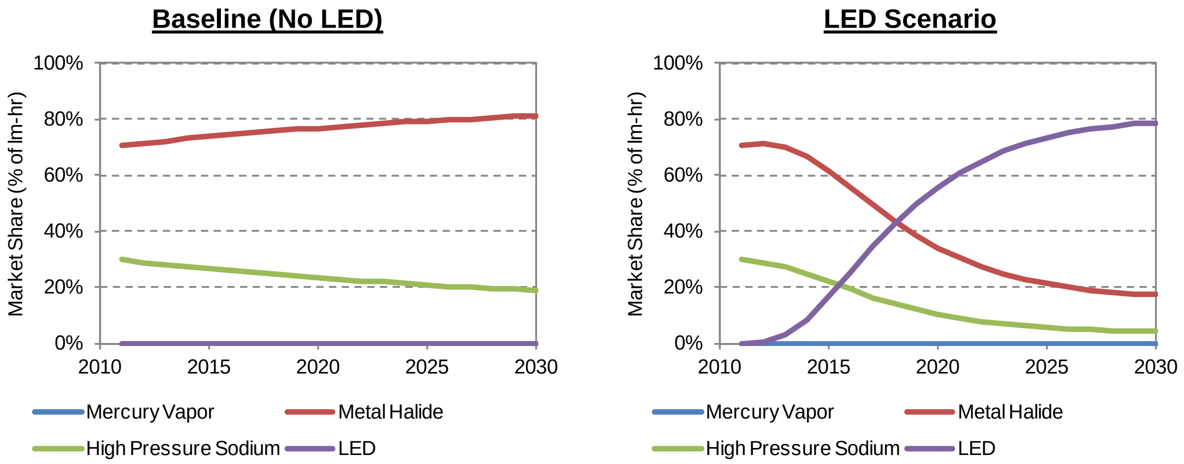

Figure 7.15 Industrial HID Market Share Forecast, 2010 to 2030

As in the commercial sector, the penetration of LED luminaires into the industrial HID submarket is forecasted to accelerate more rapidly than in the linear fluorescent submarket. Table 7.8 indicates that LED luminaires will represent 17 percent of industrial linear fluorescent lighting sales by 2015 and will climb to 79 percent by 2030.

Table 7.8 Industrial HID Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	35	20	27	25	24	574
LED market share (% of lm-hr)	-	16.7%	55.7%	73.5%	78.6%	-
Site electricity savings (TWh)	-	0	3	6	8	71
Site electricity savings (%)	-	1.4%	10.9%	23.6%	33.6%	12.3%

7.2.3 GSL–MSB, Reflector, and Miscellaneous

The GSL–MSB, reflector, and miscellaneous submarkets represent far smaller segments of the industrial and commercial sectors than linear fluorescent and HID. In the industrial sector this portion is negligible, providing less than one percent of the total lighting service in 2010. However, in the commercial sector these three submarkets provided approximately 1,400 teralumen-hours, or over 8 percent, of the entire commercial lighting service. The majority of this commercial lighting service is provided by medium screw-base incandescent and CFL lamps, pin-base CFLs, and pin-base halogen reflectors.

CFLs have significantly penetrated the commercial GSL–MSB submarket and in 2011 represented an estimated 42 percent of lumen-hour sales, with the remainder being incandescent lamps. Commercial GSL–MSB lamps are primarily found in small commercial spaces where lighting decisions are not made by professional facility managers. These small businesses generally make purchase decisions based on criteria similar to those of a residential consumer; however, historical trends indicate they are slightly more conscious of annual lighting costs.

Lamp purchases in this submarket will be significantly affected by EISA 2007 standards, and it is predicted that CFLs will dominate GSL–MSB lamp sales by 2014, representing about 94 percent of the submarket lumen-hour sales, with halogen lamps and LED lamps trailing at 5 percent and 2 percent, respectively. LEDs are forecasted to reach 70 percent market share in the commercial GSL–MSB submarket by 2030.

The commercial miscellaneous submarket mainly comprises pin-base CFL lamps, of which there are about 136 million currently installed. These lamps are similar in efficacy to medium screw-base CFLs and are becoming popular replacements for 2-ft by 2-ft troffer fixtures due to their lower cost than U-shaped alternatives. In the commercial miscellaneous submarket, LEDs are expected to achieve a market penetration of 18 percent in 2015 and 99 percent in 2030.

7.3 Outdoor Stationary

The outdoor stationary sector primarily consists of roadway, parking, traffic signal, and exterior building lighting. These lamps serve multiple purposes, including providing proper illumination for pedestrian and automotive traffic, creating a sense of personal security, and attracting attention to business and spaces. As in the commercial and industrial sectors, lighting efficiency and lifetime are of particular interest in the outdoor sector; therefore, the facility managers who purchase the majority of outdoor systems prioritize low annual costs. In particular, long lifetime is a high priority due to the potentially high maintenance costs associated with outdoor lighting. Pacific Gas and Electric Company (PG&E) estimates that maintenance costs range from 15 to 25 percent of the annual costs for traditional technologies (Cook, Sommer, & Pang, 2008). HID lamps have historically been the lighting technologies of choice due to their ability to affordably satisfy the high lumen output requirements of outdoor lighting; HID sources represented more than half of the installed lamp base and provided 86 percent of the lighting service in the outdoor stationary sector in 2010.

The most common HID lighting technologies in the outdoor sector are metal halide and HPS lamp and ballast systems. Historically, HPS has dominated the outdoor HID submarket, having replaced most mercury vapor installations and leaving only a small percentage of outdoor installations with this far less-efficient technology. More recently, metal halide lamp and ballast systems have become a major contender due to their superior color rendering and controllability. The miscellaneous submarket represents nearly half of the installed lamp base; however, it provided merely 14 percent of the total outdoor lighting service in 2010. Many of the lighting technologies in this submarket are of unspecified lamp type, limited by the resolution of data provided by the 2010 LMC, and were therefore included in the miscellaneous submarket. For example, much of the lighting in the outdoor stationary sector is produced by linear fluorescent lamp and ballast systems in applications such as parking garages. However, insufficient data is available to determine the technology mix between T12, T8, and T5 lamp and ballast systems.

The outdoor sector has long operating hour requirements and provides the second most lighting service after the commercial sector at 5,500 teralumen-hours in 2010. LED lighting has tremendous potential for the outdoor sector. Of all sectors, LEDs are expected to penetrate this sector the quickest because it is dominated by HID lamp and ballast systems, which have high initial costs; this means that LED luminaires will become cost-competitive sooner. By 2030, LED luminaires are projected to represent 87 percent of outdoor lighting sales, which correlates to a 46 percent reduction from the baseline energy consumption. Over the course of the analysis period, the market penetration of LED lighting could save 670 terawatt-hours of electricity, equal to the power consumed by nearly 54 million households in one year.

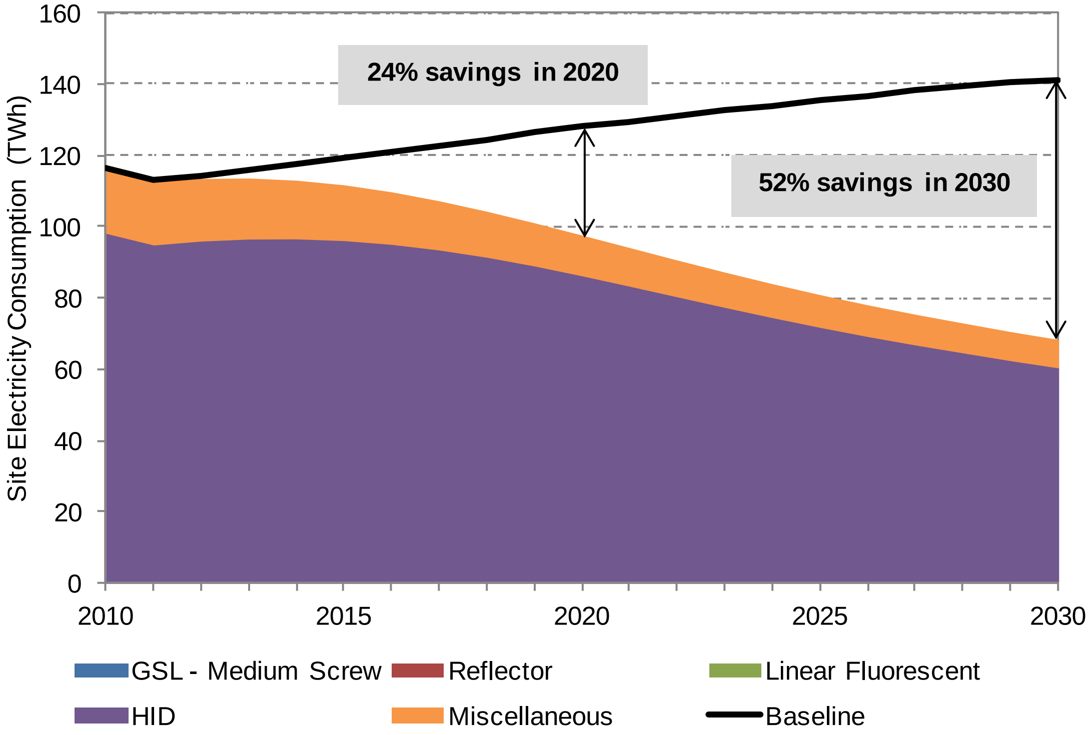

Figure 7.16 Outdoor Stationary Lighting Energy Consumption Forecast, 2010 to 2030

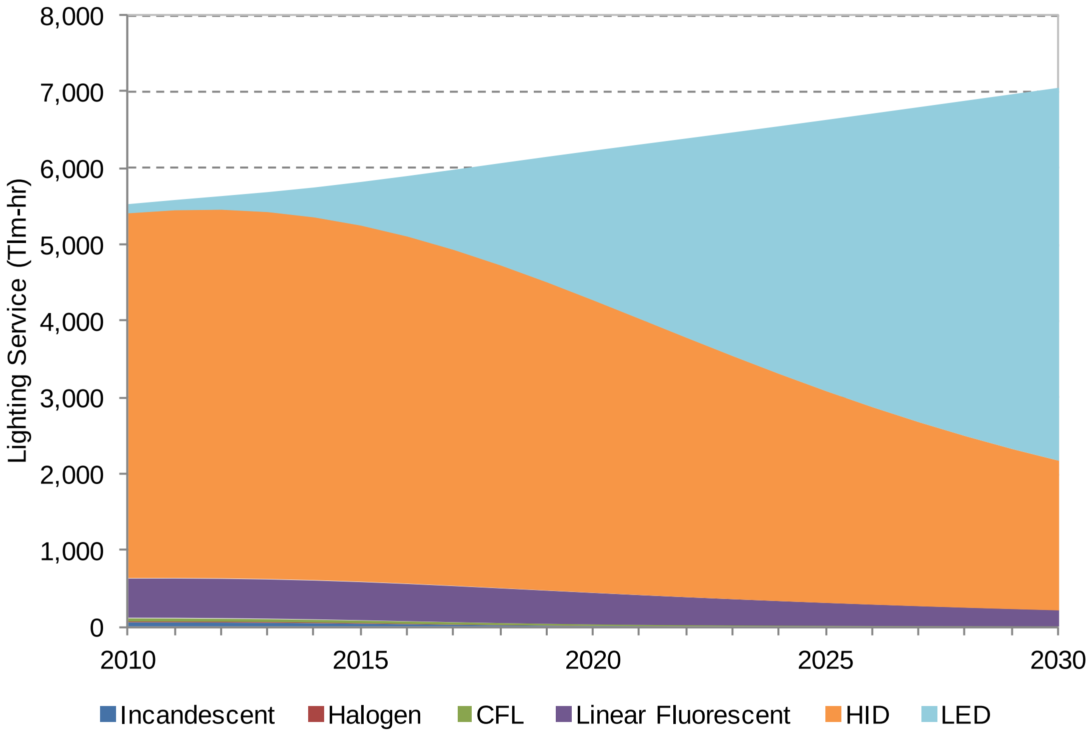

Figure 7.17 Outdoor Stationary Lighting Service Forecast, 2010 to 2030

7.3.1 HID

As shown in Figure 7.16 and Figure 7.17, the HID submarket, which provided 86 percent of the total outdoor lighting service at 4,800 teralumen-hours in 2010, is by far the largest energy consumer of all the outdoor lighting submarkets. As previously stated, HPS lamp and ballast systems have historically dominated the outdoor stationary HID submarket, having largely displaced older and inefficient mercury vapor lighting technology. However, more recently metal halide has begun to penetrate the outdoor lighting market. Metal halide sources are somewhat less efficacious than HPS, but offer white light and superior color rendition, in contrast with the yellowish light that distinguishes HPS. Metal halide and HPS are considered competitors in some applications; however, outdoor consumers will typically choose metal halide for any application in which color rendering or appearance is important. Figure 7.18 shows that metal halide lamp and ballast systems will achieve market share parity with HPS in 2020, with HPS currently representing an estimated 57 percent of lumen-hour sales in the outdoor stationary HID submarket, while metal halide systems and LED luminaires are 42 percent and 1.5 percent, respectively. In the baseline scenario, metal halide lamp systems are predicted to continue gaining market share, reaching 57 percent of the HID submarket by 2030.

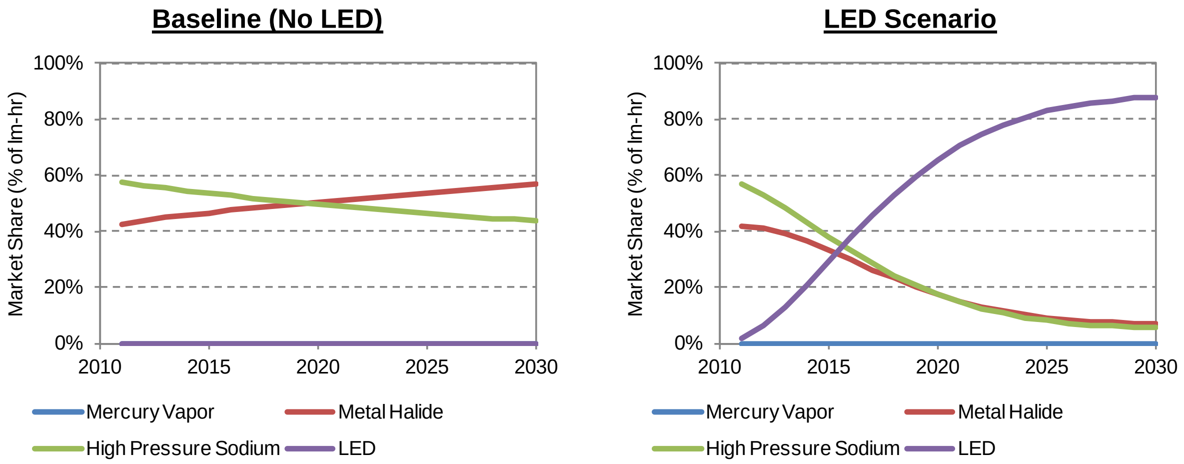

Figure 7.18 Outdoor Stationary HID Market Share Forecast, 2010 to 2030

Figure 7.18 presents the predicted lighting technology market shares for the outdoor HID submarket in the baseline and LED scenarios. LED luminaires are expected to have a significant impact on the outdoor HID submarket as they become the most economical lighting option due to the high initial cost of incumbent HID lighting systems. The lighting market model estimates that LED luminaires represented 1.5 percent of outdoor HID lighting sales in 2011 and forecasts an accelerated ascent to 65 percent by 2020. As shown in Table 7.9, LED luminaires are expected to virtually monopolize the outdoor stationary HID submarket by 2030 at 88 percent market share, resulting in a 50 percent decrease from baseline energy consumption.

Table 7.9 Outdoor Stationary HID Energy Savings Results

	2010	2015	2020	2025	2030	Cumulative (2010-2030)
Baseline site electricity consumption (TWh)	98	101	109	115	121	2,274
LED market share (% of lm-hr)	-	29.3%	65.3%	82.7%	87.8%	-
Site electricity savings (TWh)	-	5	23	44	60	532
Site electricity savings (%)	-	4.8%	20.8%	37.9%	50.0%	23.4%

7.3.2 Miscellaneous, GSL–MSB, Reflector, and Linear Fluorescent

Interestingly, the miscellaneous submarket represents almost half of the installed outdoor stationary lamp base; however, it currently provides only 14 percent of the total outdoor lighting service. This is mainly because lamp systems in this submarket typically have lower light output and fewer hours of operation—approximately 9 to 14 hours per day versus HID systems, which operate upwards of 11 hours per day. LEDs are expected to penetrate this submarket rapidly, achieving market dominance by 2030, at 83 percent of lumen-hour sales in the submarket.

GSL–MSB, reflector, and linear fluorescent lighting systems are also commonly used in outdoor stationary applications. However, these installations are generally associated with small office spaces and commercial structures. For example, incandescent and CFL MSB lamps are frequently used for outdoor retail and restaurant spaces, while linear fluorescent systems are a common lighting choice in parking garage structures. This analysis includes such lighting systems as part of the sector with which they are associated. Therefore, there are no GSL–MSB, reflector, or linear fluorescent lamps in the outdoor stationary sector in this report. In addition, the 2010 LMC, from which the base year installed lamp inventories come, does not differentiate the lighting technologies into distinct lamp types for this sector (e.g., incandescent lamps are not disaggregated by application or base type). To include these unknown lamps in the analysis, they were assigned to the miscellaneous submarket.

7.4 Forecast Model Comparison

The results of this forecast model are generally consistent with those of other studies. While these projections diverge significantly from industry and market reports in some specific instances, all analyses conclude that LED lighting has tremendous market penetration and energy savings potential. All studies agree that the LED general illumination market is still in its infancy, with all assessments of the current market estimating penetration at less than 10 percent of the general lighting market. The results of this forecast study indicate that LED lighting lumen-hour sales were negligible in 2010; this is consistent with the Morgan Stanley (2011), McKinsey (2011), and Sterne Agee (2010) analyses, which all estimate that LEDs accounted for less than one percent of unit sales in the same year. However, in value of shipments, IMS Research states that it was closer to 10 percent (Smallwood, 2011). Cree provides slightly lower results than IMS Research, with LED market share at less than five percent by value for 2010 (2010), while Philips mentioned in its second quarter report for 2011 that the company's LED lamp and luminaire sales for the previous twelve months comprised slightly more than eight percent of the value of overall lighting sales (2011).

Table 7.10 Comparison of LED Forecast Model Results

Study	Units	Region	Market Share			
			2010	2011	2015	2020
DOE, 2011	Lumen-hours	U.S.	-	0.6%	10%	36%
Morgan Stanley, 2011	Lumen-hours	World	1%	-	15%	-
McKinsey, 2011	Units	World	1%	-	19%	46%
Stern Agee, 2010	Units	World	0.45%	-	13%	-
IMS Research, 2011	USD	World	10%	-	46%	50%
Cree, 2010	USD	World	5%	-	33%	75%
Philips, 2010	EUR	World	-	8%	50%	-

In addition to discussions about the potential growth of this market, some reports included estimates of rapid decreases in LED prices in the coming years. The MYPP projections utilized by DOE's lighting market model indicate that the price of LED lighting will decrease by 20 to 50 percent per year until 2015, which is consistent with predictions provided by Sterne Agee and McKinsey. Sterne Agee and Morgan Stanley both noted that these price decreases will lead to shorter payback periods, which will drive the widespread adoption of LEDs. For a 20 percent adoption rate by units and lumen-hours, respectively, these two firms estimated that the payback period would need to be between one and four years depending on application, with the longer payback periods corresponding to commercial and industrial applications due to their longer operating hours per year.

Looking forward, DOE's model indicates that by 2015, LED lighting will reach 10 percent of lumen-hour sales with the majority coming from commercial, industrial, and outdoor installations. Morgan Stanley, McKinsey, and Sterne Agee predict that LED lighting will obtain market shares of 15 percent by lumen-hours, 13 percent by units, and 19 percent by units by 2015, respectively. Other studies predict larger growth, with Cree reporting that the industry consensus on LED lighting market value is approximately $50 billion with a 33 percent share by value of the overall lighting market by 2015. By value, Philips foresees a 50 percent market share, and IMS Research expects LED lighting to have a 46 percent market share by 2015.

By 2020, this analysis predicts that LED lighting products will contribute 36 percent of lumen-hours sold, with large growth seen in all sectors. It is then predicted that the rapid growth of the LED lighting market will slow because the long life of LED lighting will reduce the need for replacements, thereby limiting new opportunities for growth. Therefore, it is estimated that LEDs will comprise 74 percent of the overall lighting market by 2030. Predictions beyond the 2015 timeline seem to vary greatly, with Cree indicating that the LED market will have a market value of $120 billion in 2020, nearly 80 percent of the overall lighting market, while McKinsey conservatively predicts that LED lights will reach 46 percent of lumen-hour sales. In addition, IMS Research foresees a near freeze in growth by 2018 and a subsequent market contraction. However, due to the large uncertainty in the lighting market and varying assumptions made within each of these analyses, it is difficult to say with certainty how successfully LEDs will penetrate the general illumination market in the long term. To account for this high degree of uncertainty, Appendix B describes the results of the sensitivity analyses for the lighting market forecast model.

8 Conclusions

Over the last few decades, advances in lighting technologies, such as the development of T8 and T5 fluorescent tubes, electronic ballasts, and pulse-start metal halide HID lamps, have yielded considerable energy savings in the lighting market. Regulatory actions by Congress and the U.S. DOE have cemented those improvements into the U.S. lighting market by establishing minimum standards which effectively remove inefficient lighting products from the market. Over the coming decades, LED white-light sources promise to offer even greater energy savings if they achieve projected price and performance attributes. As LED technology advances, it will become better suited to a broader array of applications, the light quality will improve, efficacies will increase, and prices will fall. The national energy savings that will result by 2030 will depend on how quickly and to what extent these developments occur.

Assuming the performance of LED lighting products will be capable of satisfying general lighting requirements of the market by 2030, their market penetration and energy savings potential will be driven primarily by economics, taking into account the initial price, operating cost, maintenance costs, and lifetime. In the modeled LED scenario, LED products displace light sources in all sectors by the end of the analysis period, but the most significant energy savings primarily occur in applications where annual economics drive lighting decision-making or where inefficacious technologies remain dominant due to their ability to satisfy unique size, shape, or color temperature constraints (which LED lighting is expected to meet). Specifically, LEDs are expected to be particularly successful in penetrating the following submarkets:

- <u>Screw-base reflectors in the commercial and industrial sectors.</u> Competitors for these sockets are largely inefficient incandescent and halogen products, which are popular in applications such as the production and display of fashion goods, where color rendering is important and operating hours are long. LEDs, able to mimic high light quality of these incumbent products at much lower operating cost, will pose a serious threat to incumbent technologies in such applications.
- <u>HID lamps in the outdoor stationary sector.</u> Due to remote or inaccessible installation and exposure to weather conditions, maintenance and replacement labor rates are high in this sector. Therefore, there is strong economic incentive to reduce the frequency of maintenance and replacement. Already penetrating this market, LEDs have even further market potential as their long life continues to increase, bringing down annual costs to approximately half of HPS annual costs by 2030.

In addition, the lighting market model predicts high penetration of LED lamps in the miscellaneous residential market, namely decorative incandescent lamps. These lamps are manufactured in relatively low volumes, and therefore higher production costs are transferred to the consumer. This, in combination with their low efficacy, results in a high market penetration prediction for LED lamps. However, it is important to note that there is considerable uncertainty surrounding the future costs and performance of LED products for decorative applications, as the form factor of lamps in these applications is often even further constrained than lamps for general service applications. As mentioned in Chapter 5, the model assumes a single efficacy and cost for all LED lamps. Whether the LED lamps in these applications meet those cost and performance assumptions will greatly affect the penetration of LEDs.

However, energy savings potential only occur where successful market penetration and sufficient size of market intersect. Of these high market share potential applications just described, residential miscellaneous lamps and outdoor stationary HID lamps also hold promise for high energy savings potential due to the sizeable demand for light in these applications, as depicted in Figure 8.1. In addition, one area of tremendous energy savings potential stands out: the commercial linear fluorescent submarket. This submarket is by far the largest in the lighting industry, composing almost half (46.8 percent) of the total lumen-hour consumption in the U.S. in 2010. Despite comparatively moderate LED market penetration (66.5 percent market share in 2030), the magnitude of demand for light in these applications yields very high energy savings potential—54 terawatt-hours in 2030.

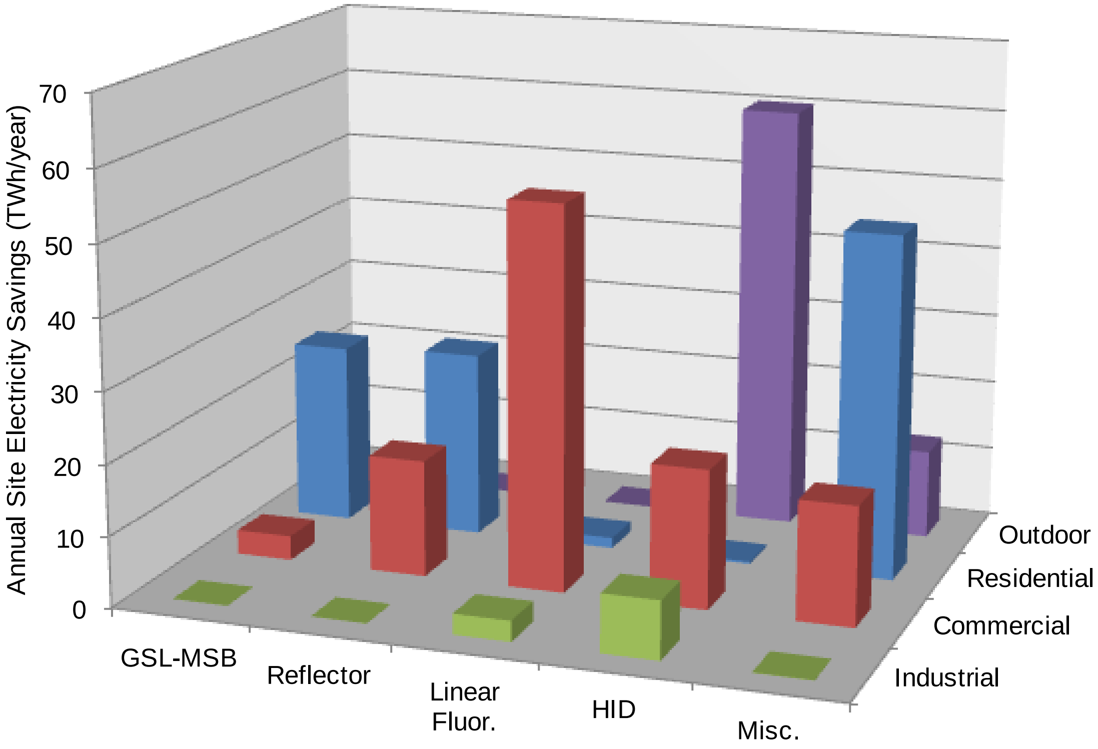

Figure 8.1 Annual Energy Savings Breakdown in 2030

Table 8.1 Annual Electricity Savings Breakdown in 2030

Submarket	Electricity Savings (TWh)				
	Residential	Commercial	Industrial	Outdoor	Total
GSL-MSB	26	3	0	0	**29**
Reflector	26	17	0	0	**43**
Linear Fluorescent	1	54	3	0	**58**
HID	0	20	8	60	**88**
Miscellaneous	49	17	0	13	**78**
Total	**102**	**111**	**11**	**73**	**297**

In summary, the commercial and residential sectors have the largest energy savings potential, as shown in Figure 8.1. These sectors contribute 37 and 34 percent, respectively, to the annual 2030 energy savings, while the outdoor stationary sector contributes 25 percent and the industrial sector contributes 4 percent. In the commercial sector, the reason for this development is that the vast majority of lumen-hours in the installed stock of lamps is in the commercial sector; thus, any penetration into that sector will yield large savings. The residential sector has high energy savings potential because its installed lighting stock is dominated by incandescent lamps, which are very inefficacious and provide ample room for improvement. The outdoor stationary and industrial sectors have relatively low energy savings potential because their higher average efficacies will make it more difficult for LED sources to penetrate. For example, the outdoor stationary sector already has energy-efficient sources such as HPS, so even though this sector has the highest efficacy values, its proportion of energy savings in 2030 is just 25 percent. Thus, the energy savings from the penetration of a more efficacious source (i.e., LED lamps and luminaires) has the greatest impact from an energy savings perspective where inefficient sources enjoy widespread popularity.

In order for the energy savings forecast to be realized, LED lighting products will need to achieve substantial improvements in price, efficacy, and operating life. If these improvements are met, the economics will drive increasing LED market share through the end of the analysis period and beyond. Thus, improvements in the price and performance of LED devices are critical research objectives. These improvements are an important consideration for industry researchers interested in developing products that are considered cost-effective in the market and tapping into the huge potential energy savings presented in white-light applications. Similarly, efficacy improvements are critical in order to save energy, rather than increase energy consumption through the promulgation of less efficient light sources. Careful investment and management of R&D could realize significant national benefits through the development and deployment of efficacious, inexpensive LED general illumination devices.

Appendix A LED Price and Performance Improvement Targets

The price and performance projections used as inputs to this analysis are derived from targets identified in DOE’s 2011 SSL R&D MYPP and 2011 SSL R&D Manufacturing Roadmap. The MYPP establishes projections for the improvement of best in class products through 2020, which this analysis then extrapolates to 2030. Because the inputs to this analysis represent average lighting products on the market, LED performance projections are lagged by one year for luminaires, and LED price and performance projections are lagged by two years for lamps.

Table A.1 LED Price and Performance Projections

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lamp																					
Efficacy (lm/W)	36.9	48.3	61.7	77.6	94.8	112.5	129.3	145.0	159.1	171.5	182.2	187.9	192.2	195.3	197.7	199.4	200.6	201.5	202.1	202.5	202.9
Cost ($/klm)	$55.2	$31.0	$21.5	$16.5	$13.4	$11.3	$9.7	$8.5	$7.6	$6.9	$6.3	$5.8	$5.3	$5.0	$4.6	$4.4	$4.1	$3.9	$3.7	$3.5	$3.3
Life (1,000 hr)	25.0	33.0	36.6	39.6	42.1	44.1	45.7	46.8	47.7	48.3	48.8	49.1	49.4	49.6	49.7	49.8	49.8	49.9	49.9	49.9	50.0
Luminaire																					
Efficacy (lm/W)	69.9	84.6	99.8	115.8	131.2	145.5	157.8	168.6	178.0	186.2	193.4	196.1	198.2	199.7	200.8	201.6	202.1	202.6	202.9	203.1	203.3
Cost ($/klm)	$180.9	$108.5	$77.5	$60.3	$49.4	$41.8	$36.3	$32.0	$28.6	$25.9	$23.7	$21.8	$20.2	$18.8	$17.6	$16.5	$15.6	$14.8	$14.0	$13.3	$12.7
Life (1,000 hr)	25.0	33.0	36.6	39.6	42.1	44.1	45.7	46.8	47.7	48.3	48.8	49.1	49.4	49.6	49.7	49.8	49.8	49.9	49.9	49.9	50.0
Luminaire (Outdoor)																					
Efficacy (lm/W)	69.9	84.6	99.8	115.8	131.2	145.5	157.8	168.6	178.0	186.2	193.4	196.1	198.2	199.7	200.8	201.6	202.1	202.6	202.9	203.1	203.3
Cost ($/klm)	$180.9	$108.5	$77.5	$60.3	$49.4	$41.8	$36.3	$32.0	$28.6	$25.9	$23.7	$21.8	$20.2	$18.8	$17.6	$16.5	$15.6	$14.8	$14.0	$13.3	$12.7
Life (1,000 hr)	50.0	54.1	58.8	62.7	65.8	68.2	70.0	71.4	72.4	73.1	73.7	74.0	74.3	74.5	74.6	74.7	74.8	74.9	74.9	74.9	75.0

Appendix B Sensitivity Analyses

Several sensitivity runs were conducted to assess the model's sensitivity to certain inputs and to consider how alternative assumptions or scenarios may impact the analytical findings. Five critical areas were identified for consideration via a sensitivity analysis: 1) alternative technology diffusion curves for LEDs, 2) alternative LED lighting technology improvement scenarios, 3) alternative LED lighting cost scenarios, 4) alternative conventional lighting technology improvement scenarios, and 5) and alternative energy efficiency-induced retrofit rate.

The range of energy savings in 2030 resulting from these various analyses are presented in Table B. 1 below, expressed in terawatt-hours and percent of baseline consumption. From these ranges it is apparent that future energy savings from the penetration of LEDs into the general illumination market depend upon reductions in LED prices and display a relatively low degree of correlation with the price or performance of competing technologies. Rate of technology diffusion, LED efficacy and lifetime improvements, and an increased rate of lighting retrofits and renovations will moderately impact the degree to which LED white-light sources fulfill their energy savings potential.

Table B. 1 Impact of Sensitivity Analyses in 2030

Sensitivity Analysis	Description	Energy Savings Range Between Scenarios, 2030	
		TWh	Percent
Technology Diffusion Rate	Low: Uses technology diffusion curve derived from historical electronic ballast, T8 fluorescent lamps, and CFL data High: Uses aggressive technology diffusion curve derived from historical LCD TV, PC, and DVD data	64	9.9%
LED Technology Improvement	Low: Deflates MYPP efficacy limit by 10% and assumes no lifetime improvement High: Inflates MYPP efficacy limit by 10% and increases initial luminaire lifetime to 50,000 hours and final lamp and luminaire lifetime to 100,000 hours	71	11.0%
LED Price Improvement	LED prices adjusted by ±50%	99	15.3%
Conventional Technology Improvement	Low: No price or performance improvement High: Doubles improvement in cost, efficacy, and lamp lifetime	17	1.8%
Retrofit Rate	High: Uses 15% retrofit rate	59	9.2%

Appendix B.1 LED Lighting Technology Diffusion Curve

As discussed in Section 6.1, the LED scenario presented in the main section of this report, which serves as the reference scenario for all sensitivity analyses, assumes that LED lighting will follow a technology diffusion curve similar to other historical lighting technologies (e.g., T8 fluorescent lamps, electronic fluorescent ballasts). However, interviews with some SSL manufacturers indicate that due in part to their potential to be integrated with networked lighting systems to smart buildings, LED market adoption may occur at a rate faster than the historical lighting diffusion rate. To account for the uncertainty in the rate of technological diffusion, this sensitivity analyzes the impact of using a more aggressive technology diffusion curve for LED lighting, depicted in the figure below, derived from historical market share data of other technologies that exhibited rapid diffusion (e.g., LCD TVs, personal computers, DVDs). This study also considers the possibility that LED technology will diffuse slower than the historical lighting diffusion rate due to unforeseen effects. The curve used for this slow diffusion sensitivity analysis was developed by PNNL and yields lower LED market penetration due to its inclusion of historical CFL market share data. CFLs have experienced a notably rocky path to market for various reasons, and as such this diffusion curve is only considered as a sensitivity analysis. The figure also includes the technology diffusion curve used in the reference scenario analysis for comparison.

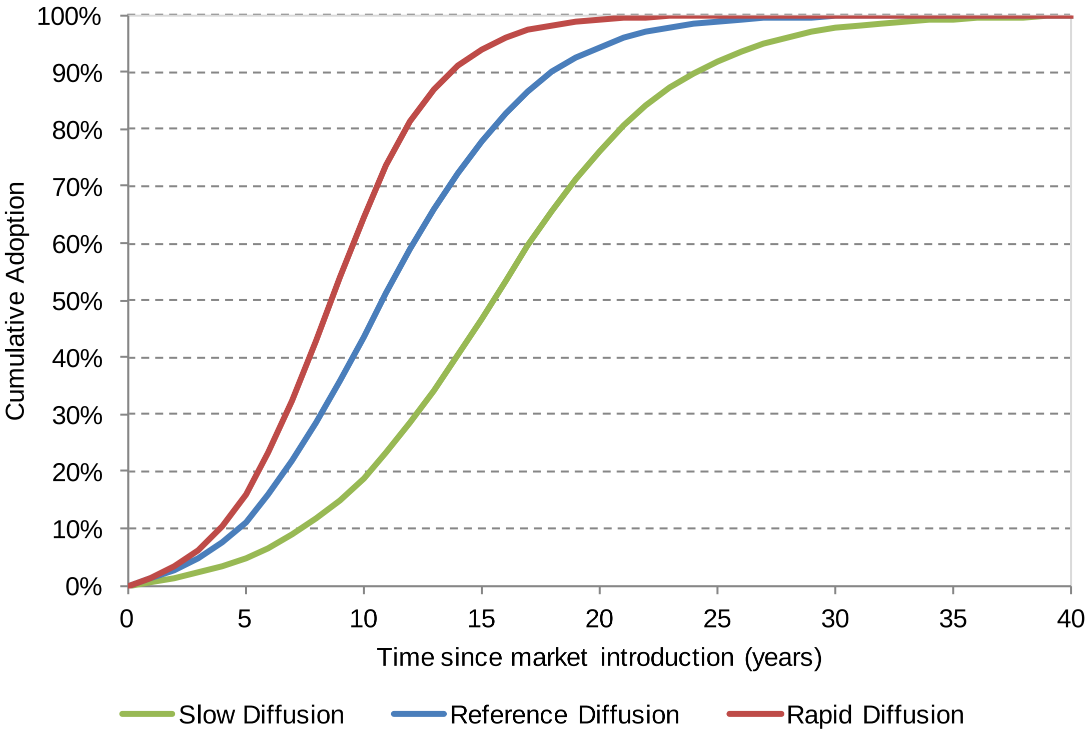

Figure B. 1 LED Technology Diffusion Curve Sensitivity Scenarios

Table B. 2 Technology Diffusion Curve Sensitivity Scenario Results

		2010	2015	2020	2025	2030	Cumulative (2010-2030)
Slow	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	4.3%	21.3%	43.4%	64.3%	-
	Site electricity savings (TWh)	-	9	78	166	251	1,985
	Site electricity savings (%)	-	1.5%	12.3%	25.8%	38.8%	14.7%
Reference	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	9.5%	35.8%	59.0%	73.7%	-
	Site electricity savings (TWh)	-	21	122	217	297	2,672
	Site electricity savings (%)	-	3.3%	19.4%	33.9%	45.8%	19.7%
Rapid	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	13.7%	45.2%	65.3%	76.2%	-
	Site electricity savings (TWh)	-	30	148	243	315	3,033
	Site electricity savings (%)	-	4.7%	23.5%	37.9%	48.7%	22.4%

Appendix B.2 LED Lighting Technology Improvement

As discussed in Chapter 5, the reference LED scenario assumes that efficacy and lifetime improvements in LED lighting will track the MYPP projection. However, because the MYPP only provides performance projections for best in class LED luminaire products, a delay factor of one year is incorporated in the analysis to represent the average market performance of an LED luminaire (i.e., the average market LED luminaire performance is two years behind that of best in class LED luminaire products). Similarly, a delay of two years is used to represent the losses associated with the less efficient LED lamp products.

As the future performance improvement of LEDs could have a significant impact on the rate of penetration into the general illumination market and the resulting energy savings, this sensitivity analysis examines two additional scenarios. The first scenario, “High LED Technology Improvement,” assumes that LED efficacy projections will converge to an efficiency limit 10 percent greater than the limit identified in the MYPP. This scenario also increases the initial luminaire (both indoor and outdoor) lifetime to 50,000 hours and increases final lamp and luminaire lifetime to 100,000 hours in 2030. The second scenario, “Low LED Technology Improvement,” assumes that efficacy will plateau at 10 percent lower than the MYPP limits and that there will be no improvement to LED lamp or luminaire lifetime. The LED technology improvement sensitivity scenarios and their results are presented on the following pages.

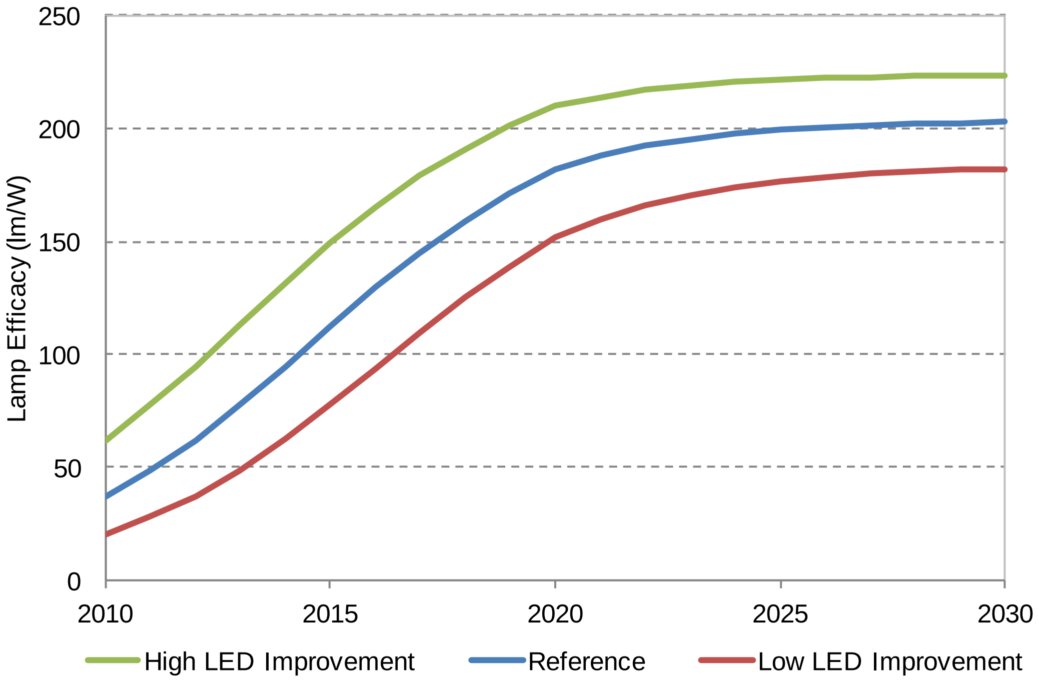

Figure B. 2 LED Lamp Efficacy Improvement Sensitivity Scenarios

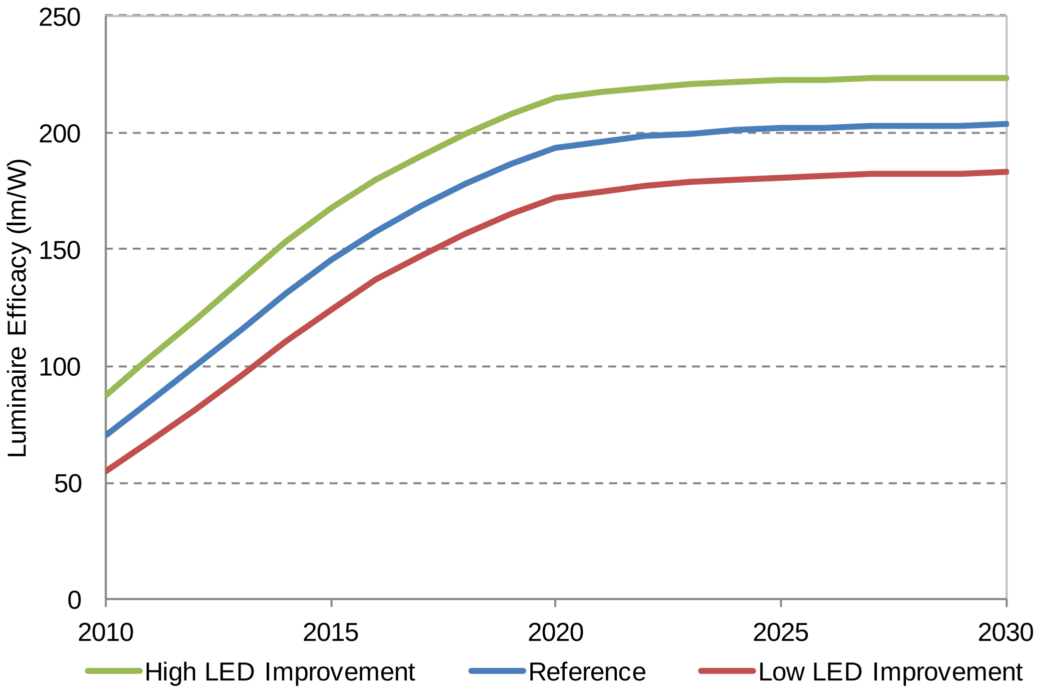

Figure B. 3 LED Luminaire Efficacy Improvement Sensitivity Scenarios

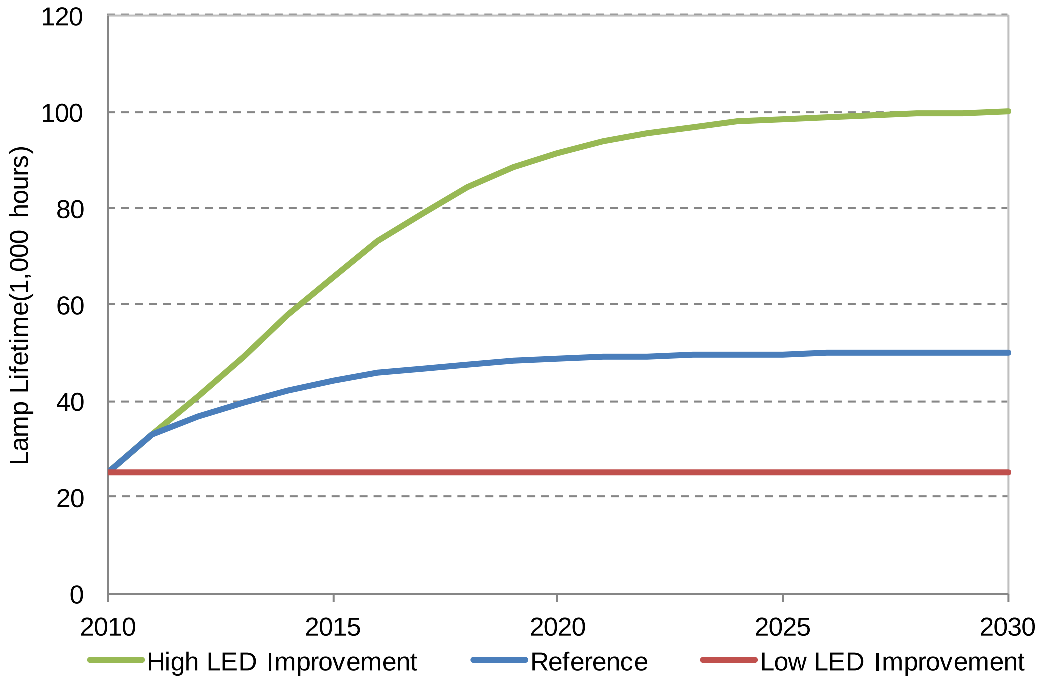

Figure B. 4 LED Lamp Lifetime Improvement Sensitivity Scenarios

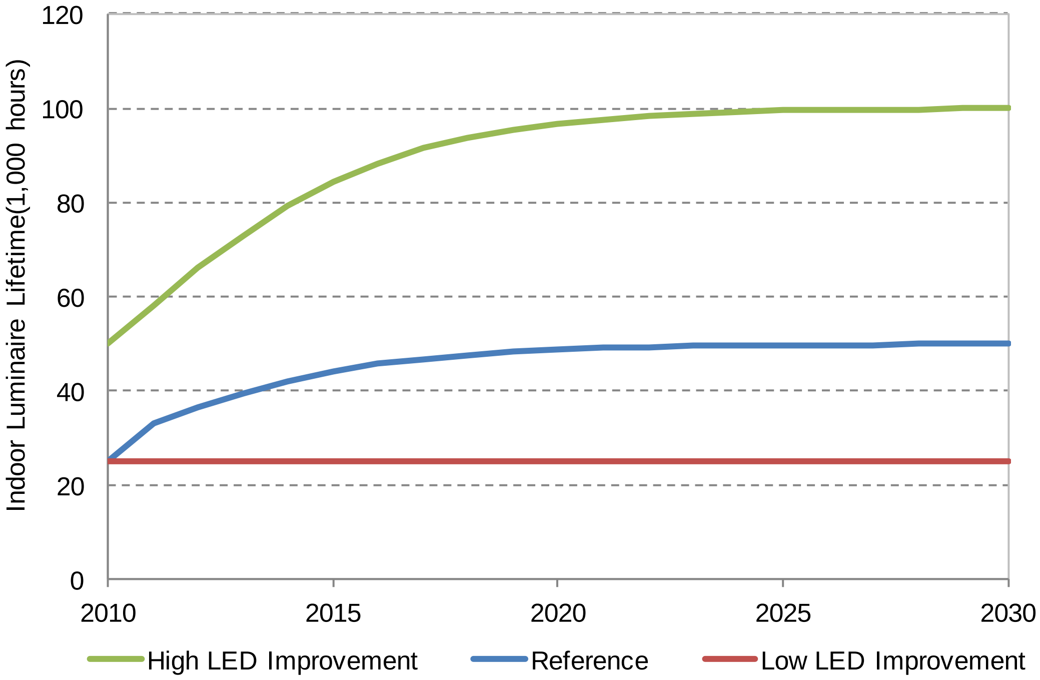

Figure B. 5 LED Indoor Luminaire Lifetime Improvement Sensitivity Scenarios

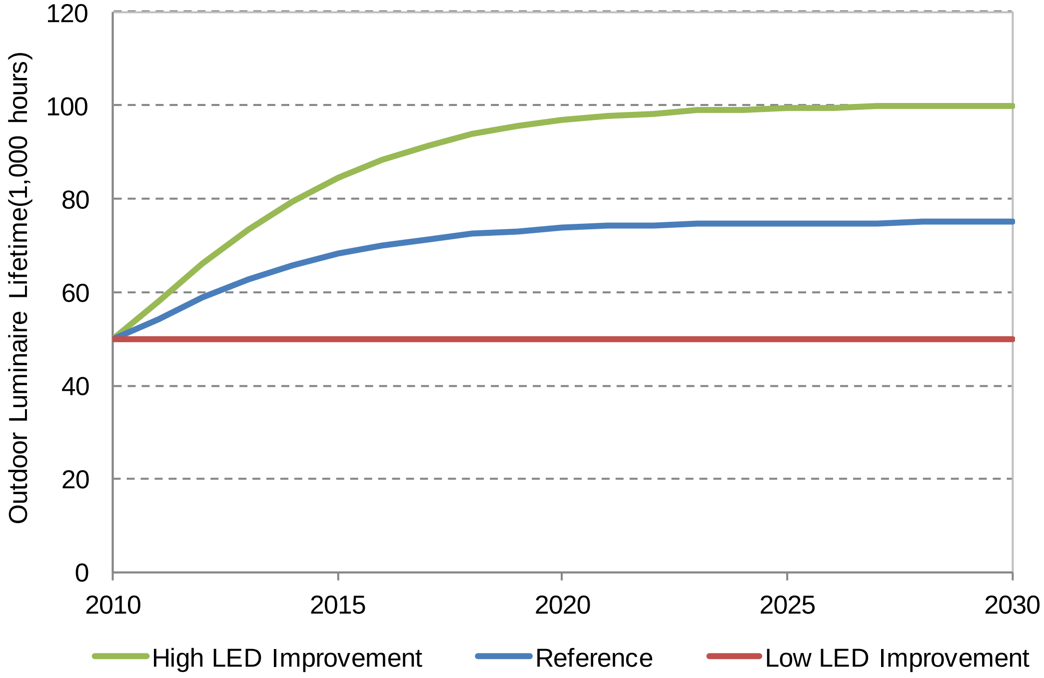

Figure B. 6 LED Outdoor Luminaire Lifetime Improvement Sensitivity Scenarios

Table B. 3 LED Technology Improvement Sensitivity Scenario Results

		2010	2015	2020	2025	2030	Cumulative (2010-2030)
Low	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	7.5%	29.6%	50.4%	64.7%	-
	Site electricity savings (TWh)	-	17	105	186	254	2,284
	Site electricity savings (%)	-	2.6%	16.7%	29.1%	39.2%	16.9%
Reference	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	9.5%	35.8%	59.0%	73.7%	-
	Site electricity savings (TWh)	-	21	122	217	297	2,672
	Site electricity savings (%)	-	3.3%	19.4%	33.9%	45.8%	19.7%
High	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	11.4%	38.9%	63.2%	77.8%	-
	Site electricity savings (TWh)	-	25	135	239	325	2,945
	Site electricity savings (%)	-	3.9%	21.4%	37.3%	50.1%	21.8%

Appendix B.3 LED Lighting Cost Improvement

As discussed in Chapter 5, the reference LED scenario assumes that cost improvements in LED lighting will track the MYPP and Manufacturing Roadmap projections. However, there is significant uncertainty associated with projecting prices over a 20-year analysis period for a technology as new and rapidly changing as LED lighting. In addition, utility or government incentives that encourage the adoption of energy efficient technologies such as LEDs (effectively lowering the price of LED lighting) could significantly affect the penetration of LED lighting, and thus the energy savings. Therefore, this report evaluates two sensitivities to the reference LED scenario.

The first scenario, "High LED Prices," assumes that LED lamp and luminaire prices exceed those assumed in Chapter 5 by 50 percent. The second scenario, "Low LED Prices" assumes that LED lighting costs are 50 percent lower than those presented in Chapter 5. The price sensitivity scenarios and their results are presented below.

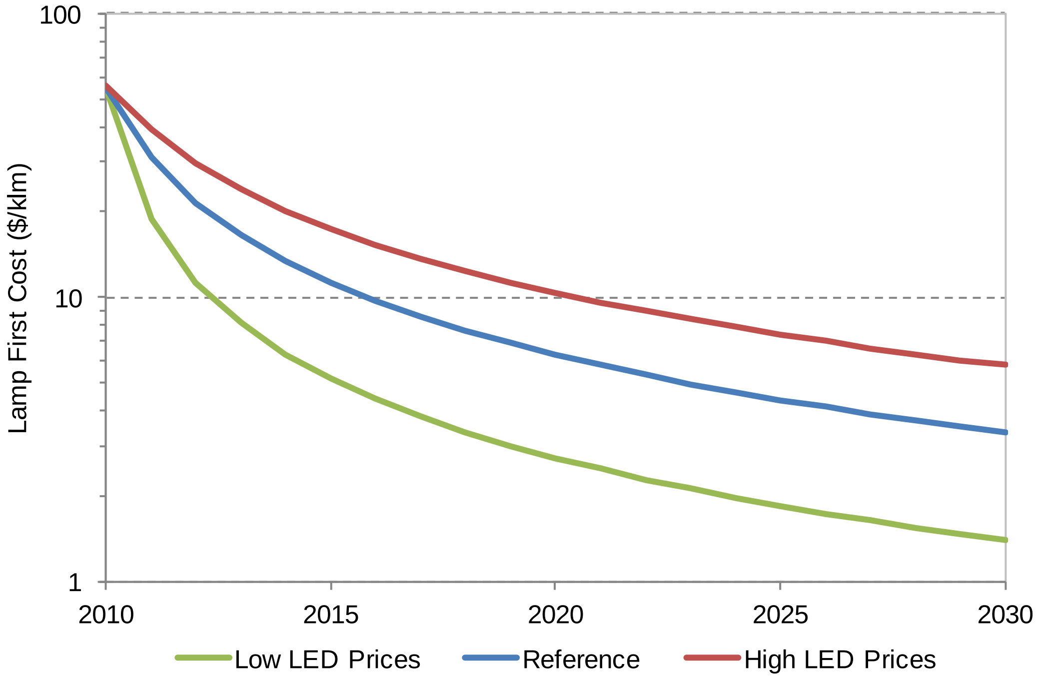

Figure B. 7 LED Lamp Price Sensitivity Scenarios

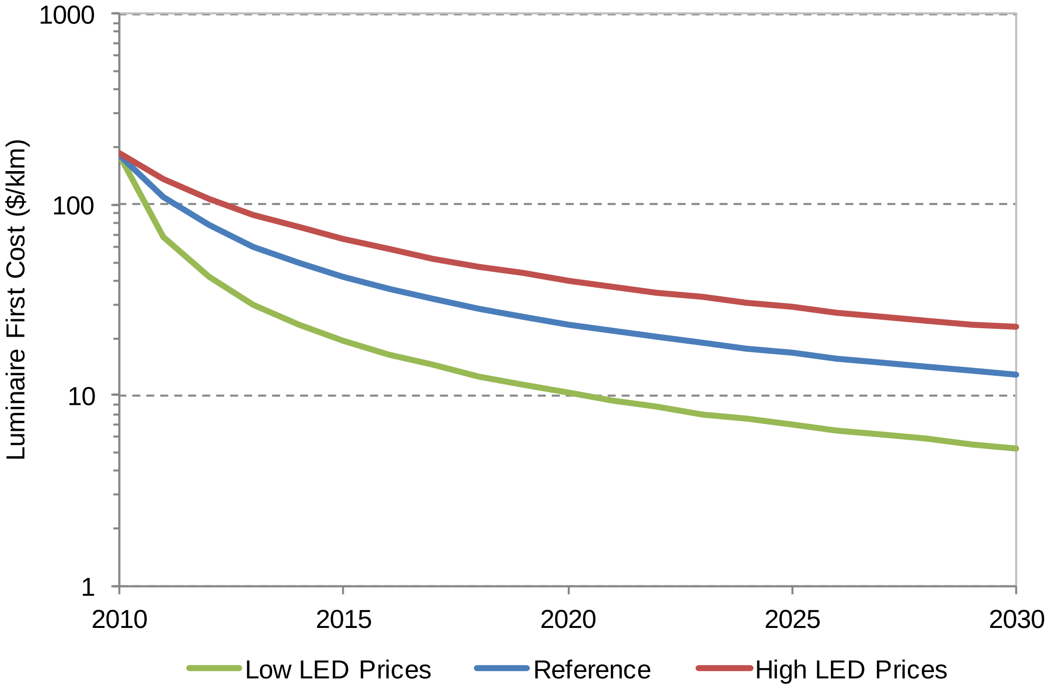

Figure B. 8 LED Luminaire Price Sensitivity Scenarios

Table B. 4 LED Price Sensitivity Scenario Results

		2010	2015	2020	2025	2030	Cumulative (2010-2030)
Low	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	17.0%	52.7%	77.5%	87.4%	-
	Site electricity savings (TWh)	-	33	155	262	343	3,257
	Site electricity savings (%)	-	5.3%	24.5%	40.8%	52.9%	24.1%
Reference	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	9.5%	35.8%	59.0%	73.7%	-
	Site electricity savings (TWh)	-	21	122	217	297	2,672
	Site electricity savings (%)	-	3.3%	19.4%	33.9%	45.8%	19.7%
High	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	6.2%	24.0%	40.2%	53.0%	-
	Site electricity savings (TWh)	-	14	100	177	243	2,161
	Site electricity savings (%)	-	2.3%	15.8%	27.5%	37.5%	16.0%

Appendix B.4 Conventional Lighting Technology Improvement

As LEDs continue to improve, manufacturers of conventional lighting technology may invest in R&D to maintain market competitiveness. This may result in improvements to the average efficacy, lifetime, and cost of conventional technologies sold over the 20-year analysis period. As discussed in Chapter 4, the primary analysis assumes technology improvements based on historical market information, interviews with manufacturers, and technical reports. To examine the sensitivity of lighting energy savings to conventional technology improvement, this sensitivity considered two additional scenarios: “No Conventional Technology Improvement” and “High Conventional Technology Improvement”. The “No Conventional Technology Improvement” scenario assumes that the cost and performance characteristics of conventional technologies remain unchanged from the 2010 values. The “High Conventional Technology Improvement” scenario assumes that the improvement in the cost and performance characteristics of conventional technologies double relative to those presented in Chapter 4. The results of these sensitivity scenarios are presented below.

Table B. 5 Conventional Technology Improvement Sensitivity Scenario Results

		2010	2015	2020	2025	2030	Cumulative (2010-2030)
None	**Baseline site electricity consumption (TWh)**	694	637	634	646	654	13,596
	LED market share (% of lm-hr)	-	9.4%	36.0%	59.5%	74.5%	-
	Site electricity savings (TWh)	-	21	124	223	306	2,734
	Site electricity savings (%)	-	3.3%	19.6%	34.6%	46.7%	20.1%
Reference	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	9.5%	35.8%	59.0%	73.7%	-
	Site electricity savings (TWh)	-	21	122	217	297	2,672
	Site electricity savings (%)	-	3.3%	19.4%	33.9%	45.8%	19.7%
High	**Baseline site electricity consumption (TWh)**	694	634	628	637	642	13,475
	LED market share (% of lm-hr)	-	9.6%	35.5%	58.3%	72.9%	-
	Site electricity savings (TWh)	-	21	120	212	289	2,612
	Site electricity savings (%)	-	3.3%	19.2%	33.3%	45.0%	19.4%

Appendix B.5 Energy Efficiency-Induced Retrofits

The primary analysis assumes a rate of lighting fixture retrofits and renovations of five percent of the installed base per year. This rate is kept constant in both the baseline and the LED scenarios. However, as LED lamps and luminaires improve in efficiency and cost, it is possible that the presence of LED options may cause some consumers to retrofit their lighting systems prior to the expected end-of-life. While the magnitude of this effect is highly uncertain, this sensitivity analyzes the energy savings impacts if an additional 10 percent of the installed base is retrofitted in the LED case relative to the no-LED baseline case.

Table B. 6 Energy Efficiency-Induced Retrofit Rate Sensitivity Scenario Results

		2010	2015	2020	2025	2030	Cumulative (2010-2030)
Reference	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	9.5%	35.8%	59.0%	73.7%	-
	Site electricity savings (TWh)	-	21	122	217	297	2,672
	Site electricity savings (%)	-	3.3%	19.4%	33.9%	45.8%	19.7%
High	**Baseline site electricity consumption (TWh)**	694	635	631	641	648	13,535
	LED market share (% of lm-hr)	-	10.9%	42.8%	68.3%	80.9%	-
	Site electricity savings (TWh)	-	38	166	285	356	3,481
	Site electricity savings (%)	-	6.0%	26.3%	44.4%	55.0%	25.7%

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