Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030

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COMMENTS

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ABBREVIATIONS

AEO	Annual Energy Outlook
CRI	Color rendering index
DOC	Department of Commerce
DOE	Department of Energy
EISA 2007	Energy Independence and Security Act of 2007
EIA	Energy Information Administration (DOE)
HID	High intensity discharge
kWh	Kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light emitting diode
lm/W	Lumens per watt
NAICS	North American Industry Classification System
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
OLED	Organic light emitting diode
R&D	Research and development
SECA	Solid State Energy Conversion Alliance
SSL	Solid-state lighting
U.S.	United States

1. Introduction

Solid-state lighting (SSL) has the potential to revolutionize the lighting market through the introduction of highly energy-efficient, longer-lasting, versatile light sources, including high-quality white light. Previously relegated to colored-light applications such as traffic signals and exit signs, SSL products are now successfully competing with conventional technologies including incandescent and fluorescent lamps in general illumination applications. SSL can be found in directional lamp fittings such as down-lights and under-cabinet lighting; in area light fittings such as replacement two-foot by two-foot ceiling fixtures and roadway lighting; and in niche applications such as commercial refrigeration display lighting and automobile day-running lamps.

SSL technology continues to advance at a rapid pace, with improvements being achieved in efficacy, light quality, and operating life. In addition, manufacturing improvements and market competition are putting downward pressure on retail prices, benefiting consumers. As industry and government investment continues to improve the performance and reduce the costs associated with this technology, SSL will become more competitive with conventional light sources and can be expected to capture increasing shares of the general illumination market. This analysis attempts to quantify the national energy savings that would accrue due to the increasing market penetration of energy-efficient solid state lighting.

The U.S. Department of Energy (DOE) and National Electrical Manufacturers Association (NEMA) are collaborating on a Next Generation Lighting Initiative to accelerate the development of white-light SSL and position the U.S. as a global leader in this technology. 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. SSL has also been included in the Energy Independence and Security Act of 2007 and the American Recovery and Reinvestment Act of 2009. Both of these laws expanded DOE's SSL work supporting research and programs to accelerate market adoption and save energy.

In early 2009, DOE's SSL program updated price and performance projections in its multi-year program plan, based on input from the industry and the scientific community (DOE, 2009). The estimates given in the multi-year program plan project performance improvements over time, including higher efficacy values and reduced retail prices. Advancements in SSL technology over the last two decades have contributed to a gradual market penetration in colored and some specialty white-light niche applications (DOE, 2008). The analysis contained in this report considers these updated estimates to determine the impact on national energy consumption if SSL were to achieve projected price and performance targets from the multi-year program plan. This report updates the previously published estimates of energy savings potential from SSL in general illumination applications published in 2006 (DOE, 2006), 2003 (DOE, 2003), and 2001 (DOE, 2001). This report presents an estimate of the national energy savings that could be realized through the market penetration of energy-efficient SSL if the technology achieves certain forecasted price and performance objectives. To develop this estimate of energy savings, a model was developed of the U.S. national lighting market, considering various lighting technologies, end-use sectors and end-use applications within those sectors. This report presents input assumptions, the methodology and the findings of this analysis.

1.1. Analytical Approach

The methodology followed in structuring and developing a model of the U.S. lighting market and evaluating consumer decisions about lighting technologies is outlined below:

1. Estimate Lighting Service — utilizing the estimated lighting inventory published in the U.S. Lighting Market Characterization report (DOE, 2002), the 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). It then uses the percentage change in square footage between 2001 and 2010 (est.) to bring the lumen-hours of lighting service forward to 2010, the start of the analysis period for this study.
2. Group Together Similar Quality Types of Lighting — using the color rendering index (CRI) of each light source as an indicator of light quality, the model apportions the lumen service for the base year into four lighting quality bins.[1]
3. Forecast Lumen Demand — holding lumen demand per square foot of floor space constant within each sector, forecast lumen demand from 2010 to 2030 by applying the building construction projection forecasts provided by the National Energy Modeling System (NEMS) in the Annual Energy Outlook 2009 (EIA, 2009).
4. Lighting Technology Adjustment to Account for New Regulations — the model takes into account legislation and DOE regulations that are final and in place, including for example the Energy Independence and Security Act of 2007 and DOE's final rule for general service fluorescent lamps and incandescent reflector lamps, published on July 14, 2009 (74 FR 34080). The model does not take into account draft or pending legislation, as both the effective date and level of standard are uncertain. The model accounts for the new regulations by shifting lumens between different lighting technologies, such as from T12 to T8 and from general service incandescent lamps to compact fluorescent lamps and halogen.
5. Market Turnover — using an adjustable stock model, estimate the lumen "turnover" (i.e., annual available lumen market) in the U.S., based on new installations (new construction), replacement lamps, and retrofit fixtures. This turnover is calculated based on the published lamp lives of the baseline 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 floor space in the various sectors. The calculated lumen turnover constitutes the available lighting market into which LED and OLED lamps and fixtures compete.
6. Conventional Technology Improvement Forecast — recognizing that the incumbent, conventional lighting technologies will work to compete with the new SSL market entrant, the model allows for both cost reductions and performance improvements in efficacy and operating life for conventional (i.e., incandescent/halogen, fluorescent and high intensity discharge) lighting technologies. Three performance improvement scenarios are constructed (see Chapter 4), with varying degrees of improvement. The improvements for this forecast are introduced linearly over the 20-year analysis period.
7. SSL Technology Improvement Forecast — the model bases the price and performance curves for LED and OLED technologies on those published in the DOE's Solid-State Lighting Research and Development Multi-Year Program Plan FY'09-FY'15. (DOE, 2009) The improvement trends are then extrapolated out to 2030 (see Chapter 5).
8. Lighting Service Costs — the model calculates forecasted costs associated with lighting service

[1] To simplify the market analysis, CRI bins (groups of CRI values) are created to associate similar lighting services estimated within each sector. While CRI as a single metric cannot capture all the distinctions between lighting technologies, it is convenient and captures fundamental differences in lighting services. For more information on the CRI bins, see Chapter 2 of this report.

based on today's market and anticipated improvements for new installations (i.e., fixture, ballast and lamp) and luminaire operation (i.e., electricity, maintenance, and replacement lamps).

9. Economic Lighting Market Model — the model calculates LED and OLED market penetration (separately) based on competition between LED / OLED and the conventional lighting technologies. The model awards lumens of service to either SSL or conventional lighting sources based on a calculated payback period and estimated consumer response curves (see Chapter 6). In this way, the model incorporates variability into the lighting market that is reflective of national electricity prices by sector, and acceptable consumer payback periods.
10. Calculate Energy Savings — relative to a baseline of energy consumption where it is assumed that there are no LED or OLED products sold in the U.S. market, the model calculates energy savings considering LED and OLED products being sold into the lighting market, taking into account all the aforementioned variables and factors. The result is a calculated year-on-year energy savings basis, spanning the analysis period.

The 10-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 lumen demand projection from 2010 to 2030 (Chapter 2)
- Available lumen market — turnover in the installed base of lighting (Chapter 3)
- Conventional technology improvement projection from 2010 to 2030 (Chapter 4)
- SSL technology improvement estimates based on the Multiyear Program Plan (Chapter 5)
- Paybacks and lighting model market penetration (Chapter 6)
- Stock model changes and resultant energy savings estimates (Chapter 7)
- Consideration of a wide range of SSL prices and efficacies (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. These 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 energy savings estimate of SSL 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 SSL.

- SSL Retrofit Lamps — the model assumes that SSL technology manufacturers will produce SSL lamps that can be installed directly into existing fixtures, such as medium screw-base sockets (E26) or medium-bipin T8 fluorescent luminaires. This assumption tends to increase the energy savings estimate as it removes barriers to entry that otherwise might exist, such as having SSL market penetration contingent on the costly replacement of fixtures.
- Constant Lighting Intensity — it is assumed that levels of lighting intensity (lumens per square foot) in buildings remains constant over the analysis period (2010-2030). This assumption will tend to decrease the estimate of energy savings from SSL, because it will require that SSL match the source lumen output levels of conventional sources in all applications. Due to the fact that

SSL has a more compact and directional light emission source, the optical losses would tend to be lower and thus equivalent levels of area illumination could be achieved with fewer source-lumens. Furthermore, it is possible that the market may respond to higher energy prices and increasing levels of environmental concern through smart design. For example, taking advantage of task lighting luminaires and lighting control regimens (e.g., occupancy sensors) to create responsive, localized lighting designs would enable a reduction in the overall ambient lighting levels (and associated energy consumption).

- SSL Performance Improvement Curves — the market penetration model is driven by assumptions built into the price and performance improvement projections of LEDs and OLEDs considered separately over the analysis period. Any deviation from this projection could cause the energy savings estimate to be higher or lower. If the price and performance projections are not achieved, the market economics underpinning the energy savings estimate would not be realized and the actual energy savings would be lower. Similarly, if the price and performance projections exceed those used in this analysis, then market penetration would be greater, and energy savings higher.
- Simple Payback — the economic portion of the model assumes the lighting market responds primarily to simple payback, which focuses on a comparison of first cost and operating cost savings across all sectors. This assumption would tend to increase the energy savings estimate as it assumes people respond to this single indicator, when there are many other factors taken into account in an actual lighting equipment purchasing decision, including acceptance and availability of the technology. (N.B. in order to account for these market barriers that are more difficult to quantify, the model incorporates a five-year lag whereby once a particular replacement opportunity becomes economically viable for SSL, that share of lumen-hours of light output is spread over a five year period, rather than assuming all the cost-effective installations switch to SSL in the first year).
- Simple Payback Response Curves — the model utilizes payback period response curves to award market share based on the calculated payback. These payback curves represent an average for the entire sector, and could cause the energy savings estimate to be higher or lower, based on whether the actual average is above or below the estimated value of the payback curve.
- CRI Light Quality — while there are several metrics that describe the quality of light, no single metric is able to capture all aspects of light quality. This analysis uses CRI as an indicator of quality, differentiating between tasks that require low, medium, high and very high CRI. This assumption does not have any influence over the stated energy savings estimate, rather it is simply a convenient surrogate for classifying and differentiating between lighting technologies.
- Competition within CRI Bins — the analysis subdivides the national lighting inventory into groups of similar CRI ratings by sector. Competition for the substitution of replacement lamps as well as the installation of new and retrofit fixtures occurs within those CRI bins. During the analysis period, end-users cannot substitute a technology from a different CRI bin. This assumption may lead to underestimating the energy savings from LED, as lighting consumers may be willing to accept a lower value CRI. For example, the use of incandescent lamps in a residential garage may not be a function of the high CRI of incandescent lamps, but rather the fact that it is a low first-cost lamp that typically doesn’t have long daily operating hours. In that application, consumers may readily accept a lower CRI LED lamp as an alternative, however the model only permits the substitution of very high CRI LED lamps because that was the CRI of the lighting technology being replaced.
- Lighting Demand Growth Rate — the model incorporates growth rates that project new construction over a twenty-year period. This assumption is based on historical trends, and should not cause any variance in the energy savings estimate.

2. Lighting Inventory and Lumen Demand Projection

This analysis forecasts the demand for lighting services using the U.S. Lighting Market Characterization report (DOE, 2002) to estimate the national lighting demand (in teralumen-hours[2]) and then groups this service by lighting color quality (using CRI bins). The baseline lighting demand is then divided by the total building floor space inventory from the NEMS database to ascertain the lighting demand per square foot of building space. Lighting demand per square foot is then held constant in each sector, and total national lumen demand increases over the analysis period using floor space growth estimates from the AEO 2009 for residential and commercial sectors and by user-input for industrial and outdoor stationary sectors. These growth rates range from 1.00 — 1.65 percent per annum.

2.1. National Lighting Demand

To determine the national demand for lighting services, estimates of the installed base of lamps, wattages, average operating hours and efficacies were derived from the U.S. Lighting Market Characterization report (DOE, 2002). All these inputs are combined to develop the inventory described in this section. The Lighting Market Characterization report estimates the installed base of lighting in the U.S. considering nearly thirty different lamp types:

- **Incandescent:** general service (A-line) incandescent, general service incandescent reflector, incandescent specialty
- **Halogen**: general service halogen, halogen reflector; halogen miniature reflectors, reflector low-voltage halogen
- **Fluorescent:** T5 lamps, T8 lamps, T12 lamps, compact fluorescent lamp plug-in, compact fluorescent screw-in, compact fluorescent lamp plug-in reflector, compact fluorescent lamp screw-in reflector, circline, induction discharge, miscellaneous fluorescent
- **High Intensity Discharge:** mercury vapor, metal halide, high pressure sodium, low pressure sodium[3]

For each of the lamp types, the lamp wattage by sector is multiplied by the estimated installed base of lamps and the annual operating hours. For fluorescent and high intensity discharge (HID) lamps, ballast losses are included with the lamp wattage estimate. This provides a lighting system kilowatt hour (kWh) consumption per annum building estimate (for the residential, commercial, and industrial sectors) and an aggregate national estimate for the outdoor stationary sector. These values are then multiplied by their respective weighted-average light source efficacies, converting the national annual energy demand per building into an annual lighting service demand per building. For example, if a residential dwelling consumed 100 kWh of electricity for general service incandescent lighting, this would be converted into 1300 kilolumen-hours per year 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 general service incandescent lamp. Efficacy ratings are tracked by sector because the average installed wattages vary by sector. Often, higher incandescent wattage lamps of the same type have higher efficacy ratings,

[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.

[3] Note: although low-pressure sodium is itself not a high-intensity discharge lamp, it is classified in this lamp type for convenience, as it is often used in HID-type applications.

and increasing wattages and efficacies will both contribute to greater annual lumens of service. Conversely, fluorescent lamps tend to have increasing efficacy at lower wattages.

Table 2-1 presents the data used in the model for the various lighting technologies in the baseline inventory as well as the CRI of the lamps. The average wattage, efficacy, and CRI are primarily extracted from the U.S. Lighting Market Characterization study (DOE, 2002); however, a few minor updates have been incorporated as new and better shipment information became available, including average wattage of halogen and T5 fluorescent lamps.

Table 2-1. Average Lamp Wattage, Efficacy, and Color Rendering Index

Lamp Type		Wattage (watts)				Efficacy (lm/W)				CRI
	Sub-classification	Res	Com	Ind	Out	Res	Com	Ind	Out	All
Incandescent										
	Standard - General Service	63	83	126	138	13	14	16	16	100
	Standard - Reflector	102	104	102	103	13	14	14	14	100
	Halogen - General Service	57	75	-	-	16	17	-	-	100
	Halogen - Reflector	91	150	185	167	15	20	25	18	100
	Halogen - Reflector, Low Volt	-	48	58	-	-	13	13	-	100
	Low Wattage (less than 25W)	-	15	19	-	-	10	10	-	100
Fluorescent										
	T5	-	28	28	-	-	95	95	-	78
	T8 - less than 4 ft	-	23	23	-	-	66	66	-	80
	T8 - 4 ft	32	33	31	-	83	83	83	-	80
	T8 - more than 4 ft	-	50	53	105	-	84	84	84	68
	T8 - U-bent	-	34	32	-	-	81	81	-	80
	T12 - less than 4 ft	-	29	32	-	-	60	60	-	71
	T12 - 4 ft	41	45	44	-	68	68	68	-	70
	T12 - more than 4 ft	-	93	95	190	-	69	69	69	76
	T12 - U-bent	-	46	46	-	-	64	64	-	67
	Compact - Plug-in	-	17	31	-	-	60	60	-	82
	Compact - Screw-in	18	16	14	-	55	55	55	-	82
	Compact - Plug-in - reflector	-	16	-	-	-	55	-	-	82
	Compact - Screw-in - reflector	11	16	14	-	55	55	55	-	82
	Circline	-	30	35	-	-	60	60	-	73
	Induction Discharge	-	-	-	-	-	-	-	-	85
	Miscellaneous Fluorescent	-	18	34	150	-	55	55	55	80
High Intensity Discharge										
	Mercury Vapor	179	200	225	215	38	43	43	43	45
	Metal Halide	-	472	438	311	-	60	60	60	65
	High Pressure Sodium	79	260	258	216	100	100	100	100	22
	Low Pressure Sodium	-	104	90	180	-	113	113	113	10

Note: dash ("-") indicates no data for that light source / sector combination.
Source: DOE, 2002, with minor updates where new data have become available.

The right-most column of Table 2-1 provides the CRI ratings used for each of the light sources tracked in the U.S. Lighting Market Characterization report (DOE, 2002). These CRI values are taken from major lamp manufacturer catalogues and are used to classify the lumen-hours of lighting service from that lamp type and sector into four CRI bins. The CRI bins were created to group together the annual lighting demand according to lighting service quality. Although CRI as a single metric cannot capture all the distinctions between lighting technologies, it is a convenient, readily understood measure that is representative of fundamental differences in lighting service enabling a greater degree of equivalency when considering SSL replacement technologies in the model.

One of the modeling assumptions made was that the demand for lumens in any given CRI bin will not shift out of that bin during the analysis period. In other words, if a particular application uses 85 CRI light in 2010, it will be classified as "High CRI" and that same lighting service in 2030 will still be "High CRI." Although this assumption may not accurately reflect the marketplace (e.g., where a consumer may substitute a lower or higher CRI source because it is less expensive or offers some desirable feature), the assumption requires SSL sources to achieve equivalent performance (i.e., CRI) before they are eligible to compete economically with the conventional technologies. The CRI bins that were created for this analysis are presented in Table 2-2 with some example lamps that are typical of those CRI ranges.

Table 2-2. CRI Bins and Typical Lamps Associated with Each Bin

CRI Bin	CRI Range	Example Lamps
Low CRI	0 – 40 CRI	Mercury Vapor, High Pressure Sodium
Medium CRI	41 – 75 CRI	T12 Linear Fluorescent, Circline, Metal Halide
High CRI	76 – 90 CRI	T8 Linear Fluorescent, Compact Fluorescent Lamps
Very High CRI	91 – 100 CRI	Incandescent, Halogen

Using the aforementioned sectors and CRI bins, the model creates sixteen market segments that group together the projected annual lighting demand into four sectors and four CRI bins. This four-by-four matrix is illustrated in Figure 2-1.

Residential Low CRI	Commercial Low CRI	Industrial Low CRI	Outdoor Low CRI
Residential Med CRI	Commercial Med CRI	Industrial Med CRI	Outdoor Med CRI
Residential High CRI	Commercial High CRI	Industrial High CRI	Outdoor High CRI
Residential V.High CRI	Commercial V.High CRI	Industrial V.High CRI	Outdoor V.High CRI

Figure 2-1. Market Matrix of Sectors and Color Bins for National Lighting Demand[4]

2.2. National Lumen Demand Projection

The lumen-hour demand calculated by sector and CRI bin is projected over the analysis period to estimate the growth in lighting demand between 2010 and 2030. The lumen-hour demand calculated in 2001 from the Lighting Market Characterization report (DOE, 2002) was divided by the cumulative national floor space for each sector to determine a lumen-hour of lighting demand per square foot of building space. Then, the NEMS projections for square feet of building growth by sector (EIA, 2009) were used to bring the lumen-hour demand forward to 2010, and then to project demand between 2010 to 2030, holding the lumen intensity per square foot constant. This assumption is based on the premise that in the future, people occupying a space will continue to expect today's illuminance levels, CRI, and duration of service. For the residential sector, the annual lighting demand in 2009 is approximately 22.9 kilolumen-hours per square foot while for the commercial sector, the demand is more than ten times higher, 321.8 kilolumen-hours per square foot. The lighting service is higher due to the longer operating hours and higher levels of illumination in commercial floor space compared with residential.

NEMS provides annual average growth estimates of floor space in the residential and commercial sectors (EIA, 2009), which are used to project increases in lumen demand moving forward. The residential floor space increases by an average 1.65 percent per annum over the 20-year analysis period and the commercial sector floor space increases by an average of 1.25 percent over the analysis period. Unfortunately, NEMS does not provide a growth estimate for the industrial or outdoor stationary sectors, so these sectors were assumed to be 1.00 percent per annum to recognize the fact that there will be growth, but there is some uncertainty whether the growth rate in the industrial and outdoor stationary sectors is as aggressive as the residential and commercial sectors.

[4] This matrix of sector and color bins is based on the inventory published in the U.S. Lighting Market Characterization, DOE, 2002.

Thus, the average annual growth rates used in the analysis, representing the annual growth in lumen demand between 2010 and 2030, are as follows:

Residential	1.65 percent growth
Commercial	1.25 percent growth
Industrial	1.00 percent growth
Outdoor Stationary	1.00 percent growth

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 human behavior/preference would be highly speculative. The error of not making this adjustment to the lighting density estimate 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 SSL to compete.

Table 2-3 presents the estimated lumen-demand for each of the sixteen markets in 2010 — four CRI bins by four end-use sectors. Working from the baseline inventory and the projected growth in floor space, the model projects the demand for lighting service throughout the United States. And, due to a market shift[5] from T12 to T8 lamps, driven by the fluorescent ballast and fluorescent lamp standards, the base case projection includes a relatively large demand for high CRI lumens. The dominant sectors in terms of projected lighting service are the commercial and industrial medium and high CRI, the outdoor stationary low CRI, and the residential and commercial very high CRI.

Table 2-3. Sector and CRI Bins of Teralumen-hours Lighting Demand in 2010

(Tlm-hr/yr)	Residential	Commercial	Industrial	Outdoor	CRI-Bin Total
Low CRI	104	1,097	776	4,205	6,182
Medium CRI	1,207	11,395	2,752	360	15,714
High CRI	537	10,986	5,330	68	16,921
Very High CRI	2,670	2,608	89	115	5,482
Sector Totals	4,518	26,086	8,946	4,748	44,298

Note: Totals may be slightly different from the sum of the whole numbers presented for each cell of the table due to rounding.

One of the updates to the analysis published in this report is the incorporation of several new regulatory measures on conventional light sources. These include both regulations from Congressional action (e.g., incandescent lamp regulations in EISA 2007) as well as energy efficiency standards that were promulgated by DOE (e.g., the fluorescent lamp efficacy standard, published in July 2009). These

[5] Because T12 and T8 lamps are classified in different CRI bins and the model does not allow substitution of lamps between CRI bins, a manual adjustment was made by which half of the U.S. Lighting Market Characterization Volume I (DOE, 2002) lumen service in the medium CRI (T12) bin was moved to the high CRI (T8) bin starting in the base year. This adjustment to the baseline takes into account the changing of ballasts and lamps that will occur over the 20-year analysis period because of the two standards.

regulatory measures are important to consider in the context of this analysis, because they force an improvement in the efficacy of the conventional technologies, making it more difficult for SSL technology to compete and penetrate into the general illumination lighting market. Paybacks become longer, requiring SSL to achieve higher efficacy levels and lower price points before the market starts to shift. The following list summarizes the regulatory measures that are taken into account in this revised analysis. Additional information on these regulations can be found by following the links provided in the footnotes below.

- Fluorescent Lamp Ballasts — two regulations: (1) a DOE energy conservation standard that becomes applicable to full wattage new ballasts in 2005–2006, and retrofit ballasts in 2010 (65 FR 56740) and (2) legislative standards for energy saver ballasts (e.g., F34T12) that become effective 2009–2010 from the Energy Policy Act of 2005.[6] Both these regulatory measures shift the market from T12 (medium CRI) to T8 (high CRI) fluorescent lamps.
- General Service Incandescent Lamps — passed as part of EISA 2007, this standard will essentially phase out the most common, least efficient incandescent lamps by 2012–2014. It also establishes a minimum threshold efficacy of 45 lm/W starting in 2020, which is modeled as a shift to lamps that have a very high CRI and an efficacy of 45 lm/W. See Section 321 of EISA 2007.[7]
- Fluorescent Lamps — a DOE energy conservation standard that applies to fluorescent lamps manufactured after July 14, 2012, adopting an efficacy standard that shifts the fluorescent market to T8 lamps (74 FR 34080).[8]
- Incandescent Reflector Lamps — a DOE energy conservation standard that applies to lamps manufactured after July 14, 2012, adopting an efficacy that requires premium halogen technologies (74 FR 34080).[9]
- Metal Halide Lamp Fixtures — passed as part of EISA 2007, this standard sets minimum efficiency requirements on ballasts that operate metal halide lamp fixtures. See Section 324 of EISA 2007.[10]

Figure 2-2 illustrates the net impact of the sector-growth rates and the regulatory-based changes in the baseline technology. This diagram presents the national lumen-hour demand growth in teralumen-hours per year by CRI bin, which grows steadily over the analysis period of 2010 to 2030. By this account, lumen-hour demand in the United States is estimated to increase by approximately 28.8 percent over the next two decades. The very high CRI (primarily incandescent) and medium CRI (primarily T12 fluorescent) both decrease in absolute and percentage terms. The incandescent share decreases due to the incandescent lamp regulation in EISA 2007, being replaced by halogen lamps (also very high CRI) and integrally ballasted compact fluorescent lamps (high CRI). The medium CRI bin, which is dominated by T12 lamps, shifts to the high CRI bin which is dominated by T8 lamps, driven by both the fluorescent lamp ballast regulation and the fluorescent lamp regulation. Thus, the high CRI group expands its share, adsorbing teralumen-hours from both organic growth and the very-high CRI and medium CRI color bins shifting due to the new regulations.

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6 http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_bills&docid=f:h6enr.txt.pdf

7 http://leahy.senate.gov/issues/FuelPrices/EnergyIndependenceAct.pdf

8 http://www1.eere.energy.gov/buildings/appliance_standards/residential/incandescent_lamps_standards _final_rule.html

9 http://www1.eere.energy.gov/buildings/appliance_standards/residential/incandescent_lamps_standards _final_rule.html

10 http://leahy.senate.gov/issues/FuelPrices/EnergyIndependenceAct.pdf

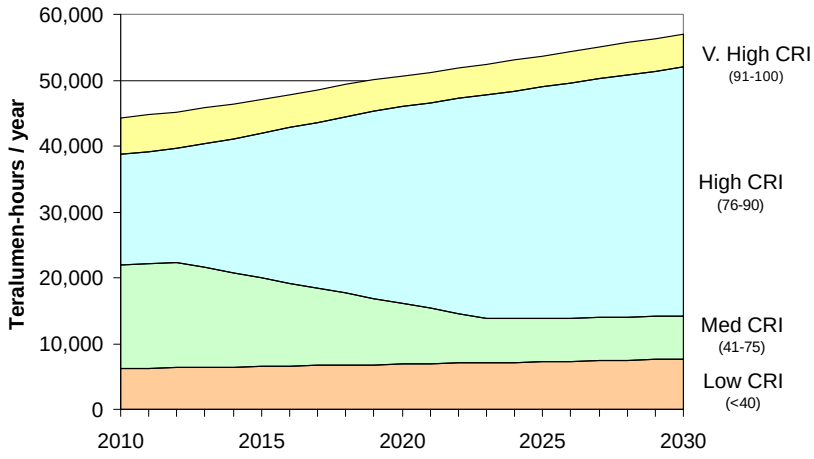

Figure 2-2. Market Forecast of Lumen-Hour Demand by CRI Bin

Because the lumen-hour demand (or source lumen output) per unit area is held constant in each sector over the analysis period, the projected growth in demand (28.8 percent) appears significant. However, evaluating this projection on a per capita basis, the lumen demand is projected to increase by only 7 percent over the analysis period, going from 142.8 megalumen-hours[11] per person per year in 2010 to 152.7 megalumen-hours per person per year in 2030.[12]

Table 2-4 and Table 2-5 present the teralumen-hours of lighting demand by major light source group and by CRI bin for the years 2010, 2015, 2020, 2025, and 2030. These tables provide a more detailed look at the projected lighting demand. Comparing these two tables and reviewing the CRI values presented in Table 2-1, the following is important to keep in mind: a) the incandescent and halogen lamps are contributors to the very-high CRI bin; b) the fluorescent sector is split between the high CRI and medium CRI bins, and c) the HID sector is divided between the medium CRI (i.e., metal halide) and low CRI (i.e., high and low pressure sodium, mercury vapor) bins. Note that there is also a reduction in the teralumen-hours of lighting service for incandescent lamps due to the EISA 2007 regulation, and it is assumed that three quarters of those covered lamps shift to compact fluorescent lamps and the balance shifts to halogen. In addition, a second regulation on general service lamps in EISA 2007 is modeled to take effect starting in 2020 that requires all lamps to be at least 45 lm/W. The model classifies the compliant product as premium halogen lamps, which are exactly 45 lm/W. To illustrate this market shift, Table 2-4 provides the teralumen-hours of annual lighting demand derived from halogen lamps separately from those for incandescent.

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11 One megalumen-hour is approximately equal to a 100W incandescent lamp operating continuously for one month. Or, alternatively, it is approximately equivalent to a 100W lamp, operated for 3-hours per day, for 220 days.

12 Population estimates for 2010 (310.2 million) and 2030 (373.5 million) are from the U.S. Census Bureau, Population Division, U.S. Department of Commerce, http://www.census.gov/population/www/projections/summarytables.html

Table 2-4. Teralumen-hours of Annual Lighting Demand by Light Source Technology

Lamp Source Type	2010	2015	2020	2025	2030
Incandescent	3,926	2,858	1,063	525	207
Halogen	1,556	2,354	3,535	4,205	4,816
Fluorescent	27,911	30,428	33,906	36,119	38,470
HID	10,899	11,477	12,139	12,821	13,545
Total	44,292	47,117	50,643	53,670	57,037

Note: Totals may be slightly different from the sum of the whole numbers presented for each cell of the table due to rounding.

The shift in teralumen-hours of lighting service from the medium CRI and very high CRI bins to the high CRI bin is evident looking across the projected years presented in Table 2-5. Driven by the aforementioned regulatory measures, both the medium CRI and very high CRI groups experience a reduction in absolute terms of lighting service between 2010 and 2030 even though lighting demand as a whole is increasing.

Table 2-5. Teralumen-hours of Annual Lighting Demand by CRI Bin

CRI Bin	2010	2015	2020	2025	2030
Low CRI (<40)	6,176	6,501	6,859	7,231	7,622
Med CRI (41-75)	15,714	13,464	9,230	6,587	6,566
High CRI (76-90)	16,921	21,940	29,956	35,123	37,827
Very High CRI (91-100)	5,482	5,212	4,598	4,730	5,022
Total	44,292	47,117	50,643	53,670	57,037

Note: Totals may be slightly different from the sum of the whole numbers presented for each cell of the table due to rounding.

The lumen demand forecast constitutes the first critical input to determine the energy savings potential of SSL. Understanding what type and how much of a particular lighting service will be required in the future is fundamental to estimating how the market may respond to the influx of new, cost-efficient, white-light sources. The next section of this report considers the construct of the market, in terms of new installations, replacements and retrofits.

3. Available Market: Turnover of Lighting Installed Base

Building on the national estimate of the projected annual lumen-hour demand, the next step is to determine how much of the lighting market is replaced each year. This turnover represents the available market opportunity for SSL to compete with conventional lighting technologies within each of the CRI bins. To calculate this estimate, three categories of available lumen-hours of lighting market are evaluated in the model:

- *New Construction* — new fixtures installed each year due to floor space growth in each sector, determined by the NEMS growth projection (see section 2.2 of this report) and the apportionment of lighting intensity per unit floor space. For the lumen-hours of service in this category, SSL competes with conventional technologies on a lamp plus fixture cost basis. That is, the costs considered include the cost of the lamp, fixture, and ballast (if appropriate) for both the incumbent conventional technology and the SSL technology.

- *Replacements* — lamps that burn out and are replaced during a calendar year. This calculation of the available lighting market is based on a comparison of the operating hours of the lighting technologies and the lamps servicing the stakeholder needs. For this analysis, similar to how integrated-ballast compact fluorescent lamps are a direct replacement for general service incandescent lamps, the model assumes that companies developing SSL technology will produce lamps that match conventional technologies and are able to be installed directly into existing lighting fixtures (see discussion below). Thus, in the replacement market, SSL systems (including the cost of the driver electronics or 'ballast') competes with conventional lighting technologies (including the initial cost of the lamp[13]).

- *Retrofits* — lamps 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 5 percent each year in each sector, or a mean retrofit cycle of 20 years. As with the new construction category, in this retrofit market, SSL systems will compete with conventional lighting technologies on a basis that is inclusive of new fixture costs.

For the replacement lamps category, a simplifying assumption is made that SSL lamps will be designed to be installed directly into conventional lighting fixtures, in place of incandescent lamps or fluorescent tubes. This simplifying assumption was made because it isn't possible to anticipate exactly what products may be available in the future market. In today's market for example, there are SSL lamps that can be installed directly into these sockets as direct replacements for MR-16, A-19, and T8 lamps. This assumption of being directly replaceable was necessary in order to compete SSL and conventional technologies on a socket-availability basis in the lighting market model.

Considering end-users who may retire less efficient equipment early due to a desire to achieve energy savings, the lighting market model does not account for these end-users separately. These voluntary-upgrade end-users are captured and represented in the fixed 5 percent of lumen demand retrofits calculated annually.

[13] Except for integrally ballasted CFLs, where the replacement CFL price includes the ballast that operates the lamp.

These three components — new construction, replacements and retrofits — are summed together to determine the total available market in each sector, as illustrated in Figure 3-1 for the first year of the analysis period. As discussed above, in the market model cost-assessment calculation, new construction and retrofits incorporate both a lamp and a fixture price while replacements only consider the lamp price.

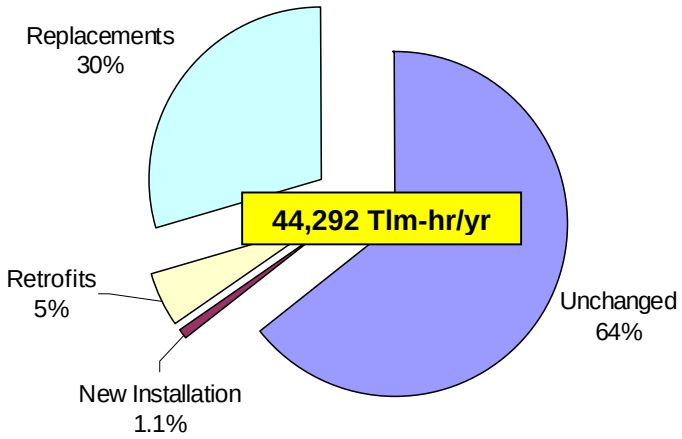


Figure 3-1. Annual Lumen-Hour Market Turnover in 2010

Note that as shown in Figure 3-1, approximately 38.1 percent of the installed annual lumen-hour demand is replaced or installed in 2010. This installed base turnover rate determines the maximum penetration rate of any new lighting technology. As longer-life SSL technologies begin penetrating into the market over the analysis period, the turnover occurs more slowly because there are fewer lamp failures in a given year. Thus, in percentage terms, the available lumen market in 2010 is larger than that in 2030. This holds true for the reference case and the SSL scenarios, as the lamp lives of both the conventional technologies and the SSL lamps are assumed to improve over the analysis period (see Chapters 4 and 5). The computer model follows the purchasing decisions of lighting consumers annually from 2010 to 2030, and the lighting stock turnover (i.e., the available lumen market) is adjusted by the model based on the lamp life of the lighting technologies selected and installed.

With a projected lumen-hour demand and an estimate of lumen-hour capacity available in the market for installation 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 SSL sources, and general market demand, the performance and cost characteristics of conventional lighting technologies are expected to improve over the 20-year analysis period. Changes are introduced linearly as percentage improvements over the analysis period, 2010 to 2030. The model adjusts (i.e., improves) the lamp efficacy, operating life, and first cost for the three primary groups of conventional lighting technologies — incandescent/halogen, fluorescent, and high intensity discharge.

For this study, three conventional lighting technology improvement scenarios were evaluated — low, medium and high. Table 4-1 presents the assumed percentage improvements in each of the critical performance and cost parameters for these three scenarios. These improvement scenarios for the conventional lighting technologies are based on conversations with industry researchers studying efficacy and other improvements to those technologies. The default scenario used in the analysis (for which all the analysis results are presented in this report) is the medium baseline.

Table 4-1. Technological Improvement Potential for Conventional Technologies

Change between 2010 and 2030		Incandescent	Fluorescent	High Intensity Discharge
Low Baseline Scenario	Efficacy (lm/W)	2%	2%	10%
	Lamp life	5%	5%	10%
	Lamp price	-5%	-5%	-5%
Medium Baseline Scenario	Efficacy (lm/W)	5%	5%	15%
	Lamp life	10%	10%	15%
	Lamp price	-10%	-10%	-10%
High Baseline Scenario	Efficacy (lm/W)	10%	10%	20%
	Lamp life	15%	15%	20%
	Lamp price	-15%	-15%	-15%

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 SSL is relatively small because these are mature technologies (particularly incandescent and fluorescent) and many have already been in competition with each other (particularly fluorescent and high intensity discharge). For simplicity, the percent performance improvements over the analysis period (2010 to 2030) are introduced linearly.

In order to more closely assess how these performance changes actually impact the technologies used in the analysis, the base year (2010) and target year (2030) spreadsheet tables are constructed in the model to introduce the improvements over the analysis period into each of the four sectors. The following tables present the performance improvement in the base year and in 2030. Lighting technologies not appearing in the tables for any given sector indicate that the Lighting Market Characterization (DOE, 2002) did not

record any lighting use for that lighting technology in that sector.

Table 4-2. Residential Sector Conventional Technologies Improvement, 2010 and 2030

				Baseline Technology 2010			Medium Technology Improvement Potential by 2030		
Lamp Types	Mean Watts (W)	CRI	Fixture Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)
Incandescent							**5%**	**10%**	**-10%**
Standard - General Service	63	100	17.80	13	1.2	0.60	13.7	1.3	0.54
Standard - Reflector	102	100	17.80	13	2.0	2.75	13.7	2.2	2.48
Halogen - General Service	57	100	17.80	16	3.0	3.50	16.8	3.3	3.15
Halogen - Reflector	91	100	17.80	15	2.5	3.00	15.8	2.8	2.70
Halogen - Reflector Low Volt	-	-	-	-	-	-	-	-	-
Low Wattage (< 25W)	-	-	-	-	-	-	-	-	-
Fluorescent							**5%**	**10%**	**-10%**
T5	-	-	-	-	-	-	-	-	-
T8 - less than 4 ft	-	-	-	-	-	-	-	-	-
T8 - 4 ft	32	80	59.40	83	20.0	2.00	87.2	22.0	1.80
T8 - more than 4 ft	-	-	-	-	-	-	-	-	-
T8 - U-bent	-	-	-	-	-	-	-	-	-
T12 - less than 4 ft	-	-	-	-	-	-	-	-	-
T12 - 4 ft	41	70	59.40	68	20.0	1.50	70.9	22.0	1.35
T12 - more than 4 ft	-	-	-	-	-	-	-	-	-
T12 - U-bent	-	-	-	-	-	-	-	-	-
Compact - Plug-in	-	-	-	-	-	-	-	-	-
Compact - Screw-in	18	82	17.80	55	10.0	3.00	57.8	11.0	2.70
Compact - Plug-in Reflector	-	-	-	-	-	-	-	-	-
Compact Screw-in Reflector	11	82	17.80	55	10.0	5.25	57.8	11.0	4.73
Circline	-	-	-	-	-	-	-	-	-
Induction Discharge	-	-	-	-	-	-	-	-	-
Miscellaneous Fluorescent	-	-	-	-	-	-	-	-	-
High Intensity Discharge							**15%**	**15%**	**-10%**
Mercury Vapor	179	45	60.00	38	24.0	15.00	43.1	27.6	13.50
Metal Halide	-	-	-	-	-	-	-	-	-
High Pressure Sodium	79	22	60.00	100	20.0	12.00	115.0	23.0	10.80
Low Pressure Sodium	-	-	-	-	-	-	-	-	-

Note: dash ("-") indicates no data for that light source and this end-use sector combination.

Table 4-3. Commercial Sector Conventional Technologies Improvement, 2010 and 2030

				Baseline Technology 2010			Medium Technology Improvement Potential by 2030		
Lamp Types	Mean Watts (W)	CRI	Fixture Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)
Incandescent							**5%**	**10%**	**-10%**
Standard - General Service	83	100	14.20	14	2.5	1.00	14.7	2.8	0.90
Standard - Reflector	104	100	14.20	14	2.0	2.75	14.7	2.2	2.48
Halogen - General Service	75	100	14.20	17	2.8	3.50	17.9	3.0	3.15
Halogen - Reflector	150	100	14.20	20	3.5	3.00	21.0	3.9	2.70
Halogen - Reflector Low Volt	48	100	14.20	13	4.0	3.75	13.7	4.4	3.38
Low Wattage (< 25W)	15	100	14.20	10	2.5	0.65	10.5	2.8	0.59
Fluorescent							**5%**	**10%**	**-10%**
T5	28	82	100.00	95	20.0	8.50	99.8	22.0	7.65
T8 - less than 4 ft	23	80	80.00	66	17.5	3.00	69.3	19.3	2.70
T8 - 4 ft	33	80	85.00	83	20.0	2.00	86.6	22.0	1.80
T8 - more than 4 ft	50	68	85.00	84	13.8	6.00	88.2	15.1	5.40
T8 - U-bent	34	80	70.00	81	20.0	7.50	85.1	22.0	6.75
T12 - less than 4 ft	29	71	80.00	60	12.8	2.25	63.0	14.0	2.03
T12 - 4 ft	45	70	85.00	68	20.0	1.50	70.9	22.0	1.35
T12 - more than 4 ft	93	76	85.00	69	14.5	3.50	71.9	16.0	3.15
T12 - U-bent	46	67	70.00	64	15.0	5.50	67.2	16.5	4.95
Compact - Plug-in	17	82	17.80	60	15.0	3.00	62.5	16.5	2.70
Compact - screw-in	16	82	17.80	55	10.0	3.00	57.8	11.0	2.70
Compact - Plug-in Reflector	16	82	17.80	55	10.0	5.25	57.8	11.0	4.73
Compact Screw-in Reflector	16	82	17.80	55	10.0	5.25	57.8	11.0	4.73
Circline	30	73	17.80	60	11.0	3.50	63.0	12.1	3.15
Induction Discharge	-	-	-	-	-	-	-	-	-
Miscellaneous Fluorescent	18	80	50.00	55	10.0	2.25	57.8	11.0	2.03
High Intensity Discharge							**15%**	**15%**	**-10%**
Mercury Vapor	200	45	70.00	43	24.0	21.00	49.5	27.6	18.90
Metal Halide	472	65	110.00	80	20.0	17.00	92.0	23.0	15.30
High Pressure Sodium	260	22	70.00	100	20.0	12.00	115.0	23.0	10.80
Low Pressure Sodium	104	10	70.00	113	18.0	22.00	129.4	20.7	19.80

Note: dash ("-") indicates no data for that light source and this end-use sector combination.

Table 4-4. Industrial Sector Conventional Technologies Improvement, 2010 and 2030

				Baseline Technology 2010			Medium Technology Improvement Potential by 2030		
Lamp Types	Mean Watts (W)	CRI	Fixture Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)
Incandescent							**5%**	**10%**	**-10%**
Standard - General Service	126	100	14.20	16	2.5	1.00	16.8	2.8	0.90
Standard - Reflector	102	100	14.20	14	2.0	2.75	14.7	2.2	2.48
Halogen - General Service	-	-	-	-	-	-	-	-	-
Halogen - Reflector	185	100	14.20	25	3.5	3.00	26.3	3.9	2.70
Halogen - Reflector Low Volt	58	100	14.20	13	4.0	3.75	13.7	4.4	3.38
Low Wattage (< 25W)	19	100	14.20	10	2.5	0.65	10.5	2.8	0.59
Fluorescent							**5%**	**10%**	**-10%**
T5	28	82	100.00	95	20.0	8.50	99.8	22.0	7.65
T8 - less than 4 ft	23	80	53.00	66	17.5	3.00	69.3	19.3	2.70
T8 - 4 ft	31	80	59.40	83	20.0	2.00	86.6	22.0	1.80
T8 - more than 4 ft	53	68	59.40	84	13.8	6.00	88.2	15.1	5.40
T8 - U-bent	32	80	41.60	81	20.0	7.50	85.1	22.0	6.75
T12 - less than 4 ft	32	71	53.00	60	12.8	2.25	63.0	14.0	2.03
T12 - 4 ft	44	70	59.40	68	20.0	1.50	70.9	22.0	1.35
T12 - more than 4 ft	95	76	59.40	69	14.5	3.50	71.9	16.0	3.15
T12 - U-bent	46	67	41.60	64	15.0	5.50	67.2	16.5	4.95
Compact - Plug-in	31	82	17.80	60	15.0	3.00	62.5	16.5	2.70
Compact - Screw-in	14	82	17.80	55	10.0	3.00	57.8	11.0	2.70
Compact - Plug-in Reflector	-	-	-	-	-	-	-	-	-
Compact Screw-in Reflector	14	82	17.80	55	10.0	5.25	57.8	11.0	4.73
Circline	35	73	17.80	60	11.0	3.50	63.0	12.1	3.15
Induction Discharge	-	-	-	-	-	-	-	-	-
Miscellaneous Fluorescent	34	80	50.00	55	10.0	2.25	57.8	11.0	2.03
High Intensity Discharge							**15%**	**15%**	**-10%**
Mercury Vapor	225	45	70.00	43	24.0	21.00	49.5	27.6	18.90
Metal Halide	438	65	110.00	80	20.0	17.00	92.0	23.0	15.30
High Pressure Sodium	258	22	70.00	100	20.0	12.00	115.0	23.0	10.80
Low Pressure Sodium	90	10	70.00	113	18.0	22.00	129.4	20.7	19.80

Note: dash ("-") indicates no data for that light source and this end-use sector combination.

Table 4-5. Outdoor Stationary Conventional Technologies Improvement, 2010 and 2030

				Baseline Technology 2010			Medium Technology Improvement Potential by 2030		
Lamp Types	Mean Watts (W)	CRI	Fixture Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)	Mean Efficy. (lm/W)	Lamp Life (khrs)	Lamp Price ($)
Incandescent							**5%**	**10%**	**-10%**
Standard - General Service	138	100	14.20	16	2.5	1.00	16.8	2.8	0.90
Standard - Reflector	103	100	14.20	14	2.0	2.75	14.7	2.2	2.48
Halogen - General Service	-	-	-	-	-	-	-	-	-
Halogen - Reflector	167	100	14.20	18	3.5	3.00	18.9	3.9	2.70
Halogen - Reflector Low Volt	-	-	-	-	-	-	-	-	-
Low Wattage (< 25W)	-	-	-	-	-	-	-	-	-
Fluorescent							**5%**	**10%**	**-10%**
T5	-	-	-	-	-	-	-	-	-
T8 - less than 4 ft	-	-	-	-	-	-	-	-	-
T8 - 4 ft	-	-	-	-	-	-	-	-	-
T8 - more than 4 ft	105	68	59.40	84	14.4	6.00	88.2	15.1	5.40
T8 - U-bent	-	-	-	-	-	-	-	-	-
T12 - less than 4 ft	-	-	-	-	-	-	-	-	-
T12 - 4 ft	-	-	-	-	-	-	-	-	-
T12 - more than 4 ft	190	76	59.40	69	15.2	3.50	71.9	16.0	3.15
T12 - U-bent	-	-	-	-	-	-	-	-	-
Compact - Plug-in	-	-	-	-	-	-	-	-	-
Compact - Screw-in	-	-	-	-	-	-	-	-	-
Compact - Plug-in reflector	-	-	-	-	-	-	-	-	-
Compact Screw-in reflector	-	-	-	-	-	-	-	-	-
Circline	-	-	-	-	-	-	-	-	-
Induction Discharge	-	-	-	-	-	-	-	-	-
Miscellaneous Fluorescent	150	80	50.00	55	10.0	2.25	57.8	11.0	2.03
High Intensity Discharge							**15%**	**15%**	**-10%**
Mercury Vapor	215	45	70.00	43	24.0	21.00	49.5	27.6	18.90
Metal Halide	311	65	110.00	80	20.0	17.00	92.0	23.0	15.30
High Pressure Sodium	216	22	70.00	100	20.0	12.00	115.0	23.0	10.80
Low Pressure Sodium	180	10	70.00	113	18.0	22.00	129.4	20.7	19.80

Note: dash ("-") indicates no data for that light source and this end-use sector combination.

5. Solid-State Lighting Technology Improvements

The U.S. Department of Energy worked with the Next Generation Lighting Industry Alliance (NGLIA), the National Electrical Manufacturers Association (NEMA), several national laboratories, and numerous researchers to develop technology roadmaps for both LEDs and OLEDs. The roadmap is contained in the DOE's SSL R&D Multi-Year Program Plan, which was published in March 2009 and is available on the Web.[14] (DOE, 2009) This multi-year program plan provided the basis for the SSL price and performance curves analyzed and presented in this report. The multi-year program plan provided projections of SSL performance and price through 2015 — these trends were then extended out 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.

For the SSL technology improvement curves, the national lighting market model does not allow for competition between LED and OLED devices, therefore energy savings calculations were performed separately on each technology. The energy savings were calculated using the LED price and performance projections and then using the OLED price and performance projections. In addition, the model makes an analytical assumption that both now and in the future, SSL manufacturers will be able to develop lamps with performance attributes similar to conventional lamps, and these sources will install directly into existing sockets. For example, consider a general service incandescent lamp, A-19. A self-ballasted LED lamp that has a cluster of LEDs in place of the tungsten filament could be fabricated as a direct replacement for that incandescent A-19 lamp. Similarly, a self-ballasted OLED lamp could be created for example, where the OLED material is deposited directly onto the surface of the pear-shaped glass bulb, and the resulting light emission pattern resembles that of a frosted incandescent A-19 lamp.

Generally, LEDs have the potential to be used in both directional and point source installations and distributed light installations, when used in conjunction with a diffuser technology. OLED technology has the potential to be used in distributed applications, such as those serviced by fluorescent lamps. However, the lighting market spreadsheet model does not track lighting service by point or distributed application, as data on the proportions of each (by installation) are not available. Therefore, this analysis competes the LED and OLED technologies against conventional lighting technologies separately, calculating the energy savings under each scenario. The analysis did not compete LED against OLED.

From a technical perspective, it is recognized that in terms of device performance (e.g., efficacy, cost, and operating life), OLED technology is currently trailing that of LEDs. OLEDs are available in the marketplace in 2009, but not for general illumination purposes as LED devices are. Today's OLED market is focused on developing products for display applications such as cell-phones, TVs, and portable computers. However, in the long-term, OLED devices are expected to achieve high efficacy in white-light production (see Appendix A). That said, operating life and cost are also projected in the model, which shows they will have countervailing impacts on the market acceptance of OLEDs. Although shorter than LEDs in the near-term, the operating life of OLEDs is projected to be the same as LEDs (50,000 hours) in the longer term. In addition, although more expensive initially, the first-cost of OLEDs is projected to be similar to that of LEDs in the long-term due to the anticipated ability to continuously manufacture OLED panels. Having a lower first cost would enhance the market potential of OLEDs, and would encourage end-users to adopt high-efficacy devices as replacements for conventional lighting technologies.

SSL technology improvement curves were adapted from DOE's Multi-Year Program Plan for 2009,

[14] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf

which had been developed by DOE in consultation with experts from industry for both LEDs and OLEDs, analyzing three critical performance metrics:

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

In order to prepare an energy savings estimate of the impact of SSL on the general illumination lighting market, this analysis considered the energy savings of LED and OLED separately, relative to a baseline of business-as-usual with conventional lamps. This baseline depicts the market in the absence of SSL, but includes the same underlying assumptions of conventional lamp technology improvement over time. The following table provides some detail on the modeling of the baseline and the SSL energy savings scenarios.

Table 5-1. SSL Market Scenario Descriptions and Maximum Price and Performance Values in 2030

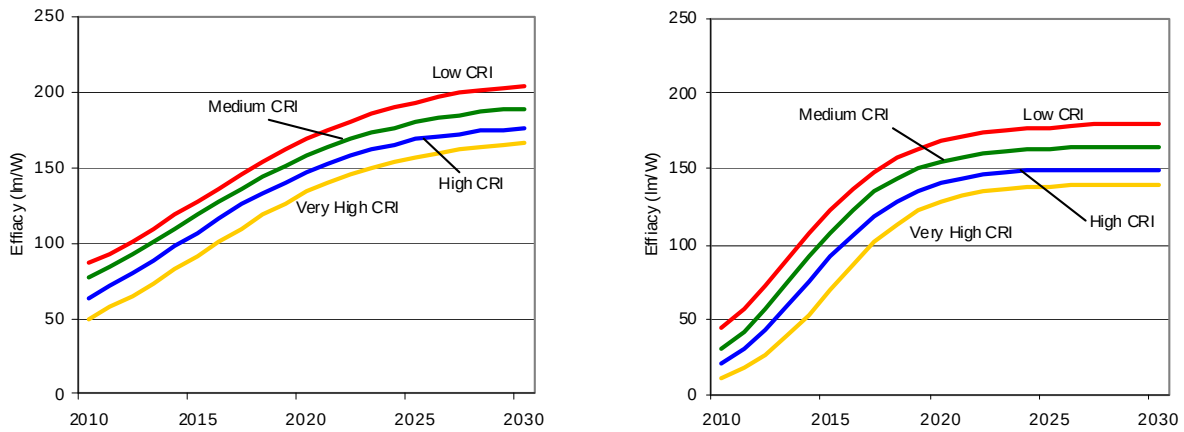
General	Discussion	CRI Bin	System Efficacy* (lm/W)	System Price* ($/klm)	System Life* (khrs)
Baseline — all SSL penetration set to zero	This scenario considers the energy consumption of the lighting market if SSL did not exist, and conventional lighting improves according to the moderate conventional technology improvement scenario selected. This scenario establishes a baseline against which the energy consumption of the other scenarios are compared.	n/a	n/a	n/a	n/a
LED	The LED scenario maintains a differential in price and performance between the four CRI bins,* and matches the system efficacy and price levels with DOE's MYPP for the Medium CRI bin from 2010 through 2020 (DOE, 2009). The MYPP does not project performance to 2030, therefore, an estimate was developed for performance in that year. The 2030 estimate is presented in this table and detailed numerical values of these projections can be found in Appendix A.	Low	204	$ 2.72	50
		Med	190	$ 4.22	50
		High	176	$ 5.03	50
		V.High	166	$ 6.15	50
OLED	The OLED scenario also maintains a differential in price and performance between the four CRI bins.* The OLED projections are based around matching DOE's MYPP for the Medium CRI bin from 2010 through 2015 (DOE, 2009). The MYPP does not project performance to 2030, nor does it project OLED efficacy beyond 150 lumens per watt, however for the purposes of this analysis, a level comparable to LED was considered.	Low	180	$ 3.52	50
		Med	165	$ 4.53	50
		High	150	$ 5.54	50
		V.High	140	$ 6.56	50

*Note: the values presented in this table maximum achieved levels of commercially available product by 2030. Based on the application of projections of one CRI bin over the next 5 to 10 years in DOE's multi-year program plan for SSL R&D (DOE, 2009), a curve-fit was applied to the forecast efficacy, price, and operating life. Values for the other CRI bins were derived from relative differences between the CRI bins published in the previous report on energy savings from SSL in general illumination (DOE, 2006). It should be noted that the efficacy values and prices presented in this table include the losses from and costs of electronic controls/drivers.

The DOE's MYPP projections of price and performance are developed through a collaborative effort between industry, academia, research laboratories, and the U.S. government.[15] The MYPP does not project SSL price and performance to 2030, nor does it provide differentiation of SSL technologies and performance by CRI bin. Rather, the MYPP provides a projection for a defined quality of light (e.g., cool-white luminaires are represented by a CRI of between 70 and 80, and a CCT of 4100-6500°K) over a specific time period. Taking that forecast which is represented by the Medium CRI bin (41 to 75) in this model, the SSL price and performance curves were adjusted until they matched the published MYPP values for that CRI bin. The other three CRI bins were then brought into alignment with the MYPP-fitted curve.

In both scenarios, the SSL technology S-Curves for each CRI bin improve in the following order — low CRI improves first, then medium, then high and finally, very high CRI. LED technology in the low-CRI bin has been under development for several decades and has already made considerable progress improving its price and performance. The performance of LED in medium, high, and very high CRI applications will lag behind low-CRI applications because these better-quality white-light sources are in earlier stages of development and the technological complexity and hurdles are greater. For OLEDs, the technology is lagging behind that of LEDs and there is uncertainty whether it can achieve the same price and performance levels of LEDs. For that reason, the 2030 values of OLEDs are lower than those of LEDs.

The following graphs present the assumed system performance improvement of LEDs and OLEDs lamps over the analysis period. The plot has four lines representing the performance of SSL technology in each of the four CRI bins. These illustrations are followed by tables, providing the actual values in five-year increments. In addition, Appendix A presents the actual values used for LEDs and OLEDs over the 20-year analysis period.



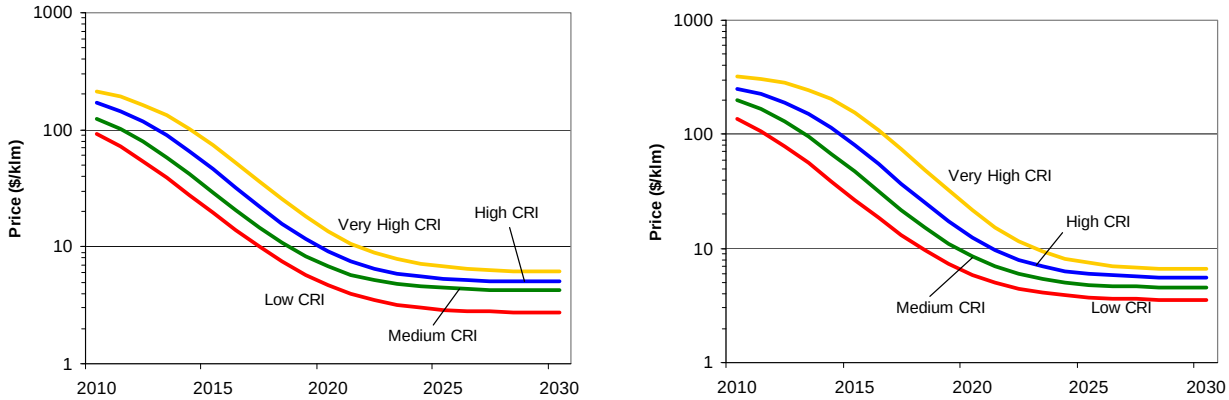
LED Efficacy Projection *OLED Efficacy Projection*

Figure 5-1. Commercialized SSL Efficacy Improvements for the SSL Scenarios

[15] 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

Figure 5-1 provides the performance improvement curves for SSL efficacy in the two scenarios. As discussed earlier, OLED performance (including efficacy) lags behind that of LED, and there is some uncertainty whether it can achieve the same efficacy levels as LED. For the OLED curves, the experts believe that the higher-quality white lights (i.e., medium, high, and very high CRI) will be more difficult to develop than the low CRI sources, as depicted in the performance improvement curves above. For more information on the projection of OLED devices and the technological barriers faced for this technology, please see DOE's SSL R&D multi-year program plan (DOE, 2009).

Figure 5-2 represents the price improvement forecasts for each of the scenarios. Note that these curves depict the price reduction from a high initial first cost to a lower projected first cost. Due to the difference in scale between 2010 and 2030, these curves are plotted against a logarithmic Y-axis. This format enables better comparison of the terminal values for LEDs and OLEDs, which are similar.

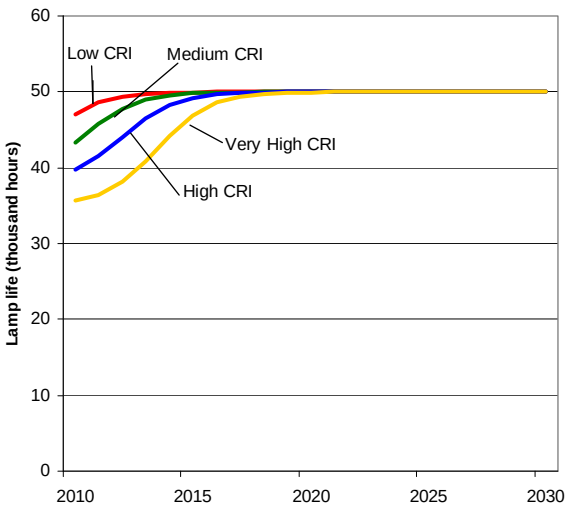


LED Price Projection *OLED Price Projection*

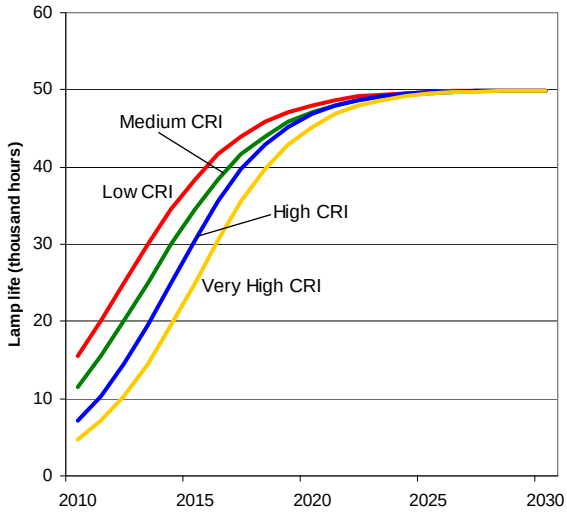
Figure 5-2. Commercialized SSL Price Improvements for the SSL Scenarios

Due to the comparative maturity of the LED technology and marketplace, the LED price projection has lower prices in the time period up through 2020. While OLEDs are more expensive initially, they eventually do achieve (approximately by 2025) a price point similar to that of LED. Having a low first cost is critical to achieving market penetration (and therefore, energy savings), particularly for first cost sensitive sectors such as the residential sector.

Figure 5-3 presents the SSL operating life projected for the two scenarios. In the most recent update of the multi year program plan, the OLED Technical Committee determined that the operating life of OLEDs should reach 50,000 hours, similar to the projected operating life for LEDs. Although some manufacturers of LED products are claiming 75,000-hour operating lives now, the DOE/NGLIA team did not discuss operating lives for SSL beyond 50,000 hours, and therefore these values represent the upper limits for this analysis. LEDs are projected to have a more rapid ascent to their ultimate target, again due to the relative maturity of this technology.



LED Life Projection



OLED Life Projection

Figure 5-3. Commercial Sector SSL Lamp Life Improvements for the SSL Scenarios

The following series of tables present the price and efficacy values for SSL technology used in each of the analysis scenarios. The first two tables provide the normalized initial price improvement ($ per kilolumen) of SSL over the analysis period for each of the CRI bins. These prices include the SSL device plus the controlling electronics / power supply. Fixture costs are added separately. For complete transparency of the inputs used in this study, detailed versions of these tables providing year-on-year results are provided in Appendix A.

Table 5-2. LED Price Improvements for the SSL Scenarios

$ per kilolumen	2010	2015	2020	2025	2030
Low CRI (<40)	$ 91.35	$ 19.61	$ 4.65	$ 2.91	$ 2.72
Med CRI (41-75)	$ 125.16	$ 29.24	$ 6.77	$ 4.44	$ 4.22
High CRI (76-90)	$ 169.49	$ 46.05	$ 9.05	$ 5.34	$ 5.03
Very High CRI (91-100)	$ 213.68	$ 74.38	$ 13.54	$ 6.73	$ 6.15

Table 5-3. OLED Price Improvements for the SSL Scenarios

$ per kilolumen	2010	2015	2020	2025	2030
Low CRI (<40)	$ 136.75	$ 26.70	$ 5.90	$ 3.73	$ 3.52
Med CRI (41-75)	$ 198.41	$ 46.77	$ 8.52	$ 4.83	$ 4.53
High CRI (76-90)	$ 250.12	$ 81.28	$ 12.54	$ 6.01	$ 5.54
Very High CRI (91-100)	$ 324.42	$ 154.36	$ 21.59	$ 7.46	$ 6.56

As shown in Table 5-2 and Table 5-3, the price difference between LEDs and OLEDs is more evident in the near-term, 2010 and 2015. The differences between LED and OLED start to converge around 2020, with OLEDs costing only slightly more (at most one dollar per kilolumen) than LEDs by 2025. In the final year of analysis (2030), the retail prices (inclusive of SSL device, driver, fixture and optics) are similar, as reflected in these tables.

Table 5-4 and Table 5-5 provide the efficacy improvement curves for SSL technology used in each of the analysis scenarios. As discussed earlier, the OLED technology lags behind that of the LED technology in the near term, but it closes the gap around 2015. As discussed earlier, DOE's MYPP (DOE, 2009) does not contemplate OLED efficacy levels above 150 lumens per watt, therefore the ultimate value projected for OLEDs is lower than that of LEDs.

Table 5-4. LED Efficacy Improvements for the SSL Scenarios

Lumens per watt	2010	2015	2020	2025	2030
Low CRI (<40)	86.2	127.5	168.8	193.5	204.1
Med CRI (41-75)	77.7	118.5	157.6	180.3	189.8
High CRI (76-90)	64.3	107.1	147.3	168.5	176.3
Very High CRI (91-100)	50.2	91.6	133.5	156.8	165.8

Table 5-5. OLED Efficacy Improvements for the SSL Scenarios

Lumens per watt	2010	2015	2020	2025	2030
Low CRI (<40)	43.6	122.6	168.2	178.1	179.7
Med CRI (41-75)	30.8	107.7	154.9	163.7	164.8
High CRI (76-90)	21.3	91.6	140.6	148.9	149.9
Very High CRI (91-100)	11.6	70.0	128.4	138.9	139.9

Finally, Table 5-6 and Table 5-7 provide a comparison of the SSL operating life assumed in these two scenarios. As discussed earlier in this document and in the SSL R&D multi-year program plan (DOE, 2009), LEDs are not subject to the encapsulation challenges that OLEDs experience. For example, reactions caused by permeation of air and water into the OLED materials can reduce the operating life of the device. However, the technical team supporting the SSL R&D multi-year program plan believes that in spite of this, OLED lamps will have operating lives that approach that of LED.

Table 5-6. LED Operating Life Improvements for the SSL Scenarios

Thousand hours	2010	2015	2020	2025	2030
Low CRI (<40)	47.1	50.0	50.0	50.0	50.0
Med CRI (41-75)	43.3	49.8	50.0	50.0	50.0
High CRI (76-90)	39.7	49.2	50.0	50.0	50.0
Very High CRI (91-100)	35.6	46.9	50.0	50.0	50.0

Table 5-7. OLED Operating Life Improvements for the SSL Scenarios

Thousand hours	2010	2015	2020	2025	2030
Low CRI (<40)	15.5	38.4	48.0	49.7	50.0
Med CRI (41-75)	11.6	34.5	47.1	49.6	49.9
High CRI (76-90)	7.1	30.5	46.9	49.6	50.0
Very High CRI (91-100)	4.8	25.0	45.2	49.5	49.9

6. Lighting Model Market Penetration

Each year, new lamps enter the market as old lamps are replaced or retrofitted. The net result is a turnover in "lumen stock" of 38 percent in the first year (see Figure 3-1). As the annual market is captured by more efficient lighting technology with long operating lives, the stock itself gradually becomes more efficacious and longer-lived, reducing the turnover in lumen stock. Thus, as new SSL lamps are installed, which tend to be longer-lasting than some of the conventional technologies, the lumen stock turnover diminishes slightly, as more and more sockets use these new SSL lamps.

Chapters 4 and 5 discuss how the model tracks the evolution of price and performance attributes for conventional lighting technologies and SSL, respectively. To simplify the analysis, it was assumed that SSL will eventually meet the requirements of any application, and that CRI must be matched with the conventional technology before it can compete for that socket.[16] In reality though, once SSL achieves a CRI milestone and is able to compete for available lumens in a CRI bin, it clearly must provide some financial or performance advantage over conventional technologies in order to achieve widespread penetration. This chapter discusses how the spreadsheet model accounts for price and operating cost considerations in the lighting market simulation.

The model is structured around four market sectors (residential, commercial, industrial, and outdoor stationary) and four CRI bins (low, medium, high, and very high). Each of these sixteen markets has a mix of applications, each with its own set of operating hours, illuminance levels, and blend of conventional technologies. These sixteen markets are further subdivided into thirty-two markets, i.e., 16 markets for those that only incorporate the lamp price (replacements) and 16 markets for those installations that incorporate both a lamp and an estimated fixture price for new installations and retrofits. The fixture costs are based on U.S. Census data for typical fixtures of incandescent, fluorescent, and HID lamp installations. For conventional sources, the fixture prices include ballast costs, if required. For SSL sources, these ballast costs have been deducted from the fixture prices, because the SSL cost per kilolumen already includes the cost of the driver electronics for the light source.

To allow us to consider these 32 markets in even finer detail, the model further divides each of these 32 markets into 35 sub-bins based on the initial price-per-kilolumen (e.g., 0–$0.50/klm, $0.51–$1.00/klm, $1.01–$1.50/klm, etc.). For example, consider the fact that there is a certain demand for high-CRI light in the residential sector replacement lamp market that is satisfied by several lighting sources. Each of these lamp sources has its own price per lumen, efficacy, annual operating hours, lamp life, and so on. By creating price sub-bins within the larger CRI and sector bins, the model develops a demand curve for certain sectors and CRI bins at specific price points. Furthermore, new and retrofit opportunities (i.e., incorporating fixture and lamp prices) are tracked separately from the replacement (i.e., lamp price only) opportunities. Thus, there are also 35 initial price per kilolumen bins (fixture and lamp) in each of the 16 markets for the lamp, ballast, and fixture price. In total then, the model evaluates 35 price sub-bins in 32 markets, ultimately evaluating market penetration opportunities for SSL technology in 1,120 sub-markets.[17]

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[16] SSL sources offer a degree of freedom that is not available from other light sources. For example, end-users could modify the color temperature, color rendering, and light output via computer-control input.

[17] The 1,120 sub-markets are the product of four sectors (Residential, Commercial, Industrial, and Outdoor Stationary), four CRI bins (Low, Medium, High, and Very High), two groups (Replacement, New and Retrofit) and 35 first cost sub-bins. New and retrofit market are treated as one market because they both incorporate fixture costs.

The model awards available market share to competing lighting technologies based on simple payback, or the ratio of first year incremental purchase price to first year incremental savings. While simple payback may not be the best method for deciding which new lighting technology to purchase, it has several advantages to other methodologies such as levelized lighting cost or life-cycle cost. First, if purchasers perform any mathematical financial evaluation at all, it is likely to be simple payback. Literature provides confirmation regarding the ranges of simple payback that purchasers consider acceptable in various sectors (LBNL, 1999). Second, simple payback has been found to be a fairly robust predictor of purchasing behavior across products when decisions are based on energy cost savings. Third, simple payback is an intuitive measure of financial return, thus making it easier to review the projections of the model. The simple payback calculation we use is as follows:

$$\text{Simple Payback (yr)} = \frac{-\,\Delta\text{Purchase Price (\$/klm)}}{\Delta\text{Annual Electricity Cost (\$/klm/yr)} + \Delta\text{Annual Lamp Replacement Cost(\$/klm/yr)}}$$

Where:

- The Δ represents the difference between the solid-state source and the established blend of competing conventional technologies in each sub-market.
- *Purchase Price* includes the lamp price and, in the case of the new and retrofit markets, the fixture price.
- *Annual Electricity Cost* is a function of the mean annual operating hours and efficacy for each sub-market, the sector electricity price, and the lumen demand.
- *Annual Lamp Replacement Cost* is a function of the mean lamp life, annual operating hours, and lamp price, as well as a labor charge.

Electricity prices used for the operating cost evaluation are derived from the Energy Information Administration's Annual Energy Outlook 2009 (Table 3. Energy Prices by Sector and Source), as presented in Table 6-1 (EIA, 2009). The electricity prices were inflated from 2007 to 2010 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.

Table 6-1. Electricity Price Projections in 2010 Dollars per Kilowatt-hour

$/kWh	2010	2015	2020	2025	2030
Residential electricity price	0.102	0.110	0.116	0.118	0.123
Commercial electricity price	0.089	0.092	0.099	0.101	0.106
Industrial electricity price	0.060	0.062	0.067	0.069	0.073
Outdoor Stationary electricity price	0.089	0.092	0.099	0.101	0.106

Source: EIA, 2009

Any simple payback period can elicit a range of responses in the market depending on the internal implicit discount rates of the purchasers. To capture the appropriate range of responses, this spreadsheet model uses market payback response curves developed by Arthur D. Little, Inc. These curves relate the mean payback to the fraction of the ultimate market captured. The curves are presented in Figure 6-1.

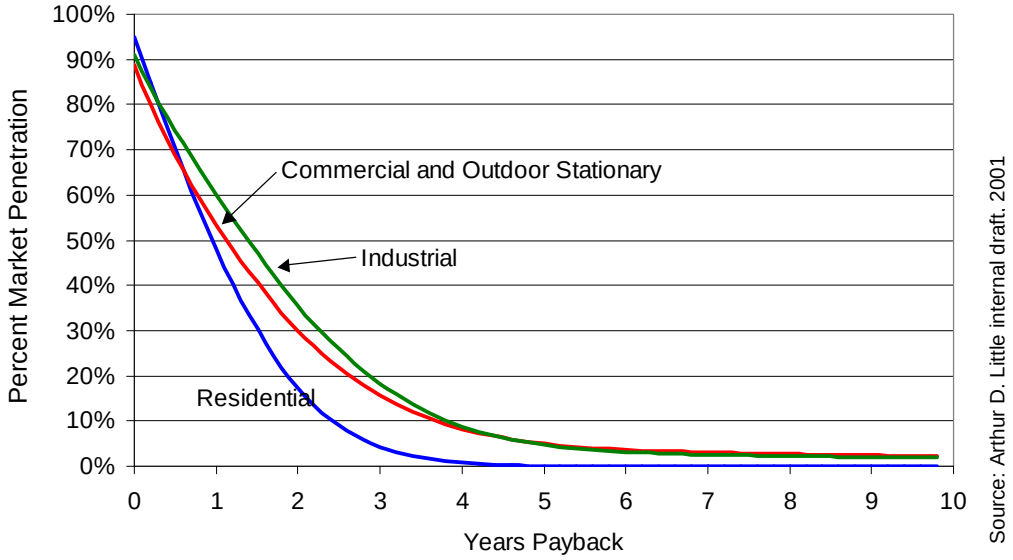

Figure 6-1. Market Response Curves Used to Determine Market Penetration

The curves are interpreted as follows — for the residential sector, if SSL technology were to offer the market a two-year payback, it would be awarded approximately 20 percent of the available market that year. Likewise, if SSL were to offer a one-year payback, it would be awarded approximately 45 percent of the available market. As evident in Figure 6-1, the residential curve is steeper than that of the commercial or industrial sectors, indicating that the residential sector is less willing to accept longer-term paybacks. For the outdoor stationary sector, the commercial sector payback curve was used. For a sensitivity analysis of a more aggressive (i.e., steeper) residential payback acceptance curve, please see Appendix B.

Depending on the comparative costs evaluated in the market penetration analysis, the simple payback calculation can have four possible outcomes, which are presented in Table 6-2.

Table 6-2. Purchase Decisions Based on SSL and Conventional Technology Comparison

SSL First Cost	SSL Operating Cost	SSL Market Penetration
Higher	Higher	Zero percent; no market penetration.
Higher	Lower	The result given by the market share penetration curve (Figure 6-1) is attributed to SSL.
Lower	Higher	The result given by the market share penetration curve (Figure 6-1) is attributed to the conventional technology.[18]
Lower	Lower	Economics compel sector to switch to SSL; maximum available market will switch to SSL.

In the fourth scenario presented in Table 6-2, the "maximum available market" switches to SSL. Under this condition, the model awards the maximum percentage market penetration to SSL, as defined by the market share penetration curves at zero years payback. For the residential sector, this represents 95 percent of the available lumens. For the commercial and outdoor stationary sectors, this represents 89 percent, and for the industrial sector, this represents 91 percent of the available lumens. No sector offers 100 percent market conversion to SSL because there are always groups of a particular sector who are slow to adopt a new technology, and may reject it for several years despite compelling economics and proven performance.

Furthermore, the model recognizes that even under the most ideal conditions, market penetration is not instantaneous. Due to the rapid development of SSL projected in our model, payback periods occasionally decline rapidly, implying a dramatic takeover of some sub-markets. This result is unlikely to occur because of the barriers inherent in ramping up manufacturing capacity, communicating benefits to lighting designers and purchasers, and stocking distribution channels. Thus, the model incorporates a market lag to distribute the market penetration award over time. The market lag function is calibrated such that a one-year market award is stretched over a period of five years, with an equal share (20 percent) of the penetration occurring each year over a five-year period. The lag function has the effect of smoothing out market penetration in the sub-markets, but has little effect on the overall results of the model, since those sub-markets that are affected most represent only a tiny fraction of the overall lighting demand.

[18] In this case, the conventional lighting technology is the one with the "payback," so the payback curves apply to the conventional technology rather than to SSL.

7. Stock Model and Energy Savings Calculation

The model's economic analysis engine competes the annually available teralumen-hours of lighting service between SSL lamps and fixtures and conventional sources. In each of the CRI bins and sectors, SSL lamps and fixtures gradually capture market share as their price and performance improves, and the technology becomes more competitive on a life-cycle cost basis. Figure 7-1 is an example of the output from the model for the commercial sector, lamps-only market. This is one of the eight primary economic markets[19] in the model. This diagram shows that as the LED technology improves over the analysis period, it captures an increasing percentage of the available commercial lamp market. In particular, very high CRI, the bin that is primarily represented by incandescent and halogen lamps, is shown to quickly be of interest to the commercial sector, with 80 percent or more of all replacement lamps being SSL around 2025. Low CRI LED technology then captures the market, replacing conventional sources like mercury vapor and high pressure sodium lamps. The low CRI LED technology is able to do this because its costs are rapidly declining, and its efficacy is projected to achieve 127 lm/W by 2015, 169 lm/W by 2020 and 193 lm/W by 2025 — all of which exceed the typical efficacy of the conventional sources in that color bin. In the high CRI bin, LED technology is competing with linear and compact fluorescent lamp technology, which are already efficacious, cost-efficient light sources, hence there is a delay in market penetration for the high CRI bin.

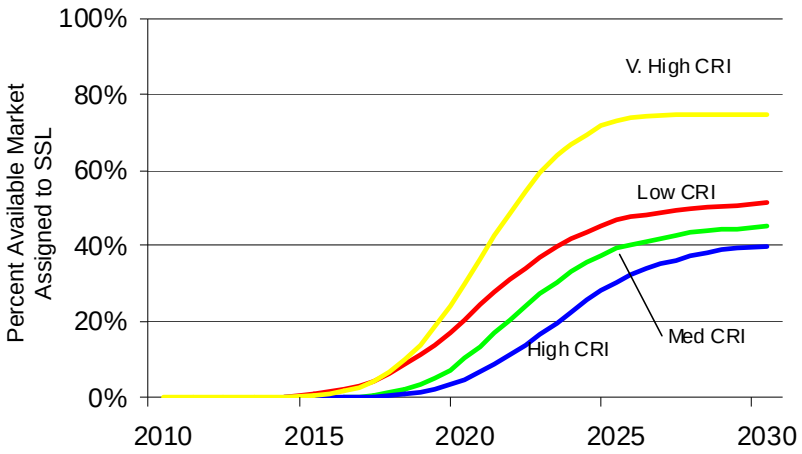

Figure 7-1. Commercial Sector Lamps Market Purchasing LED

The percent of available market awarded to SSL is a critical component of the estimated energy savings. The national energy savings are based on changes in the efficacy of the installed stock of national lighting technologies. Figure 7-2 illustrates the change in stock efficacy for the reference scenario and the LED energy savings scenario. In the reference scenario (i.e., baseline), no SSL technology enters the market and thus, lighting performance improves gradually, as the conventional technologies improve under the medium technology improvement scenario (see Chapter 4). In the LED energy savings scenario, efficacy improvements to the installed base of lighting technology in each CRI bin increase more rapidly due to improvements in both conventional lighting and SSL technologies. The influence of the market adopting

[19] The primary markets are differentiated by sector and whether the first cost includes just the lamp cost or the lamp cost and the fixture cost.

highly efficacious LED sources is clearly evident, for example, as the low CRI technology segment for the commercial sector shifts from a starting value of 83 lm/W in 2010 to 131 lm/W in 2030 under the LED scenario. Similarly, the installed stock of very high CRI lamps more than doubles its efficacy from a starting value of 14 lm/W in 2010 to 45 lm/W by 2030. Overall, under the LED scenario, the fleet average efficacy of lighting in the U.S. increases by 53 percent, going from 66 lm/W in 2010 to 103 lm/W in 2030. Under the OLED scenario, a similar trend is observed, with the fleet average efficacy increasing by 41 percent, going from 66 lm/W in 2010 to 94 lm/W in 2030.

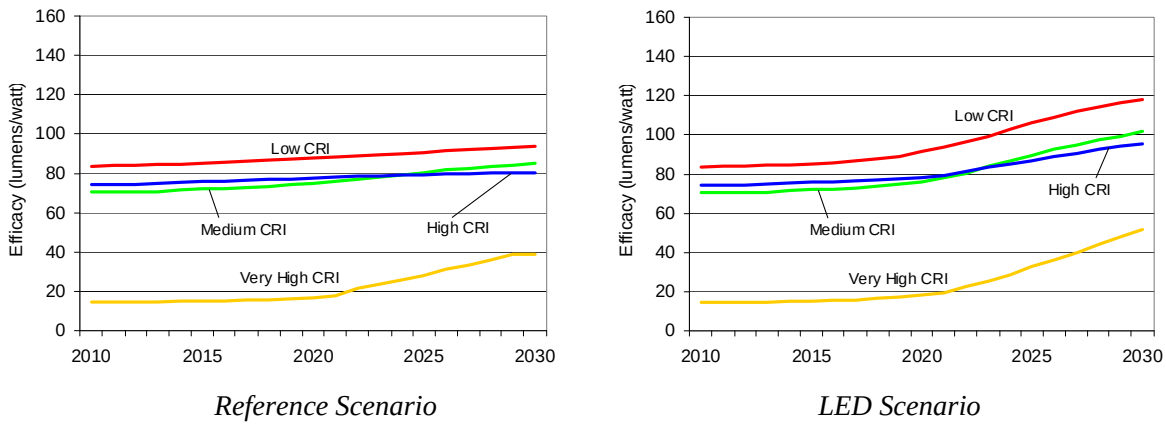

Figure 7-2. Stock Efficacy for CRI Bins for Reference and LED Scenarios

Furthermore, the stock lamp life also changes over time, as longer-lasting light sources, both conventional and SSL, are introduced into the lighting stock. And, as discussed in Chapter 3, the longer operating lives of the lamps installed will decrease the available lumen turnover over the analysis period. Starting from 36 percent socket turnover in 2010, the model projects a reduction to 34 percent turnover in 2030 under the reference scenario and 17 percent turnover in 2030 under the LED scenario. Figure 7-3 illustrates the impact on the average lamp life in the national inventory stock model over the analysis period. The change in lamp life is presented for the reference and the LED scenarios. As LED technology enters the market, with its longer operating life (50k hours assumed), the average lamp life stock of the national installed base increases. This increase is most dramatic for very-high CRI, which experiences a significant LED penetration, particularly in the commercial sector.

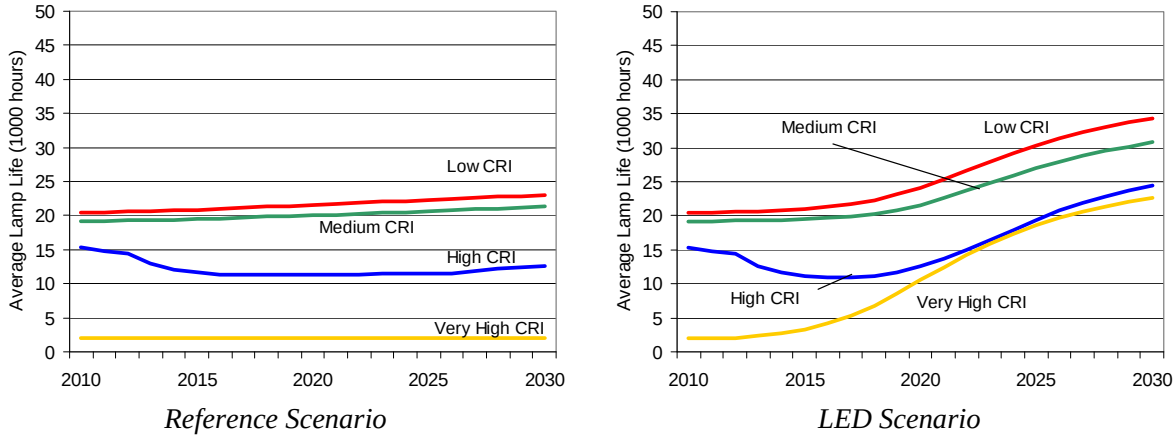

Figure 7-3. Stock Average Lamp Life by CRI Bin in Reference and LED Scenarios

As shown in Figure 7-3, the overall stock average lamp life increases gradually in the reference scenario, where the conventional technologies improve according to the medium performance improvement scenario discussed in Chapter 4. However, a more significant increase in lamp operating life is experienced by the installed base under the LED scenario, whereby low CRI improves by 75 percent from approximately 20,000 hours of average operating life to more than 30,000 hours over the analysis period. An increase of more than 20,000 hours is projected for the very high CRI lamps, which shifts from approximately 1,000 hours to nearly 26,000 by 2030. This shows that as SSL penetrates the marketplace in the accelerated investment scenario, the longer lamp life has an impact on the installed base average lamp life.

In Figure 7-3, in both the Reference and LED energy savings scenario, the average lamp life of High CRI decreases between 2010 and approximately 2015. The reason for this anticipated slight decrease in life is due to the shift from incandescent lamps to compact fluorescent lamps, which have a shorter anticipated lifetime than the T8 fluorescent lamps, that dominate that CRI bin. As the proportion of CFLs increases, the overall average operating life of the High CRI bin decreases slightly, but later improves under both scenarios (particularly the LED scenario, where long-life high CRI LEDs start to enter the market around 2015).

Figure 7-4 presents the projected national primary energy consumption by lighting through 2030[20] for the LED and OLED scenarios. The LED scenario shows greater energy savings in the near-term, with a departure from the reference line starting around 2015. The OLED scenario also begins to impact the general illumination market with approximately a one or two year lag. Note that, as discussed earlier, the LED and OLED scenarios are not competed with each other, but rather are competed independently against the reference scenario of conventional technologies.

In Figure 7-4, it is evident that the reference baseline of energy consumption shows two decreases in

[20] While projecting the energy consumption for lighting, we have assumed that the ratio of primary energy consumption to end-use electricity consumption remains constant at the 2005 forecasted level of 10,744 BTU/kWh (DOE Core Databook, 2003), which was used in the previous energy savings estimates reports (DOE, 2003 and DOE, 2006). This avoids confusion on energy savings resulting from power system efficiency gains versus those from more efficacious lighting sources, and enables comparability with previous studies.

energy consumption, between 2011 and 2020, and between 2020 and 2027. As discussed in section 2-2, the 2011–2020 reduction in baseline energy consumption reflects the effect of several regulatory standards: the U.S. DOE energy conservation standards on fluorescent lamp ballasts (65 FR 56740); general service fluorescent lamps and incandescent reflector lamps (74 FR 34080); and the legislative standards promulgated in EISA 2007 on general service incandescent lamps (Section 321) and metal halide lamp fixtures (Section 324). The second reduction in baseline energy consumption, occurring between 2020 and 2023, reflects a minimum standard contained in EISA 2007 that all general service lamps will achieve at least 45 lm/W (Section 321). By incorporating these regulatory standards into the baseline reference case, the energy consumed by lighting nationally will decrease, even as the lumen demand (see Section 2.2) is increasing. In other words, as consumers purchase these compliant products and install them, the absolute energy consumed for lighting declines, even as the lumen demand is increasing (see Figure 2-2).

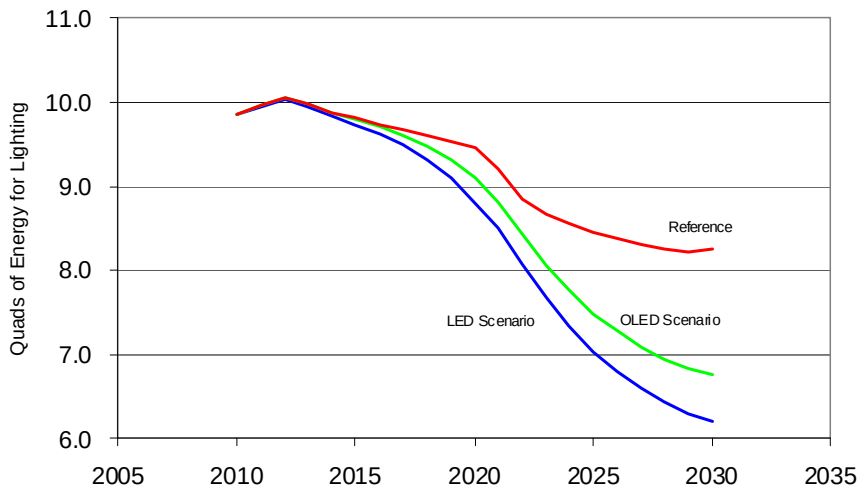

Figure 7-4. National Energy Consumption for Lighting through 2030 for Each Scenario (Quads)

Starting at the point when the energy efficiency regulations take effect, the competitive market into which LEDs and OLEDs are competing becomes considerably more difficult. As shown in Figure 7-4, between 2011 and 2015, the energy savings due to LED and OLED market penetration is relatively small, as SSL technologies have yet to achieve higher efficacy and lower price points in order to compete in the recently-regulated energy-efficient lighting market. Starting around 2016, the price and performance become sufficiently attractive that the forecasted energy consumption for lighting drops in absolute terms even as the lumens of service are increasing.

While the OLED scenario is slower in capturing energy savings, the scenario does anticipate energy savings that approach those of the LED scenario by the end of the analysis period (2030). This is due in part to the assumption that the technology will achieve the projected price and performance estimates discussed in this report. In addition, as both LEDs and OLEDs are projected to attain a 50,000-hour operating life, the available lumen turnover in any given year diminishes. This means that "early adopter" sockets of SSL technology get locked into that technology for long periods of service at the efficacy of the SSL sources at that time. The impact of the "early adopters" contributes to a slowing in the lumen market turnover, which reduces the number of opportunities for higher-efficacy SSL to enter the market.

This impact contributes to the reduction in slope of the energy consumption for both the LED and OLED scenarios in the final years of the analysis (see Figure 7-4).

Table 7-1 presents the energy savings terms of both quads of primary energy and terawatt-hours of site[21] electricity consumption.

Table 7-1. Energy Savings Estimates from LED and OLED Scenarios

(Quads of primary energy consumption and TWh of site electricity consumption)

Scenario	2015	2020	2025	2030	Cumulative (2010 - 2030)
Reference	9.81 quads 911 TWh	9.45 quads 878 TWh	8.46 quads 785 TWh	8.26 quads 768 TWh	n/a n/a
Quads of primary energy savings and TWh of site electricity savings relative to Reference					
LED Scenario	0.07 quads 7 TWh	0.65 quads 60 TWh	1.42 quads 132 TWh	2.05 quads 190 TWh	16.02 quads 1,488 TWh
OLED Scenario	0.01 quads 1 TWh	0.36 quads 33 TWh	0.96 quads 90 TWh	1.51 quads 140 TWh	10.49 quads 974 TWh

In the LED scenario, approximately 2.05 quads of primary energy, or about 190 TWh, can be saved annually by 2030. Under the OLED scenario approximately 1.51 quads of primary energy, or about 140 TWh can be saved. Compared to projected reference case energy consumption for lighting in 2030, the LED scenario represents a reduction of 25% and the OLED scenario, 18%. Both scenarios represent an actual reduction in lighting energy consumption (in absolute terms) compared to the start of the analysis period, 2010. In other words, in 2010 lighting energy consumption is estimated to be approximately 9.81 quads of energy. By 2030, under the LED and OLED scenarios, lighting energy consumption is estimated to be 6.22 quads and 6.76 quads, respectively, both well below the 2010 level.

As discussed in Chapter 4, three scenarios are considered for the performance improvement of the conventional (i.e., incandescent, fluorescent, and HID) lighting technologies. Table 7-2 provides the energy savings in 2030 for each of these baseline technology scenarios, compared to the LED and OLED scenarios. The variability in the two scenarios between the low and high conventional technology improvement scenarios relative to the medium scenario is about the same.

[21] This is the electricity consumed on the customer side of the electric meter. It does not include losses due to generation, transmission and distribution. The primary energy consumption value incorporates these losses.

Table 7-2. Variability of Energy Savings due to Conventional Technology Improvement

SSL Performance Scenarios	Low Improvement Conventional Technology	Medium Improvement Conventional Technology	High Improvement Conventional Technology
Reference (Quads for lighting in 2030)	8.70 Quads	8.26 Quads	8.10 Quads
LED Scenario (Quads ***saved*** in 2030)	2.42 Quads	2.05 Quads	1.89 Quads
OLED Scenario (Quads ***saved*** in 2030)	1.77 Quads	1.51 Quads	1.39 Quads

For LEDs, the range is +0.37 and -0.16 quads, indicative of the competitive nature of the market under each scenario. For OLEDs, the range is similar, at +0.26 and -0.12 quads. From these values, it is clear that as conventional technology improves, the market becomes more competitive (and more efficient), so the energy savings from SSL technology would diminish slightly. Under the low improvement scenario, the LEDs and OLEDs are able to capture more market share and thus increase the energy savings derived from the SSL technologies. However, for both the LED and OLED scenarios, even under the high degree of technological improvement for conventional technology,[22] the energy savings attributable to either SSL technology in 2030 is at least 1.39 quads.

To put these savings in perspective, a quad of energy saved is approximately equal to the average annual per capita energy consumption of 2.9 million people in the United States. Or, alternatively, it is equivalent to 167 million barrels of oil, or about 16 days of imported oil to the U.S.

The value of the energy savings that would accrue to lighting end-users is substantial. One quad of primary energy used to generate electricity for lighting in today's dollars is valued at approximately $8.3 billion. Thus, the potential financial benefit that would accrue to consumers from switching to energy-efficient SSL technology is significant. These same consumers would be paying more for their SSL lighting technology on a first cost basis, which would off-set some of these energy savings; however, as evaluated in this model (and shown in Figure 6-1), consumers would achieve acceptable payback periods and would save a significant amount of energy.

[22] The high improvement of conventional technology assumes that relative to 2010 values, by 2030 average efficacies of incandescent lamps have increased by 10 percent, efficacies of fluorescent lamps by 10 percent, and efficacies of HID lamps by 20 percent. The high-improvement scenario assumes that median operating life increases by 15 percent for incandescent, 15 percent for fluorescent, and 20 percent for HID lamps. Finally, lamp prices of the conventional technologies are all assumed to have reduced by 15 percent relative to 2010 prices for incandescent, fluorescent, and HID lamps.

8. Conclusions

Over the last few decades, advances in lighting technologies such as the development of T8 and T5 fluorescent tubes, electronic ballasts, pulse-start metal halide HID lamps and others have yielded considerable energy savings to the lighting market. Regulatory actions by Congress and the U.S. DOE have cemented those improvements into the U.S. lighting market, adopting minimum standards and thereby removing inefficient lighting products from the market. Over the coming decades, SSL sources promise to offer even greater energy savings if they achieve projected price and performance attributes. As SSL 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 SSL will be capable of satisfying general lighting requirements of the market by 2030, its market penetration and energy saving potential will be driven primarily by economics — taking into account the initial price, operating cost, maintenance, and lifetime. In both the LED and OLED scenarios, SSL displaces light sources in all sectors by the end of the analysis period, but the significant energy savings are primarily from the displacement of fluorescent lamps and halogen lamps in the commercial sector. As shown in Figure 8-1, the majority of the 190 TWh saved in 2030 under the LED scenario are derived from LED lamps and fixtures displacing fluorescent lamps (high CRI), particularly in the commercial sector, where operating hours are longer and end-users are more aware of full life-cycle cost. LEDs also penetrate the very high CRI bin in all four sectors, further contributing to the energy savings.

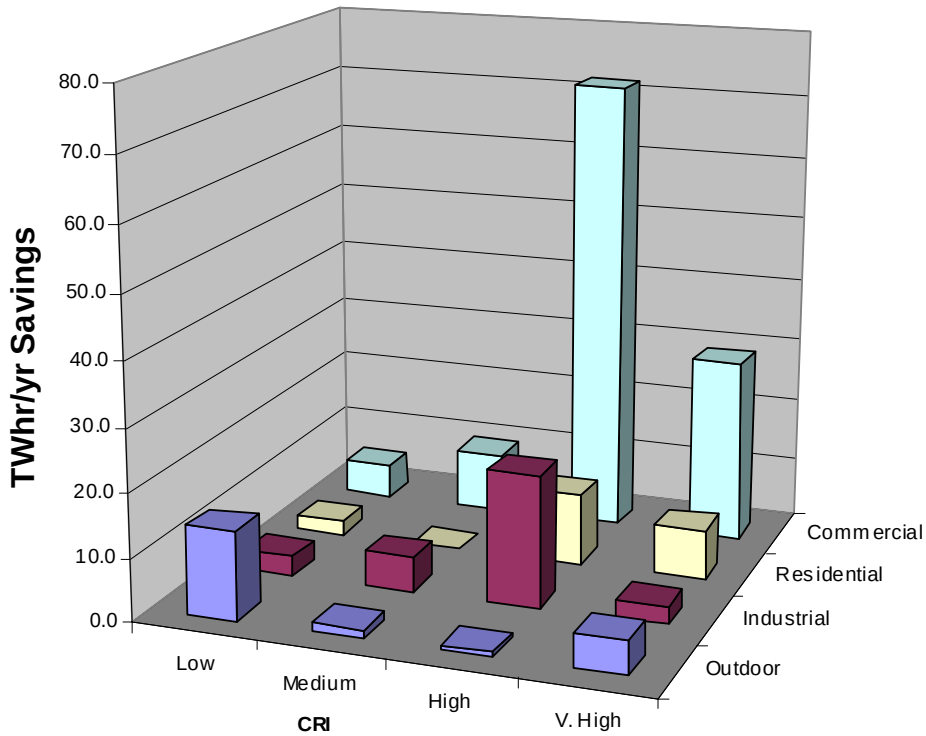

Figure 8-1. Electricity Savings Breakdown for the LED Scenario in 2030

As discussed in Chapter 7, SSL is penetrating all sectors and all CRI bins. Looking specifically at the LED scenario, very high CRI has the largest energy savings potential from SSL, as shown in Figure 8-1. The high CRI bin contributes 55 percent to the 2030 energy savings, while the very high CRI bin contributes 24 percent, the low CRI contributes 13 percent and the medium contributes 8 percent. There are two reasons for this development: first, the vast majority of lumens in the installed stock of lamps is in the high CRI bin (increased through Congressional and DOE regulatory measures), thus any penetration into that market will yield large savings; and second, the higher efficacies of some sources within the bins considered will make it more difficult for SSL sources to penetrate. For example, the low CRI bin already has energy-efficient sources such as high pressure sodium, so even though this bin has the highest efficacy values, its proportion of energy savings in 2030 is just 13 percent. Thus, the energy savings from the penetration of a more efficacious source (i.e., LED lamps and fixtures) has the greatest impact from an energy savings perspective in the high CRI bin.

In order for the estimated energy savings projection to be realized, SSL will need to achieve substantial improvements in price, efficacy and operating life. If these improvements are met, the economics would support SSL increasing its market share through the end of the analysis period and beyond. Relative to the reference case, the LED and OLED investment scenarios considered are both projected to reduce lighting energy consumption in absolute terms over the 20-year analysis period while the annual lumens delivered increases by 28.8 percent. This estimated reduction of 2.05 quads for LED (or 1.51 quads for OLEDs) in 2030 will contribute to peak electricity savings as commercial lighting is a peak load contributor through both direct consumption and indirect (i.e., reducing HVAC loads) consumption. This reduction will ease pressure on the transmission and distribution system during these peak times, and contribute to a cleaner environment.

Considering the medium improvement scenario for the conventional technologies, Figure 8-2 illustrates how efficacy and price influence the energy saving potential of SSL in the market model. Along the bottom of the graph is efficacy, with performance improving from left to right. Along the right-side of the graph is price, which decreases moving from top to bottom. Thus, the lower right corner of the graph represents the lowest price and highest efficacy combination. These values shown on these axes represent the target (i.e., final) values for SSL sources by CRI bin (low, medium, high, and very high) in 2030. Finally, the surface of Figure 8-2 is stratified, showing the quads of primary energy that could be saved (relative to the reference scenario) if SSL achieves the price and performance targets shown on each axis.

Figure 8-2 provides guidance for SSL R&D planning, as it shows the relative importance of improving both efficacy and price in order to achieve energy savings objectives. Four dots appear in the upper left-hand corner, representing the 2001, 2003, 2006, and 2009 estimates of white-light SSL performance. For 2003, the typical white-light available on the market is shown as $350/klm and 25 lm/W. For 2006, the white-light SSL source was set at $120/klm and 40 lm/W. In 2009, there was a doubling in efficacy compared to 2006 and a further reduction in cost per kilolumen. The relative positioning of these dots illustrates the trend of increasing efficacy and reducing price. As the technology continues to improve along this trajectory, greater national energy savings will result.

In the lower left portion of the graph, two bands are shown that represent negative energy savings. This scenario represents a combination of a very low-cost[23] LED product that has a very low efficacy rating. In this section of the graph, the market migrates to this LED product on a basis of first cost, abandoning more efficacious light sources such as fluorescent and HID lamps. If this were to happen, this would have

[23] The lowest price plotted on the right-hand axis of Figure 8-2 is $0.50 per kilolumen, which is approximately the 2010 price of a 60-watt general service A-19 incandescent lamp.

the net effect of increasing energy consumption for lighting nationally, hence the calculated negative energy savings.

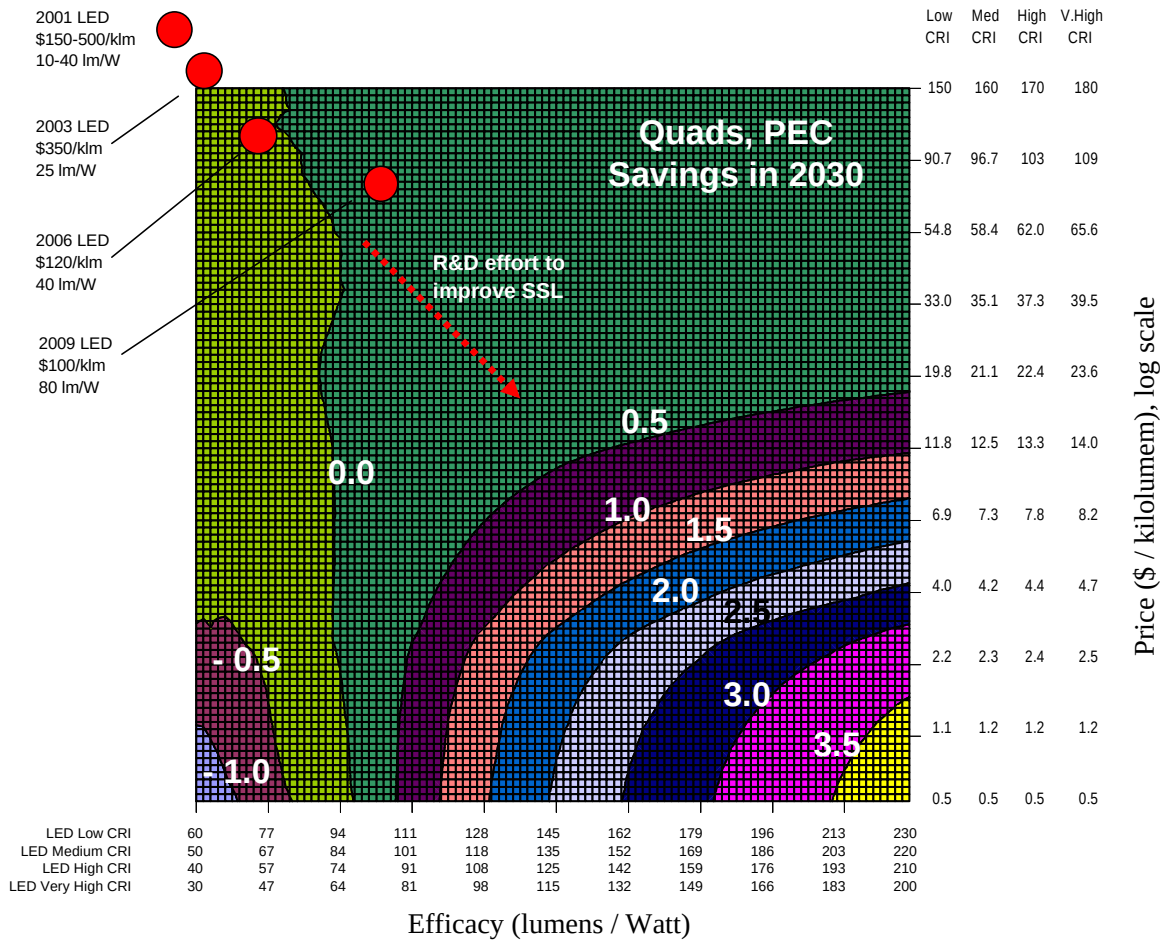

Figure 8-2. Quads of Primary Energy Savings over LED Reference Scenario

Thus, improvements in the price and performance of SSL 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. Figure 8-2 illustrates the range of national energy savings potential that exists with SSL. Careful investment and management of R&D could realize these significant national benefits through the development of efficacious, inexpensive SSL general illumination devices.

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Appendix A. SSL Technology Performance Improvement Projections

Table A.1. Performance Improvement Curves for LEDs with Extrapolation to 2030

LEDs	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low CRI																					
Efficacy (lm/w)	86.2	93.4	101.2	109.6	118.5	127.5	136.5	145.4	153.8	161.6	168.8	175.2	180.9	185.8	190.0	193.5	196.5	199.0	201.1	202.7	204.1
Lamp Cost ($/klm)	91.4	71.7	53.9	39.2	27.9	19.6	13.9	10.0	7.4	5.7	4.6	3.9	3.5	3.2	3.0	2.9	2.8	2.8	2.8	2.7	2.7
Lamp Life (1000 hrs)	47.1	48.6	49.4	49.7	49.9	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Medium CRI																					
Efficacy (lm/w)	77.7	84.9	92.7	101.1	109.7	118.5	127.2	135.6	143.6	151.0	157.6	163.6	168.7	173.2	177.0	180.3	183.0	185.2	187.0	188.5	189.8
Lamp Cost ($/klm)	125.2	102.1	79.0	58.4	41.7	29.2	20.5	14.6	10.8	8.3	6.8	5.8	5.2	4.8	4.6	4.4	4.3	4.3	4.3	4.2	4.2
Lamp Life (1000 hrs)	43.3	45.7	47.7	49.0	49.5	49.8	49.9	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
High CRI																					
Efficacy (lm/w)	64.3	71.7	79.9	88.7	97.9	107.1	116.3	125.1	133.3	140.7	147.3	153.1	158.0	162.2	165.6	168.5	170.8	172.6	174.2	175.4	176.3
Lamp Cost ($/klm)	169.5	145.1	117.5	89.9	65.5	46.0	31.8	22.1	15.7	11.6	9.0	7.5	6.5	5.9	5.6	5.3	5.2	5.1	5.1	5.0	5.0
Lamp Life (1000 hrs)	39.7	41.5	44.0	46.5	48.3	49.2	49.7	49.9	49.9	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Very High CRI																					
Efficacy (lm/w)	50.2	57.2	64.9	73.4	82.3	91.6	100.8	109.9	118.4	126.3	133.5	139.7	145.2	149.8	153.6	156.8	159.4	161.6	163.3	164.7	165.8
Lamp Cost ($/klm)	213.7	191.7	164.1	133.1	102.0	74.4	52.4	36.4	25.4	18.1	13.5	10.7	8.9	7.8	7.1	6.7	6.5	6.3	6.2	6.2	6.2
Lamp Life (1000 hrs)	35.6	36.4	38.1	40.8	44.2	46.9	48.6	49.4	49.7	49.9	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0

Note: the values for the medium CRI bin in these tables are based on the projections contained in DOE's SSL R&D Multi-Year Program Plan FY'09FY'15, which is available on the web: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf The multi-year program plan projects price, performance, and life for one CRI bin through 2015. These projections were then extrapolated to 2030 using an S-shaped curve-fit, and estimates were made of the relative improvements for the other CRI bins not projected.

Table A.2. Performance Improvement Curves for OLEDs with Extrapolation to 2030

OLEDs	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low CRI																					
Efficacy (lm/w)	43.6	57.4	73.1	90.0	106.9	122.6	136.4	147.7	156.6	163.3	168.2	171.8	174.3	176.1	177.3	178.1	178.7	179.1	179.4	179.6	179.7
Lamp Cost ($/klm)	136.8	106.0	78.4	55.8	38.8	26.7	18.5	13.1	9.6	7.3	5.9	5.0	4.4	4.1	3.9	3.7	3.6	3.6	3.6	3.5	3.5
Lamp Life (1000 hrs)	15.5	20.1	25.0	29.9	34.5	38.4	41.6	44.0	45.8	47.1	48.0	48.7	49.1	49.4	49.6	49.7	49.8	49.9	49.9	49.9	50.0
Medium CRI																					
Efficacy (lm/w)	30.8	42.8	57.3	73.9	91.1	107.7	122.2	134.2	143.3	150.1	154.9	158.2	160.5	162.0	163.0	163.7	164.1	164.4	164.6	164.8	164.8
Lamp Cost ($/klm)	198.4	165.0	129.5	96.1	68.1	46.8	31.7	21.7	15.2	11.1	8.5	6.9	6.0	5.4	5.1	4.8	4.7	4.6	4.6	4.5	4.5
Lamp Life (1000 hrs)	11.6	15.5	20.1	25.0	29.9	34.5	38.4	41.6	44.0	45.8	47.1	48.0	48.7	49.1	49.4	49.6	49.7	49.8	49.9	49.9	49.9
High CRI																					
Efficacy (lm/w)	21.3	30.9	43.4	58.4	75.0	91.6	106.6	119.1	128.7	135.7	140.6	143.8	146.0	147.4	148.4	148.9	149.3	149.6	149.7	149.8	149.9
Lamp Cost ($/klm)	250.1	224.2	190.9	152.8	114.6	81.3	55.4	37.1	24.9	17.3	12.5	9.7	8.0	7.0	6.4	6.0	5.8	5.7	5.6	5.6	5.5
Lamp Life (1000 hrs)	7.1	10.3	14.5	19.5	25.0	30.5	35.5	39.7	42.9	45.2	46.9	47.9	48.7	49.1	49.5	49.6	49.8	49.9	49.9	49.9	50.0
Very High CRI																					
Efficacy (lm/w)	11.6	17.9	26.8	38.8	53.5	70.0	86.5	101.2	113.2	122.1	128.4	132.6	135.3	137.1	138.2	138.9	139.3	139.6	139.7	139.8	139.9
Lamp Cost ($/klm)	324.4	307.6	282.1	246.4	202.1	154.4	110.1	74.4	48.9	32.1	21.6	15.3	11.6	9.4	8.2	7.5	7.0	6.8	6.7	6.6	6.6
Lamp Life (1000 hrs)	4.8	7.1	10.3	14.5	19.5	25.0	30.5	35.5	39.7	42.9	45.2	46.9	47.9	48.7	49.1	49.5	49.6	49.8	49.9	49.9	49.9

Note: the values for the medium CRI bin in these tables are based on the projections contained in the DOE's SSL R&D 2009 Multi-Year Program Plan FY'09–FY'15, which is available on the web: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf The multi-year program plan projects price, performance, and life for one CRI bin through 2015. These projections were then extrapolated to 2030 using an S-shaped curve-fit, and estimates were made of the relative improvements for the other CRI bins not projected.

Appendix B. National Lighting Market Sensitivity Runs

A few 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. Three critical areas were identified for consideration of a sensitivity analysis: 1) one-year acceleration of the LED price and performance curves, 2) alternative electricity price scenarios, and 3) use of a steeper residential payback curve.

Sensitivity Analysis B.1 — One-Year Acceleration of SSL Price and Performance Curves

If the LED price and performance improvement projections were to be accelerated by one year — that is, all the curves shift one year to the left — there would be considerable benefit to the nation. Compared to the energy savings of the LED default scenario in this analysis (2.05 quads of energy savings in 2030), the one-year acceleration would achieve 2.17 quads of energy savings in 2030, for a savings of an additional 0.12 quads of energy from SSL. Over the time period of analysis, an additional 3.36 quads of cumulative energy savings would be realized, representing an additional 21 percent in cumulative energy savings over the analysis period.

Sensitivity Analysis B.2 – Electricity Price Sensitivity Runs

Four alternative scenarios were examined to ascertain the impact of different electricity prices on the energy savings estimates from SSL price and performance improvement. These scenarios were all compared against the LED scenario.

Scenario	Description	Energy Savings	Discussion
EIA 2009 reference case	AEO 2009 forecasted annual electricity prices, as summarized in table 6-1 of this report.	2.05 quads	Energy savings relative to the reference case of no SSL and moderate improvement in conventional lighting technologies
Flat electricity price	Hold the electricity price constant at 2010 levels for the complete time period of analysis. Residential: $0.102 Commercial: $0.089 Industrial: $0.060 Outdoor: $0.089	1.92 quads	Energy savings from SSL decreases by 0.13 quads over reference case electricity prices. The future electricity price is projected to be higher than the 2010 price, thus the payback periods associated with SSL get longer and the market penetration (and subsequent energy savings) is lower.
Inflate electricity prices by 50%	Consider annual electricity prices that are 50% higher than those projected by AEO 2006, as summarized in Table 6-1 of this report. For example, this is the commercial electricity price: 2010: $0.133 / kWh 2015: $0.138 / kWh 2020: $0.148 / kWh 2025: $0.151 / kWh 2030: $0.159 / kWh	2.40 quads	Energy savings from SSL increases by 0.35 quads in 2030, and by significant amounts overall. While this scenario (50% higher electricity prices) is not considered likely by EIA, it is clear that as electricity prices increase, so will energy savings from more efficient devices like SSL, as consumers are driven to be more cost-conscious. This also indicates that areas with electricity prices above the average will likely see SSL market penetration first.
EIA high electricity price projection scenario	Consider the EIA/AEO 2009 high electricity price projection. Below are the commercial electricity prices: 2010: $0.098 / kWh 2015: $0.100 / kWh 2020: $0.105 / kWh 2025: $0.108 / kWh 2030: $0.113 / kWh	2.11 quads	Energy savings from SSL are slightly higher than the reference case, as electricity becomes slightly more expensive (on average, 6.9% above reference scenario prices), making SSL marginally better able to capture market share and saving more energy.

Sensitivity Analysis B.3 – Adjustment to the Residential Payback Curve

As discussed in Chapter 6 of this report, market share of SSL is awarded based on the payback period calculated for each sector, and the estimated percent market penetration associated with the payback period. For lighting technologies, the sector least tolerant of payback periods tends to be the residential sector, as depicted in Figure 6-1. This sensitivity analysis considers a scenario where the residential payback curve is shifted even further to the left, so that a one-year payback would not result in a 50 percent market penetration, but instead 25 percent. The figure below shows the reference case residential payback curve and the sensitivity analysis payback curve.

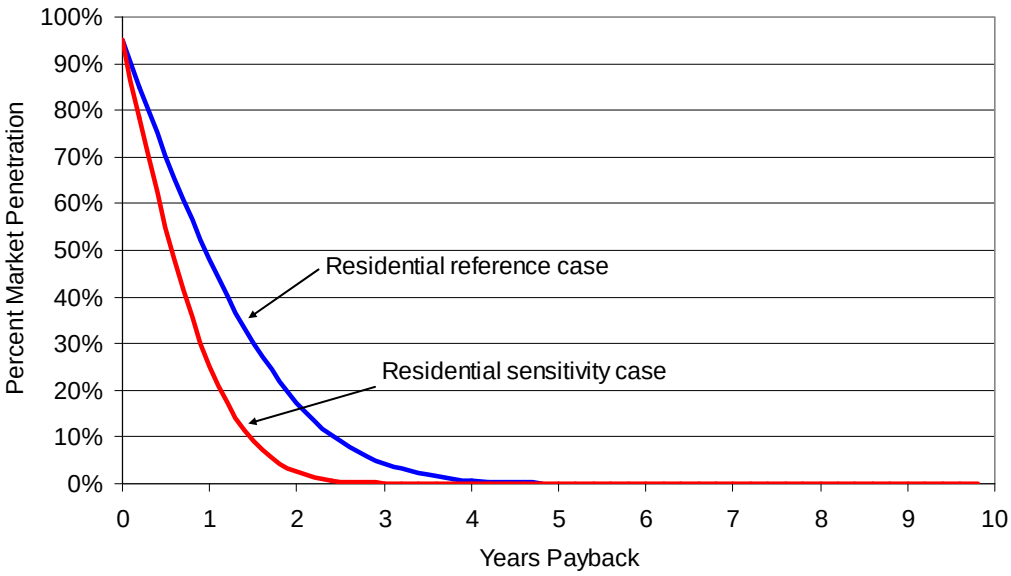

Figure B.1 Residential Market Penetration Curves for Reference and Sensitivity

Due to the substantial change in payback period associated with the residential sector, the threshold that SSL must surpass in order to be accepted by the residential sector becomes more difficult. Shorter payback periods — most less than one year — are required before substantial market shares of available lumen-hours of service can be awarded to SSL.

In the reference case, looking across all sectors, the energy savings from the LED scenario is 2.05 quads. Changing just the residential payback market penetration curve to the sensitivity shown in Figure B.1 reduces those energy savings by 0.04 quads to 2.01 quads of energy savings in 2030. This shift is small because the energy savings contribution from the residential sector is small relative to the commercial and industrial sectors. This fact is also evident from Figure 8-1, which shows the energy savings contribution from the residential sector to be considerably smaller than the commercial sector.

Appendix C. A Few Examples of DOE Program Support for SSL R&D

Since 2000, the DOE has recognized the great potential for energy savings from SSL, and has built a program around these technologies that has encouraged and supported the development of U.S. expertise and intellectual property in these areas. In addition to supporting manufacturers and researchers, DOE is also cognizant of the needs and quality expectations of the market, and therefore is also supporting programs that will address consumer quality standards. The following are some examples of areas where DOE has active programs that support SSL, and will help the U.S. lighting market realize the energy savings potential quantified in this report:

- DOE's SSL R&D priorities are updated every year, based on input from stakeholders. Each year, DOE releases an updated version of the SSL R&D Multi-Year Program Plan, reflecting new trends, forecasts, and inputs from DOE's annual research and development conference and round-table discussions with industry experts. In addition, DOE publishes an updated version of the Manufacturing Roadmap every year. Both of the Multi-Year Program Plan and the Manufacturing Roadmap help to guide the development of DOE R&D solicitations and DOE planning for the coming year. More information can be found at: http://www1.eere.energy.gov/buildings/ssl/projects.html

- DOE manages a program called CALiPER, which independently tests SSL products introduced into the market to validate product performance claims and provide information on product trends and market readiness. This program protects consumers against unscrupulous manufacturers who make claims of performance in excess of the products they are retailing. All DOE's test results are published online, and are available at: http://www1.eere.energy.gov/buildings/ssl/caliper.html

- DOE supports the development of industry testing standards for SSL products. DOE facilitates ongoing dialogue and collaboration with key standards setting organizations, and offers technical assistance in the development of new standards. More information on the standards development work can be found at: http://www1.eere.energy.gov/buildings/ssl/standards.html

- DOE is running a lighting design competition set in motion by EISA 2007 called the "L Prize." The L Prize competition will substantially accelerate U.S. shift from inefficient, dated lighting products to innovative, high-performance products. This prize is a cash award for the company first able to produce a quality product that meets specified performance criteria, including efficacy (>90 lm/W for a 60W general lamp replacement, >123 lm/W for a reflector lamp replacement, and >150 lm/W for a "21st Century Lamp") as well as quality of light and long operating life. Information on this competition can be found at: http://www.lightingprize.org/

- DOE convenes a series of conferences for leaders from industry, research institutions, utilities, energy efficiency organizations, manufacturers, trade groups, lighting designers, distributors, and many others to share updates and strategies for moving SSL to market. These conferences are centered around three general themes: (1) Solid-State Lighting Research and Development; (2) Solid-State Lighting Manufacturing and (3) Solid-State Lighting Market Introduction. These three conferences occur annually, and information can be found on upcoming conferences on DOE's SSL website: http://www.ssl.energy.gov/

- SSL Quality Advocates, a voluntary pledge program jointly developed by DOE and NGLIA,

works to assure that LED lighting, as it reaches the market, is represented accurately. Encouraging the development of high-quality products that perform as claimed is essential to buyer satisfaction and will help drive market acceptance of SSL products. More information is available at: http://www1.eere.energy.gov/buildings/ssl/advocates.html

These are just a few examples of the market and technology support activities that DOE is undertaking to support the development of SSL technology in the U.S, and to facilitate the realization of energy savings potential. For more information on DOE's SSL program, please visit http://www.ssl.energy.gov/ and register for periodic updates on developments and announcements from the program.