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

## Final Report

Prepared for:

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Navigant Consulting Inc.
1801 K Street, NW  Suite 500
Washington DC, 20006

December 2006

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## COMMENTS

The Department of Energy is interested in receiving comments on the material presented in this report. If you have any comments on the material presented in this report, please submit your feedback to Jim Brodrick at the following address:

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# ABBREVIATIONS

| | |
|---|---|
| AEO | Annual Energy Outlook |
| CRI | color rendering index |
| DOC | Department of Commerce |
| DOE | Department of Energy |
| EIA | Energy Information Administration (DOE) |
| HID | high intensity discharge |
| kWh | kilowatt hour |
| LBNL | Lawrence Berkeley National Laboratory |
| LED | light emitting diode |
| 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 |
| US | 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 and more versatile light sources. Advancements in SSL technology over the last two decades have contributed to a gradual market penetration in colored and some specialty white-light markets (DOE, 2003a). As industry and government investment continues to improve the performance and reduce the costs associated with this technology, SSL is expected to start competing with conventional light sources for market share in general illumination applications.

The U.S. Department of Energy is leading 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), which formally established this Initiative in Section 912, allocated $350 million in funding between 2007 and 2013 for this critical work.

In early 2006, the Department's SSL Initiative updated its price and performance projections based on input from the industry and the scientific community (DOE, 2006). These projections anticipate that the performance of light emitting diodes (LEDs) and organic light emitting diodes (OLEDs) will improve while their retail prices decrease. 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. This report serves as an update to earlier estimates of energy savings from SSL in general illumination applications published in 2003 (DOE, 2003b), and in 2001 (DOE, 2001).

## 1.1. Analysis Approach

The approach followed in structuring this analysis and constructing a spreadsheet model to project and evaluate consumer decisions in the U.S. lighting market is outlined below:

1. Determine Lighting Demand – Utilizing the lighting market inventory estimate published in the Lighting Market Characterization report (DOE, 2002), use the average efficacies, wattages and operating hours to convert the lighting inventory into lumen-hours of lighting service.
2. Group Similar Lighting Types – Use the color rendering index (CRI) of each light source to apportion the lumen service in the base year into four lighting quality bins.[1]
3. Forecast Lighting Demand – Use the new building construction projection provided by the National Energy Modeling System (NEMS) in the Annual Energy Outlook 2006 to forecast lumen demand from 2007 to 2027 (EIA, 2006).
4. Market Turn-Over – Create an adjustable stock-model that determines the lumen "turn-over" (i.e., annual available lumen market) in the U.S., based on new installations (new construction), replacement lamps, and retrofit fixtures.
5. Conventional Technology Improvement Forecast – Estimate the improvements in cost, efficacy and operating life of conventional technologies in response to competition from SSL sources. Three performance improvement scenarios were constructed (see Chapter 4).

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[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 that are necessary to construct the market model. For more information on the CRI bins, see Chapter 2 of this report.

6. SSL Technology Improvement Forecast – Based on the price and performance curves published in the SSL Research and Development Portfolio Multiyear Program Plan, FY'07 – FY'12, extrapolate curves to 2027. (see Chapter 5).
7. Lighting Service Costs – Project lighting costs based on today's market and anticipated improvements for installation (fixture, ballast and lamp) and operation (electricity, maintenance and replacement lamps).
8. Economic Lighting Market Model – Using an economic model of the U.S. lighting market, calculate SSL market penetration based on competition between both conventional technologies and SSL. Incorporate variability to account for differences in national electricity price and acceptable consumer payback periods by sector.
9. Calculate Energy Savings – Relative to a hypothetical basecase of no SSL sold into the lighting market, calculate the energy savings under the projected SSL technology performance scenario.

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

- Lighting inventory and lumen demand projection from 2007 to 2027 (Chapter 2)
- Available lumen market - turnover in the installed base of lighting (Chapter 3)
- Conventional technology improvement projection from 2007 to 2027 (Chapter 4)
- SSL technology improvement estimates (Chapter 5)
- Paybacks and lighting model market penetration (Chapter 6)
- Stock model and energy savings calculation (Chapter 7)

### 1.2. Simplifying Assumptions

In constructing the lighting market model, several simplifying assumptions were made to manage the analytical complexity of the lighting market. These assumptions are discussed in detail in this report, but are listed here for convenience and clarity of presentation. Some of these assumptions have the result of increasing the energy savings potential (e.g., the availability of SSL retrofit lamps) while others may reduce the savings potential (e.g., CRI bins).

- SSL Retrofit Lamps – the model assumes that SSL technology manufacturers will produce SSL lamps that can be installed directly into existing fixtures, such as E-26 sockets or T-8 fluorescent luminaires.
- Constant Lighting Intensity – it is assumed that levels of lighting intensity (lumens per square foot) or lumen demand in buildings in 2001 remain constant over the analysis period (2007-2027).
- SSL Performance Improvement Curves – the model is driven by the price and performance improvement projections for LEDs and OLEDs considered separately over the analysis period.
- Simple Payback – the economic portion of the model assumes the lighting market responds primarily to simple payback, which emphasizes the importance of first cost across all sectors.
- Simple Payback Response Curves – the model utilizes payback period response curves to award market share based on the calculated payback.
- CRI Light Quality – while there are several metrics to describe quality of light, no one metric is able to capture all aspects. This analysis uses CRI as an indicator of the light quality,

differentiating between tasks that require low, medium, high and very high CRI.

- CRI Bins – the analysis subdivides the national lighting inventory into groups of similar CRI ratings by sector. Competition for substitution of replacement lamps or new or retrofit fixtures occurs within those CRI bins.
- Lighting Demand Growth Rate – the model incorporates growth rates that projects new construction over a twenty-year period.

A modification was made to the baseline apportionment of lighting service by CRI bin for this report. The baseline projection of fluorescent lighting was adjusted to take into account the replacement of T12 installations by T8 over the analysis period. Driven by favorable economics, better quality product and two new ballast standards (DOE's fluorescent ballast standard published September 19, 2000 (65 FR 56740) and the ballast standard contained in Energy Policy Act of 2005 (P.L. 109-58)), the market is shifting towards T8. The impact of a market migration from T12 toward T8 changes the CRI bins into which the basecase lighting service is apportioned: T12 lamps are primarily grouped in the medium CRI bin while T8 lamps are largely grouped in the high CRI bin. One half of the lumen-hours of service provided by T12 fluorescent lamps in the 2001 national lighting inventory estimate were transferred to T8 fluorescent lamps over the analysis period. Due to the fact that T8 lamps are better performing and have lower operating costs, this adjustment to the baseline of lighting service would have the effect of slightly reducing the energy savings calculated from SSL, as it would require the SSL devices to be even more advanced and less expensive before they could compete successfully with T8 lamps.

## 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 lighting color quality (using CRI bins). This baseline lighting demand is then divided by the building floorspace 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 2006 for residential and commercial sectors and by user-input for industrial and outdoor stationary sectors. These growth rates range from 1.0 – 1.6 % 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 used from the U.S. Lighting Market Characterization report (DOE, 2002). The Lighting Market Characterization estimated the installed base of lighting in the U.S. considering nearly thirty different lamp types:

- **Incandescent:** general service incandescent; general service incandescent reflector; general service halogen; halogen reflector; halogen reflector low-voltage; low wattage (< 25W) incandescent.

- **Fluorescent:** T5; T8 less than four feet; T8 four feet; T8 more than four feet; T8 U-bent; T12 less than four feet; T12 four feet; T12 more than four feet; T12 U-bent; compact fluorescent plug-in; compact fluorescent screw-in; compact fluorescent plug-in reflector; compact screw-in reflector; circline; induction discharge; miscellaneous fluorescent.

- **High Intensity Discharge:** mercury vapor; metal halide; high pressure sodium; low pressure sodium.

For each of these sources, the lamp wattage by sector is multiplied by the estimate of the installed number of lamps per building and the annual operating hours. For fluorescent and high intensity discharge (HID) lamps, ballast losses are included with the lamp wattage. This provides a kWh consumption per 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 light source efficacies, converting the annual energy demand per building into an annual lighting service demand per building. Efficacy ratings are tracked by sector because the average installed wattages vary by sector. Often, higher wattage lamps of the same type have higher efficacy ratings, and increasing wattages and efficacies will both contribute to greater annual lumens of service. Note too that the T12 installations are shifted to T8 installations due to the impact of the fluorescent ballast standard, which started to take effect in 2005.

Table 2-1 presents the average lamp efficacies from the U.S. Lighting Market Characterization report (DOE, 2002) that were used to convert the national lighting inventory into a national lighting service (delivered lumen) estimate. For example, if a residential dwelling consumed 100 kilowatt-hours 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 kilowatt-hours of electricity consumption by 13 lumens per watt, the efficacy of a residential general service incandescent lamp.

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[2] Due to the magnitude of calculated national lumen demand, the notation "tera" is used, denoting 10E+12 (1,000,000,000,000) lumen-hours of annual lighting service.

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

| Lamp Type | | Wattage (watts) | | | | Efficacy (lumens per watt) | | | | 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 | 14 | 14 | 14 | 14 | 100 |
| | Halogen - General Service | 200 | 64 | - | - | 20 | 17 | - | - | 100 |
| | Halogen - Reflector | 205 | 226 | 452 | 167 | 20 | 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 | - | 8 | 10 | - | - | 95 | 95 | - | 85 |
| | 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 | 80 |
| | T8 - U-bent | - | 34 | 32 | - | - | 81 | 81 | - | 85 |
| | 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 | 68 |
| | 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 | - | - | 50 | 50 | - | 73 |
| | Induction Discharge | - | - | - | - | - | - | - | - | 85 |
| | Miscellaneous fluorescent | - | 18 | 34 | 150 | - | 55 | 55 | 55 | 80 |
| **High Intensity Discharge** | | | | | | | | | | |
| | Mercury vapor | 179 | 331 | 409 | 239 | 38 | 55 | 55 | 55 | 33 |
| | Metal halide | - | 472 | 438 | 311 | - | 100 | 100 | 100 | 68 |
| | High pressure sodium | 79 | 260 | 394 | 216 | 100 | 100 | 100 | 100 | 22 |
| | Low pressure sodium | - | 104 | 90 | 180 | - | 113 | 113 | 113 | - |

Note: dash (“-“) indicates no data for that light source / sector combination.
Source: DOE, 2002.

The right-most column of Table 2-1 provides the CRI ratings for each of the light sources tracked in the Lighting Market Characterization report (DOE, 2002). These color rendering index (CRI) values were derived from major lamp manufacturer catalogues. In order to classify the lumen-hours of lighting service in each sector, four CRI bins were created that group together the annual lighting demand according to lighting service quality. While CRI as a single metric cannot capture all the distinctions between lighting technologies, it is a convenient, readily understood metric and captures fundamental differences in lighting services that are necessary to construct the spreadsheet model.

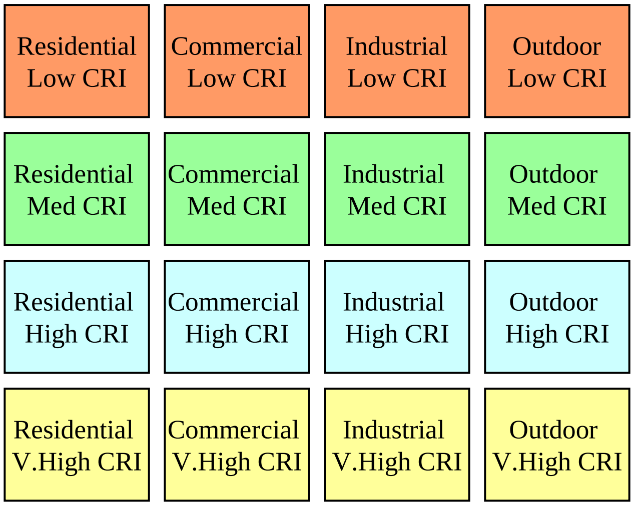
One of the modeling assumptions made was that the demand for lumens in any given CRI bin will not shift out of that bin during the analysis period. In other words, if a particular application uses 90 CRI light in 2007, it will require 90 CRI light in 2027. While this assumption may not accurately reflect 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 (CRI) before they are eligible to replace the conventional technologies such as incandescent lamps. 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 four foot, T12 greater than 4 foot, Circline |
| High CRI | 76 – 90 CRI | T8 four foot, Compact Fluorescent Lamps |
| Very High CRI | 91 – 100 CRI | Incandescent, Halogen |

Using the aforementioned sectors and CRI bins, a matrix of sixteen market segments was created, reflecting the annual lumen demand. This matrix is illustrated in Figure 2-1.

**Figure 2-1. Market Matrix of Sectors and Color Bins for National Lighting Demand[3]**



| | | | |
|---|---|---|---|
| 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 |

## 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 2007 and 2027. The lumen-hour demand calculated in 2001 from the Lighting Market Characterization report (DOE, 2002) was divided by the cumulative national floor-

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

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, 2006) were used to project lumen-hour demand growth from 2007 to 2027, 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 is approximately 21.4 kilolumen-hours per square foot while for the commercial sector, the demand is more than ten times higher, 307.3 kilolumen-hours per square foot.

NEMS provides annual average growth estimates of floor-space in the residential and commercial sectors (EIA, 2006); however unfortunately, no growth estimate is readily available for the industrial and outdoor stationary sectors. Thus, growth rates for the industrial and outdoor stationary sectors are assumed to be 1.00% per annum. This growth rate was selected to recognize that there is growth in these two sectors, but there is some uncertainty whether square feet of illuminated space in the industrial and outdoor stationary sectors is growing as quickly as the residential and commercial sectors.

| | |
|---|---|
| Residential | 1.56% growth |
| Commercial | 1.55% growth |
| Industrial | 1.00 % growth |
| Outdoor Stationary | 1.00% growth |

It should be noted that because light emission from LEDs is highly directional, a scenario where task lighting becomes more common in the future can 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, making an assumption about the performance of future fixtures and adjusting the lumen intensity up or down would be speculative. The error of not making an adjustment to the lighting density estimate in each sector leads to a conservative estimation of energy savings, because 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 a detailed break-down of the estimated lumen-demand by sector in 2007. 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, as discussed earlier, with the market shifting[4] from magnetic to electronic ballasts due to the Department's energy conservation standard published in 2000 and the standards set by the Energy Policy Act of 2005, the basecase 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 very high CRI.

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[4] 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 two decade analysis period because of the two standards.

**Table 2-3. Sector and CRI Bins of Teralumen-hours Lighting Demand in 2007**

| *(Tlm hr/yr)* | Residential | Commercial | Industrial | Outdoor | CRI-Bin Total |
|---|---|---|---|---|---|
| Low CRI | 36 | 1,054 | 726 | 4,229 | 6,044 |
| Medium CRI | 738 | 9,878 | 4,403 | 584 | 15,603 |
| High CRI | 811 | 11,164 | 3,771 | 64 | 15,810 |
| Very High CRI | 2,909 | 2,019 | 42 | 90 | 5,060 |
| Sector Totals | 4,495 | 24,116 | 8,941 | 4,966 | 42,518 |

Figure 2-2 illustrates the impact of the growth rates applied annually to each of the sectors. This diagram presents the growth in lumen-hour demand nationally in teralumen-hours per year by CRI bin. These lighting demand projections extend over the energy savings analysis period of 2007 to 2027. By this account, lumen-hour demand in the United States is estimated to increase by approximately 31.5% over the next two decades.

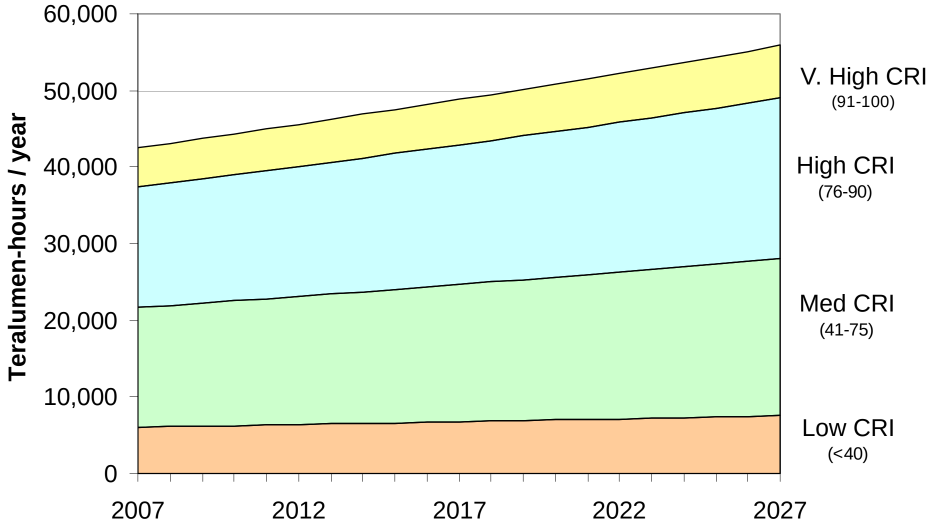

**Figure 2-2. Market Forecast of Lumen-Hour Demand by CRI Bin**

Because the lumen-hour demand (or source lumen output) per unit area is held constant in each sector over the analysis period, and is tied to floor-space projections, the projected growth in demand (31.5%) appears significant. Evaluating this projection on a per capita basis, the lumen demand is projected to increase 11% over the analysis period, going from 141 megalumen-hours[5] per person per year in 2007 to 158 megalumen-hours per person per year in 2027.[6]

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 2007, 2012, 2017, 2022 and 2027. These tables provide a more detailed look at

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[5] One megalumen-hour is approximately equivalent to a 100W incandescent lamp operating continuously for one month. Or, alternatively, its approximately equivalent to a 100W lamp, operated for 3-hours per day, for 220 days.
[6] Population estimates for 2007 (300.9 million) and 2027 (355.0 million) are from the U.S. Census Bureau, Population Division, U.S. Department of Commerce, http://www.census.gov/ipc/www/usinterimproj/

the projected lighting demand. Comparing these two tables and reviewing the CRI values presented in Table 2-1, the incandescent sector is the only important contributor to the very-high CRI bin, the fluorescent sector is split between the high CRI and medium CRI bins, and 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.

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

| Lamp Source Type | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Incandescent | 5,060 | 5,505 | 5,952 | 6,404 | 6,859 |
| Fluorescent | 24,421 | 26,253 | 28,169 | 30,232 | 32,441 |
| HID | 13,032 | 13,844 | 14,698 | 15,612 | 16,589 |
| **Total** | 42,513 | 45,602 | 48,820 | 52,249 | 55,888 |

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

| CRI Bin | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | 6,039 | 6,381 | 6,739 | 7,119 | 7,522 |
| Med CRI (41-75) | 15,603 | 16,728 | 17,907 | 19,175 | 20,532 |
| High CRI (76-90) | 15,810 | 16,988 | 18,221 | 19,550 | 20,976 |
| Very High CRI (91-100) | 5,060 | 5,505 | 5,952 | 6,404 | 6,859 |
| **Total** | 42,513 | 45,602 | 48,820 | 52,249 | 55,888 |

The lumen demand forecast constitutes the first critical component of the SSL market model. 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 a new, cost-efficient white-light source. 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 estimate of the projected national annual lumen-hour demand, the next step is to determine how much of the lighting market is replaced each year. This turnover represents the lumens available in the market for competition within each of the CRI bins. To arrive at this estimate, three categories of lumen-hour lighting market are created:

- *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.

- *Replacements* – lamps that burn out and are replaced during a calendar year. This calculation of 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, we assume that companies developing SSL technology will produce lamps with form-factors matching conventional technologies that are able to be installed directly into existing lighting fixtures (see discussion below). Thus, in the replacement market, SSL (including the cost of the operating electronics or 'ballast') competes with conventional lighting technologies (only the cost of the lamp).

- *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 a constant 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 the retrofit market, SSL technology competes with conventional lighting technologies inclusive of 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 which can be installed directly into existing sockets and can serve as replacements for MR-16 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. Literature reviewed suggests that only about 1 percent of floor-space every ten years undergoes lighting retrofits purely for energy savings reasons (EELA, 2000). Thus, these end-users would be captured and represented in the fixed 5% of lumen demand retrofits calculated annually.

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.

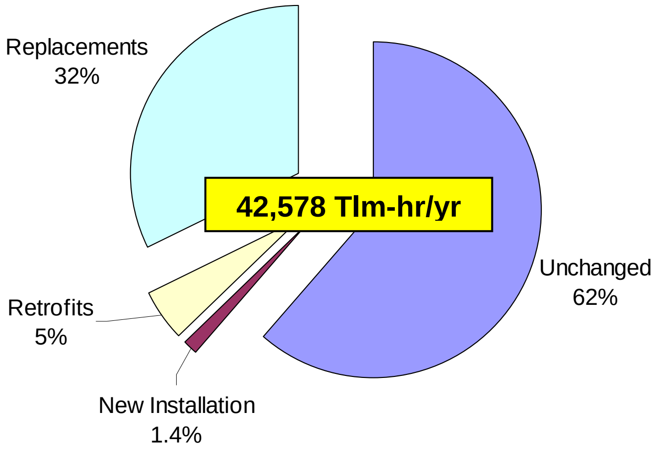

**Figure 3-1. Annual Lumen-Hour Market Turnover in 2007**

Note that as shown in Figure 3-1, approximately 38% of the installed annual lumen-hour demand is replaced or installed in 2007. 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 2007 is larger than that in 2027. 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 2007 to 2027, 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 two decade period of this market analysis. Changes are determined on a percentage basis from the year 2007 to 2027. The model is able to adjust the lamp efficacy, operating life and cost for the three primary groups of conventional lighting technologies – incandescent, fluorescent and high intensity discharge.

For this analysis, three conventional technology improvement scenarios are 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. The improvements used here can be modified on a sectoral and lighting technology basis. The default scenario (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 2007 and 2027 | | Incandescent | Fluorescent | High Intensity Discharge |
|---|---|---|---|---|
| Low Baseline Scenario | Efficacy (lm/W) | 2% | 5% | 10% |
| | Lamp life | 5% | 10% | 10% |
| | Lamp price | -5% | -5% | -5% |
| Medium Baseline Scenario | Efficacy (lm/W) | 5% | 10% | 20% |
| | Lamp life | 10% | 20% | 20% |
| | Lamp price | -10% | -10% | -10% |
| High Baseline Scenario | Efficacy (lm/W) | 10% | 20% | 30% |
| | Lamp life | 20% | 30% | 30% |
| | 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 small since many of these technologies are already in competition with each other at certain relative cost levels. Due to the maturity of most of these technologies, there is limited opportunity for cost reduction and performance improvement overall. For simplicity, the percent performance improvements shown in the table for these conventional lighting technologies are introduced linearly, over the 2007 to 2027 analysis period.

In order to more closely assess how these performance changes actually impact the technologies used in the analysis, the base year (2007) and target year (2027) spreadsheet tables for each of the four sectors are provided on the following pages. Numerical values for efficacy, lamp life and price for the medium baseline scenario are presented. 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[7], 2007 and 2027

| | | | | Baseline Technology 2007 | | | Medium Technology Improvement Potential by 2027 | | |
|---|---|---|---|---|---|---|---|---|---|
| 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 | 1.0 | 0.50 | 14 | 1.1 | 0.45 |
| Standard - Reflector | 102 | 100 | 17.80 | 14 | 1.5 | 2.25 | 15 | 1.7 | 2.03 |
| Halogen - General Service | 200 | 100 | 17.80 | 20 | 2.8 | 3.50 | 21 | 3.0 | 3.15 |
| Halogen - Reflector | 205 | 100 | 17.80 | 20 | 3.5 | 3.00 | 21 | 3.9 | 2.70 |
| Halogen - Reflector low volt | - | - | - | - | - | - | - | - | - |
| Low wattage (< 25W) | - | - | - | - | - | - | - | - | - |
| **Fluorescent** | | | | | | | **10%** | **20%** | **-10%** |
| T5 | - | - | - | - | - | - | - | - | - |
| T8 - less than 4 ft | - | - | - | - | - | - | - | - | - |
| T8 - 4 ft | 32 | 80 | 17.90 | 87 | 20.0 | 2.00 | 91 | 24.0 | 1.80 |
| T8 - more than 4 ft | - | - | - | - | - | - | - | - | - |
| T8 - U-bent | - | - | - | - | - | - | - | - | - |
| T12 - less than 4 ft | - | - | - | - | - | - | - | - | - |
| T12 - 4 ft | 41 | 70 | 17.90 | 68 | 20.0 | 1.50 | 74 | 24.0 | 1.35 |
| T12 - more than 4 ft | - | - | - | - | - | - | - | - | - |
| T12 - U-bent | - | - | - | - | - | - | - | - | - |
| Compact - plug-in | - | - | - | - | - | - | - | - | - |
| Compact - screw-in | 18 | 82 | 17.80 | 55 | 10.0 | 5.50 | 61 | 12.0 | 4.95 |
| Compact - plug-in reflector | - | - | - | - | - | - | - | - | - |
| Compact screw-in reflector | 11 | 82 | 17.80 | 55 | 10.0 | 8.00 | 61 | 12.0 | 7.20 |
| Circline | - | - | - | - | - | - | - | - | - |
| Induction Discharge | - | - | - | - | - | - | - | - | - |
| Miscellaneous fluorescent | - | - | - | - | - | - | - | - | - |
| **High Intensity Discharge** | | | | | | | **20%** | **20%** | **-10%** |
| Mercury vapor | 179 | 33 | 86.70 | 38 | 20.0 | 15.00 | 45 | 24.0 | 13.50 |
| Metal halide | - | - | - | - | - | - | - | - | - |
| High pressure sodium | 79 | 22 | 86.70 | 100 | 20.0 | 19.00 | 120 | 24.0 | 17.10 |
| Low pressure sodium | - | - | - | - | - | - | - | - | - |

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

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[7] The baseline technology values used for the analysis published in this paper are the same values that were used in the previous (November 2003) report. The authors of this report reviewed all the price and performance data for the conventional technologies listed in tables 4-2 through 4-5, and did not identify any values that had changed significantly from the previous analysis.

### Table 4-3. Commercial Sector Conventional Technologies Improvement, 2007 and 2027

| | | | | Baseline Technology 2007 | | | Medium Technology Improvement Potential by 2027 | | |
|---|---|---|---|---|---|---|---|---|---|
| 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 | 15 | 2.8 | 0.90 |
| Standard - Reflector | 104 | 100 | 14.20 | 14 | 1.5 | 2.25 | 15 | 1.7 | 2.03 |
| Halogen - General Service | 64 | 100 | 14.20 | 17 | 2.8 | 3.50 | 18 | 3.0 | 3.15 |
| Halogen - Reflector | 226 | 100 | 14.20 | 20 | 3.5 | 3.00 | 21 | 3.9 | 2.70 |
| Halogen - Reflector low volt | 48 | 100 | 14.20 | 13 | 4.0 | 3.75 | 14 | 4.4 | 3.38 |
| Low wattage (< 25W) | 15 | 100 | 14.20 | 10 | 2.5 | 0.65 | 11 | 2.8 | 0.59 |
| **Fluorescent** | | | | | | | **10%** | **20%** | **-10%** |
| T5 | 24 | 78 | 53.00 | 95 | 20.0 | 2.00 | 105 | 24.0 | 1.80 |
| T8 - less than 4 ft | 23 | 80 | 53.00 | 66 | 17.5 | 3.00 | 73 | 21.0 | 2.70 |
| T8 - 4 ft | 33 | 80 | 59.40 | 83 | 20.0 | 2.00 | 91 | 24.0 | 1.80 |
| T8 - more than 4 ft | 50 | 68 | 59.40 | 84 | 13.8 | 6.00 | 92 | 16.5 | 5.40 |
| T8 - U-bent | 34 | 80 | 41.60 | 81 | 20.0 | 7.50 | 89 | 24.0 | 6.75 |
| T12 - less than 4 ft | 29 | 71 | 53.00 | 60 | 12.8 | 2.25 | 66 | 15.3 | 2.03 |
| T12 - 4 ft | 45 | 70 | 59.40 | 68 | 20.0 | 1.50 | 74 | 24.0 | 1.35 |
| T12 - more than 4 ft | 93 | 76 | 59.40 | 69 | 14.5 | 3.50 | 75 | 17.4 | 3.15 |
| T12 - U-bent | 46 | 67 | 41.60 | 64 | 15.0 | 5.50 | 70 | 18.0 | 4.95 |
| Compact - plug-in | 17 | 82 | 14.20 | 60 | 15.0 | 5.50 | 65 | 18.0 | 4.95 |
| Compact - screw-in | 16 | 82 | 14.20 | 55 | 10.0 | 5.50 | 61 | 12.0 | 4.95 |
| Compact - plug-in reflector | 16 | 82 | 14.20 | 55 | 10.0 | 8.00 | 61 | 12.0 | 7.20 |
| Compact screw-in reflector | 16 | 82 | 14.20 | 55 | 10.0 | 8.00 | 61 | 12.0 | 7.20 |
| Circline | 30 | 73 | 14.20 | 50 | 11.0 | 3.50 | 55 | 13.2 | 3.15 |
| Induction Discharge | - | - | - | - | - | - | - | - | - |
| Miscellaneous fluorescent | 18 | 80 | 34.10 | 55 | 10.0 | 2.25 | 61 | 12.0 | 2.03 |
| **High Intensity Discharge** | | | | | | | **20%** | **20%** | **-10%** |
| Mercury vapor | 331 | 33 | 108.00 | 55 | 20.0 | 22.00 | 66 | 24.0 | 19.80 |
| Metal halide | 472 | 68 | 108.00 | 100 | 13.8 | 60.00 | 120 | 16.5 | 54.00 |
| High pressure sodium | 260 | 22 | 108.00 | 100 | 20.0 | 22.00 | 120 | 24.0 | 19.80 |
| Low pressure sodium | 104 | 10 | 108.00 | 113 | 16.0 | 22.00 | 135 | 19.2 | 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, 2007 and 2027

| | | | | Baseline Technology 2007 | | | Medium Technology Improvement Potential by 2027 | | |
|---|---|---|---|---|---|---|---|---|---|
| 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 | 1.50 | 17 | 2.8 | 1.35 |
| Standard - Reflector | 102 | 100 | 14.20 | 14 | 1.5 | 2.25 | 15 | 1.7 | 2.03 |
| Halogen - General Service | - | - | - | - | - | - | - | - | - |
| Halogen - Reflector | 452 | 100 | 14.20 | 25 | 3.5 | 3.00 | 26 | 3.9 | 2.70 |
| Halogen - Reflector low volt | 58 | 100 | 14.20 | 13 | 4.0 | 3.75 | 14 | 4.4 | 3.38 |
| Low wattage (< 25W) | 19 | 100 | 14.20 | 10 | 2.5 | 0.65 | 11 | 2.8 | 0.59 |
| **Fluorescent** | | | | | | | **10%** | **20%** | **-10%** |
| T5 | 24 | 78 | 53.00 | 95 | 20.0 | 2.00 | 105 | 24.0 | 1.80 |
| T8 - less than 4 ft | 23 | 80 | 53.00 | 66 | 17.5 | 3.00 | 73 | 21.0 | 2.70 |
| T8 - 4 ft | 31 | 80 | 59.40 | 83 | 20.0 | 2.00 | 91 | 24.0 | 1.80 |
| T8 - more than 4 ft | 53 | 68 | 59.40 | 84 | 13.8 | 6.00 | 92 | 16.5 | 5.40 |
| T8 - U-bent | 32 | 80 | 41.60 | 81 | 20.0 | 7.50 | 89 | 24.0 | 6.75 |
| T12 - less than 4 ft | 32 | 71 | 53.00 | 60 | 12.8 | 2.25 | 66 | 15.3 | 2.03 |
| T12 - 4 ft | 44 | 70 | 59.40 | 68 | 20.0 | 1.50 | 74 | 24.0 | 1.35 |
| T12 - more than 4 ft | 95 | 76 | 59.40 | 69 | 14.5 | 3.50 | 75 | 17.4 | 3.15 |
| T12 - U-bent | 46 | 67 | 41.60 | 64 | 15.0 | 5.50 | 70 | 18.0 | 4.95 |
| Compact - plug-in | 31 | 82 | 14.20 | 60 | 15.0 | 5.50 | 65 | 18.0 | 4.95 |
| Compact - screw-in | 14 | 82 | 14.20 | 55 | 10.0 | 5.50 | 61 | 12.0 | 4.95 |
| Compact - plug-in reflector | - | - | - | - | - | - | - | - | - |
| Compact screw-in reflector | 14 | 82 | 14.20 | 55 | 10.0 | 8.00 | 61 | 12.0 | 7.20 |
| Circline | 35 | 73 | 14.20 | 50 | 11.0 | 3.50 | 55 | 13.2 | 3.15 |
| Induction Discharge | - | - | - | - | - | - | - | - | - |
| Miscellaneous fluorescent | 34 | 80 | 34.10 | 55 | 10.0 | 2.25 | 61 | 12.0 | 2.03 |
| **High Intensity Discharge** | | | | | | | **20%** | **20%** | **-10%** |
| Mercury vapor | 409 | 33 | 108.00 | 55 | 20.0 | 22.00 | 66 | 24.0 | 19.80 |
| Metal halide | 438 | 68 | 108.00 | 100 | 13.8 | 60.00 | 120 | 16.5 | 54.00 |
| High pressure sodium | 394 | 22 | 108.00 | 100 | 20.0 | 20.00 | 120 | 24.0 | 18.00 |
| Low pressure sodium | 90 | 10 | 108.00 | 113 | 16.0 | 22.00 | 135 | 19.2 | 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, 2007 and 2027

| | | | | Baseline Technology 2007 | | | Medium Technology Improvement Potential by 2027 | | |
|---|---|---|---|---|---|---|---|---|---|
| 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 | 1.50 | 17 | 2.8 | 1.35 |
| Standard - Reflector | 103 | 100 | 14.20 | 14 | 1.5 | 2.25 | 15 | 1.7 | 2.03 |
| Halogen - General Service | - | - | - | - | - | - | - | - | - |
| Halogen - Reflector | 167 | 100 | 14.20 | 18 | 3.5 | 3.00 | 19 | 3.9 | 2.70 |
| Halogen - Reflector low volt | - | - | - | - | - | - | - | - | - |
| Low wattage (< 25W) | - | - | - | - | - | - | - | - | - |
| **Fluorescent** | | | | | | | **10%** | **20%** | **-10%** |
| T5 | - | - | - | - | - | - | - | - | - |
| T8 - less than 4 ft | - | - | - | - | - | - | - | - | - |
| T8 - 4 ft | - | - | - | - | - | - | - | - | - |
| T8 - more than 4 ft | 105 | 68 | 59.40 | 84 | 17.5 | 6.00 | 92 | 21.0 | 5.40 |
| T8 - U-bent | - | - | - | - | - | - | - | - | - |
| T12 - less than 4 ft | - | - | - | - | - | - | - | - | - |
| T12 - 4 ft | - | - | - | - | - | - | - | - | - |
| T12 - more than 4 ft | 190 | 76 | 59.40 | 69 | 20.0 | 3.50 | 75 | 24.0 | 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 | 34.10 | 55 | 10.0 | 2.25 | 61 | 12.0 | 2.03 |
| **High Intensity Discharge** | | | | | | | **20%** | **20%** | **-10%** |
| Mercury vapor | 239 | 33 | 108.00 | 55 | 20.0 | 15.00 | 66 | 24.0 | 13.50 |
| Metal halide | 311 | 68 | 108.00 | 100 | 13.8 | 20.00 | 120 | 16.5 | 18.00 |
| High pressure sodium | 216 | 22 | 108.00 | 100 | 20.0 | 19.00 | 120 | 24.0 | 17.10 |
| Low pressure sodium | 180 | 10 | 108.00 | 113 | 16.0 | 22.00 | 135 | 19.2 | 19.80 |

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

## 5. Solid-State Lighting Technology Improvements

The Department of Energy worked with the Next Generation Lighting Industry Alliance (NGLIA), the National Electrical Manufacturers Association (NEMA), and several national laboratories and numerous researchers to develop technology roadmaps for both LEDs and OLEDs. Expanding upon the February 2005 roadmap is the Department's multi-year program plan for SSL, published in March 2006, which is available on the web: http://www.netl.doe.gov/ssl/PDFs/SSLMultiYearPlan.pdf. This multi-year program plan provided the basis for the SSL price and performance curves analyzed and presented in this report. The multi-year plan provided projections of SSL performance and price through 2015; these trends were extended out to 2027 for the purposes of this analysis. Tables providing the exact price and performance improvement targets used in this analysis can be 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. The underlying analytical assumption of this approach is that in the future, SSL device manufacturers would be able to create lamps with the same form-factor and performance as conventional lamps, and these sources would 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, where the OLED material is painted directly onto the surface of the pear-shaped glass bulb, emitting light in all directions.

Generally, LEDs have the potential to be used in both directional / point source installations and distributed light installations, when used in conjunction with a diffuser technology. OLEDs have 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 competed 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 LEDs. OLEDs are available in the marketplace in 2006, 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 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. The operating life of OLEDs is expected to be shorter than LEDs (20k hours as opposed to 50k), and the first-cost of OLEDs will be similar to that of LEDs in the long-term due to the anticipated ability to continuously manufacture OLED panels. Having a shorter operating life reduces the duration of the energy savings for individual lamps, but also releases sockets for installation of new, more efficacious technology more frequently. 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.

Technology improvement curves were developed by the Department in consultation with experts from industry for both LEDs and OLEDs, analyzing three critical consumer parameters:

- Efficacy (lumens per watt)
- 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 SSL's impact 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.

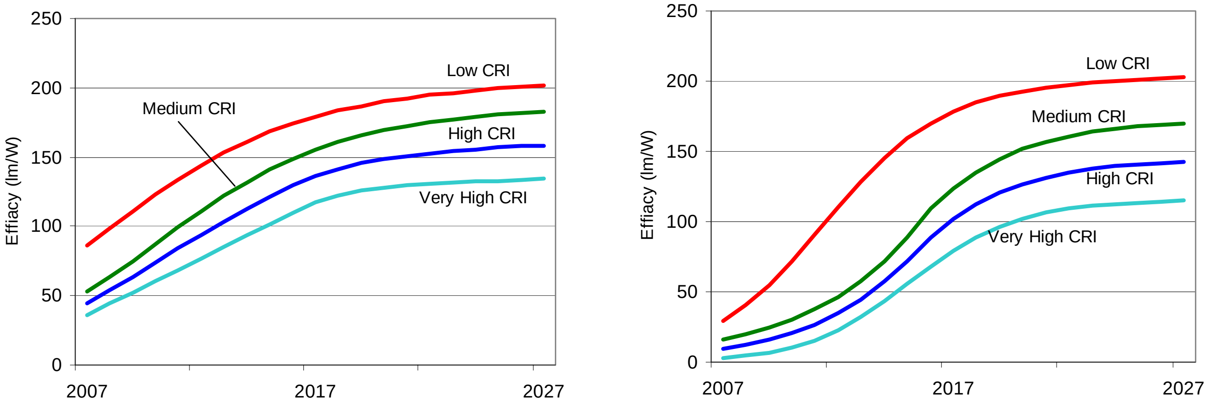
**Table 5-1. Description of the SSL Market Scenarios and Maximum Price and Performance Values in 2027**

| Scenario | General | Discussion | CRI Bin | Efficacy* | Price* | Life* |
|---|---|---|---|---|---|---|
| Reference | All SSL penetration is set to zero | 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 three scenarios is compared. | n/a | n/a | n/a | n/a |
| LED | Based on DOE / NGLIA estimate for LED, projected to 2027 | This scenario is based on the assumption that the Department of Energy continues to support R&D into LED technology. By 2027, very-high CRI LED technology is projected to be approximately ten times more efficient than incandescent lamps and last fifty times longer, however its selling price is still projected to be more than ten times as expensive, limiting penetration in the residential sector, which is more first-cost sensitive. | Low | 202 lm/W | 1.82 $/klm | 50 khrs |
| | | | Med | 183 lm/W | 2.13 $/klm | 50 khrs |
| | | | High | 159 lm/W | 3.99 $/klm | 50 khrs |
| | | | V.High | 134 lm/W | 5.88 $/klm | 50 khrs |
| OLED | Based on DOE / NGLIA estimate for OLED, projected to 2027 | This scenario is based on the assumption that the Department continues to support R&D into OLED technology. By 2027, high-CRI OLED technology is projected to be nearly twice as efficient as T8 fluorescent lamps, have the same operating life and cost about five times more on a dollar per kilolumen basis. At this point, the payback periods are becoming sufficiently short that OLEDs start to become cost-competitive with fluorescent lamps. | Low | 203 lm/W | 1.78 $/klm | 20 khrs |
| | | | Med | 170 lm/W | 2.63 $/klm | 20 khrs |
| | | | High | 143 lm/W | 4.50 $/klm | 20 khrs |
| | | | V.High | 115 lm/W | 6.39 $/klm | 20 khrs |

*Note: the values in these cells represent the maximum achieved levels of commercially available product by the end of the analysis period (2027). These projections are based on DOE's multi-year program plan for SSL which spans the time period of 2007 through 2015 (DOE, 2006). Based on other information contained in the multi-year program plan, the SSL projections were assigned to one or more CRI bins. A curve-fit was applied to the Department's multi-year program plan's forecasted values, and efficacy, price and life projections were forecast to 2027. 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 applications (DOE, 2003). Detail on the underlying assumptions, including color quality, operating life and costs are given in the multi-year program plan (DOE, 2006). Note that the efficacy values presented in this table and used in the model include losses for electronic controls and the prices include the cost of those electronics. This is also true for the conventional technologies that require ballasts, i.e., fluorescent and HID sources.

The price and performance projections given in Table 5-1 are based on a collaborative effort between industry and the U.S. government working together to solve common technology development problems by leveraging resources and sharing risks.[8] In both scenarios, the SSL technology S-Curves for each CRI bin improve in the following sequence – low, medium, high and very high. 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 that of the 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; however the industry experts project that the price and performance improvements will accelerate in the near future, positioning OLEDs at comparable price and performance levels with LED in 2027.

The following graphs present the S-curves for the price and performance of the two scenarios. Each 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. Finally, for complete transparency, Appendix A presents the actual values used for LEDs and OLEDs over the twenty-year analysis period.



*LED Efficacy Projection*

*OLED Efficacy Projection*

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

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, but is projected to accelerate rapidly, particularly between 2007 and 2017, positioning white-light OLED devices as a distributed source in the market. 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 the DOE's SSL multi-year program plan. (DOE, 2006)

Figure 5-2 represents the price improvement forecasts for each of the scenarios. Note that these curves

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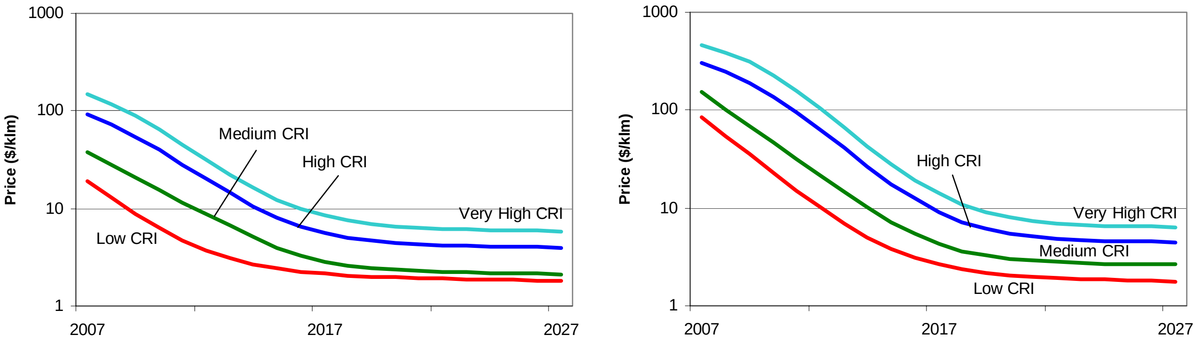
[8] An SSL Partnership between DOE and the Next Generation Lighting Industry Alliance (Alliance) was created in February 2005, in response to a competitive solicitation. The Alliance is a consortium of for-profit manufacturers established to accelerate SSL development and commercialization, and is administered by the National Electrical Manufacturers Association. More information, including a copy of the Memorandum of Understanding, can be found on the Department's website at: http://www.netl.doe.gov/ssl/partnership.html

depict the price reduction from a high initial first cost to a lower projected first cost. Due to the difference in scale between 2007 and 2027, these curves are plotted on an logarithmic Y-axis. This format enables better comparison of the terminal values, which are very similar.

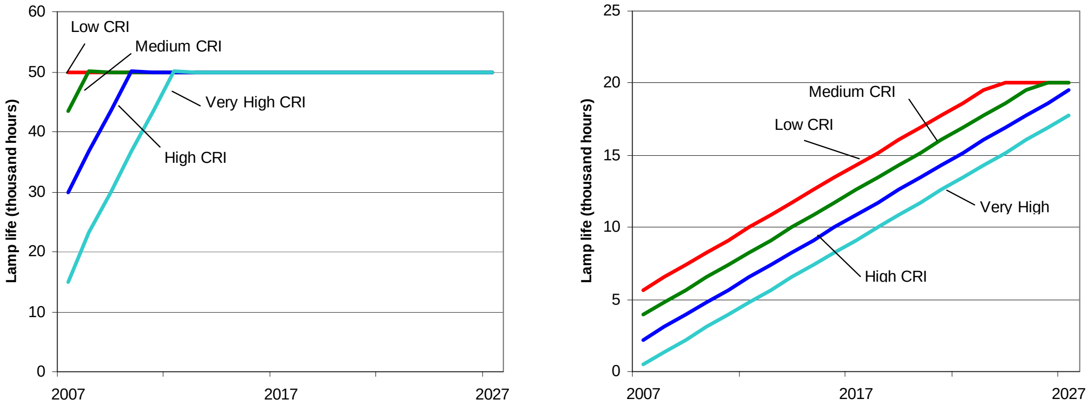


*LED Price Projection* *OLED Price Projection*

**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 2017. While OLEDs are more expensive initially, they eventually do achieve (around 2022) 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 the residential sector.

Figure 5-3 presents the SSL operating life projected for the two scenarios. Note that these two figures are not plotted on the same Y-axis – the LED projection approaches 50,000 hours of service while the OLED projection approaches 20,000. The LED operating life is projected to quickly achieve 50,000 hours of service while the OLEDs are projected to achieve 20,000 hours by the end of the analysis period. Operating life durations beyond 50,000 and 20,000 hours were not discussed by the NGLIA / DOE Team, and therefore represent the upper limits for this analysis. LEDs show a more rapid ascension to their ultimate target, again due to the relative maturity of this technology.



*LED Life Projection* *OLED Life Projection*

**Figure 5-3. Commercial 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. More detailed versions of these tables, presenting all the annual values used in the model, are provided in Appendix A.

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

| ($ per kilolumen) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | $19.08 | $3.69 | $2.14 | $1.92 | $1.82 |
| Med CRI (41-75) | $37.64 | $8.75 | $2.83 | $2.25 | $2.13 |
| High CRI (76-90) | $92.34 | $20.06 | $5.60 | $4.19 | $3.99 |
| Very High CRI (91-100) | $147.31 | $31.48 | $8.42 | $6.16 | $5.88 |

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

| ($ per kilolumen) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | $83.32 | $10.05 | $2.66 | $1.92 | $1.78 |
| Med CRI (41-75) | $151.56 | $21.40 | $4.33 | $2.80 | $2.63 |
| High CRI (76-90) | $305.70 | $62.71 | $9.13 | $4.86 | $4.50 |
| Very High CRI (91-100) | $460.11 | $104.13 | $13.97 | $6.95 | $6.39 |

As shown in Table 5-2 and Table 5-3, the price difference between the two scenarios is more evident in the near-term, 2007 and 2012. The differences between LED and OLED start to blur by 2017, with OLEDs costing only slightly more (at most 79 cents per kilolumen) than LEDs by 2022. In the final year of analysis, the industry experts project very similar retail prices for these two technologies by 2027, 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 2017.

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

| (lumens per watt) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | 86.6 | 144.0 | 179.1 | 194.6 | 201.9 |
| Med CRI (41-75) | 53.1 | 111.0 | 155.3 | 175.0 | 183.1 |
| High CRI (76-90) | 44.7 | 93.9 | 141.5 | 152.9 | 158.6 |
| Very High CRI (91-100) | 36.3 | 76.8 | 122.2 | 130.7 | 134.0 |

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

| (lumens per watt) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | 28.8 | 110.0 | 178.4 | 197.3 | 203.1 |
| Med CRI (41-75) | 15.8 | 46.5 | 123.4 | 160.8 | 170.1 |
| High CRI (76-90) | 9.3 | 34.5 | 112.1 | 134.9 | 142.6 |
| Very High CRI (91-100) | 2.9 | 22.6 | 89.0 | 109.0 | 115.1 |

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 multi-year program plan (DOE, 2006), 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.

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

| (thousand hours) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Med CRI (41-75) | 43.3 | 50.0 | 50.0 | 50.0 | 50.0 |
| High CRI (76-90) | 30.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Very High CRI (91-100) | 15.0 | 50.0 | 50.0 | 50.0 | 50.0 |

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

| (thousand hours) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Low CRI (<40) | 5.7 | 10.0 | 14.3 | 18.6 | 20.0 |
| Med CRI (41-75) | 4.0 | 8.3 | 12.6 | 16.9 | 20.0 |
| High CRI (76-90) | 2.2 | 6.5 | 10.9 | 15.2 | 19.5 |
| Very High CRI (91-100) | 0.5 | 4.8 | 9.1 | 13.5 | 17.8 |

## 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. As the annual market is captured by more efficient lighting technology with long operating lives, the stock itself gradually becomes more efficacious. As these new SSL lamps are installed, which tend to be longer-lasting than some of the conventional technologies, such as incandescent lamps, the lamp market turn-over diminishes slightly, as more and more sockets use these new SSL lamps.

In Chapters 4 and 5, we discussed how the model tracks the evolution of price and performance attributes for both conventional lighting technologies and SSL. To simplify the analysis, we assumed that SSL will eventually meet the requirements of any application, and that CRI is the only performance attribute on which it will compete.[9] 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. In this chapter we discuss how the spreadsheet model accounts for price and operating cost considerations in the lighting market simulation.

As discussed in Chapter 2, there are 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 characteristic 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: 1) sixteen markets for those that only incorporate the lamp price (replacements) and 2) sixteen markets for those installations which incorporate both a lamp and fixture price (new installations and retrofits). The fixture costs are based on U.S. Census data for typical fixtures for 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 operating electronics for the light source.

To allow us to consider these thirty-two markets in even finer detail, the model further divides each of the markets into thirty-five 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 instance, today there is a certain demand for high-CRI light in the residential sector that is satisfied by several lighting sources. Each source has its own price-per-lumen, efficacy, annual operating hours, lamp life, and so on. By creating price sub-bins within the larger CRI 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 thirty-five initial price-per-kilolumen bins (fixture and lamp) in each of the sixteen markets for the lamp, ballast and fixture price. In total, the model evaluates market penetration opportunities for SSL technology in 1,120 sub-markets.[10]

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

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[9] SSL sources offer a degree of freedom that isn't available from other light sources. For example, end-users could modify the color temperature, color rendering, light output via computer-control input from the end-user.

[10] 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 thirty-five first-cost sub-bins. New and retrofit market are handled as one market because they both incorporate fixture costs.

may not be the best method for determining which new lighting technology to purchase, it has several advantages to other methodologies like 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, we have found that simple payback is 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 sectoral 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.

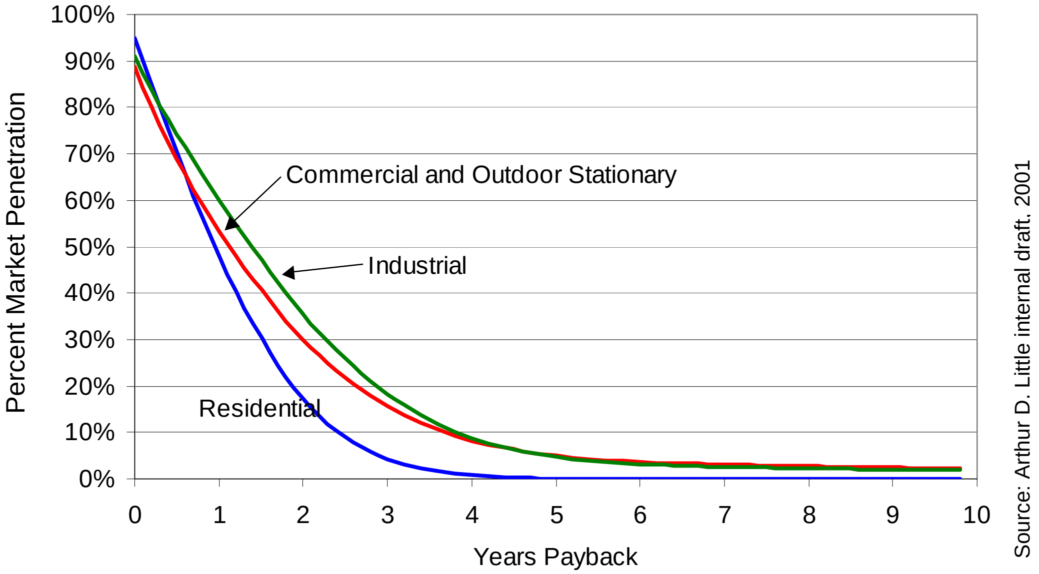
Electricity prices used for the operating cost evaluation are derived from the Energy Information Administration’s Annual Energy Outlook 2006, as presented in Table 6-1 (EIA, 2006). The electricity prices were adjusted to 2005 dollars. In the absence of an electricity price for the outdoor stationary sector, it was assumed that these customers experienced the same electricity prices as the commercial sector.

**Table 6-1. Electricity Price Projections in 2005 Dollars per Kilowatt-hour**

| ($/kWh) | 2007 | 2012 | 2017 | 2022 | 2027 |
|---|---|---|---|---|---|
| Residential electricity price | 0.092 | 0.086 | 0.085 | 0.086 | 0.087 |
| Commercial electricity price | 0.084 | 0.076 | 0.076 | 0.078 | 0.079 |
| Industrial electricity price | 0.060 | 0.052 | 0.053 | 0.055 | 0.055 |
| Outdoor Stationary electricity price | 0.084 | 0.076 | 0.076 | 0.078 | 0.079 |

Source: EIA, 2006.

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 penetration 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.



Source: Arthur D. Little internal draft. 2001

**Figure 6-1. Market Penetration 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 2-year payback, it would be awarded approximately 20% of the available market that year. Likewise, if SSL were to offer a 1-year payback, it would be awarded approximately 45% 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. Table 6-2 presents those outcomes.

**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.[11] |
| 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

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[11] 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.

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% of the available lumens. For the commercial and outdoor stationary sectors, this represents 89%, and for the industrial sector, this represents 91% of the available lumens. No sector offers 100% market conversion to SSL because there are always groups within 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 – sometimes as rapidly as full penetration within a single year. This result is highly unlikely to actually 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 spike from zero to full market penetration is stretched over a period of five years, with an equal share (20%) 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.

## 7. Stock Model and Energy Savings Calculation

The model's economic analysis engine competes the annually available teralumen-hours of lighting service between SSL technology and conventional sources. In each of the CRI bins, SSL gradually captures market share as its price and performance improve, and it becomes more competitive on a life-cycle cost basis. Figure 7-1 is an example of the output for the LED scenario, commercial sector, lamps-only market. This is one of the eight primary economic markets[12] in the model. This diagram shows that as the LED technology improves, 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 2020. Similarly, low CRI LED technology quickly 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 144 lm/W by 2012, 179 lm/W by 2017 and 194 lm/W by 2022 – all of which exceed the typical efficacy of the conventional sources. In the high CRI bin, LED technology is competing primarily with T8 fluorescent lamp technology, which is already an efficacious, cost-efficient source, hence there is a delay in market penetration for this CRI bin.

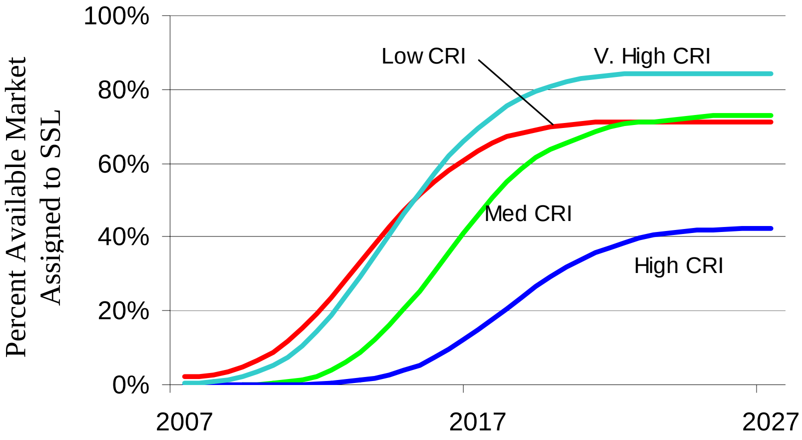

**Figure 7-1. Portion of Annual Lamps Market for Commercial Sector, LED Scenario**

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 base of national lighting technologies. Figure 7-2 illustrates the change in stock efficacy for the reference scenario and the LED scenario. In the reference scenario, no SSL technology enters the market and thus, lighting performance improves only as the conventional technologies improve as discussed in Chapter 4. In the LED scenario, efficacy improvements to the installed base of lighting technology in each CRI bin increase due to improvements in both conventional lighting and SSL technologies. The influence of the market adopting highly efficacious LED sources is clearly evident, as for example, as the low CRI technology segment for the commercial sector shifts from a starting value of 86 lumens per watt in 2007 to 155 lumens per watt in 2027 under the LED scenario.

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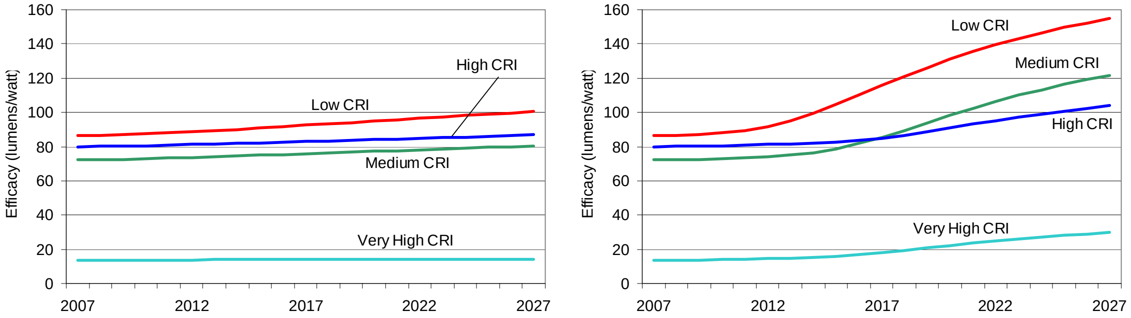
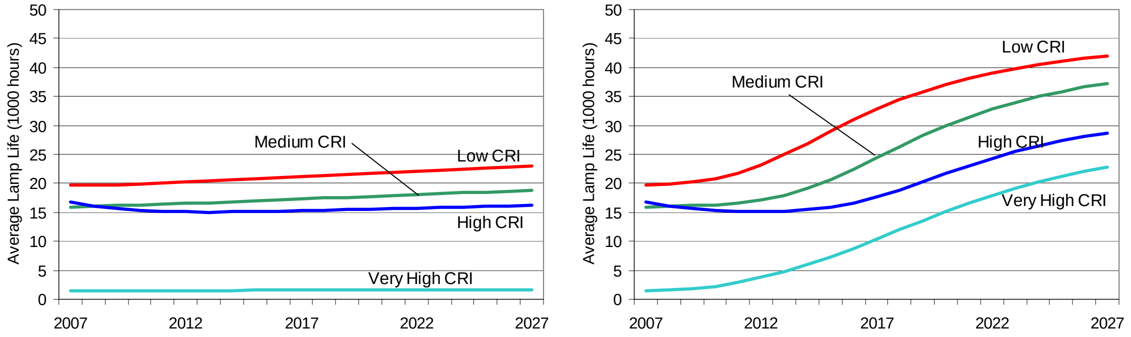
[12] The primary markets are differentiated by sector and whether the first cost includes just the lamp cost or the lamp cost and the fixture cost.



*Reference Scenario* *LED Scenario*

**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 from 38 percent in 2007 to 33% in 2027 under the reference scenario and 16% in 2027 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 both 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.



*Reference Scenario* *LED Scenario*

**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 dramatic increase in lamp operating life is experienced by the installed base under the LED scenario, whereby low CRI doubles from approximately 20,000 hours of average operating life to more than 40,000 hours over the analysis period. An increase of approximately 20,000 hours is also experienced by the very high CRI lamps, which shifts from approximately 1,000 hours to nearly 23,000. 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.

Figure 7-4 presents the projected energy consumption by lighting through 2027[13] for the LED and OLED

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[13] While projecting the energy consumption for lighting, we have assumed that the ratio of Primary Energy

scenarios. The LED scenario shows greater energy savings in the near-term, with a departure from the reference line starting around 2010. The OLED scenario starts to impact the general illumination market around 2015. 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.

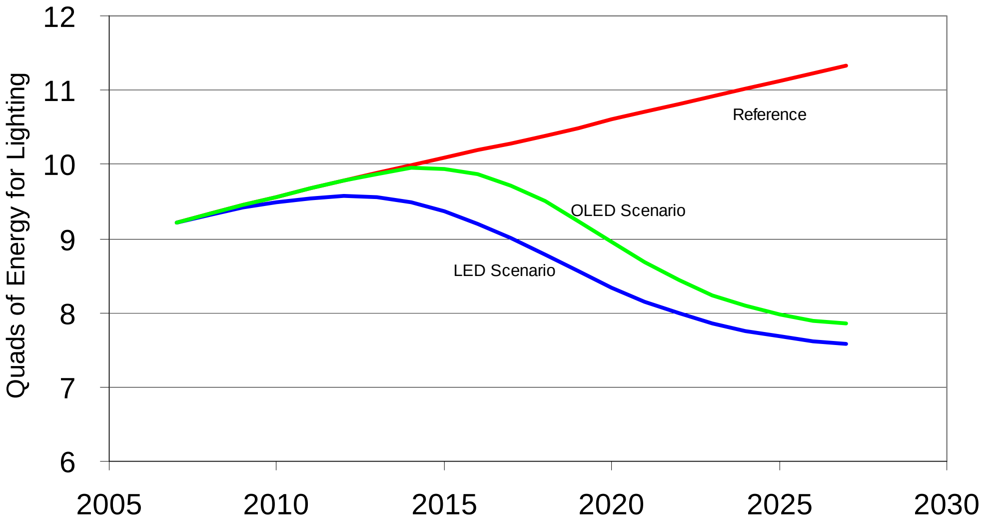

**Figure 7-4. National Energy Consumption for Lighting Through 2027 for Each Scenario (Quads)**

While the OLED scenario is later in capturing energy savings, the scenario does anticipate rapid energy savings that approaches that of the LED scenario by the end of the analysis period (2027). This is due in part to the technology performance curve that is projected by industry experts. In addition, as LEDs are projected to quickly attain a 50,000 hour operating life, the available lumen turn-over in any given year diminishes. This means then that sockets which are "early adopters" of LED technology get locked into that technology for 50,000 hours of service at the efficacy the LED sources had at that time. This impact of the "early adopters" contributes to a slowing in the LED scenario lumen market turn-over, which reduces the number of opportunities for higher-efficacy LEDs to enter the market. This impact is evident in the gradual leveling of the energy consumption plot in Figure 7-4.

Table 7-1 presents the energy savings terms of both quads of primary energy and terawatt-hours of site[14] electricity consumption.

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Consumption to end-use electricity consumption remains constant at the 2005 forecasted level of 10,744 BTU/kWh (DOE Core Databook, 2003). This avoids confusion over energy savings resulting from power system efficiency improvements versus those gains made through the installation of more efficacious lighting sources.

[14] 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 7-1. Energy Savings Projections 2012 – 2027**

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

| Scenario | 2012 | 2017 | 2022 | 2027 | Cumulative |
|---|---|---|---|---|---|
| *Reference* | 9.78 quads<br>908 TWh | 10.29 quads<br>956 TWh | 10.81 quads<br>1004 TWh | 11.33 quads<br>1,052 TWh | n/a<br>n/a |
| *Quads of primary energy savings and TWh of site electricity savings relative to Reference* | | | | | |
| *LED Scenario* | 0.21 quads<br>19 TWh | 1.29 quads<br>120 TWh | 2.81 quads<br>261 TWh | 3.75 quads<br>348 TWh | 32.5 quads<br>3,019 TWh |
| *OLED Scenario* | 0.00 quads<br>0 TWh | 0.57 quads<br>53 TWh | 2.37 quads<br>220 TWh | 3.48 quads<br>323 TWh | 24.8 quads<br>2,303 TWh |

In the LED scenario, approximately 3.75 quads of primary energy, or about 348 TWh, can be saved annually by 2027. Under the OLED scenario approximately 3.48 quads of primary energy, or about 323 TWh can be saved. Both of these estimates represent approximately a 33 percent reduction in the projected energy consumption for lighting in 2027 over the reference scenario, and represents an actual reduction in lighting energy consumption (in absolute terms) compared to the start of the analysis period, 2007. In other words, in 2007 lighting energy consumption is estimated to be approximately 9.21 quads of energy. By 2027, under the LED and OLED scenarios, lighting energy consumption is estimated to be 7.58 quads and 7.85 quads, respectively, both below the 2007 level. The annual electricity savings in 2027 (348 TWh for LEDs or 323 TWh for OLEDs) represent the equivalent annual output of forty 1000MW power plants operating at 90 percent availability.

As discussed in Chapter 4, three scenarios are considered for the performance improvement of the conventional (incandescent, fluorescent and HID) lighting technologies. Table 7-2 provides the energy savings in 2027 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.

**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<br>(Quads for lighting in 2027) | 11.79 Quads | 11.33 Quads | 10.67 Quads |
| LED Scenario<br>(Quads ***saved*** in 2027) | 4.25 Quads | 3.75 Quads | 3.14 Quads |
| OLED Scenario<br>(Quads ***saved*** in 2027) | 3.92 Quads | 3.48 Quads | 2.91 Quads |

For LEDs, the range is +0.50 and -0.60 quads, indicative of the competitive nature of the market under each scenario. For OLEDs, the range is similar, at +0.44 and -0.57 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. However, for both the LED and OLED scenarios, even under the high degree of technological improvement for conventional technology[15], the energy savings attributable to either SSL technology in 2027 is approximately 3.0 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 electricity in today's dollars is valued at approximately $7 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 receive reasonable payback periods and would, in turn, save a considerable amount of energy.

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[15] The high improvement of conventional technology assumes that relative to 2007 values, by 2027 average efficacies of incandescent lamps have increased by 10%, efficacies of fluorescent lamps by 20% and efficacies of HID lamps by 30%. The high improvement scenario assumes that median operating life increases by 10% for incandescent and 20% for fluorescent and HID lamps. Finally, lamp prices of the conventional technologies are all assumed to have reduced by 15% relative to 2007 prices.

## 8. Conclusions

Over the last few decades, lighting technologies such as T8 and T5 fluorescent tubes, electronic ballasts, metal halide HID lamps and other advances have yielded considerable energy savings to the lighting market. Over the coming decades, SSL sources could 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 potential national energy savings that will result by 2027 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 2027, its market penetration and energy saving potential will be driven primarily by economics – incorporating 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 incandescent lamps in commercial and residential applications. As shown in Figure 8-1, the majority of the 348 TWh saved in 2027 under the LED scenario are derived from LED lamps and fixtures displacing incandescent lamps (very high CRI), particularly in the commercial and residential sectors. LED substitutes in the medium CRI bin in both the commercial and industrial sectors also contribute significant portions of energy savings.

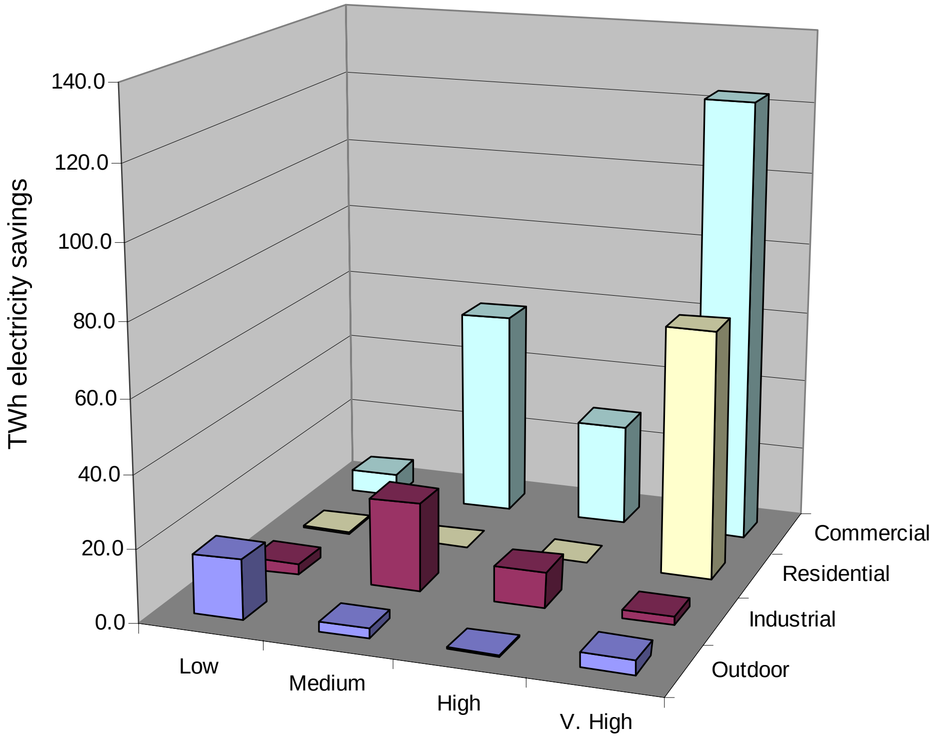

**Figure 8-1. Electricity Savings Breakdown for the LED Scenario in 2027**

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. More specifically, while 29% of the LED lumen-hours in 2027 enter the market in the very high CRI bin, more lighting service is provided by the high CRI (36%) and medium CRI (41%) bins of delivered lumens. However, the contributions of energy savings from these three CRI bins in 2027 are disproportionate; the very high CRI bin contributes 57% to the 2027 energy savings, while the high CRI and medium CRI contribute significantly less – 11% and 24%, respectively. The reason for this disparity is the higher efficacy of the medium and high CRI stock (largely fluorescent) relative to the very high CRI bin (largely incandescent) in the reference scenario. Thus, the energy savings from the penetration of a more efficacious source (i.e., LED lamps and fixtures) has a greater impact from an energy savings perspective in the very high CRI bin than in the high CRI bin.

In order to achieve the energy savings projection in this report, SSL will need to achieve substantial improvements in price, efficacy and operating life. If these objectives are met, SSL should achieve gradually increasing market impacts up through the end of the analysis period and beyond. Relative to the reference case, the two SSL scenarios considered are both projected to reduce lighting energy consumption in absolute terms over the twenty year analysis period while the annual lumens delivered increases by 31.5 percent. This estimated reduction of 3.75 quads for LED (or 3.48 quads for OLEDs) in 2027 will contribute to peak electricity savings, since commercial lighting is a peak load contributor through both direct consumption and indirect consumption (i.e., reduced HVAC loads). This reduction will ease pressure on the transmission and distribution system during these peak times, and contribute to a cleaner environment.

This energy savings estimate is based on a reference scenario of performance improvements of conventional technology as discussed in Chapter 4. If another technology (e.g., compact fluorescent lamps) were to displace the incandescent lamps before SSL very high CRI devices evolved to replace them, the energy savings potential of SSL would be lower because the efficacy of the baseline competition would be higher.

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. The surface of this figure is banded, 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. These axes provide the target values for SSL sources by CRI bin (low, medium, high and very high) in 2027. These results differ somewhat from those discussed in Chapter 7, because for the purposes of creating Figure 8-2, the targets plotted on the two axes are achieved in 2027.

The labeled boundaries of primary energy savings on the surface show the energy savings at the corresponding price and efficacy targets, as they appear along the axes. 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, 2005 and 2006 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 2005, this typical white-light is estimated as $150/klm and 35 lm/W; 2006 estimates show the typical white-light source at $120/klm and 40 lm/W. The relative positioning of these dots illustrates the trend of increasing efficacy and reducing price.

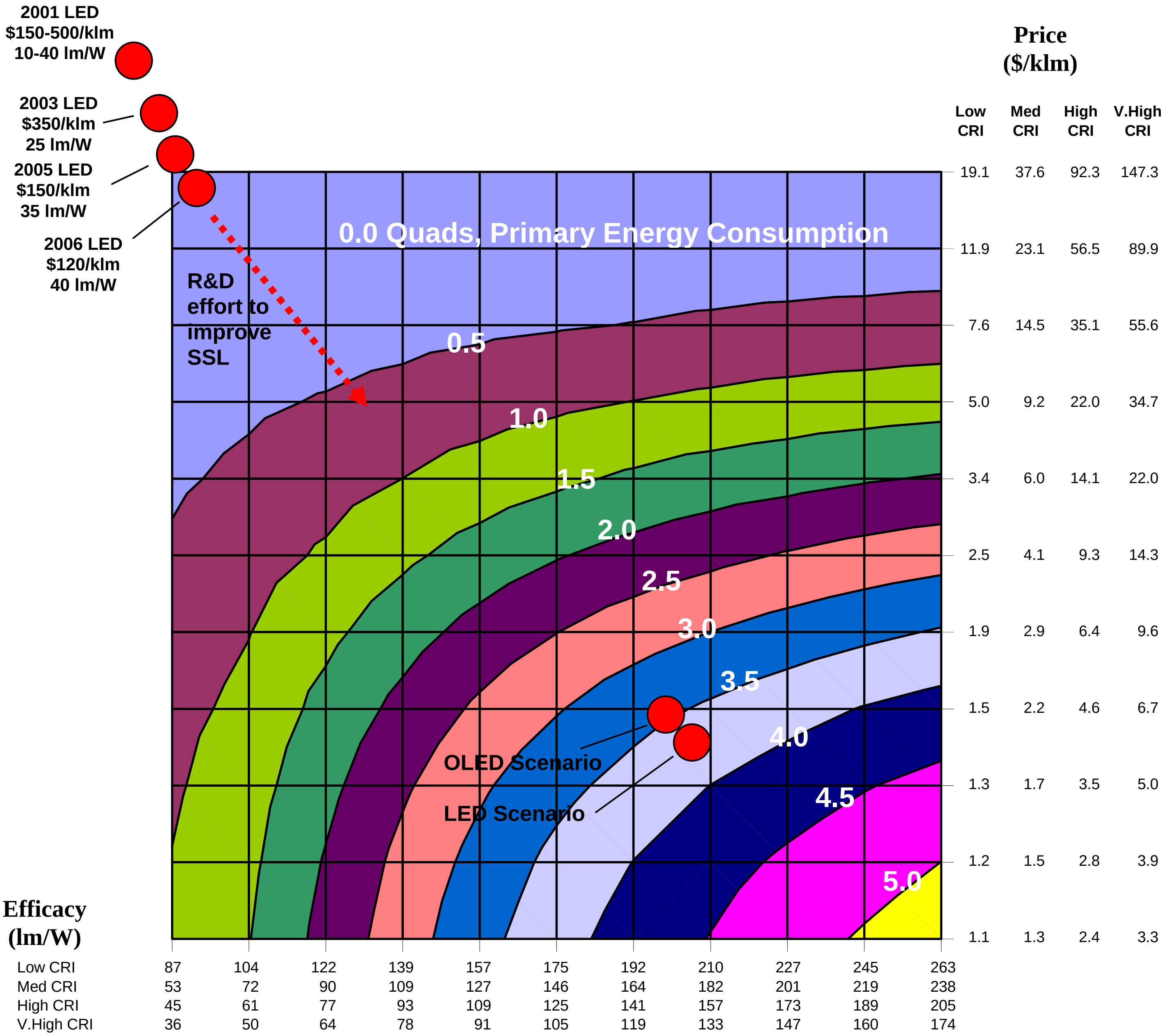

**Figure 8-2. Quads of Primary Energy Savings Over Reference Scenario**

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 2027

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| LED | 86.6 | 98.8 | 111.0 | 122.7 | 133.8 | 144.0 | 153.2 | 161.2 | 168.1 | 174.1 | 179.1 | 183.3 | 186.9 | 189.9 | 192.5 | 194.6 | 196.5 | 198.1 | 199.5 | 200.7 | 201.9 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| LED | 19.1 | 12.9 | 8.9 | 6.3 | 4.7 | 3.7 | 3.1 | 2.7 | 2.4 | 2.2 | 2.1 | 2.1 | 2.0 | 2.0 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.8 | 1.8 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| LED | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Medium CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| LED | 53.1 | 63.7 | 75.2 | 87.2 | 99.2 | 111.0 | 122.0 | 132.0 | 141.0 | 148.7 | 155.3 | 160.8 | 165.4 | 169.3 | 172.4 | 175.0 | 177.2 | 179.0 | 180.6 | 182.0 | 183.1 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| LED | 37.6 | 27.9 | 20.8 | 15.5 | 11.6 | 8.8 | 6.6 | 5.1 | 4.0 | 3.3 | 2.8 | 2.6 | 2.4 | 2.3 | 2.3 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.1 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| LED | 43.3 | 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 | 50.0 | 50.0 | 50.0 | 50.0 |
| High CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| LED | 44.7 | 54.0 | 63.8 | 73.8 | 83.9 | 93.9 | 103.5 | 112.7 | 121.4 | 129.4 | 136.3 | 141.5 | 145.5 | 148.6 | 151.0 | 152.9 | 154.4 | 155.7 | 156.8 | 157.7 | 158.6 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| LED | 92.3 | 72.5 | 54.6 | 39.7 | 28.3 | 20.1 | 14.4 | 10.6 | 8.1 | 6.6 | 5.6 | 5.0 | 4.6 | 4.4 | 4.3 | 4.2 | 4.1 | 4.1 | 4.0 | 4.0 | 4.0 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| LED | 30.0 | 36.7 | 43.3 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Very High CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| LED | 36.3 | 44.3 | 52.4 | 60.4 | 68.6 | 76.8 | 85.1 | 93.4 | 101.8 | 110.0 | 117.2 | 122.2 | 125.6 | 127.9 | 129.6 | 130.7 | 131.6 | 132.3 | 133.0 | 133.5 | 134.0 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| LED | 147.3 | 117.3 | 88.6 | 64.1 | 45.1 | 31.5 | 22.3 | 16.2 | 12.4 | 9.9 | 8.4 | 7.5 | 6.9 | 6.5 | 6.3 | 6.2 | 6.1 | 6.0 | 5.9 | 5.9 | 5.9 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| LED | 15.0 | 23.3 | 30.0 | 36.7 | 43.3 | 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 |

Note: that the values in these tables are based on the projections contained in the Department's March 2006 multi-year program plan for SSL, which is available on the web: http://www.netl.doe.gov/ssl/PDFs/SSLMultiYearPlan.pdf The multi-year program plan projects price, performance and life for one CRI bin from 2007 through 2015. These projections were then extrapolated to 2027 using a 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 2027

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 28.8 | 40.1 | 54.5 | 71.5 | 90.5 | 110.0 | 128.7 | 145.2 | 159.0 | 170.0 | 178.4 | 184.7 | 189.3 | 192.7 | 195.3 | 197.3 | 198.9 | 200.2 | 201.3 | 202.2 | 203.1 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 83.3 | 54.5 | 35.3 | 22.9 | 15.0 | 10.1 | 7.0 | 5.1 | 3.9 | 3.1 | 2.7 | 2.4 | 2.2 | 2.1 | 2.0 | 1.9 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 5.7 | 6.5 | 7.4 | 8.3 | 9.1 | 10.0 | 10.9 | 11.7 | 12.6 | 13.5 | 14.3 | 15.2 | 16.0 | 16.9 | 17.8 | 18.6 | 19.5 | 20.0 | 20.0 | 20.0 | 20.0 |
| | | | | | | | | | | | | | | | | | | | | | |
| Medium CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 15.8 | 19.6 | 24.3 | 30.2 | 37.4 | 46.5 | 57.7 | 71.5 | 88.8 | 109.4 | 123.4 | 135.2 | 144.5 | 151.6 | 156.9 | 160.8 | 163.8 | 166.0 | 167.6 | 169.0 | 170.1 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 151.6 | 102.0 | 68.7 | 46.4 | 31.5 | 21.4 | 14.6 | 10.1 | 7.0 | 5.5 | 4.3 | 3.6 | 3.2 | 3.0 | 2.9 | 2.8 | 2.7 | 2.7 | 2.7 | 2.7 | 2.6 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 4.0 | 4.8 | 5.7 | 6.5 | 7.4 | 8.3 | 9.1 | 10.0 | 10.9 | 11.7 | 12.6 | 13.5 | 14.3 | 15.2 | 16.0 | 16.9 | 17.8 | 18.6 | 19.5 | 20.0 | 20.0 |
| | | | | | | | | | | | | | | | | | | | | | |
| High CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 9.3 | 12.0 | 15.6 | 20.3 | 26.5 | 34.5 | 44.7 | 57.3 | 72.1 | 88.7 | 101.4 | 112.1 | 120.5 | 126.9 | 131.5 | 134.9 | 137.4 | 139.2 | 140.6 | 141.7 | 142.6 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 305.7 | 245.7 | 188.5 | 136.9 | 94.5 | 62.7 | 40.8 | 26.6 | 17.6 | 12.4 | 9.1 | 7.2 | 6.1 | 5.5 | 5.1 | 4.9 | 4.7 | 4.6 | 4.6 | 4.5 | 4.5 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 2.2 | 3.1 | 4.0 | 4.8 | 5.7 | 6.5 | 7.4 | 8.3 | 9.1 | 10.0 | 10.9 | 11.7 | 12.6 | 13.5 | 14.3 | 15.2 | 16.0 | 16.9 | 17.8 | 18.6 | 19.5 |
| | | | | | | | | | | | | | | | | | | | | | |
| Very High CRI | | | | | | | | | | | | | | | | | | | | | |
| Efficacy (lm/w) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 2.9 | 4.4 | 6.8 | 10.4 | 15.5 | 22.6 | 31.8 | 43.0 | 55.5 | 68.0 | 79.4 | 89.0 | 96.5 | 102.1 | 106.1 | 109.0 | 111.0 | 112.5 | 113.6 | 114.4 | 115.1 |
| Lamp Cost ($/klm) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 460.1 | 389.6 | 308.5 | 227.6 | 157.6 | 104.1 | 67.1 | 43.1 | 28.3 | 19.3 | 14.0 | 10.8 | 9.0 | 7.9 | 7.3 | 6.9 | 6.7 | 6.6 | 6.5 | 6.4 | 6.4 |
| Lamp Life (1000 hours) | | | | | | | | | | | | | | | | | | | | | |
| OLED | 0.5 | 1.4 | 2.2 | 3.1 | 4.0 | 4.8 | 5.7 | 6.5 | 7.4 | 8.3 | 9.1 | 10.0 | 10.9 | 11.7 | 12.6 | 13.5 | 14.3 | 15.2 | 16.0 | 16.9 | 17.8 |

Note: that the values in these tables are based on the projections contained in the Department's March 2006 multi-year program plan for SSL, which is available on the web: http://www.netl.doe.gov/ssl/PDFs/SSLMultiYearPlan.pdf The multi-year program plan projects price, performance and life for one CRI bin from 2007 through 2015. These projections were then extrapolated to 2027 using a 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. There were three critical areas which were identified for consideration of a sensitivity analysis – one year acceleration of the LED price and performance curves, alternative electricity price scenarios, and 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 (3.75 quads of energy savings in 2027), the one-year acceleration would achieve 3.87 quads of energy savings in 2027, for a savings of an additional 0.12 quads of energy from SSL. Over the time period of analysis, an additional 4.0 quads of energy savings would be realized, representing an additional 12 percent in 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 2006 reference case | AEO 2006 forecasted annual electricity prices, as summarized in table 6-1 of this report. | 3.75 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 2007 levels for the complete time period of analysis.<br>Residential: $0.092;<br>Commercial: $0.084;<br>Industrial: $0.060 and<br>Outdoor: $0.084. | 3.88 quads | Energy savings from SSL increases by 0.13 quads over reference case electricity prices. As electricity becomes more expensive in the out-years of the analysis (on average, 8.0% above reference scenario prices), shorter payback periods from SSL are calculated and thus greater levels of market penetration. |
| 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:<br>2007: $0.127 / kWh<br>2012: $0.114 / kWh<br>2017: $0.114 / kWh<br>2022: $0.117 / kWh<br>2027: $0.119 / kWh | 4.41 quads | Energy savings from SSL increases by 0.66 quads in 2027, and by significant amounts overall. While this scenario of 50% higher electricity prices is not considered likely by the Energy Information Administration, 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. |
| The EIA low electricity price projection scenario | Consider the EIA/AEO 2006 low electricity price projection relative to the AEO 2006 reference price scenario, summarized in table 6-1. Below are the Commercial electricity prices:<br>2007: $0.084 / kWh<br>2012: $0.073 / kWh<br>2017: $0.072 / kWh<br>2022: $0.074 / kWh<br>2027: $0.075 / kWh | 3.71 quads | Energy savings from SSL are decreased relative to the reference case, as electricity becomes less expensive (on average, 3.8% below reference scenario prices), making it more difficult to SSL to capture market share. |
| The EIA high electricity price projection scenario | Consider the EIA/AEO 2006 high electricity price projection. Below are the Commercial electricity prices:<br>2007: $0.086 / kWh<br>2012: $0.081 / kWh<br>2017: $0.081 / kWh<br>2022: $0.081 / kWh<br>2027: $0.083 / kWh | 3.80 quads | Energy savings from SSL are slightly higher than the reference case, as electricity becomes slightly more expensive (on average, 4.1% above reference scenario prices), making SSL 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% market penetration, but instead 25%. The figure below shows the reference case residential payback curve and the sensitivity analysis payback curve.

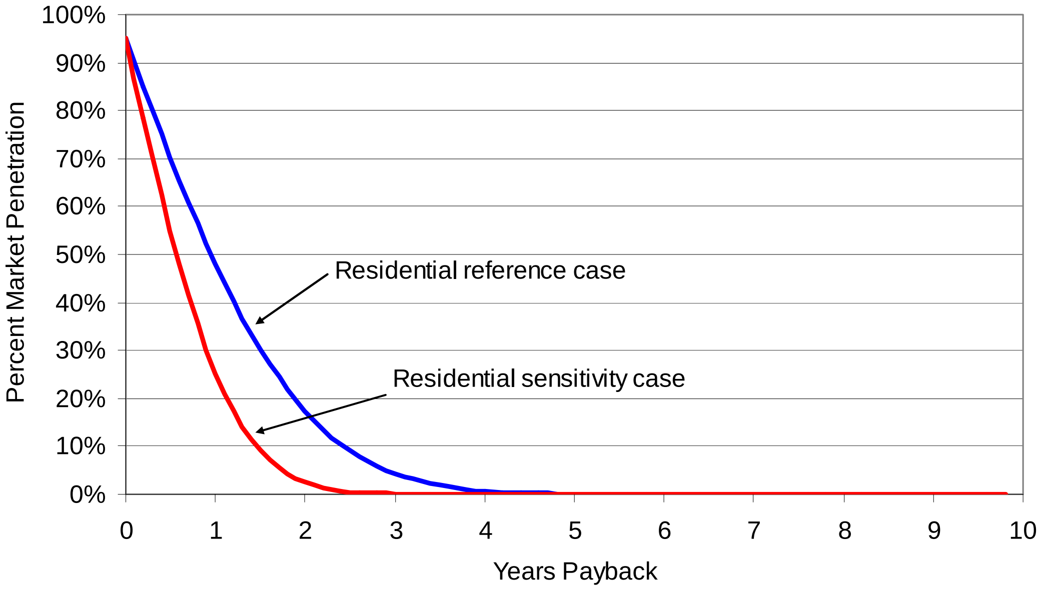

**Figure B.1 Residential Market Penetration Curves for Reference and Sensitivity**

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 LED scenario is 3.75 quads. Changing just the residential payback market penetration curve to the sensitivity shown in Figure B.1 reduces those energy savings by more than 0.34 quads to 3.41 quads of energy savings in 2027.

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