Energy Savings Potential of Solid State Lighting in General Illumination Applications

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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 by November 30, 2004 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
EELA	Energy Efficient Lighting Association
EIA	Energy Information Administration (DOE)
HID	High Intensity Discharge
kWh	Kilo-watt 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
OIDA	Optoelectronics Industry Development Association
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.[1] 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 scientific and research communities forecast that as the performance of light emitting diodes (LEDs) and organic light emitting diodes (OLEDs) improves, their costs will simultaneously decrease (OIDA, 2002a; OIDA, 2002b). The analysis described in this report considers these estimates and others to determine the impact on national energy consumption if SSL were to achieve projected price and performance targets. Energy savings will result from consumers choosing SSL sources in general illumination (white-light) applications such as offices, retail establishments and homes.

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 bins.[2]
3. Project Lighting Demand – Use the new building construction projection provided by the National Energy Modeling System (NEMS) in the Annual Energy Outlook 2003 to forecast lumen demand from 2005 to 2025 (EIA, 2003).
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).
6. Solid State Lighting Technology Improvement Forecast - In consultation with industry experts, estimate the improvements in cost, efficacy and operating life of SSL sources. Two scenarios of SSL improvement were developed for this analysis, a moderate investment scenario and an accelerated investment scenario (see Chapter 5).

[1] To review the niche markets for SSL in 2002, see *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*, Navigant Consulting, Inc., Washington DC, November 2003.
[2] 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 can not 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.

7. Lighting Service Costs - Project lighting costs based on today's market and anticipated improvements for installation (fixture and lamp) and operation (electricity, maintenance and replacement lamps).
8. Economic Lighting Market Model - Develop an economic model of the U.S. lighting market that calculates SSL market penetration based on performance improvements of both conventional technologies and SSL. Incorporate variability into the model to reflect distributions of national electricity pricing and acceptable consumer payback periods.
9. Calculate Energy Savings – Calculate the difference in energy consumption that results under a given SSL technology performance scenario compared with the baseline.

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 2005 to 2025 (Chapter 2)
- Available lumen market - turnover in the installed base of lighting (Chapter 3)
- Conventional technology improvement projection from 2005 to 2025 (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.

- Constant Lighting Intensity – it is assumed that levels of lighting intensity (lumens per square foot) in buildings in 2001 remains constant over the analysis period (2005-2025).
- CRI Light Quality – there are several metrics to describe quality of light, no one metric being able to capture all aspects. The model uses CRI as an indicator of the light quality, differentiating between tasks that require low, medium, high and very high CRI.
- CRI Bins – the model 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. End-users cannot substitute a technology from a different CRI bin.
- SSL Performance Improvement Curves – the model combines the performance improvement projections for LEDs and OLEDs over the analysis period.
- 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.

2. Lighting Inventory and Lumen Demand Projection

To create a national lighting market model, the first step is to forecast the demand for lighting services over the analysis period. The analytical model uses the Lighting Market Characterization report (DOE, 2002) to estimate the national lighting demand (in teralumen-hours[3]) and lighting color quality (using CRI bins). This baseline lighting demand is then divided by the building 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 growth estimates in floor-space from the AEO 2003 for residential and commercial sectors and by user-input for industrial and outdoor stationary sectors. These growth rates range from 1-2% 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. 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. Generally, 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.

Table 2-1 presents the efficacies from the U.S. Lighting Market Characterization report (DOE, 2002) that were instrumental in converting the national lighting inventory into a national lighting service estimate. The average lamp wattages are provided to facilitate review of the efficacies. As mentioned above, the efficacies are used to convert annual electricity consumption for lighting into annual lighting service. 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.

[3] 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	-	78
	T8 - less than 4 ft	-	23	23	-	-	66	66	-	80
	T8 - 4 ft	-	33	31	-	-	83	83	-	80
	T8 - more than 4 ft	-	50	53	105	-	84	84	84	68
	T8 - U-bent	-	34	32	-	-	81	81	-	80
	T12 - less than 4 ft	-	29	32	-	-	60	60	-	71
	T12 - 4 ft	41	45	44	-	68	68	68	-	70
	T12 - more than 4 ft	-	93	95	190	-	69	69	69	76
	T12 - U-bent	-	46	46	-	-	64	64	-	67
	Compact - plug-in	-	17	31	-	-	60	60	-	82
	Compact - screw-in	18	16	14	-	55	55	55	-	82
	Compact - plug-in - reflector	-	16	-	-	-	55	-	-	82
	Compact - screw-in - reflector	11	16	14	-	55	55	55	-	82
	Circline	-	30	35	-	-	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	10

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 convenient, readily understood and captures fundamental differences in lighting services that are necessary to construct the spreadsheet model.

A modeling assumption was made 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 2005, it will require 90 CRI light in 2025. 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.

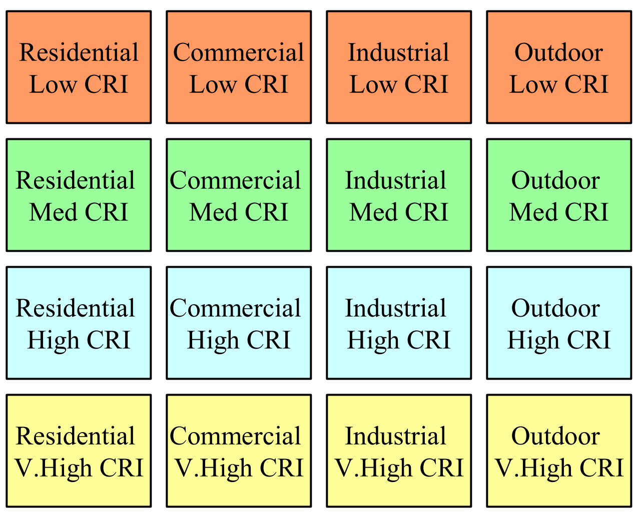
The CRI bins that were created for this analysis are presented in Table 2-2 with some example lamps that are typical of those CRI ranges.

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, T8 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 is created, reflecting the annual lumen demand. This matrix is illustrated in Figure 2-1.

Figure 2-1. Market Matrix of Sectors and Color Bins, Based on 2001 Inventory



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 2005 and 2025. The lumen-hour demand calculated in 2001 from the Lighting Market Characterization report (DOE, 2002) is divided by the cumulative national floor-space for each sector to determine a lumen-hour of lighting demand per square foot of building space. Then, the NEMS projections for square feet of building growth by sector (EIA, 2003) are used to project lumen-hour demand growth from 2005 to 2025, holding the lumen intensity per square foot constant. This assumption is based on the premise that in the future, people occupying 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, 307.0 kilolumen-hours per square foot.

NEMS provides annual growth estimates of floor-space in the residential and commercial sectors (EIA, 2003), 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% per annum.

Residential	1.22% growth
Commercial	1.43% 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 replace distributed sources, 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 simply be speculative. The error of not making an adjustment to the lighting density estimate in each sector is not considered significant because any reduction in lighting density would equate to a further reduction in energy consumption. And, the energy savings potential with solid state sources would only be greater under this scenario, because fewer lumens are used to perform an appropriately lit task with a SSL point source than would be required to flood-light the same task in the reference case.

Table 2-3 presents a detailed break-down of the estimated lumen-demand by sector in the base-year of analysis, 2005. Note that the dominant sectors in terms of lighting demand are the commercial medium and high CRI, the industrial high CRI and the outdoor stationary low CRI.

Table 2-3. Sector and CRI Bins of Teralumen-hours Lighting Demand in 2005

(Tlm-hr/yr)	Residential	Commercial	Industrial	Outdoor	CRI-Bin Total
Low CRI	33	1,021	711	4,145	5,910
Medium CRI	1,336	12,451	3,755	572	18,113
High CRI	62	7,932	4,258	64	12,316
Very High CRI	2,632	1,956	41	88	4,717
Sector Totals	4,062	23,361	8,765	4,868	41,056

Figure 2-2 illustrates the impact of the growth rates applied annually to each of the sectors. This diagram presents the growth in lumen demand nationally in teralumen-hours per year by CRI bin. These lighting demand projections extend over the energy savings analysis period of 2005 to 2025. By this account, lighting demand in the United States is estimated to increase by approximately 29% over the next two decades.

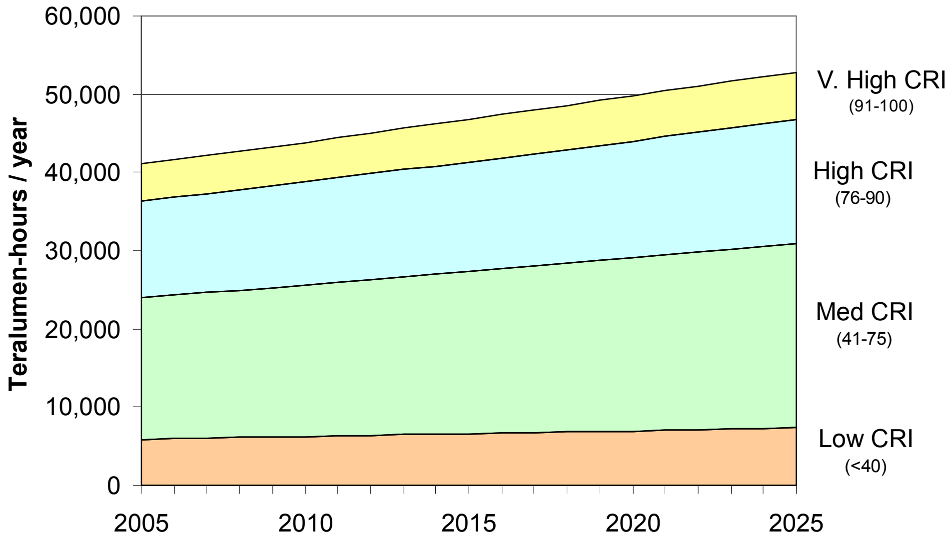


Figure 2-2. Market Forecast of Lumen Demand by CRI Bin

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 2005, 2010, 2015, 2020 and 2025. These tables provide a more detailed look at the projected lighting demand. Comparing these two tables and reviewing the CRI values presented in Table 2-1, the incandescent sector is the only 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 split between the medium CRI and low CRI bins.

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

Lamp Source Type	2005	2010	2015	2020	2025
Incandescent	4,717	5,067	5,429	5,767	6,108
Fluorescent	23,618	25,255	27,058	28,862	30,703
HID	12,717	13,478	14,303	15,150	16,026
Solid State	5	5	6	6	6
Total	41,056	43,806	46,796	49,785	52,844

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

CRI Bin	2005	2010	2015	2020	2025
Low CRI (<40)	5,910	6,237	6,586	6,947	7,324
Med CRI (41-75)	18,113	19,366	20,742	22,117	23,521
High CRI (76-90)	12,316	13,135	14,039	14,953	15,891
Very High CRI (91-100)	4,717	5,067	5,429	5,767	6,108
Total	41,056	43,806	46,796	49,785	52,844

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 market dynamics may respond. 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 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* – the new fixtures that are installed each year due to floor space growth in a particular sector, determined by the NEMS growth projection 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* – the lamps that burn out during a calendar year. This calculation is based on a comparison of the operating hours of the lighting technologies and the lamps servicing the stakeholder needs. For this analysis, just as industry has done with compact fluorescent lamps being a direct replacement for a general service incandescent lamp, we assume that companies developing SSL technology will produce lamps that are able to be installed directly into existing lighting fixtures, replacing conventional technologies (see discussion below).

- *Retrofits* – the lamps and fixtures replacing existing lamps and fixtures during renovation or remodeling. This replacement occurs before the 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.

As discussed above for the Replacements category, the model simplifies the market by assuming that SSL lamps will be developed that can be directly installed into conventional lighting fixtures, in place of incandescent lamps or fluorescent tubes. This is used as a simplifying assumption because we can't anticipate what products may be available in the future market. There are SSL lamps available today which retrofit into incandescent-type (e.g., E-26) sockets, however there is uncertainty around the form which products to replace fluorescent tubes may take. The assumption of directly replaceable was necessary in order to compete SSL and conventional technologies on a socket-availability basis.

The market turnover model does not attempt to account for end-user decisions to retire less efficient equipment early due to a desire to achieve energy savings (i.e., "lighting retrofits"). Literature reviewed suggests that only about 1 percent of floor-space every ten years undergoes lighting retrofits purely for energy savings reasons.[4] Thus, this would be captured in the fixed 5% of lumen demand retrofitted 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. As discussed above, new construction and retrofits incorporate both a lamp and a fixture price while replacements only considers the lamp price.

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[4] Energy Efficient Lighting Association (EELA) *Fact Sheet*, February 2000.

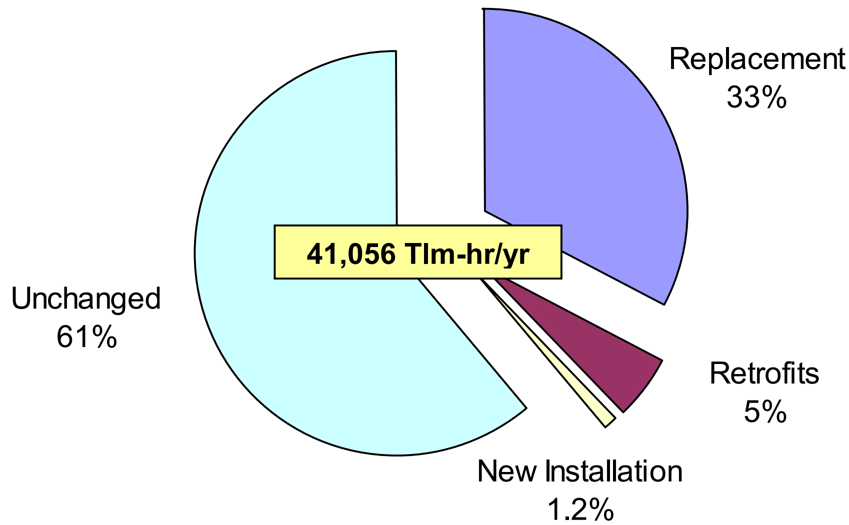


Figure 3-1. Annual Lumen Market Turnover in 2005

Note that as shown in Figure 3-1, approximately 40% of the installed annual lumen-hour demand is replaced or installed in 2005. This installed base turnover rate determines the maximum penetration rate of any new lighting technology. As longer-life lighting technologies are introduced into the market, the turnover occurs more slowly because there are fewer lamp failures in a given year. Thus, in percentage terms, the available lumen market in 2005 is larger than that in 2025. This hold true for the reference case, as the lamp lives of the conventional technologies are assumed to improve (see Chapter 4). This also holds true under the SSL scenarios, as the SSL lamp lives are projected to exceed those of the conventional technologies (see Chapter 5). Thus, in 2025, instead of nearly 40% of the annual lumen market available, under the reference scenario, only 33% is available, and under the accelerated investment scenario, the market is reduced to just 19% (note: for an explanation of the reference and accelerated investment scenarios, please see Chapter 5).

The computer model follows the purchasing decisions of lighting consumers annually from 2005 to 2025, and the lighting stock turnover (i.e., the available lumen market) is adjusted depending on the lamp life of the lighting technologies that are 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 2005 to 2025. The model is able to adjust the lamp efficacy, operating life and cost for the three primary groups of conventional lighting technologies.

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 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 2005 and 2025		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. Due to the maturity of these technologies, there is little room for cost improvement without sacrificing performance and for many technologies, limited opportunity for improvement overall. For simplicity, the performance improvements of these conventional lighting technologies are introduced on a linear basis over the 2005 to 2025 period.

In order to more closely assess how these performance changes actually impact the technologies used in the analysis, the base year (2005) and target year (2025) 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. All the dollar values presented in these tables are constant 2005 dollars.

Table 4-2. Residential Sector Conventional Technologies Improvement, 2005 and 2025

				Baseline Technology 2005			Medium Technology Improvement Potential by 2025		
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	-	-	-	-	-	-	-	-	-
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	-	-	-	-	-	-	-	-	-

Table 4-3. Commercial Sector Conventional Technologies Improvement, 2005 and 2025

				Baseline Technology 2005			Medium Technology Improvement Potential by 2025		
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	8	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	17.5	2.00	91	21.0	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

Table 4-4. Industrial Sector Conventional Technologies Improvement, 2005 and 2025

				Baseline Technology 2005			Medium Technology Improvement Potential by 2025		
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	2.5	16	14.20	1.50	17	2.8	1.35
Standard - Reflector	102	100	1.5	14	14.20	2.25	15	1.7	2.03
Halogen - General Service	-	-	-	-	-	-	-	-	-
Halogen - Reflector	452	100	3.5	25	14.20	3.00	26	3.9	2.70
Halogen - Reflector low volt	58	100	4.0	13	14.20	3.75	14	4.4	3.38
Low wattage (< 25W)	19	100	2.5	10	14.20	0.65	11	2.8	0.59
Fluorescent							**10%**	**20%**	**-10%**
T5	10	78	20.0	95	53.00	2.00	105	24.0	1.80
T8 - less than 4 ft	23	80	17.5	66	53.00	3.00	73	21.0	2.70
T8 - 4 ft	31	80	17.5	83	59.40	2.00	91	21.0	1.80
T8 - more than 4 ft	53	68	13.8	84	59.40	6.00	92	16.5	5.40
T8 - U-bent	32	80	20.0	81	41.60	7.50	89	24.0	6.75
T12 - less than 4 ft	32	71	12.8	60	53.00	2.25	66	15.3	2.03
T12 - 4 ft	44	70	20.0	68	59.40	1.50	74	24.0	1.35
T12 - more than 4 ft	95	76	14.5	69	59.40	3.50	75	17.4	3.15
T12 - U-bent	46	67	15.0	64	41.60	5.50	70	18.0	4.95
Compact - plug-in	31	82	15.0	60	14.20	5.50	65	18.0	4.95
Compact - screw-in	14	82	10.0	55	14.20	5.50	61	12.0	4.95
Compact - plug-in reflector	-	-	-	-	-	-	-	-	-
Compact screw-in reflector	14	82	10.0	55	14.20	8.00	61	12.0	7.20
Circline	35	73	11.0	50	14.20	3.50	55	13.2	3.15
Induction Discharge	-	-	-	-	-	-	-	-	-
Miscellaneous fluorescent	34	80	10.0	55	34.10	2.25	61	12.0	2.03
High Intensity Discharge							**20%**	**20%**	**-10%**
Mercury vapor	409	33	20.0	55	108.00	22.00	66	24.0	19.80
Metal halide	438	68	13.8	100	108.00	60.00	120	16.5	54.00
High pressure sodium	394	22	20.0	100	108.00	20.00	120	24.0	18.00
Low pressure sodium	90	10	16.0	113	108.00	22.00	135	19.2	19.80

Table 4-5. Outdoor Stationary Conventional Technologies Improvement, 2005 and 2025

				Baseline Technology 2005			Medium Technology Improvement Potential by 2025		
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	13.8	6.00	92	16.5	5.40
T8 - U-bent	-	-	-	-	-	-	-	-	-
T12 - less than 4 ft	-	-	-	-	-	-	-	-	-
T12 - 4 ft	-	-	-	-	-	-	-	-	-
T12 - more than 4 ft	190	76	59.40	69	14.5	3.50	75	17.4	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

5. Solid State Lighting Technology Improvements

Researchers anticipate that SSL technology will follow the generally recognized model of technology advancement over time. Based on an anticipated performance target, new technology generally achieves that target by improving exponentially at first, then linearly, and then asymptotically. This type of performance improvement is referred to as an "S-Curve", as the shape of the curve resembles the letter "S". As shown in Figure 5-1, the Y-axis represents the percentage of the technological performance target achieved and the X-axis represents time.

The technology S-curve illustrated in Figure 5-1 has three distinct phases. First, as researchers make initial breakthroughs, there is exponential performance improvement as SSL emerges from its invention period. In the second stage, SSL technology improves linearly, as continued R&D investment builds on prior breakthroughs and advances the technology. In the third stage, the technology asymptotically approaches 100% of its target value, as it becomes a mature technology with limited potential for improvement.

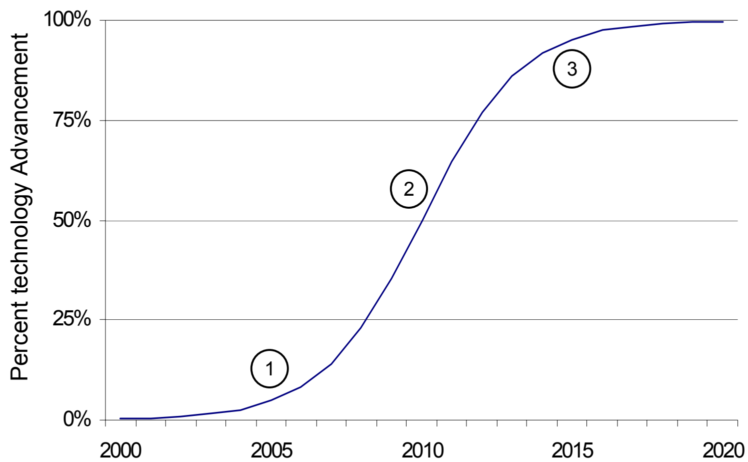


Figure 5-1. Example of a Technology S-Curve

All technologies are systems whose performance can be influenced by many different variables and specifications. The best technology performance metrics to track are those that link directly to some customer utility. For example, technology S-curves have been used to track the density of transistors on a computer chip, as the number of transistors relates directly to the functionality and performance of that chip (Betz, 1993). For SSL, the performance metrics considered in this model are all related to customer utility – the chip efficacy, the cost and the operating life.

For each of these, a technology S-curve incorporates some natural limit, anticipated by experts to be the value the technology will achieve over an evaluation period. Once the natural limit has been determined, the slope of the approach to achieve that limit is estimated, based on analysis of research to date, technology development curves in related technologies, and consultation with researchers working on that technology.

Over the last three years, the U.S. Department of Energy has worked with the Optoelectronics Industry Development Association (OIDA), the National Electrical Manufacturers Association (NEMA) and several national laboratories and numerous researchers (>300 attendees at 7 workshops) to create technology roadmaps for both LEDs and OLEDs. These technology roadmaps provide estimates of the expected price and performance improvements of these technologies over time. Tables presenting the summary targets published in the technology roadmaps can be found in Appendix A (OIDA 2002a, OIDA 2002b).

For the SSL technology improvement curves, a simplifying assumption was made in order to compete SSL sources against the conventional lighting technologies. The technological improvement curves of SSL devices presented in this chapter represent the aggregate of both LED and OLED devices. It is recognized that LEDs have greater application potential in point source installations, such as those currently serviced by incandescent or HID lamps; while OLEDs have greater potential in distributed illumination applications, such as those serviced by fluorescent lamps. From an application perspective, the lighting market spreadsheet model does not track lighting service by point or distributed source, as data on the proportions of each in the national lighting market are not readily available. And, it is recognized that certain point sources can be used as distributed sources if they are utilized in an appropriate fixture that avoids direct line-of-sight to the source such as a torchiere fixture or a T5 fluorescent lamp fixture.

From a technical perspective, it is recognized that in terms of device performance (e.g., efficacy, cost and operating life), OLED technology is currently trailing that of LEDs. OLEDs are available in the marketplace, but not for general illumination purposes as some LED devices are. Today's OLED market is focused on display applications such as cell-phones and portable computers. However, in the long-term, OLED devices are expected to achieve the same efficacy in white-light production (e.g., OIDA reports indicate both are expected to achieve 200 lumens per watt in 2020, as shown in Appendix A). But, while efficacy may be equal, important differences in operating life and cost are anticipated which will have countervailing impacts on the market acceptance of OLEDs relative to LEDs. The operating life of OLEDs is expected to be shorter than LEDs (20k hours as opposed to 100k), and the first-cost of OLEDs is expected to be less expensive than LEDs due to the ability to continuously manufacturer OLED panels. Having a shorter operating life reduces the duration of the energy savings and lengthens payback periods associated with OLED technology. However, having a lower first cost would make these devices more attractive to the market, and would encourage end-users to adopt 200 lumen-per-watt devices as replacements for existing, less efficient conventional lighting technology. Thus, it is difficult to assess whether the simplifying assumption of combining the performance improvement curves of LEDs and OLEDs into one SSL technology improvement estimate will increase or decrease energy savings.

Technology improvement S-curves were developed for SSL sources analyzing three critical consumer parameters:

- Efficacy (lumens per watt)
- Lamp price (dollars per kilolumen)
- 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, a reference case and two technology improvement scenarios were created. From these, the differential energy consumption associated with each scenario determines the energy savings. Table 5-1 describes the development of these scenarios. The table also presents the maximum achievable limits for price, efficacy and operating life. As discussed above, these limits represent one of the most critical aspects of technology S-curve modeling. These variables are adjusted in each scenario to reflect the level of research and development investment, which in turn reflects the interest (both industry and government) in developing SSL technology to its full potential.

Table 5-1. Description of the SSL Market Scenarios and Maximum S-Curve Values

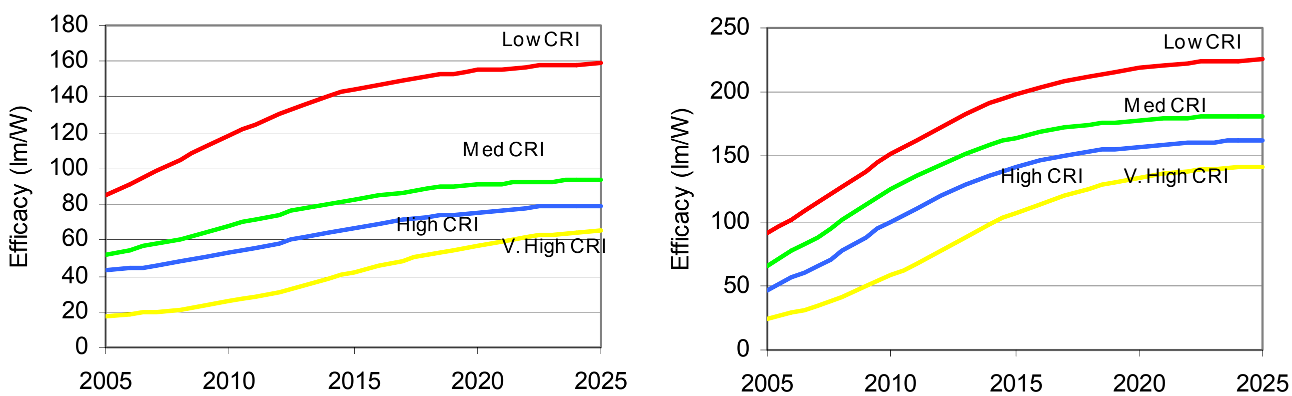
Scenario	General	Discussion	CRI Bin	Efficacy Limit*	Price Limit*	Life Limit*
Reference	All SSL penetration is set to zero	Considers the energy consumption of the lighting market if SSL did not exist, and conventional lighting improves according to the conventional technology improvement scenario selected. 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
Moderate Investment	A national investment of approximately $50 million per year.	Government and industry work together on R&D issues associated with SSL; however, the level of investment is not sufficient to jump-start this technology and realize significant energy savings. The rate of SSL technology advancement is not as great as the accelerated investment scenario. Medium-CRI LED technology is estimated to achieve 93 lm/W and $4.3/klm by 2025.	Low	160 lm/W	1.9 $/klm	80 khrs
			Med	95 lm/W	4.1 $/klm	75 khrs
			High	81 lm/W	5.4 $/klm	70 khrs
			V.High	70 lm/W	6.8 $/klm	65 khrs
Accelerated Investment	A national investment of approximately $100 million per year	Government and industry work together under an accelerated technology scenario, whereby R&D activities are conducted to both improve performance (efficiency and life) as well as reduce costs. Under this scenario, the medium-CRI LED technology achieves 181 lm/W and $2.5/klm by 2025.	Low	229 lm/W	1.2 $/klm	100 khrs
			Med	183 lm/W	2.4 $/klm	100 khrs
			High	164 lm/W	3.1 $/klm	100 khrs
			V.High	145 lm/W	3.9 $/klm	100 khrs

*Note: the values in these cells represent the S-curve maximum achievable price and performance limits that are anticipated in each scenario. These limits represent 100% of the SSL technology goal, which may not be achieved by the end of the analysis period (i.e., SSL technology performance improvements continue beyond 2025).

In the moderate and accelerated investment scenarios, the level of annual investment reflects an assumption that manufacturers and the U.S. government will work together to solve common technology development problems by leveraging resources and sharing risks.[5] Neither investment scenario is as optimistic in terms of SSL price and performance improvement as the targets presented in the most recent SSL technology roadmaps (OIDA, 2002a; OIDA, 2002b). These targets suggest high CRI values of 200 lm/W and less than $2/klm.

In both scenarios, the SSL technology S-Curves for each CRI bins improve in the following sequence – low, medium high and very high CRI. SSL technology in the low-CRI bin has been under development for more than a decade and has already made considerable progress improving its price and performance. The performance of SSL in medium, high and very high CRI applications will lag behind that of the low-CRI applications because they are in earlier stages of development and the technological complexity and hurdles are greater. For some parameters and some CRI bins, the developmental S-curves extend beyond the analysis period end-date of 2025.

The following graphs present the S-curves for the price and performance of the two investment 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 B presents the actual values used annually in each of these technology S-curves over the twenty-year analysis period.



Moderate Investment *Accelerated Investment*

Figure 5-2. SSL Efficacy Improvements for the Investment Scenarios

Figure 5-2 provides the performance improvement curves for SSL efficacy in the two investment scenarios. Note that the Y-axis differs between the two graphs, such that although the performance projection may look similar between the two, they are plotted on different scales. For the moderate investment scenario, the maximum achieved value of low CRI is 160 lm/W in 2025 while for the accelerated scenario, its 229 lm/W, or 43% more efficient.

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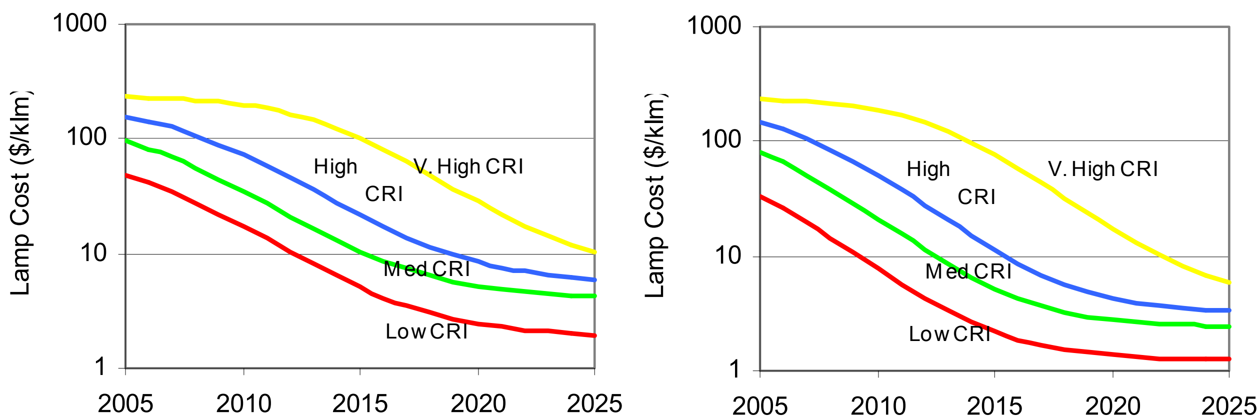
[5] A possible model for how this government – industry partnership may function is the Solid State Energy Conversion Alliance (SECA), initiated in the fall of 1999. SECA is an alliance of government, industry, and the scientific community founded to accelerate development of environmentally friendly solid oxide fuel cells using commonly available fossil fuels. More information can be found at: http://www.seca.doe.gov/

Figure 5-3 represents the price improvement forecasts for each of the scenarios. Please note that these are inverted S-curves, as the price is reducing from a high initial first cost to a lower projected first cost. Due to the difference in scale between 2005 and 2025, these S-curves are plotted on an logarithmic Y-axis. This format enables better comparison of the terminal values between scenarios.

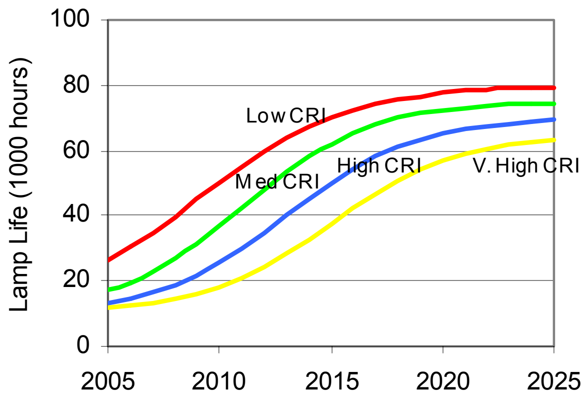


Moderate Investment *Accelerated Investment*

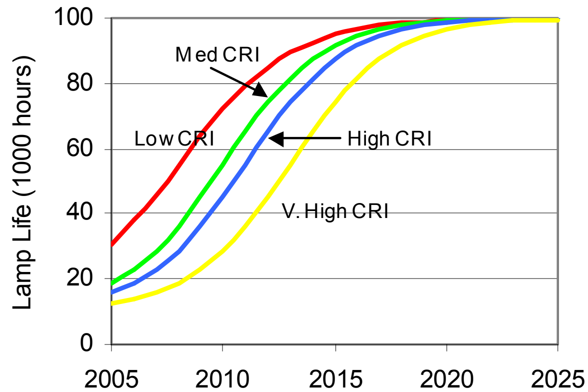
Figure 5-3. SSL Price Improvements for the Investment Scenarios

The lower resulting prices of SSL are evident in the accelerated investment scenario, relative to the moderate investment scenario. For instance in 2005, high CRI technology is being offered in the market at $3.30 as compared with $6.00 under the moderate investment. The lower first-cost in the accelerated investment scenario will lower the first-cost barrier and shorten payback periods, encouraging market adoption of this new technology.

Figure 5-4 presents the SSL operating life projected for the two investment scenarios. These two figures are plotted on the same Y-axis in order to clearly show the difference in anticipated long-term operating life. Under the moderate investment scenario, one hundred thousand hours of operating life is not achieved.



Moderate Investment



Accelerated Investment

Figure 5-4. SSL Lamp Life Improvements for the Investment 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 price improvement ($ / kilolumen) of SSL over the analysis period for each of the CRI bins. More detailed versions of these tables, presenting the actual values used in the model annually, are provided in Appendix B.

Table 5-2. SSL Price for the Moderate Investment Scenario

($ per kilolumen)	2005	2010	2015	2020	2025
Low CRI (<40)	47.7	17.3	5.1	2.4	2.0
Med CRI (41-75)	95.5	34.9	10.5	5.2	4.3
High CRI (76-90)	157.0	73.3	21.7	8.5	6.0
Very High CRI (91-100)	232.6	198.2	101.5	28.4	10.3

Table 5-3. SSL Price for the Accelerated Investment Scenario

($ per kilolumen)	2005	2010	2015	2020	2025
Low CRI (<40)	32.8	7.8	2.2	1.4	1.2
Med CRI (41-75)	81.2	21.2	5.2	2.8	2.5
High CRI (76-90)	145.9	51.0	11.2	4.3	3.3
Very High CRI (91-100)	230.8	185.3	77.1	17.4	5.8

As shown in Table 5-2 and Table 5-3, the price difference between the two scenarios is evident not just in 2025, but also during the interim years. In 2015 for example, High CRI SSL still costs $21.70 in the moderate investment scenario whereas it costs just $11.20 in the accelerated investment scenario. The price improvement of SSL under the accelerated investment scenario is such that over the entire analysis period, SSL has a lower first cost, enhancing its market attractiveness relative to the moderate investment scenario.

Table 5-4 and Table 5-5 provide the efficacy improvement curves for the moderate and accelerated investment scenarios. Again, as shown in these tables, the accelerated investment scenario performance metrics are consistently better than the moderate investment – during the interim years as well as the analysis terminal year.

Table 5-4. SSL Efficacy for the Moderate Investment Scenario

(lumens per watt)	2005	2010	2015	2020	2025
Low CRI (<40)	85.3	118.5	143.7	154.8	158.5
Med CRI (41-75)	52.2	67.5	82.8	90.8	93.7
High CRI (76-90)	42.7	53.0	68.9	75.6	79.3
Very High CRI (91-100)	17.3	25.7	45.0	57.3	65.7

Table 5-5. SSL Efficacy for the Accelerated Investment Scenario

(lumens per watt)	2005	2010	2015	2020	2025
Low CRI (<40)	90.3	151.7	198.4	218.8	225.6
Med CRI (41-75)	65.5	124.2	164.6	178.1	181.5
High CRI (76-90)	47.1	99.0	147.0	158.1	162.3
Very High CRI (91-100)	24.7	57.8	113.8	133.8	142.3

Finally, Table 5-6 and Table 5-7 provide a comparison of the SSL operating life assumed in these two scenarios. As discussed earlier, the accelerated investment scenario is projected to achieve higher overall operating hours due to its high level of investment.

Table 5-6. SSL Operating Life for the Moderate Investment Scenario

(thousand hours)	2005	2010	2015	2020	2025
Low CRI (<40)	26.2	50.2	70.1	77.5	79.4
Med CRI (41-75)	17.1	36.9	62.1	72.3	74.5
High CRI (76-90)	13.4	25.6	50.1	65.2	69.1
Very High CRI (91-100)	11.6	18.1	37.5	56.9	63.4

Table 5-7. SSL Operating Life for the Accelerated Investment Scenario

(thousand hours)	2005	2010	2015	2020	2025
Low CRI (<40)	30.8	72.1	94.8	99.3	99.9
Med CRI (41-75)	18.6	55.0	91.4	99.0	99.9
High CRI (76-90)	15.7	45.0	87.2	98.5	99.8
Very High CRI (91-100)	12.4	28.5	74.0	96.3	99.6

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 approximately 40% 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 efficient and longer lasting.

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 made the fundamental assumption that SSL will eventually meet the requirements of any application, and that CRI is the only performance attribute on which it will compete.[6] 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 segmented into thirty-two markets according to those installations which incorporate both a lamp and fixture price (new installations and retrofits) and those that only incorporate the lamp price (replacements).

To allow us to consider these thirty-two markets in even finer detail, we break each of them down into thirty-five sub-bins based on the initial price-per-lumen (e.g., 0-$0.50/klm, $0.51-$1.00/klm, $1.01-$1.50/klm). 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, we build a demand curve for certain sectors and CRI bins at specific prices. Furthermore, we project demand for new, replacement, and retrofit lumens separately. Since the new and retrofit lumens incorporate the lamp and fixture price, we develop thirty-five more bins in each of the sixteen markets based on the lamp and fixture price. In total, the model evaluates penetration opportunities for SSL technology in 1,120 sub-markets.[7]

The model awards available market share to various lighting technologies based on simple payback, or the ratio of first year incremental purchase price to first year incremental savings. While simple payback may not be the best method for basing a decision of which new lighting technology to purchase, it has several advantages to other methodologies like levelized lighting cost or lifecycle 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

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

[7] 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.

intuitive measure of financial return, thus making it easier to review the projections of the model.

The simple payback calculation we use is based on one provided in E Source, Inc.'s *Lighting Technology Atlas* (1997):

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

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 2003, as presented in Table 6-1 (EIA, 2003). The electricity prices were adjusted to 2005 dollars as that is the base year of the analysis period.

Table 6-1. Electricity Price Projections in 2005 Dollars

($/kWh)	2005	2010	2015	2020	2025
Residential electricity price	0.078	0.076	0.077	0.078	0.079
Commercial electricity price	0.069	0.067	0.069	0.072	0.073
Industrial electricity price	0.043	0.043	0.044	0.045	0.046
Outdoor Stationary electricity price	0.069	0.067	0.069	0.072	0.073

Source: EIA, 2003

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.

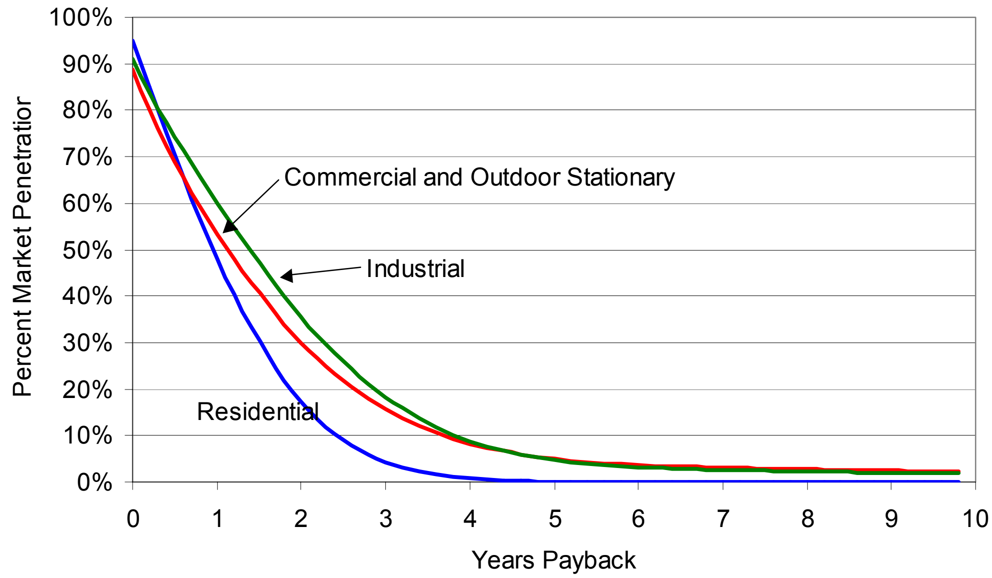

Figure 6-1. Market Penetration Curves Used to Determine Market Penetration

The curves are read 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.

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.[8]
Lower	Lower	Economics compel sector to switch to SSL; maximum available market will switch to SSL.

[8] 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.

In the fourth scenario presented in Table 6-2, the "maximum available market" switches to SSL. Under this condition, the model awards the maximum percentage market penetration to SSL, as defined by the market share penetration curves at zero years payback. For the residential sector, this represents 95% 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 of a particular sector who are slow to adopt a new technology, and may reject it for several years despite compelling economics and proven performance.

Furthermore, the model recognizes that even under the most ideal conditions, market penetration is not instantaneous. Due to the rapid development of SSL projected in our model, payback periods occasionally decline rapidly, implying a dramatic takeover of some sub-markets – 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 the five year period. The lag function has the effect of smoothing out market penetration in the sub-markets, but has little effect on the overall results of the model since those sub-markets that are affected most represent only a tiny fraction of the overall lighting demand.

7. Stock Model and Energy Savings Calculation

The economic analysis 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 from one of the eight primary economic markets[9] in the model, commercial fixtures under the accelerated investment scenario. This diagram shows that as the SSL technology improves, it captures an increasing percentage of the available lumen market.

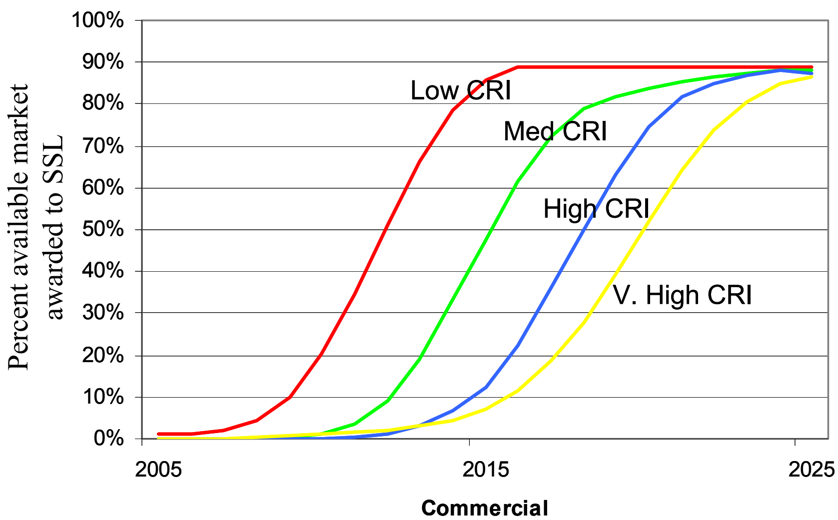

Figure 7-1. SSL Portion of Annual Lumen Market for Commercial Fixtures

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 accelerated investment 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 accelerated investment scenario (illustration on the right of Figure 7-2), 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 SSL sources is clearly evident, as for example, the low CRI technology segment shifts from a reference scenario value of 100 lumens per watt to an accelerated investment scenario of approximately 160 lumens per watt.

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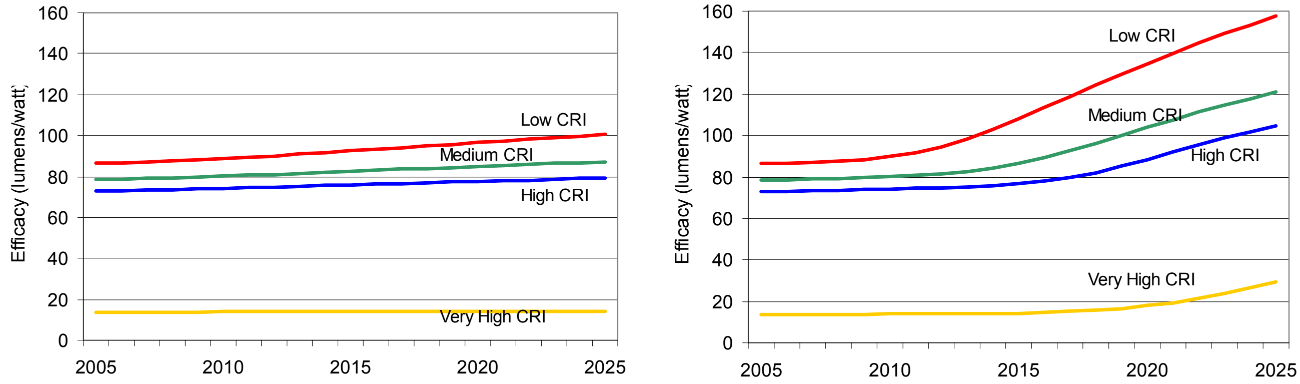
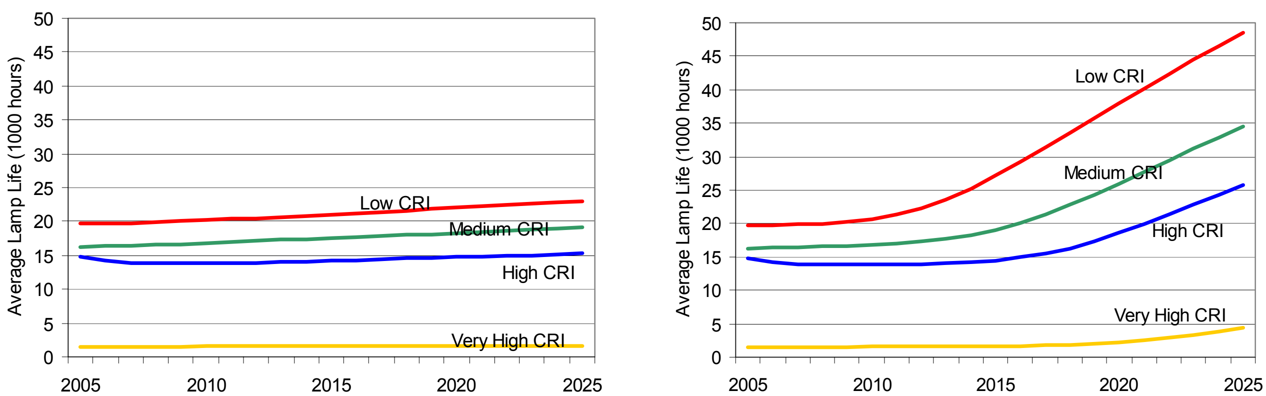
[9] The primary markets are differentiated by sector and whether the first cost includes just the lamp cost or the lamp cost and the fixture cost.



Reference Scenario *Accelerated Investment*

Figure 7-2. Stock Efficacy for CRI Bins for Reference and Accelerated 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 approximately 40 percent in 2005 to 33% in 2025 under the reference scenario and 19% in 2025 under the accelerated investment 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 accelerated investment scenarios.



Reference Scenario *Accelerated Investment*

Figure 7-3. Stock Average Lamp Life by CRI Bin in Reference and Accelerated Investment

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 accelerated investment scenario, whereby low CRI increases from approximately 20,000 hours of average operating life to nearly 50,000 hours over the analysis period. A similarly dramatic increase is experienced by the very high CRI lamps, which experience a shift from approximately 1,000 hours to nearly 5,000. 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 2025[10] for the two investment scenarios outlined in Chapter 5. The moderate investment scenario reflects a low level of effort on the part of government and industry in developing better SSL devices, particularly white-light sources. In 2025, the moderate investment scenario is estimated to contribute approximately 1.23 quads of energy savings. The accelerated investment scenario considers the case where the government and industry work as partners to share the risk and accelerate development of white-light, general illumination SSL technologies. In this scenario, 3.51 quads of energy are saved relative to the reference case, with the trend line continuing to show increased savings. Thus, additional energy savings are anticipated in the years following this and the other scenarios.

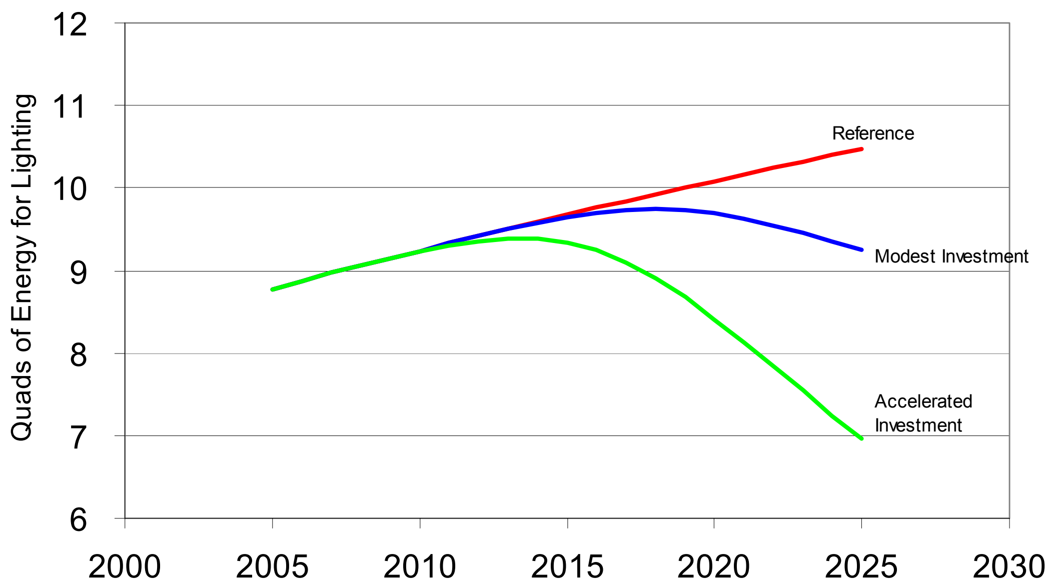


Figure 7-4. Energy Consumption for Lighting Through 2025 for Each Scenario (Quads)

As seen in Figure 7-4, the first significant energy savings in the modest investment scenario are seen in 2015, while the accelerated investment scenario starts to yield energy savings five years earlier in 2010. Table 7-1 presents the energy savings terms of both quads of primary energy and terawatt-hours of site[11] electricity consumption.

[10] While projecting the energy consumption for lighting, we have assumed that the ratio of Primary Energy Consumption to end-use electricity consumption remains constant at the 2005 forecasted level of 10,744 BTU/kWh (DOE Core Databook, 2003). This avoids confusion on energy savings resulting from power system efficiency gains versus those from more efficacious lighting sources.

[11] This is the electricity consumed on the customer side of the 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 2010 – 2025

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

Scenario	2010	2015	2020	2025	Cumulative
Reference	9.24 quads 858 TWh	9.68 quads 899 TWh	10.08 quads 936 TWh	10.47 quads 972 TWh	n/a
Quads of primary energy savings and TWh of site electricity savings relative to Reference					
Moderate Investment	0.00 quads 0 TWh	0.04 quads 3 TWh	0.39 quads 36 TWh	1.23 quads 114 TWh	5.44 quads 505 TWh
Accelerated Investment	0.01 quads 1 TWh	0.34 quads 31.3 TWh	1.67 quads 155 TWh	3.51 quads 326 TWh	19.9 quads 1848 TWh

In the moderate investment scenario, approximately 1.23 quads of primary energy, or about 114 TWh, can be saved in 2025. Under the accelerated investment scenario – where SSL meets more aggressive price reduction and performance improvement targets – approximately 3.51 quads of primary energy, or about 326 TWh can be saved. This is approximately a 33 percent reduction in the projected energy consumption for lighting in 2025 over the reference scenario, and represents a real reduction in lighting energy compared to the start of the analysis period (2005).

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 2025 for each of these baseline technology scenarios, compared to the two SSL investment scenarios. The medium improvement scenario is used for all the analysis results presented in this report. The variability in percentage terms is approximately 15-20% for the moderate investment and approximately 12-15% in the accelerated investment. In quad terms, the variability is +/- 0.2 quads for the moderate investment and +/- 0.5 quads in the accelerated investment.

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

SSL Performance Scenarios	Low Improvement Conventional Technology	Medium Improvement Conventional Technology	High Improvement Conventional Technology
Reference (Quads in 2025)	10.90 Quads	10.47 Quads	9.87 Quads
Moderate Investment (Quads saved in 2025)	1.42 Quads	1.23 Quads	0.99 Quads
Accelerated Investment (Quads saved in 2025)	3.94 Quads	3.51 Quads	2.98 Quads

The value of the energy savings that would accrue to lighting end-users is substantial. By multiplying the kilowatt-hours of savings due to SSL market penetration by the AEO 2003 forecasted electricity prices, annual savings figures by sector are estimated. Of these, the electricity savings in the commercial sector, which consumes 51% of all the national lighting energy (DOE, 2002), are much larger than the other sector. Across all sectors, the cumulative total of electricity savings over the analysis period is $128.6 billion dollars[12]. Of this, approximately 72% will be saved by the commercial sector, followed by $13 billion, or approximately 10% by the residential sector, 10% for the outdoor stationary and $9.8 billion, or 8% by the industrial sector.

Figure 7-5 presents the electricity savings as they occur, moving from the base year 2005 through 2025. As expected from their high level of energy savings, the commercial sector appears to be an early adopter of SSL, with nearly $1 billion of savings in 2015 and rising to $15 billion in 2025. The residential sector is slower to adopt SSL, but when it does (starting around 2020), it adopts the technology at approximately the same rapidly increasing rate as the commercial sector had 7 years earlier.

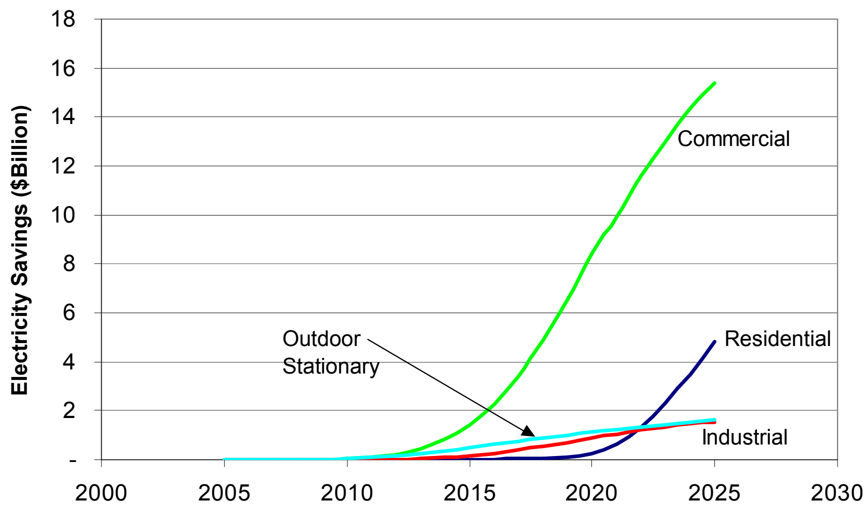


Figure 7-5. Electricity Savings by Sector Due to SSL Market Penetration

This valuation of energy savings cannot be treated in isolation – under any SSL performance improvement scenario, there will be manufacturing costs associated with acquiring the capital equipment necessary to produce SSL lamp devices that satisfy the demand for SSL products. In order to arrive at an estimate of the investment necessary, an estimate of the industry revenues projected over the analysis period is required. Figure 7-6 presents the industry revenues by CRI bin under the accelerated investment scenario. This estimate is determined by the model and is based on the annual operating hours, the teralumen-hours of lighting service provided multiplied by the dollars per kilolumen for SSL devices each year, yielding $ of SSL revenue. The industry revenue decreases from 2020 to 2025 primarily because the cost of SSL devices continues to decrease according to the technology improvement S-curves discussed in Chapter 5.

[12] The total value of electricity savings over the analysis period, undiscounted and tracked in the model by sector on an annual basis; electricity savings are multiplied by AEO 2003 forecasted electricity prices.

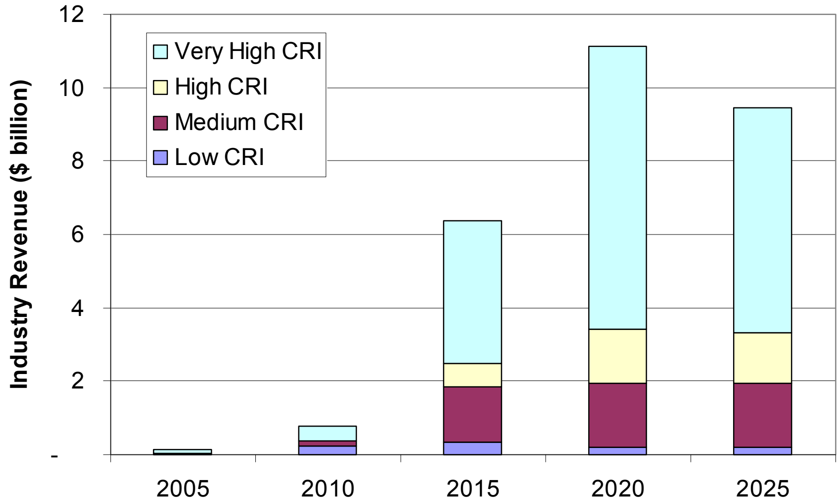


Figure 7-6. Industry Revenue Estimate from SSL General Illumination Sales

Next, the level of capital investment necessary to sustain the necessary SSL production volumes must be determined. Reviewing the Annual Survey of Manufacturers (DOC, 2002), proportions of capital expenditures for plant and equipment were calculated from total value of shipments. Recognizing the uncertainty in future product design and manufacturing processes, a sector that seems to be a reasonable proxy for that of a future SSL industry is NAICS code 334413, *Semiconductor and Related Device Manufacturing*. A five-year (1997 – 2001) simple average of the capital expenditures as a percent of revenue for this sector was calculated as 14.7%. For comparison, the general lighting industry which is less capital intensive and very mature (NAICS code 3351, *Electric Lighting Equipment Manufacturing*), has a five year average capital expenditure rate of 2.9% of revenue. Integrated chip manufacturers provide another point of comparison, having a ratio as high as 28% of revenue for capital expenditures. Assuming a range of capital intensity between 14.7% and 28% of revenue and an average depreciation period of 7.4 years[13], in order to service annual revenues of $11 billion dollars in 2020, it will be necessary to build up between $12 and $23 billion in plant, property and equipment. Furthermore, it will be necessary to spend an additional $1.5 to $3 billion annually to maintain these assets.

[13] Assuming 16% of capital expenditures are for buildings and other structures with a 20 year depreciation life and 84% of expenditures are for machinery and equipment with a five year depreciation life for NAICS code 334413, *Semiconductor and Related Device Manufacturing,* (DOC, 2002).

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 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 2025 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 2025, its market penetration and energy saving potential will be driven primarily by economics – incorporating initial price, operating cost, maintenance and lifetime. In the moderate investment and accelerated investment 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 326 TWh saved in 2025 are derived from SSL displacing incandescent lamps (very high CRI), particularly in the commercial and residential sectors.

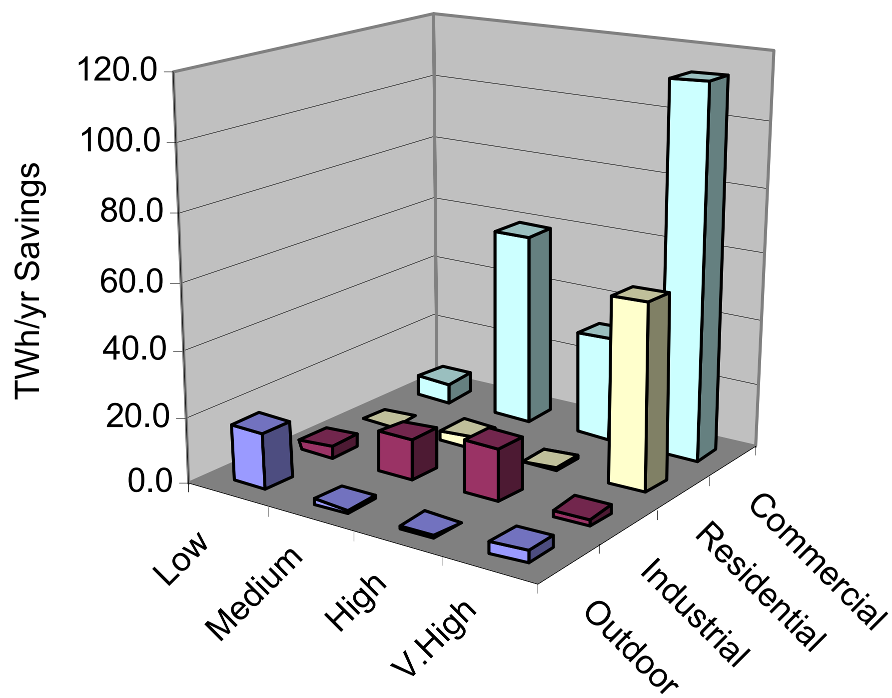


Figure 8-1. Energy Savings Breakdown for the Accelerated Investment Scenario in 2025

As discussed in Chapter 7, SSL is penetrating all sectors and all CRI bins, with medium CRI being the largest SSL lighting service (Teralumen-hours/annum) provider in 2025. However, as shown in Figure 8-1, the majority of energy savings is coming from the very high CRI bin. More specifically, 36% of the SSL lumen-hours in 2025 enter the market in the medium CRI bin, compared with 27% from the very high

CRI bin. However, the contributions in terms of energy savings for these two sectors in 2025 are reversed – the medium CRI bin contributes 23% to the cumulative 2025 savings and the very high CRI contributes 54% - more than double that of medium CRI. The reason for this disparity is due to the higher efficacy of the medium CRI stock compared to the very high CRI bin. Thus, the energy savings from the penetration of a more efficacious source (i.e., SSL) has a greater impact from an energy savings perspective in the very high CRI bin than in the medium CRI bin.

In order to achieve the energy savings projection for the accelerated investment scenario, 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 accelerated investment scenario is projected to decrease lighting energy consumption in absolute terms over the analysis period while the annual lumens delivered increase by 29%. This estimated reduction of 3.51 quads in 2025 will contribute to peak electricity savings as commercial lighting is a peak load contributor through both direct consumption and indirect (i.e., contributor HVAC loads) consumption. This reduction will ease pressure on the transmission and distribution system during these peak times, and contribute to a cleaner environment. In terms of energy savings, if SSL is successful and reduces lighting energy consumption by 3.51 quads, the construction of approximately forty-one 1000 MW power plants could be avoided. Not having to build the power stations will save utilities money, but the real savings accrue to lighting consumers, who will save $128.6 billion[14] on their electricity bills.

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 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 shows the quads of primary energy that could be saved (as compared with the reference scenario) if SSL achieves the price and performance targets shown on each axis. These axes provide the target values for SSL sources CRI bin (low, medium, high and very high) in 2025. These results differ somewhat from those discussed in Chapter 5, because for the purposes of creating Figure 8-2, the targets plotted on the two axes, no matter how aggressive, are achieved in 2025. We have plotted on this surface the price and performance in 2025 of the moderate investment scenario and accelerated investment scenarios to illustrate their relative positions.

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. For example, the efficacy and price targets for the moderate investment scenario fall midway between the 1.0 and 1.5 quad line, at approximately 1.23 quad savings. The accelerated investment scenario occurs on the 3.5 quad line, indicative of its savings estimate.

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. Three dots appear in the upper left-hand corner, off the scale of the surface plot. These dots represent the 2001 and 2003 estimates of white-

[14] The total value of electricity savings over the analysis period, undiscounted and tracked in the model by sector on an annual basis; electricity savings are multiplied by AEO 2003 forecasted electricity prices.

light SSL performance. For 2003, two dots are plotted, representing the best white-light available in the market ($350/klm, 25 lm/W) and the best lab device (no price, 75 lm/W). The relative positioning of the 2001 and 2003 dots show that industry is moving in the right direction, improving the efficiency while reducing the price.

Along the lower left portion of Figure 8-2, negative quad numbers are shown which illustrate what could potentially happen if the efficacy of SSL devices is not improved. If for instance, SSL efficacies remain at their 2005 performance levels and manufacturers focus exclusively on reducing the cost to the $0.50 / kilolumen, energy consumption for lighting will actually increase, as the market transitions from more efficient conventional technology to less efficient SSL technology. This increase in energy consumption would occur throughout the analysis period, culminating in a 0.5 to 1.5 quad increase over the reference case in 2025. This is a possible consequence of no action on an R&D program to improve the efficacy of SSL devices.

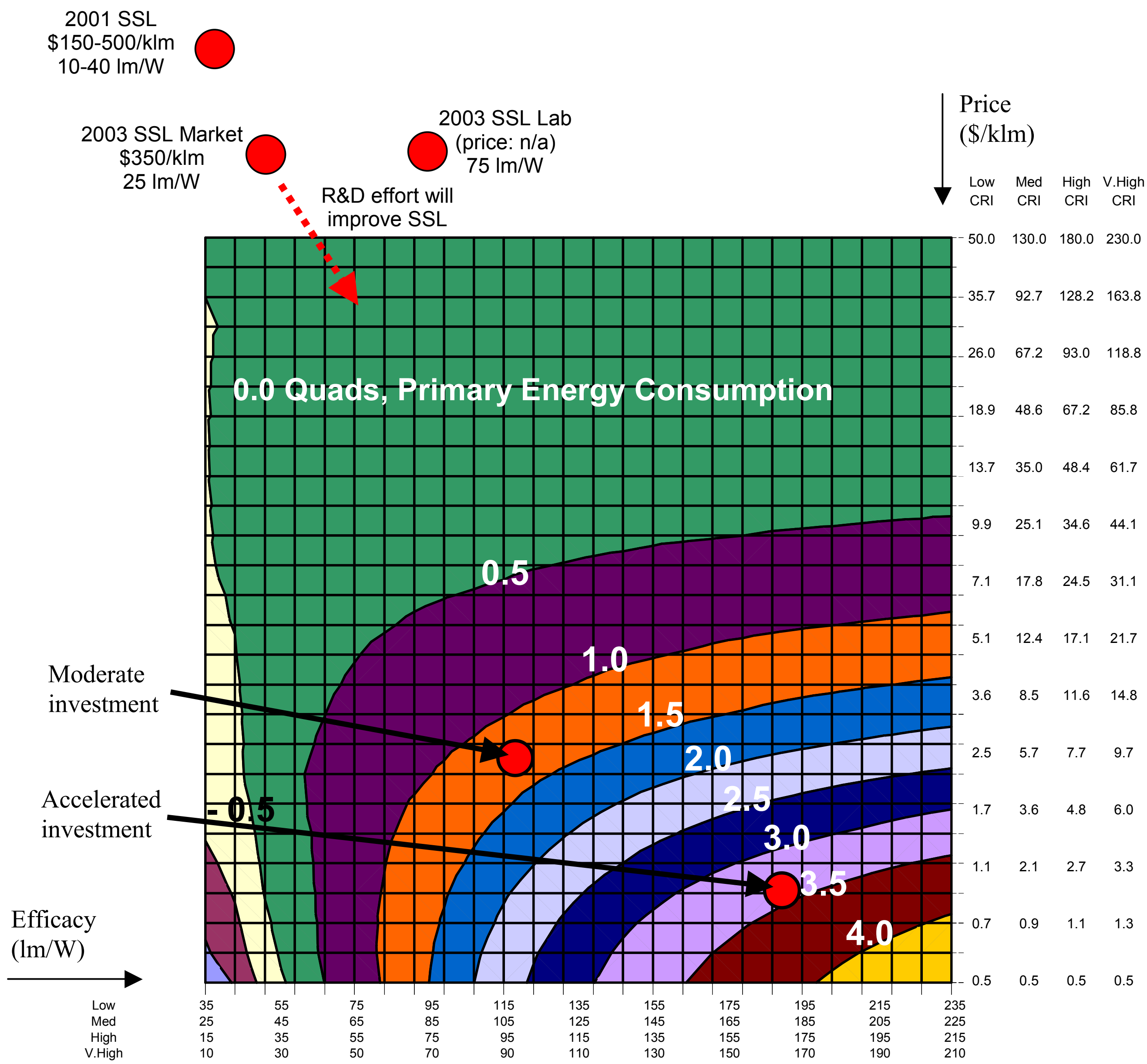


Figure 8-2. Accelerated Investment – Quads of Primary Energy Savings Over Reference

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.

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Appendix A. Technology Roadmap Targets

The OIDA published two technology roadmaps for SSL, one on Light Emitting Diodes (OIDA 2002a) and one on Organic Light Emitting Diodes (OIDA, 2002b). The summary tables of the projected price and performance of SSL sources from each report are presented here.

Table A-1. Technology Roadmap Price and Performance Improvements for LEDs

	2002	2007	2012	2020
Luminous Efficacy (lm/W)	25	75	150	200
Lifetime (thousand hours)	20	>20	>100	>100
Flux (lumens per lamp)	25	200	1,000	1,500
Lumen Cost ($ per kilolumen)	$200	$20	<$5	<$2
Color Rendering Index	75	80	>80	>80
Lighting Markets Penetrated	Low-flux	Incandescent	Fluorescent	All

Source: OIDA, 2002a.

Table A-2. Technology Roadmap Price and Performance Improvements for OLEDs

	2002	2007	2012	2020
Luminous Efficacy (lm/W)	10	50	150	200
Lifetime (thousand hours)	0.3	5	10	20
Flux (lumens per device)	10	3,000	6,000	12,000
Lumen Cost ($ per kilolumen)	>$200	~50%	$5	<$1

Source: OIDA, 2002b.

Appendix B. SSL Performance Improvement Curves

Table B.1. Performance Improvement Curves for the Moderate Investment Scenario

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Low CRI																					
Efficacy (lm/w)	85.3	91.5	98.2	105.0	111.8	118.5	124.7	130.4	135.5	139.9	143.7	146.9	149.5	151.7	153.4	154.8	155.9	156.8	157.5	158.0	158.5
Lamp Cost ($/klm)	47.7	40.9	34.2	27.8	22.1	17.3	13.4	10.4	8.1	6.3	5.1	4.1	3.5	3.0	2.7	2.4	2.3	2.1	2.1	2.0	2.0
Lamp Life (1000 hours)	26.2	30.2	34.8	39.8	45.0	50.2	55.2	59.8	63.8	67.2	70.1	72.4	74.2	75.6	76.7	77.5	78.1	78.6	79.0	79.2	79.4
Medium CRI																					
Efficacy (lm/w)	52.2	54.8	57.6	60.8	64.1	67.5	70.9	74.2	77.4	80.2	82.8	85.0	86.9	88.4	89.8	90.8	91.7	92.4	92.9	93.4	93.7
Lamp Cost ($/klm)	95.5	82.0	68.5	55.8	44.5	34.9	27.1	21.1	16.4	13.0	10.5	8.6	7.3	6.4	5.7	5.2	4.9	4.6	4.5	4.3	4.3
Lamp Life (1000 hours)	17.1	19.6	22.9	26.8	31.6	36.9	42.5	48.1	53.4	58.2	62.1	65.4	67.9	69.8	71.3	72.3	73.1	73.6	74.0	74.3	74.5
High CRI																					
Efficacy (lm/w)	42.7	44.2	46.0	48.1	50.4	53.0	55.7	58.5	61.3	64.0	66.6	68.9	71.0	72.8	74.3	75.6	76.7	77.6	78.3	78.9	79.3
Lamp Cost ($/klm)	157.0	142.1	125.4	107.7	90.0	73.3	58.5	45.9	35.7	27.7	21.7	17.2	13.8	11.4	9.7	8.5	7.6	6.9	6.5	6.2	6.0
Lamp Life (1000 hours)	13.4	14.8	16.5	18.9	21.9	25.6	29.9	34.8	40.0	45.2	50.1	54.4	58.1	61.1	63.5	65.2	66.6	67.5	68.2	68.7	69.1
Very High CRI																					
Efficacy (lm/w)	17.3	18.4	19.8	21.4	23.4	25.7	28.3	31.3	34.5	38.0	41.5	45.0	48.5	51.7	54.7	57.3	59.6	61.6	63.2	64.6	65.7
Lamp Cost ($/klm)	232.6	229.4	224.8	218.4	209.7	198.2	183.5	165.7	145.3	123.4	101.5	81.1	63.3	48.7	37.1	28.4	22.0	17.4	14.2	11.9	10.3
Lamp Life (1000 hours)	11.6	12.3	13.2	14.4	16.0	18.1	20.9	24.3	28.2	32.7	37.5	42.3	46.8	50.7	54.1	56.9	59.0	60.6	61.8	62.7	63.4

Table B.2. Performance Improvement Curves for the Accelerated Investment Scenario

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Low CRI																					
Efficacy (lm/w)	90.3	101.8	114.1	126.8	139.4	151.7	163.2	173.8	183.2	191.4	198.4	204.2	209.1	213.1	216.3	218.8	220.9	222.5	223.8	224.8	225.6
Lamp Cost ($/klm)	32.8	25.6	19.5	14.5	10.6	7.8	5.7	4.3	3.3	2.6	2.2	1.9	1.7	1.5	1.4	1.4	1.3	1.3	1.3	1.3	1.2
Lamp Life (1000 hours)	30.8	37.9	46.1	55.0	63.9	72.1	79.2	84.9	89.3	92.5	94.8	96.5	97.6	98.4	98.9	99.3	99.5	99.7	99.8	99.9	99.9
Medium CRI																					
Efficacy (lm/w)	65.5	76.3	88.0	100.3	112.5	124.2	135.0	144.4	152.5	159.2	164.6	168.8	172.1	174.7	176.6	178.1	179.2	180.1	180.7	181.2	181.5
Lamp Cost ($/klm)	81.2	65.6	51.3	38.9	28.9	21.2	15.5	11.4	8.6	6.6	5.2	4.3	3.7	3.3	3.0	2.8	2.7	2.6	2.5	2.5	2.5
Lamp Life (1000 hours)	18.6	22.8	28.5	36.0	45.0	55.0	65.0	74.0	81.5	87.2	91.4	94.3	96.3	97.6	98.5	99.0	99.4	99.6	99.7	99.8	99.9
High CRI																					
Efficacy (lm/w)	47.1	55.8	65.7	76.5	87.8	99.0	109.8	119.7	128.4	135.9	142.0	147.0	150.9	154.0	156.3	158.1	159.5	160.5	161.3	161.8	162.3
Lamp Cost ($/klm)	145.9	127.0	106.6	86.2	67.3	51.0	37.9	27.8	20.3	15.0	11.2	8.6	6.9	5.6	4.8	4.3	3.9	3.6	3.5	3.4	3.3
Lamp Life (1000 hours)	15.7	18.6	22.8	28.5	36.0	45.0	55.0	65.0	74.0	81.5	87.2	91.4	94.3	96.3	97.6	98.5	99.0	99.4	99.6	99.7	99.8
Very High CRI																					
Efficacy (lm/w)	24.7	29.1	34.6	41.2	49.0	57.8	67.5	77.5	87.5	97.2	106.0	113.8	120.4	125.9	130.3	133.8	136.5	138.6	140.2	141.4	142.3
Lamp Cost ($/klm)	230.8	226.5	220.4	211.9	200.3	185.3	166.8	145.2	121.9	98.6	77.1	58.5	43.5	32.0	23.5	17.4	13.1	10.2	8.1	6.7	5.8
Lamp Life (1000 hours)	12.4	13.7	15.7	18.6	22.8	28.5	36.0	45.0	55.0	65.0	74.0	81.5	87.2	91.4	94.3	96.3	97.6	98.5	99.0	99.4	99.6

Appendix C. Lighting Market Model Sensitivity Analysis

To account for uncertainty and variability in the forecasts made by the lighting market model, Navigant Consulting used Crystal Ball™ software to conduct a Monte Carlo simulation and sensitivity analysis for the accelerated investment scenario. Overall, we found that the accuracy of the lighting market model is +/- 25%. Sources of uncertainty and variability included in the sensitivity are listed in Table C-1.

Table C-1. Sensitivity Analysis Input Assumptions

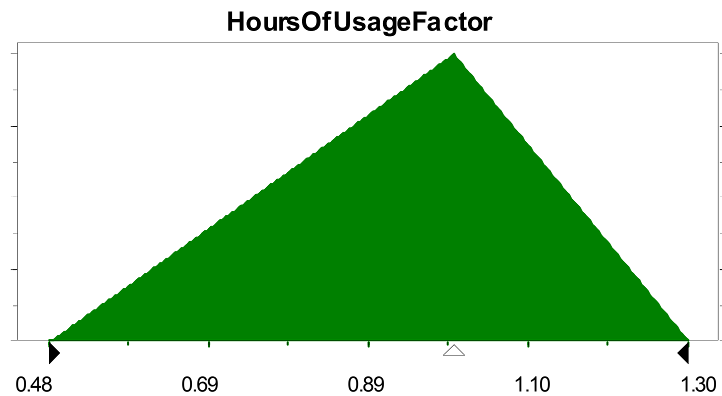
Uncertainty and Variability	Data Source	Estimated Relative Accuracy	Relative Range Source
Electricity Price Projections	AEO Projection	+ 0% / -20%	EIA 2002. AEO projections compared to historical data are 10% high (Sanchez, 2002).
Conventional Technology Performance - (Cost, Life, Efficacy) Projections	Navigant Estimates	+/- 5%	Navigant Estimate. Current conventional technologies are mature and performance is well known.
SSL Ultimate Performance Projections - (Cost, Life, Efficacy)	Experts from SSL Industry	N/A	N/A
Timing of SSL Improvements	Experts from SSL Industry	N/A	N/A
Hours of Usage	Lighting Market Characterization Report	-48% / +130%	DOE 2002, Chapter 7. Total lighting electricity consumption estimates from other sources vary from –48% to +130% compared to the LMC Report. It is unknown whether this is due to # of lamps, hours of usage, or lamp wattage, so hours of usage was selected as a proxy
Number of Lamps per Building	Lighting Market Characterization Report	+/- 5%	
Number of Buildings	Lighting Market Characterization Report	+/- 5%	Accuracy is high given large number of data sources – RECS, CBECS, US Census, etc.
Market Growth Projections	NEMS/Assumed	+/- 30%	Unknown, dependent on economic growth scenario
Market Segmentation: % Retrofits	Assumed	+/- 5% (abs)	Based on an assumed 20 year fixture lifetime

The largest source of variability is the price and performance improvement curves for SSL, which were generated in close consultation with experts from industry. A type of sensitivity analysis for the model's performance relative to various cost and efficiency points is presented in Chapter 8 of this report. Thus, no sensitivity analysis was conducted on these variables as part of the Monte Carlo sensitivity analysis.

Rather, the S-curve performance was held constant at the accelerated investment scenario and all the other model inputs were allowed to vary.

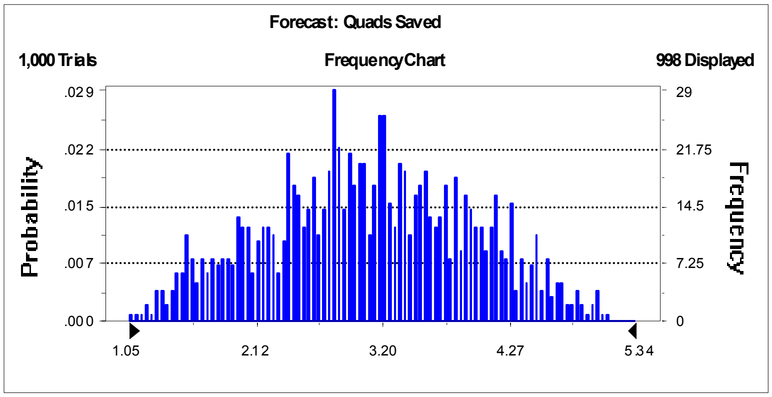
Thus, the sources of uncertainty in the model were bounded by the estimated data source accuracies listed in the table above. These include market growth assumptions, baseline technology performance projections, and electricity price projections. Note that the lighting market characterization data over-estimates annual lighting consumption compared to other studies, and AEO electricity price projections tend to be higher than historical prices. In both these cases, slightly skewed distributions are used (see the HoursOfUsage figure below for an example).

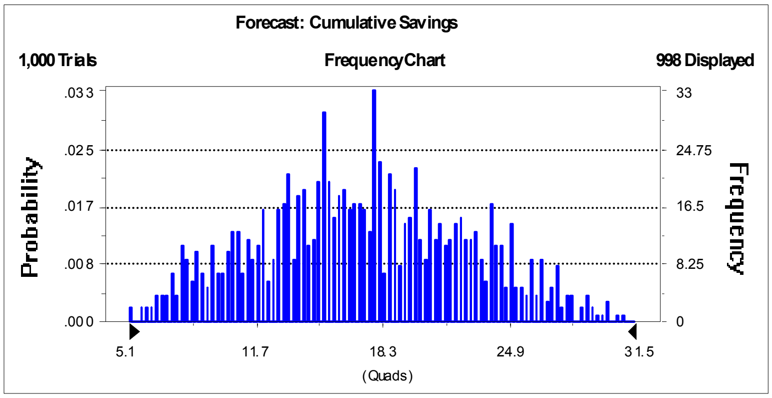
A Monte Carlo simulation is composed of a large number of runs (1,000 or more). During a single run, each input is assigned a random value based on a probability distribution, and the output is calculated using the solid state lighting model and stored. To estimate model accuracy to first order, a minimum / mean / maximum triangular probability distribution was chosen for all of the above variables:



For example, on run 1, a random number generator estimates a hour of usage factor of 1.10; this is multiplied by all "hours of usage" figures found in the Lighting Market Characterization (DOE 2002), yielding a 10% higher estimate of usage; all other variables are similarly estimated by random number generation, and the lighting market model output (total quads of annual savings in 2025) is calculated and stored. On run 2, 0.89 is generated; run 3 generates 1.0, etc.; the minimum/mean/maximum triangular distribution above governs the probability of the hours of usage input factor being between 0.48 and 1.3, and it is most likely to be the mean of 1.

After greater than a thousand runs, the stored SSL model outputs can be displayed as a prediction of model accuracy. This is shown below.

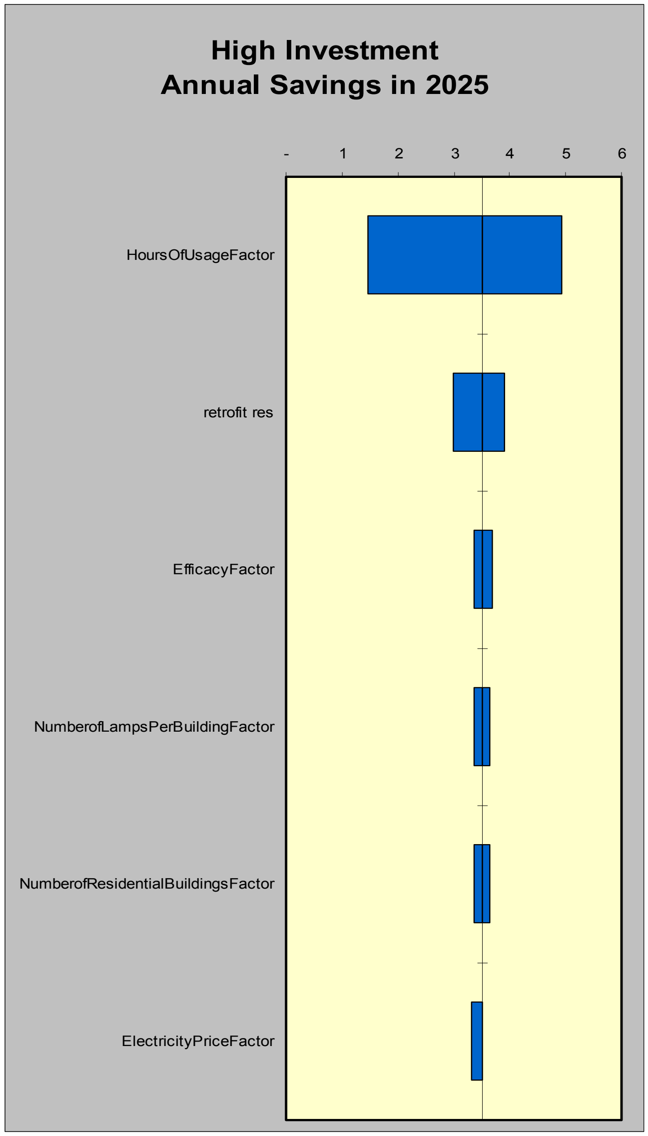




The Monte Carlo simulation predicts 3.1 +/- 0.9 of annual quads savings in 2025, given the broad input distributions assumed in Table B-1. This is slightly less than the 3.5 quads for the nominal model values. Cumulative energy savings from 2005 through 2025 are predicted to be 17.3 quads, +/- 5.5 quads; this is less than 19.9 quads nominally.

The reason for this discrepancy lies in the "Hours of Usage" triangular probability distribution assumed (and shown previously). A close look at the distribution shows that a value of 0.9 (or –10%) is more likely than a value of 1 (no adjustment); so the simulation results show savings ~10% less than the unadjusted nominal model.

A sensitivity analysis was also conducted on the lighting market model that varies each of the variables listed in Table C-1 individually. This shows how each individual variable affects the total quad savings, or how sensitive the final result is to a particular variable. This tornado plot is shown below:



It clearly shows that the hours of usage, the proxy for the uncertainty associated with the total annual lighting consumption determined by the Lighting Market Characterization, is the primary uncertainty.