Energy Savings Potential of Solid State Lighting in General Lighting Applications

Final Report

Prepared by
Arthur D. Little, Inc.

for

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OFFICE OF

BUILDING TECHNOLOGY,

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List of Acronyms and Abbreviations

ADL	Arthur D. Little
CRI	Color Rendering Index
DOE	Department of Energy
GE	General Electric
GLS	General Lighting Service
HID	High Intensity Discharge
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
NEMS	National Energy Modeling System
OLED	Organic Light Emitting Diode
PEC	Primary Energy Consumption
SSL	Solid State Lighting
US	United States
klm	kilolumen
lm	lumen
W	Watt

Acknowledgements

1   Introduction

Research investment in solid state lighting (SSL) sources is accelerating the development of this technology, improving its efficiency to produce useful light. Today, SSL sources can be found in many applications requiring colored ("monochromatic") light, such as exit signs, traffic signals, and automobile brake lights. In the recent past, technological breakthroughs have started to establish SSL sources of white light. As investment leads to technology improvements as well as reductions in manufacturing costs, SSL may start to compete for market share with conventional light sources, such as incandescent, fluorescent and high intensity discharge (HID) lamps.

The Department of Energy asked Arthur D. Little (ADL) to conduct an independent assessment of the U.S. lighting market and project the impact SSL may have on national energy consumption. The impact would result from lighting consumers choosing SSL sources for both niche and mainstream lighting applications. The approach used by ADL is outlined below:

1. Utilize the lighting market estimate provided in the *Draft Phase I Inventory*[1] to create base year 2000
2. Convert the lighting market estimate to lumen-hours[2] of service provided at a given color rendering index[3] (CRI)
3. Estimate lumen demand over 20 years using new building construction growth projections
4. Conduct research and interviews to determine anticipated improvements in price and efficacy of conventional technologies in response to competition from SSL
5. Project lighting costs based on today's market and anticipated improvements for installation (fixture and lamp) and operation (electricity and replacement lamps)
6. Conduct research and interviews to project improvements in the cost, efficacy, life and CRI of SSL sources
7. Create a stock-adjustment that determines the lumen "turn-over" (i.e., annual available lumen-hour market) in the U.S., based on new installations, replacement lamps and retrofits
8. Develop a financial model of the U.S. lighting market that calculates SSL market penetration based on performance improvements of both conventional technologies and SSL
9. Incorporate variability into the financial model to reflect distributions of national electricity pricing and hours of operation
10. Estimate the difference in energy consumption that would result from each scenario compared with the baseline, defined as zero SSL penetration

As stated above, the lighting market model is based on the *Draft Phase I Inventory*, which is currently being revised with new data. Part of this revision will update the *Inventory* data from the mid 1990's through to 2000, as well as offering a weighting by geography. We do not expect these modifications to have a significant effect on our SSL projections, except possibly to reduce the occurrence of incandescent lamps in the commercial and industrial sectors. This could eliminate some of the low hanging fruit available for SSL.

This report provides detail on each of the steps outlined above in the ADL approach, including inputs, simplifying assumptions and results.

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[1] *U.S. Lighting Market Characterization, Phase I — Inventory* (Draft for Review Only); Arthur D. Little, Inc. and XENERGY, Inc., Prepared for the Office of Building Technology, State and Community Programs, U.S. Department of Energy, May 17, 2000.

[2] A lumen-hour is a measure of lighting service and duration. A 'lumen' is the SI unit of luminous flux, defined as the quantity of light emitted in a unit solid angle (1 steradian) by a point source with uniform intensity of 1 candela.

[3] The Color Rendering Index (CRI) is a measure of the color shift observed when an object is illuminated by a light source as compared with a reference source of comparable color temperature. The CRI scale ranges from 0 to 100. For example, incandescent lamps have a CRI rating of 100 and fluorescent lamps are rated between 65 and 85.

2   Forecasting the Lumen Demand

2.1   *Draft Phase I Inventory*

The baseline estimate of the U.S. lighting market is taken from the *Draft Phase I Inventory* that is being prepared by Arthur D. Little and Xenergy Inc., with DOE funding. This study examines national lighting usage by sector (residential, commercial, industrial and other[4]) and technology (incandescent, fluorescent, high intensity discharge and SSL). Table 2.1 provides a list of the lamp types and their respective sub-classifications in the *Draft Phase I Inventory*. The *Inventory* provides data at the sub-classification level for the residential, commercial, industrial and other sectors.

Table 2.1 Lamp Types and Sub-Classifications of the U.S. Lighting Market *Draft Phase I Inventory*

Lamp Type	*Inventory* Sub-classifications
Incandescent	Standard - General Service; Standard – Reflector; Halogen - General Service; Halogen – Reflector; Halogen - Reflector, low voltage; Low wattage (less than 25W); Misc. incandescent
Fluorescent	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; T12 – more than 4 ft; T12 – U-bent; Compact – plug-in; Compact – screw-in; Compact – plug-in reflector; Compact – screw-in reflector; Circline; Induction Discharge; Misc. fluorescent
High Intensity Discharge	Mercury vapor; Metal halide; High pressure sodium; Low pressure sodium; Xenon; Electrodeless (e.g. sulfur)
Solid State	LED; Electroluminescent

For each of the sub-classifications, data are provided for each sector by an average wattage, lamps per building and hours of operation. These parameters are averaged across the U.S., based on the data presented in the draft *Inventory*. These inputs to the model cover each of the four lighting sectors and each of the *Inventory* sub-classifications listed in Table 2.1. Table 2.2 lists the average lumen-hour-weighted data of the inputs used in the model.

Table 2.2 Lamp Wattage, Number of Lamps and Hours of Usage (weighted average)

Lamp	Lamp Wattage by Sector (Watts)				Number of Lamps / Building				Hours of Usage per Day			
	Res	Com	Ind	Oth	Res	Com	Ind	Oth	Res	Com	Ind	Oth
Incandescent	66	82	99	143	31	51	17	n/a	1.8	10.8	15.8	10
Fluorescent	38	49	60	117	5.6	254	738	n/a	2.2	10.1	13.9	10
HID	150	340	408	204	0.0	5	39	n/a	2.2	10.3	14.9	11

The *Draft Phase I Inventory* also specifies technical characteristics of the technologies, including wattage, efficacy, CRI, and lamp life, as shown in Table 2.3.

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[4] The "Other" category includes stationary aviation, billboard, traffic and street lighting. It does not include mobile lighting end uses such as automobiles or airplanes.

Table 2.3 Model inputs – Technical Parameters of Lighting Sources[5]

	Efficacy (lm/W)	Color Rendering Index	Lamp Life (1000 hrs)	Lamp Price[6] ($/klm)
Incandescent				
Standard – General Service	15	100	1	0.56
Standard – Reflector	10	100	2	4.77
Halogen – General Service	17	100	3	3.00
Halogen – Reflector	14	100	4	13.11
Halogen Reflect. low voltage	9	100	4	9.19
Low wattage (less than 25W)	8	100	3	5.35
Miscellaneous incandescent	12	100	2	n/a
Tube Fluorescent				
T5	88	78	20	n/a
T8 – less than 4 ft	59	75	18	2.29
T8 – 4 ft	83	80	18	0.74
T8 – more than 4 ft	83	68	14	1.45
T8 – U-bent	81	80	20	2.89
T12 – less than 4 ft	55	71	13	1.40
T12 – 4 ft	68	70	20	0.50
T12 – more than 4 ft	69	76	15	0.54
T12 – U-bent	61	67	15	1.96
Compact – plug-in	60	82	15	5.33
Compact – screw-in	55	82	10	10.58
Compact – plug-in reflector	55	82	10	n/a
Compact, screw-in reflector	55	82	10	21.59
Circline	40	73	11	2.92
Induction Discharge	67	85	100	n/a
Miscellaneous fluorescent	55	80	10	0.41
High Intensity Discharge				
Mercury vapor	38	33	29	1.53
Metal halide	100	68	12	1.22
High pressure sodium	100	22	29	0.71
Low pressure sodium	113	10	18	1.20
Xenon	45	n/a	10	n/a
Electrodeless (e.g. sulfur)	100	n/a	10	n/a

Using these technical values and the operating hours given in Table 2.2, the *Inventory* estimate of lighting use in the U.S. is used to calculate lumen-hours of service per year.[7] This quantification of annual lumen-hour demand (i.e., lamp service) is then grouped according to the CRI quality of the light. Four CRI ranges were developed in consultation with Steven Johnson of Lawrence Berkeley National Laboratory (LBNL) and Edward Petrow of Lincoln Technical Services:

- Low-CRI (10-69)
- Med-CRI (70-79)
- High-CRI (80-89)
- Very High-CRI (90-100)

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[5] For this table, these values are across all sectors – a national average. However within the model, parameters vary by sector (e.g., commercial sector average wattage of an incandescent GLS lamp is 83 Watts, while the residential GLS is 63 Watts).

[6] "n/a" means that the source type is not present in any of the sectors in a noticeable quantity.

[7] Due to the magnitude of calculated lumen demand in the U.S., the notation "tera" is used, denoting 10E+12 (1,000,000,000,000) lumen-hours of operation per year.

Thus, the model is based on a 4 x 4 matrix of lighting demand, consisting of end-use sectors and CRI bins. For the year 2000, Table 2.4 provides an indication of the relative sizes of these bins.

Table 2.4 *Inventory* Lumen-Hour Output by Sector and Color Rendering Index, 2000 (Tlm-hr/yr)

	Residential	Commercial	Industrial	Other
Low CRI	9	3,097	2,016	2,119
Medium CRI[8]	1,095	13,508	3,833	59
High CRI[8]	51	421	70	66
Very High CRI	1,875	913	27	81
Total:	3,030	17,939	5,946	2,325

2.2   Lighting Growth Projection and Available Market

The lumen-hour demand, classified by CRI, is assumed to grow at the same rate as the national floor space. We assume that people occupying space will continue to expect today's level of lighting service in the future in terms of illuminance levels, CRI and duration of service.

Thus, lumen-hour demand in 2000 is divided by the amount of floor-space in a given sector to determine the lumen-hours of demand per square foot of building space. Then, National Energy Modeling System (NEMS) projections for square feet of building growth by sector are used to project lumen-hour demand growth between 2000 and 2020[9]. NEMS provides growth estimates in the residential and commercial sectors, however the growth rate for the industrial and "other" categories is assumed to be the same as the commercial rate. Figure 2.1 provides a plot of the teralumen-hours per year of lighting demand by CRI, as it is projected over the next two decades.

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[8] In the CRI bins established, T-12 lamps are considered "medium" CRI and T-8 lamps are considered "high" CRI. The *Lighting Inventory* upon which these estimates are currently based is more representative of the lighting stock in the early 1990's and therefore does not reflect the transition to T-8 lamps that has occurred over the last decade. An update of the *Lighting Inventory* is currently underway. However, for this study, it is important to note that solid state lighting must compete increasingly with T-8 lamps rather than T-12 lamps, and that T-8's and T-5's pose a more formidable barrier than do T-12's because of the higher efficacies.

[9] Energy Information Administration, Annual Energy Outlook 2001, National Energy Modeling System run AEO2001.D101600A.
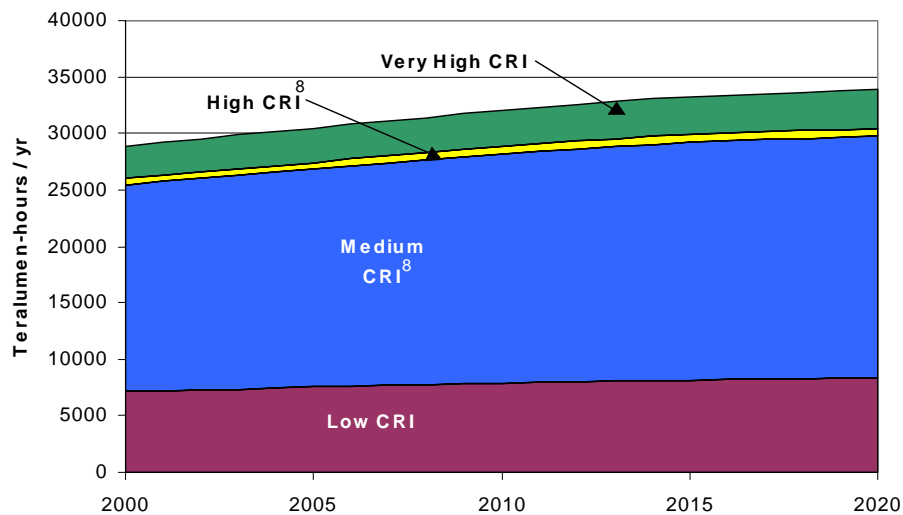
Figure 2.1 Projected Teralumen-hours lighting demand in the U.S. by CRI bin

With an estimate of the projected lighting service provided by the entire lighting stock in the U.S., the next step is to determine how much of the lighting market is replaced each year. To arrive at this estimate, three categories of annually available lumen-hour lighting market were established, based on observed market dynamics. They are:

- *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 our apportioning of floor space to the various CRI bins.
- *Replacements* – the lamps that burn out during a calendar year. Similar to CFLs, which are a direct replacement for a GLS lamp, we assume that companies developing SSL technology may produce a lamp that directly installs into existing lighting fixtures, displacing the conventional technology.
- *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. We assume that this occurs at a rate of 5 percent each year, or a mean retrofit cycle of 20 years. SSL technology competes with other technologies for the retrofit market inclusive of fixture costs. We do not attempt to model decisions to retire less efficient equipment early, for the specific reasons of achieving energy savings (e.g., "lighting retrofits"). However, evidence suggests that only about 1 percent of floorspace per decade undergoes lighting retrofits purely for energy savings.[10]

The three are summed together to determine the total available market in each sector, as illustrated in Figure 2.2.

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[10] EELA *Fact Sheet*, February 2000.
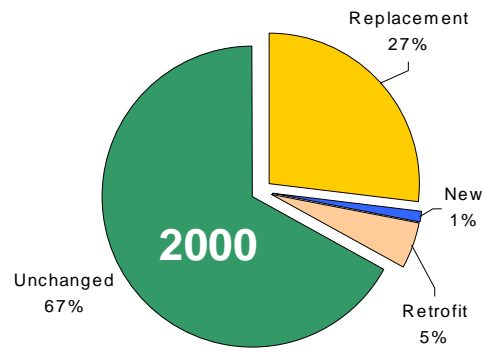
Figure 2.2 Lumen Market Turnover for 2000

Note that only 33 percent of the lumen-hour demand is replaced or installed per year, determining the maximum penetration rate of a new technology. And, 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. The computer model follows the purchasing decisions of lighting consumers annually from 2001 to 2020, 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 the lumen-hour demand projected and an estimate of lumen-hour capacity available in the market for installation each year, the next step is to determine how these lighting technologies develop and compete in the market.

3   Developments in Lighting Technology

3.1   *Conventional Technology Improvements*

In response to competition from SSL sources and general market dynamics, we adjusted the performance and cost characteristics of conventional lighting technologies (incandescent, fluorescent, and high intensity discharge) over the two decades of market analysis. As indicated in Table 3.1, changes are determined on a percentage basis from the year 2000 to 2020, and these changes (relative to base year 2000) are gradually introduced over the projection period. The adjusted parameters include:

- Lamp efficacy
- Color rendering index
- Lamp life
- Fixture price
- Lamp price

Table 3.1 Assumed Technology Changes 2000-2020 – Conventional Lighting Sources[11]

Change between 2000 and 2020	Incandescent	Fluorescent	High Intensity Discharge
Efficacy (lm/W)	0%	2%	16%
CRI	0%	9%	5%
Lamp life	0%	0%	10%
Fixture price	0%	0%	-5%
Lamp price	0%	-8%	-8%

The potential for properties of established technologies to react to the emergence of a new light source such as SSL is very small since established technologies already compete against each other. There is little room for cost improvement without sacrificing performance, and they are not likely to perceive SSL as a legitimate threat in time to make the necessary investment for radical breakthroughs. Therefore, since these technologies are mature, we introduced these adjustments on a linear basis over the 2000 to 2020 period.

3.2   *Solid State Lighting Technology Improvements*

Similar to the conventional lighting technologies, we would expect SSL to follow the generally recognized model of technology advance over time. In the case of SSL, small gains will be achieved in the coming few years, followed by massive improvement as many companies realize the potential of the technology and invest heavily. While in the final stages, the improvement approaches its asymptotic limit of 100 percent of the technological limit for that attribute. The three SSL parameters that were modeled using just such an S-Curve were:

- Efficacy (lumens per watt)
- Lamp price (dollars per kilolumen)
- Lamp life (hours of use)

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[11] These conventional technology adjustments were developed in consultation with Steven Johnson of LBNL and Edward Petrow of Lincoln Technical Services.

The starting and finishing points were based either on existing curves that were available from literature or telephone interviews with industry experts.

Low-CRI SSL technology has been under development since 1968 and has already made considerable progress. We would expect the higher CRI SSL technologies to lag behind the performance of the low CRI technologies because they are in earlier stages of development and the technological complexity and hurdles are greater. In today's LED market, red light LEDs are readily available and widely installed in niche applications, while "white" LEDs are only starting to emerge. For some parameters and some CRI bins, development extends beyond 2020.

Three scenarios are run in the model, each achieving different technology improvement curves, shown in Figures 3.1 to 3.3. In all cases, the aforementioned price and performance improvements for conventional technologies were included in the calculation.

- The *Reference Case* is a projection where all SSL penetration is set to zero.

- The *Base Case* reflects our unaltered set of assumptions and projections regarding SSL under "business-as-usual" conditions. By 2010, medium-CRI LED technology efficacy reaches 45 lm/W and its price falls to $36/klm.

- The *Technology Breakthrough Case* reflects a more aggressive SSL technology development rate compared to the *Base Case*. Here, medium-CRI LED technology achieves 110 lm/W by 2010 at a price of $14/klm.

- The *Price Breakthrough Case* reflects a radical drop in SSL price projections compared to the *Base Case*, with the same technology development as the *Technology Breakthrough Case*. Here, the price of medium-CRI LED lamps drops to $7/klm by 2010 and $0.50/klm by 2020.

The *Technology Breakthrough Case* and the *Price Breakthrough Case* were created following discussions with industry experts and a review of draft and published material. The *Technology Breakthrough Case* follows the "revolutionary scenario" developed by Sandia National Laboratories.[12] In this scenario, with "accelerated effort" in the development of SSL technology, solid state achieves a 160 lm/W in 2020, a lifetime of 100,000 hours and a price of $12/klm. The *Price Breakthrough Case* is an attempt to show the market potential of SSL if it can reduce its first cost price to be at today's average first cost price for incandescent and fluorescent technologies – approximately $0.50/klm.

[12] *Transforming the Lighting Sector with Semiconductor Lighting Technologies*, T. Drennen (Sandia), R. Haitz (Agilent), J. Tsao (Sandia). Paper presented at the 21st Annual Meeting of the USAEE/IAEE Conference, Philadelphia, PA 24-27 September 2000.

Figure 3.1 SSL Technology Improvement: Lamp Price

Base Case Scenario

Technology Breakthrough

Price Breakthrough
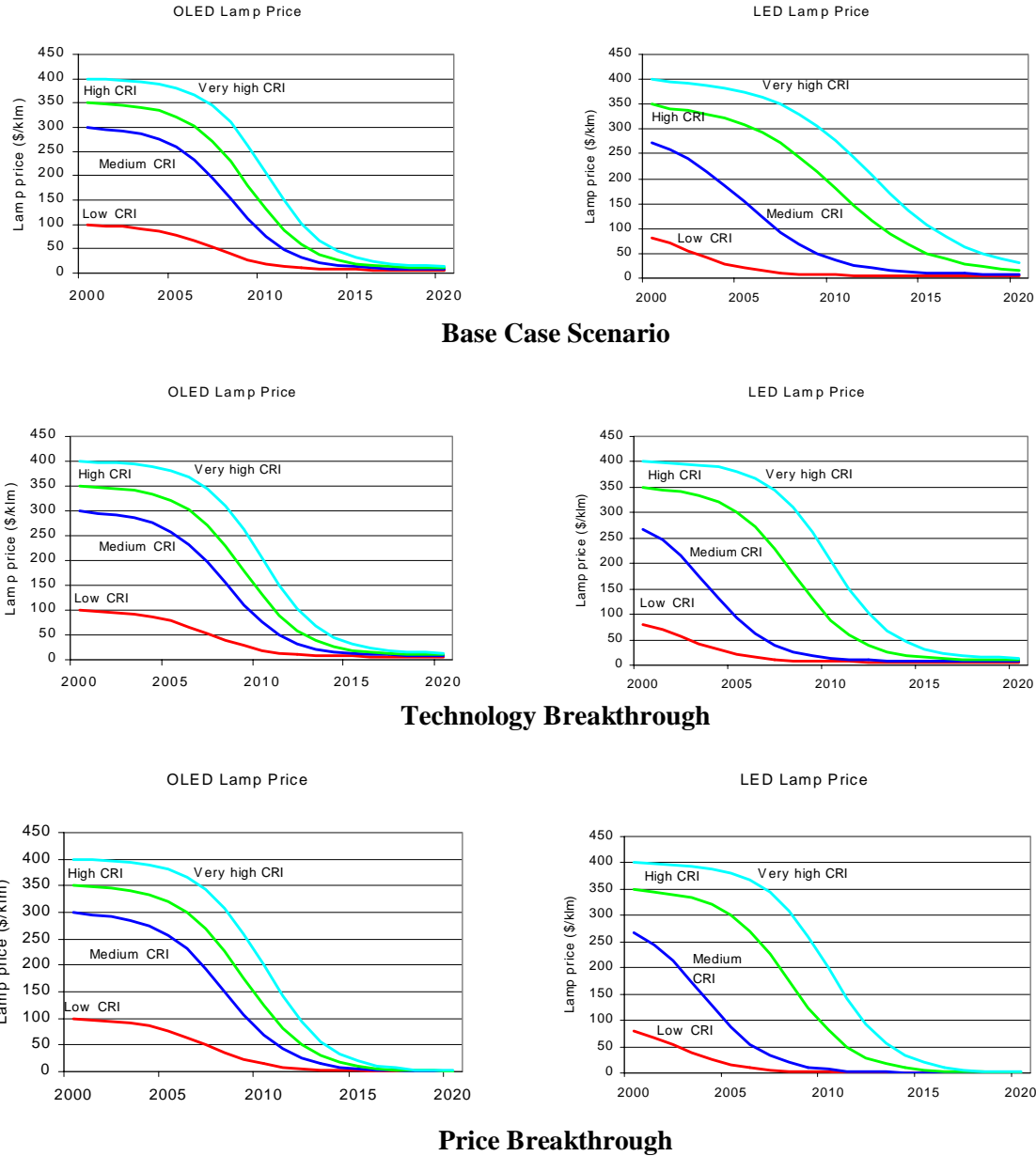
In these three scenarios, the OLED development curves are similar, with *Base Case* and *Technology Breakthrough Case* sharing the same price projection, reaching $6-14/klm in 2020. OLEDs in the *Price Breakthrough Case* settle at a lower point, $0.5-1.5/klm. Due to the scale of the vertical axis in these plots, this difference may not be immediately noticeable.

On the LED side, the *Base Case* projects a less aggressive advancement in price compared with the other LED price progression scenarios. Like OLEDs, the *Technology Breakthrough Case* achieves a $6-14/klm while the *Price Breakthrough Case* is the most aggressive, reaching $0.5-1.5/klm. The shape of the LED curves differ slightly from the OLED curves due to the more advanced state of knowledge and performance improvements demonstrated over recent decades.

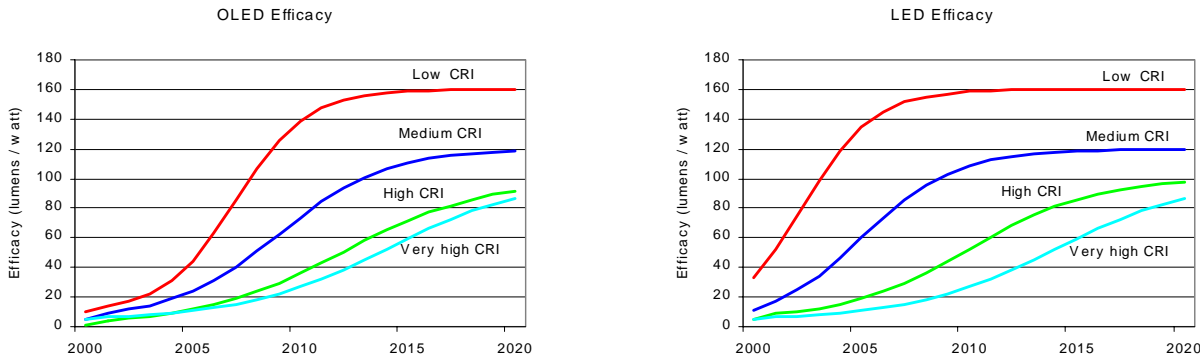## Figure 3.2 SSL Technology Improvement: Lamp Life – All Scenarios
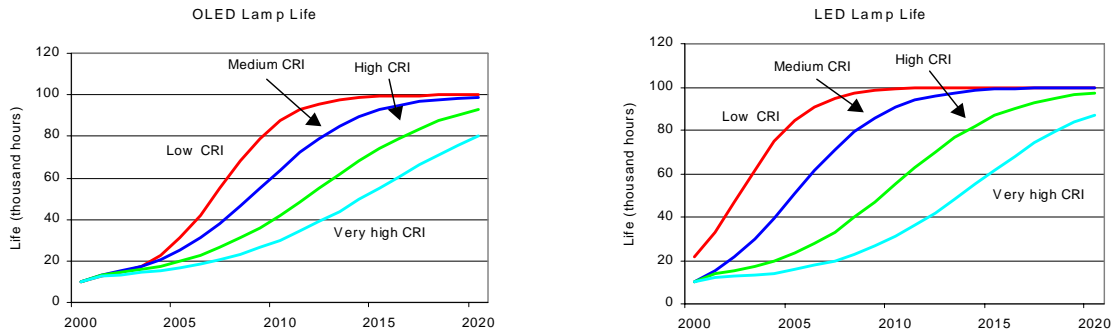
The improvements in lamp life for all three scenarios are assumed to be the same, following the progression shown in Figure 3.2.

Figure 3.3 SSL Technology Improvement: Efficacy
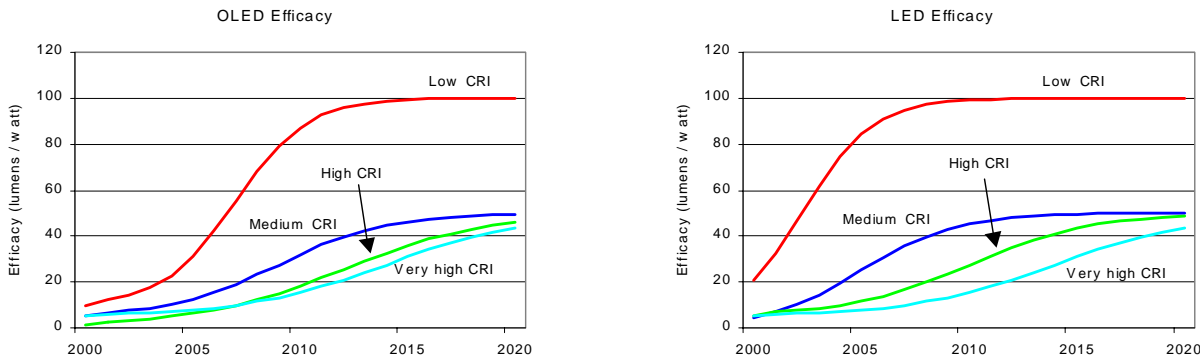
Base Case Scenario

Technology and Price Breakthrough Cases

Figure 3.3 illustrates the differences modeled between the business-as-usual *Base Case* and the *Technology* and *Price Breakthrough Cases*. In addition to having lower overall targets, the *Base Case* has a slower development of Medium, High and Very High CRI SSL. In the *Technology* and *Price Breakthrough Cases*, it is assumed that higher targets will be achieved, and at a faster rate compared to the *Base Case*.

The following table summarizes the relative performance and cost of SSL and conventional lighting technologies. For the conventional technologies, the figures presented are lumen-weighted averages of their anticipated use.

Table 3.2 Summary – Projected Light Source Attributes in 2020

Technology	Scenario	Efficacy (lm/W)	Price ($/klm)
Medium CRI LED	Base Case	50	8.30
	Tech Breakthrough	120	8.00
	Price Breakthrough	120	0.50
Conventional Technology	Incandescent (Residential GLS)	14	0.55
	Fluorescent	69	0.70
	HID	99	0.61

4 Market Penetration

Each year new lumens enter the market and old lumens are retired. The result is a turnover in the lumen stock. As the annual market is captured by more efficient technology, the more efficient technology penetrates the stock, making the stock itself more efficient. Thus, the fraction of the annual lumen market captured by SSL directly impacts national energy consumption.

In chapters 2 and 3 we discussed how we modeled the evolution of performance attributes for both solid state and conventional lighting. We made the fundamental assumption that SSL will eventually meet the requirements of any application, and that CRI is the only performance attribute upon which it will compete. However, once SSL achieves a CRI milestone and is able to compete for lumens in a CRI bin, it clearly must provide some financial advantage versus competing technologies for it to achieve widespread penetration. In this chapter we discuss how we incorporate price and operating cost consideration into our model of market penetration.

4.1 Price Bins

We have established four market sectors—residential, commercial, industrial, and other—and four CRI bins—low, medium, high, and very high. Each of these sixteen markets has a characteristic blend of applications, each with its own set of operating hours, illuminance levels, and blend of conventional technologies. To allow us to consider these sixteen markets in even finer detail, we break each of them again into 35 bins based on price-per-lumen. For instance, today there is a certain demand for high-CRI light in the residential sector that is satisfied by a blend of lighting sources. Each source has a characteristic price on a lumen basis. Based on the blend of light sources within a price bin (most bins contain only one light source), the bin will have its own characteristic efficacy, annual operating time, life, etc. By creating bins based on price within CRI bins, we eliminate the distinctions of individual light sources and build a demand curve for certain CRI light at specific prices. Furthermore, we project demand for new, replacement, and retrofit lumens separately. Since new and retrofit lumens compete for fixtures as well as sources, we develop 35 more bins in each of the sixteen markets based on source and fixture price. All in all, we are modeling market penetration in each of 1,120 sub-markets.[13]

4.2 Payback Period

We use simple payback, or the ratio of first year incremental purchase price to first year incremental savings, to allocate market share in each sub-market. 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. The literature provides confirmation regarding the ranges of simple payback that purchasers consider acceptable in various sectors.[14] Second, we have found that simple payback is a fairly robust predictor of purchasing behavior across products when decisions are based on energy cost savings. Third, simple payback is an intuitive measure of financial return, thus making it easier to review the projections of the model against intuition.

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[13] Four sectors, four CRI bins, and two groups of 35 price bins (with and without fixtures). Since they both compete with fixtures, the new and retrofit market are effectively a single market in our model, although we account for each of them separately.

[14] Kulakowski, Susan. *Large Organizations' Investments in Energy Efficient Building Retrofits*. Ernest Orlando Lawrence Berkeley National Laboratory, University of California. March 1999.

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 price projections are from the NEMS and are presented in Table 4.1. We discuss how we varied these prices across the population in section 4.5.

Table 4.1 Electricity Price Projections from NEMS, Adjusted to 2000 dollars

Year	Residential ($/kwh)	Commercial ($/kwh)	Industrial ($/kwh)	Other[15] ($/kwh)
2000	0.080	0.073	0.045	0.073
2005	0.076	0.067	0.041	0.067
2010	0.075	0.064	0.040	0.064
2015	0.074	0.063	0.039	0.063
2020	0.074	0.063	0.039	0.063

4.3 OLED/LED Blend

The model projects the energy savings that would result from the introduction of any light source based on price, efficacy, life-span and CRI, as long as that source is capable of being installed in any fixture and is suitable for any application. We have modeled two types of these sources: LEDs and OLEDs. They differ only by their rates of development (OLEDs lag LED) and fixture costs (OLEDs eventually will not require fixtures).

Rather than competing OLEDs and LEDs against each other, we can pre-assign a blend to each market and CRI bin. Those blended characteristics are then used to compete against conventional technology. However, due to the projected lag in OLED development, the energy savings potential from SSL as a whole is highest when the OLED blend ratio is set to zero. Therefore, for the purposes of this report, we chose to fix the OLED blend at zero to fully illustrate the potential benefits of SSL in general.

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[15] "Other" electricity price assumed to be equal to Commercial electricity price

4.4 Market Share

A given simple payback period can elicit a range of responses in the market depending on the internal implicit discount rates of the purchasers. For instance, when all non-financial considerations are equal (which is what we assume by establishing CRI bins), some purchasers will be willing to accept a four-year payback, but most will not. Most will accept a two-year payback.

To capture this range of responses, we apply curves developed over the years at Arthur D. Little, to the mean payback in each sub-market. The curves relate the mean payback to the ultimate market fraction captured. The curves are presented in Figure 4.1.
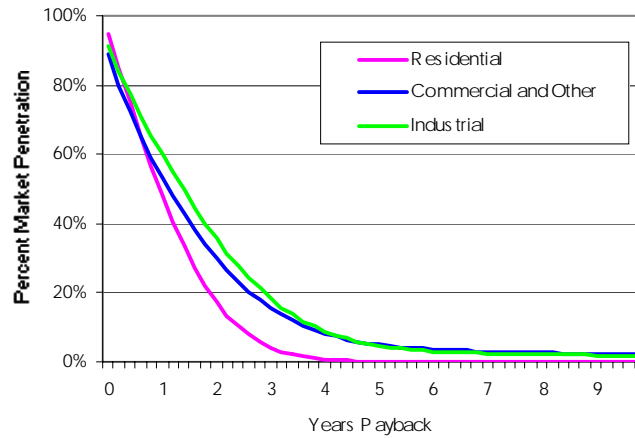

Figure 4.1 ADL Market Penetration Curves Used to Determine Consumer Choice

Depending on the comparative costs associated with each technology, the simple payback calculation can have different interpretations. Table 4.2 provides those interpretations.

Table 4.2 Purchaser Decision based on Payback

Payback	SSL First Cost	SSL Operating Cost	SSL Market Share Interpretation
< 0	Higher	Higher	0 percent
> 0	Higher	Lower	The result given by the market share curve is attributed to SSL
> 0	Lower	Higher	The result given by the market share is attributed to the conventional technology[16]
< 0	Lower	Lower	Maximum share

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

4.5 Variability

Striving to prevent the model from making "all-or-nothing" decisions, we recognize that within a sub-market, operating hours and costs vary and create a range of paybacks. Thus, while the "mean" payback for a sub-market may be three-years, a fraction of that market may see significantly lower paybacks, and a fraction may see significantly higher paybacks. The portion with lower paybacks could provide a foothold for new, more efficient, technology such as solid state, and we did not want to overlook that possibility.

To estimate how paybacks might be distributed, we performed a Monte Carlo analysis to establish a normalized distribution of paybacks for each sector. We varied electricity prices according to the distribution of electricity prices at the state level[17] and the operating hours according to the distribution of hours present in the data tables underlying the *Draft Phase I Inventory* report. We did not vary any other parameter that effect operating cost, nor did we vary the purchase price. The results of the analysis are presented in Figure 4.2.
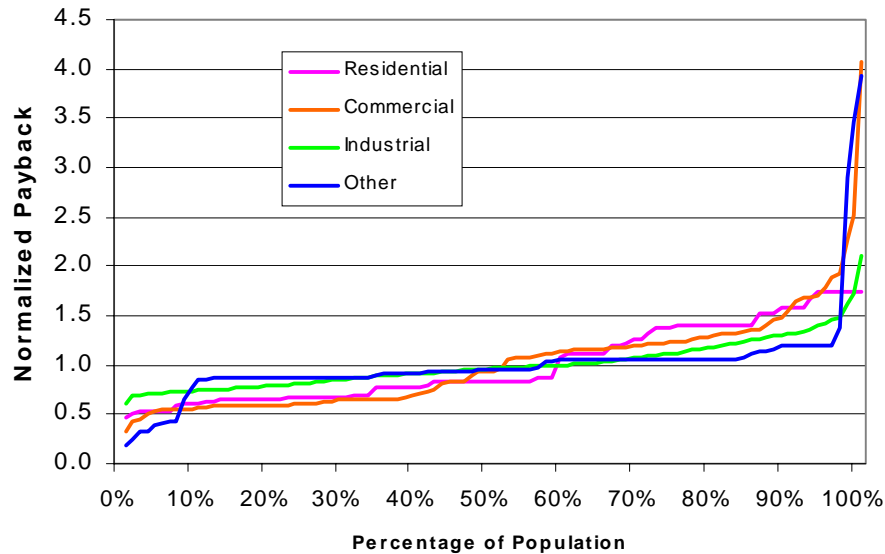

Figure 4.2 Distribution of Normalized Payback Periods by Sector

Thus, if the mean payback for a residential sub-market is 3.0 years (normalized payback of 1.0, representing the 60th percentile), we would expect that 30 percent of the market will experience paybacks of longer than 3 years but shorter than 4.5 years (normalized payback of 1.5, representing the 90th percentile).

4.6 Lag

We recognize that even under the most optimistic conditions, market penetration is not instantaneous. Due to the rapid development of SSL projected in our model, payback periods occasionally decline just as 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

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[17] Energy Information Agency, Electric Power Annual 1999, Volume II

ramping up manufacturing capacity, communicating benefits to purchasers, and stocking the distribution channels. We incorporated a market lag into our model to stretch market penetration over time.

Our lag function is calibrated such that a one year spike from zero to full market penetration is stretched over a period of six years, with 90 percent of the penetration occurring over the first five years. Also, the smaller the annual jump, the less effect the lag function exerts. Where *i* is the year for which the penetration is being estimated, the function is:

$$\text{Market Share}_i = \text{Market Share}_{i-1} + \Delta\text{Market Share}\left(1 - 0.83 \bullet \Delta\text{Market Share}\right)$$

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.

5   Lighting Market Model Results

5.1   Scenario review

As discussed in 3.2, we ran one reference scenario and three SSL scenarios to illustrate the types of targets that will have to be achieved if SSL is to make a substantial impact on general lighting energy consumption in the future:

- The *Reference Case* is a projection where all SSL penetration is set to zero.

- The *Base Case* reflects our unaltered set of assumptions and projections regarding SSL under "business-as-usual" conditions. By 2010, medium-CRI SSL technology efficacy reaches 45 lm/W and its price falls to $36/klm.

- The *Technology Breakthrough Case* reflects a more aggressive SSL technology development rate compared to the *Base Case*. Here, medium-CRI SSL technology achieves 110 lm/W by 2010 at a price of $14/klm.

- The *Price Breakthrough Case* reflects a radical drop in SSL price projections compared to the *Base Case*, with the same technology development as the *Technology Breakthrough Case*. Here, the price of medium-CRI SSL lamps drops to $7/klm by 2010 and $0.50/klm by 2020.

5.2   Market Penetration

The projections of market penetration in each of the sixteen sector / CRI combinations are presented in Appendix A, Figure A.1 through Figure A.3.

The *Base Case* and *Technology Breakthrough Case* display similar results. Due to the advanced state of development and competition versus other high-price and high-efficiency sources like HID, as we would expect, SSL penetrates faster in low-CRI applications. Some markets, such as Residential, Very High-CRI never develop, primarily due to the late development of cost competitive solid state sources and the long payback periods. However, Very High-CRI SSL does make substantial inroads into the Commercial, Industrial, and Other sectors beginning around 2010. Those are likely to be long operating hour applications. Of course, that assumes that the applications will not be taken over by compact fluorescent lighting prior to the emergence of SSL.

The *Price Breakthrough Case* projects substantial market penetration in all sectors after 2010. In fact, SSL achieves almost total dominance by 2020 under this scenario, indicating that it represents effectively the upper limit to potential energy savings over a 20-year horizon.

Finally, Figure 5.1 compares the overall penetration of SSL in each of the cases. In this plot, SSL's ability to capture the aggregate available lumen market (annual lighting market) is depicted by the three lines.
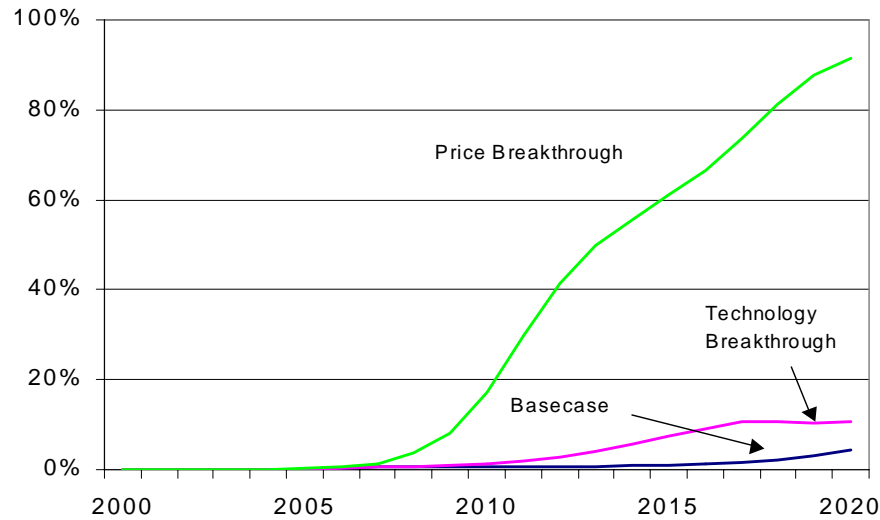
Figure 5.1 The Percentage of the Annual Available Lumen Market Captured by SSL

To make an allowance for lighting consumers who tend to shy away from new technology, the model has built in maximum penetration rates that vary by sector. In Figure 5.1, the *Price Breakthrough* scenario is rapidly approaching its maximum rate.

5.3 Energy Savings

Energy savings are derived from the model by increases in the efficacy of the national lighting stock. Plots of the change in stock efficacy can be found in Appendix B, Figure B.1 through Figure B.3. These figures illustrate the improvements in stock efficacy for the *Base Case*, *Technology Breakthrough Case*, and *Price Breakthrough Case*. The stock efficacy improvement lags the market penetration of SSL, due to the size of the lighting market replaced each year (see Section 2.2). Furthermore, as longer-life light sources, both SSL and conventional, are introduced to the lighting stock, the turnover (Figure 2.2) will decrease from 33 percent, reducing the magnitude of the incremental annual efficacy improvements and the resultant energy savings.

Figure 5.2 presents the projected energy consumption by lighting through 2020[18] for each of the cases. Three results are immediately apparent. First, under any of the scenarios, we would expect energy savings from SSL lighting to accrue after 2010. Second, because SSL does not succeed in penetrating high-demand markets in either the conservative *Base Case* nor the *Technology Breakthrough Case*, radical technology breakthroughs alone do not guarantee substantially more energy savings. Third, of the three scenarios, the *Price Breakthrough Case*, offers the most substantial energy savings potential over the long term.

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[18] 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 2000 level (3.220 : 1). This avoids confusion on energy savings resulting from power system efficiency gains versus those from more efficacious lighting sources.
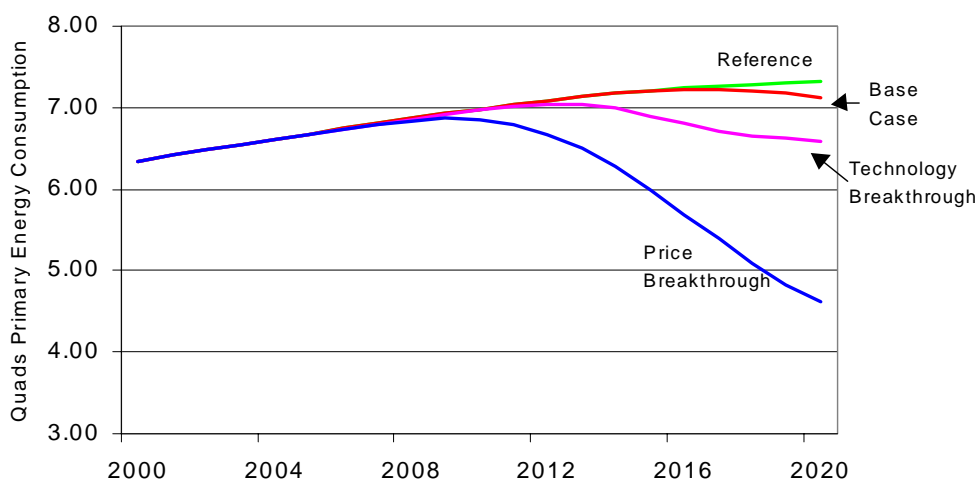
Figure 5.2 Energy Consumption for Lighting Through 2020 for Each Case

Table 5.1 presents the energy savings in both quads of primary energy and terawatt-hours of on-site[19] electricity use.

Table 5.1 Energy Savings Projections 2005 – 2020

(Quads of Primary Energy and TWh of end-use Electricity)

Scenario	2005	2010	2015	2020	Cumulative
Reference Case	6.7 quads 607 TWh	7.0 quads 636 TWh	7.2 quads 656 TWh	7.3 quads 667 TWh	n/a
Savings versus Reference					
Base Case	0.00 quads 0 TWh	0.00 quads 0 TWh	0.01 quads 1 TWh	0.20 quads 18 TWh	0.50 quads 45 TWh
Technology Breakthrough Case	0.00 quads 0 TWh	0.02 quads 1 TWh	0.31 quads 28 TWh	0.74 quads 67 TWh	3.73 quads 340 TWh
Price Breakthrough Case	0.00 quads 0 TWh	0.13 quads 12 TWh	1.21 quads 110 TWh	2.70 quads 246 TWh	14.42 quads 1312 TWh

Thus, the *Base Case* scenario achieves a 0.20 quad savings in primary energy, or 18 TWh of end-use electricity in 2020. If the *Technology Breakthrough Case* is achieved, these savings could be as high as 0.74 quads of primary energy, or about 67 TWh of electricity. The greatest savings occurs under the *Price Breakthrough Case* – where SSL meets more aggressive price reduction targets – and captures 2.7 quads of primary energy, or about 246 TWh. This is over 35 percent of the projected energy consumption for lighting in 2020 in the *Reference Case*.

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[19] This is the electricity consumed on the customer side of the meter. It does not include losses due to generation, transmission and distribution as the primary energy consumption figure does.

The carbon savings associated with these energy savings forecasts are shown in Table 5.2. They are the emissions avoided at the power station due to the reduced electrical consumption for lighting relative to the *Reference Case*.

Table 5.2 Carbon Savings Projections 2005 – 2020

(10[6] Tonnes of Carbon Equivalent)[20]

Scenario	2005	2010	2015	2020	Cumulative
Reference Case	104.00	108.83	112.35	114.13	n/a
Savings versus Reference					
Base Case	0.00	0.03	0.11	3.16	7.74
Technology Breakthrough Case	0.01	0.24	4.85	11.47	58.13
Price Breakthrough Case	0.02	1.99	18.84	42.10	224.67

As mentioned in Section 3.2, our *Technology Breakthrough Case* follows the "revolutionary scenario" developed by Sandia National Laboratories.[21] The end-use electricity savings projected by Sandia with "accelerated effort" in SSL research is 167 TWh in 2025. Our model found a savings potential of 67 TWh in 2020. If our model were extended to the year 2025 and accelerated growth of SSL continued in the market, we would find a similar, although probably slightly lower electricity savings estimate.

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[20] Assumes constant 15.58 million metric tons of carbon emissions per quad for all 20 years (BTS Core Databook, 2000). In actuality, efficiency gains in both electrical generation transmission and distribution may reduce the quantity of carbon projected to be saved in 2020, however for ease of interpretation of the table, the carbon emissions per quad of Primary Energy have been held constant at the 2000 level.

[21] *Transforming the Lighting Sector with Semiconductor Lighting Technologies*, T. Drennen (Sandia), R. Haitz (Agilent), J. Tsao (Sandia). Paper presented at the 21st Annual Meeting of the USAEE/IAEE Conference, Philadelphia, PA 24-27 September 2000.

6   Conclusion

Just as fluorescent and HID sources have provided tremendous energy savings over the last few decades, SSL sources have the potential to offer substantial energy savings in general lighting. As the technology advances, it will become better suited to a broader array of applications, light quality will improve, efficacies will increase, and prices will fall. The potential national energy savings that will result by 2020 depend on how quickly and to what extent these developments occur.

Assuming the performance of SSL will be capable of satisfying all general lighting needs by 2020, its market penetration, and therefore its energy saving potential, will be driven by economics. In the *Base Case* and *Technology Breakthrough Case*, SSL displaces some HID lighting in low-CRI applications, but the energy savings accrue primarily from the displacement of incandescent lamps in commercial and industrial applications. The energy savings potential is less than 0.5 quads of primary energy (45.5 TWh end-use electricity). But, if another technology like CFL displaces those incandescent lamps before an acceptable SSL alternative arrives, the energy savings potential would be even less.

However, if SSL achieves a price breakthrough, far more energy savings will result. In the *Price Breakthrough Case*, where prices drop as low as incandescent lamps, SSL achieves full market penetration in almost all applications by 2020. At an ultimate efficacy of 120 lm/W, nearly 3 quads of primary energy (273 TWh end-use electricity) would be saved each year. Higher efficacies would mean even larger savings.

Figure 6.1 illustrates how efficacy and price influence the energy saving potential of SSL. The surface shows the quads of primary energy that could be saved (as compared with the *Reference Case*) if SSL achieves the given performance and price targets shown on the axes. Each axis provides the values of these targets for SSL sources by CRI bin (low, medium, high and very high) in 2020.

The results differ somewhat from those in our scenarios since, for the purposes of generating Figure 6.1, all the targets, no matter how aggressive, are achieved by 2020. That said, we have marked the three cases (*Base Case*, *Technology Breakthrough Case* and *Price Breakthrough Case*) on the surface to illustrate their relative positions.

The labeled boundaries of primary energy consumption on the surface state the energy saved at the corresponding performance targets, as they appear along the axes. For example, the efficacy and price targets for the *Technology Breakthrough Case* scenario place it midway between the 0.5 and 1.0 quad line, at approximately 0.74 quad savings.
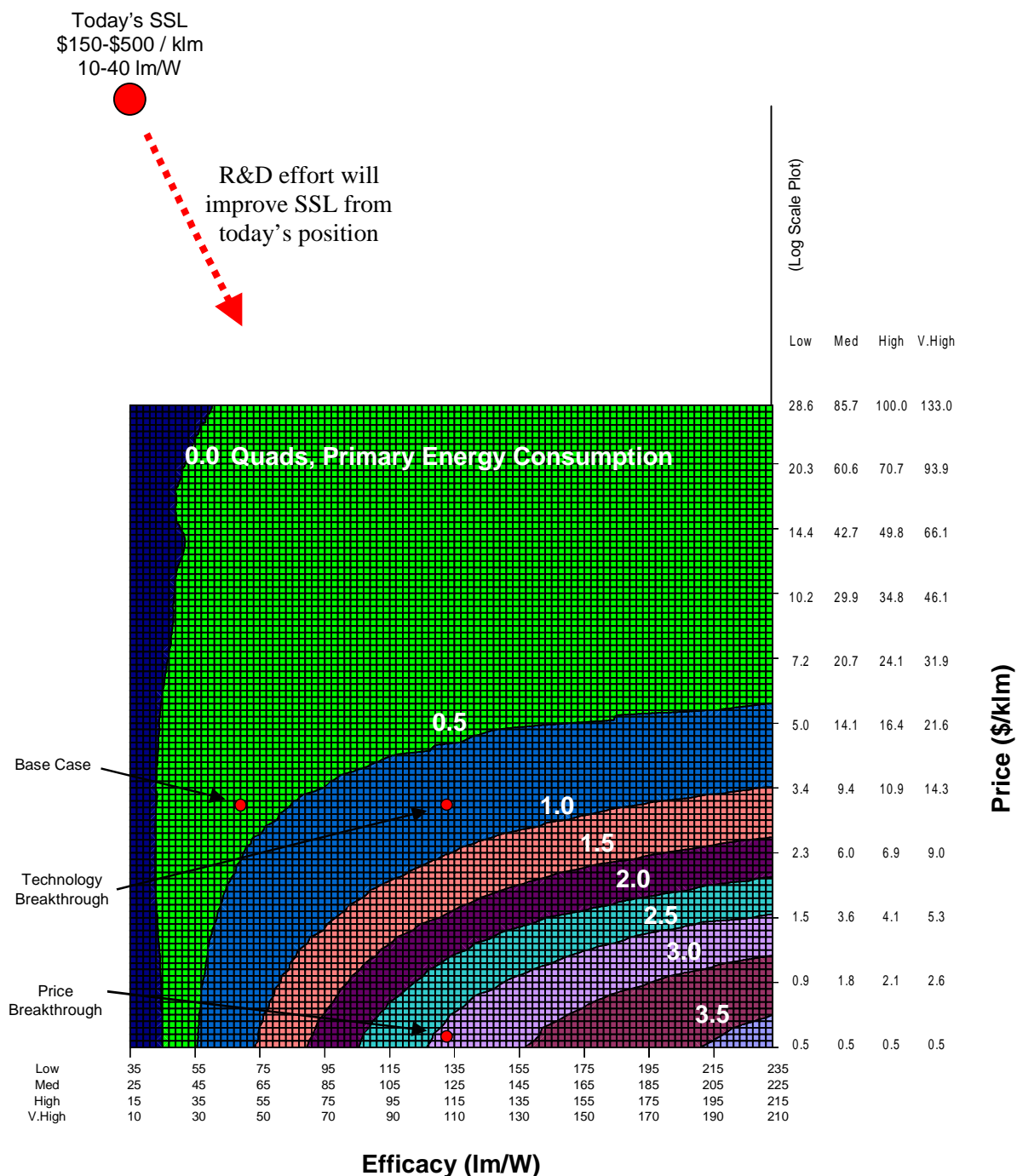
Figure 6.1 Primary Energy Savings in 2020 for Combinations of Price and Efficacy Targets (quads)

Three aspects of this figure are notable. First, depending on the efficacy they ultimately attain, white SSL prices in the range of $15 per kilolumen will be required to result in approximately a half quad of energy savings, versus $300-$500 per kilolumen today (off the scale in Figure 6.1). Second, low price coupled with low efficacy can be counterproductive, allowing SSL to displace more efficient but more expensive conventional sources like fluorescent. In order to ensure some noticeable energy savings, efficacy must exceed 30 lm/W, regardless of price. Third, different combinations of prices and efficacy can achieve the

same energy savings result. This is intuitive, but knowing the tradeoffs can help identify the "path of least resistance" to energy savings.

Improvements in the performance and efficacy of solid state sources will always be critical research objectives. Improvements in price (or more appropriately, cost) should also be an important consideration for researchers interested in penetrating the market and tapping into the huge potential energy savings offered by "white" SSL sources.

APPENDICES

A. Market Penetration Curves for the Three Scenarios

Figure A.1 Market Penetration of Solid State Lighting – *Base Case*
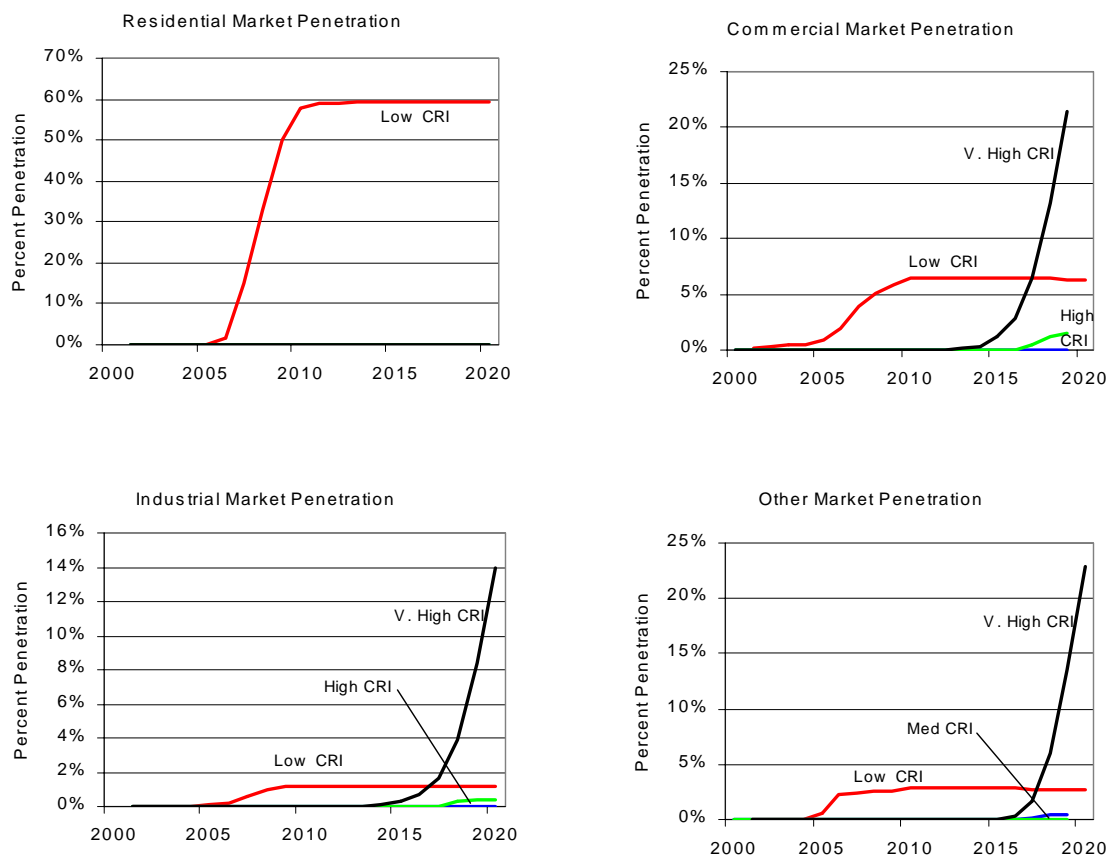
Figure A.2 Market Penetration of Solid State Lighting – *Technology Breakthrough Case*
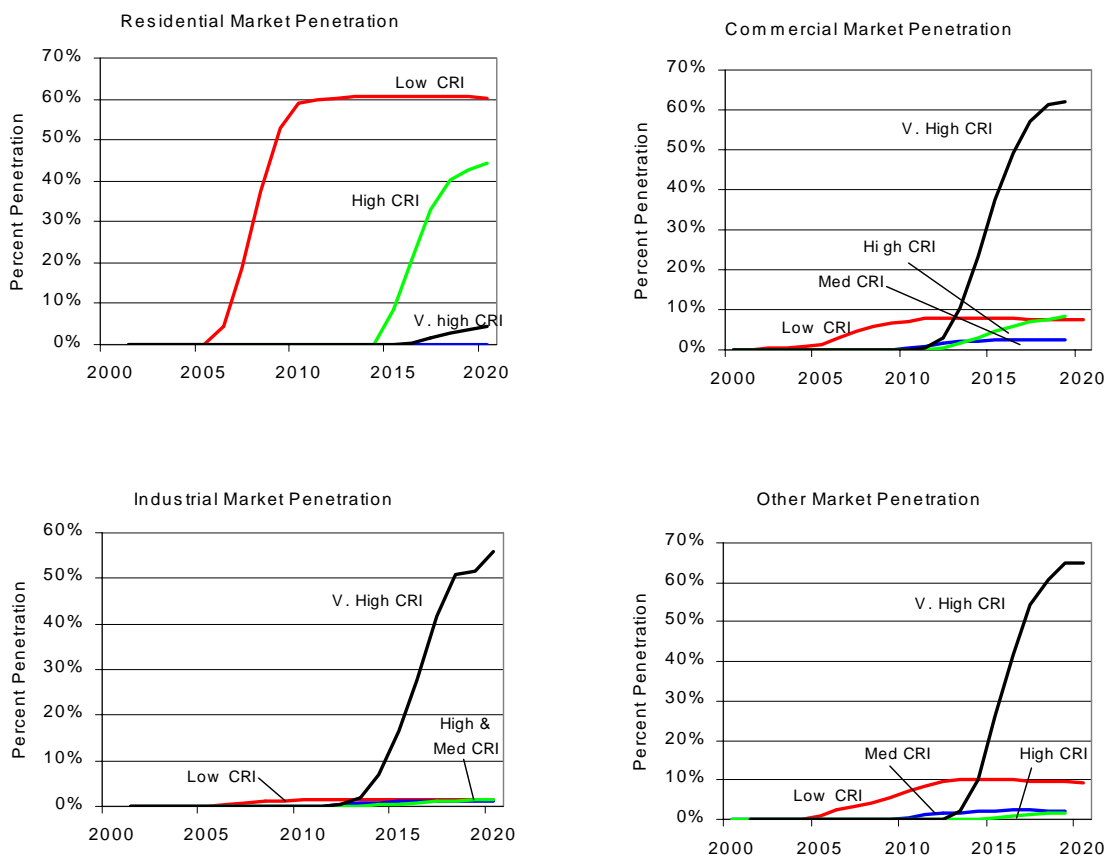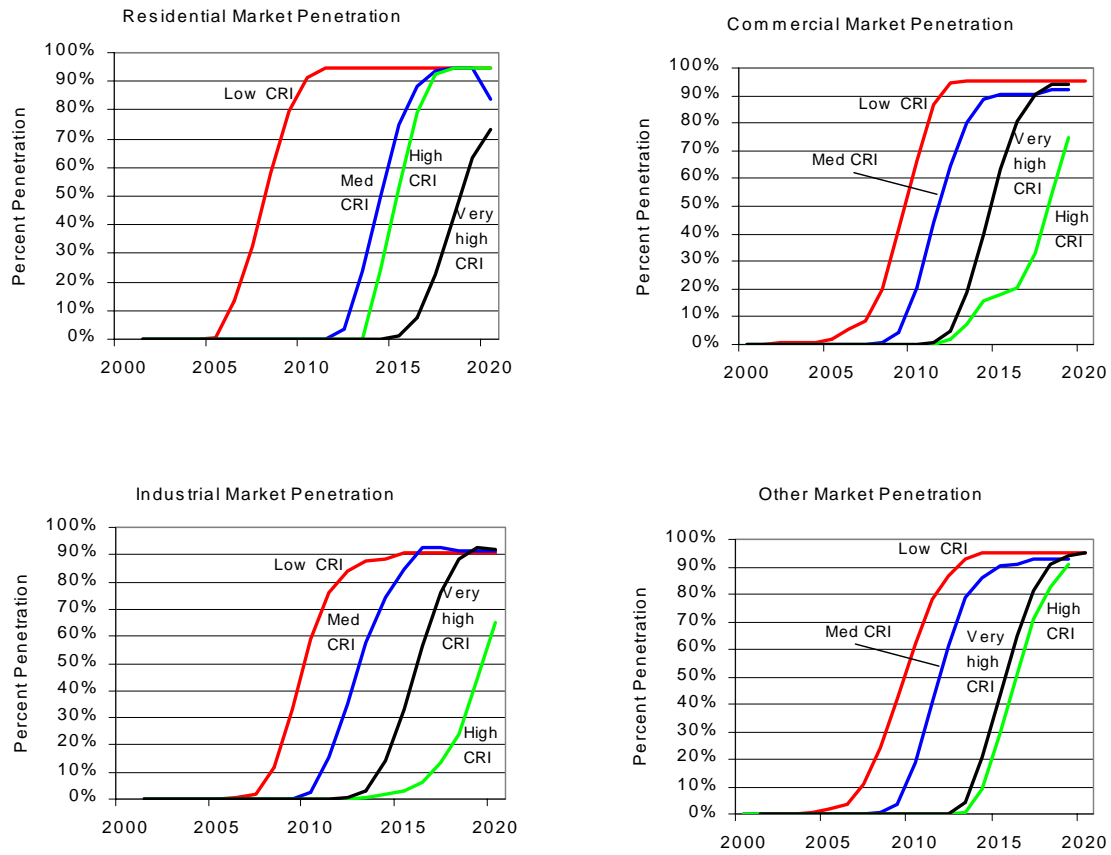
Figure A.3 Market Penetration of Solid State Lighting – *Price Breakthrough Case*

B. Plots of the Changing Stock Efficacy Due to SSL Penetration
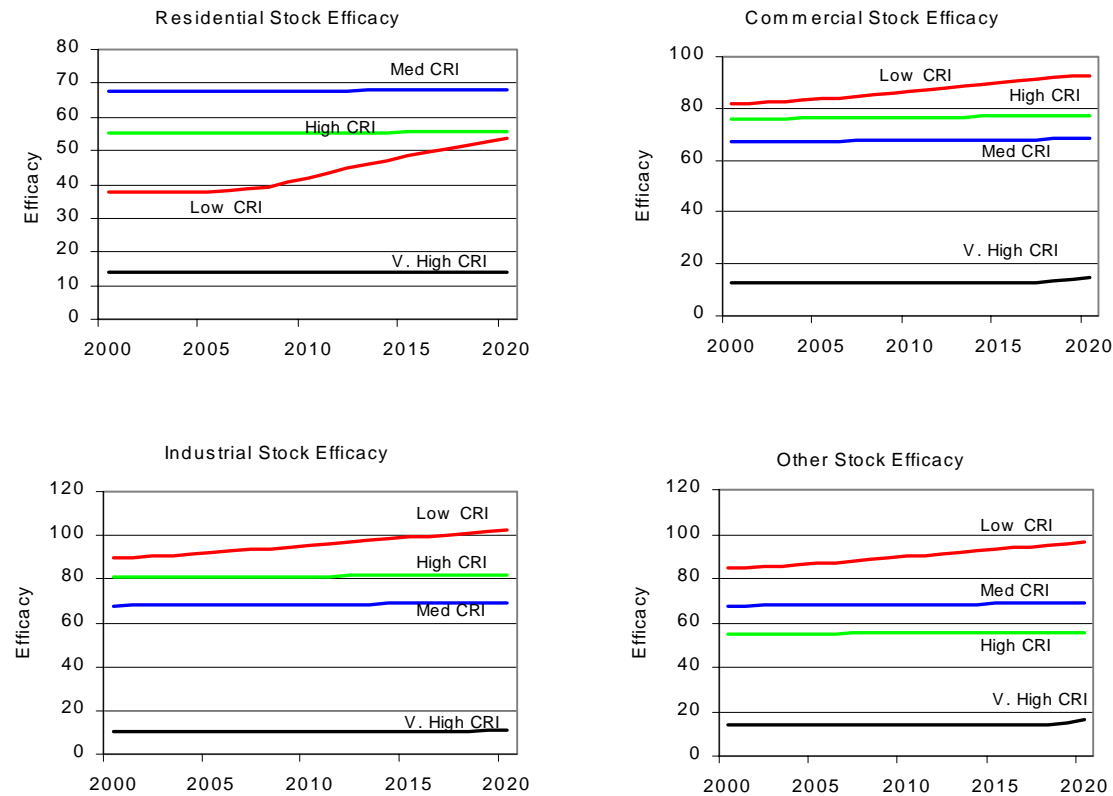
Figure B.1 Stock Efficacy – *Base Case*
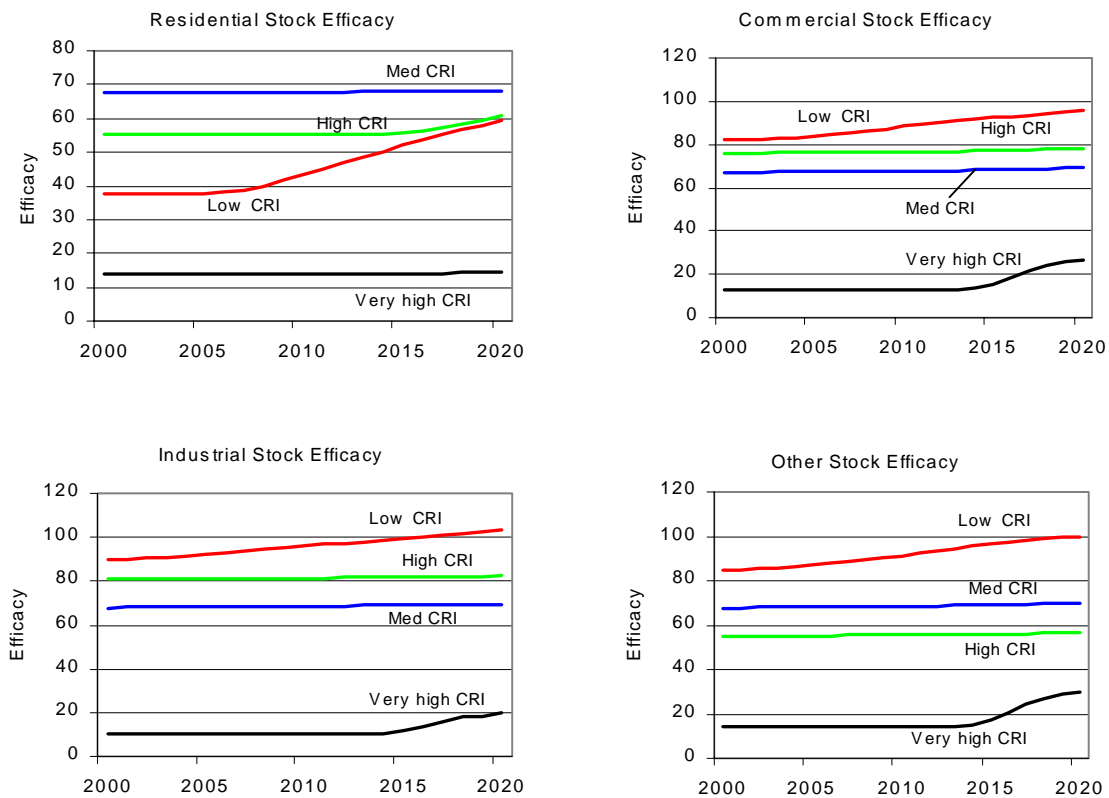
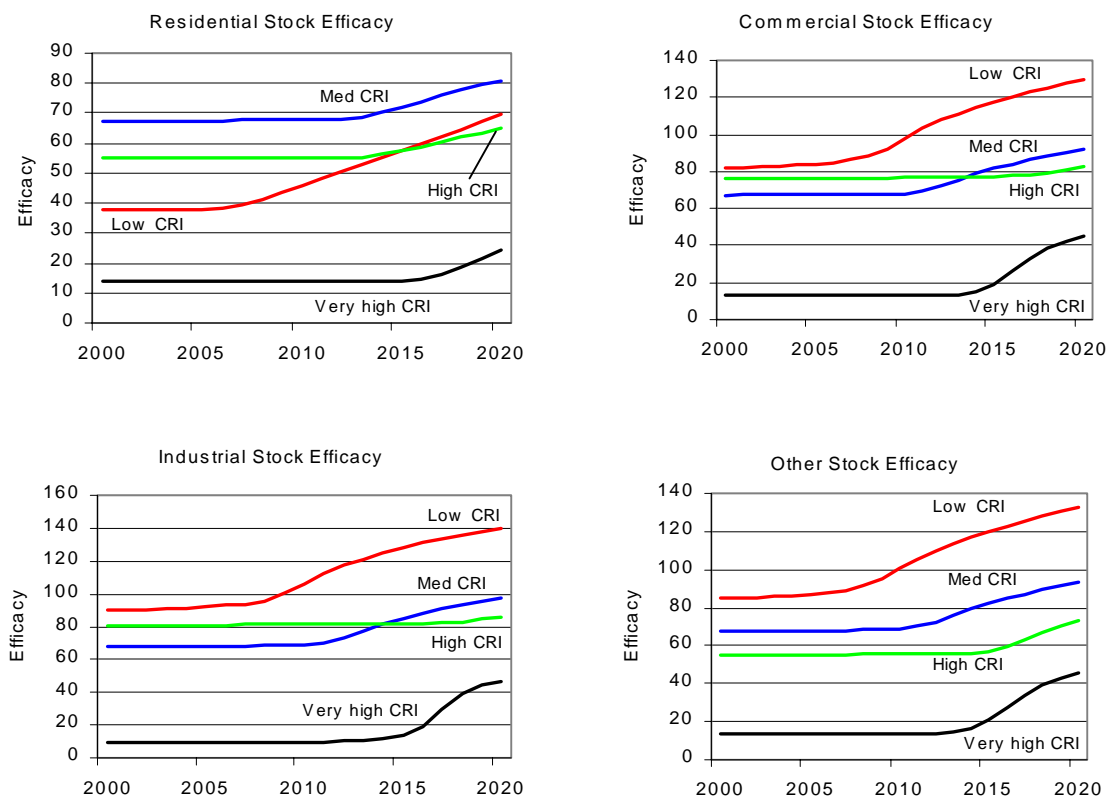**Figure B.2 Stock Efficacy – *Technology Breakthrough Case***

Residential Stock Efficacy

Commercial Stock Efficacy

Industrial Stock Efficacy

Other Stock Efficacy

Figure B.3 Stock Efficacy – *Price Breakthrough Case*

Residential Stock Efficacy

Commercial Stock Efficacy

Industrial Stock Efficacy

Other Stock Efficacy