LED Lamp Quality

Codes and Standards Enhancement (CASE) Initiative
For PY 2013: Title 20 Standards Development

Analysis *of* Standards Proposals for
LED Replacement Lamp Quality

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1 Executive Summary

The Pacific Gas and Electric Company (PG&E) and San Diego Gas & Electric (SDG&E) Codes and Standards Enhancement (CASE) Initiative Project seeks to address energy efficiency opportunities through development of new and updated Title 20 standards. Individual reports document information and data helpful to the California Energy Commission (CEC) and other stakeholders in the development of these new and updated standards. The objective of this project is to develop CASE Reports that provide comprehensive technical, economic, market, and infrastructure information on each of the potential appliance standards. This CASE Report covers quality standards options for light emitting diode (LED) replacement lamps.

LED replacement lamps, relative newcomers to the general service lighting market, are dramatically more efficient than incandescent lamps, and their efficacy continues to improve at a fast rate. Average LED efficacy will soon far outpace that of compact fluorescent lamps as well. Currently a small portion of the lighting market in terms of overall sales, LEDs have the potential to cut lighting loads in the United States (U.S.) by nearly one half by 2030, (DOE 2012d) if the general service and directional lighting markets accept them in large numbers. However, one of the most important factors affecting the rate and scope of any LED market transformation is the extent to which consumers are satisfied with the early LED products they purchase. The proposed Title 20 standard aims to ensure a minimum level of LED replacement lamp quality in order to build and maintain consumer satisfaction with LED lamps. To do this, the standard aims to set requirements that result in LED lamps with performance characteristics that are similar to, if not indistinguishable, from those of the incandescent lamps they are designed to replace. In support of this standards proposal, the CASE Team has conducted significant research including product performance testing, literature review, and analyses of the market, feasibility, product cost, and savings potential. All of this research is presented in this CASE Initiative.

The proposed standards would require certain LED replacement lamps to meet minimum performance requirements, addressing the following key parameters: color quality, longevity, dimmability, flicker, noise, light distribution, start time, efficacy, and labeling. The goals of this Title 20 standards proposal are similar to the goals behind the CEC Staff Report approved in December 2012 entitled "Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification" (CA Voluntary Specification). However, the proposals in this CASE initiative would result in mandatory, minimum requirements for all LED lamps.

2 Overview & Context

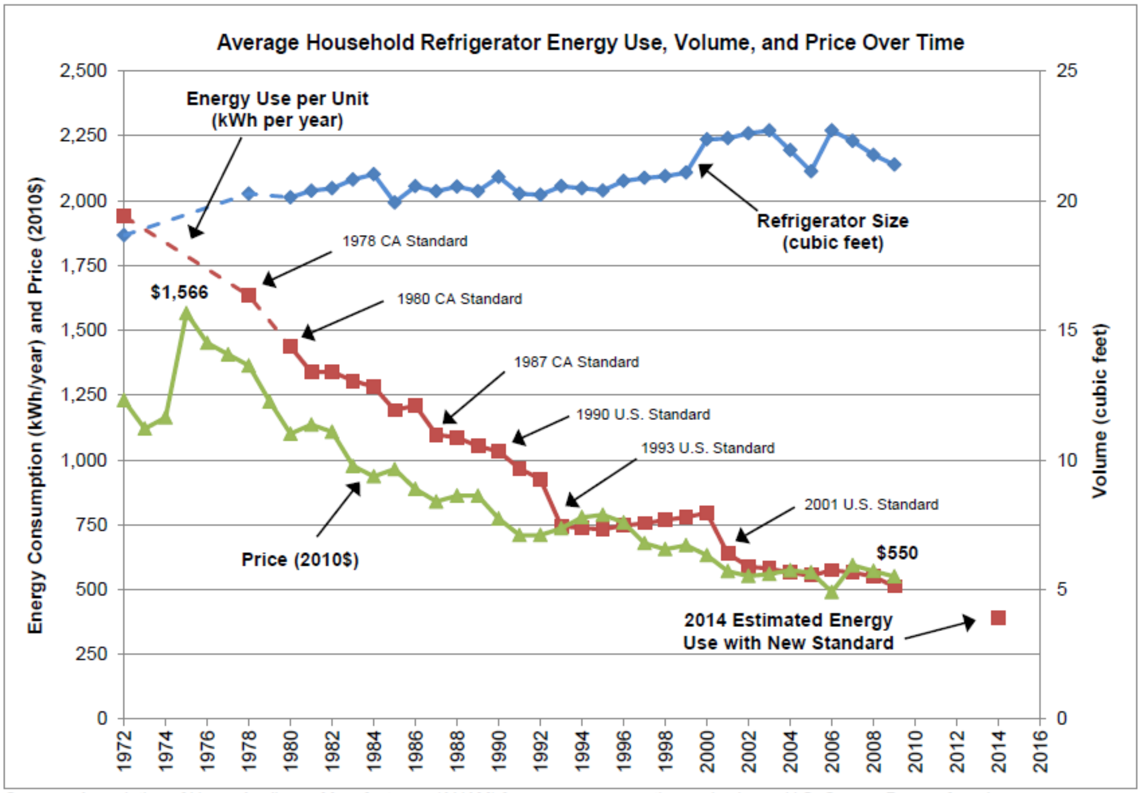
2.1 Background

Compact fluorescent lamps (CFLs) were introduced into the U.S. market in the late 1970's and quickly showed promise as an energy efficient replacement for the incandescent lamp. They drew roughly a quarter of wattage drawn by their incandescent counterparts, and they lasted several times longer. Beginning in the late 1980's, utilities began to implement promotional and incentive/giveaway programs to bring down the price of CFLs in order to increase CFL market share. Over the next two decades, enormous investments were made in these CFL programs. Expected to transform the market and bring about significant energy savings, CFLs became the most recognizable symbol of an increasingly prevalent energy efficiency movement.

However, as explained in a recent white paper published by the California Lighting Technology Center (CLTC), (Siminovitch & Papamichael 2011), despite the initial buzz associated with the lamps, and the support of programs that drove down CFL cost, the anticipated market transformation did not happen. By 1991, CFLs achieved only 1% of U.S. lamp sales volume. Ten years later, in the fourth quarter of 2001, U.S. CFL sales had achieved only 2.1% of the national lamp market. (PNNL 2006) The next decade showed increased growth, and the U.S. CFL market share hit a high of 22% in 2007. However, this dropped to 16% in 2009. (DOE 2010b) In terms of total sockets converted,[1] CFLs were estimated to make up roughly a third of all residential sockets in the U.S. as of 2010. (DOE 2012e) In summary, the average efficacy of general service lamps in the residential sector in 2010 was only about 25%-30% higher than the average efficacy of residential lamps in the 1970's, despite the availability of CFLs that are four times more efficient than incandescent lamps and offer a significantly lower lifecycle cost.

This slow adoption of high efficiency lamps is especially noteworthy when compared to the market penetration of other high efficiency consumer products. The average residential refrigerator sold in 2010 was roughly 380% more efficient than the average refrigerator sold in 1972. As shown in Figure 2.1, modern refrigerators use about a quarter of the energy despite being slightly larger on average than their 1970's counterparts. (ASAP 2011)

[1] The percentage of sockets containing CFLs is larger than the percentage of annual shipments due to longer CFL life and less frequent need of replacement.



Sources: Association of Home Appliance Manufacturers (AHAM) for energy consumption and volume; U.S. Census Bureau for price

Notes: a. Data includes standard-size and compact refrigerators.
b. Energy consumption and volume reflect the DOE test procedure published in 2010.
c. Volume is adjusted volume, which is equal to the fresh food volume + 1.76 * freezer volume.
d. Prices represent the manufacturer selling price (e.g. excluding retailer markups) and reflect products manufactured in the U.S.

Figure 2.1 Average Refrigerator Energy Use, 1972 – 2008

Source: ASAP 2011

A similar story exists for many other end uses as well. Average air conditioner efficiency increased by 300% between 1970 and 2010. (BPA) Average clothes washer efficiency increased 310% between 1990 and 2010. Dishwasher efficiency increased roughly 110% over the same period. (Perry 2011) Another example of this trend that may be more applicable to the lighting market is the recent advancement in television efficiency, as shown below in Figure 2.2. This market experienced a similar transformation, though in a much shorter period of time. In 2012, average television power density (Watts per square inch of screen) was roughly a quarter of the average television power density in 2006. Efficiency improved by 400% in that 6 year span.

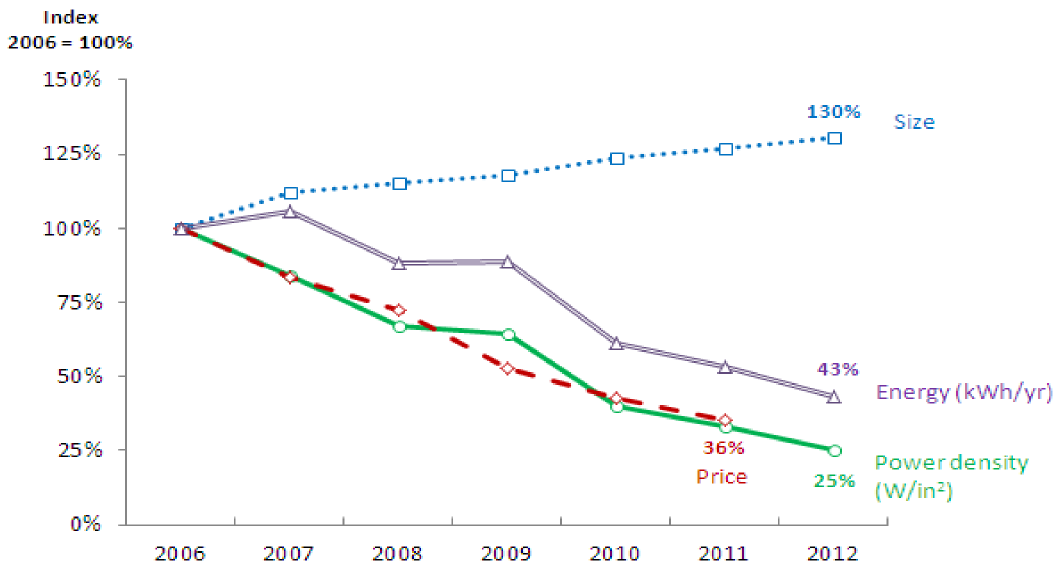


Figure 2.2 Television trends since 2006

These instances of complete market transformation were made possible by industry innovation. Just as important were the external market forces that pushed the markets such as voluntary incentive programs, and ultimately, progressive state and federal efficiency standards that mandated higher efficiency. However, none of the mandatory efficiency standards set for these products would have been feasible if the products had not achieved consumer acceptance. In all cases, the high efficiency products were not only cost effective, but also had equivalent or better performance; they provided functionality that was largely indistinguishable from that of their predecessors. Similar market transformation has not been achieved in the general service lighting market largely because CFLs did not provide an indistinguishable level of performance from their incandescent counterparts.

As explained by the California Energy Commission in its Final Staff Report on the Voluntary California Quality LED Lamp Specification, recent research into purchasing decision drivers supports this conclusion. McKinsey's 2011 Lighting the Way report suggests that consumer lighting purchase decisions are driven as much by light quality than they are by the cost of the lamp. As shown in the Figure 2.3 below, 20 percent of residential respondents rated light quality as the most important decision criterion for fixture installation – which is on par with the 22 percent who rated purchase price as the most important factor. In all other market segments, light quality was by far the most important factor.

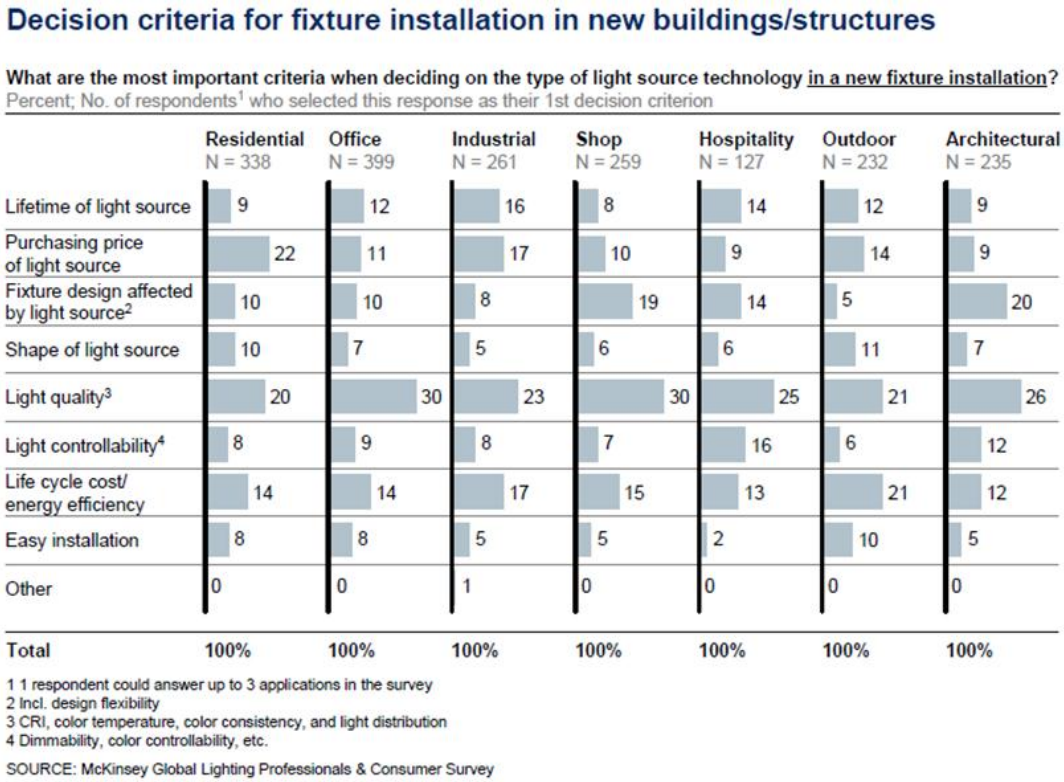


Figure 2.3 Decision Criteria for Lighting Installations

2.1.1 Consumer Preference and CFL Performance

Over the past few decades, several research efforts attempted to understand what was holding back the CFL market transformation. Studies were conducted by independent research institutions such as the Electric Power Research Institute (EPRI), and the Lighting Research Center (LRC), as well as by utility groups, such as the Northwest Energy Efficiency Alliance (NEEA), and by public entities like the National Laboratories, on behalf of government agencies such as the U.S. Department of Energy (DOE), and the CEC. These studies set out to identify consumer perceptions of and experience with CFL lighting, and to rank consumer priorities for their lighting purchases. They identified consumer preferences for certain lamp characteristics, and dissected consumer purchase decisions. They also conducted testing of CFLs to better understand their performance, light quality, and limitations.

The following is a timeline of some of these studies that were done in the U.S. over the course of two decades:

- 1992 EPRI; Perceptions of Compact Fluorescent Lamps in the Residential Market
- 1993 LRC; Quality vs Economy in Home Lighting: How Can we Find the Balance?
- 1993 LRC; Residential Lighting Incentive Programs: What are the Alternatives to Compact Fluorescent Lamps
- 1997 (HMG for) CEC; Lighting Efficiency Technology Report
- 1999: NEEA; LightWise; Market Progress Evaluation Report #1
- 2003: LRC; Increasing Market Acceptance of Compact Fluorescent Lamps
- 2006: PNNL for DOE; Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market

Findings from these studies, each of which took a slightly different angle in establishing its methodology, show that there are a number of different reasons for the slow adoption of CFLs, and these reasons may have changed over time. While there is not a simple explanation, at a high level were two issues that cut across all the studies: CFLs were too expensive and consumers often did not like them. These two findings were linked of course – the results of the studies generally found that consumers were not willing to pay more for CFLs when they did not perceive a significant benefit or improved utility (or, as in many cases, when the CFL was perceived as less desirable than the alternative).

A closer review of these consumer studies finds that among the consumer complaints about CFL performance, a few common themes emerged, listed in Table 2.1below.

Table 2.1 Common themes from consumer preference studies for CFL lamps

Theme	Specific Concerns
Compatibility	CFLs don't fit in existing sockets, and are not compatible with existing sockets with dimmers.
Light Quality	CFLs have poor light levels and harsh, cold, or "unfriendly" light. CFLs provide inconsistent light color. Consumers experience headaches under fluorescent lighting.
Performance	CFLs don't live up to their long life claims; early failure. CFLs buzz, hum, or flicker. CFLs have a delayed start and a slow run up time (to full brightness).

CFL prices did come down dramatically, from $15 to $20 or more, down to $2 or less, often with the support of utility rebate programs (many of these programs even gave CFLs away for free), and marketing campaigns espoused the benefits of CFLs. That these low prices and marketing campaigns did not result in a greater market transformation to CFLs is a clear indication that the consumer dissatisfaction with CFLs may have been a bigger factor than price in contributing to the low adoption rates experienced by CFLs.

Interestingly, many aspects of CFL quality did improve over time. Some CFLs are now dimmable, and most are now compact enough to fit in typical fixtures. Some now provide improved color rendering, and many have "warm" color (2700 Kelvin) that is fairly consistent from lamp to lamp. For many consumers, the damage may have been done when so much promotion, especially in the early years, went into products that were not satisfactory in the eyes of most consumers. In the words of Ed Crawford, the head of the North American Lighting Division at Philips, the world's largest lighting company, "Some of the early compact fluorescent products, they were not ready for prime time. They buzzed, they had lousy color, and they made everything kind of grey-ish, green." After their initial experiences with these lamps, many consumers have lost confidence in CFLs and negative perceptions have persisted despite gradual product improvement over time.

2.1.2 Consumer Preference and LED Lamp Performance

A number of studies have been completed over the years to assess consumer preference for and reaction to different aspects of light quality or lighting product performance, such as Lighting Research Center (LRC) research into acceptability of flicker or minimally perceptible color differences between light sources. However, extensive research efforts specifically designed to assess consumer reactions specific a variety of LED lamps with different performance characteristics is not widely available. LED replacement lamps are still so new to the market that it is unlikely that a significant amount of work has been done on this topic. To address this PG&E and CLTC are currently partnering to develop a methodology to conduct such a comprehensive study in 2013-2014. This research effort will likely take more than a year to complete but its results should be able to assist future efforts around updated quality specifications and standards for various lighting projects.

In the meantime, to provide an anecdotal glimpse into the LED replacement lamp market, the CASE Team has conducted a research effort into the customer reviews of LED replacement lamps provided at online retail outlets like HomeDepot.com and BestBuy.com. In conducting this research, our Team has looked at a relatively small number of comments, submitted on a select group of products, from a short list of online vendors; this effort was not intended to provide a statistically significant analysis of consumer preference trends. Additionally, many of the consumers purchasing LED lamps in 2013 and providing comments online are likely to be early adopters and/or otherwise represent a unique subset of consumers; this study was not intended to represent a cross-section of the whole population. Rather, this study aims to provide a high level perspective of some of the reactions to LED lamps that consumers have had so far, and to identify any common themes observed in these consumer reactions. A summary of this research is provided here.

The CASE Team reviewed over 200 individual customer reviews, spanning 11 unique product models, sold at 3 different online retailers. Some of the reviews consist of a written comment, others only a rating of 1-5 stars, and many include both. The lamps reviewed included 6 A-lamps, 4 PAR lamps and 1 MR lamp, and they had a wide range of performance features. Several of the lamps were ENERGY STAR® qualified, others were not. Several were marketed as dimmable, others were not. Color temperature ranged from 2700 to 5000K.

The majority of customer reviews were positive. Of the ratings using the 5-star system, the LED lamps averaged 4.2 stars. The highest scoring lamp averaged 4.5 stars, while the lowest performer averaged 3.5 stars. However, roughly 25% of the commenters had serious complaints about the performance of their lamps and were clearly not satisfied with their purchase. The table below shows the most common categories for these more serious complaints, along with the number of times a complaint was logged that related to each category.

Table 2.2 Common complaints logged about LED replacement lamps at online vendor sites

Complaint Category	# of complaints
Light color	11
Dimmability	10
Hum / audible noise	7
Early Failure	6
Flicker	5
Too Expensive	4
Slow Start Time	1

The results of this study were mixed. On the one hand, the majority of respondents rated their LED lamps highly. On the other hand, a significant number of commenters did have very negative experiences with their LED purchases. Many of the written complaints indicated that the consumer was planning to return the lamps or was otherwise no longer using them.

Though these studies provide valuable insight into several common consumer reactions to CFL and LED lamps, they do not conclusively resolve three key general questions associated with consumer lighting preferences:

1. Which lamp performance attributes are most important to consumers?
2. What level of performance is considered acceptable for each performance attribute (or what level will result in widespread consumer satisfaction with energy efficient replacement lamps)?
3. How much are consumers willing to pay for these specific levels of performance?

Further research is needed in this area to attempt to answer these questions. To the extent possible, the research being proposed currently by PG&E and CLTC will address these questions. In the absence of robust studies that answer all of these questions clearly, the proposals in this CASE initiative are intended to ensure that LED lamps provide performance that is comparable to the incumbent technology that consumers are used to; the CASE Team believes that the traditional incandescent lamp is the best guide for the development of LED replacement lamps that will satisfy consumers. Particularly since LED product costs are forecasted to come down so quickly the potential to offer true equivalency to incandescent lamps will encourage market transformation and optimize the energy savings potential from LED lamps.

2.2 The LED Opportunity

LED lamps are demonstrating the potential to be a game changer in residential lighting, just as CFLs were three decades ago. LEDs clearly offer great energy savings potential – some LED replacement lamp efficacies are already exceeding 100 lumens per watt (lpw), and LED manufacturer Cree, Inc., recently announced an individual LED chip that achieves 200 lpw. (Cangeloso 2012a) As with CFLs, LEDs also show promise when it comes to longevity, with many manufacturers claiming 25 to 50 year lamp lives.[2] While average prices remain high, forecasts show costs coming down quickly over the next few years (See Chapter 8, Economic Analysis), which encourages optimism in the energy efficiency community that these products may lead to big savings. There is also a huge amount of momentum building in the LED manufacturing community – significant investments are being made in LED lighting, and the value of the LED lighting industry nearly doubled in 2010 alone. (Brite 2011) New manufacturers besides the traditional lighting industry leaders are steadily entering the LED lamp market as well, including consumer electronics manufacturers such as Samsung, Toshiba, Vizio, Panasonic, and RCA, as well as many younger lighting companies, such as CREE, CRS, Nexxus, Soraa, and others.

Given this potential and momentum, a transformation of the market appears to be imminent, particularly as the Energy Independence and Security Act of 2007 (EISA) lamp standards are being phased in from 2011 – 2014, requiring improved efficiency A-lamps (met by more expensive halogen technology). However, as we learned in the case of CFLs, the mass consumer adoption of LEDs and the resulting energy savings is not guaranteed, nor is it assured to happen quickly. The rate and extent of this transformation will depend on a number of things, but primarily lamp prices and consumer satisfaction with the technology.

That prices will decrease quickly and efficacies will rise quickly are very safe bets for those tracking the LED market. In 2000 at the Strategies in Light conference, Dr. Roland Haitz presented his observations of the cost of LEDs, in what would eventually come to be known in the LED industry as Haitz's Law. Dr. Haitz

[2] Assuming approximately 1,000 hours of operation per year, and manufacturer claims of 50,000hr lamp life.

stated that every decade, the cost per lumen falls by a factor of 10 while the amount of light generated increases by a factor of 20 for a given wavelength. Note the logarithmic scale on the y axis in Figure 2.4 below.

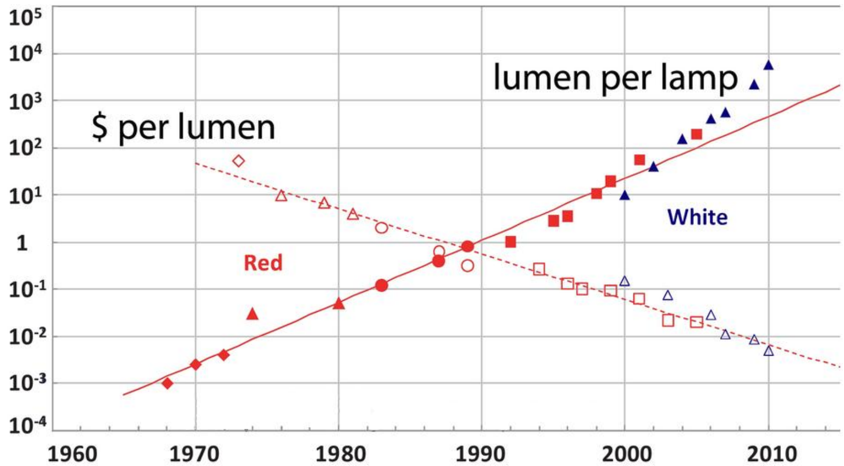


Figure 2.4 Haitz's Law

Source: University of Wisconsin

As of early 2013, manufacturer announcements of new performance milestones and production techniques that will increase efficacies are coming out on a monthly if not weekly basis. Increases in efficacy bring prices down because fewer LEDs are needed per lamp and because less heat is generated that needs to be dissipated; the cost of thermal management (e.g. heat sinks) drops with improved efficacy. These types of forecasts showing the cost points and efficacy gains expected over the coming years have been circulated widely, and generally align with Haitz's law.

However, it is far less certain whether consumers will like these LED lamps when they do become available at more reasonable prices. It is not a given that consumers will keep them installed, that they will purchase more of them after the first purchase, or that they will recommend them to their personal networks. In fact, LEDs may find they already have an uphill battle because they are a new, highly efficient lighting technology, and many consumers may inadvertently associate them with CFLs and the stigmas of inadequate performance and quality that many CFLs carry.

There is already a wide range of performance among LED replacement lamp products. As shown in subsequent sections of this report, many products are being made that accurately render the colors of the objects they illuminate and that provide a color appearance that is similar to that of the incandescents consumers are used to. Most new LED replacement lamps are now dimmable, and manufacturers are focusing on providing dimmability not just on specific new dimmers, but on the dimmers that consumers are likely to have in their homes already. Manufacturers are investing in other features of the lamp that they hope consumers will never notice – reducing the amount of time they take to turn on, eliminating noise (humming or buzzing) and flicker, emulating an incandescent lamp's natural color shift as it dims, and minimizing any slight differences in color between multiple lamps of the same model. Many manufacturers are also investing in and marketing aspects of the lamps they hope consumers will notice, such as the ability to control the lamp with a smart phone, and to change the color based on time of day or mood.

On the other hand, some products are being made without an emphasis on quality. Some have electrical components that are not designed to last nearly as long as the LED chips themselves, which could lead to product failure long before the advertised lamp life value (which is based on predicted lumen maintenance, not actual product life). Some lamps have poor color rendering capabilities, while others market themselves as "incandescent equivalents" despite having much cooler (whiter/bluer) color than incandescent lamps, or providing far less light than the "equivalent" lamps they are marketed to replace. Some lamps provide an inconsistent, non-uniform distribution of light, despite appearing to the consumer to be a typical omni-directional lamp shape.

This CASE Initiative presents the opportunity to address these issues of consumer satisfaction through the adoption of a mandatory minimum standard for LED Quality. This CASE proposal recommends that CEC adopt these mandatory standards and set an effective date on or before January 1, 2016.

3 Product Description

Light-emitting diodes (LEDs) are semiconductor light sources that generate electroluminescence. Most LEDs operate at low voltage and on DC current, which requires them to be operated with a driver to convert line voltage to lower voltage and supplies the LED's with the current they need. LEDs have been adapted to be used in lamp shapes designed to replace omni-directional (e.g. A-lamp, candelabra) and directional (e.g. PAR, MR, BR) lamps. These products are made with integral drivers in the lamp base. Although LEDs lamps only accounted for 0.3% of lamp sales in the U.S. in 2010, rapid technological advances in the past few years have decreased costs while increasing the variety available to consumers. (DOE 2012e) Some of the common benefits of LED technology include:

- High luminous efficacy (Minimal nonvisible UV and IR radiation)
- Resistance to mechanical failure / extended life time
- Dimming and control capability
- Opportunity for color tuning
- Rapid on-off cycling capability without detrimental effects
- Directional light emission
- Size and form factor
- Instant on at full output
- Improved performance at cold temperatures (DOE 2012a)
- No toxicity upon breakage
- Low to no hazardous waste

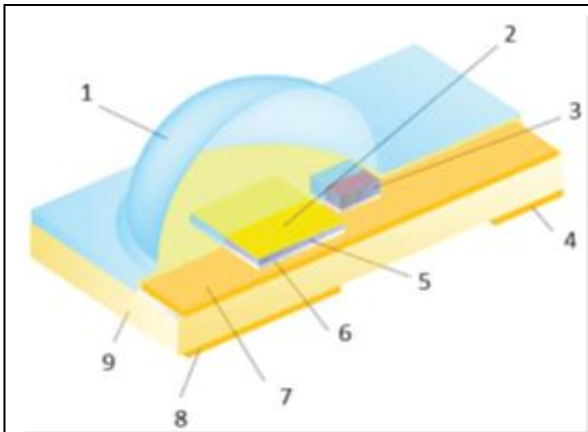
3.1 History

LEDs have been used successfully in several applications over the past 50 years. They began being used as indicator lights in electronics in the 1960s. Early LEDs were very dim and were inherently non-white, nearly monochromatic light sources, so this initial use was ideal for them. Over the next several decades, advancements in semiconductor technology and optics and materials technology led to the development of brighter and more efficacious LEDs. LED efficiency and light output has risen exponentially, with a doubling occurring approximately every 36 months since the 1960s. (Wikipedia 2013) Significant gains were made in the 1990's, when high-brightness blue LEDs were developed and eventually mixed with other colored LEDs to create light that appears white. (Stern 2012; McKinsey 2011) For the next 15 years LEDs were mainly used for mobile, laptop, and television backlighting. In the past few years, rapid technological advancements have led to brighter and cheaper LEDs which have now been incorporated into replacement lamps and other luminaires used for general lighting. Most of the early LED replacement lamps were lower lumen products (40W equivalents or less), but these were followed by 60Wequivalent lamps, 75W equivalents, and most recently (late 2012), 100W equivalents. Between August 2012 and March 2013, new product lines were announced at least on a monthly basis, including but not limited to the following:

- 3M LED Advanced Lightbulb, August 2012 (Wright 2012)
- Philips Hue, October 2012 (Stern 2012)
- Osram Sylvania Ultra LED, November 2012 (Sylvania 2012)
- Best Buy Insignia LED, November 2012 (Cree 2012)
- Philips A19 LED (white when off), December 2012 (Cangeloso 2012b)
- Cree, March 2013 (Bautista 2013)

3.2 Technology

LEDs consist of a tiny chip of semiconducting material encased in an LED package and mounted onto a circuit board. This is then attached to a structure designed to resemble traditional lamp forms and function in existing fixtures, as shown in Figure 3.1 below.



1. Silicone Lens
2. Phosphor Plate
3. Transient Voltage Suppressor
4. Cathode
5. LED Chip
6. Bond Layer
7. Metal Interconnect Layer
8. Thermal Bed
9. Ceramic Substrate

Source: Philips Lumileds, U.S. DOE, http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_advantage.pdf

Figure 3.1 LED Package Design

The color of the emitted light depends on the type of semiconducting material used in the chip. LEDs do not naturally produce white light; two technologies have been incorporated into LED designs in order to expand their range from being used as small colored electronic indicator lights to white light replacements for incandescent and fluorescent lamps used in general lighting. As shown in the figure below, the LED lamps designed to replace A-line, directional, and linear lamps use phosphor conversion, Red-Green-Blue (RGB) systems, or a hybrid method to produce white light. Phosphor conversion LEDs consists of a phosphor placed on or near the LED to convert the blue or UV light it produces to white. RGB systems combine several monochromatic LEDs in green, red, and blue on the same circuit board array—when these colors are combined, they produce a white light. Hybrid systems utilize both technologies in the same lamp. (DOE 2012d)

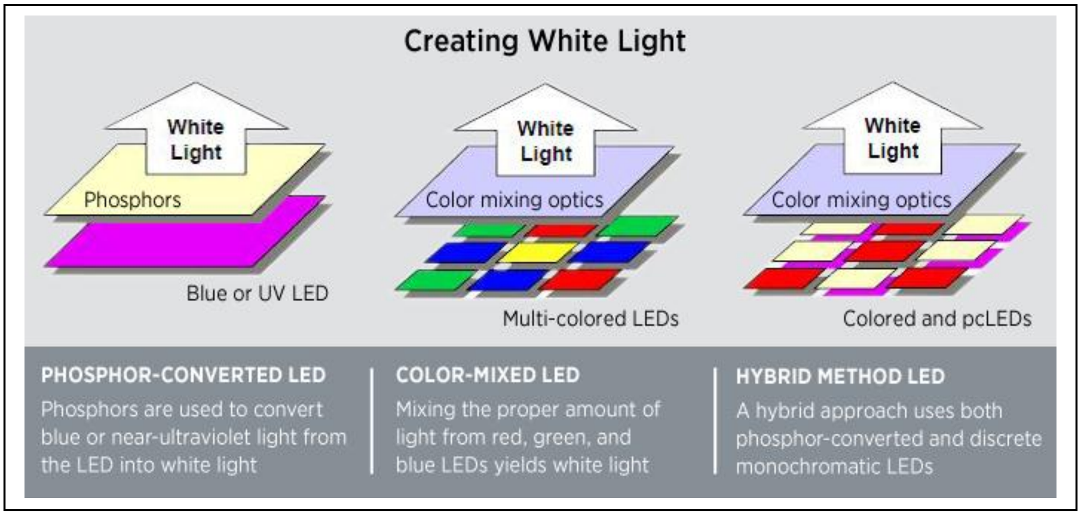


Figure 3.2 White LED Light Technologies.

Source: DOE 2012d

3.3 Lamp Types

3.3.1 General Service and Decorative Lamps (Omni-directional Lamps)

General Service Lamps (GSLs) are used for general service lighting applications where the light is designed to be distributed in all directions (omni-directional). GSLs are the largest installed stock of any lighting type, comprising over 53% of U.S. lighting. (DOE 2012e) They are especially common in the residential sector. Nationally, DOE estimated that GSLs consumed about 150 TWh of electricity in 2010. (DOE 2012e) The most common type of GSL is the A19 type lamp (referred to herein as an A-lamp), while decorative GSLs can come in many shapes, including globe, or candle shaped lamps. ANSI Standard lamp shapes include A, BT, P, PS, S, T, B, BA, C, CA, DC, F, and G lamps.

The incandescent versions of these lamps are generally considered to be omni-directional lamps, though some LED versions of these lamp types may not distribute light in all directions. Figure 3.3 below shows a range of LED general service replacement A-lamp shapes. Figure 3.4 shows decorative LED lamps including two candelabra and one globe lamp.

Figure 3.3 LED General Service A-lamps

Source: DOE 2012f

Figure 3.4 LED Decorative Lamps

Source: Google images

3.3.2 Directional Lamps

Directional lamps, such as parabolic aluminized reflector (PAR) or multifaceted reflector (MR) lamps are commonly used in retail applications, for general lighting and as spotlights. Directional lamps come in a wide variety of shapes, diameters (ranging from 2" or less, to more than 5"), and beam angles (ranging from below 10° to above 60°). ANSI standard directional shapes include R, PAR, BR, ER, and MR. For the purposes of this CASE effort, directional lamps with a diameter greater than or equal to 2.25 inches (e.g. R20, BR30, PAR38) are considered "large diameter directional lamps" and those with a diameter less than 2.25 inches (eg. MR16, PAR11) are considered "small diameter directional lamps."

DOE estimated that national energy consumption by directional lamps in 2010 was estimated to be on the order of 50 TWh.[3] Figure 3.5 illustrates several different types of directional LED replacement lamps.

Figure 3.5 LED directional Lamps

Source: Google Images

3.4 Base Types

Just as there are several different lamp shapes, many lamp bases exist to accommodate various fixture sockets. The most common type of base for A-type GSL lamps is the medium screw base (also known as Edison base), which is used for most A-type incandescent lamps and CFLs. These bases are labeled with "E" for Edison, followed a number denoting the diameter of the base, in millimeters. The standard A-type screw-in lamp in the U.S. is E26. Examples of screw-in bases can be seen in Figure 3.3. Conversely, many lamps have pin bases, including those used to satisfy Title 24's "high-efficacy" luminaires requirements. These are labeled with "G," usually followed by another letter (e.g. "GU") and a number denoting the distance between the two pins, in millimeters. Some of the most common lamp base types include, E12 (Candelabra), E17, E26, GU5.3, GU10, and GU24 bases.

[3] Assumed to be equal to the sum of MR16 lamp consumption plus PAR, BR, and R-shaped lamps.

4 Manufacturing and Market Channel Overview

4.1 Manufacturing Overview

The bill of materials used in the development of LED replacement lamps varies widely and is notably different than that of traditional lighting technologies, which has led to a shift in traditional industry roles. (McKinsey 2011) In addition to the major manufacturers in the lighting industry, many smaller companies have formed to serve the LED market specifically. Some companies have come from other sectors to join the LED lighting market as well – including consumer electronics companies like Samsung, as well as materials companies like 3M.

The LED general service lighting market is made up of several smaller sub-markets, with some manufacturers focusing on the light sources (e.g. LED packages or LED arrays), others focusing on the electronics and control gear (eg LED drivers), others focusing on other mechanical components of the lamps, (including thermal management systems, adhesives, etc), and others working to package all of these components into replacement lamp products. Major LED manufacturers providing light sources for the lamp industry include Nichia, Osram Opto Semiconductors, Cree, Inc., and Philips Lumileds. Some companies have become more vertically integrated, producing LEDs and incorporating them into their own replacement lamp designs. Cree, for example, in addition to selling LED packages, now sells a line of self-ballasted LED general lighting replacement lamps.

Currently there are over 500 manufacturers participating in the voluntary DOE LED Lighting Facts program. Though there are too many to list here, some of the LED lamp manufacturers are shown below:

- Bulb America
- Cree
- EARTHLED
- Feit
- GE
- LEDnovation
- LG
- Lighting Science Group
- MSI
- Osram Sylvania
- Philips
- Samsung
- Solais
- Soraa
- Switch Lighting
- TCP
- Toshiba
- 3M

With this variety of suppliers there is also a huge amount of variation in design strategies. As explained by Maury Wright in a February 2013 article in LEDs magazine, manufacturers are taking many different approaches to meet the challenge of producing less expensive, highly efficient, quality LED replacement lamps. This includes different thermal management designs, LED array configurations, and light distribution strategies including mirrors or reflectors.

4.2 Supply Chain

LED replacement lamps are now offered at nearly all hardware and home improvement stores (both “brick and mortar” and online) including Home Depot, Lowe’s, Ace Hardware, and other big box stores such as Costco and Wal-Mart. They are also available at some consumer electronics stores, including Best Buy. Some of these retailers have entered into co-branding partnerships with LED manufacturers to release their own line of products. This includes the Home Depot EcoSmart LED brand and Best Buy’s Insignia brand LED lamp. The availability of LED replacement lamps at these vendors has increased significantly in the past 2 to 3 years. In the commercial sector, LED lamps are also sold through a large assortment of online vendors and through traditional lighting distributors.

5 Energy Usage and Product Quality

5.1 Test Methods

5.1.1 Current Test Methods

Table 5.1 below lists the test procedures most widely recognized by the lighting industry in the U.S. for testing LED replacement lamps. ENERGY STAR references these test procedures below for the majority of its specifications as well.

Table 5.1 Industry Standard Test Procedures for the Measurement of LED Lamp Performance

Organization	Test Procedure	Description
ANSI	C78.20-2003	Electric Lamps—A, G, PS and Similar Shapes with E26 Medium Screw Bases
ANSI	C78.21-2011	Electric Lamps—PAR and R Shapes
ANSI	C78.377-2011	Specifications for the Chromaticity of Solid State Lighting Products
ANSI	C82.77-2002	Harmonic Emission Limits—Related Power Quality Requirements for Lighting Equipment
ANSI/IES	RP-16-10	Nomenclature and Definitions for Illuminating Engineering
CIE	Pub. No. 13.3-1995	Method of Measuring and Specifying Color Rendering of Light Sources
CIE	Pub. No. 15:2004	Colorimetry
IES	LM-79-08	Electrical and Photometric Measurements of Solid-State Lighting Products
IES	LM-80-08	Measuring Lumen Maintenance of LED Light Sources
IES	TM-21-11	Projecting Long Term Lumen Maintenance of LED Light Sources
NEMA	SSL4-2012	SSL Retrofit Lamps: Suggested Minimum Performance Requirements
NEMA	SSL7A-2013	Phase Cut Dimming for Solid State Lighting: Basic Compatibility

DOE is currently conducting a rulemaking to establish Federally-recognized test procedures for LED lamp lumen output, input power, CCT, and lumen maintenance/lifetime. It is expected that DOE's test procedures will be based heavily on the test procedures above, specifically the IES' LM-79, LM-80, and TM-21.

5.1.2 Proposed Test Methods

For the purposes of this standard, the above test procedures will be utilized where possible. The above test procedures are sufficient for the measurement of luminous flux, luminous intensity distribution, efficacy, correlated color temperature (CCT), color rendering index (CRI), color consistency (between lamps), lumen maintenance, power factor, start time, harmonic distortion, and wattage.

However, several lamp performance parameters that are included in this proposal, to our knowledge, do not currently have test procedures or metrics that are widely recognized as "industry standard." These include rated lamp life (distinct from lumen maintenance tests), flicker, dimmability, and noise. Various tests have been used by other entities, and others are still under development.

With respect to lamp life / lamp failure, in its recent rulemaking to establish "ecodesign" requirements for LED lamps, the European Commission established requirements for "lamp survival factor" and "premature failure rate" though test procedures for these metrics have not yet been published. There is also a working group in the U.S. called the LED Systems Reliability Consortium, headed up by DOE, and including other stakeholders such as manufacturers and the National Laboratories, that is looking into lamp life measurement procedures. This group is exploring various accelerated life tests as well as stress testing, and is interested in predicting early failure as well as realistic lamp life tests that are based on the whole system, as opposed to just the lumen maintenance of the LEDs.

ENERGY STAR is currently developing a test procedure to measure dimming performance, and this procedure should be completed in 2013 for inclusion in ENERGY STAR's final Lamps Specification. This test procedure will include a procedure for the measurement of flicker and noise output across the dimming range.

The CASE Team expects test procedures for all of these measurements to be available before adoption of this standard, and for consistency the proposal is to leverage these industry vetted test procedures where possible, rather than to introduce separate, California-specific test procedures for these metrics.

5.2 Quality & Performance Attributes of LED Replacement Lamps

The recent flood of products into the market has produced both high and low-quality lamps. Some are capable of replacing incandescent lamps with little or no noticeable difference. Others fall short on certain performance attributes and thus do not make suitable replacement products. Following is an overview of many of the key performance parameters of replacement lamps.

This section also provides an overview of the range and distribution (where available) of current LED lamp performance across these key metrics. Much of the data shown here was derived from the Lighting Facts Database, an online resource maintained by DOE that includes performance data for thousands of LED products. For some performance metrics that are not commonly made available by manufacturers, and to verify the reported claims, PG&E has been funding LED product testing efforts at the CLTC since 2012. Many of these testing results are referenced or summarized here; others are expected later in 2013 and will be delivered to the CEC as they become available to assist with the Rulemaking process. This testing has assessed the performance of 25 A-lamps, 8 PAR38 lamps, 4 PAR30 lamps, 4 PAR20 lamps, and 20 MR16 lamps.

Where available, this section also includes graphs that demonstrate the rate of product improvement in recent years, and in some cases, provides forecasts into the future.

5.2.1 Light Output

Consumers are accustomed to certain levels of light which they associate with specific lamp wattages of traditional incandescent lamps. These typical incandescent A-lamp wattages and their associated lumen packages are shown in Table 5.2 below, along with their market shares (RER 2001). The most common incandescent A-lamp is the 60W lamp, but 75W and 100W lamps are both common as well. The sales-weighted average wattage of traditional A-lamps is 70W, and the sales-weighted average lumen output of traditional A-lamps is 1,003 lumens. For the purposes of this CASE Report, a value of 1,003 is considered to be a representative lumen output for an A-lamp.

Table 5.2 Traditional market share of A-lamps by lumen output

Traditional Incandescent A-lamp			Market Share
Wattage Bin	Typical Wattage	Typical Lumen Output	
25 - 45	40	450	20%
46 - 64	60	800	34%
65 - 85	75	1,100	21%
86 - 125	100	1,600	24%
126 - 150	150	2,600	1%
Sales Weighted Average Lumens		**1,003**	

For large diameter directional lamps, the CASE Team utilized the analysis conducted by DOE in its current rulemaking process for incandescent reflector lamps. The DOE analysis assumes three baseline lamps – a 90W PAR38 lamp with 1,314 lumens, a 75W PAR38 lamp with 1,050 lumens, and a 50W PAR30 lamp with 630 lumens. Table 5.3 below shows these three lamp types, their market share, and the resulting value of 1,060 lumens for a representative large diameter directional lamp.

Table 5.3 Traditional market share of large diameter directional lamps by lumen output

Traditional Incandescent Large Diameter Directional Lamp			Market Share
Product Type	Wattage	Typical Lumen Output	
90W PAR38	90	1,314	42%
75W PAR38	75	1,050	33%
50W PAR30	50	630	24%
Sales Weighted Average Lumens		**1,060**	

For small diameter directional lamps, the CASE Team utilized the research conducted by the Small Diameter Directional Lamp CASE Team. Table 5.4 below shows this research and the sales weighted average lumen output of 649 lumens for a representative small diameter directional lamp.

Table 5.4 Traditional market share of small diameter directional lamps by lumen output

Traditional Incandescent Small Diameter Directional Lamp		
Wattage	Typical Lumen Output	Market Share
50	750	70%
35	500	20%
20	240	10%
Sales Weighted Average Lumens	**649**	

For decorative lamps, the CASE Team relied on the 2010 Lighting Market Characterization study which shows that the average lumen output for decorative lamps is 479 lumens. This value is used in this CASE Report as the lumen output of a representative decorative lamp.

In sum, for the purposes of the Report, a "representative" lumen output value has been identified for each lamp type, and this value is assumed to be the average or typical lumen output provided historically by that lamp category. These values are shown in Table 5.5 below.

Table 5.5 Representative Historical Lumen Output by Lamp Type

Lamp Type	**Representative Light Output (Lumens)**
General Service (A-lamp)	1,003
Decorative Lamp	479
Small Diameter Directional Lamp	649
Large Diameter Directional Lamp	1,060

Despite these historical average lumen output values by lamp shape, early generations of LED replacement lamp products generally had much lower lumen outputs, making them impractical as replacements for many incandescent lamps. DOE testing of LED lamps through its CALiPER Program has shown that some LED products marketed as replacements for high wattage lamps have lower lumen output than their traditional counterparts, which is likely to lead to dissatisfaction among customers (DOE 2011). For example, some A-line products marketed as 60W replacements may only provide as much light as a typical 40W incandescent A-lamp. Likewise, some LED MR16s marketed as 50W replacements may only provide as much light as typical 35W halogen MR16. As LED technology has continued to improve, however, higher lumen products are now increasingly capable of replacing all variety of general service or directional incandescent lamps. True 60W equivalent A-lamps (those achieving 750 – 900 lumens) are now commonplace, and higher lumen lamps capable of replacing 75W and 100W A-line incandescents are now available as well. As explained earlier, several manufacturers have announced true 100W equivalent A-lamps since fall 2012. These lamps make up only 2% of the A-lamps on the Lighting Facts Database but now that the industry has begun to develop these products, they are likely to become more common because this is historically such a common lumen output for incandescent lamps (DOE 2013a). Table 5.6 below shows the current distribution of LED A-lamps by lumen bin and wattage equivalency, in the Lighting Facts Database.

Table 5.6 Current Distribution of LED A-Lamps by Lumen Bin

Product Class		Average Power Draw (W)	Percentage of Products in Lighting Facts Database
Wattage Equivalency	Lumen Bin		
<40	<310	4.5	15%
40	310-749	7.6	60%
60	750-1049	12.0	20%
75	1050-1489	16.1	2%
100	1490-2600	22.7	2%

Source: Derived from Lighting Facts Database

Figure 5.1 through Figure 5.4 show the rate of change from 2010 – 2013 of the LED lamp products being added to the Lighting Facts Database during that period, and also project out these trends over the next several years. These figures show that the average lumen output and the maximum values of products being added to the database are both increasing rapidly over time.

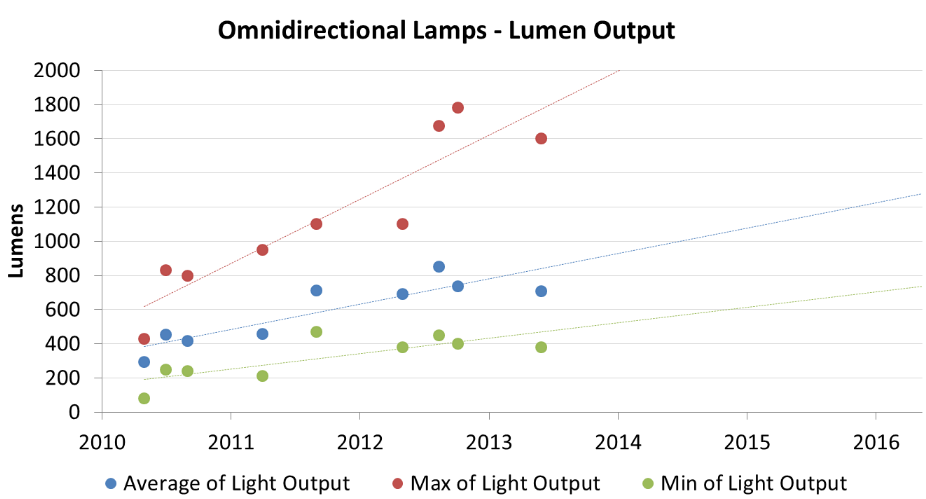


Figure 5.1 Minimum, average and maximum lumen output of LED A-lamps added to the Lighting Facts Database, 2010-2013

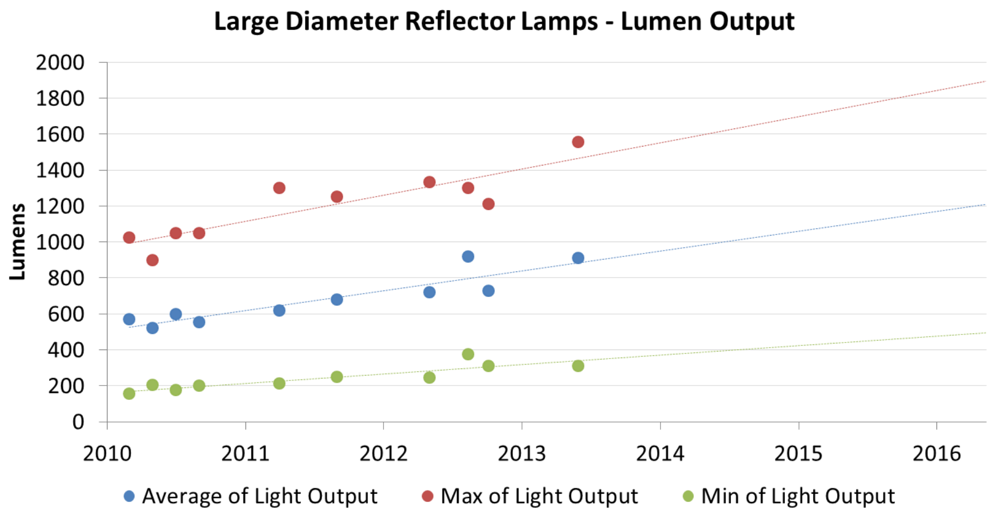


Figure 5.2 Minimum, average and maximum lumen output of large diameter directional LED lamps added to the Lighting Facts Database, 2010-2013

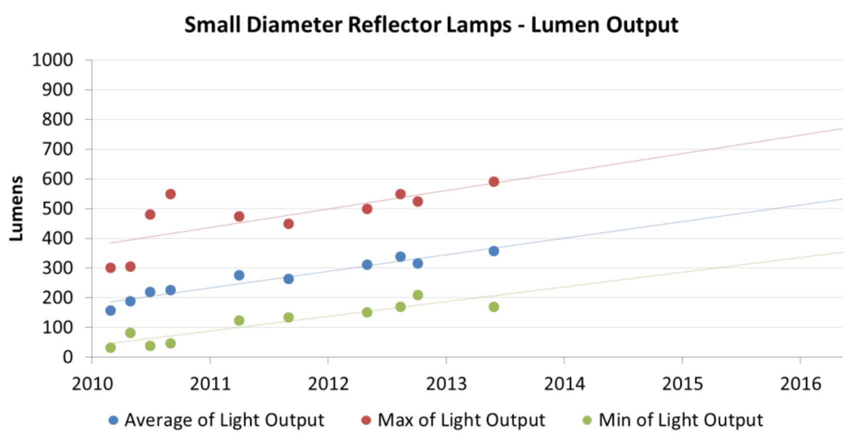


Figure 5.3 Minimum, average and maximum lumen output of small diameter directional LED lamps added to the Lighting Facts Database, 2010-2013

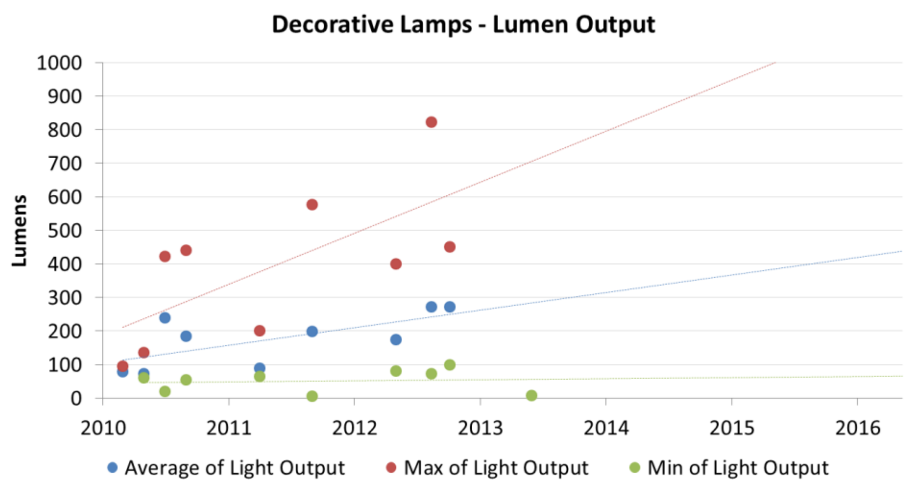


Figure 5.4 Minimum, average and maximum lumen output of decorative LED lamps added to the Lighting Facts Database, 2010-2013

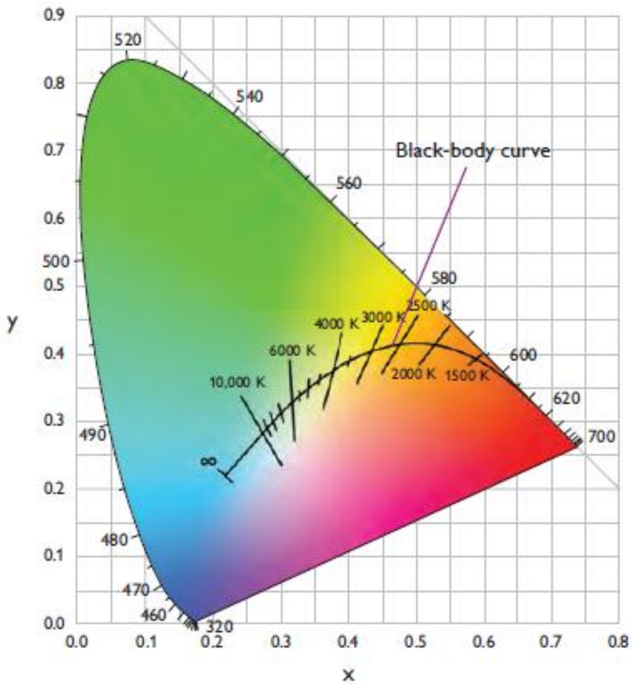
Given the projected upward trajectory for the lumen output of all four categories of LED lamps, this CASE Report assumes that by 2016, LED lamps will provide the same lumen output, on average, as that provided historically by their incandescent counterparts.

Another metric that is of particular importance to MR and PAR lamps and related to perceived brightness is center beam candlepower (CBCP), which is a measure of a lamp's light intensity (measured in candelas) at the center of the beam angle. Because MR lamps and PAR lamps are often used in retail and other applications that require precise beam control and very targeted light, this measure of a lamp's "punch" is often more useful to lighting designers than the lamp's total lumen output (which does not describe where the light is projected). The target or expected CBCP of traditional incandescent or halogen incandescent products depends on both the wattage of the lamp, the beam angle, and to some extent, the lamp shape. EPA has a tool that it maintains on the ENERGY STAR website that is an equivalency calculator for center beam candlepower. A user can enter the wattage and beam angle of a specific incandescent lamp type being replaced, and the calculator identifies the target minimum CBCP that should be provided by a replacement lamp.

Measured light output and center beam candle power data for A-lamps and directional lamps has been provided to CEC previously in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.2 Correlated Color Temperature (CCT)

Correlated color temperature (CCT) is a measure of the color of the light produced by a light source at or near the black body curve. It is measured in Kelvin (K), with higher temperatures signifying "cooler" light (more white/blue tint), and lower temperatures signifying "warmer" light (more yellow/red tint). The CCT of a light source refers to the color of a theoretical black body radiator when heated to the point of incandescence. The heated black body radiator generates light that changes from yellow hues to blue hues as the temperature in Kelvin gets hotter, as shown by the course of the curved black line on the graph below. Artificial light sources are generally designed to provide light at various places along this curve. A lamp with a 2700K CCT produces light that is on or near the black body curve, at or near the2700K value of the curve.



The black-body curve defines the range of color temperatures, from warm (reddish) to cool (bluish), within the CIE 1931 color space.

Figure 5.5 The Black Body Curve in the 1931 CIE Color Space

Source: Philips Optibin

One of the advantages of LED lamps over traditional lighting technologies is that they can be finely tuned to produce a wide range of color temperatures by mixing different colored LED chips in the same array. This tuning technique can also be used to shift the color of light according to the task being performed, or according to time of day, to mimic the natural change of daylight color temperature.

Incandescent and halogen incandescent lamps typically provide light in the range from 2600K to 3000K (with 2700K being most common), while LEDs generally have color temperatures ranging from 2600K up to 6000K or higher. While this range of available color temperatures is an advantage of LED technology, it can also be considered a barrier to consumer acceptance. Customers looking to replace their incandescent lamps may expect warm, 2700K light, but could inadvertently buy lamps of a cooler color (e.g. 5000K), and be disappointed by the whiter, almost blue-tinted light. Even small changes in color temperature may be unwelcome – a 3000K replacement lamp installed in a room with other 2700K incandescent lamps may appear to be cool or harsh by comparison.

Below is a graph showing the distribution of LED replacement lamp products across different nominal CCT bins, from the Lighting Facts Database. About 30% of LED A-lamps are nominally 2700K, and over 40% are nominally 3000K. The other 30% are cooler color temperatures, including almost 20% that are 5000K or higher. This trend is similar for directional lamps as well.

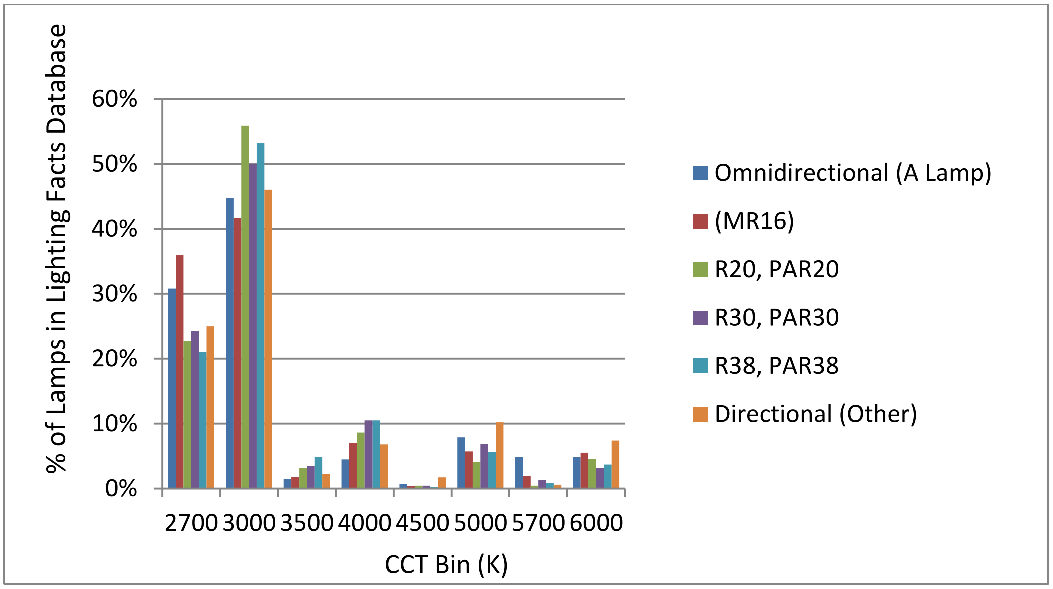


Figure 5.6 Distribution of Replacement Lamps across CCT Bins, by Lamp Type

Figure 5.7 below shows the maximum, average and minimum CCT values for the LED A-lamps being added to the Lighting Facts Database over the last few years. This graph shows that the maximum CCT of available lamps is increasing, while the minimum values are holding steady at around 2600K. The average value is decreasing during that time, however, indicating that the majority of new lamps being added to the data base are lower color temperature lamps.

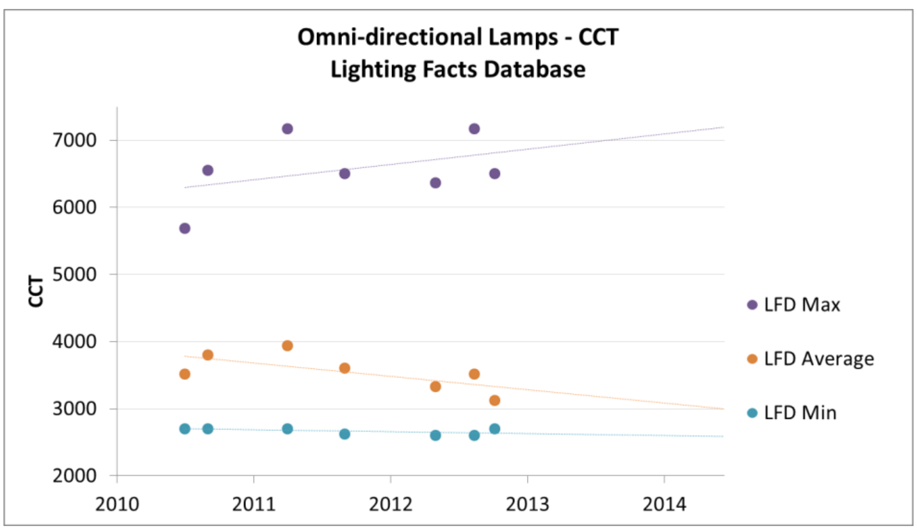


Figure 5.7 Distribution of Replacement Lamps across CCT Bins, by Lamp Type

Measured color temperature data for A-lamps and directional lamps was also provided to CEC previously in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.3 Color Consistency

One challenge of LED manufacturing is generating consistent color (chromaticity) from chip to chip during production, which can result in perceptible color variation between lamp samples. Chromaticity variations can occur along (parallel to) the black body curve, resulting in color changes from yellow tints to blue tints (also referred to as changes in CCT), or they can occur across (perpendicular to) the curve, resulting in color changes from pink to green tints. This is commonly referred to as "Delta u, v," or Duv, a reference to distance from the Plankian locus on the 1976 CIE color space diagram. Figure 5.8 below, from the National Institute of Standards and Technology, demonstrates these two dimensions of chromaticity variations (Ohno 2011).

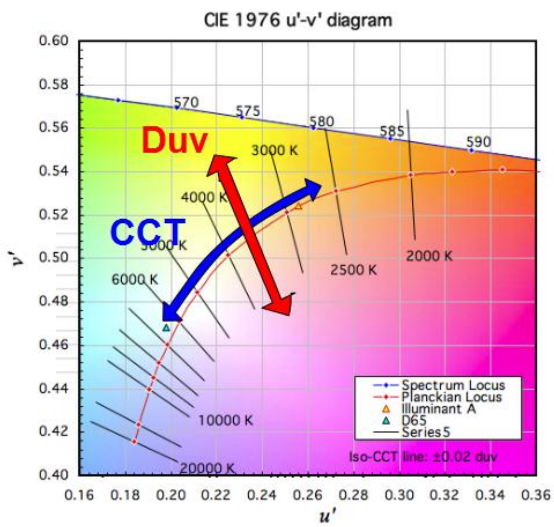


Figure 5.8 The two dimensions of chromaticity variations: CCT and Duv

An ANSI standard (ANSI/ NEMA C78.377-2008) provides guidance to manufacturers on the ranges of chromaticity variation for by lamps claiming to provide certain color temperatures. The standard defines a series of 8 chromaticity bins centered around unique center points; the size of the bin dictates the amount of variation allowed.

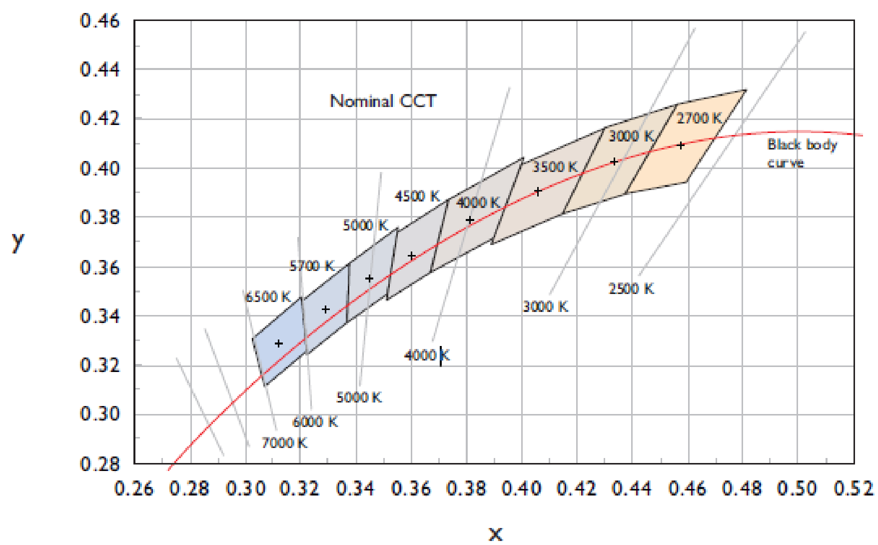


Figure 5.9 7-step MacAdam Quadrangles on the CIE 1931 Color Space

Source: Philips Color Kinetics; Optibin Technology Overview

Differences in color that can be perceived by the human eye have been quantified and mapped out in the CIE color space, in large part due to developments made in the 1940's by David MacAdam to advance this field. A change in color that can be just barely perceived by the human eye has come to be called a MacAdam step. It is also frequently called a minimum perceptible color difference (MPCD). Lamps that are not closely matched to each other may stand out in a lighting installation, and lead to consumer dissatisfaction in many applications. Generally speaking, color differences of 1-2 MacAdam steps are very difficult to discern, while 4 MacAdam step differences become more readily apparent. 7 MacAdam step color difference is immediately noticeable. However, a number of studies have been done on this subject, and research has shown that multiple factors affect the perceptibility of color differences, including where in the color space the color points are, the brightness of the light sources, the proximity of the light sources to each other, background/subject color, and whether the lamps themselves are directly visible. One study conducted by the Lighting Research Center (LRC 2004) developed the following criteria for 'acceptable' levels of minimum color consistency:

- 2-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- 4-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are not directly visible or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

While the current ANSI standard provides a valuable method for consistency across manufacturers, it allows for 7-step MacAdam quadrangles, meaning that lamps of the same nominal CCT (that is, with color points within a specific ANSI standard color temperature bin) may still exhibit significant color variation. The most recent version of ANSI C78-377, released in 2011, added a definition for a 4-step MacAdam quadrangle, but still maintained the traditional 7 step quadrangle as the minimum recommended level of performance.

Color variation between incandescent lamps has not historically been perceptible, so designing for color consistency has not been a point of focus for incandescent lamp manufacturers. Many LED manufacturers, on the other hand, are tightening their binning process for improved color consistency in the hopes that consumers will not notice a color change between lamps, and many are spending considerable effort promoting their achievements in color consistency between lamps. Various product lines now claim color consistency of 4 steps, 3 steps, or 2 steps (Philips 2010; Philips 2012; Cree 2011 & Xicato 2009), within certain lamp models, though these numbers are often not reported or are not reported in a consistent way so as to be easily identified and compared.

Testing completed by CLTC in 2013 has investigated color consistency by comparing the measured color points of ten different A-lamp models (10 samples each). This type of research can be used to determine whether the color points of nine of the ten samples fall within an ANSI 7-step quadrangle, whether they fall within an ANSI 4-step quadrangle, and how much variation exists between the samples. A high level summary of the ten lamps' chromaticity performance is shown in Table 5.7 below.

Table 5.7 Summary of CLTC Color Consistency Testing

Lamp Sample	Target Color Bin	Within ANSI 7-step Quadrangle?	Within ANSI 4 -step Quadrangle?	Maximum distance in 1931 (x,y) CIE color space between test points
Omni-01	3000	Yes	No	0.005
Omni-02	2700	Yes	No	0.011
Omni-03	2700	Yes	No	0.004
Omni-04	2700	Yes	Yes	0.005
Omni-05	2700	Yes	Yes	0.007
Omni-06	3000	Yes	Yes	0.004
Omni-07	Unclear (2700/3000)	No	No	0.012
Omni-08	3000	Yes	No	0.013
Omni-09	3000	Yes	No	0.008
Omni-10	2700	No	No	0.022

As shown in the table above, the majority (80%) of lamp models have at least nine out of ten measured color points contained within an ANSI 7-step color bin. A minority (30%) have at least nine of ten color points contained within an ANSI 4-step color bin. The testing also shows a wide range of color consistency between samples, from 0.004 to .022 in the 1931 CIE color space. For all the lamp models tested, the average distance between color points as 0.009, and six of the ten products tested achieved this level or better. Interestingly, several lamps achieve very tight color consistency with each other (1 or 2 steps of color difference or less), despite not falling within the 4 step ANSI quadrangle. This suggests that controlling for very tight color consistency is feasible, but that manufacturers have not been aiming their color points to fall in the ANSI 4-step bins (likely because no standards body has yet required them to).

Figure 5.10 below demonstrates an example of one lamp model tested by the CLTC (over 10 samples represented by small 'x' marks) with very tight color consistency, but which does not fall within the ANSI 4-step quadrangle for 2700K. The blue lines in this figure represent the 4-step quadrangle, while the green lines represent the 7-step quadrangle. The black line cutting through the middle of the image is the black body locus.

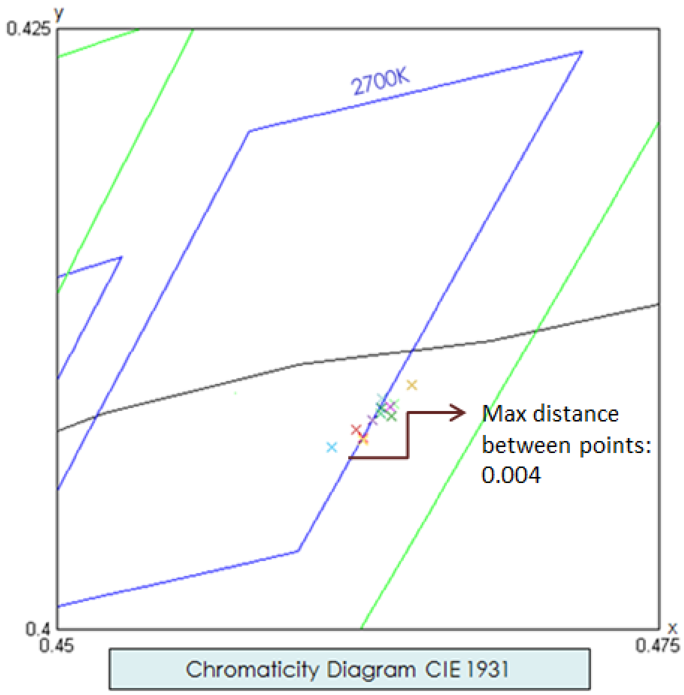


Figure 5.10 Color Consistency Measurements for CLTC Test Lamp Omni-03

Source: CLTC testing for PG&E, 2013

The graph below shows another tested model (over 10 samples tested, color points represented by "x") that has very poor color consistency. Some of the samples land in the 3000K quadrangle, while others are in the 2700K quadrangle. The maximum distance between points in the color space is 0.012.

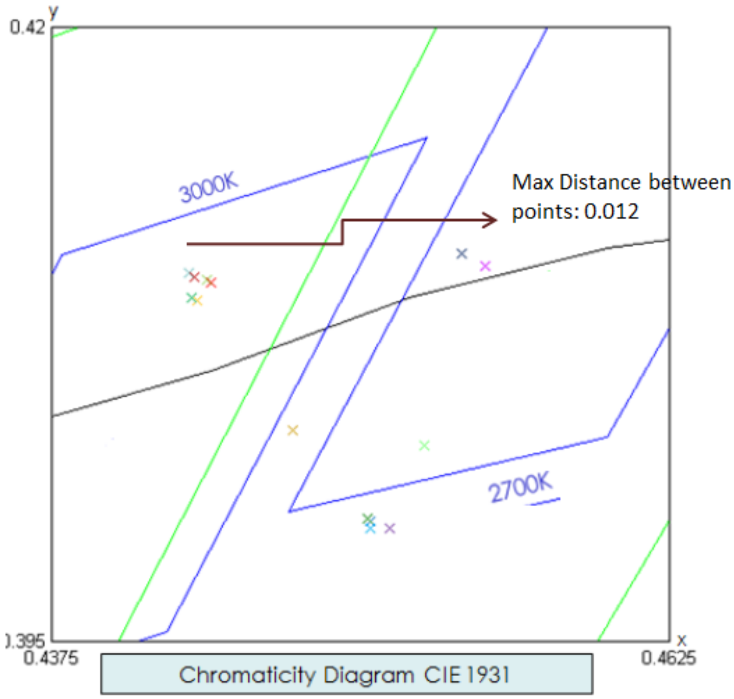


Figure 5.11 Color Consistency Measurements for CLTC Test Lamp Omni-07

Source: CLTC testing for PG&E, 2013

Measured color consistency data for A-lamps and directional lamps was also provided to the CEC previously in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.4 Color Rendering (Color Quality/Accuracy)

The ability of the light sources to render the true colors of an object (referred to as color rendering) is a very important measure of light quality and product utility for consumers. The internationally recognized metric is the Color Rendering Index (CRI) metric, which utilizes a scale from 0 to 100. CRI is a measure of how accurately a light source renders the colors of the objects being illuminated, compared to a reference light source of the same color temperature (CEC 2012a). For lower color temperature light, the reference source is a theoretical black body radiator when heated to the specific temperature in question (in K). For higher color temperatures, the reference source is daylight of the same color temperature. For practical purposes an incandescent filament is considered to be essentially equivalent to the theoretical black body; incandescent lamps are therefore generally said to have a CRI of 100 by definition. While100 CRI is considered to be perfect light quality (no color distortion), an 80 CRI source (which is 20 units from 100) could be considered to have twice as much color distortion or color inaccuracy as a 90 CRI source (which is only 10 units from 100).

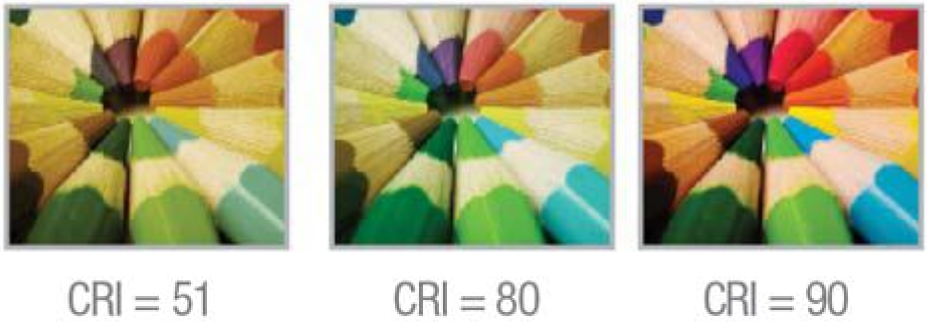


Figure 5.12 Illustrative example of color rendition under light sources of different CRI Values

Source: Lighting Matters' LED Blog, lightingmatters.com.au/blog/ledlight-quality-cri/

Residential consumers in particular are accustomed to high CRI sources, as incandescent lamps (with 100 CRI) are the predominant lamps in the residential sector. According to DOE, 60% of the total lighting demand in the U.S. residential sector in 2010 is for light above 90 CRI (DOE 2010a, p. 9). As a point of reference, compact fluorescent lamps have typically provided light in the range of 76-90 CRI (DOE 2010a, p. 7). The CRI of LED light sources ranges from below 40 to the high 90's (the highest CRI on the Lighting Facts Database is 97). There are currently 109 replacement lamp products in the Lighting Facts Database with a CRI above 90, offered from 15 different manufacturers (DOE 2013a).

The calculation procedure for the measurement of CRI involves measurement of 14 specific test color samples (TCS) under the source in question, and a calculation of the color differences of each color sample compared to its color under the reference light source. The CRI value (also referred to as R_a) is the average color difference of the first 8 color samples, a subset of the group that contains relatively low saturated colors that are evenly distributed over the complete range of hues. Light sources with higher CRI values render these eight colors well, and in doing so, generally render most of the color spectrum very well. However, in some cases a light source may achieve a high R_a value without rendering all colors equally well, and in this way, the CRI metric is not perfect. Other metrics have been developed and proposed, such as Color Quality Scale (CQS) and Gamut Area Index (GAI) but CRI remains the most common metric in use today.

Table 5.8 Test Color Samples used in the calculation of CRI

Test Color # (R_1-R_{14})	Munsell Notation	CIE Specification x	CIE Specification y	CIE Specification Y	ISCC-NBS Name	Approximate Appearance
1	7.5 R 6/4	0.375	0.331	29.9	Light grayish red	
2	5 Y 6/4	0.385	0.395	28.9	Dark grayish yellow	
3	5 GY 6/8	0.373	0.464	30.4	Strong yellow green	
4	2.5 G 6/6	0.287	0.4	29.2	Moderate yellowish green	
5	10 BG 6/4	0.258	0.306	30.7	Light bluish green	
6	5 PB 6/8	0.241	0.243	29.7	Light blue	
7	2.5 P 6/8	0.284	0.241	29.5	Light violet	
8	10 P 6/8	0.325	0.262	31.5	Light reddish purple	
9	4.5 R 4/13	0.567	0.306	11.4	Strong red	
10	5 Y 8/10	0.438	0.462	59.1	Strong yellow	
11	4.5 G 5/8	0.254	0.41	20	Strong green	
12	3 PB 3/11	0.155	0.15	6.4	Strong blue	
13	5 YR 8.4	0.372	0.352	57.3	Light yellowish pink (Caucasian complexion)	
14	5 GY 4/4	0.353	0.432	11.7	Moderate olive green (leaf green)	

Source: IESNA Handbook 10^{th} Edition

Many manufacturers also report their R9 values, the color rendering value for a ninth, saturated red color. This value has become a more important indicator because it indicates how well a lamp accurately renders common materials such as skin tones, wood, food, and earth tones. Typical LED R9 values stretch from negative values up to well over 50 (some approach 90 or higher). High quality LED lamps can have much higher R9 CRI values (50+) than T8 lamps and poor quality LED lamps.

The following graphs show the distribution of LED replacement lamp products across several bins of CRI ranges (both Ra and R9), by lamp type. Figure 5.13 and Figure 5.14 also indicate the minimum required levels in the ENERGY STAR specification. These graphs show that the vast majority of lamps have a CRI between 80 and 90, and about 5% of lamps have a CRI above 90. Depending on lamp type, about 10% to 20% of lamps have a CRI below 80. R9 values are slightly more spread out, with the bulk of lamps in the 0-50 range, but with a significant percentage of lamps above 50.

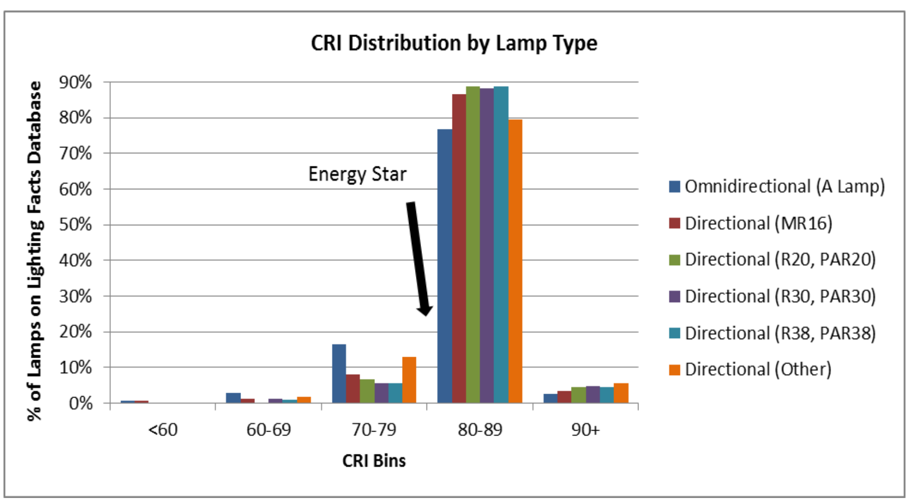


Figure 5.13 Distribution of Replacement Lamps across CRI (R_a) Bins, by Lamp Type

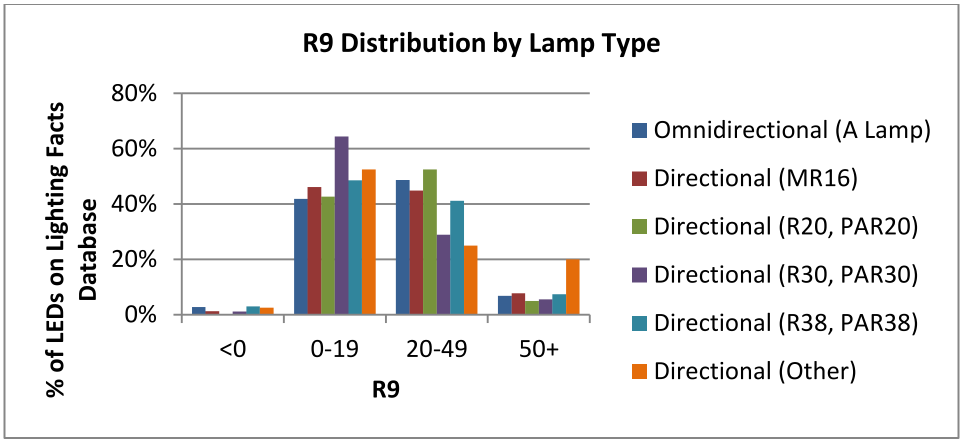


Figure 5.14 Distribution of Replacement Lamps across CRI (R_9) Bins, by Lamp Type

Figure 5.15 below shows the distribution of LED replacement lamp products at each individual CRI value (rather than CRI bin), by lamp type. This shows that most lamps currently have CRI values between 80 and 84.

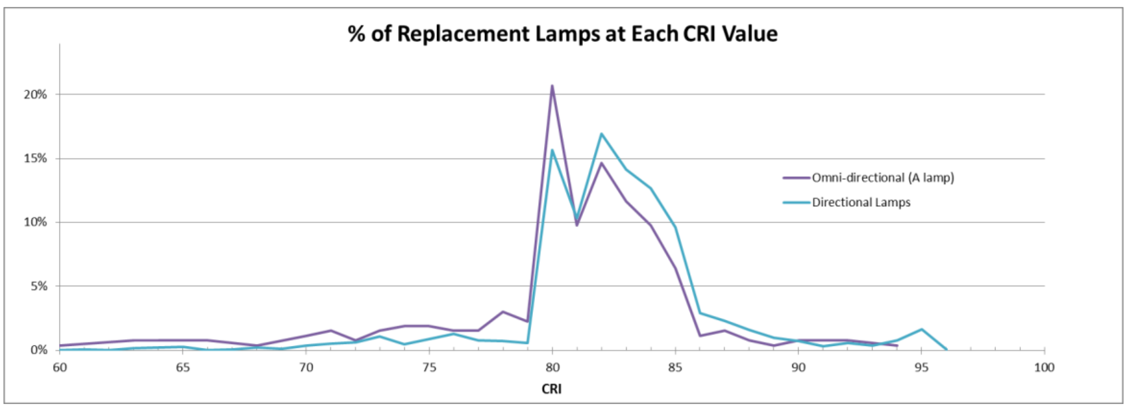


Figure 5.15 Distribution of Replacement Lamps at each unique CRI value, by Lamp Type

CRI has been improving in LED lamps in recent years. The following graphs show the maximum, average, and minimum CRI values of all omni-directional and directional products added to the Lighting Facts Database in several time increments, since the middle of 2010. In that time, the maximum values have trended from the mid 80's to the mid 90's, while the average values have increased from mid 70s to low 80s. The trend lines drawn are for illustrative purposes only, but suggest if current trends continue, the average CRI of LED replacement lamps could be in the low 90s within about three years. We expect this trend to be accelerated in California as result of the new Title 24 requirement that LED luminaires be 90 CRI in order to qualify as "high efficacy" lighting, along with the California Voluntary Quality LED Lamp Specification, which requires 90 CRI for rebate eligibility.

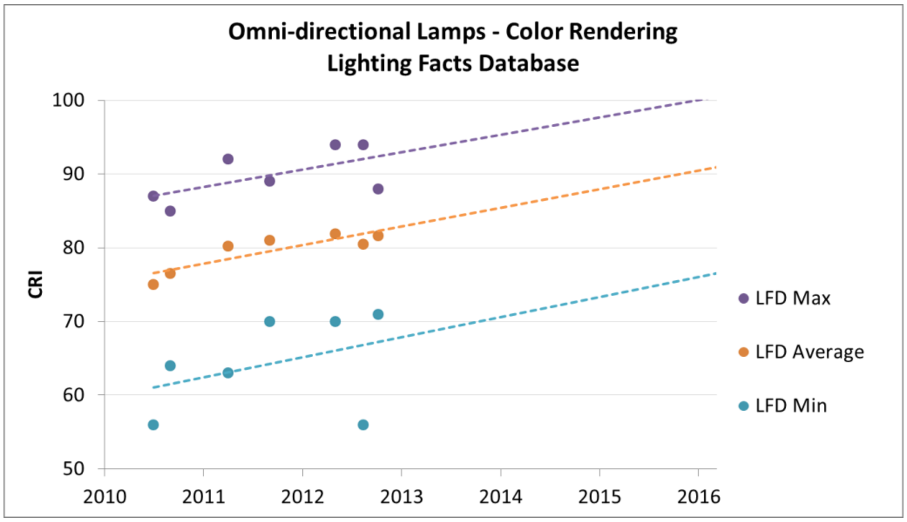


Figure 5.16 Omni-directional LED Lamp CRI trends from 2010 through 2012

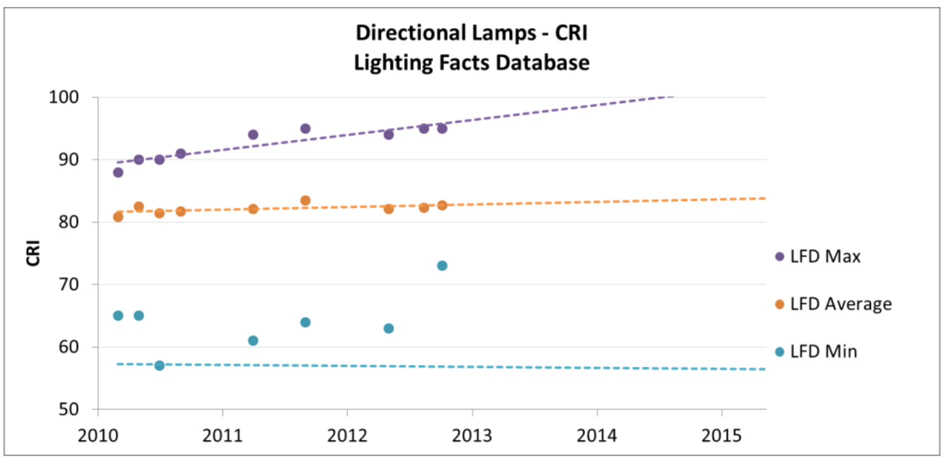


Figure 5.17 Directional LED Lamp CRI trends from 2010 through 2012

Measured color rendering index (R_a and R_9) data for A-lamps and directional lamps was also provided previously in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.5 Efficacy

The efficacy of LED lamps varies widely, depending both on the LED package itself as well as the lamp design. LEDs are sensitive to the thermal and electrical operating conditions, and the light output and efficacy of the LED can be depleted if not paired with a well-designed lamp (DOE 2012d). The least efficacious omni-directional lamps available have efficacies of approximately 40 lpw, while the more efficacious omni-directional lamps tend to achieve 90 – 100 lpw (the highest efficacy on the Lighting Facts Database is nearly 120lpw). In a sign of things to come, LED manufacturer Cree recently announced its achievement of 200 lpw in an LED package in a lab environment (Cree 2013), though efficacy will be significantly lower when these LEDs are incorporated into lamps. By comparison, incandescent A-lamp efficacy ranges from about 10-20 lpw.

The figure below shows the distribution of LED replacement lamps across several efficacy bins, by lamp type. The vast majority of lamps meet ENERGY STAR efficacy requirements (which vary based on lamp type, size, and/or wattage), with A-lamps outpacing directional lamps in terms of lpw. More than 60% of A-lamps have efficacies higher than 60 lpw, while fewer than 30% of MR lamps hit that mark.

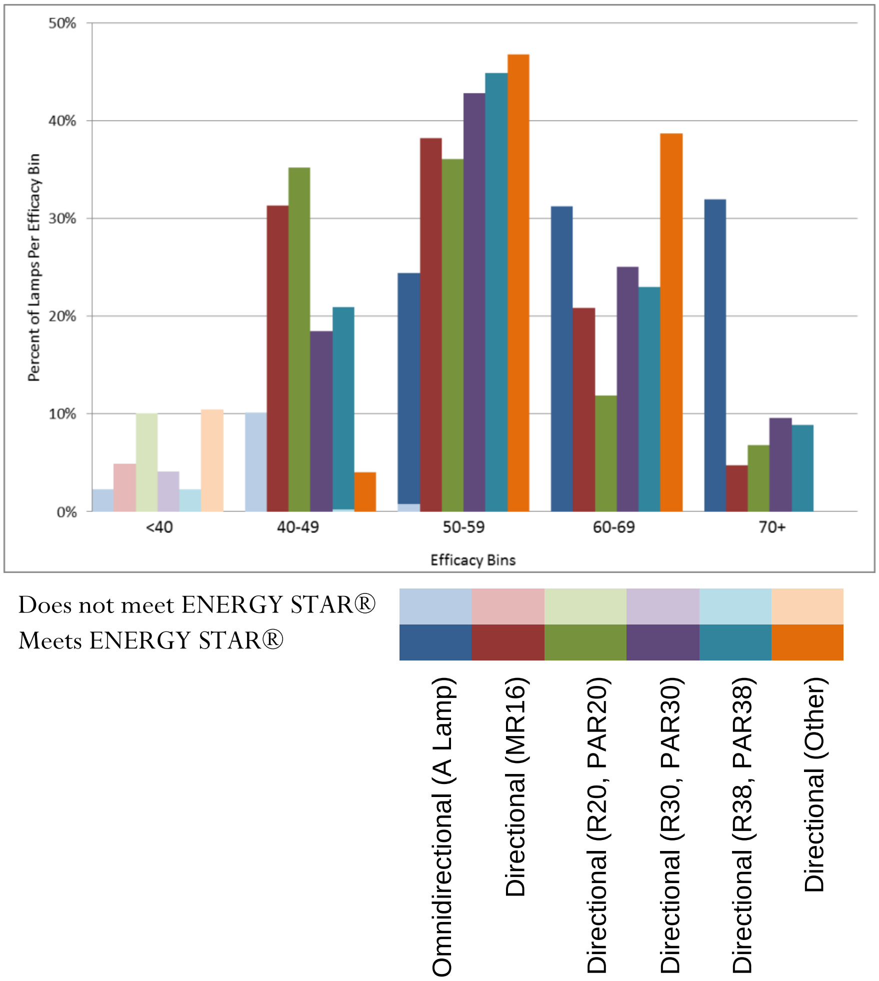


Figure 5.18 Distribution of Replacement Lamps across Efficacy Bins, by Lamp Type

LED efficacy is also improving very quickly. The graphs below demonstrate efficacy trends and forecasts for omni-directional and directional lamps.

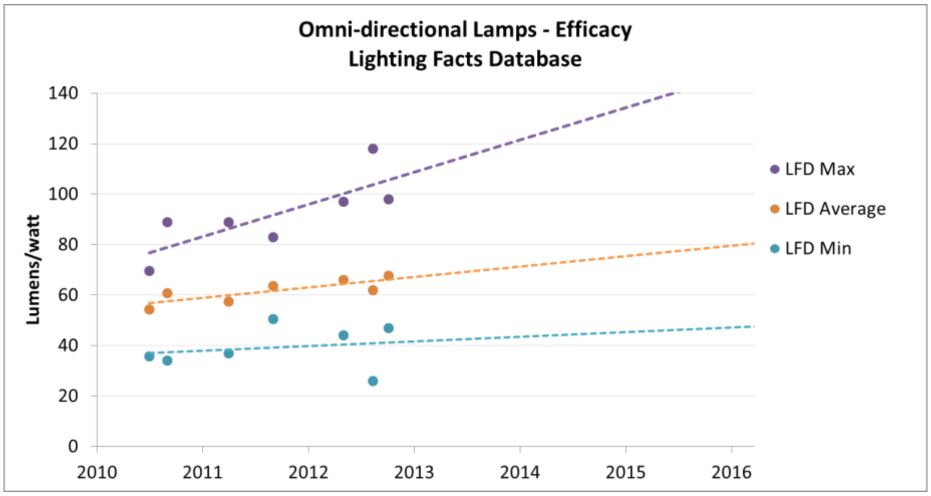


Figure 5.19 Omni-directional LED Lamp Efficacy trends from 2010 through 2012

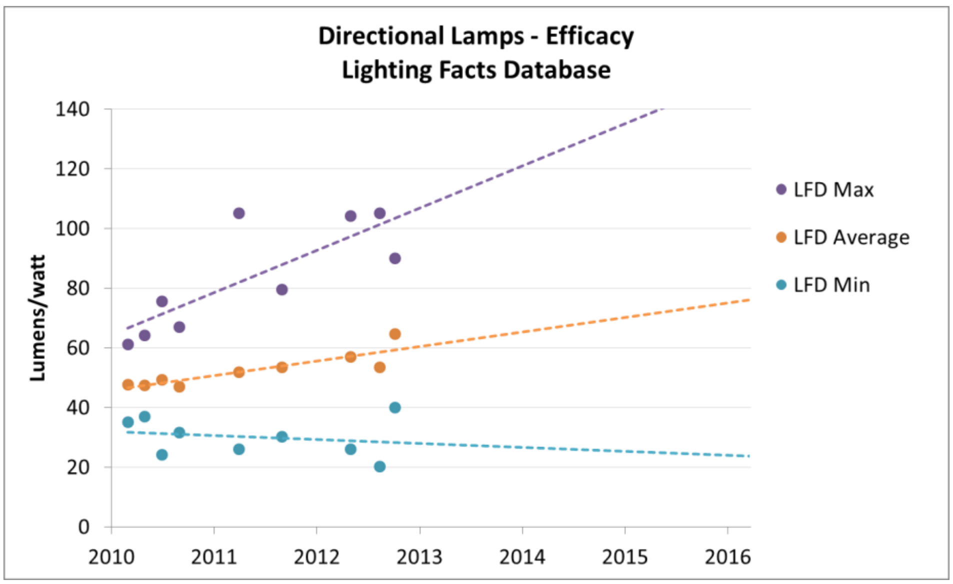


Figure 5.20 Directional LED Lamp Efficacy trends from 2010 through 2012

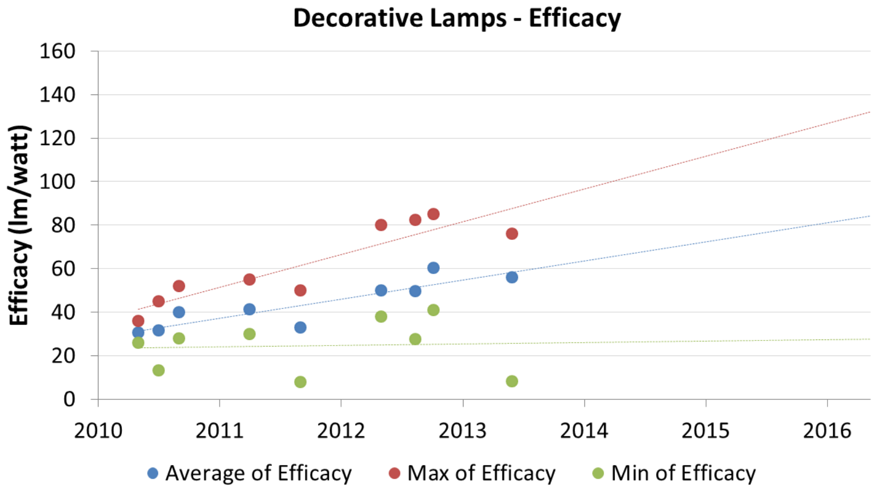


Figure 5.21 Decorative LED Lamp Efficacy trends from 2010 through 2012

These observed values are consistent with other efficacy improvement projections that have been circulating in the lighting industry in recent years. This jump in efficacy from approximately 60 to 100 lpw in a span of two to three years around 2010 was consistent with other estimates offered at lighting conferences and in manufacturer estimates.

Measured efficacy data for A-lamps and directional lamps was also provided previously to the CEC in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.6 Interaction of CRI and Efficacy

Efficacy is defined as the ratio of luminous flux to power. Luminous flux is a measure of visible light, or more specifically, the perceived power of light, from a light source. The measurement of luminous flux aims to account for the sensitivity of the human eye by weighting the power of the light at each wavelength in the visible band. Light outside the visible band does not contribute to the measurement of luminous flux. This weighting is done using the 1931 CIE photopic luminosity function, which values light energy at certain wavelengths over light energy at others. This photopic luminosity curve, shown in Figure 5.22 below, values spectral power emitted by a light source in the green and yellow part of the visible spectrum (with a peak at around 555nm).

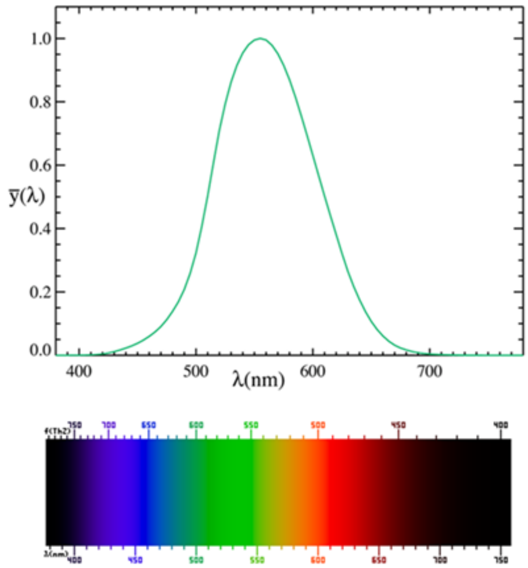


Figure 5.22 1931 CIE photopic luminosity function

This methodology is imperfect because the human visual system is more complex than this curve would suggest. For one thing, the human eye perceives wavelengths of light differently under bright conditions (photopic vision) than it does under dim conditions (scotopic vision). Secondly, for light to stimulate the brain it must be absorbed by photoreceptors in the eye's retina. There are three types of cone photoreceptors responsible for color vision, each defined in large part by the photopigment contained within that photoreceptor (RPI 2004). These three cone photoreceptors are centered around perception of red, green and blue light, respectively, as shown in the Figure 5.23 below.

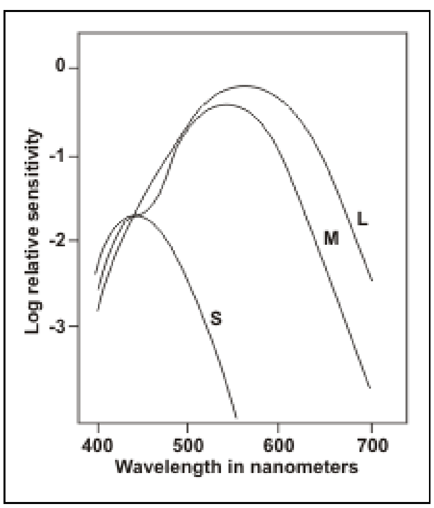


Figure 5.23   The spectral absorption curves of the three cone types (RPI 2004).

Light sources can be designed to maximize luminous flux values by providing a significant amount of lighting power at or near the 555 nm wavelength, but without providing a significant amount of light in other wavelengths. This results in a light source that is technically highly efficacious, but severely lacking in color quality. The spectral power distribution of a low pressure sodium lamp (LPS), for example, is shown below in Figure 5.24. An LPS light source may have an efficacy of 160 lpw, but the light color appears to be yellow-orange and objects of different colors being illuminated by this light source can be virtually indistinguishable from one another due to the monochromatic nature of the source.

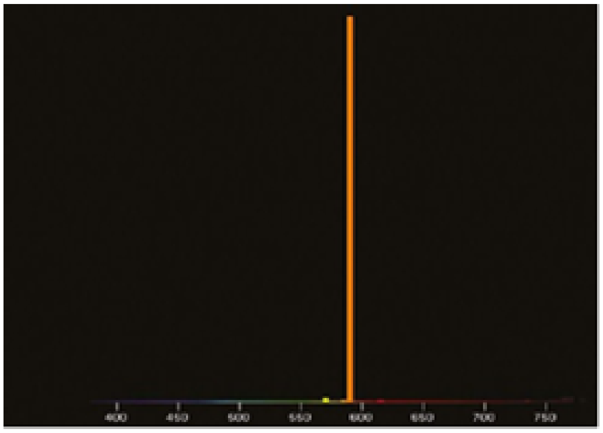


Figure 5.24 The spectral power distribution curve of a low pressure sodium lamp

Other artificial light sources have developed methods to produce light that is white, and which provides improved color rending. In the case of tri-phosphor fluorescent lamps, these products have evolved to provide relative spikes of energy in the red, green, and blue parts of the spectrum to create light that appears white. However, this approach results in relatively little light power in the wavelengths in between. An example of a typical fluorescent tube lamp is shown below in Figure 5.25.

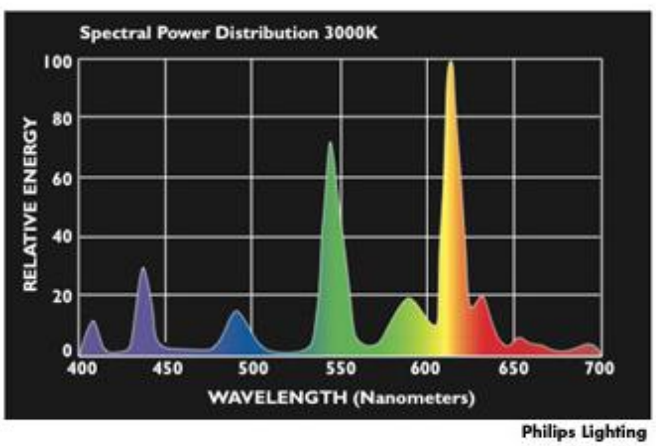


Figure 5.25 The spectral power distribution of a fluorescent lamp (Topbulb 2012).

The shortcoming with this approach to light source design is that it addresses perceived brightness and efficacy but does not address the fullness of the spectrum of light that the human eye is accustomed to in natural light sources. The spectral power distribution curves for daylight and for incandescent lamps, shown in Figure 5.26, are both much smoother – without the peaks seen in the fluorescent lamp diagram above.

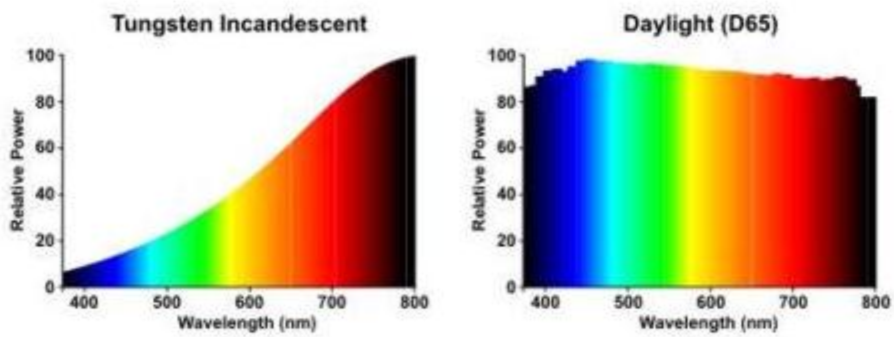


Figure 5.26 Spectral power distribution curves for incandescent lamps and daylight

In other words, a spectral power distribution that delivers the greatest luminous efficacy does not necessarily deliver the best color rendering. A light source that provides a full, consistent spectrum of light does not get "credit" for much of that light in the calculation of luminous efficacy, yet that light may be just as important to the end user. In very simplified terms, one metric essentially addresses quantity (perceived brightness) while the other addresses quality (perceived fullness or accuracy). In practice, the human eye responds to both.

The CASE Team asserts that the power drawn by different LED replacement lamps is more important from an energy savings perspective than the photopic efficacy, when taking other metrics like the relative CRI and luminous flux of each lamp to into consideration. While some amount of light (photopic lumens) and efficacy may be sacrificed in order to improve color rendering, wattage need not be increased to maintain adequate, comfortable light for the end user (in other words, the difference in luminous flux is made up for by the improved quality of the light). Consider the two hypothetical LED replacement lamps (60W equivalents) shown in Table 5.9 below. Though one provides slightly more lumens (and higher photopic luminous efficacy), both are clearly in the range of incandescent 60W equivalency, from a lumen standpoint.[4] However, from a color rendering perspective, one is very close to offering incandescent-equivalent performance while the other is not (94 CRI vs. 80 CRI).

Table 5.9 Two hypothetical 60W equivalent LED replacement lamps; Efficacy vs. CRI

	Lumens	Efficacy	CRI	Watts
LED Lamp A	900	100	80	9
LED Lamp B	800	89	94	9

From an energy perspective, both draw 9W of power, and therefore offer the exact same energy savings potential on a per lamp basis. In this case, the lamp model that will ultimately save more energy is the one that is accepted, purchased, and installed in greater quantities by consumers.

A tradeoff between luminous efficacy and CRI is not precisely quantified to date, though one DOE study suggests that the maximum potential efficacy for products in the 76-90 CRI range might be higher than the maximum potential efficiency of products in the 91-100 CRI range (DOE 2010a). The study indicates efficacy potential may be 10-15% higher for the lower CRI products in the near term, but shows this value

[4] The Energy Independence and Security Act of 2007 set lumen bins for its General Service Incandescent lamp standards, and the bin designed to encompass 60W equivalent lamps ranged from 750 lumens to 1,049 lumens.

decreasing over time. By 2030, DOE predicts that the maximum efficacy potential for the lower CRI bin will be 176 lpw, while the maximum potential for higher CRI products could be 166 lpw (a difference of 6%). Assuming an average lumen output of 1003 lumens, this amounts to a 5.9W product and a 5.5W product, or a difference of 0.4W.

Despite the tradeoff that may exist between high luminous efficacy and high CRI, in practice, high efficacy and high CRI are not mutually exclusive. In fact, an analysis of the Lighting Facts Database in April 2013 showed that products achieving high CRI (above 90) have the same efficacy, on average, as products below 90 CRI. Of the more than 2,000 replacement lamp products in the database, about 5% have CRI above 90. The average efficacy of these lamps is 57.5 lpw, while the average of efficacy of lamps below 90 CRI is 57.3 lpw (0.2 lpw lower).

Below is a graph that demonstrates this point another way; it shows efficacy plotted against CRI, for a specific subset of lamps representing the most common product type (A-lamps, 750-1100 lumens, CCT<3100) in the Lighting Facts Database. Though one might expect to see a downward slope indicating a decrease in efficacy coincident with an increase in CRI, in fact the opposite is true. The highest efficacy products (those above 85 lpw) are available in a range of CRIs, from ~85 to ~94 CRI.

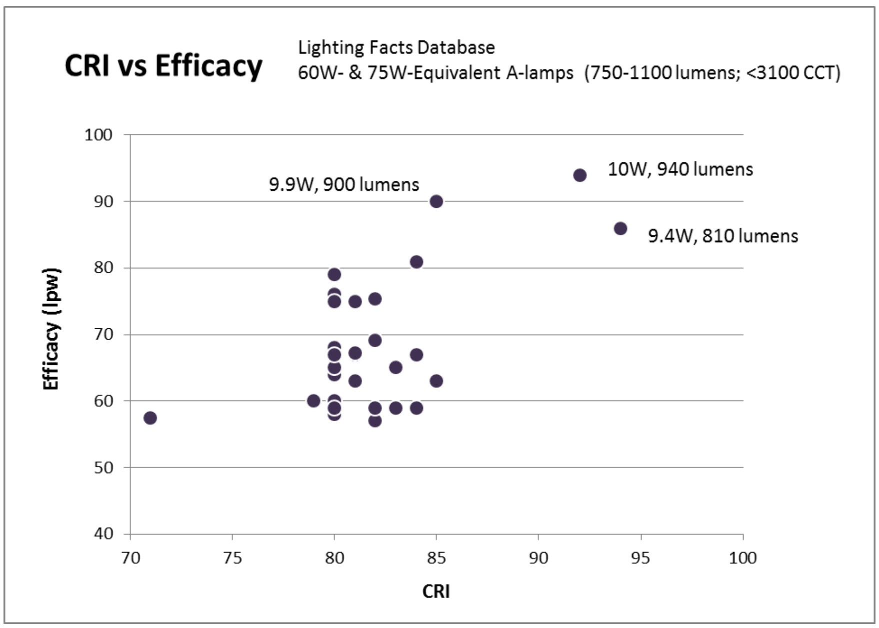


Figure 5.27 Efficacy vs. CRI in the Lighting Facts Database

5.2.7 Light Distribution

Unlike tungsten filaments in incandescent lamps, LEDs emit light semi-spherically, rather than spherically. This can increase the application efficacy for task lighting and other applications for directional lighting, such as recessed cans. It can also pose a challenge for lamp manufacturers designing replacement lamps for A-line incandescent lamps and other historically omni-directional light sources. Incandescent A-lamps emit light in a near 360 degree pattern, with some light directed back towards the base of the lamp. Many LED lamps have shown they can mimic this light distribution, while others project light primarily in one direction (away from the base) (DOE 2012a, p. 2). Often called "snow-cone" lamps because of their appearance, these lamps may not provide the light distribution consumers expect out of an A-line lamp. The image below shows two table lamps side by side, with a "snow-cone" product on the left and a true omni-directional product on the right. The table lamp on the left does not cast any light back down towards the surface, while the lamp on the right provides light distribution more similar to a traditional incandescent.

Figure 5.28 Light distribution comparison of two LED A-lamps in table lamps

Source: GE Lighting Catalog: GE energy smart ® LED Replacement Lamps

Figure 5.29 below demonstrates the light distribution measurement for an incandescent lamp (the black line), an omni-directional LED A lamp with similar light distribution (blue line), and a "snow-cone" LED A lamp with light emitted only away from the base (red line).

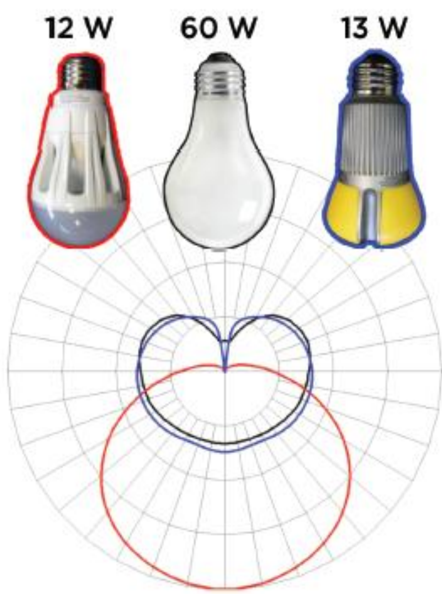


Figure 5.29 Photometric measurements of light distribution of two LED A-lamps compared to incandescent

Source: DOE 2011

To improve consistency in the distribution of light around the lamp, the final draft ENERGY STAR specification for A-lamps requires that each measured luminous intensity value (in candelas) vary by no more than 50% from the average of all measured values, and that 90% of the luminous intensity measured values vary by no more than 25% from the average of all measured values. It also requires at least 5% of total flux (lumens) to be emitted in the 135° to 180° zone to ensure some light is projected back towards the lamp base. This proposal was altered from a previous draft version of the specification (draft 3) after EPA determined that some incandescent lamps could not meet the initial proposal.

Detailed light distribution data are not easily accessible for many lamps in a format that can be quickly used to assess the performance of the market. Hence, PG&E co-funded research at the CLTC to measure the directionality of a selection of A-lamps. Of the 25 lamps tested, 11 pass the current ENERGY STAR proposed requirement. Measured light distribution data for A-lamps was previously provided to the CEC in a CLTC Test Report (PG&E 2013b).

5.2.8 Dimming

The 2010 Lighting Market Characterization study estimated that the percentage of residential incandescent sockets operating on dimmers in the U.S. was about 13% (among halogen sockets, the value was much higher – at about 25%) (Navigant 2012). The study also found that 25% of living room sockets were on dimmers, which is noteworthy since living rooms are also shown to consume a significant amount of lighting energy due to above average lamps per room and above average hours of use per day.

In California, the percentage of sockets on dimmers is assumed to be much higher than the national average, due largely to the state's building energy code (Title 24) which has promoted the use of dimmers in new construction since the 2005 update that first required all hard-wired lighting in living rooms, dining rooms, and bedrooms (among other room types) to be either "high-efficacy" or to be controlled be a dimmer. Because "high-efficacy" fixtures are pin-based by definition, all screw-based sockets in these rooms must be operated by dimmers. The 2008 code further increased this requirement by applying it to 50% of kitchen lighting as well. Title 24 has also had a large impact on non-residential dimming, with increased requirements for controllability that will require dimming in almost all commercial spaces. Starting in 2014, these non-residential Title 24 requirements will apply not only to new construction but to many lighting retrofit projects as well.

A study published in 2011 (based on 2010 market research) entitled, "Efficiency Characteristics and Opportunities for New California Homes," confirmed a higher rate of dimmer switches in California than the national average. The study found 20% of single family residential sockets were on dimmers, while 33% of single family wattage was controlled by a dimmer (Proctor, Chitwood & Wilcox 2011). Assuming about 1% of the building stock is new each year and compliant with current codes, this CASE Report assumes that by the time this standard takes effect, about 25% of residential and commercial replacement lamp sockets will be controlled by dimmers.

In terms of consumer satisfaction, LED's represent an important opportunity with respect to dimming potential. Because incandescent lamps are readily dimmable down to less than 1% of light without flicker, buzz, or cutting in and out, many consumers had been frustrated when CFLs did not dim or exhibited poor performance when installed in dimming sockets. On the other hand, most LED lamps are designed to be used with dimmers, so this represents a clear opportunity to avoid one of the major setbacks suffered by CFLs. 83% of directional lamps and 65% of omni-directional lamps in the Lighting Facts Database are listed as "dimmable." Another advantage of LEDs is that they generally maintain their efficacy when dimmed, as opposed to incandescent lamps which experience dramatically reduced efficacy when dimmed. This means that dimming an LED lamp to 50% light output also reduces power by about 50%, resulting in significant energy savings (see below for results of CLTC testing on this metric).

In practice however, the term "dimmable" has no industry-accepted definition, and some lamps may exhibit better performance than others. In fact, LED lamp dimming performance can be highly dependent on matching compatible system components (e.g. the driver and dimmer combinations). Potential negative performance attributes during LED dimming include flicker,[5] audible noise, premature lamp failure, limited dimming range, failure to light (DOE 2012a), or low power factor and THD. Some products may "drop out" at a relatively high dimmed point (30 – 50% dimmed). Some products may demonstrate a "pop-on" phenomenon, whereby a light source that's been turned off in a dimmed state cannot be turned back on in the dimmed state, but instead requires the user to raise the dimmer setting above some threshold before the light will "pop on." Some may experience other unpredictable flashing ("pop-corning") or inability to turn off completely ("ghosting").

Many of these problems are not inherent to the LEDs, but instead are the result of LED driver and dimmer incompatibility. The majority of the installed base of traditional line-voltage dimming controls is made up of phase-cut dimmers that cut out part of the AC wave form; these were designed for incandescent light sources. The most common phase-cut dimmer in the residential sector is a "triac" dimmer, which cuts the leading edge of each half sine wave. The dimmer senses each zero-crossing of the AC input, and waits for a variable delay period before turning on the triac switch and delivering the AC to the load (Cooper 2011). Another type of phase control eliminates the trailing edge of each half sine wave (often referred to as reverse phase control) and is more often used with electronic low voltage applications. These two phase controls are shown in Figure 5.30 below.

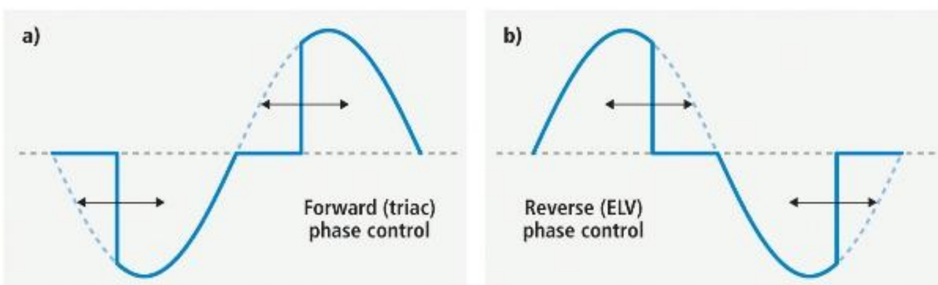


Figure 5.30 Impact of Phase Control on AC Waveforms

Source: Cooper 2011

Phase control results in a predictable reaction in a simple resistive load such as an incandescent lamp filament. As shown in Figure 5.31 below, a phase cut dimmer that cuts Vrms from 120V to 60V results in roughly a 50% reduction in light output in the incandescent lamp.

[5] Though often associated with dimming, flicker is addressed separately in Section 5.2.9 below.

Figure 5.31 Phase-Cut Dimmer control of incandescent lamp

Source: Broderick, 2013

LED lamps are much more complex than incandescent lamps. The main difference is that LED lamps are controlled by integral drivers, which are a very different type of load than a resistive incandescent filament. The LED driver must convert AC power to low-voltage DC power and the driver provides current to the LEDs. When the AC waveform is altered by the dimmer, the driver must "interpret" that change and conduct a transfer function to translate it into a control signal that the LEDs will respond to.

Another difference is that incandescent filaments do not cool instantly when current is reduced or cut, which means light is maintained for some period of time even when current is reduced (a phenomenon known as "latency"). LEDs on the other hand, react very quickly to even small variations in current, and even phosphor-converted or remote phosphor LEDs tend to have very little latency.

Two common strategies utilized to reduce the light output of LED lamps are constant current reduction (CCR) and pulse-width-modulation (PWM) dimming. As the name suggests, CCR dimming reduces the current being supplied to the LEDs at a constant rate, as shown in Figure 5.32 below.

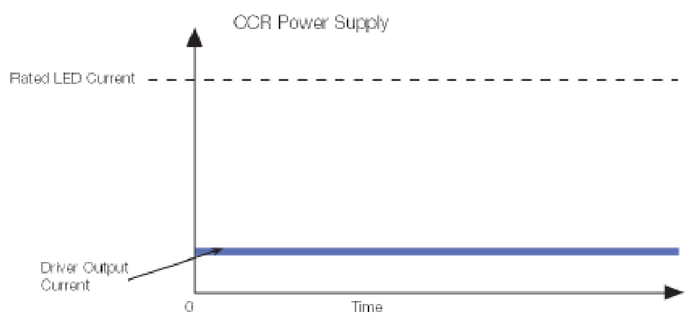


Figure 5.32 Constant Current Reduction (CCR) Dimming

Source: Lutron; Dimming LEDs via PWM and CCR

PWM is defined as the variation of time that a square (or rectangular) wave shape spends at the LED's rated current and the time it spends at no current. Increasing the amount of time that the drive current spends at the low level results in dimming of the lamp. Generally speaking, a lamp with current flowing only 25% of the time will provide 25% as much light as it does when current is constant at rated current. The figure below shows an example of an LED wave form being adjusted using PWM, with relative current on the y-axis. The graph on the left represents a lower light level state (less time at high current), while the far right graph represents higher light level.

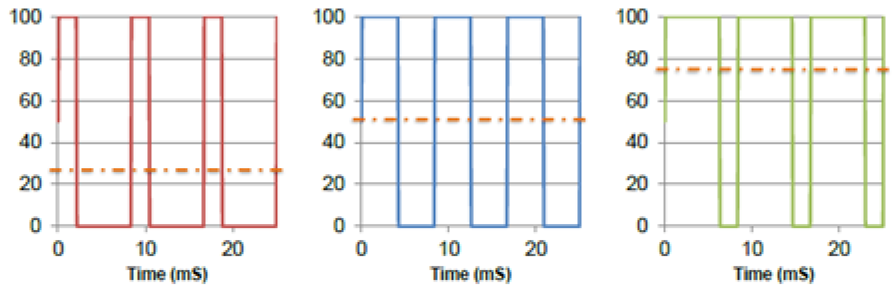


Figure 5.33 Demonstration of Pulse Width Modulation (PWM) of a current wave form

Source: PNNL

There are unique performance characteristics associated with each of these strategies. For example, the color temperature of an LED is a factor of the current supplied to it, so CCR dimming may change the diode CCT through the dimmed range, while PWM typically does not. For this reason, CCR dimming can result in unwanted color shifts, particularly for lamps that utilize color mixing LEDs (e.g. RGB systems). Operating LEDs below their design current in a CCR system can have other positive or negative impacts on the LEDs as well, including reduction in operating temperature which generally increases efficacy and lamp life. Another example is that the light modulation associated with PWM may be perceived as flicker if the frequency is not high enough, while this is not an issue with CCR. (Flicker is discussed in more depth in the following section.) If the frequency is high enough to avoid flicker issues, PWM typically allows for better dimmed control down to very low light levels, whereas some LEDs may have trouble operating at very low currents in a CCR system dimmed to low levels.

The LED industry has made significant progress over the last several years to address the dimming issues associated with LEDs and improve compatibility and performance. While some products are designed only to be used with specific (often newer) dimmers, a growing number of products are being designed to be compatible with a wide range of dimmers, including most, if not all, existing phase-cut dimmers. Specific performance attributes are improving as well. While some lamps may drop out at 20%, 30%, or even higher light levels, other drivers have been introduced which claim to dim LEDs down to 1% (Lutron 2011).

Little standardization exists to quantify these performance values, though recent progress has been made in this regard as well. The NEMA Solid State Lighting section, which comprises 24 major manufacturers of LED lamps, dimmers and controls, and drivers, recently finished development a standard called NEMA SSL-7A that addresses compatibility requirements and test procedures for qualifying LED light engines and forward phase-cut dimmers. This document was approved by NEMA in early April 2013 and was made available for purchase in late April. Though it does not apply to the installed base of phase-cut dimmers, it does identify performance requirements for new phase-cut dimmers and new LED products. The standard identifies two types of LED light engines (Type 1 and Type 2 LLEs) as well as two types of forward phase-cut dimmers (Type 1 and Type 2 dimmers). LED lamps that are built to be compliant with the NEMA SSL 7A as Type 1 LLE's will demonstrate a minimum level of compatibility with dimmers that are compliant as Type 1 dimmers. Likewise, LED lamps that are built to be compliant with the NEMA SSL 7A as Type 2 LLE's will demonstrate a minimum level of compatibility with dimmers that are compliant as Type 2 dimmers. This standard will not eliminate all compatibility issues in the market but it represents a significant step forward on this issue. California has an opportunity to leverage this work and require LED lamps to be SSL7A compliant.

Another attribute of LED dimming performance relates to the color temperature provided by the light throughout the dimming range. When incandescent lamps dim, their color temperature naturally lowers significantly. In other words, the light color experiences a shift in chromaticity (towards red), and many consumers may expect this performance feature. LEDs do not necessarily mimic this color shift during dimming, though some lamp models have been released which have been designed to provide a similar “red shift,” including the Philips DimTone BR30 lamp which automatically lowers color temperature from 2700K to 2200K when dimmed (Philips 2013). This is an important feature that should be considered in future specifications for quality LED lighting, but to date, this has not been an area of focus for LED product development. Future work should be done to identify a typical incandescent lamp color temperature curve across the dimming range that can serve as a guide for LED manufacturers, and quality lighting programs, such as the L-Prize program or tiered incentive programs, should incentivize and encourage the development of these products. In the meantime, LED quality specifications should at least ensure that LED lamps do not automatically shift towards colder color temperatures when dimmed, as this would represent the exact opposite effect consumers are accustomed to.

The testing conducted by CLTC on behalf of PG&E and CLASP in 2012 and 2013 has explored the range of dimming performance, including measurements of color temperature, efficacy, CRI, power factor, and noise, among others, across the dimming range. CLTC initially completed dimming testing of 25 omni-directional lamps on a simulated dimmer (power supply) and tested 5 of the lamps on a variety of commercial dimmers. Test measurements were taken at 100%, 75%, 50%, 25%, and at each lamp’s minimum light level. 24 of the 25 products were found to be dimmable and were able to dim well below 20% of light output. 21 of the 24 dimmable products were capable of dimming below 10%, with an average minimum dimming level below 5% light output.

Figure 5.34 demonstrates the average of the measured light output relative to power drawn for lamps through their dimming range. Between 25% and 100% power, efficacy was found to be maintained at about 99%-102% of the efficacy achieved at full power. For most lamps, a drop in efficacy was observed at the low end of the dimming range. At the lowest dimmed setting, which was at about 8% of full power on average, light output dropped to 4% of full output light on average (in other words, efficacy dropped to about half of the full power efficacy).

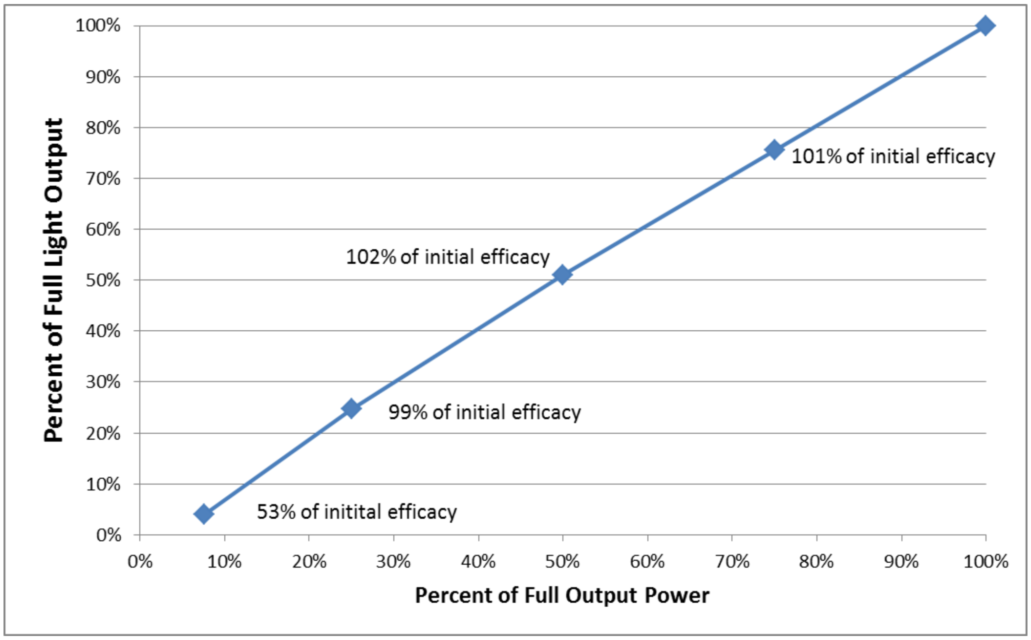


Figure 5.34 Power versus light output through dimmed range; average of 25 lamps tested
Source: CLTC testing for PG&E, 2013

CLTC testing also investigated the impacts of dimming on correlated color temperature, as shown in Table 5.10 below. The table shows that several of the lamps tested had a notable color shift (100-300°), and in all cases these were decreases in color temperature, resulting in a "warmer" color during dimming (similar to incandescent lamps). Only five of the products tested had an increase in CCT to a cooler color temperature when dimmed, and these changes were minimal (less than 20°). Most of the lamps tested did not exhibit a significant color shift during dimming. Additional analysis and results from the CLTC's dimming testing will be delivered to the CEC under a separate report cover.

Table 5.10 Impact of dimming on CCT in omni-directional lamp testing at CLTC, 2013

Lamp	CCT @ 100% Power	CCT @ 25% Power	Delta
OMNI-01	3,083	2,992	91
OMNI-02	2,663	2,669	-6
OMNI-03	2,628	2,615	13
OMNI-04	2,652	2,639	13
OMNI-05	2,727	2,575	152
OMNI-06	2,958	2,933	25
OMNI-07	2,955	2,949	6
OMNI-08	3,049	3,038	11
OMNI-09	3,117	3,019	98
OMNI-10	2,588	2,303	285
OMNI-11	3,011	2,989	22
OMNI-12	5,014	4,777	237
OMNI-13	3,001	2,911	90
OMNI-14	2,631	2,643	-12
OMNI-15	2,692	2,707	-15
OMNI-16	2,789	2,514	275
OMNI-17	2,739	2,595	144
OMNI-18	2,809	2,827	-18
OMNI-20	2,811	2,801	10
OMNI-21	2,767	2,756	11
OMNI-22	2,981	2,951	30
OMNI-23	2,846	2,849	-3
OMNI-24	2,945	2,935	10
OMNI-25	3,042	3,019	23

5.2.9 Flicker

Flicker (specifically photometric flicker) is defined as the modulation of luminous flux, and it generally exists to some extent in all major lighting technologies, including incandescent, halogen, metal halide, fluorescent, and LED, though it may or may not always be perceptible (Poplawski, 2011). Some sources, such as magnetically ballasted fluorescent, are notorious for exhibiting easily perceptible flicker, often leading to negative consumer reactions ranging from slight annoyance, to headaches, to potentially more significant health concerns for some users. Incandescent lamps generally do not generate perceptible flicker, while LED replacement lamps exhibit varying degrees of flicker. Though flicker may exist in many LED light sources at full power, perceptible flicker has often been observed during dimmed states.

Though measurement of flicker is not common practice for all light sources, there are two common metrics used to quantify the presence of flicker in a light source. The first is Flicker Index; the second is Percent Flicker (also known as amplitude modulation). The graphical representation below shows one period of a wave form exhibiting some modulation of luminous flux, and it can be used to help demonstrate the way Flicker Index and Percent Flicker are calculated.

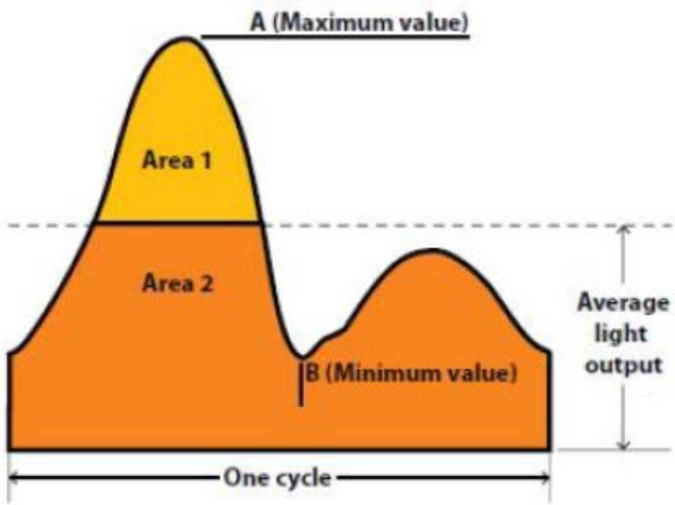


Figure 5.35 Periodic Wave Form Representation for Traditional Flicker Metrics

Equation 5.1 Percent Flicker

$$\text{Percent Flicker} = 100\% \times (\text{Max-Min}) / (\text{Max} + \text{Min})$$

Equation 5.2 Flicker Index

$$\text{Flicker Index} = \text{Area above Mean} / \text{Total Area}$$

While Percent Flicker is a simpler metric, it does not account for variations in shape or duty cycle of the flicker wave form. The primary difference between the two metrics can be seen in the image below, taken from the 2011 report, “Exploring Flicker in SSL Integral Replacement Lamps.” (Poplawski 2011) It shows three wave forms of different shapes, each with a Percent Flicker of 100%, but with varying Flicker Indices that range from .250 to .500, based on the wave form shape.

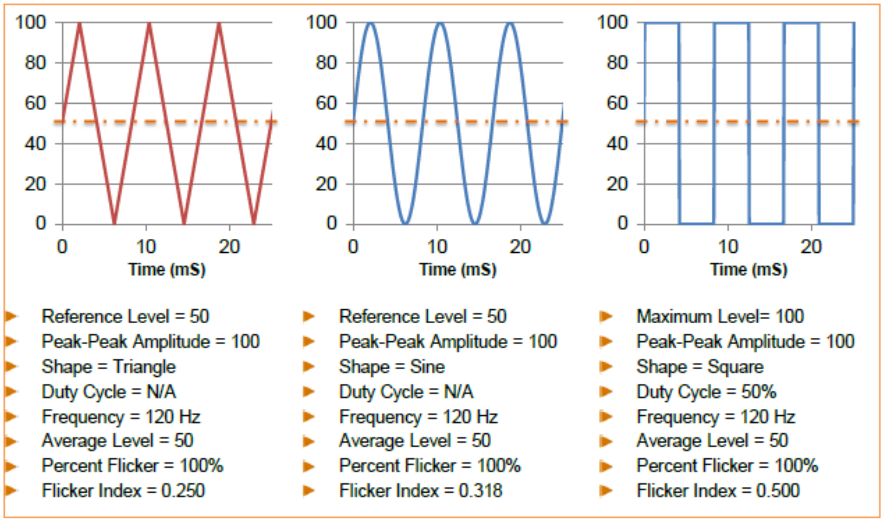


Figure 5.36 Comparison of three wave forms at 120Hz

Source: PNNL

A significant amount of work has been done to investigate the presence of flicker in various light sources and also to explore human perception of flicker, dating back over 80 years. Various studies since the seventies have shown that perception of flicker can vary based on a number of factors relating to the light source, including overall (maximum) light levels, frequency of the flicker wave form, shape of the wave form, and the amplitude of modulation. These studies also found that perception of flicker varies based on factors relating to the test subjects and test set up, including age of subjects and viewing angle. Notably, numerous studies found that even when flicker was not perceptible, it could still cause negative reactions from people, including headaches and reduced visual performance (Wilkins 1989, Veitch 1995).

One of the more recent studies into this field was conducted by the Lighting Research Center in 2011. Using human subjects, LRC was able to quantify the percentage of test subjects who detected various levels of flicker, as well as the test subjects' reaction to the flicker (in terms of acceptability). Some of the most notable findings from this study are shown in the two graphs below.

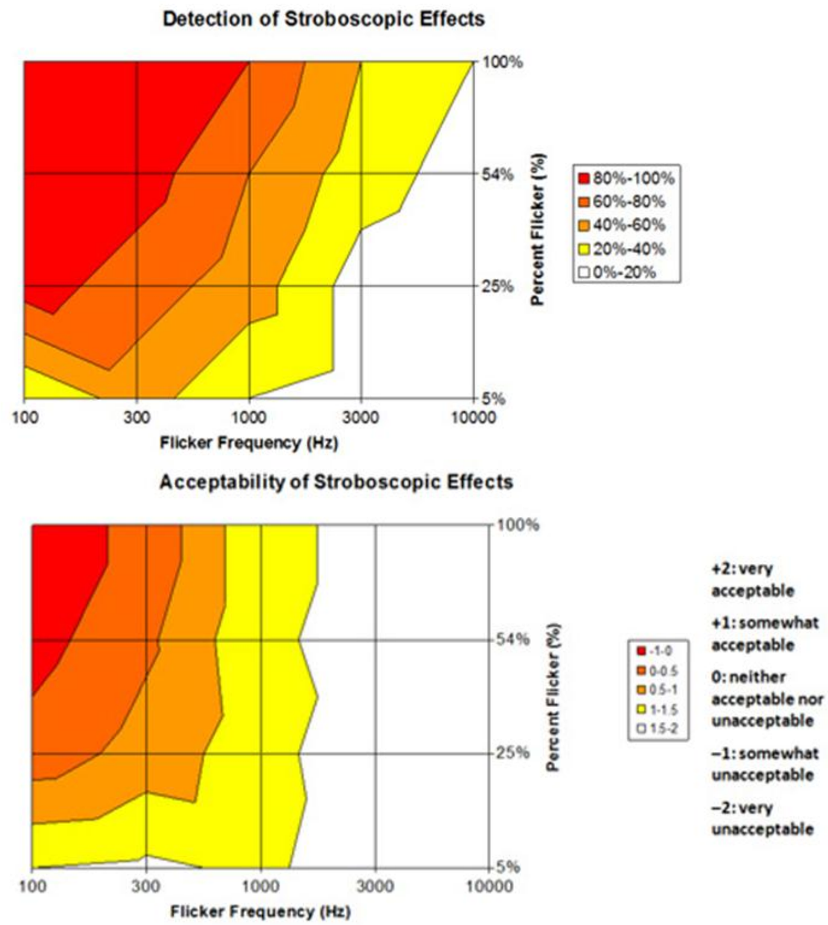


Figure 5.37 Consumer perception of and reaction to variation in Percent Flicker at different flicker frequencies

The figures above demonstrate that Percent Flicker alone is not sufficient to assess consumer reaction or acceptability of a light source, but that the frequency at which the flicker is occurring is also an important parameter. As frequency increases, the perceptibility of flicker decreases. As shown in the LRC study, 80-100% of test subjects detected modulation of 30% at 100 Hz, but 0-20% of subjects noticed the same 30% modulation at 10,000 Hz. Neither Flicker Index nor Percent Flicker accounts for the role of frequency variation in human response to flux modulation.

The existence of perceptible flicker in a light source (and/or levels of flicker that result in reduced visual performance or adverse health risks for end users) is a major threat to the adoption of that light source. Unfortunately, no consistent, publically-available test data or any kind of flicker rating exists for the vast majority of LED lamps on the market today (for example, there are no reported flicker values in the Lighting Facts Database). However, research conducted over the last few years at PNNL on behalf of DOE, has found that a wide range of flicker performance exists among LED replacement lamps and luminaires. While incandescent and halogen incandescent lamps tested all had a flicker index below .05 and a percent flicker below 15%, LED products tested had flicker index ranging from 0 to 0.5, and percent flicker ranging from 0 to 100%. Almost half of the LED products performed very well, with flicker index below 0.05, and nearly two thirds were below 0.20. The remaining one third of products had flicker indices between 0.20 and 0.50.

This CASE report is proposing flicker requirements for LED lamps, both at full output and dimmed states, to ensure that only products exhibiting little to no flicker are sold in CA. In fact, California has a history of regulating flicker in its building code and appliance standards regulations. The 2008 Title 24 included mandatory requirements for several dimming control devices in Section 119, stipulating that dimmers offer "reduced flicker operation through the dimming range, so that the light output has an amplitude modulation of less than 30 percent for frequencies less than 200 Hz." This requirement was moved from Title 24 into Title 20 in 2012 and still exists there, applying to stand alone Dimmer Controls. ENERGY STAR is also currently developing a new flicker requirement and test procedure as part of its recent specification development process, expected out later in 2013.

To further assess the dimming and flicker performance of various high performing lamps on the market, PG&E has co-funded flicker testing at the CLTC. CLTC measured modulation of luminous flux both on a power supply (for 24 lamps) and on six different dimmers (for 5 of the lamps). A Fourier analysis was conducted to filter out the modulation at or below specific frequencies. The lamps were also dimmed to record their Percent Flicker values at 100% power, 75% power, 50% power, 25% power, and at the lamps' minimum dimmed state. The results of this testing were then compared to the California Title 24 standards (30% frequency at 200 Hz).

Out of 24 omni-directional lamps tested, exactly half of those products tested on the power supply (12 out of 24) maintained a Percent Flicker less than 30%, at frequencies less than 200hz, throughout the dimmed range (down to 25% of full power). 2 of the 5 lamps tested on real dimmers achieved this level of performance. There were no inconsistencies between the results from testing on the 6 real dimmers vs. the results from testing on the power supply. In other words, the products that failed on any of the dimmers also failed on all the other dimmers and on the power supply. The products that passed on any of the dimmers also passed on all the other dimmers and on the power supply.

A future CLTC test report will contain more details about this testing and the measured values; Table 5.11 below shows a summary of the testing results, with the passing products marked in green.

Table 5.11 CLTC flicker testing results from 100% - 25% of full power, compared to historical Title 24 low flicker operation requirement (30% amplitude modulation at frequencies less than 200hz)

Lamp	Power Supply	Dimmer A	Dimmer B	Dimmer C	Dimmer D	Dimmer E	Dimmer F
Omni1	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*
Omni2	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*
Omni3	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*
Omni4	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*	*Pass*
Omni5	*Pass*						
Omni6	*Pass*						
Omni7	*Fail*						
Omni8	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*	*Fail*
Omni9	*Fail*						
Omni10	*Pass*						
Omni11	*Pass*						
Omni12	*Pass*						
Omni13	*Fail*						
Omni14	*Fail*						
Omni15	*Pass*						
Omni16	*Pass*						
Omni17	*Pass*						
Omni18	*Pass*						
Omni20	*Pass*						
Omni21	*Fail*						
Omni22	*Fail*						
Omni23	*Fail*						
Omni24	*Fail*						
Omni25	*Fail*						

5.2.10 Audible Noise

Audible noise refers to the sound created by the driver in the lamp, and is often most notable when a lamp is paired with a dimmer. Some lamps may exhibit some audible noise on certain dimmers but not on others (Conner 2013). Audible noise is measured using A-weighted (low levels) decibels, dBA. Currently, audible noise is not included on the US Lighting Facts label nor is it documented in the Lighting Facts Database. However, it is included in the proposed ENERGY STAR Lamps Specification, (Version 1 Final Draft) as a requirement in the dimming section. The ENERGY STAR draft specification requires that lamps shall not emit noise above 24 dBA at 1 meter, for 80% of tested lamp/dimmer combinations (EPA 2013). The requirement applies at full output and in dimmed states. Future testing funded by PG&E will address audible noise levels in currently available LED lamp and dimmer combinations.

5.2.11 Power Factor

Power factor is defined as the ratio of the active power to the apparent power in a system, and as such power factor values range from 0 to 1. This is a standardized metric, with higher numbers signifying a better power factor. Products with power factor of 1 are said to have perfect power factor (or "unity") because all of the power in the circuit is being used to perform work. Incandescent lamps are resistive loads and have power factor of unity. Electronic products tend to have power factors lower than one due to the presence of reactive loads that store power and result in a time difference between the current and voltage waveforms. A product with poor power factor draws significantly more power from the grid than is needed to perform its designed task. Though barely detectable on the meter side of a low wattage product (such as a 10W lamp), these losses can quickly add up and require significant additional generation capacity in an electrical grid. Current LED products range from well below 0.5 to well over 0.9.

The figure below shows the distribution of LED replacement lamps across the range of power factors, by lamp type. Among A-lamps, almost 50% have a Power Factor above 0.90. About 30% have a power factor between 0.70 and 0.90, and about 20% of A-lamps have power factor below 0.70.

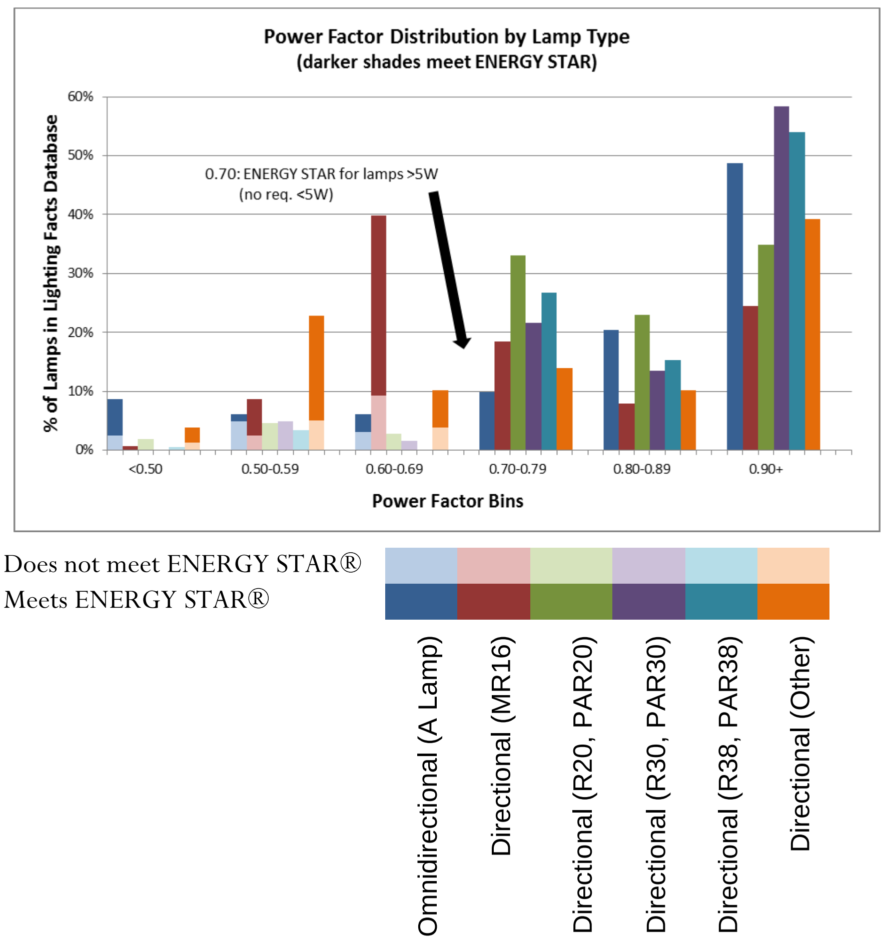


Figure 5.38 Distribution of Replacement Lamps across Power Factor Bins, by Lamp Type

Measured power factor data for A-lamps and directional lamps was also provided to the CEC in CLTC Test Reports (PG&E 2013a, PG&E 2013c).

5.2.12 Lifetime / Warranty / Lumen Maintenance

Along with efficacy, one of the strongest assets of LEDs is their long rated lifespan. While most incandescent lamps have a rated life between 1,000 and 2,000 hours, many LED products have a rated life of over 35,000 hours and a warranty of 5 years. DOE GATEWAY analyses show that affordable payback periods for LED replacement projects are determined more by their maintenance savings rather than their energy savings potential (DOE 2012a). LEDs do not tend to fail suddenly (as an incandescent lamp does), but instead slowly decrease in light output over time. Lumen maintenance values are therefore generally reported in terms of "L70," or the number of hours of operation that will elapse before the lamp's light output will be 70% of its original light output. Because reaching this point can take many tens of thousands of hours, the lumen maintenance values that are reported for most products have not been measured but projected based on the observed lumen maintenance data after 6,000 hours (following the guidelines of industry standards IES LM-80 and TM-21). However, these lumen maintenance projections apply to the LEDs themselves and do not take into consideration other possible failure modes of the lamp – particularly driver failure, which, depending on driver design, may happen long before the L70 point of the LEDs. For this reason, other metrics to assess early failure or survival factors for LED lamps are currently under development by a DOE-led working group. The new ENERGY STAR Lamps Specification also includes elevated temperature performance requirements and rapid cycling stress test requirements – both designed to put stress on the electronics in the lamp to identify poor performers. Additionally, in its recent EcoDesign requirements for LED lamps, the European Union included a metric called Premature Failure Rate. All of these are extremely useful metrics in helping to prevent early lamp failure, which is a performance issue with a high likelihood of consumer dissatisfaction. The other reason these tests are important is that they can be completed in relatively fast testing periods (less than 1,000 hours), unlike lumen maintenance ("rated life") testing which takes 3,000-6,000 hours. Therefore, it is realistic for a manufacturer to do these tests before bringing a product to market.

In addition to these early failure and stress testing metrics, product warranties are one of the best tools that manufacturers have to assure customers of a well-made integral lamp product that is designed to last as long as the LEDs. Not all lamps currently carry warranties, but most lamps that do carry either a 3-year or 5-year warranty, according to data from the ENERGY STAR Qualified Product List. Based on 3 hours of use per day, a 3-year warranty would amount to approximately 3,200 hours of operating time, and a 5-year warranty would amount to approximately 5,500 hours of operation, both far below the typical lumen maintenance (L70) claims made by manufactures of 25,000 – 50,000 hours.

5.2.13 Start Time, Warm-up Time

Many LED lamps have little to no warm-up delay, and most turn on almost instantly at full brightness. This is a particularly advantageous feature when replacing fluorescent, high-intensity discharge (HID), and high-pressure sodium lamps, which take anywhere from a few seconds to several minutes to reach full brightness. However, not all LED lamps are created equally; some may have noticeably slower start times or warm-up times than others. Additionally, start time and warm-up time are not commonly reported metrics for LED lamps, so it is difficult to assess the range of performance on the market today. During the public discussions hosted by the CEC around the adoption of the CEC Voluntary Quality Specification, some manufacturer representatives noted that 0.5 seconds was a realistic start time performance requirement for LED lamps. Product testing has been planned for 2013 to assess these metrics for a cross – section of commercially available lamps.

5.3 Product Performance for Qualifying and Non-Qualifying Products

The CASE Team has used a combination of the above available data from the Lighting Facts Database and individual product testing by the CLTC or other available data to establish an average value for each quality metric for both non-qualifying and qualifying products, as of early 2013. These values in the table below represent the average or typical performance values for products that do not meet the standards proposals ('Non-Qualifying') contained in this document and the average or typical performance values for products that do meet the standards proposals in this report ('Qualifying').

Table 5.12 Summary of Product Performance Metrics – Qualifying and Non-qualifying Values; 2012/2013

Performance Attribute	Representative Non-Qualifying LED Lamp	Representative Qualifying LED Lamp
CRI (R_a)	82	92
R_9	21	71
Efficacy: Omni	69 lpw	86 lpw
Efficacy: Directional	60 lpw	69 lpw
Efficacy: Decorative	48 lpw	65 lpw
Start Time	1.0 second	0.4 seconds
Dimmability	Not dimmable (or poor dimming performance)	Dimmable (with good dimming performance)
Power Factor	0.72	.95
Flicker	50% Flicker (at full output)	7% Flicker (at full output)
Audible Noise	Tbd	Tbd
Warranty	None	5 Year
CCT	2700K	2700K
Color Consistency	4 MacAdam Steps	2 MacAdam Steps

For efficacy and wattage, because these are the metrics most closely related to product operating cost and are necessary components of the energy use analysis, the CASE Team has developed performance forecasts during the analysis period from 2016 – 2031 for both qualifying and non-qualifying LED products, as well as for the incumbent major technology types, as shown in the tables below. These tables contain wattage forecasts for representative lamps providing 1,003 lumens (omni-directional), 1,060 lumens (large diameter directional), 679 lumens (small diameter directional), and 479 lumens (decorative).

Table 5.13 Non-Standards Case A-lamp Efficacy and Wattage Forecasts by Technology

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	20	45	45	45	50	22	22	22
CFL	61	61	61	61	16	16	16	16
LED	87	109	131	153	11.6	9.2	7.7	6.6

Table 5.14 Standards Case A-lamp Efficacy and Wattage Forecasts by Lamp Type

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	20	45	45	45	50	22	22	22
CFL	61	61	61	61	16	16	16	16
LED	108	136	163	191	9.3	7.4	6.1	5.3

Table 5.15 Non-Standards Case Large Diameter Directional Efficacy and Wattage Forecasts by Technology

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	18	19	19	19	60	57	57	57
CFL	53	53	53	53	20	20	20	20
LED	76	95	115	134	14.0	11.1	9.2	7.9

Table 5.16 Standards Case Large Diameter Directional Efficacy and Wattage Forecasts by Lamp Type

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	18	19	19	19	60	57	57	57
CFL	53	53	53	53	20	20	20	20
LED	89	111	134	157	11.9	9.5	7.9	6.8

Table 5.17 Non-Standards Case Small Diameter Directional Efficacy and Wattage Forecasts by Technology

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	15	21	21	21	44	31	31	31
CFL		NA				NA		
LED	76	95	115	134	8.6	6.8	5.7	4.8

Table 5.18 Standards Case Small Diameter Directional Efficacy and Wattage Forecasts by Lamp Type

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	15	21	21	21	44	31	31	31
CFL		NA				NA		
LED	89	111	134	157	7.3	5.8	4.8	4.1

Table 5.19 Non-Standards Case Decorative Lamp Efficacy and Wattage Forecasts by Technology

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	11	11	18	18	44	44	27	27
CFL	48	48	48	48	10	10	10	10
LED	60	76	91	106	8.0	6.3	5.3	4.5

Table 5.20 Standards Case Decorative Lamp Efficacy and Wattage Forecasts by Lamp Type

	Representative Lamp Efficacy (lpw)				Representative Lamp Wattage (W)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	11	11	18	18	44	44	27	27
CFL	48	48	48	48	10	10	10	10
LED	81	102	122	143	5.9	4.7	3.9	3.3

CFL efficacy was calculated based on the ENERGY STAR Qualified Products List and is not expected to improve significantly over time as manufacturers reduce investments in CFL R&D. Incandescent efficacy (including halogen incandescent) is forecasted for each lamp type based on current standards (or typical efficacy levels where no standards exist) and future expected applicable standards. For A-lamps, incandescent efficacy is projected to improve dramatically in the period around 2020 as the EISA 2007 backstop requirements of 45 lumens per watt become effective. For directional lamps, the efficacy forecasts shown here incorporate expected future standards activity for large diameter incandescent reflector lamps (current DOE rulemaking likely to be effective in 2018) and small diameter directional lamps (current Title 20 proposal in development). For decorative lamps, the wattage and efficacy shown for the period from 2016 - 2021 were based on data from the 2010 Lighting Market Characterization report. A potential future efficacy standard for incandescent decorative lamps was modeled beginning in 2022. If any of these modeled future incandescent efficacy standards do not occur, savings from a market shift to LEDs would be even more dramatic (for example, if the EISA 2007 backstop requirements are not fully implemented in 2020 but rather are phased in). In other words, this CASE report is conservative in its assumptions that incandescent lamps will achieve significant efficacy gains between now and 2031, which limits the potential savings resulting from LED adoption.

Incandescent and CFL efficacies do not change from the non-standards case to the standards case in this analysis because those technologies are not covered by this proposal.

The LED efficacies were calculated based on the aforementioned studies from DOE that projected LED efficacy improvement curves, with white light GSL lamp efficacy predicted to hit 160-200 lpw by 2030. The starting points for these curves were confirmed by the CASE Team analysis of the Lighting Facts Database efficacy trends over the past several years. The efficacy curves were applied to both the average non-qualifying LED product in 2013 (69 lpw for A-lamps) and the average qualifying LED product in 2013 (86 for A-lamps).

5.4 Per Unit Energy Savings

The majority of the savings in this standards proposal will result from the increased market adoption of LEDs due to increased consumer confidence in the technology, speeding the conversion of higher wattage incandescent lamps to LED lamps. However, the measure will also result in per unit energy savings by moving from non-qualifying LED lamps to qualifying LED lamps. Per unit energy savings will result due primarily to two aspects of the standards proposal: increased efficacy and required dimmability. The savings analyses for these measures follow in the sections below.

5.4.1 Increased Efficacy

In 2016 (the first year this proposed standard would take effect), non-qualifying general service LED lamps are forecasted to provide 87 lpw, while qualifying general service LED lamps will achieve 108 lpw. Assuming an average lamp light output of 1,003 lumens, A-lamps will draw 11.6W and 9.3W, respectively, for a wattage reduction of 2.3W.

Among large diameter directional lamps, assuming an average lumen output of 1,060 lumens, non-qualifying and qualifying lamps will draw 14.0W and 11.9W, respectively, for a wattage reduction of 2.0W.

Among small diameter directional lamps, assuming an average lumen output of 649 lumens, non-qualifying and qualifying lamps will draw 8.6W and 7.3W, respectively, for a wattage reduction of 1.2W.

Among decorative lamps, assuming an average lumen output of 479 lumens, non-qualifying and qualifying lamps will draw 8.0 Wand 5.9W respectively, for a wattage reduction of 2.0W.

Our assumptions for annual operating hours for directional lamps are based on a 2011 Navigant Study. This study estimated annual operating hours to be 840 hours in residential applications and 3,720 hours in commercial applications. According to the same study, the residential sector accounts for approximately 35% of sales, while the commercial sector accounts for 65% of sales (Navigant 2011). Applying a weighted average to these values, we estimate that a typical directional lamp is used 2,712 hours per year on average.

General service and decorative lamps are used more often in the residential sector (92% of GSL stock is residential are according to the to 2010 Lighting Market Characterization Study; DOE 2012e), with the remainder being installed in commercial or industrial applications. Using the same hours of use assumptions as above, general service and decorative lamps are assumed to operate 1,095 hours per year on average.

Table 5.21 below shows the annual energy savings that will result from the increased efficacy of qualifying lamps. Note that these are the savings that will be achieved by lamps that are not installed in dimming sockets (which is about 75% of the total lamp sockets).

Table 5.21 Per Unit Annual Energy Savings by Lamp Type (for lamps not installed in dimming sockets)

	Per Unit Annual Energy		
Lamp Type	Non-Qualifying kWh/yr	Qualifying kWh/yr	Savings (kWh/yr)
General Service A-lamp	12.7	10.2	2.5
Large Diameter Directional	37.9	32.4	5.5
Small Diameter Directional	23.2	19.8	3.4
Decorative	8.7	6.5	2.2

5.4.2 Dimmability

As explained in Section 5.2.8 above, this CASE report assumes that approximately 25% of California lamp sockets will operate on dimmers when this code takes effect, with this number increasing due to the ongoing impacts of California building codes that have been passed in the last ten years. Qualifying dimmable LED lamps that are installed in these dimming sockets will achieve additional energy savings over non-dimmable lamps, as shown in this section.

Based on testing completed by the CLTC, we have identified the average wattage draw of Qualifying LED lamps throughout the dimmed range as shown in Table 5.22 below.

Table 5.22 Average power draw of LED lamps at various dimmed states (as % of full power)

Dimmed Level (Light Output)	Average power draw each dimmed level (as % of full power)
Full output	100%
75% power	74%
50% power	49%
25% power	25%

We assume that on average, lamps installed on dimmers will be operated in various dimmed modes throughout the year and have generated an approximate dimming profile in order to identify the energy usage of a Qualifying dimmable LED lamp when operated on a dimmer. Table 5.23 below shows the annual operating hours that are assumed at each dimmed level, while Table 5.24 calculates the total energy use at each dimmed level, per lamp type.

Table 5.23 Assumed hours spent at each dimmed level, by lamp type

Dimmed Level	Assumed percentage of time spent at each dimmed level	**Omni-directional** (GSL and decorative) hours **Total: 1,095**	**Directional** (Small and Large Diameter) hours **Total: 2,712**
Full output	50%	548	1,356
75% power	17%	183	452
50% power	17%	183	452
25% power	17%	183	452

Table 5.24 Assumed hours spent at each dimmed level, by lamp type

	General Service A-lamp		**Large Diameter Directional Lamp**		**Small Diameter Directional Lamp**		**Decorative Lamp**	
Dimmed Level	Wattage at dimmed level	Annual kWh at dimmed level	Wattage at dimmed level	Annual kWh at dimmed level	Wattage at dimmed level	Annual kWh at dimme d level	Wattage at dimmed level	Annual kWh at dimmed level
Full output	9.3	5.1	11.9	16.1	7.3	9.9	5.9	3.2
75% power	6.9	1.3	8.9	4.0	5.4	2.5	4.4	0.8
50% power	4.6	0.8	5.8	2.6	3.6	1.6	2.9	0.5
25% power	2.4	0.4	3.0	1.4	1.9	0.8	1.5	0.3
Total annual kWh		**7.6**		**24.1**		**14.8**		**4.8**

Table 5.25 demonstrates the annual energy use of Non-Qualifying and Qualifying lamps when installed in dimming sockets and the energy savings for each, by lamp type. This represents typical savings that will be achieved by lamps that are eventually installed in sockets controlled by dimmers (which is about 25% of the total lamp sockets).

Table 5.25 Per Unit Energy Savings by Lamp Type (for lamps installed in dimming sockets)

	Per Unit Energy (dimming sockets)		
	Non-Qualifying	Qualifying	Savings
Lamp Type	kWh/yr	kWh/yr	(kWh/yr)
General Service A-lamp	13.8	7.6	6.2
Large Diameter Directional	37.9	24.1	13.8
Small Diameter Directional	23.2	14.8	8.4
Decorative	8.7	4.8	3.9

Assuming about 25% of sockets in California are operated by dimmers, Table 5.26 below provides a weighted average of per unit annual energy savings for lamps installed in California, by lamp type.

Table 5.26 Weight average per unit annual energy savings by lamp type (for lamps installed in typical CA sockets)

		Annual Energy Savings (kWh)			
		General Service A-lamp	Large Diameter Directional Lamp	Small Diameter Directional Lamp	Decorative Lamp
Not Installed on Dimmer	75%	2.1	5.5	3.4	2.2
Installed on Dimmer	25%	6.2	13.8	8.4	3.9
Weighted Average Per Unit Annual Energy Savings		**3.1**	**7.6**	**4.6**	**2.6**

6 Market Saturation & Sales

6.1 Current Market Situation

6.1.1 Total Shipments and Stock

The total stock of omni-directional lamp sockets in California was approximately 400 million in 2010. (DOE 2012e) At that time, LED lamps made up less than 0.3% of the total stock of sockets, but this value has likely increased since 2010 as prices have decreased and quality has improved. The 2010 saturation of lamps by technology type is shown in the table below.

Table 6.1 California Installed Stock by Lamp Type and Technology Type, 2010

	General Service Omni-Directional Stock	**Decorative Stock**	**Large Diameter Directional Stock**	**Small Diameter Directional Stock**
Product Type	Units	Units	Units	Units
Incandescent (inc. halogen)	253,017,783	75,785,836	52,115,280	14,518,135
CFL	135,716,307	40,650,794	27,954,135	-
LED	3,905,647	1,169,849	804,465	145,865
Total	**392,639,738**	**117,606,480**	**80,873,880**	**14,664,000**

Source: Derived from the 2010 Lighting Market Characterization Study, U.S. DOE; converted to CA values based on CA 12.1% of U.S. population. (DOE 2012e)

6.2 Future Market Adoption of LED Lamps

This CASE initiative is based on the premise that as LED prices fall quickly, adoption rates of LED replacement lamps will largely depend on lamp quality and consumer acceptance in the coming years. Multiple LED adoption forecasts have been generated by various research organizations, though to our knowledge, none of the available studies account for potential variation in LED lamp quality, nor the fact that adoption rates will depend on the extent to which consumers accept LED technology.

Most of the studies focus on the monetary value of the LED market (rather than unit sales or conversion of sockets), so they are difficult to translate into lamp forecasts. Some of these forecasts also include other LED markets including automotive lighting and consumer electronics lighting, in addition to general lighting, also limiting their usefulness for an LED lamp forecast. That said, these studies agree that the market share of LEDs is going to increase significantly over the next 15 years, particularly as product prices come down so quickly. A summary of some of these forecasts is shown in the table below.

Table 6.2 Summary of various LED technology adoption forecasts through 2020

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

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

The January 2012 Navigant study focuses on general service lamps (omni-directional, directional, and linear) and is the most applicable to the forecasting effort being conducted here. The study, entitled Energy Savings Potential of Solid-State Lighting in General Illumination Applications, includes forecasts by lamp type and market sector, and these forecasts extend through 2030. The forecast is for general service, medium-screw base LEDs to represent 26% of the installed base of lumen-hours in the residential sector by 2020, growing to almost 69% by 2030, as shown in Table 6.3 below.

Table 6.3 Navigant Forecasted Adoption of Medium Screw Base LED General Service Lamps

Residential General Service Medium Screw Base Lamps				
	2015	2020	2025	2030
LED market share (% of installed lumen hours)	3.8%	26.0%	54.7%	68.6%

Using these forecasts as a guide, the CASE Team has modeled multiple potential adoption scenarios from 2016 – 2031 (the analysis period of this standards proposal) for general service A-lamp sockets in California. The CASE Team has proposed adoption scenarios for the standards case as well as the non-standards case, each consisting of a low, medium and high adoption rate, resulting in six unique scenarios. These forecasts represent the portion of the total installed sockets in California that would be utilizing lamps of each major technology under each scenario (the "incandescent" technology category includes halogen incandescent lamps). Note that the total number of sockets is forecasted to increase at a rate of 1.65% per annum based on increased residential building stock floor space projections from the Energy Information Agency (2009).

In the non-standards case, adoption is forecasted to be slower due to a lack of consumer satisfaction with LED products. To model this trend, the CASE Team referred to the market adoption rate of CFLs over the past 15 years. Accordingly, in the Non-Standards Case, Low Adoption Scenario, LEDs are only forecasted to grow from 3% of the socket share to about 39% in 2031. The three non-standards case scenarios are shown in Figure 6.1, Figure 6.2, and Figure 6.3 below.

Table 6.4 shows the results of these standards forecasts in 5-year increments, in table format.

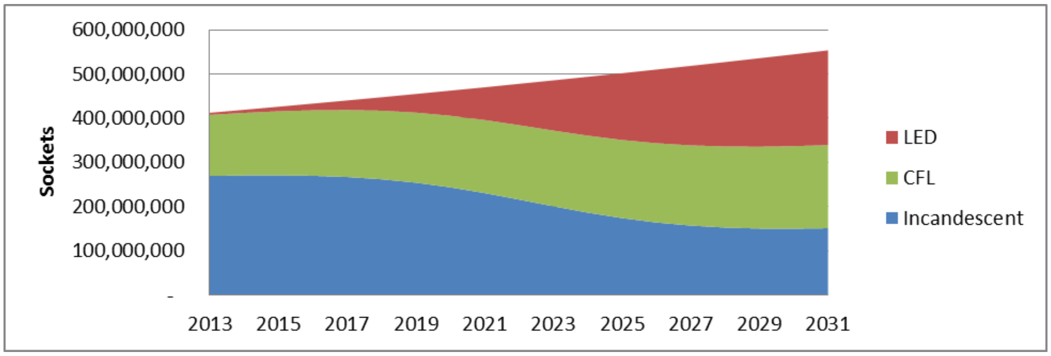


Figure 6.1 Non-Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: Low LED Adoption Scenario

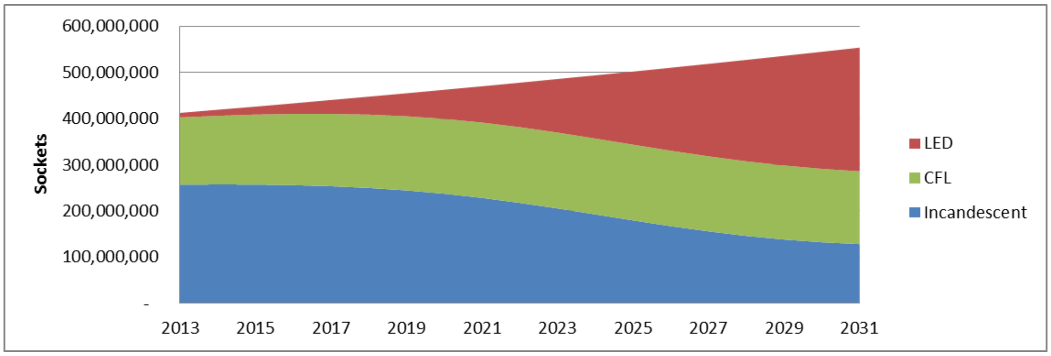


Figure 6.2 Non-Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: Moderate LED Adoption Scenario

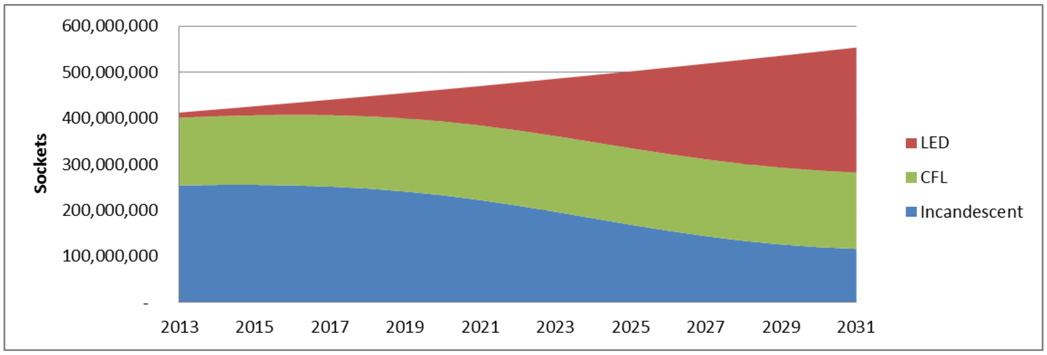


Figure 6.3 Non-Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: High LED Adoption Scenario

Table 6.4 Non-Standards Case, Low, Moderate, and High LED Adoption Scenarios

	Low LED Adoption Statewide Socket Share (%)				Moderate LED Adoption Statewide Socket Share (%)				High LED Adoption Statewide Socket Share (%)			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	62%	49%	32%	27%	59%	49%	33%	23%	59%	47%	31%	21%
CFL	34%	35%	35%	34%	36%	35%	32%	28%	35%	34%	33%	30%
LED	3%	16%	33%	39%	5%	17%	35%	48%	6%	18%	37%	49%

Directional lamps and decorative lamps were modeled in the same manner as A-lamps, using different numbers for total sockets but with the same adoption rates assumed for each technology, with the exception of small-diameter directional lamps for which no CFL market penetration was modeled.

In the standards case, a higher level of product quality is expected to lead to increased consumer satisfaction and in turn, increased adoption rates. The low adoption scenario in the standards case leads to 62% of sockets being converted to LED lamps by 2031, while the high adoption scenario results in almost 80% of sockets being converted to LEDs in that same period. The three standards case scenarios are shown in Figure 6.4, Figure 6.5, and Figure 6.6 below. Table 6.5 shows the results of these standards case forecasts in 5-year increments, in table format.

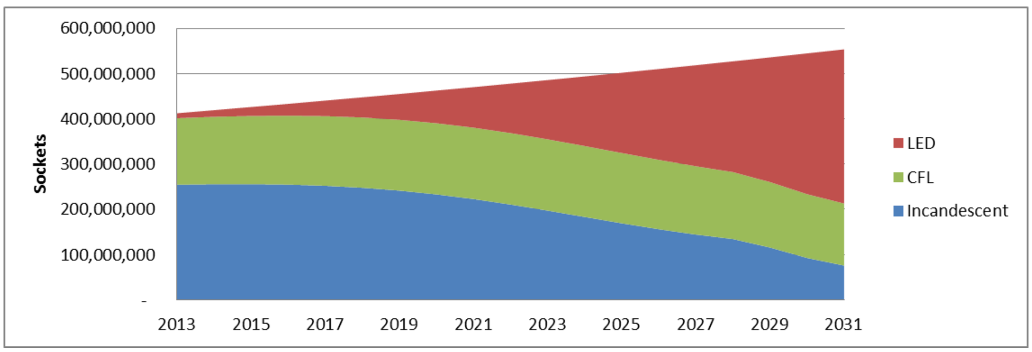


Figure 6.4 Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: Low LED Adoption Scenario

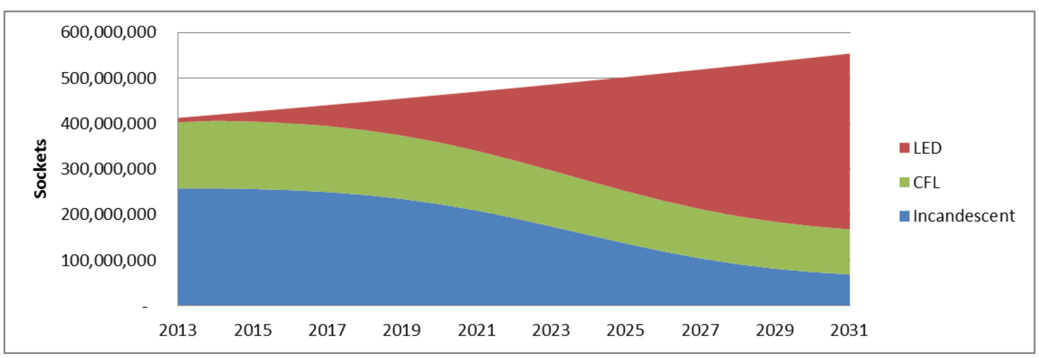


Figure 6.5 Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: Moderate LED Adoption Scenario

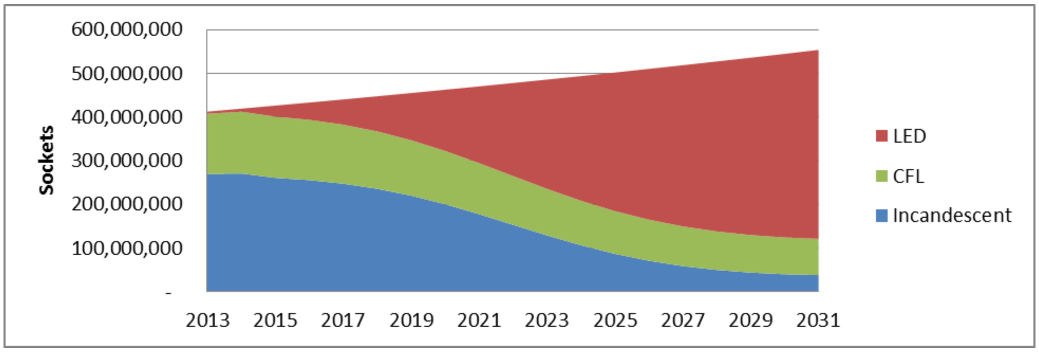


Figure 6.6 Standards Case Socket Share Projection of Incandescent, CFL, and LED A-lamps: High LED Adoption Scenario

Table 6.5 Standards Case Adoption Scenarios, Low, Moderate, and High LED Adoption

	Low LED Adoption Statewide Socket Share (%)				**Moderate LED Adoption Statewide Socket Share (%)**				**High LED Adoption Statewide Socket Share (%)**			
Product Type	2016	2021	2026	2031	2016	2021	2026	2031	2016	2021	2026	2031
Incandescent (inc. halogen)	59%	47%	31%	14%	59%	44%	23%	12%	59%	38%	14%	7%
CFL	35%	34%	30%	25%	34%	28%	22%	18%	32%	25%	18%	15%
LED	6%	19%	39%	62%	8%	28%	55%	70%	9%	37%	68%	78%

7 Savings Potential

7.1 Statewide California Energy Savings

The statewide savings analysis consists of two parts: the "first order" savings associated with a shift from Non-Qualifying LED lamps to Qualifying LED lamps (a direct result of the standard) and the "second order" savings associated with an accelerated shift away from lower efficacy incumbent technologies to higher efficacy LED products as a result of improved product quality and increased consumer satisfaction with the products. These analyses are presented in the following sections.

7.1.1 First Order Statewide California Energy Savings

The first order savings analysis assumes that in 2016, the first year the standard will take effect, LED lamps sales will make up about 1.5% of total California sockets, as projected by the CA socket model generated in the section above. Table 7.1 below shows the total statewide first year savings that will result for each lamp type.

Table 7.1 First Order per unit and statewide first year savings

Lamp Type	First Order Statewide Energy Savings Per Unit Savings (kWh/yr)	Estimated 2016 LED Shipments	Statewide First Year Savings (GWh)
General Service A-lamp	2.5	5,540,651	13.9
Large Diameter Directional	5.5	1,141,234	6.2
Small Diameter Directional	3.4	206,928	0.7
Decorative	2.2	1,659,578	3.7
Total			**24.5**

7.1.2 Second Order Statewide California Energy Savings

Using the socket share rates demonstrated in Section 6 (Market Saturation & Sales), and the efficacy and wattage forecasts presented in Section 5.3 (Product Performance for Qualifying and Non-Qualifying Products), the CASE Team developed a model to project the total statewide energy use and peak demand of the entire statewide stock of sockets for both the non-standards and standards case over a 15 year period of analysis (2016 – 2031). This model demonstrates the energy savings that results from a faster transition and more complete market adoption of LED lamps that replace higher wattage lamps. (The Team conducted an analysis of total socket energy use and demand, rather than the energy use and peak demand of annual sales, for several reasons unique to this measure. One key reason is that because of the long life of LED lamps, increased LED market share will actually result in a decrease in annual lamp sales in subsequent years.) In this 'second order' savings analysis, results are shown for general service A-lamps only. The energy use and peak demand for each adoption scenario, in the non-standards case and standards case, are shown in the tables below.

Table 7.2 California Statewide Non-Standards Case Stock Energy Use & Peak Demand;[1] Low, Moderate and Aggressive Adoption Scenarios

Low LED Adoption Scenario			Moderate LED Adoption Scenario			High LED Adoption Scenario		
Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)
2016	17,696	1,443	2016	17,185	1,401	2016	17,119	1,396
2021	9,467	772	2021	9,455	771	2021	9,378	765
2026	8,910	726	2026	8,823	719	2026	8,696	709
2031	9,018	735	2031	8,323	679	2031	8,221	670

(1) Statewide demand (and demand reduction) is quantified as coincident peak load (and coincident peak load reduction), the simultaneous peak load for all end users, as defined by Koomey and Brown (2002).

Table 7.3 California Statewide Standards Case Stock Energy Use & Peak Demand;[1] Low, Moderate and Aggressive Adoption Scenarios

Low LED Adoption Scenario			Moderate LED Adoption Scenario			High LED Adoption Scenario		
Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Consumption (GWh/yr)	Peak Demand (MW)
2016	17,104	1,395	2016	17,056	1,391	2016	17,042	1,390
2021	9,209	751	2021	8,808	718	2021	8,208	669
2026	8,264	674	2026	7,241	590	2026	6,346	517
2031	6,739	550	2031	6,212	506	2031	5,578	455

(1) Statewide demand (and demand reduction) is quantified as coincident peak load (and coincident peak load reduction), the simultaneous peak load for all end users, as defined by Koomey and Brown (2002).

The CASE Team then generated three statewide energy savings calculations. The conservative calculation compared the energy use and peak demand of the Non-Standards Case, High Adoption Scenario to the energy use and peak demand of the Standards Case, Low Adoption Scenario. The aggressive savings scenario did the opposite—it compared the energy use and peak demand of the Non-Standards Case Low Adoption Scenario to the energy use and peak demand of the Standards Case High Adoption Scenario. This calculation strategy is presented in Table 7.4, and the results are shown in Table 7.5, below.

Table 7.4 Basis for Second Order Savings Calculations

	Assumptions	
Savings Calculation	Non-Standards Case Adoption Rate Scenario	Standards Case Adoption Rate Scenario
Conservative	High	Low
Moderate	Moderate	Moderate
Aggressive	Low	High

Table 7.5 California Statewide Energy Savings & Peak Demand Reduction;[1] Conservative, Moderate and Aggressive Savings Scenarios

Conservative Savings Scenario			Moderate Savings Scenario			Aggressive Savings Scenario		
Year	Annual Energy Savings (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Savings (GWh/yr)	Peak Demand (MW)	Year	Annual Energy Savings (GWh/yr)	Peak Demand (MW)
2016	15	1	2016	129	11	2016	654	53
2021	168	14	2021	647	53	2021	1,259	103
2026	432	35	2026	1,582	129	2026	2,564	209
2031	1,481	121	2031	2,111	172	2031	3,440	281

(1) Statewide demand (and demand reduction) is quantified as coincident peak load (and coincident peak load reduction), the simultaneous peak load for all end users, as defined by Koomey and Brown (2002).

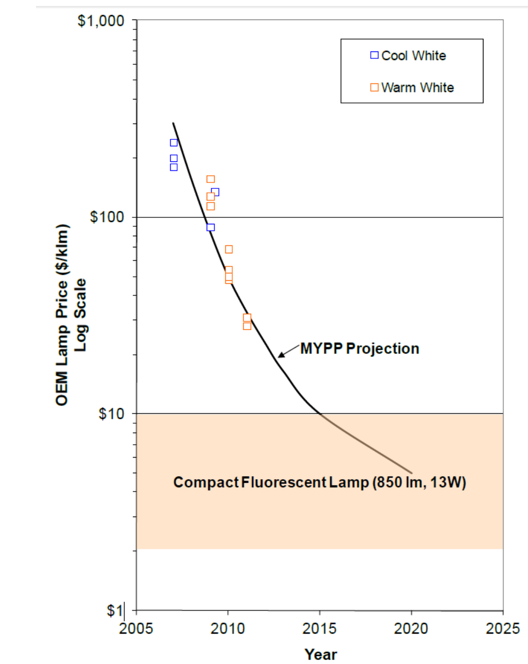
7.2 State or Local Government Costs and Savings

There are no known additional costs to state or local governments from the implementation of the standards proposal, given the CEC's existing authority for establishing appliance standards and staffing to administer the process. Energy savings are expected for local and state governments from the purchase of more efficient products as a result of the proposed standard, with the savings amount dependent on the volume of products purchased.

8 Economic Analysis

8.1 Non-Standards Case LED Lamp Cost Forecasts

LED prices are falling quickly, and according to McKinsey & Company, could theoretically become cheaper than traditional lighting technologies. (McKinsey 2011) This is due to improvements in luminous efficacy (which results in fewer LEDs needed per lamp and less heat sink material to remove excess heat), increased production efficiency, and lower material costs. Below are images from two U.S. DOE Building Technologies Program studies that forecast the relative rate of LED cost decreases over time. Figure 8.1 shows the total costs per kilolumen from white LED lamps (both warm white and cool white). Figure 8.2 shows the relative costs associated with LED lamp production (an A19 LED 60W-replacement lamp), with specific lamp components and production processes identified individually.



Source: U.S. Department of Energy, Energy Efficiency & Renewable Energy, Building Technologies Program. (April 2012. Solid-State Lighting Research & Development: Multi-Year Program Plan. Retrieved on January 30, 2013, from http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf (p. 46).

Figure 8.1 White Light Integrated LED Lamp Price Projection, in $/klm (Log Scale)

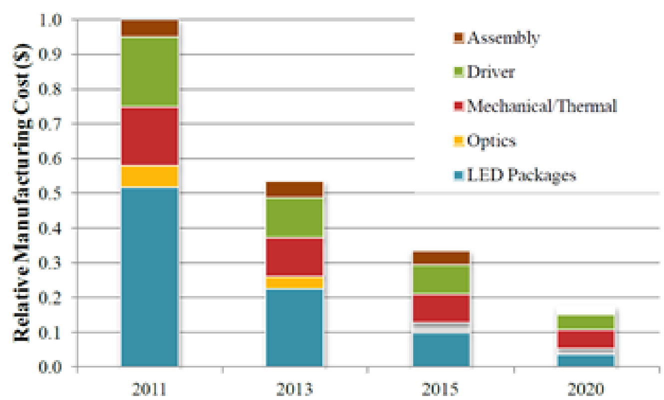


Figure 8.2 Projected Relative Manufacturing Costs for an LED A19 60W Replacement Lamp. (DOE 2012c)

In both studies, LED lamp costs in 2020 are expected to be about 10 – 20% of their 2011 cost. Additional work has been done on a more detailed level which further validates these projections. First, the US DOE CALiPER Program issued studies in 2010 and 2011 that included price data for A-lamps and directional lamps. On behalf of PG&E, the CASE Team conducted another study of LED lamp prices in 2012. The research conducted in 2012 by this CASE Team documented product prices for over 700 unique price points for almost 500 unique lamp models, including omni-directional and directional lamps. The cost values collected by the CALiPER program (2010-2011) and by the CASE Team (2012) are consistent with the 2010-2012 cost forecasts generated by the DOE Building Technologies SSL Multi-Year Program Plan (MYPP). The graph below shows the measured values from the CALiPER program and the PG&E CASE research in blue, with a fit applied to the curve to project into the future. The graph also shows in green the estimated price values in the DOE MYPP study.

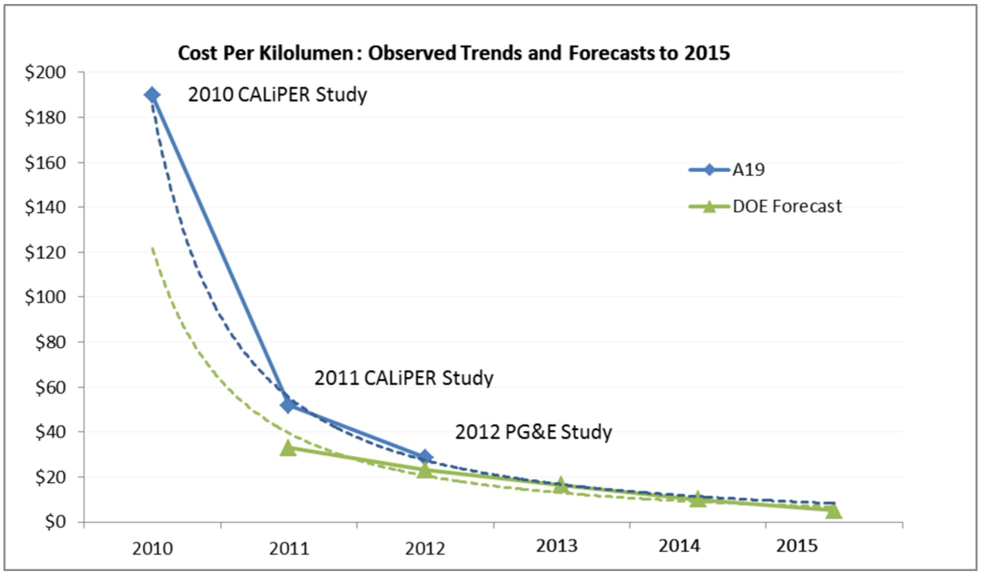


Figure 8.3 Price per Kilolumen for LED Replacement Lamps

The CASE Team has generated a price forecast curve using an average of these two curves. The results of this exercise are shown with the red line in Figure 8.4 below.

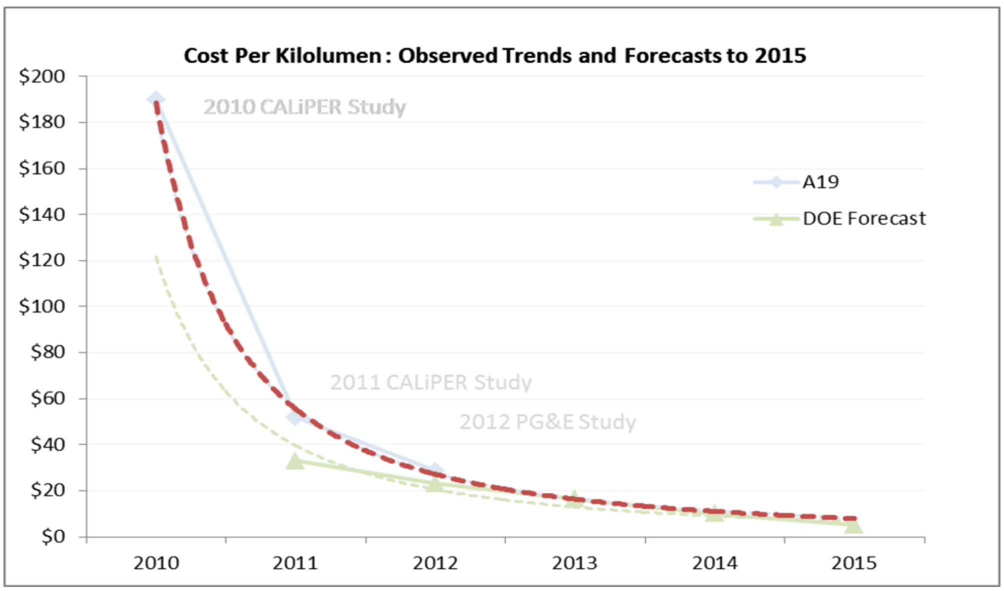


Figure 8.4 Projected Price per Kilolumen for LED Replacement Lamps

The forecasted average price per kilolumen in 2015 is approximately $10, meaning the average forecasted price for an 800 lumen lamp (60Wequivelent) is approximately $8. Cost forecasts were developed for other lamp types using similar curves fit to the surveyed price points of the other technologies. Directional lamps and decorative lamps all generally have much higher cost per kilolumen values than A-lamps, but their prices are decreasing along a similar trajectory. Table 8.1 below shows the forecasted average cost for representative lamps from 2016 through 2031.

Table 8.1 Representative LED lamp price forecasts, 2016 – 2031

	Representative Lamp Price (2013 $)			
Product Type	2016	2021	2026	2031
General Service (1,003 lumens)	$7.72	$3.11	$1.73	$1.12
Large Diameter (1,060 lumens)	13.26	$5.35	$2.97	$1.93
Small Diameter (649 lumens)	$9.56	$3.86	$2.14	$1.39
Decorative (479 lumens)	$10.40	$4.19	$2.33	$1.51

8.2 Analysis of the Incremental Cost of LED Lamp Quality

To better understand what aspects of lighting quality are most costly, and the costs to consumers associated with different aspects and levels of quality, in summer and fall of 2012, the CASE Team conducted a statistical study of LED lamp prices and characteristics. The study sought to answer these specific questions:

- Are there any statistically significant relationships between key lighting performance metrics and price?
- Which metrics have the greatest statistical linkage with price?
- What is the estimated magnitude of the effect of influential metrics on price?

To evaluate these questions, the CASE Team collected lamp price and performance characteristics from online lamp vendors, constructed a model of lamp price based on performance characteristics, and conducted a multiple regression analysis to evaluate and refine the model. A high level summary of the methodology and results is provided here, in the following sections.

8.2.1 Overview of Incremental Cost of Quality Analysis

As explained earlier in Section 8.1, the research conducted in 2012 by this CASE Team identified over 700 unique price points for over 500 unique lamp models, including omni-directional and directional lamps. Prices were identified for 247 different PAR lamps, 148 A lamps, 49 MR lamps and a smaller number of products for several other lamp shapes (BR, Candle, G, and others). Summary statistics, including the number of products, minimum price, maximum price, mean price, and standard error of the mean price, are shown in the table below.

Table 8.2 Summary statistics of price data collected for most prevalent product types

Shape	**Number of Products**	**Minimum Lamp Price ($)**	**Maximum Lamp Price ($)**	**Mean Lamp Price ($)**	**SE (% Mean)**
PAR	247	$10.17	$114.01	$53.61	2%
A	148	$5.97	$62.79	$23.03	4%
MR	49	$13.26	$49.51	$29.51	3%
BR	19	$24.97	$92.94	$49.08	11%
Candle	16	$8.97	$20.39	$13.35	6%
G	5	$14.26	$34.75	$29.30	14%

The CASE Team then collected data on a large number of performance metrics for each product for which price data was collected. Data was not available for every targeted metric. Table 8.3 shows the extent to which data was available for the targeted metrics for the three most prevalent lamp shapes. As is evident in the table, much less performance data was available for certain types of lamps and certain types of data, such as R9 values and chromaticity consistency bins, which were essentially unavailable for all lamp types. For other metrics, such as lamp wattage, total lumens, and lumen maintenance, data was available for nearly all products surveyed (as shown in by the green values in the table below). In addition to the performance metrics listed in Table 8.3, a note was made if the product was ENERGY STAR -qualified and if the product was marketed as dimmable or not (so this information is considered to be available for 100% of products).

Table 8.3 Performance Data Availability by Lamp Shape (% of products for which data was found for each metric)

Metric	A	MR	PAR	All
Watts	99%	100%	100%	100%
Distribution Type (lamp shape)	99%	100%	100%	100%
Lumens	86%	100%	100%	95%
Lumen Maintenance (L70)	84%	100%	100%	95%
CCT	83%	100%	100%	94%
Warranty	66%	55%	100%	84%
CRI	72%	100%	83%	82%
Power Factor	19%	27%	93%	61%
Beam Angle	NA	96%	36%	41%
Voltage (design)	39%	100%	2%	25%
R9	0%	0%	9%	5%
Chromaticity Consistency Bins	0%	0%	9%	5%
Zonal Lumens	0%	0%	0%	0%
Harmonic Distortion	0%	0%	0%	0%

The CASE Team then conducted a multi-variable regression analysis to evaluate and refine a model to predict product price as a function of lamp performance. As explained in more detail in the LED Lamp Quality and Price Study (previously submitted to the CEC by the CA IOUs as part of the CEC's ITP process), the model that was established was a good fit to the data; it had a statistically significant slope ($p<0.001$), included only individual effects with statistically significant slopes, and yielded homoscedastic, normally distributed residuals.

8.2.2 Results of Incremental Cost of Quality Analysis

A model based on only four basic performance characteristics, lamp shape, wattage, color rendering index (CRI), and ENERGY STAR qualification status, explained 70% of the observed variability in price. The model predicts that ENERGY STAR qualification increases lamp price by 21%, whereas each five CRI units increase lamp price by 6% and each increase of one watt increases lamp price by 5%.

Interestingly, certain performance metrics that appear superficially correlated with price did not demonstrate statistically significant independent effects on price when corrected for the influence of other metrics. For example, lumens did not demonstrate a significant influence on price, independent of the effect of wattage. Similarly, correlated color temperature (CCT), lumen maintenance (L70), warranty length, and power factor did not demonstrate statistically significant independent influences on price after correcting for the influence of other factors. Likewise, improvements in other key performance metrics such as efficacy and dimmability do not appear to increase price significantly, if at all.

Wattage alone explains approximately 50% of the observed variability in price. The exceptionally close relationship between price and wattage is likely due to the fact that lamps of higher wattage must account for additional heat, which leads to additional costs associated with thermal management (heat sinks).

Once developed, the CASE Team used the model to predict the magnitude of the impact of each independent variable on lamp price. This was accomplished by implementing the model in a spreadsheet using the following equation:

Equation 8.1 Equation to predict the magnitude of independent variables on LED lamp price

$$Price = e^{(a \times shape\ +\ b \times ES\ + c \times (CRI - CRI_{mean}) + d \times (Watts - Watts_{mean}) + constant)}$$

where

shape	= the shape of the product (A, PAR, MR, BR, R, G, Candelabra);
ES	= the ENERGY STAR® qualification status of the product (1 or 0);
CRI	= the CRI of the product;
CRI_{mean}	= the mean CRI for all products;
Watts	= the wattage of the product;
$Watts_{mean}$	= the mean wattage of all products;

and

a, b, c, d, and constant are the parameter estimates derived from the regression model. The values of the parameter estimates are as follows:

a = -0.465
b = 0.189
c = 0.013
d = 0.045
constant = 3.598

The CASE Team then used the model to develop graphs for each lamp type to demonstrate relative price impacts associated with changes in wattage, CRI, and ENERGY STAR qualification status, by lamp type, shown below.

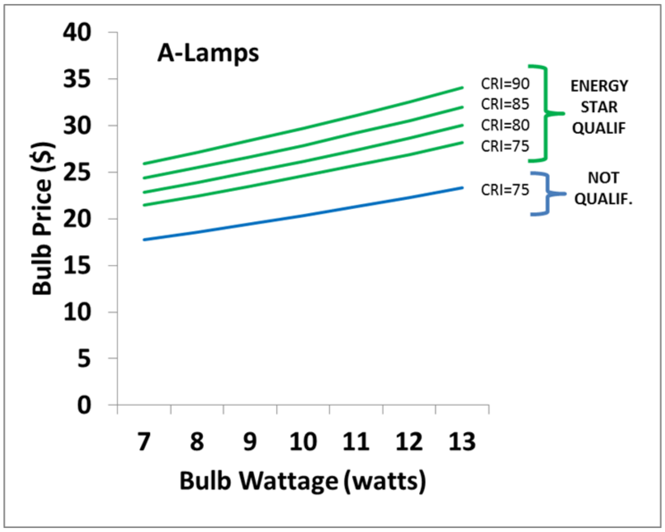


Figure 8.5 Relative impact of changes in Wattage, CRI and ENERGY STAR qualification on price of A-shape LED lamps in 2012

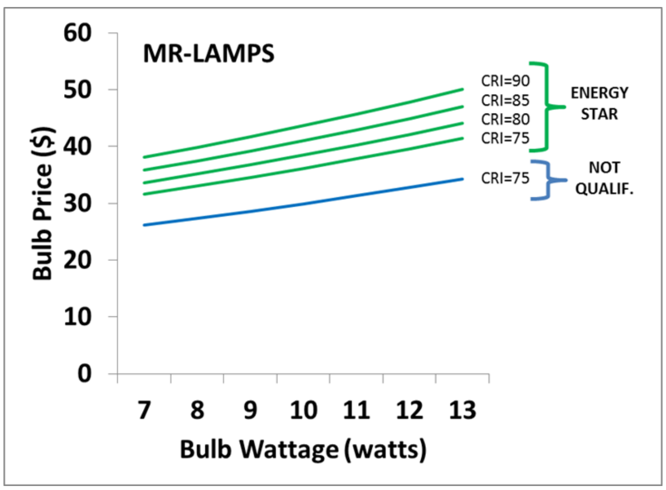


Figure 8.6 Relative impact of changes in Wattage, CRI and ENERGY STAR qualification on price of MR-shape LED lamps in 2012

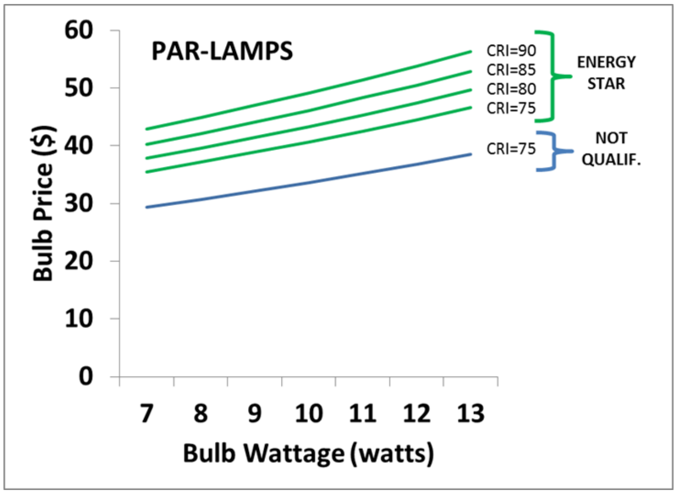


Figure 8.7 Relative impact of changes in Wattage, CRI and ENERGY STAR qualification on price of PAR-shape LED lamps in 2012

8.2.3 Next Steps for Cost of Quality Analysis

There are two next steps the CASE Team plans to conduct in fall of 2013 to further expand on the "Cost of Quality' analysis described above. First, the Team plans to update the data set by adding products that have been introduced to the market in the past year since the data were collected in 2012. The Team will consider both new models and any changes in prices that have occurred to models that are still being offered. This will allow the analysis to consider the rate of change in prices being observed, not just for lamps but also for individual aspects of lamp design.

The CASE Team also intends to add test data to the analysis so that we can account for various performance metrics for which data are not often or commonly available on manufacturer specification sheets. This will include consideration of the quality of dimming performance and dimming range, presence of flicker, color consistency between samples, and R9 values, among others. This data is being collected by the CLTC as part of its current testing program of about 60 directional and omni-directional replacement lamps and will be available by fall 2013.

8.3 Standards Case LED Lamp Incremental Cost Forecasts

For the purposes of forecasting the price of LED lamp quality into future years, the CASE Team combined results of the analysis of the incremental cost of quality with the total lamp price forecast analysis. The Team assumed that the relative incremental impact of product quality on product price will remain constant in the future. Specifically, the analysis forecasts that Qualifying LED products will continue to incur any incremental cost associated with higher CRI and with ENERGY STAR qualifications. (In reality, we expect that the adoption of mandatory standards will accelerate the rate at which incremental cost for the quality metrics comes down, due the economies of scale and commoditization that results from standards. This effect has been observed after other mandatory standards adoptions, and suggests that our assumptions here for future incremental cost may over-estimate those costs.)

This CASE Report assumes an incremental cost associated with ENERGY STAR certification and increased CRI. While this report does not propose the requirement of every element of the ENERGY STAR specification, the CASE Team believes that the ENERGY STAR qualification is a reasonable proxy for the other quality metrics being proposed as mandatory in this report, besides CRI (e.g., power factor, lamp life, start time).

An increase in CRI of 5 units in 2012 resulted in a price increase of 6% over the 2012 non-qualifying lamp price. We assume that an increase of 5 CRI units (from a forecasted market average of roughly 85 in 2016, up to the standard proposal of 90) would continue to result in a 6% increase over the 2016 forecasted non-qualifying lamp price. Similarly, ENERGY STAR certification resulted in a 21% increase in price over the 2012 non-qualifying lamp price, so we assume that the proposals in this CASE report will result in a 21% price increase in price over the non-qualifying lamp price in 2016. Together, this analysis assumes that an average Qualifying lamp will have a price that is 27% higher than an average Non-qualifying product. Table 8.4 shows the standards case LED lamp incremental cost forecasts from 2016 - 2031.

Table 8.4 Non-Qualifying and Qualifying product price forecasts, by lamp type, 2016 – 2031

	Year	Non-Qualifying Product Price	Multiplier for Incremental Cost of Quality	Qualifying Product Price	Incremental Cost
General Service	2016	$6.80	27%	$8.64	$1.84
	2021	$2.74	27%	$3.48	$0.74
	2026	$1.52	27%	$1.94	$0.41
	2031	$0.99	27%	$1.25	$0.27
Large Diameter	2016	$11.68	27%	$14.83	$3.15
	2021	$4.71	27%	$5.98	$1.27
	2026	$2.62	27%	$3.33	$0.71
	2031	$1.70	27%	$2.15	$0.46
Small Diameter Directional	2016	$8.42	27%	$10.70	$2.27
	2021	$3.40	27%	$4.31	$0.92
	2026	$1.89	27%	$2.40	$0.51
	2031	$1.22	27%	$1.55	$0.33
Decorative	2016	$9.16	27%	$11.63	$2.47
	2021	$3.69	27%	$4.69	$1.00
	2026	$2.05	27%	$2.61	$0.55
	2031	$1.33	27%	$1.69	$0.36

8.4 Design Life

Most LED replacement lamps are rated at 25,000 hours or more. In this analysis they are assumed to have a 15,000 hour minimum lifetime.

8.5 Lifecycle Cost / Net Benefit

Table 8.5 below shows the life cost and life cycle benefits per unit (qualifying LED lamp) sold in 2016. For each lamp type, the energy savings over the life of the product are greater than the incremental cost of the product, and the measure therefore has a benefit/cost ratio above 1, as shown in Table 8.6.

Table 8.5 Lifecycle Costs and Benefits per Unit for Qualifying Products Sold in 2016

Product Class	Design Life (years)	Lifecycle Costs per Unit (Present Value $)[a]			Lifecycle Benefits per Unit (Present Value $)[a]		
		Incremental Cost	Add'l Costs	**Total Costs**	Energy Savings[b]	Add'l Benefits	**Total Benefits**
General Service Lamps	14	$ 1.84	-	**$ 1.84**	$6.43	-	**$6.43**
Large Diameter Directional Lamps	6	$ 3.15	-	**$ 3.15**	$5.59	-	**$5.59**
Small Diameter Directional Lamps	6	$ 2.27	-	**$ 2.27**	$3.42	-	**$3.42**
Decorative Lamps	14	$ 2.47	-	**$ 2.47**	$5.75	-	**$5.75**

[a] Calculated using the CEC's average present value statewide energy rates that assume a 3% discount rate (CEC 2012b).

[b] For price of electricity, average annual rates were used, starting in the effective year (see Appendix A: for more details). It should be noted that while the proposed standard is cost-effective, it may be more cost-effective if using alternative rate structures. For example, marginal utility rates may more accurately reflect what customers save on utility bills as result of the standard.

Table 8.6 Lifecycle Cost Benefit Ratio for Qualifying Products and Standards Case NPV ($)

Product Class	**Lifecycle Benefit / Cost Ratio[a]**	Net Present Value ($)[b]		
		Per Unit	First Year Sales ($ million)	Stock Turnover (2031) ($ million) [c]
General Service (A-lamps)	3.5	$ 4.59	$ 87.5	$ 1,307.8
Large Diameter Directional Lamps	1.8	$ 2.43	$ 2.8	$920.8
Small Diameter Directional Lamps	1.5	$ 1.15	$ 0.2	$15.5
Decorative Lamps	2.3	$ 3.28	$ 5.4	$86.1

[a] Total present value benefits divided by total present value costs.

[b] Positive value indicates a reduced total cost of ownership over the life of the appliance.

[c] Because LED's have significantly longer product lives than the incandescent products they are intended to replace, and because the savings from this measure are primarily due to a 'second order' effect of increased market adoption of the covered product, the savings analysis in this CASE report did not assess the energy and cost of individual products purchased each year but rather the energy use and energy cost expenditures of the entire stock of incandescent, CFL, and LED sockets in California each year. Avoiding future lamp purchases is one of the benefits of increased LED adoption over time. The Stock Turnover NPV is calculated by comparing the total cumulative statewide energy cost savings, and total statewide incremental measure cost (for all sockets), over the 15 year period of analysis. This has been done utilizing the "conservative" savings scenario.

9 Acceptance Issues

9.1 Existing Standards and Specifications

If adopted, the mandatory proposals contained in this CASE initiative would not represent the first such effort to address the issue of LED replacement lamp quality. Over the past several years, a wide range of government agencies and other standards setting bodies have looked into these issues of light quality and product quality, all aimed at avoiding a significant consumer backlash to LED lamps that could set the market transformation efforts behind by many years. Most of these efforts have resulted in voluntary quality specifications; two regulatory agencies have set mandatory standards that apply to all lamps sold in their jurisdictions.

9.1.1 Voluntary LED Quality Specifications

Voluntary specifications identify a certain level of product quality that can help raise awareness among consumers about the differences in quality on the market and steer them towards better products. Often these specifications are designed to be utilized as the qualifying level for incentive programs, to ensure that rebate dollars are spent on products that are less likely to face acceptance issues among consumers. These specifications also give manufacturers a common set of higher performance criteria to aim for in their product design cycles. These specifications do not prevent lower quality products from entering the market, however.

Historically, the primary specifications used by incentive programs in California have been ENERGY STAR specifications, developed and maintained by the U.S. Environmental Protection Agency (EPA). The current ENERGY STAR specification for LED lamps is the Integral LED Lamps Specification v1.4. It has been effective since 2009 and has been revised 4 times. EPA has been working on developing a new "Lamps" specification which will combine the requirements for LEDs and CFLs into one document (though not all specs will be identical). EPA has issued five drafts of its Version 1 Lamps spec, with the latest "Final Draft" having just been released in summer 2013. It is expected that ENERGY STAR will finalize this specification in 2013. This specification contains a wide array of metrics meant to address product quality, including color maintenance, color angular uniformity, dimensional requirements, lamp toxics, and equivalency claims. This specification also includes requirements for many of the metrics that are included in this CASE initiative, including efficacy, color rendering, and color consistency. This CASE initiative will align itself with many of the proposed levels in the ENERGY STAR lamp specification, for consistency, and as appropriate.

The most relevant voluntary specification in California going forward will be the Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification (CA Voluntary Specification), which was approved by the CEC in 2012.The specification was developed at the request of the California Public Utilities Commission, which also directed the CA investor-owned utilities (IOUs) to begin using the specification as the basis for their rebate programs. This specification is intended to augment the ENERGY STAR Lamps specification. While several of the key requirements are more stringent than the ENERGY STAR lamps proposal, the specification also defers to the Lamps Spec on many of the metrics. The intent was to allow lamps to be able to meet the requirements of both the ENERGY STAR Spec and the CA Voluntary Specification. The CA Voluntary Spec identifies a high level of quality that will serve as a reach goal for LED lamp manufacturers in 2013. This CASE initiative can be considered a follow up activity in support of the goals already described in that report.

There are other voluntary quality specifications in existence or in various stages of development around the world. The solid state lighting branch of the Efficient Electrical End-Use Equipment Program at the International Energy Agency (IEA 4E SSL) maintains a quality assurance program for LED lamps that includes several tiers of lamp performance, and is intended to be available for use worldwide. A group called the Efficient Lighting Initiative maintains a "high performance specification" for non-directional self-ballasted LEDs, intended for use in developing and transition economies. Other more regional efforts exist in China (Standardization Administration of China), India (Bureau of Indian Standards), the UK (The Energy Savings Trust), and elsewhere. Most of these specifications include minimum requirements for color rendering, color temperature (including color consistency), power factor, and efficacy.

9.1.2 Mandatory LED Quality Standards

Mandatory minimum standards are essential to accompany voluntary specifications. In California, beginning in late 2013, rebates will only be available for replacement lamp products that meet the CA Voluntary Specification and this will help identify the best LED products for consumers and provide an extra incentive to purchase them. However, low quality products may still enter the market and may still be able to compete on a price basis with quality lamps being rebated through utility programs. Many consumers may still inadvertently purchase these low quality products, and be disappointed with the results. This situation can be avoided by the adoption of mandatory standards, such as those adopted in 2012 by the European Union and the Mexican National Commission for Energy Efficiency (CONUEE).

9.1.3 European Union Standards Development (Ecodesign) Process and Results

Under the Ecodesign process, the European Union (EU) sets requirements for energy-related products to achieve cost-effective reduction of greenhouse gas emissions. As such, ecodesign regulations are mandatory in 30 countries (27 European Union countries and three European Economic Area countries). On December 12, 2012, the European Commission published lighting equipment regulations, including those for LED lamps, effective January 4, 2013. For LED products these requirements will be enforced starting September 1, 2013, except for lamp survival factor and lumen maintenance requirements which are allowed until March 1, 2014 for compliance.

The ecodesign process starts with a preparatory study, which is developed by a contracted consultant and includes technical, environmental, and economic aspects of the product. It includes a full life cycle assessment and extends beyond energy into other environmental impacts, like water. The study is released in chapters with public meetings for stakeholder input, from which the European Commission develops a working document. A Consultation Forum of registered interested participants, including environmental groups, consumer interest groups, and manufacturers, is formed to review and revise the document. In parallel to the Consultation Forum, an impact assessment is conducted that analyzes the energy savings as well as water and climate impacts. The impact assessment is then published at the end of the process, along with the final regulation.

After gathering input from the Consultation Forum, the Commission then formulates the document into a draft regulation and submits it to the Interservice Consultation for evaluation by the Director Generals (DG), primarily driven by the DGs for energy, enterprise and environment. The final document is voted on by the Regulatory Committee, before being sent for review by the European Parliament. Additionally, the Commission consults with the World Trade Organization to ensure that the proposal does not violate any treaties. Once it has passed all these approval processes, the regulation is formally adopted by the Commission and published in the Official Journal of the EU.

The EU typically develops and publishes the details of the test procedures after the standards are adopted. As of late 2012, the test procedures for the new EU LED lamp standards were not yet published. The full text of the European Union standard was previously submitted to the CEC as part of the CA IOU's response the CEC's ITP, and is also publically available for download.[6] Table 9.1 below outlines the recently adopted EU ecodesign requirements for LED lamps.

Table 9.1 Summary of EU LED Lamp Mandatory Quality Standards

Functionality parameter	Requirement for Stage 1 (September 1, 2013), except where indicated otherwise
Corrected power for lamps operating on external LED lamp control gear	$P_{rated} \times 1.10$
Lamp Survival Factor at 6,000 hours	≥ 0.90
Lumen Maintenance at 6,000 hours	≥ 0.80
Number of switching cycles before failure	≥ 15,000 if rated lamp life ≥ 30,000 hours, otherwise ≥ half the rated lamp life expressed in
Starting time	< 0.5 seconds
Lamp warm-up time to 95% ϕ	< 2 seconds
Premature failure rate	≤ 5.0 % at 1,000 hours
Color rendering	≥ 80 or ≥ 65 if the lamp is intended for outdoor or industrial applications in accordance with point 3.1.3(l)
Color consistency	Variation of chromaticity coordinates within a six-step MacAdam ellipse or less
Lamp power factor (PF) for lamps with integrated control gear	P ≤ 2 W: no requirement 2 W < P ≤ 5 W: PF > 0.4 5 W < P ≤ 25 W: PF > 0.5 P > 25 W: PF > 0.9
Luminous flux multiplication factor for lumen maintenance	1+0.5x(1-LLMF)
Multiplication factors for LED lamps 20° ≤ beam angle 15° ≤ beam angle < 20° 10° ≤ beam angle < 15° beam angle < 10°	Luminous flux multiplication factor: 1 0.9 0.85 0.8

9.1.4 Mexico Standards Development Process and Results

In Mexico, mandatory energy efficiency standards fall under the jurisdiction of the National Commission for Energy Efficiency (Comision Nacional para el Uso Eficiente de la Energia - CONUEE) with the purpose to conserve non-renewable energy resources for future generations. CONUEE develops energy efficiency standards, including setting minimum energy performance levels (MEPS) and the test procedures to measure performance. In addition to establishing standards, CONUEE verifies compliance and regulates a mandatory comparative energy label for appliances.

[6] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:342:0001:0022:EN:PDF

Mexico released Official Mexican Standards (Normas Oficiales Mexicanas – NOM) for LED lamps on June 22, 2012. The standard applies to directional and omnidirectional LED lamps used with general lighting.

Product regulations for MEPS are reviewed by the National Consultative Committee of Standards for the Preservation and Rational Use of Energy Resources (Comité Consultivo Nacional de Normalización para la Preservación y Uso Racional de los Recursos Energéticos – CCNNPURRE). CCNNPURRE is comprised of representatives from the Secretariats of Economy and presided over by CONUEE. The revised proposal is then published in the Official Journal of the Federation (Diario Oficial de la Federación – DOF) and provided a public comment period for stakeholder input. CCNNPURRE incorporates public comments into the proposal and approves the final MEPS for publication in the DOF.

The full text of the Mexican standard and its test procedures were previously submitted to the CEC as part of the CA IOU's response the CEC's ITP, and they are also publically available for download online.[7] The tables below summarize the primary Mexican MEPS requirements for omni-directional and directional LED lamps.

Table 9.2 Mexican Mandatory Quality LED Standards; Minimum Luminous Efficacy

Rated range of luminous flux (lm)	Minimum luminous efficacy (lm/W)
Integrated omnidirectional LED lamps with A, BT, PS and T shaped bulbs	
Less than or equal to 325	50
Greater than 325 and less than or equal to 450	50
Greater than 450 and less than or equal to 800	55
Greater than 800 and less than or equal to 1,100	55
Greater than 1,100 and less than or equal to 1,600	55
Greater than 1,600	55
Integrated omnidirectional LED lamps with BA, C, CA, F and G shaped bulbs	
Less than or equal to 150	40
Greater than 150 and less than or equal to 300	40
Greater than 300	40
Integrated directional LED lamps with AR11, BR, ER, MR, PAR and R shaped bulbs	
Diameter ≤ 2.5 in (6.35 cm)	40
Diameter > 2.5 in (6.35 cm)	45

[7] http://www.bdlaw.com/assets/attachments/Mexico%20-%20NORMA%20Oficial%20Mexicana%20NOM-030-ENER-2012.pdf

Table 9.3 Mexican Mandatory Quality LED Standards; Correlated Color Temperature

Nominal CCT (K)	Tolerance of CCT (K)
2700	Greater than or equal to 2580 and less than 2870
3000	Greater than or equal to 2870 and less than 3220
3500	Greater than or equal to 3220 and less than 3710
4000	Greater than or equal to 3710 and less than 4260
5000	Greater than or equal to 4745 and less than 5311
6500	Greater than or equal to 6020 and less than 7040

Table 9.4 Mexican Mandatory Quality LED Standards; Maintained Minimum Luminous Flux

Rated Life (h)	Maintained minimum luminous flux (%) (measured at 25% of rated life or 6,000 hrs, whichever is greater)
Less than 15,000	83.2
Greater than or equal to 15,000 and less than 20,000	86.7
Greater than or equal to 20,000 and less than 25,000	89.9
Greater than or equal to 25,000 and less than 30,000	91.8
Greater than or equal to 30,000 and less than 35,000	93.1
Greater than or equal to 35,000 and less than 40,000	94.1
Greater than or equal to 40,000 and less than 45,000	94.8
Greater than or equal to 45,000 and less than 50,000	95.4
Greater than or equal to 50 000	95.8

Table 9.5 Mexican Mandatory Quality LED Standards; Other functionality requirements

Functionality parameter	Minimum Requirement
Initial luminous flux	≥ 90% of the nominal value marketed by the product
Color rendering index	≥ 77 ≥ 75 for integrated directional LED lamps with a CCT > 6000 K
Power factor	P ≤ 5 W: PF ≥ the value marked on the product P > 5 W: PF ≥ 0.7 for integrated omidiretional LED lamps 5 W < P ≤ 25 W: PF > 0.5 for integrated directional LED lamps P > 25 W: PF > 0.7 for integrated directional LED lamps
THD	≤ as value marked on product
Surge	7 surges with one damped sinusoidal waveform of 100kHz of 2.5kV differential mode
Resistance to thermal shock and switching	All integrated omnidirectional lamps must past thermal shock test cycles (Appendix C)
Warranty	All Lamps must offer a minum warranty of 3 years

9.2 Stakeholder Positions

Refer to "Responses to Invitation to Participate" (available at CEC's 2013 Appliance Efficiency Pre-Rulemaking page[8]) for stakeholder comments.

10 Environmental Impacts

10.1 Hazardous Materials

There are no known incremental hazardous materials impacts from the efficiency improvements as a results of the proposed standards.

10.2 Air Quality

This proposed measure is estimated to reduce total criteria pollutant emissions in California by 363,000 lbs/year in 2031 with an estimated value of $17 million, as shown in Table 10.1. Criteria pollutant emission factors for California electricity generation were calculated per MWh based on California Air Resources Board data of emission rates by power plant type and expected generation mix [CARB 2010]. The monetization of these criteria pollutant emission reductions is based on CARB power plant air pollution emission rate data times the dollar per ton value of these reductions based on Carl Moyer values where available, and San Joaquin Valley UAPCD "BACT" thresholds for sulfur oxides (SOx). These dollar per ton values vary significantly for fine particulates, as discussed in Appendix B: (CARB 2011a, CARB 2013a and San Joaquin Valley UAPCD).

Table 10.1 Estimated California Criteria Pollutant Reduction Benefits (lbs/year) in 2031

	lbs/year	**Carl Moyer $/ton (2013)**	**Monetization**
ROG	58,156	$ 17,460	$ 507,703
Nox	198,351	$ 17,460	$ 1,731,607
Sox	20,848	$ 18,300	$ 190,757
PM2.5	85,723	$ 349,200	$ 14,967,321
Total	**363,100**		**$ 17,397,400**

10.3 Greenhouse Gases

Table 10.2 shows the stock greenhouse gas savings in 2031 and the range of the societal benefits as a result of the standard: 922,000 metric tons of CO2e, equal to between $60 million and $184 million of societal benefits. The total avoided CO2e is based on CARB's estimate of 437 MT CO2e/GWh of energy savings

[8] http://www.energy.ca.gov/appliances/2013rulemaking/index.html

from energy efficiency improvements, and includes additional electrical transmission and distribution loses estimated at 7.8% (CARB 2008). The range of societal benefits per year is based on a range of annual $ per metric ton of CO_2 (in 2013 dollars) sourced from the U.S. Government's Interagency Working Group on Social Cost of Carbon (SCC) (Interagency Working Group 2013). The low end uses the average SCC, while the high end incorporates SCC values which use climate sensitivity values in the 95th percentile, both with 3% discount rate. It is important to note that this range can be lower and higher, depending on the approach used, so policy judgments should consider this uncertainty. See Appendix C: for more details regarding this and other approaches.

Table 10.2 Estimated California Statewide Greenhouse Gas Savings and Cost Savings for Standards Case in 2031

Stock GHG Savings (MT of CO_2e/yr)	**Value of Stock GHG Savings - low** ($)	**Value of Stock GHG Savings - high** ($)
922,507	$59,922,933	$183,612,912

11 Recommendations

11.1 Scope

This standards proposal applies to replacement integral LED lamps, which are defined as lamps with LEDs, an integrated LED driver, and an ANSI standard base type that is designed to connect to the branch circuit via a lampholder/socket. The standard applies to lamps with the following base types: E26, E26d, E17, E11, E12, GU24, GU10, GU5.3, and GX5.3. The scope is limited to lamps with rated nominal operating voltages of 120 (including any lamp capable of being operated at a voltage range at least partially within 110 and 130 volts), 240 or 277 VAC, or 12 or 24 VAC or VDC.

The proposal includes some requirements that apply to all covered lamp types, and other requirements that apply only to certain lamp types. The proposal also includes requirements that apply only to lamps making equivalency claims to the incandescent lamps they are intended to replace.

The standards proposal does not apply to the following product types:

- Lamps with base types not covered in ANSI standards
- Lamps providing more than 2,600 lumens
- Lamps intended to replace linear fluorescent or high-intensity discharge lamps
- Lamps incorporating power-consuming features in the on or off state which do not provide illumination (e.g. audio functions, air fresheners).
- Colored lamps (The term 'colored lamp' means a lamp designated and marketed as a colored lamp, that has a color rendering index of less than 50, and is capable of providing correlated color temperature of greater than 6,000K or less than 2,400K when operated at full light output.).

11.2 Recommended Standards Proposal

This standards proposal includes efficacy requirements by lamp shape, as shown in Table 11.1 below. These efficacy requirements are consistent with the requirements in the Final Draft of the ENERGY STAR Lamps Specification Version 1.

Table 11.1 Recommended Efficacy Standards Proposals by Lamp Shape

Lamp Type (LED lamps designed to replace lamps of these designated shapes)	**Lamp Rated Wattage (watts)**	**Minimum Lamp Efficacy (initial lm/W)**
Omni-directional	<15	55
	≥15	65
Directional (large and small diameter)	<20	40
	≥20	50
Decorative	<15	45
	15≤ W <25	50
	≥25	60

This standards proposal includes LED lamp quality requirements, as shown in Table 11.2 below. Many of these requirements are consistent with the requirements in the Final Draft of the ENERGY STAR Lamps Specification Version 1. Others are consistent with the CEC's Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification. Some requirements are based on product testing funded by PG&E in 2012 and 2013 which assessed performance of available products and the feasibility of meeting these specific requirements. These requirements are designed to address light quality, dimmability, lamp life, or electrical performance issues.

Table 11.2 Recommended Quality Standards Proposals for all Covered LED Lamps

Metric	Requirement
Color Rendering	Lamps shall have a minimum CRI (R_a) of 90; and a minimum R_9 value of 50
Correlated Color Temperature (CCT) & Chromaticity Consistency	Reported lamp model light color temperature shall correlate to one of the following nominal CCTs, per the referenced ANSI document: 2700K, 3000K, 3500K, 4000/4100K, 5000K, 6500K. Lamp color of the model shall fall within the 4-step ANSI quadrangle for the designated CCT. Tested units of a given model shall have color points within a distance of .011 from each other in the 1931 CIE Chromaticity diagram.
Dimmability	Lamps must be capable of continuous dimming without visible flicker or audible noise, from 100% - 10% of initial light output. (Continuous dimming is defined as being capable of operating at least 10 distinct levels between 100% power and off.) CCT requirement in dimmed range: CCT measured at 25% power shall be less than or equal to the CCT measured at full output.
Flicker	Lamps shall have an amplitude modulation (Percent Flicker) of less than 30 percent for frequencies less than 200 Hz, when tested at 100% power and 25% power.
Audible Noise	Lamp shall not emit noise above 24dBA, when tested at 100% power and 25% power.
Power Factor	Lamps must have a Power Factor greater than or equal to 0.9 when measured at 100% power and greater than or equal to 0.7 when measured at 25% power.
Start Time	Lamps shall have a maximum start time of 0.5 seconds.
Premature Failure Rate	All lamps tested must be operational at 1,000 hours, when tested at ambient temperature (25°C ± 5°C)
Elevated Temperature	When tested at 45°C, the lamp shall maintain ≥ 90% of the initial light output (total luminous flux) measured at ambient temperature (25°C ± 5°C)
Rapid Cycling	When cycled at 2 minutes on, 2 minutes off, or 5 minutes on 5 minutes off, lamp shall survive the lesser number of cycles: one cycle per hour of rated life or 15,000 cycles.
Warranty	Lamps shall have a minimum 3 year warranty
Compatibility with Dimmers	Lamps shall be compliant with NEMA SSL7A as either a Type 1 or Type 2 LED Light Engine (LLE)

This standards proposal includes requirements for lamps that are designed and marketed to replace incandescent lamps by making “equivalency claims,” as shown in the tables below. Table 11.3, Table 11.4

Table 11.5 and Table 11.6 include requirements by lamp shape for the amount of light that must be provided by LED lamps that claim equivalency to incandescent lamps on their product packaging or marketing. In the case of PAR and MR lamps, the standards proposal also includes a method to identify the required center beam candle power for LED lamps claiming equivalency to incandescent lamps.

As shown in Table 11.3 and lamps claiming equivalency to certain omni-directional and decorative incandescent lamps must also provide a minimum level of light distribution to ensure true omni-directionality.

Table 11.3 Recommended Light Output and Light Distribution Requirements for LED Lamps Making Equivalency Claims as Replacements for Lamps of Shapes A, BT, P, PS, S and T

Metric	Requirement	
Equivalency (Lumen Output)	Rated Wattage of the Referenced Incandescent Lamp (watts)	Minimum Lumen Output
	40	450
	60	800
	75	1100
	100	1600
	150	2600
Equivalency (Light Distribution)	Lamp luminous intensity distribution shall emulate that of the referenced incandescent lamp as follows: 90% of the luminous intensity measured values (candelas) shall vary by no more than 25% from the average of all measured values. All measured values (candelas) shall vary by no more than 50% from the average of all measured values. No less than 5% of total flux (zonal lumens) shall be emitted in the 135° to 180° zone.	

Table 11.4 Recommended Light Output and Light Distribution Requirements for LED Lamps Making Equivalency Claims as Replacements for Lamps of Shapes B, BA, C, CA, DC, F, G

Metric	Requirement		
Equivalency (Lumen Output)	Rated Wattage of the Referenced Incandescent Lamp (watts)	Globe (G) Shape Required Light Output (lumens)	All other (non-G Shape) Decorative Lamps Required Light Output (lumens)
	10		70-89
	15		90-149
	25	250-349	150-299
	40	350-499	300-499
	60	500-574	500-699
	75	575-649	
	100	650-1099	
	150	1100-1300	
Equivalency (Light Distribution)	Lamp luminous intensity distribution shall emulate that of the referenced incandescent lamp as follows: No less than 5% of total flux (zonal lumens) shall be emitted in the 110° to 180° zone.		

Table 11.5 Recommended Light Output Standards Proposals for LED Lamps Making Equivalency Claims as Replacements for Lamps of Shapes R, BR, and ER

<table>
<tr><th>Metric</th><th colspan="2">Requirement</th></tr>
<tr><td rowspan="8">Equivalency (Lumen Output)</td><td colspan="2">Reported lamp initial light output (in lumens) shall be greater than or equal to ten times the incandescent lamp's rated wattage for the following referenced incandescent lamps:
• 65 watt BR30, BR40 and ER40 lamps
• BR30, ER30, BR40 and ER40 lamps ≤ 50 watts
• R20 lamps ≤ 45 watts
• Lamps ≤ 40 watts
• Lamps smaller than 2.25" diameter
For example - a lamp replacing a 25W incandescent shall produce ≥ 250 lumens.

For all other R, BR and ER lamps not included above, reported lamp light output (in lumens) shall be greater than or equal to the product of the claimed wattage equivalency and the light output multiplier in the table below.</td></tr>
<tr><td>Rated Wattage of the Referenced Incandescent Lamp (watts)</td><td>Light Output Multiplier</td></tr>
<tr><td>40 – 50 W</td><td>10.5</td></tr>
<tr><td>51 – 66 W</td><td>11</td></tr>
<tr><td>67 – 85 W</td><td>12.5</td></tr>
<tr><td>86 – 115 W</td><td>14</td></tr>
<tr><td>115 – 155 W</td><td>14.5</td></tr>
<tr><td>156 - 205 W</td><td>15</td></tr>
</table>

Table 11.6 Recommended Light Output and Center Beam Intensity Standards Proposals for LED Lamps Making Equivalency Claims as Replacements for Lamps of Shapes PAR and MR

Metric	Requirement	
	Rated Wattage of the Referenced Incandescent Lamp (watts)	Light Output Multiplier
Equivalency (Lumen Output)	<30	9.5
	30-45	10.5
	46-65	11.5
	66-85	12.5
	86-110	13.5
	>110	14.5
Equivalency (Center Beam Candlepower)	Lamp center beam intensity shall be greater than or equal to the center beam intensity value calculated by the ENERGY STAR Center Beam Intensity Benchmark Tool for the referenced incandescent lamp. (http://www.energystar.gov/ia/products/lighting/iledl/IntLampCenterBeamTool.zip)	

Table **11.7** includes recommended standards proposals for color temperature of lamps that make equivalency claims to replace incandescent lamps.

Table 11.7 Recommended Color Temperature Standards Proposals for All Covered LED Lamps Making Equivalency Claims

Metric	Requirement
Equivalency (Light Color)	Lamp chromaticity coordinates must fall within either the 2700K or 3000K ANSI 4 step color bin

This standards proposal also includes recommended labeling / marking requirements to be included in Section 1607 of Title 20, as summarized in Table 11.8 below.

Table 11.8 Recommended Labeling/Marking requirements for covered LED Lamps

Lamp Type	**Marking Requirements** (Lamp must permanently display each of the following)
All Covered LED Lamps	Watts (rounded to nearest tenth of a W)
	Lumens (rounded to nearest 10 lumens)
	CRI (rounded to nearest whole number)
	Nominal CCT (ANSI nominal CCT bin)
	Specify whether lamp Type I or Type II NEMA SSL7A compliant using one of the following: o SSL7A TYPE I o SSL7A TYPE II
Directional Lamps only (PAR, MR, ER, BR, R Shape)	Measured beam angle (rounded to the nearest whole degree)
	Center beam candle power (rounded to the nearest 50 candela)

Lamp packaging exterior shall state "Warranty" or "Limited Warranty", the warranty period (in years), and a phone number or website address for consumer complaint resolution. The complete written warranty shall be printed on packaging exterior or included within lamp packaging.

11.3 Implementation Plan

The expected implementation for this standards proposal is for the CEC to proceed with its appliance standards rulemaking authority, from pre-rulemaking and rulemaking through adoption, and for manufacturer compliance upon effective date.

11.4 Proposed Changes to the Title 20 Code Language

This section contains the proposed changes written up as draft Title 20 code language, with changes being proposed for Sections 1602 (Definitions), 1605.3 (State Standards for Non-Federally Regulated Appliances), and 1607 (Marking of Appliances).

1602 Definitions.

(k) Lamps

Covered LED Replacement Lamp: A covered LED Replacement lamp is defined as a lamp with LEDs, an integrated LED driver, and an ANSI standard base of type E26, E26d, E17, E11, E12, GU24, GU10, GU5.3, or GX5.3, that is designed to connect to the branch circuit via a lampholder/socket, and has a rated nominal operating voltages of 120 (including any lamp capable of being operated at a voltage range at least partially within 110 and 130 volts), 240 or 277 VAC, or 12 or 24 VAC or VDC. The following product types are not considered Covered LED Lamps:

- Lamps with base types not covered in ANSI standards
- Lamps providing more than 2,600 lumens
- Lamps intended to replace linear fluorescent or high-intensity discharge lamps
- Lamps incorporating power-consuming features in the on or off state which do not provide illumination (e.g. audio functions, air fresheners).
- Colored lamps (The term 'colored lamp' means a lamp designated and marketed as a colored lamp, that has a color rendering index of less than 50, and is capable of providing correlated color temperature of greater than 6,000K or less than 2,400K when operated at full light output.).

Equivalency Claims: Equivalency Claims are defined as verbiage, diagrams, images, or other markings on product packaging or product marketing materials that suggest a replacement lamp is equivalent to an incandescent lamp. This includes claims about wattage equivalency (e.g. 10W = 60W) or messaging about the lamp intended to be replaced by an LED product (e.g.: "Replaces a 60W incandescent," or "Compare to a 90W PAR lamp"). LED lamps marketing themselves solely lamp shape and product wattage (e.g. 12W BR lamp") without making any reference to incandescent technology or equivalency are not considered to be making "Equivalency Claims."

1605.3 State Standards for Non-Federally Regulated Appliances.

(XX) LED Replacement Lamps

(1) All covered LED replacement lamps manufactured on or after the effective date shall meet the requirements shown in Tables XX-1(a) through XX-1(b) below.

Table XX-1(a) Efficacy requirements for LED Replacement Lamps

Metric	Requirement			Test Procedure	Supplemental Testing Guidance
	Lamp Type (LED lamps designed to replace lamps of these designated shapes)	Lamp Rated Wattage (watts)	Minimum Lamp Efficacy (initial lm/W)		
Efficacy	Omnidirectional	<15	55	IES LM-79-08	Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position. All calculations of efficacy values shall be carried out on a per unit basis with directly measured (unrounded) values. A 3% tolerance may be applied to the measured initial luminous flux value of each unit (e.g. [initial luminous flux of a unit X 1.03]) prior to the calculation of efficacy for the unit if the average of all measured lamps fails to meet the requirement without the tolerance. No other tolerances should be applied and the reported value for the sample shall be the average of the calculated efficacies (initial luminous flux divided by measured wattage) for all units in the sample. The reported value shall be the average of the unit values rounded to the nearest tenth.
		≥15	65		
	Directional (large and small diameter)	<20	40		
		≥20	50		
	Decorative	<15	45		
		15≤ W <25	50		
		≥25	60		

Table XX-1(b) Other Quality Requirements for LED Replacement Lamps

Metric	Requirement	Test Procedures & Reference Documents	Supplemental Testing Guidance
Color Rendering	Lamps shall have a minimum CRI (R_a) of 90; and a minimum R_9 value of 50	Measurement: IES LM-79-08 Calculation: CIE 13.3-1995	Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position. Reported R_a and R_9 values shall be the average of the unit measured values rounded to the nearest whole number.
Correlated Color Temperature & Chromaticity Consistency	Reported lamp model light color temperature shall correlate to one of the following nominal CCTs, per the referenced ANSI document: 2700K, 3000K, 3500K, 4000/4100K, 5000K, 6500K. 9 out of 10 units tested shall fall within the 4-step ANSI quadrangle for the designated CCT. 9 out of 10 units tested shall fall within a distance of .011 from each other in the 1931 CIE Chromaticity diagram.	Measurement: IES LM-79-08 Calculation: CIE 15.2004 Reference Document: ANSI C78.377-2011	Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position. Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.
Flicker	Lamps shall have an amplitude modulation (Percent Flicker) of less than 30 percent for frequencies less than 200 Hz. 9 out of 10 units tested shall meet the requirement.	ENERGY STAR® Program Requirements Product Specification for Lamps: Light Source Flicker Draft Recommended Practice Rev. July-2013 (See procedure for measuring flicker without a dimmer)	Test results obtained using the ENERGY STAR test procedure should then be run through a low-pass filter in order to filter out any modulation occurring at frequencies greater than 200 Hz. An RC low-pass filter is an example of cut-off filter that can be used to develop results for this reporting criteria.
Audible Noise	Lamp shall not emit noise above 24dBA. 80% of tested lamp/dimmer combinations must meet the requirement.	ENERGY STAR® Program Requirements Product Specification for Lamps: Noise Draft Recommended Practice Rev. July-2013	Sample Size: 1 lamp per dimmer and 4 lamps per dimmer The loudest measurement of all lamp/dimmer combinations shall be reported as the sound level. Measurement shall be on a single lamp.

Power Factor	Lamps must have a Power Factor greater than or equal to 0.9.	Measurement: ANSI C82.77-2002 Sections 6 and 7	Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position. Tested units, including low voltage lamps, shall be operated at rated voltage. The reported value shall be the average measured values of units tested rounded to the nearest tenth.
Dimmability	Lamps must be capable of continuous dimming from 100% - 10% of initial light output. (Continuous dimming is defined as being capable of operating at at least 10 distinct levels between 100% power and off.) 80% of tested lamp/dimmer combinations must meet this requirement and the following four dimming sub-requirements: Lamps shall have an amplitude modulation (Percent Flicker) of less than 30 percent for frequencies less than 200 Hz, when tested at 25% of full output power. 80% of tested lamp/dimmer combinations must meet the requirement. Lamp shall not emit noise above 24dBA, when tested 25% of full output power. 80% of tested lamp/dimmer combinations must meet the requirement. Lamps must have a Power Factor greater than or equal to 0.7 when measured at 25% of full output power. 80% of tested lamp/dimmer combinations must meet the requirement.	ENERGY STAR® Program Requirements Product Specification for Lamps: Light Output on a Dimmer Draft Recommended Practice Rev. July-2013. This test procedure shall be used in conjunction with the following four test procedures to obtain measurements at dimmed states: ENERGY STAR® Program Requirements Product Specification for Lamps: Light Source Flicker Draft Recommended Practice Rev. July-2013 (See procedure for measuring flicker with a dimmer) ENERGY STAR® Program Requirements Product Specification for Lamps: Noise Draft Recommended Practice Rev. July-2013 Measurement: ANSI C82.77-2002 Sections 6 and 7	Sample Size for all dimmability tests (continuous dimming down to 10%, flicker, noise, power factor, and color temperature): 1 lamp per dimmer and 4 lamps per dimmer. Test results obtained using the ENERGY STAR test procedure should then be run through a low-pass filter in order to filter out any modulation occurring at frequencies greater than 200 Hz. An RC low-pass filter is an example of cut-off filter that can be used to develop results for this reporting criteria. The loudest measurement of all lamp/dimmer combinations shall be reported as the sound level. Measurement shall be on a single lamp. See Section 8 of the Recommended Practice – Noise, for reporting information. The reported values shall be the measured values rounded to the nearest tenth.

	Lamp CCT measured at 25% of full output power shall be less than or equal to the CCT measured at full output. 80% of tested lamp/dimmer combinations must meet the requirement.	Measurement: IES LM-79-08	Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.
Start Time	Lamps shall have a maximum start time of 0.5 seconds.	ENERGY STAR® Program Requirements Product Specification for Lamps: Start Time Draft Test Method Rev. July-2013	Sample Size: 3 units per model. The reported value shall be the average of measured unit values tested, rounded to the nearest millisecond.
Premature Failure Rate	100% of lamps tested must be operational at 1,000 hours, when tested at ambient temperature (25°C ± 5°C)	Testing Set Up IES LM-79-08	Sample Size: 10 lamps per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
Elevated Temperature Test	When tested at 45°C, the lamp shall maintain ≥ 90% of the initial light output (total luminous flux) measured at ambient temperature (25°C)	ENERGY STAR® Program Requirements Product Specification for Lamps: Elevated Temperature Light Output Ratio Draft Test Method Rev. July-2013	Sample Size: One unit tested base-up. The reported value shall be the calculated ratio for the unit rounded to the nearest tenth.
Rapid Cycling	When cycled at 2 minutes on, 2 minutes off, or 5 minutes on 5 minutes off, lamp shall survive the lesser number of cycles: one cycle per hour of rated life or 15,000 cycles. At least 5 out of 6 units shall survive the minimum number of cycles.	Measurement: IES LM-65-10 (clauses 4,5,6)	Sample Size: 6 units per model tested base-up. The samples shall be unique for this test. Testing shall be conducted at full power. The reported value shall be the number of units surviving the minimum number of cycles.
Warranty	Lamps shall have a minimum 3 year warranty, based on continuous operation of at least 3 hours of use per day.	NA	NA
Compatibility	Lamps shall be compliant with NEMA SSL7A as either a Type 1 or Type 2 LED Light Engine (LLE)	NEMA SSL 7-A	NA

(2) All covered LED replacement lamps manufactured on or after the effective date that are marketed to replace incandescent lamps by making equivalency claims (as defined in Section 1602 (k)) on the product packaging, or any other marketing material, shall meet the requirements of the applicable table below.

Table XX-2(a) Requirements for LED Lamps Making Equivalency Claims to Incandescent Lamps of Shapes A, BT, P, PS, S or T

<table>
<tr><th>Metric</th><th colspan="2">Requirement</th><th>Test Procedures & Reference Documents</th><th>Supplemental Testing Guidance</th></tr>
<tr><td rowspan="6">Light Output Equivalency</td><td>Rated Wattage of the Referenced Incandescent Lamp (watts)</td><td>Minimum Lumen Output</td><td rowspan="6">IES LM-79-08</td><td rowspan="6">Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
A 3% tolerance may be applied to the measured initial luminous flux value of each unit (e.g. [initial luminous flux of a unit X 1.03]) if the average of all measured lamps without the tolerance fails to meet the requirement. No other tolerances shall be applied and the reported value for the sample shall be the average of the unit values and may be rounded to the nearest multiple of 5.</td></tr>
<tr><td>40</td><td>450</td></tr>
<tr><td>60</td><td>800</td></tr>
<tr><td>75</td><td>1100</td></tr>
<tr><td>100</td><td>1600</td></tr>
<tr><td>150</td><td>2600</td></tr>
<tr><td>Light Distribution Equivalency</td><td colspan="2">Lamp luminous intensity distribution shall emulate that of the referenced incandescent lamp as follows:
90% of the luminous intensity measured values (candelas) shall vary by no more than 25% from the average of all measured values. All measured values (candelas) shall vary by no more than 50% from the average of all measured values.
No less than 5% of total flux (zonal lumens) shall be emitted in the 135° to 180° zone.</td><td>IES LM-79-08</td><td>See Appendix A-1 of the ENERGY STAR Lamps V1.0 Final Draft Specification (Luminous Intensity Distribution Diagram for Omnidirectional Lamp) for diagram depicting test measurements</td></tr>
<tr><td>Light Color Equivalency</td><td colspan="2">Lamp chromaticity coordinates must fall within either the 2700K or 3000K ANSI 4 step color bin</td><td>Measurement: IES LM-79-08

Calculation: CIE 15.2004

Reference Document: ANSI C78.377-2011</td><td>Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.</td></tr>
</table>

Table XX-2(b) Requirements for LED Lamps Making Equivalency Claims to Decorative Incandescent Lamps of Shapes B, BA, C, CA, DC, F, G

<table>
<tr><th>Metric</th><th colspan="3">Requirement</th><th>Test Procedures & Reference Documents</th><th>Supplemental Testing Guidance</th></tr>
<tr><td rowspan="9">Light Output Equivalency</td><td>Rated Wattage of the Referenced Incandescent Lamp (watts)</td><td>Globe (G) Shape Required Light Output (lumens)</td><td>All other (non-G Shape) Decorative Lamps Required Light Output (lumens)</td><td rowspan="9">IES LM-79-08</td><td rowspan="9">Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
A 3% tolerance may be applied to the measured initial luminous flux value of each unit (e.g. [initial luminous flux of a unit X 1.03]) if the average of all measured lamps without the tolerance fails to meet the requirement. No other tolerances shall be applied and the reported value for the sample shall be the average of the unit values and may be rounded to the nearest multiple of 5.</td></tr>
<tr><td>10</td><td></td><td>70-89</td></tr>
<tr><td>15</td><td></td><td>90-149</td></tr>
<tr><td>25</td><td>250-349</td><td>150-299</td></tr>
<tr><td>40</td><td>350-499</td><td>300-499</td></tr>
<tr><td>60</td><td>500-574</td><td>500-699</td></tr>
<tr><td>75</td><td>575-649</td><td></td></tr>
<tr><td>100</td><td>650-1099</td><td></td></tr>
<tr><td>150</td><td>1100-1300</td><td></td></tr>
<tr><td>Light Distribution Equivalency</td><td colspan="3">Lamp luminous intensity distribution shall emulate that of the referenced incandescent lamp as follows:

No less than 5% of total flux (zonal lumens) shall be emitted in the 110° to 180° zone.</td><td>IES LM-79-08</td><td>See Appendix A-2 of the ENERGY STAR Lamps V1.0 Final Draft Specification (Luminous Intensity Distribution Diagram for Decorative Lamp) for diagram depicting test measurements</td></tr>
<tr><td>Light Color Equivalency</td><td colspan="3">Lamp chromaticity coordinates must fall within either the 2700K or 3000K ANSI 4 step color bin</td><td>Measurement: IES LM-79-08

Calculation: CIE 15.2004

Reference Document: ANSI C78.377-2011</td><td>Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.</td></tr>
</table>

Table XX-2(c) Requirements for LED Lamps Making Equivalency Claims to Directional Incandescent Lamps of Shapes R, ER, and BR

<table>
<tr><th>Metric</th><th colspan="2">Requirement</th><th>Test Procedures & Reference Documents</th><th>Supplemental Testing Guidance</th></tr>
<tr><td rowspan="8">Light Output Equivalency</td><td colspan="2">Reported lamp initial light output (in lumens) shall be greater than or equal to ten times the incandescent lamp's rated wattage for the following referenced incandescent lamps:
• 65 watt BR30, BR40 and ER40 lamps
• BR30, ER30, BR40 and ER40 lamps ≤ 50 watts
• R20 lamps ≤ 45 watts
• Lamps ≤ 40 watts
• Lamps smaller than 2.25" diameter
For example - a lamp replacing a 25W incandescent shall produce ≥ 250 lumens.

For all other R, BR and ER lamps not included above, reported lamp light output (in lumens) shall be greater than or equal to the product of the claimed wattage equivalency and the light output multiplier in the table below.</td><td rowspan="8">Measurement:
IES LM-79-08</td><td rowspan="8">Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
A 3% tolerance may be applied to the measured initial luminous flux value of each unit (e.g. [initial luminous flux of a unit X 1.03]) if the average of all measured lamps without the tolerance fails to meet the requirement. No other tolerances shall be applied and the reported value for the sample shall be the average of the unit values and may be rounded to the nearest multiple of 5.</td></tr>
<tr><td>Rated Wattage of the Referenced Incandescent Lamp (watts)</td><td>Light Output Multiplier</td></tr>
<tr><td>40 – 50 W</td><td>10.5</td></tr>
<tr><td>51 – 66 W</td><td>11</td></tr>
<tr><td>67 – 85 W</td><td>12.5</td></tr>
<tr><td>86 – 115 W</td><td>14</td></tr>
<tr><td>115 – 155 W</td><td>14.5</td></tr>
<tr><td>156 - 205 W</td><td>15</td></tr>
<tr><td>Light Color Equivalency</td><td colspan="2">Lamp chromaticity coordinates must fall within either the 2700K or 3000K ANSI 4 step color bin</td><td>Measurement:
IES LM-79-08

Calculation:
CIE 15.2004

Reference Document:
ANSI C78.377-2011</td><td>Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.</td></tr>
</table>

Table XX-2(d) Requirements for LED Lamps Making Equivalency Claims to Directional Incandescent Lamps of Shapes MR and PAR

<table>
<tr><td>Metric</td><td colspan="2">Requirement</td><td>Test Procedures & Reference Documents</td><td>Supplemental Testing Guidance</td></tr>
<tr><td rowspan="7">Light Output Equivalency</td><td>Rated Wattage of the Referenced Incandescent Lamp (watts)</td><td>Light Output Multiplier</td><td rowspan="7">Measurement: IES LM-79-08</td><td rowspan="7">Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
A 3% tolerance may be applied to the measured initial luminous flux value of each unit (e.g. [initial luminous flux of a unit X 1.03]) if the average of all measured lamps without the tolerance fails to meet the requirement. No other tolerances shall be applied and the reported value for the sample shall be the average of the unit values and may be rounded to the nearest multiple of 5.</td></tr>
<tr><td><30</td><td>9.5</td></tr>
<tr><td>30-45</td><td>10.5</td></tr>
<tr><td>46-65</td><td>11.5</td></tr>
<tr><td>66-85</td><td>12.5</td></tr>
<tr><td>86-110</td><td>13.5</td></tr>
<tr><td>>110</td><td>14.5</td></tr>
<tr><td>Center Beam Intensity Equivalency</td><td colspan="2">Lamp center beam intensity shall be greater than or equal to the center beam intensity value calculated by the ENERGY STAR Center Beam Intensity Benchmark Tool for the referenced incandescent lamp. (http://www.energystar.gov/ia/products/lighting/iledl/IntLampCenterBeamTool.zip)</td><td>Measurement: IES LM-79-08</td><td>Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
A 3% tolerance may be applied to the measured initial center beam intensity value of each unit (e.g. [initial center beam candelas of a unit X 1.03]) if the average of all measured lamps without the tolerance fails to meet the requirement. No other tolerances shall be applied and the reported value for the sample shall be the average of the unit values and may be rounded to the nearest multiple of 50.</td></tr>
<tr><td>Light Color Equivalency</td><td colspan="2">Lamp chromaticity coordinates must fall within either the 2700K or 3000K ANSI 4 step color bin</td><td>Measurement: IES LM-79-08

Calculation: CIE 15.2004

Reference Document: ANSI C78.377-2011</td><td>Sample Size: 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position.
Reported CCT shall be the average of the unit measured values rounded to the nearest whole number.</td></tr>
</table>

Section 1607. Marking of Appliances.

(d) Energy Performance Information.

(##) LED Replacement lamps

(A) Each LED replacement lamp shall be marked permanently and legibly, in characters no less than 1/16th in., with the following product performance metrics:

- Watts (rounded to nearest tenth of a W)
- Lumens (rounded to nearest 10 lumens)
- CRI (rounded to nearest whole number)
- Nominal CCT (ANSI nominal CCT bin)
- Specify whether lamp Type I or Type II NEMA SSL7A compliant using one of the following:
    - SSL7A TYPE I
    - SSL7A TYPE II

(B) Each directional LED (of lamp shape PAR, R, BR, ER, MR) shall be marked permanently and legibly, in characters no less than 1/16th in., with the following product performance metrics:

- Measured beam angle, rounded to the nearest whole degree
- Center beam candle power, rounded to the nearest 50 candela

(C) The exterior packaging of all covered LED replacement lamp shall state "Warranty" or "Limited Warranty", the warranty period (in years, minimum of 3), and a phone number or website address for consumer complaint resolution. The complete written warranty shall be printed on packaging exterior or included within lamp packaging.

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Appendix A: Cost Analysis Assumptions

The electricity rates used in the analysis of this CASE Report were derived from projected future prices for residential, commercial and industrial sectors in the CEC's "Mid-case" projection of the 2012 Demand Forecast (2012), which used a 3% discount rate and provide prices in 2010 dollars. The sales weighted average of the 5 largest utilities in California was converted to 2012 dollars using an inflation adjustment of 1.07 (DOL 2013). A sector weighted average electricity rate was then calculated using an assumed split 20% commercial, 80% residential. This split is based on the 2010 DOE Lighting Market Characterization (LMC) Report and adjusted for the purposes of this CASE study. In the LMC study, the weighted average distribution of all replacement lamps is approximately 90% residential and 10% commercial (with industrial sales negligible). Because residential electricity prices are forecasted to be higher than commercial, the CASE team adjusted these forecasts and assumed less than 90% of lamps would be installed in the residential sector, to be conservative in our estimates. See the rates by year below in Table A.1.

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Table A.1 Statewide Weighted Average Electricity Rates 2015 - 2040 (PG&E, SCE, SDG&E, LADWP and SMUD - 5 largest Utilities) in 2012 cents/kWh

Year	Residential	Commercial	Industrial	Sector Weighted Average
2015	16.66	14.53	11.30	16.24
2016	16.86	14.70	11.42	16.43
2017	17.08	14.88	11.55	16.64
2018	17.31	15.08	11.69	16.86
2019	17.54	15.27	11.83	17.09
2020	17.83	15.52	12.00	17.37
2021	18.17	15.83	12.22	17.70
2022	18.52	16.14	12.44	18.05
2023	18.88	16.45	12.66	18.40
2024	19.25	16.78	12.89	18.76
2025	19.62	17.10	13.12	19.12
2026	20.00	17.44	13.36	19.49
2027	20.39	17.78	13.60	19.87
2028	20.79	18.13	13.85	20.26
2029	21.19	18.49	14.11	20.65
2030	21.60	18.85	14.37	21.05
2031	22.02	19.22	14.63	21.46
2032	22.45	19.60	14.91	21.88
2033	22.89	19.98	15.18	22.31
2034	23.33	20.37	15.47	22.74
2035	23.79	20.78	15.76	23.19
2036	24.25	21.18	16.05	23.64
2037	24.72	21.60	16.36	24.10
2038	25.20	22.03	16.67	24.57
2039	25.69	22.46	16.98	25.05
2040	26.20	22.90	17.31	25.54

Appendix B: Criteria Pollutant Emissions and Monetization

B.1 Criteria Pollutant Emissions Calculation

To calculate the statewide emissions rate for California, the incremental emissions between CARB's high load and low load power generation forecasts for 2020 were divided by the incremental generation between CARB's high load and low load power generation forecast for 2020. Incremental emissions were calculated based on the delta between California emissions in the high and low generation forecasts divided by the delta of total electricity generated in those two scenarios. This emission rate per MWh is intended to provide a benchmark of emission reductions attributable to energy efficiency measures that could help achieve the low load scenario instead of the high load scenario. While emission rates may change somewhat over time, 2020 was considered a representative year for this measure.

B.2 Criteria Pollutant Emissions Monetization

Avoided ambient ozone precursor and fine particulate air pollution benefits were monetized based on avoided control costs rather than damage costs due to the availability of emission control cost-effectiveness thresholds, as well as challenges in quantifying a specific value for damages per ton of pollutants.

Two sources of data for cost-effectiveness thresholds were evaluated. The first is Carl Moyer cost-effectiveness thresholds for ozone precursors and fine particulates (CARB 2011a, CARB 2013a and 2013b). The Carl Moyer program has provided incentives for voluntary reductions in criteria pollutant reductions from a variety of mobile combustion sources as well as stationary agricultural pumps that meet specified cost-effectiveness cut-offs.

The second is the San Joaquin Valley UAPCD Best-Available Control Technology ("BACT") cost-effectiveness thresholds study. Pollution reduction technologies that are not yet demonstrated in practice (in which case they are required without a cost-effectiveness evaluation) can be required at new power plants and other sources if technologically feasible and within cost-effectiveness thresholds. San Joaquin Valley UAPCD conducted a state-wide study as the basis for updating their BACT thresholds in 2008.

This CASE report relies primarily on the Carl Moyer thresholds due to their state-wide nature and applicability to combustion sources[9]. In addition, the Carl Moyer fine particulate values for fine particulate apply to combustion sources with specific health impacts, while BACT thresholds include both combustion sources and dust. The Carl Moyer values are somewhat more conservative for ozone precursors than San Joaquin Valley UAPCD BACT thresholds, and significantly higher for fine particulate[10].The Carl Moyer program does not address sulfur oxides, however, thus the San Joaquin BACT thresholds were used for this pollutant.

Price reports for California Emission Reduction Credit (ERCs, i.e. air pollution credits purchased to offset regulated emission increases) for 2011 and 2012 were also compared to the values selected

[9] Further evaluation of the qualitative impacts of combustion fine particulate emissions from power generation and transportation sources may be beneficial.

[10] We note that both the Carl Moyer and San Joaquin Valley UAPCD BACT cost-effectiveness thresholds for fine particulates fall within the wide range of fine particulate ERC trading prices in California in 2011 and 2012.

in this CASE report. For each pollutant there is a wide range of ERC values per ton that are both higher and lower than the values per ton used in this CASE report [CARB 2011b and 2012]. Due to wide variability and low trading volumes, ERC values were evaluated for comparative purposes only.

Appendix C: Greenhouse Gas Valuation Discussion

The climate impacts of pollution from fossil fuel combustion and other human activities, including the greenhouse gas effect, present a major risk to global economies, public health and the environment. While there are uncertainties of the exact magnitude given the interconnectedness of ecological systems, at least three methods exist for estimating the societal costs of greenhouse gases: 1) the Damage Cost Approach 2) the Abatement Cost Approach and 3) the Regulated Carbon Market Approach. See below for more details regarding each approach.

C.1 Damage Cost Approach

In 2007, the U.S. Court of Appeals for the Ninth Circuit ruled that the National Highway Transportation Traffic Safety Administration (NHTSA) was required to assign a dollar value to benefits from abated carbon dioxide emissions. The court stated that while there are a wide range of estimates of monetary values, the price of carbon dioxide abatement is indisputably non-zero. In 2009, to meet the necessity of a consistent value for use by government agencies, the Obama Administration established the Interagency Working Group on the Social Cost of Carbon to establish official estimates (Johnson and Hope).

The Interagency Working Group primarily uses estimates of avoided damages from climate change which are valued at a price per ton of carbon dioxide, a method known as the damage cost approach.

C.1.1 Interagency Working Group Estimates

The Interagency Working Group SCC estimates, based on the damage cost approach, were calculated using three climate economic models called integrated assessment models which include the Dynamic Integrated Climate Economy (DICE), Policy Analysis of the Greenhouse Effect (PAGE), and Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) models. These models incorporate projections of future emissions translated into atmospheric concentration levels which are then translated into temperature changes and human welfare and ecosystem impacts with inherent economic values. As part of the Federal rulemaking process, DOE publishes estimated monetary benefits using Interagency Working Group SCC values for each Trial Standard Level considered in their analyses, calculated as a net present value of benefits received by society from emission reductions and avoided damages over the lifetime of the product. The recent U.S. DOE Final Rulemaking for microwave ovens contains a Social Cost of Carbon section that presents the Interagency Working Group's most recent SCC values over a range of discount rates (DOE 2013b) as shown in Table C.1. The two $ metric ton of values used in this CASE report were taken from the two highlighted columns, and converted to 2013 dollars.

Table C.1 Social Cost of CO_2 2010 – 2050 (in 2007 dollars per metric ton of CO_2) (source: Interagency Working Group on Social Cost of Carbon, United States Government, 2013)

Discount Rate	5.0%	3.0%	2.5%	3.0%
Year	Avg	Avg	Avg	95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

The Interagency Working Group decision to implement a global estimate of the SCC rather than a domestic value reflects the reality of environmental damages which are expected to occur worldwide. Excluding global damages is inconsistent with U.S. regulatory policy aimed at incorporating international issues related to resource use, humanitarian interests, and national security. As such, a regional SCC value specific to the Western United States or California specifically should be at similarly inclusive of global damages. Various studies state that certain values may be understated due to the asymmetrical risk of catastrophic damage if climate change impacts are above median predictions, and some estimates indicate that the upper end of possible damage costs could be substantially higher than indicated by the IWG (Ackerman and Stanton 2012, Horii and Williams 2013).

C.2 Abatement Cost Approach

Abating carbon dioxide emissions can impose costs associated with more efficient technologies and processes, and policy-makers could also compare strategies using a different by estimating the annualized costs of reducing one ton of carbon dioxide net of savings and co-benefits. The cost of abatement approach could reflect established greenhouse gas reduction policies and establish values for carbon dioxide reductions relative to electricity de-carbonization and other measures. (While recognizing the potential usefulness of this method, this report utilizes the IWG SCC approach and we note that the value lies within the range of abatement costs discussed further below.)

The cost abatement approach utilizes market information regarding emission abatement technologies and processes and presents a wide-range of values for the price per ton of carbon dioxide. The California Air

Resources Board data of the cost-effectiveness of energy efficiency measures and emission regulations would provide one source of potential data for an analysis under this method. To meet the AB 32 target, ARB has established the "Cost of a Bundle of Strategies Approach" which includes a range of cost-effective strategies and regulations (CARB 2008b). The results of this approach within the framework of the Climate Action Team Macroeconomic Analysis are provided for California, Arizona, New Mexico, the United States, and a global total identified in that same report, as shown in Table C.2 below.

Table C.2 Cost-effectiveness Range for the CAT Macroeconomic Analysis

Exhibit 3: Cost-effectiveness Range for the CAT Macroeconomic Analysis, Selected States, United States, Global -

State	Cost-effectiveness Range $/ ton CO_2eq	Tons Reduced MMtCO_2e/yr	Percent of BAU
California 2020 (CAT[1], CEC[2])	- 528 to 615	132	22
Arizona[3] 2020	- 90 to 65	69	47
New Mexico[4] 2020	- 120 to105	35	34
United States (2030)[5]	-93 to 91	3,000	31
Global Total (2030)	-225 to 91	26,000	45

Source:
1. Climate Action Team Updated Macroeconomic Analysis of Climate Strategies, Presented in the March 2006 Climate Action Team Report, September 2007.
2. California Energy Commission, *Emission Reduction Opportunities for Non-CO2 Greenhouse Gases in California*, July 2005, ICF ($/MTC$0_2$eq).
3. Arizona Climate Change Advisory Group, *Climate Change Action Plan*, August 2006, ($/MTC$0_2$eq).
4. New Mexico Climate Change Advisory Group, Final Report, December 2006.
5. McKinsey & Company, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* December 2007.
6. The McKinsey Quarterly, McKinsey & Company, *A Cost Curve for Greenhouse Gas Reduction*, Fall 2007.

Source: CARB 2008b

Energy and Environmental Economics (E3) study defines the cost abatement approach more specifically as electricity de-carbonization and is based on annual emissions targets consistent with existing California climate policy. Long-term costs are determined by large-scale factors such as electricity grid stability, technological advancements, and alternative fuel prices. Near-term costs per ton of avoided carbon could be$200/ton in the near-term (Horii and Williams 2013), thus as noted earlier the value used in this report may be conservative.

C.3 Regulated Carbon Market Approach

Emissions allowance markets provide a third potential method for valuing carbon dioxide. Examples include the European Union Emissions Trading System and the California AB32 cap and trade system as described below. Allowances serve as permits authorizing emissions and are traded through the cap-and-trade market between actors whose economic demands dictate the sale or purchase of permits. In theory, allowance prices could serve as a proxy for the cost of abatement. However, this report does not rely on the prices of cap-and-trade allowances due to the vulnerability of the allowance market to external fluctuations, and the influence of regulatory decisions affecting scarcity or over-allocation unrelated to damages or abatement costs.

C.3.1 European Union Emissions Trading System

The European Union Emissions Trading System (EU ETS) covers more than 11,000 power stations, industrial plants, and airlines in 31 countries. However, the market is constantly affected by over-supply following the 2008 global recession and has seen prices drop to dramatic lows in early 2013, resulting in the practice of "back-loading" (delaying issuances of permits) by the European parliament. At the end of June 2013, prices of permits dropped to $5.41/ton, a price which is well below damage cost estimates and sub-optimal for encouraging innovative carbon dioxide emission abatement strategies.

C.3.2 California Cap & Trade

In comparison, California cap-and-trade allowance prices were reported to be at least $14/ton in May of 2013, with over 14.5 million total allowances sold for 2013 (CARB 2013b). However, cap-and-trade markets are likely to cover only subsets of emitting sectors of the industry covered by AB 32. In addition, the market prices of allowances are determined only partly by costs incurred by society or industry actors and largely by the stringency of the cap determined by regulatory agencies and uncontrollable market forces, as seen by the failure of the EU ETS to set a consistent and effective signal to curb carbon dioxide emissions.