LED Replacement Lamps

Response to California Energy Commission
2013 Pre-Rulemaking Appliance Efficiency
Invitation to Participate

Docket Number: 12-AAER-2B; Lighting

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Prepared for:

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Summary

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). However, LEDs will not deliver significant energy savings and the market will not be transformed if consumers do not have positive experience with LED lamps. There are large variations in the level of product quality provided by LEDs today, and while many products are showing dramatic improvement in terms of quality, other products are available that are likely to disappoint consumers and turn them off from future LED lamp purchases. California has an opportunity to develop mandatory quality standards for LED lamps that will help ensure consumer satisfaction with LED lamps and help enable one of the largest energy savings market transformations in California history.

The information below provides direct response to the California Energy Commission's (CEC) Invitation to Participate (ITP) for the 2013 Appliance Efficiency Pre-Rulemaking, regarding LED Replacement Lamp Quality, including reference to several primary sources, some of which are attached separately. This document includes all of the questions asked in the ITP, even for those with no response. Below is a summary of the responses to the data requests outlined in CEC's Invitation to Participate:

Data Request: All Lighting Categories

1. **Category definition and scope**: Enclosed are recommended product classes based on general service incandescent lamp definitions and exclusions from the Energy Independence and Security Act of 2007
2. **Standards (existing or under development)**: Enclosed are summaries of the two existing mandatory standards from the EU and Mexico
3. **Test procedures (existing or under development)**: Enclosed is a list of existing test procedures relevant to LED replacement lamps
4. **Sources of test data (confidential or public)**: Enclosed are test results from testing completed in 2012 and 2013 at the California Lighting Technology Center
5. **Energy use metrics**: Included in "Relevant performance indicators" section below
6. **Relevant performance indicators**: (Including Energy use metrics, Range of typical performance for each indicator, and product development trends): Enclosed is an analysis of publically available data (originating from the DOE SSL Lighting Facts Database, the ENERGY STAR Qualifying Product List) that shows typical range of performance for each indicator. These analyses include trend-lines projecting product improvement out over the next several years.
7. **Range of typical performance for each indicator**: Included in "Relevant performance indicators" section above.
8. **Incremental costs of energy efficiency features**: Included in "Cost of improved color consistency & quality" Section below.

9. **Product development trends**: Included in "Relevant performance indicators" section above.
10. **Market barriers to energy efficiency**: No response provided
11. **Number of California small businesses associated with manufacture, sale, distribution, or installation**: No response provided
12. **Market share by lamp category and by sector (commercial vs. residential)**: Enclosed is a summary of market share data from the 2010 Lighting Market Characterization Study.
13. **How do consumers identify efficient products on the market?**: No response provided

Data Requests: Light Emitting Diode (LED) Lamps

1. **Logical product categorization for analysis & market share by category**: Included in "Category definition and scope" section and "Market share by lamp category and by sector" section above.
2. **LM-79 and TM-21 reports**: No response provided
3. **Types of dimming circuitry & minimum dimming levels**: Included in "Relevant performance indicators" section above.
4. **Patent or proprietary technology issues**: No response provided
5. **Cost of improved color consistency & quality**: Enclosed is a statistical analysis conducted with data from several hundred lamps in the replacement lamp market, which assesses the impacts of various quality features on the end user sale price.

Any other information relevant to this proceeding

1. **Cost Forecast**: Enclosed is an analysis showing LED lamp forecast per kilolumen from 2013 – 2030.
2. **Zhaga Consortium**: Enclosed is a write up of the background and goals of the Zhaga Consortium, including information about their publically available standards for light engine interconnects.
3. **CFL consumer acceptance**: Enclosed is a listing of existing studies documenting consumer dis-satisfaction with CFLs, as well as CFL market share data documenting the slow and incomplete adoption of CFLs over the past 30+ years.

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1 Data Requests: All Lighting Categories

1.1 Category definition and scope

The Energy Independence & Security Act of 2007 (EISA 2007) includes several definitions for product classes that may be helpful in establishing scope of coverage for LED replacement lamps. For `general service' lamps for example, EISA includes lamps that:

- are intended for general service applications;
- have a lumen range of not less than 310 lumens and not more than 2,600 lumens; and
- are capable of being operated at a voltage range at least partially within 110 and 130 volts.

EISA also includes several exemptions for specific lamp types that are specialty lamps, some of which may be appropriate for use in establishing scope of coverage and exemptions in CA. Some of the EISA exemptions that might be appropriate for use in CA are listed below:

- an appliance lamp;
- a black light lamp;
- a bug lamp
- a colored lamp;
- an infrared lamp;
- a left-hand thread lamp;
- a marine lamp;
- a marine signal service lamp;
- a mine service lamp;
- a plant light lamp;
- a rough service lamp;
- a shatter-resistant lamp (including a shatter-proof lamp and a shatter-protected lamp);
- a sign service lamp;
- a silver bowl lamp;
- a showcase lamp;
- a vibration service lamp;

1.2 Standards (existing or under development)

1.2.1 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 amongst 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 four drafts of its version 1 Lamps spec, with the latest being released in early 2013 (EPA 2013). It is expected that ENERGY STAR will finalize this spec later 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 letter, including efficacy, color rendering, and color consistency.

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. The document outlines the CEC's position on LED quality and provides an explanation of and a significant amount of discussion on the relevance of various performance metrics in general service lighting (CEC 2012).

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 (http://ssl.iea-4e.org/task-1-quality-assurance). 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.

1.2.2 Mandatory LED Quality Standards

Mandatory minimum standards for LED lamps will be a valuable tool to accompany voluntary rebate programs, by ensuring that there are more rebate-eligible products on the market. 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. Consumers may inadvertently purchase these low quality products, and some may be disappointed by the results. This situation can potentially be avoided or lessened 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).

1.2.3 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 (EU 2012). 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. **Table 1** below outlines the recently adopted EU Ecodesign requirements for LED lamps.

Table 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} × 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	Luminous flux multiplication factor:
20° ≤ beam angle	1
15° ≤ beam angle < 20°	0.9
10° ≤ beam angle < 15°	0.85
beam angle < 10°	0.8

1.2.4 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.

Mexico released Official Mexican Standards (Normas Oficiales Mexicanas – NOM) for LED lamps on June 22, 2012 (CONUEE 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 tables below summarize the primary Mexican MEPS requirements for omni-directional and directional LED lamps.

Table 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

Table 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 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 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

1.3 Test procedures (existing or under development)

Table 6 below lists the test procedures most widely recognized by the lighting industry in the US for testing LED replacement lamps. ENERGY STAR references these test procedures below for the majority of its specifications as well.

Table 6 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
ANSI/ISO	ANSI S12.55-2006/ISO 3745:2003	Acoustics - Determination of sound power levels of noise sources using sound pressure - Precision methods for anechoic and hemi-anechoic rooms
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
ISO	7574-4: 1985	Acoustics - Statistical methods for determining and verifying stated noise emission values of machinery and equipment - Part 4: Methods for stated values for batches of machines
NEMA	SSL3	High-Powered White LED Binning for General Illumination
NEMA	SSL4	Retrofit Lamps: Minimum Performance Requirements
NEMA	SSL6	Solid State Lighting for Incandescent Replacement – Dimming
NEMA	SSL7A	Phase Cut Dimming for Solid State Lighting: Basic Compatibility

The Department of Energy 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 LM-79, LM-80, and TM-21.

1.4 Sources of test data (confidential or public)

In 2012 and 2013 the California Lighting Technology Center, on behalf of PG&E and the Collaborative Labeling and Appliance Standards Program (CLASP) conducted testing of a batch of LED replacement lamps, including both general service (A lamps) and directional lamps (PAR and MR lamps). The testing included photometric and electrical testing, and focused specifically on product quality parameters such as lumen output, efficacy, color quality, color consistency, power factor, light distribution, and spectral power distribution. The testing was conducted on multiple samples of each selected lamp model to assess sample-to-sample variation. Testing was done in multiple lamp orientations to compare base-up, base-down, and horizontal performance of the lamps. Much of the testing and analysis is still being completed and will be submitted to the CEC later in 2013, including additional analysis of lamp flicker and lamp dimming performance, as well as testing on additional lamps.

Three Test Reports, covering A-lamps and PAR lamps (MR lamp testing is on-going) have been included as attachments to this ITP response. They are listed below, and they can also be found in the references section of this document:

- Omni-Directional Lamp Testing; Report Draft (PG&E 2013a)
- A-Lamp Omnidirectional Beam Pattern Analysis; Draft Report (PG&E 2013b)
- Directional Lamp Testing; Report Draft (PG&E 2013c)

1.5 Energy use metrics

Included in Section 1.6 "Relevant performance indicators," below.

1.6 Relevant performance indicators (including energy use metrics, range of typical performance for each indicator, and product development trends)

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 the Department of Energy 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 is also funding current LED product testing efforts at the CLTC. Some of these testing results are included here; others are expected by the middle of 2013 and will be incorporated into this report when available.

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

1.6.1 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 7** 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 weighed average lumen output of traditional A-lamps is 1003 lumens.

Table 7 Current market share of GSL by wattage and 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	1100	21%
86 - 125	100	1600	24%
126 - 150	150	2600	1%

Sales Weighted Averages

	Watts	**Lumens**
	70	1003

Early generations of LED products had much lower lumen outputs than this weighted average of 1003 lumens, making them impractical as replacements for most incandescent lamps. Over time, lamps with higher and higher lumen output have been brought to market, increasing the viability of LED replacement lamps. That said, DOE testing of LED lamps through its CALiPER Program has shown that some LED products marketed as replacements for high wattage lamps had a much 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 such a common lumen range of incandescent lamps (DOE 2013).

Table 8 below shows the current distribution of LED A-lamps by lumen bin and wattage equivalency, in the Lighting Facts Database.

Table 8 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 1 and Figure 2 show the rate of change from 2010 – 2013 of the products being added to the Lighting Facts Database during that period. These figures show that the average lumen output and the maximum values of products being added to the database are both increasing over time.

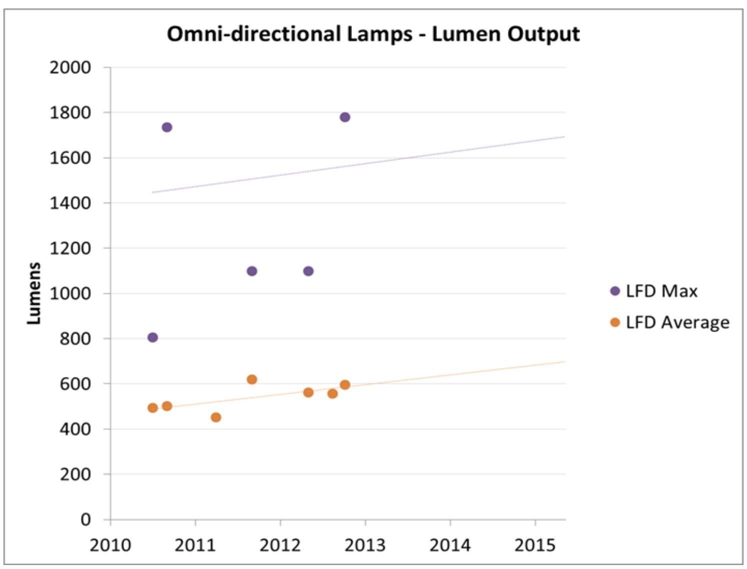


Figure 1 Average and maximum lumen output of A-lamps added to the Lighting Facts Database, 2010-2012

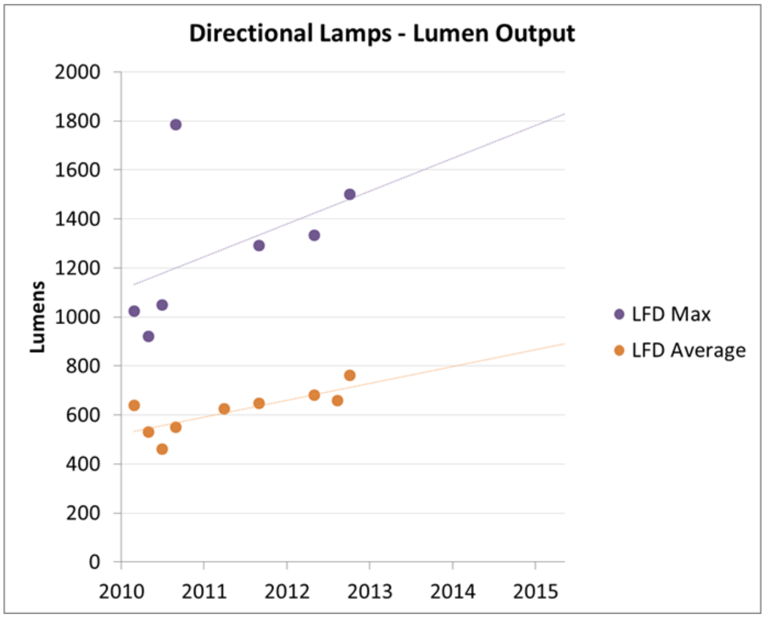
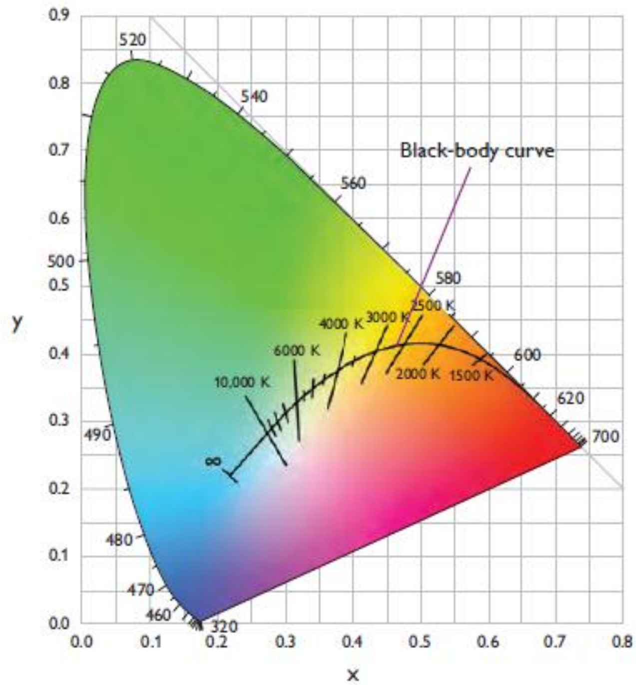


Figure 2 Average and maximum lumen output of directional lamps added to the Lighting Facts Database, 2010-2012

Measured light output data for A-lamps and directional lamps is also provided in the attached CLTC Test Reports (PG&E 2013a, PG&E 2013c).

1.6.2 Correlated Color Temperature (CCT)

Correlated color temperature (CCT) is a measure of the color of the light produced by an artificial light source. 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 3 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.

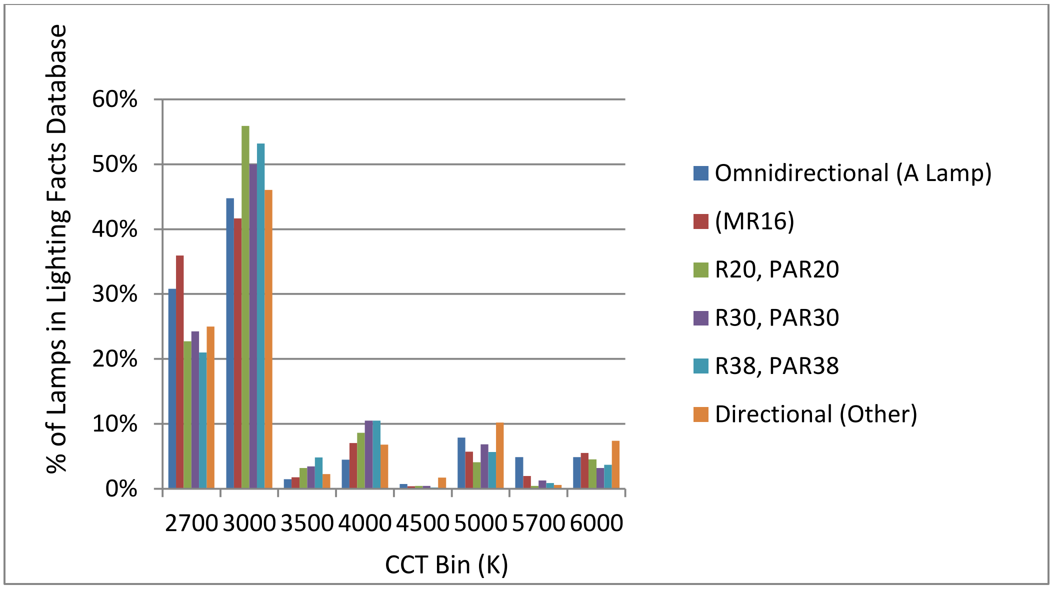


Figure 4 Distribution of Replacement Lamps across CCT Bins, by Lamp Type

Figure 5 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.

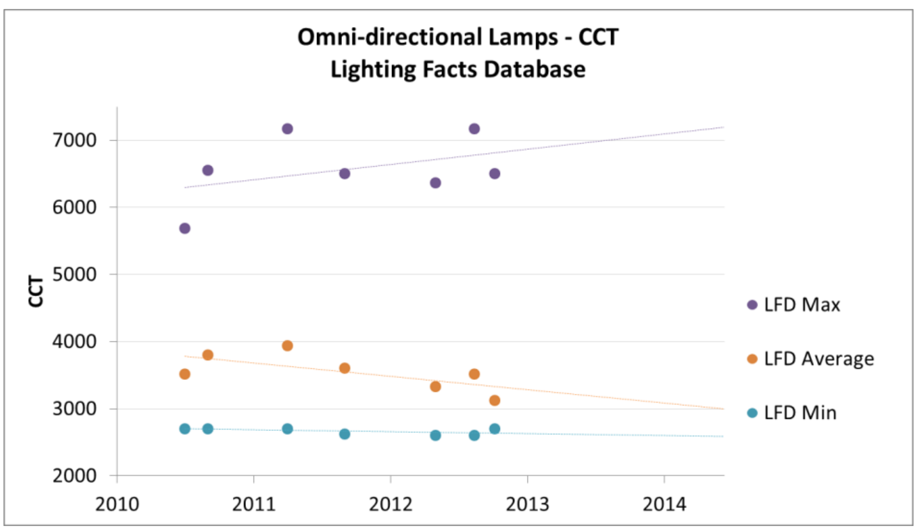


Figure 5 Distribution of Replacement Lamps across CCT Bins, by Lamp Type

Measured color temperature data for A-lamps and directional lamps is also provided in the attached CLTC Test Reports (PG&E 2013a, PG&E 2013c).

1.6.3 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 (referred to as "Delta u, v," or Duv). **Figure 6** below, from the National Institute of Standards and Technology, demonstrates these two dimensions of chromaticity variations (Ohno 2011).

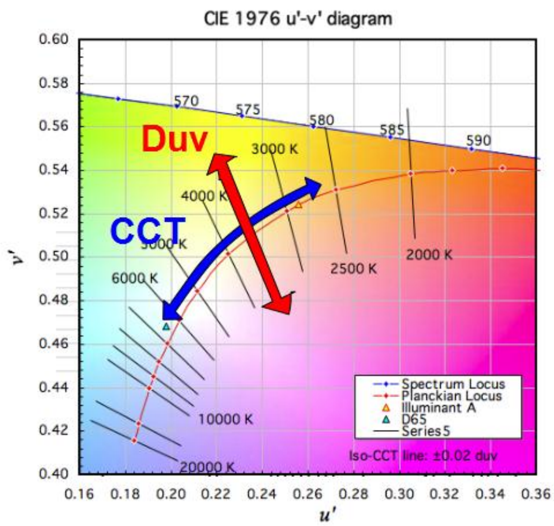


Figure 6 The two dimensions of chromaticity variations: CCT and Duv

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.

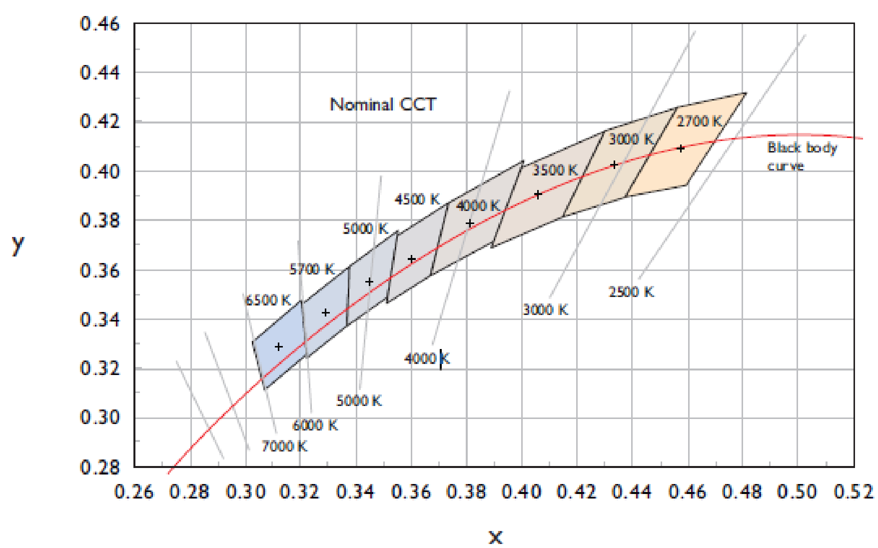


Figure 7 7-step MacAdam Quadrangles on the CIE 1931 Color Space
Source: Philips Color Kinetics; Optibin Technology Overview

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). Color differences of 1-2 MacAdam steps are generally very difficult to discern, while 4 MacAdam step differences become more readily apparent. 7 MacAdam step color difference is immediately noticeable. Lamps that are not closely matched to each other may stand out in a lighting installation, and lead to consumer dissatisfaction.

While the current ANSI standard provides a valuable method for consistency across manufacturers, it currently 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 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, and 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.

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

1.6.4 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 2012). 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).

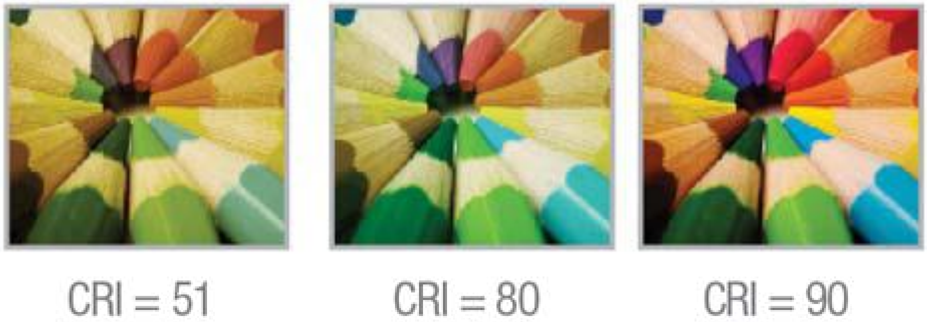


Figure 8 Illustrative example of color rendition under light sources of different CRI Values.
Source: Lighting Matters' LED Blog, lightingmatters.com.au/blog/ledlight-quality-cri/

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 2013).

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 9 Test Color Samples used in the calculation of CRI
Source: IESNA Handbook 10th Edition

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)	

Many manufacturers also report their R_9 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 R_9 values stretch from negative values up to well over 50 (some approach 90 or higher). High quality LED lamps can have much higher R_9 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 R_a and R_9), by lamp type. Figure 9 and **Figure 10** 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 - 20% of lamps have a CRI below 80. R_9 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.

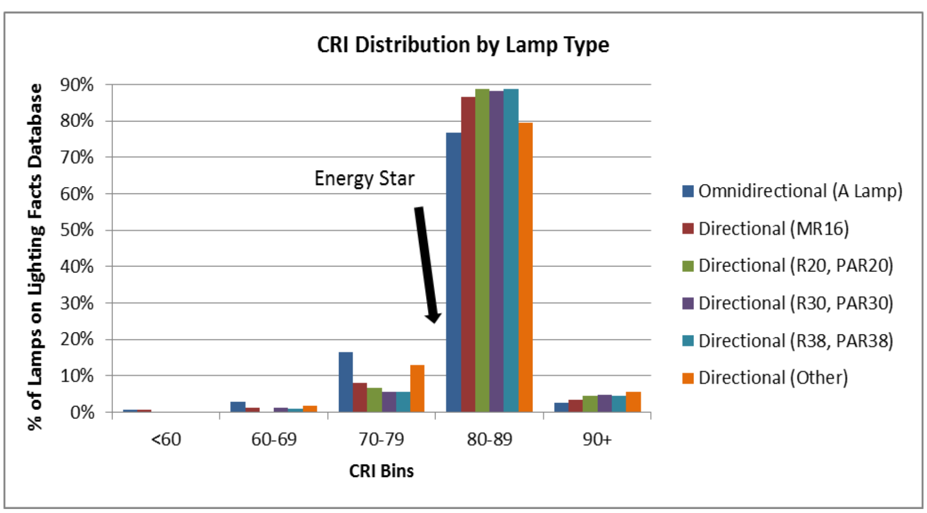


Figure 9 Distribution of Replacement Lamps across CRI (R_a) Bins, by Lamp Type

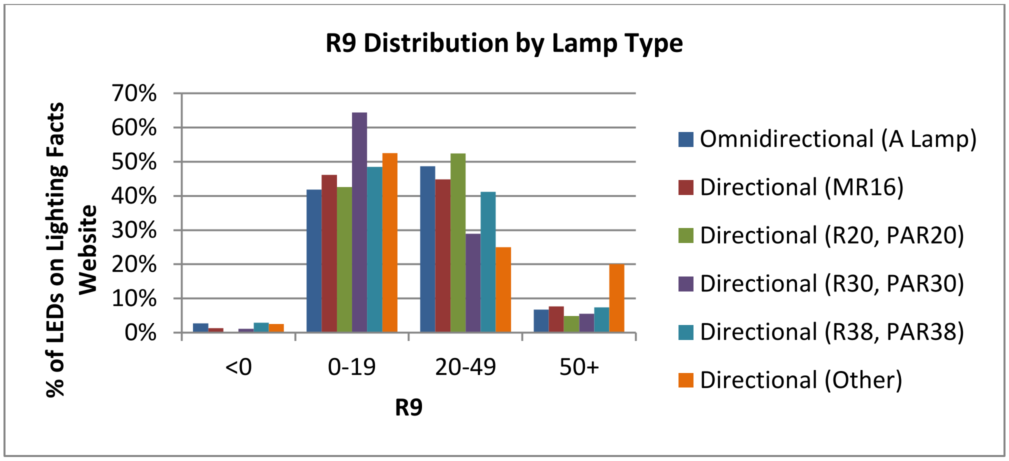


Figure 10 Distribution of Replacement Lamps across CRI (R_9) Bins, by Lamp Type

Figure 11 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.

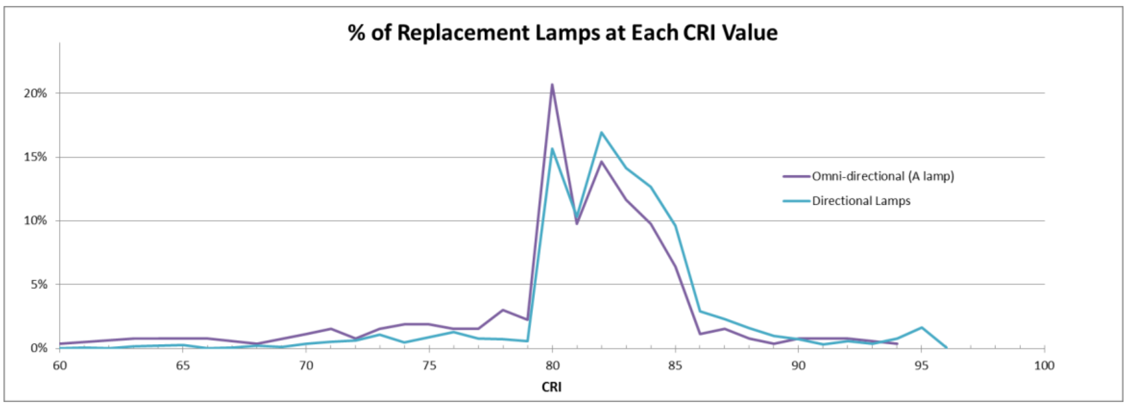


Figure 11 Distribution of Replacement Lamps at each unique CRI value, by Lamp Type

CRI has been improving rapidly 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 will 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.

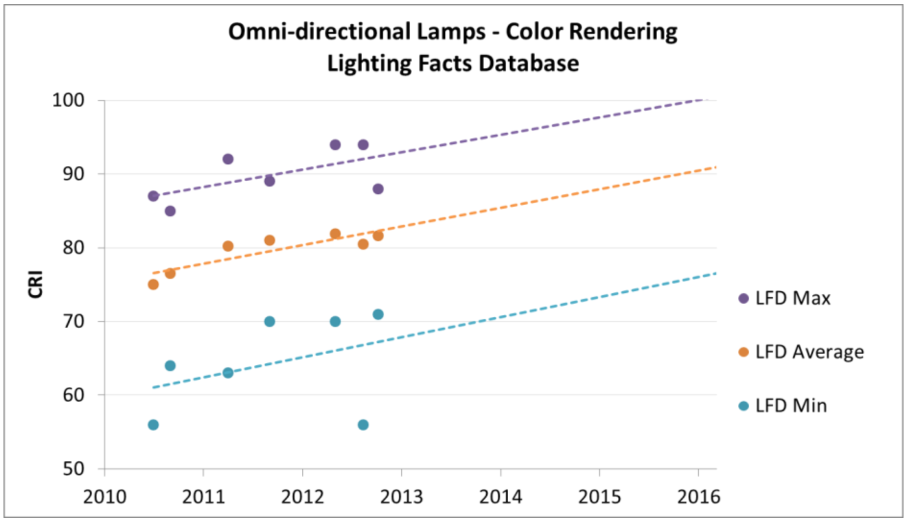


Figure 12 Omni-directional LED Lamp CRI trends from 2010 through 2012

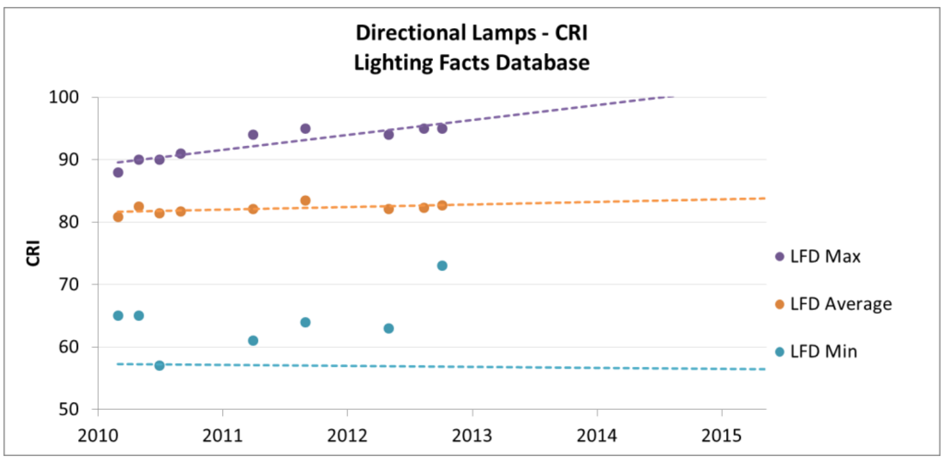


Figure 13 Directional LED Lamp CRI trends from 2010 through 2012

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

1.6.5 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 the lab (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 amongst 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.

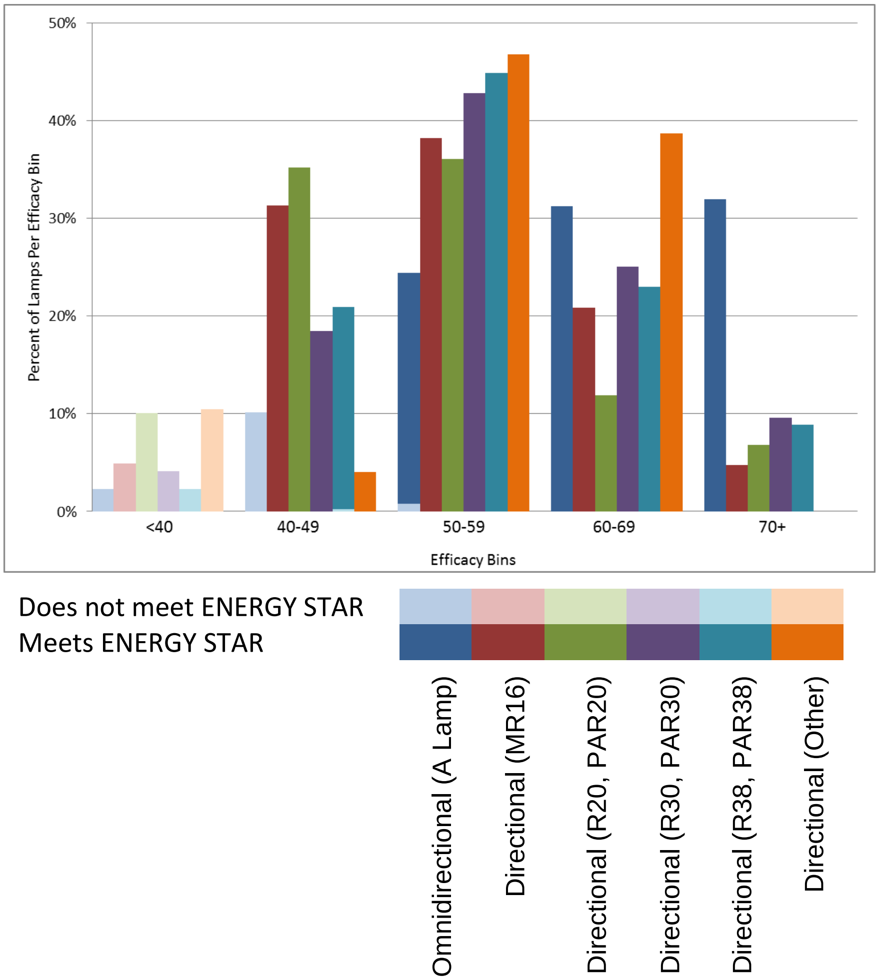


Figure 14 Distribution of Replacement Lamps across Efficacy Bins, by Lamp Type

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

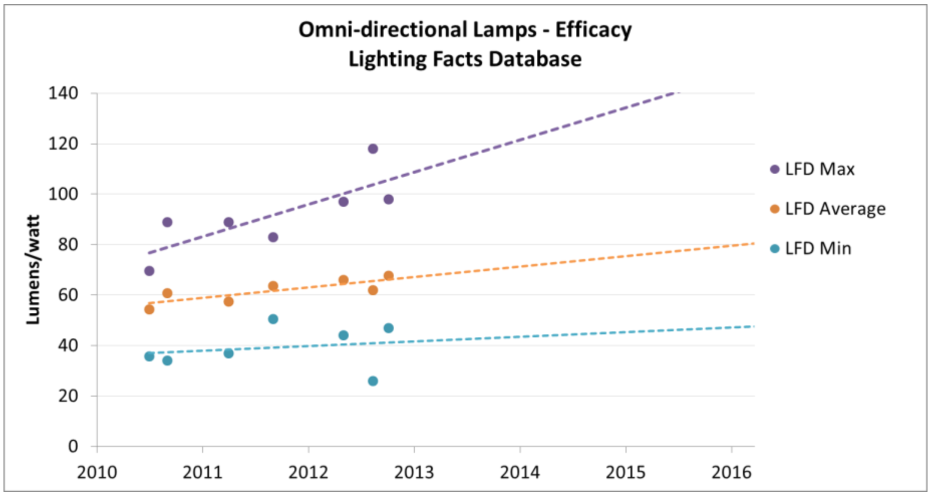


Figure 15 Omni-directional LED Lamp Efficacy trends from 2010 through 2012

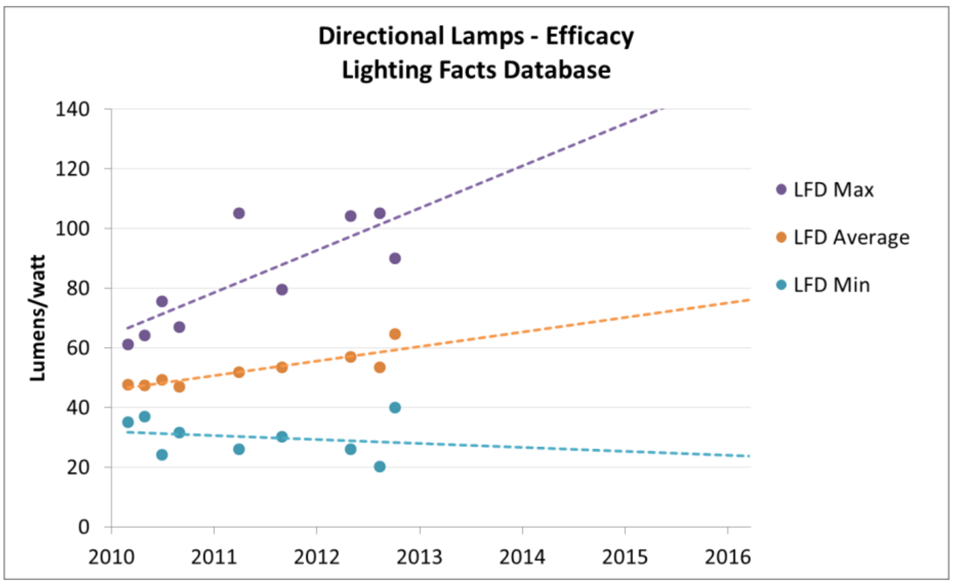


Figure 16 Directional LED Lamp Efficacy trends from 2010 through 2012

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 is also provided in the attached CLTC Test Reports (PG&E 2013a, PG&E 2013c).

1.6.6 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 5.20** 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).

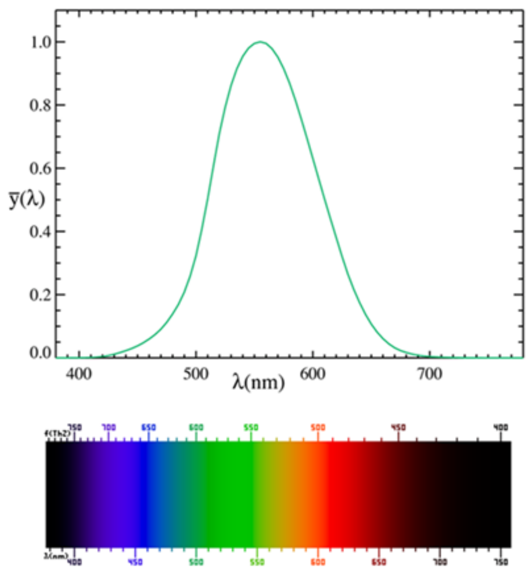


Figure 17 1931 CIE photopic luminosity function

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 below.

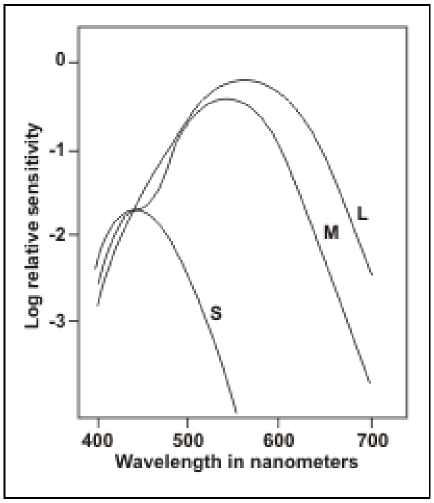


Figure 18   The spectral absorption curves of the three cone types (RPI 2004).

Artificial 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 lacking severely lacking in color quality. The spectral power distribution of a low pressure sodium lamp (LPS), for example, is shown below in **Figure 5.22**. 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.

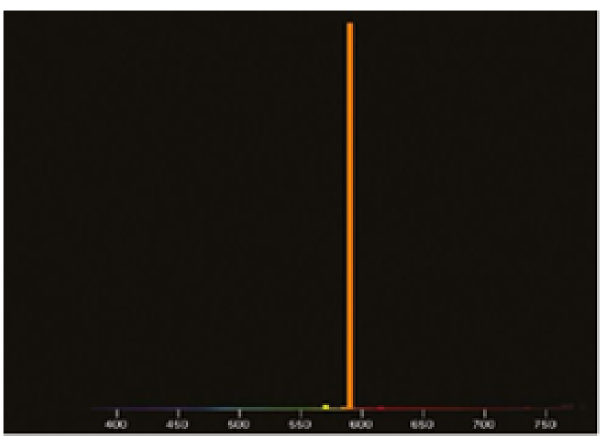


Figure 19   The spectral power distribution curve of a low pressure sodium lamp

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 20.

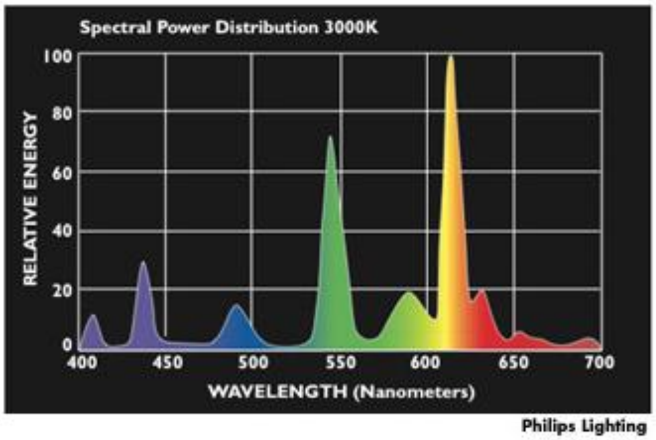


Figure 20 The spectral power distribution of a fluorescent lamp (Topbulb 2012).

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 are both much smoother – without the peaks seen in the diagram above in Figure 20.

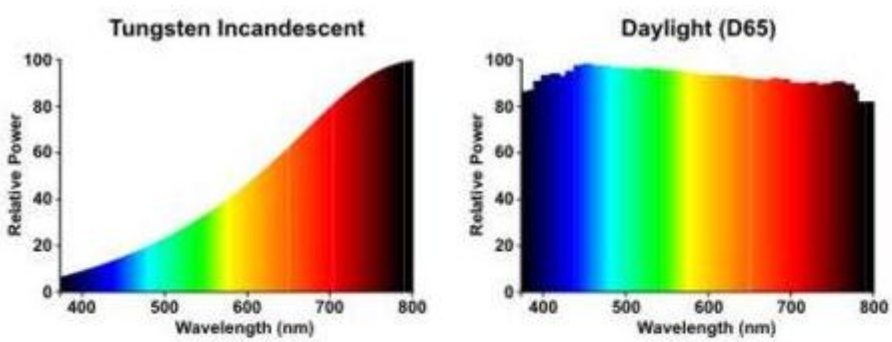


Figure 21 Spectral power distribution curves for incandescent lamps and daylight

In other words, a spectral power distribution that delivers the greatest luminous efficacy does not necessarily deliver the best color rendering. An artificial 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.

While some degree of efficacy, as calculated using the 1931 CIE photopic luminosity function, may be sacrificed in a light source that improves color rendering, wattage need not be increased to maintain adequate, comfortable light for the end user. Consider the two hypothetical LED replacement lamps (60W equivalents) shown in **Table 10** 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.[1] 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 10 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. The lamp model that will save more energy is the one that is 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 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 (above 85 lpw) are available in a range of CRIs, from ~85 to ~94 CRI.

[1] 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 1049.

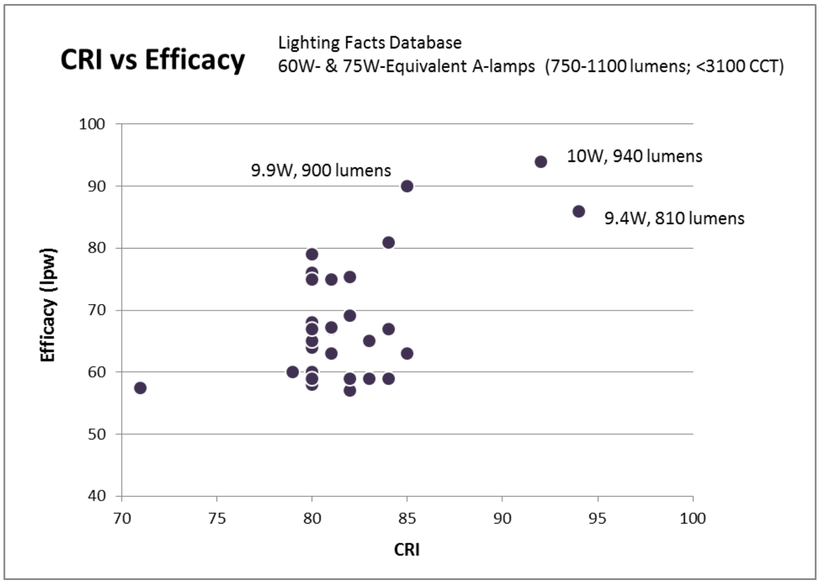


Figure 22 Efficacy vs. CRI in the Lighting Facts Database

1.6.7 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 23 Light distribution comparison of two LED A-lamps in table lamps
Source: GE Lighting Catalog: GE energy smart ® LED Replacement Lamps

The latest draft ENERGY STAR specification for A-lamps requires that each measured luminous intensity value (in candelas) vary by no more than 20% 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. The figure 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).

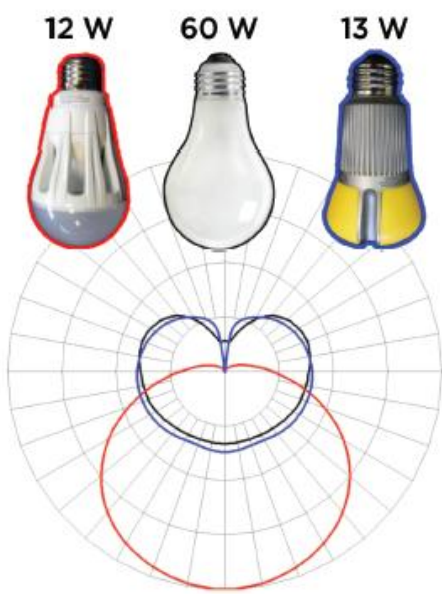


Figure 24 Photometric measurements of light distribution of two LED A-lamps compared to incandescent
Source: DOE Report, Establishing LED Equivalency;
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/establishing-led-equivalency.pdf

Detailed light distribution data is not easily accessible for many lamps in a format that can be quickly used to assess the performance of the market. Measured light distribution data for A-lamps is provided in the attached CLTC Test Report (PG&E 2013b).

1.6.8 Dimming

Because incandescent lamps are readily dimmable down to less than 1% of light, without flicker, buzz, or cutting in and out, many consumers were frustrated when CFLs did not dim or exhibited poor performance when installed in dimming sockets. On the other hand, most LED bulbs 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. **Figure 5.25** demonstrates this near 1:1 ratio of light to power.

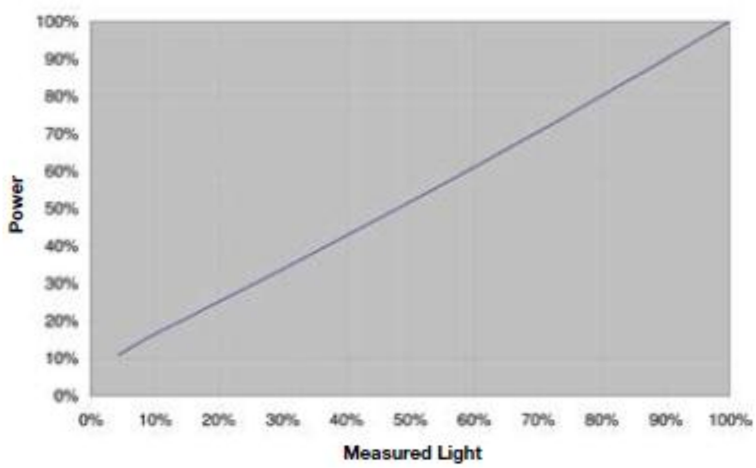


Figure 25 Power vs. Measured Light for a Typical LED Driver
Source: Lutron; Controlling LEDs

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[2], audible noise, premature lamp failure, limited dimming range, or failure to light (DOE 2012a). 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

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

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 26 below.

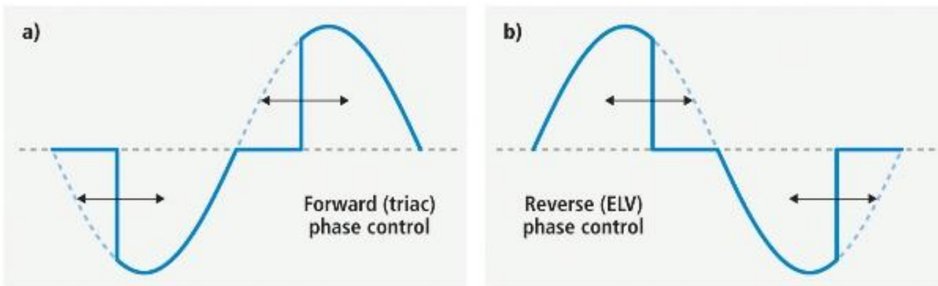


Figure 26 Impact of Phase Control on AC Waveforms
Source: Cooper David, LED lighting must work with legacy dimming technologies; June 2011; http://ledsmagazine.com/features/8/6/9

Phase control results in a predictable reaction in a simple resistive load such as an incandescent lamp filament. As shown in Figure 27 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.

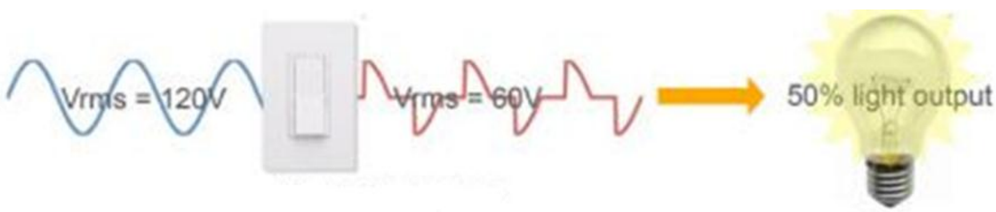


Figure 27 Phase-Cut Dimmer control of incandescent lamp
Source: Brodrick, James; http://ecmweb.com/lighting-amp-control/led-dimming-dilemma

LED lamps are much more complex than incandescent lamps. The main difference is that LED lamps are controlled by integral drivers, which are 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 28 below.

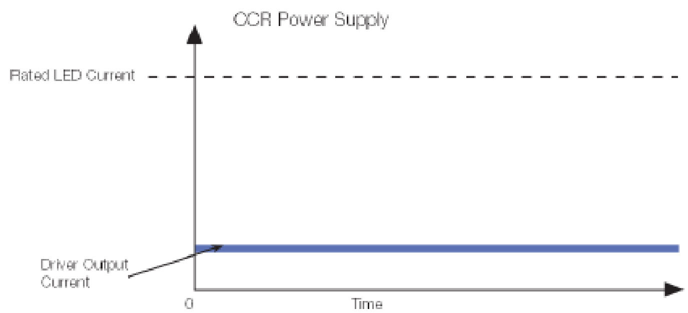


Figure 28 Constant Current Reduction (CCR) Dimming
Source: Lutron; Dimming LEDs via PWM and CCR

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.

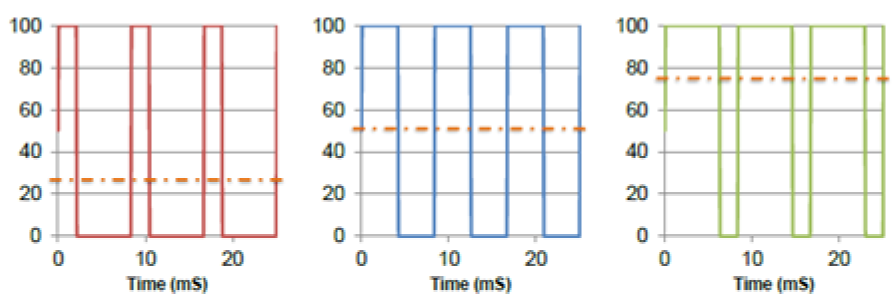


Figure 29 Demonstration of Pulse Width Modulation (PWM) of a current wave form
Source: PNNL

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. A NEMA committee has been developing a standard called NEMA SSL-7A which will address compatibility requirements and test procedures for qualifying LED light engines and forward phase cut dimmers. This document was approved by NEMA in April 2013 and was made available for purchase in late April. Additionally, the ENERGY STAR program is currently developing a dimming test procedure and specification the Lamps Specification, which should also help inform any dimming proposals for this Title 20 initiative.

Another attribute of LED dimming performance that has not been discussed in depth here 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 shifts to a more red hue, 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 while dimming (Philips 2013). This feature that should be considered in future specifications for quality LED lighting.

The testing currently being conducted by CLTC on behalf of PG&E and CLASP is addressing dimming performance. When results are available they will be delivered to the CEC.

1.6.9 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 metrics defined in the IES Handbook 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.

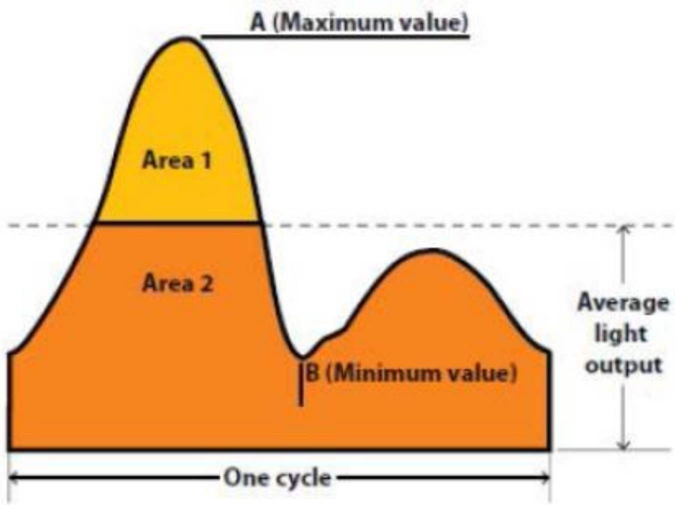


Figure 30 Periodic Wave Form Representation for Traditional Flicker Metrics

Flicker Index is defined using the following equation:

Flicker Index = 100% x (Max-Min) / (Max + Min)

Percent Flicker is defined using the following equation:

Percent Flicker = Area above Mean / 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 PNNL's 2011 report, "Exploring Flicker in SSL Integral Replacement Lamps." 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.

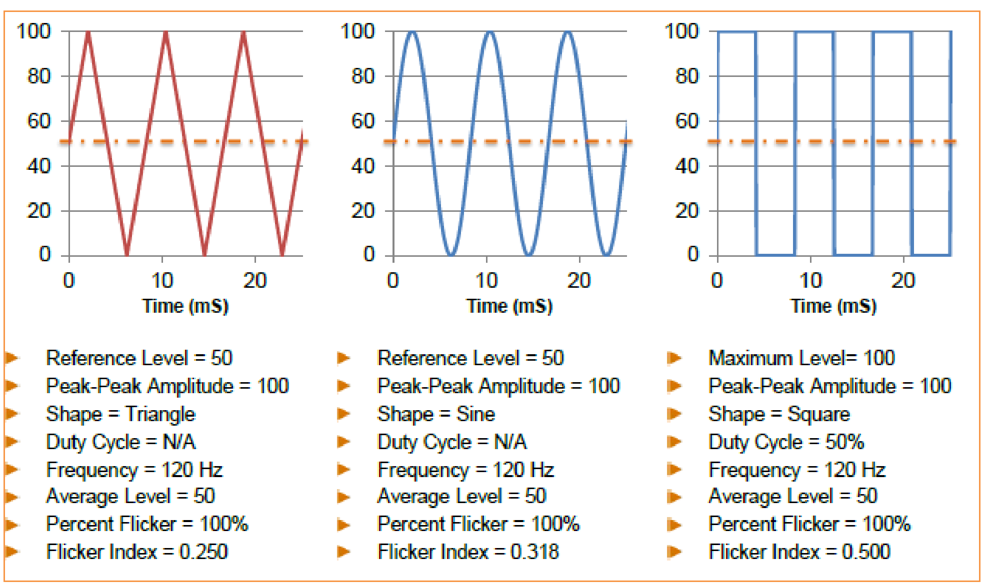


Figure 31 Comparison of three wave forms at 120Hz

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 at least to the 1970's. Various studies since then have showed 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 figures below.

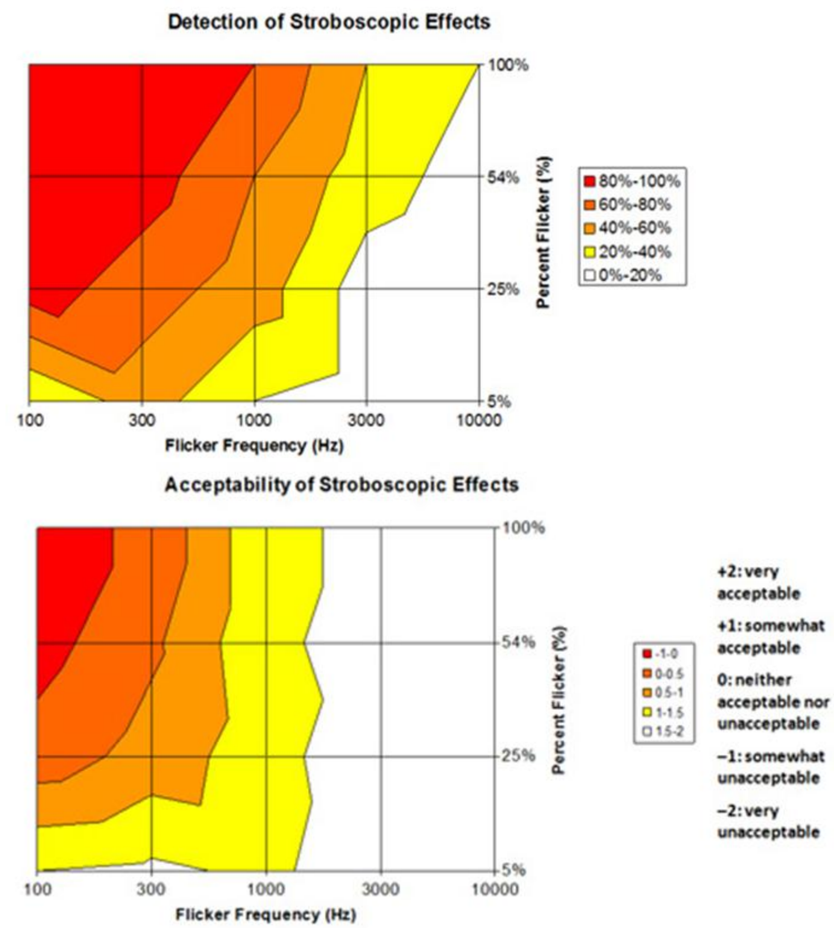


Figure 32 Consumer perception of and reaction to variation in Percent Flicker at different flicker frequencies

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 at10,000 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 in 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. Almost all of the flicker wave forms observed were at a fundamental frequency of 120Hz.

California has a history of regulating flicker in its building code and appliance standards regulation. 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 is currently co-funding flicker testing being completed at the CLTC. When results are available they will be delivered to the CEC.

1.6.10 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 documents in the Lighting Facts Database. However, it is included in the proposed ENERGY STAR® Lamps Specification, (Version 1 Draft 4) 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 may address audible noise levels in currently available LED lamp and dimmer combinations.

1.6.11 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, such as capacitors or inductors 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.

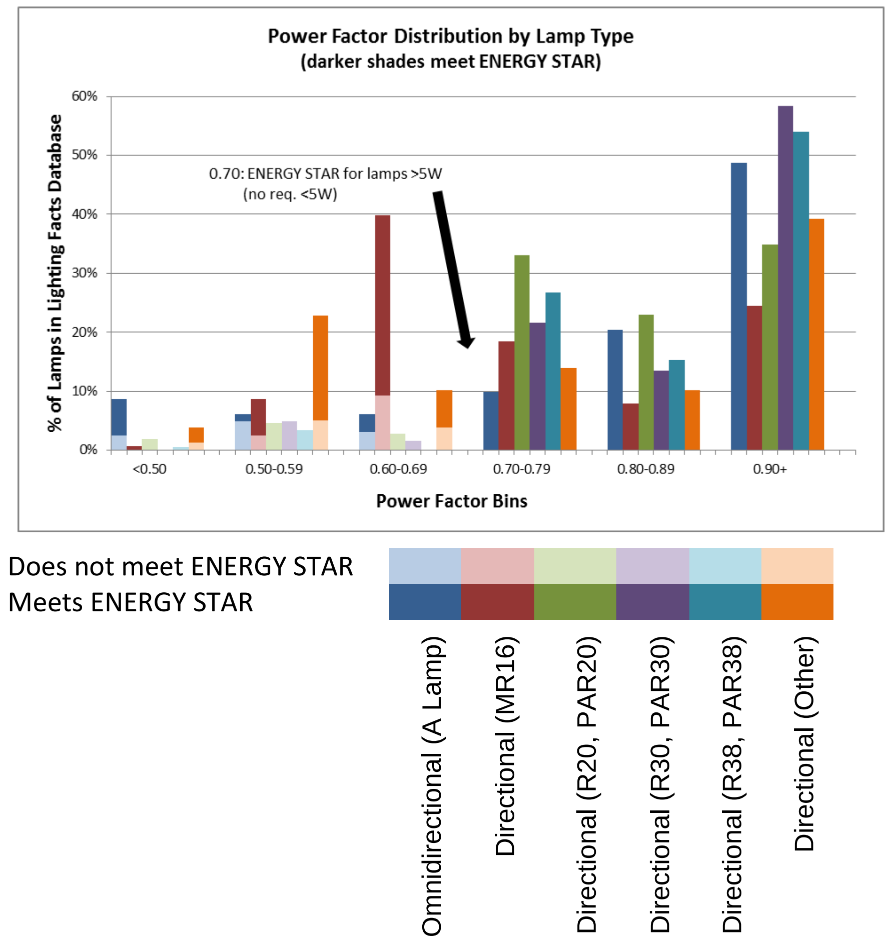


Figure 33 Distribution of Replacement Lamps across Power Factor Bins, by Lamp Type

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

1.6.12 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 by their maintenance savings rather than their energy savings potential (DOE 2012a). LEDs don't tend to fail suddenly (as an incandescent lamp does), but instead they very slowly decrease in light output. 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; they have been 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. ENERGY SAR includes lumen maintenance requirements, rated life requirements, and rapid cycling stress test requirements. Additionally, in its recent EcoDesign requirements for LED lamps, the European Union included a metric called Lamp Survival Factor and another called Premature Failure Rate. The definitions and test procedures for these two metrics are not yet available, but they are expected this year.

In the meantime, 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 about 3,200 hours of operating time, and a 5 year warranty would amount to about 5,500 hours of operation, both far below the typical lumen maintenance (L70) claims made by manufactures of 25,000 – 50,000 hours.

1.6.13 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. Future testing may be funded by PG&E to address audible noise levels in currently available LED lamp and dimmer combinations.

1.7 Range of typical performance for each indicator

Included in Section 1.6 "Relevant performance indicators," above.

1.8 Incremental costs of energy efficiency and quality features

Included in 2.5 "Cost of improved color consistency & quality" section below.

1.9 Product development trends

Included in Section 1.6 "Relevant performance indicators," above.

1.10 Market barriers to energy efficiency

No response provided.

1.11 Number of California small businesses associated with manufacture, sale, distribution, or installation

No response provided.

1.12 Market share by lamp type and by sector

The U.S. market share of general service (omni-directional) lamps and reflector (directional) lamps depends largely on the end use. The vast majority of general service lamps are in the residential sector (DOE 2012e). The majority of reflector lamps are also found in the residential sector, though they are used slightly more in commercial spaces than their omni-directional counterparts.

Table 11 U.S. Market Share of General Service and Directional Lamps by Market Sector

	Residential	Commercial	Industrial	All Sectors
General Service Lamp	4,166,448,500 (94.5%)	239,618,500 (5.4%)	978,000 (0.02%)	4,392,322,000 (100%)
Reflector Lamp	722,146,500 (88.1%)	97,413,500 (11.9%)	488,000 (0.1%)	834,771,000 (100%)

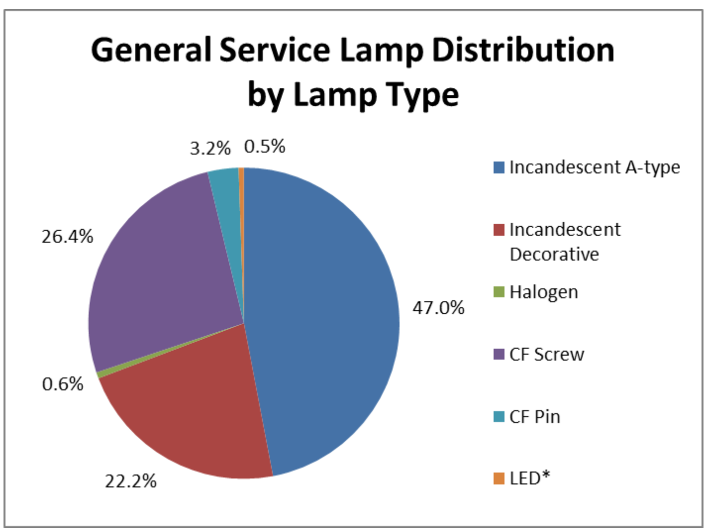


Figure 34. Distribution of General Service Lamps by lamp technology.
***The "LED" category in 2010 US DOE Lighting Market Characterization Study does not distinguish between lamp types. For these graphs, it is assumed that half of the total LED lamps are general service lamps, and half are directional lamps.**

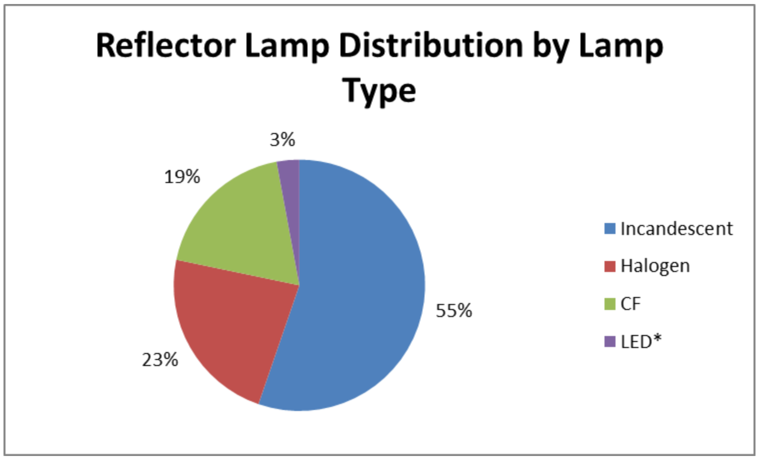


Figure 35. Distribution of Directional Lamps by lamp technology.
***The "LED" category in 2010 US DOE Lighting Market Characterization Study does not distinguish between lamp types. For these graphs, it is assumed that half of the total LED lamps are general service lamps, and half are directional lamps.**

1.13 How do consumers identify efficient products on the market?

No response provided.

2 Data Requests: Light Emitting Diode (LED) Lamps

2.1 Logical product categorization for analysis & Market share by category

Included in "1.1Category definition and scope" section and "1.12 Market share by lamp category and by sector" section above.

2.2 LM-79 and TM-21 reports

No response provided.

2.3 Types of dimming circuitry & minimum dimming levels

Included in Section 1.6 "Relevant performance indicators," above.

2.4 Patent or proprietary technology issues

No response provided.

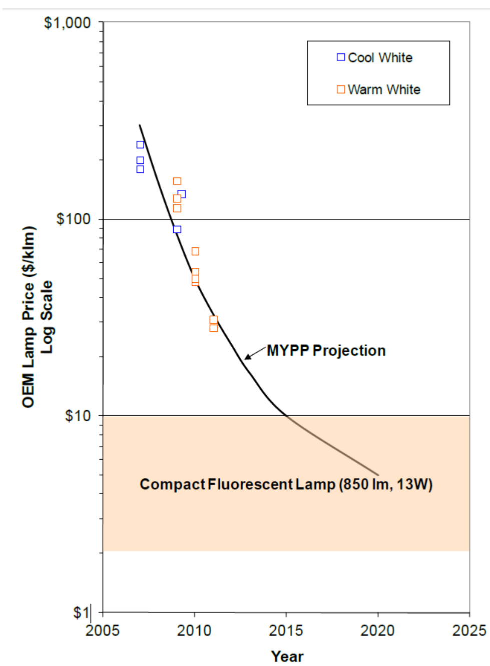
2.5 Cost of improved color consistency & quality

Enclosed in Appendix A of this document is a statistical analysis, conducted with data from several hundred LED lamps in the replacement lamp market, that assesses the impacts of various quality features on end user sale price.

3 Any Other Information Relevant to This Proceeding

3.1 Cost Forecast

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, 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 1** shows the total costs per kilolumen from white LED lamps (both warm white and cool white). Figure 2 Projected Relative Costs for an LED A19 60W Replacement Lamp (DOE 2012c, p. 17).Figure 2 shows the relative costs associated with LED lamp production specifically (an A19 LED 60W-replacement lamp), with specific lamp components and production processes identified individually.



Source: DOE 2012b, p. 46 (p. 46).

Figure 1 White Light Integrated LED Lamp Price Projection, in $/klm (Log Scale)

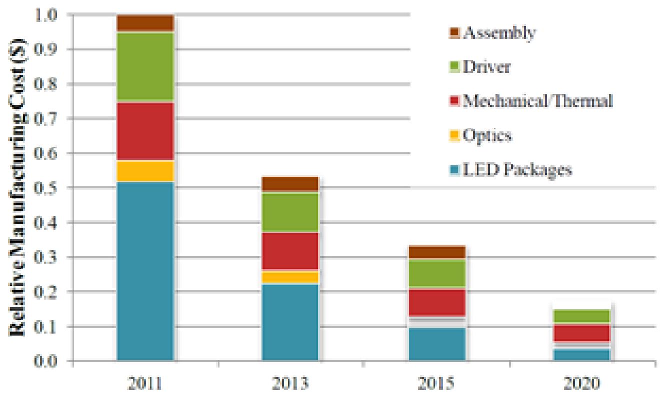


Figure 2 Projected Relative Costs for an LED A19 60W Replacement Lamp (DOE 2012c, p. 17).

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 cost data for A-lamps and directional lamps. On behalf of PG&E, the CASE team conducted a study of LED lamp costs in 2012. The research conducted in 2012 by this CASE team documented product costs 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 also 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.

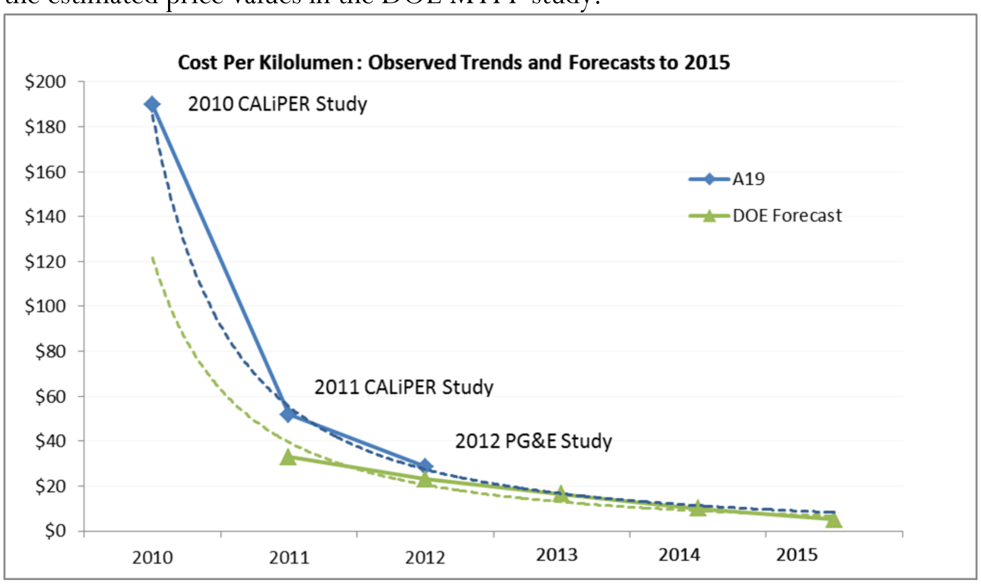


Figure 3 Price per Kilolumen for LED Replacement Lamps

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 the graph below.

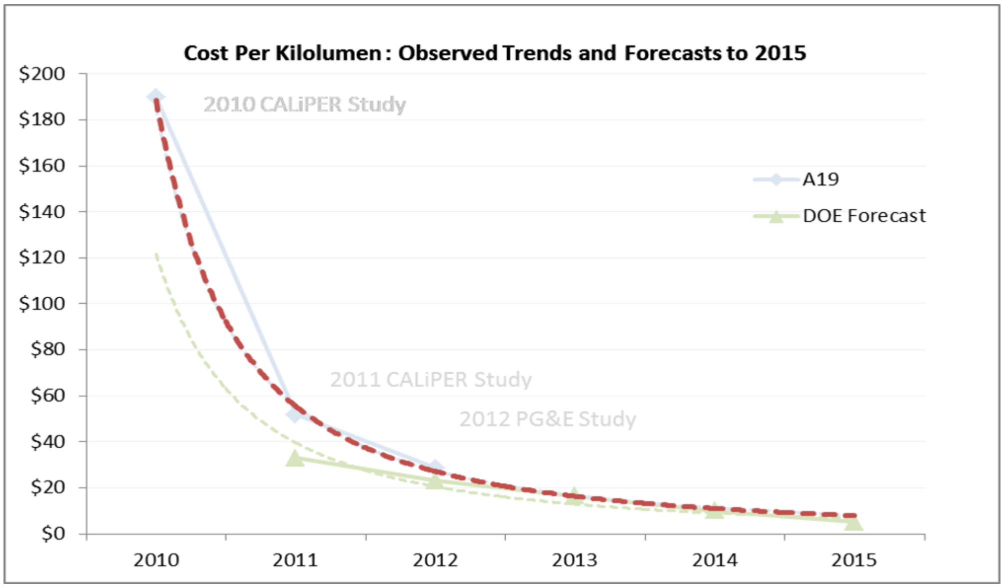


Figure 4 Projected Price per Kilolumen for LED Replacement Lamps

The forecasted average price per kilolumen in 2015 is approximately $10, meaning the average forecasted price for an 800 lumen (60Wequivelent) is approximately $8**. Table 12** below shows the forecasted average cost for a representative 1,003 lumen A-lamp from 2016 through 2031.

Table 12 Cost per lamp forecast, 2016 – 2031

	Representative Lamp Cost (2013$)			
Product Type	2016	2021	2026	2031
LED A-lamp (1,003 lumens)	$6.84	$2.68	$1.46	$0.93

3.2 The Zhaga Consortium

Most LEDs sold to date, especially for interior applications, have been permanent, i.e. the light source components cannot be replaced without replacing the entire fixture, including the mechanical, electrical and thermal management components. Light source irreplaceability was not a problem, given generally long lifetimes, when LED luminaires were specialty or even novelty products, but LEDs are gaining market share in many general lighting applications. The only common replaceable LED light source would be screw-in or pin-based LED replacement lamps, which can suffer from shortcomings in heat-sinking and optical performance because they are used in fixtures designed for incandescent or fluorescent sources.

Industry leaders, including National Electrical Manufacturers Association (NEMA) and the Department of Energy (DOE) Designer Roundtable, have recognized that future LED products will need replaceable components to address several concerns: initial product failure, ease of maintenance, current inability to upgrade even as efficacy quickly improves, repair from external damage, as well as end-of-life failure. In response, over 230 manufacturers and industry leaders have come together to form the Zhaga Consortium, which aims to develop specifications to enable interchangeability of LED light sources made by different manufacturers. The International Electrotechnical Commission (IEC) expects to publish new standards for the LED interconnects that have been developed by the Zhaga Consortium. These interconnects will not use the same sockets available today because of the importance of thermal management and other concerns specific to LEDs. Given the broad support behind this effort from manufacturers representing the majority of fixtures sold in California, these sockets may become new product standards for decades to come.

Below are two photographs of a Zhaga-certified LED product currently on the market, in which the LED light engine is part of a white plastic disc that connects, in accordance with Zhaga-specified mechanical, thermal and optical interfaces, with an optical lens and a thermal heat sink. The lower photo shows the light engine component on its own. When light engine efficacy increases, this portion of the fixture could be upgraded while leaving the rest of the fixture intact, unlike most common LED fixtures.

Figure 5 Zhaga-certified LED product

The Zhaga base type system could follow a path similar to the history of the GU-24 base type in California. GU-24 was introduced as a base for high-efficacy CFL lamps, and Title 20 appliance code designated GU-24 for high-efficacy sources only before low-efficacy sources with GU-24 came on the market. Subsequently, GU-24 bases were added to Title 24 building codes as a high-efficacy base type, allowing installations of GU-24 sockets to qualify as high-efficacy.

Zhaga Consortium members develop a set of specifications, called a Book, in members-only meetings. They publish the specifications once the certification is ready to begin for that Book or when certified products are on the market for that Book. The Consortium has discussed, but not finalized, plans to transition their specifications to a public standards body, most likely the International Electrotechnical Commission, when each specification Book is mature. At that point and likely not before, California appliance standards could reference the public specification. Currently there are 8 Zhaga books in various stages of development. The first three of them are available for public download; the others are only available to members (to date). Below is a list of the 8 Zhaga books, including links to Books 1 - 3:

Book 1 - Common definitions and generic interfaces.

Book 2 - A socketable light engine with integrated control gear - mainly used in downlight applications (65mm base)
Book 3 - A round engine with separate control gear - used in spot lighting and other applications that need a point light source
Book 4 - A flat emitter streetlight engine with separate control gear
Book 5 - A socketable light engine with separate electronic control gear
Book 6 - A compact socketable LED light engine with integrated electronic control gear
Book 7 - Several indoor light engines with separate electronic control gear
Book 8 - A socketable light engine with integrated control gear - mainly used in downlight applications (85mm base)

A fuller picture of the Zhaga Consortium's current activities and industry connections is available from their April email newsletter, sent 4/30/2013:

> Welcome to the April 2013 newsletter from the Zhaga Consortium.
>
> The Zhaga Consortium continues to add new members from throughout the international lighting industry. More and more products designed according to Zhaga specifications are reaching the market, and the official database of Certified Products (www.zhagastandard.org/products/certified-products.html) continues to expand.
>
> **Zhaga welcomes new members**
> Membership of the international Zhaga Consortium continues to grow. A total of 285 member companies from around the globe are involved in the development of interface specifications for LED light sources.
> More: www.zhagastandard.org/news/38/zhaga-welcomes-new-members
>
> **Electrical Contractor magazine publishes in-depth article on Zhaga**
> A new article published in the April 2013 issue of Electrical Contractor magazine discusses the benefits of Zhaga specifications for different user groups.
> More: www.zhagastandard.org/news/37/electrical-contractor-magazine-publishes-in-depth-article-on-zhaga
>
> **Tridonic, Samsung unveil Zhaga-based products**
> Zhaga members Samsung and Tridonic recently published press releases describing their Zhaga-based products. These and other similar announcements can be viewed on the "News from Zhaga Members" page on the Zhaga website.
> More: www.zhagastandard.org/news/40/tridonic-samsung-unveil-zhaga-based-products
>
> **Zhaga plans participation at GILE and LpS**
> The international Zhaga Consortium will take part in several lighting-industry events later this year, including the Guangzhou International Lighting Exhibition (GILE – June 9-12) and the LED Professional Symposium (LpS – September 24-26).
> More: www.zhagastandard.org/news/41/zhaga-plans-participation-at-gile-and-lps

Zhaga meeting takes place in Milan
The 21st Zhaga meeting took place in Milan, Italy, on March 19-21, 2013. Members of the Zhaga Consortium, which is developing interface specifications for LED light engines, discussed recent progress including the publication of the Book 2 specification.
More: www.zhagastandard.org/news/39/zhaga-meeting-takes-place-in-milan

About Zhaga
Zhaga is an industry-wide cooperation that develops specifications to enable the interchange of LED light engines made by different manufacturers.

General introductory information about Zhaga: www.zhagastandard.org/about-us

Details of individual Zhaga interface specifications: www.zhagastandard.org/specifications

We welcome your feedback and comments on Zhaga. We have a section of our website devoted to frequently-asked questions (FAQs) at: www.zhagastandard.org/faq

If you have additional questions or comments about Zhaga, please use our contact form: www.zhagastandard.org/contact

Best regards,
Tim Whitaker
Marketing Communications
The Zhaga Consortium
Web: www.zhagastandard.org
Email: marcom@zhagastandard.org

3.3 CFL consumer acceptance

Several studies have been conducted to identify consumer perceptions of and experience with CFL lighting, and to rank consumer priorities for their lighting purchases. 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

Below is a timeline of the CFL market share, documenting the slow and incomplete adoption of CFLs over the past 30+ years.

Table 13 CFL Market Share 1970-presentr lamp forecast, 2016 – 2031

Year	CFL Market Share
Late 1970s	CFLs introduced into U.S. market. They drew roughly a quarter of wattage drawn by their incandescent counterparts, and they lasted several times longer.
Late 1980s	Utilities begin to implement promotional and incentive/giveaway programs to bring down the price of CFLs in order to increase CFL market share.
1991	CFLs achieved only 1% of U.S. lamp sales volume.
2001	In the fourth quarter of 2001, U.S. CFL sales achieved only 2.1% of the national lamp market (DOE 2006).
2007	CFL market share hits a high of 22%.
2009	CFL market share drops to 16%. (DOE 2010b)
2010	In terms of total sockets converted,[3] CFLs estimated to make up roughly a third of all residential sockets in the U.S (DOE 2012e).

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

4 References

(References attached separately are highlighted in grey)

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Appendix A: LED Lamp Quality and Price Study

Table *of* Contents

Executive Summary

Background

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, Energy Solutions, on behalf of PG&E, 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, Energy Solutions collected lamp price and performance characteristics from the internet, constructed a model of lamp price based on performance characteristics, and conducted a multiple regression analysis to evaluate and refine the model.

Results

A model based on only four basic performance characteristics, bulb shape, wattage, color rendering index (CRI), and ENERGY STAR qualification status, explained 70% of the observed variability in price (p-value<0.001). The model predicts that ENERGY STAR qualification increases lamp price by 21%, whereas each increase of five CRI units increases 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, lumen output did not demonstrate a significant influence on price, independent of the effect of wattage. Similarly, correlated color temperature (CCT), dimmability, 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.

Wattage alone explains approximately 50% of the observed variability in price. The exceptionally close relationship between price and wattage may be related to the cost of the heat sink element.

Conclusions

The statistical study of the relationship between LED lamp price and quality suggests that higher quality does not always come at a significantly higher cost. Each five unit improvement in CRI is likely to increase bulb price by about 6%, less than a third of the increase caused by ENERGY STAR qualification alone. Improvements in other key performance metrics, such as efficacy, dimmability or lumen maintenance, do not appear to increase price significantly, if at all.

Next Steps

On behalf of PG&E, the California Lighting Technology Center is conducting independent tests of LED lamp performance characteristics. To evaluate whether manufacturer claims biased the findings, the analysis performed on manufacturer reported data will be repeated using the results of the independent testing. The

CASE team would also welcome LM-79 reports or other detailed spec sheets from manufacturers of LED replacement lamp products, because this would provide more data for many of the metrics where data could not be found publically.

Energy Solutions may also update the analysis on manufacturer-reported data using new price data available in 2013. Repeating the analysis with new price data will help evaluate the stability of the relationships between price and performance implied by the model, and will also allow analysis of price changes over time.

Details

Methods Details

Data Sources and Approach

Lists of LED lamp models and performance characteristics published by Lighting Facts and the EPA ENERGY STAR program were used as a starting point for the research. The performance data included in the Lighting Facts and ENERGY STAR lists were recorded in a database, along with the corresponding model numbers. Prices for each model number were researched on vendor websites using the manufacturer name and model number as Google search terms. Most A-lamp and PAR data was collected in summer 2012, with additional MR data collected in fall of 2012. Vendors included both online-only (e.g., Amazon.com) and traditional brick-and-mortar stores (e.g., Home Depot) that also sell products through the internet. Products from outside the lists published by Lighting Facts and ENERGY STAR were added to the study by using Google to search for terms such as "LED lamps", "LED A Lamps", "LED PAR replacements", and "LED MR replacements." The performance data available from Lighting Facts and the EPA ENERGY STAR program was supplemented using cut sheets, LM79 reports, and other product documentation provided by manufacturers and/or vendors. All performance data obtained in the study represented manufacturers' claims only. Results from independent testing currently underway will be incorporated into the analysis at a future date.

Two methods were used to avoid duplicating products in the dataset. First, a maximum of four different product model, identification, or code numbers or descriptors was associated with each new product or price point record. Each of the four fields was automatically cross referenced against all four fields of the other records to identify possible duplicates. Apparent duplicates were investigated and resolved manually. Second, duplications in key performance data were identified. Apparent duplicates were investigated and resolved manually. If other performance characteristics were found to distinguish the duplicates, products were treated as unique models. If no other performance characteristics were found to distinguish the apparent duplicates, then product records were deleted to leave only one unique product.

Overview of Data Collected

Energy Solutions staff collected performance information on 1,068 product model numbers and 702 different price points. Staff sought primarily to identify and record a representative price point for each product and corresponding set of performance characteristics, but occasionally collected multiple price points for the same product when significant variability was observed. No prices were found for more than half of the model numbers for which performance data was available. Two price points were identified for 93 products and a single price point was identified for 378 products. Three or more price points were identified for an additional 36 products. For each unique product, the average of all identified price points was used in the analysis.

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 Table A.1.

Table A.1. Summary statistics of price data collected for most prevalent product types.

Shape	N (number of products)	Minimum Price ($)	Maximum Price ($)	Mean 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%

Energy Solutions sought to collect data on a large number of performance metrics for each product. Data was not available for every targeted metric. Table A.2 shows the extent to which data was available for the targeted metrics for the three most prevalent bulb shapes. As is evident in the table, much less performance data was available for A lamps and certain types of data, such as R9 values and chromaticity consistency bins, were essentially unavailable for all bulb types. In addition to the performance metrics listed in Table A.2, a note was made if the product was ENERGY STAR-qualified and if the product was marketed as dimmable (so this information is considered to be available for 100% of products).

Table A.2. Performance Data Availability by Bulb Shape (% of products for which data was found)

Metric	A	MR	PAR	All
Watts	99%	100%	100%	100%
Distribution Type (bulb 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	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%

Results Details

Multiple Regression Analysis

The regression analysis was developed through an iterative process of model formulation including appropriate variable transformations, examination of model goodness of fit and significance, examination of the goodness of fit and significance of individual effects, and examination of residual distributions. A model of the form fit the data well visually (Figure A.1), had a statistically significant slope ($p<0.001$), included only individual effects with statistically significant slopes, and yielded homoscedastic, normally distributed residuals (Figure A.2 & A.3). The model had an adjusted r^2 value of 0.7, meaning that the model explains 70% of the observed variability in price. Interactions between performance characteristics were explored, but no interactions increased the explanatory strength of the model.

$$\text{Log(Price)} = a\ \textbf{shape} + b\ \textbf{ENERGY STAR} + c\ \textbf{CRI} + d\ \textbf{Watts} + \text{constant}$$

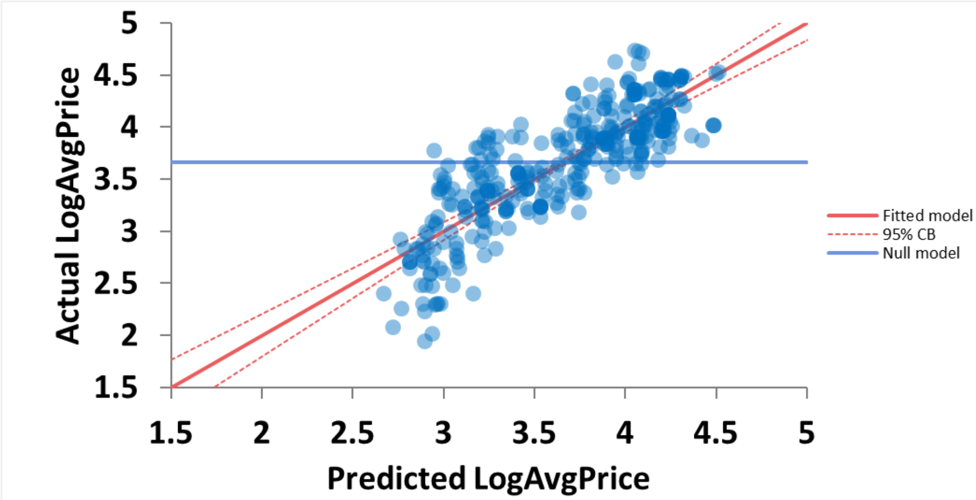


Figure A.1. Effect of multiple regression model of lamp price, showing actual lamp prices as a function of the lamp prices predicted by the model.

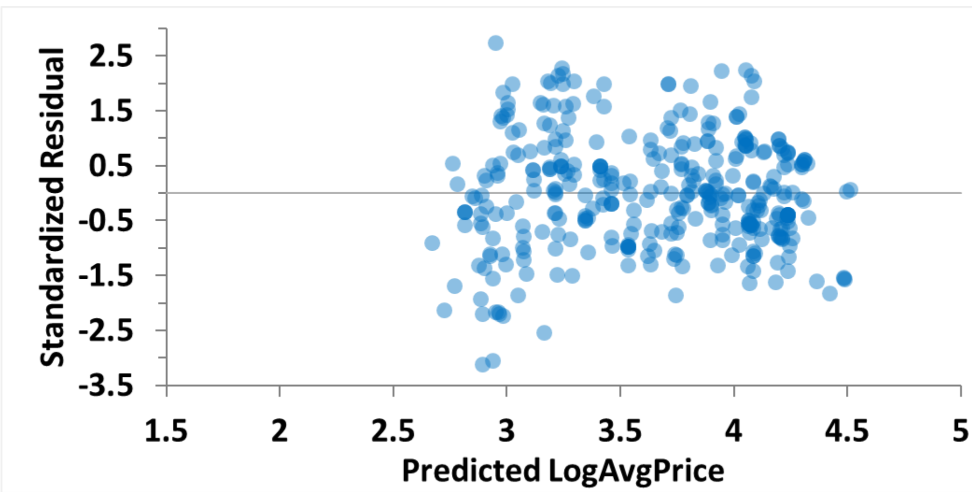


Figure A.2. Standardized residuals of multiple regression model of lamp price as a function of lamp prices predicted by the model.

The absence of any apparent curvature or heteroscadasticity indicates that the model form is reasonably good and that the assumptions that make inferences about the statistical significance of regression parameters valid have not been violated.

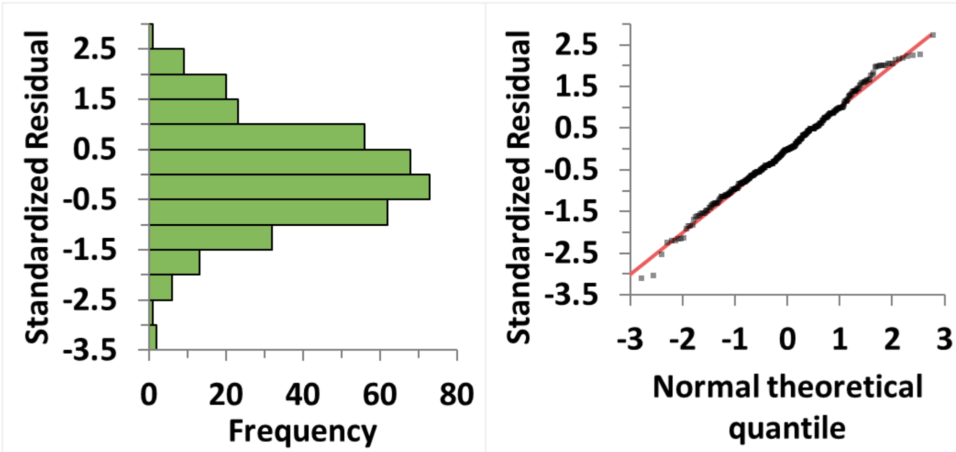
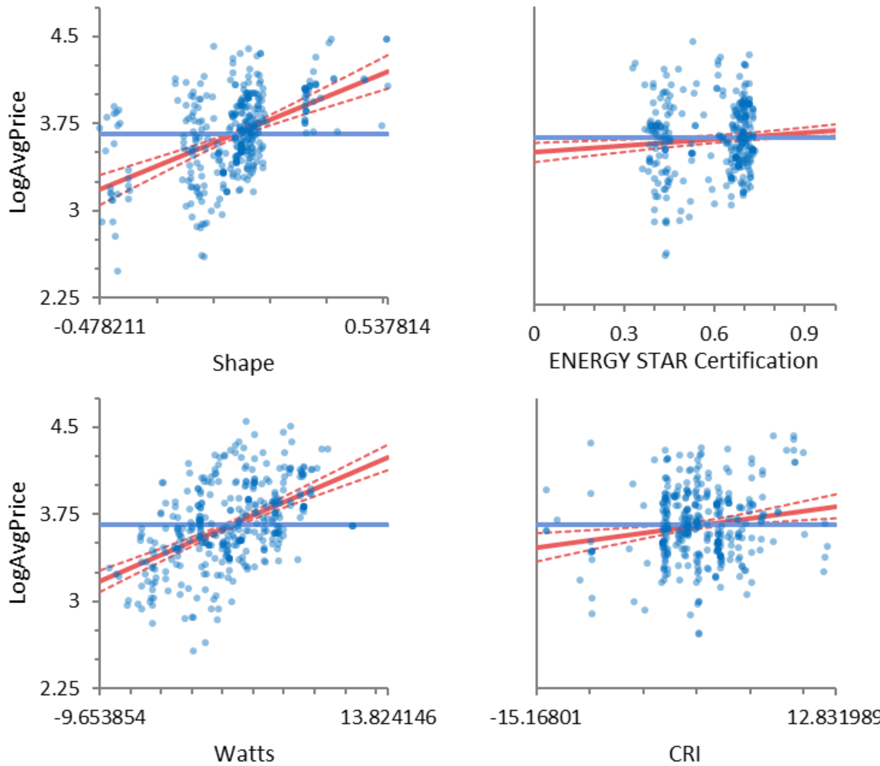


Figure A.3. Distribution of standardized residuals of multiple regression model of lamp price.

Normal distribution provides confirmation that the assumptions that make inferences about the statistical significance of regression parameters valid have not been violated.

Significance of Individual Performance Characteristics

Only four performance metrics demonstrated statistically significant effects on price: bulb shape, ENERGY STAR qualification, CRI, and wattage. The slopes of the individual effects of these four variables, and the p-value reflecting the statistical significance of their slopes, are shown in Figure 4. When included in the model, other variables, such as lumens, efficacy, dimmability, CCT, L70 lumen maintenance, warranty length, and power factor, did not have slopes that were statistically different from zero (p-value > 0.05). Interestingly, wattage alone explained about 50% of the observed variability in price. It is possible that the cost of the heat sink element explains the close relationship between wattage and price.



Term	P-value
Shape	<0.0001
ENERGY STAR Certification	0.0008
CRI	0.0014
Watts	<0.0001

Figure A.4. Independent effects of individual performance characteristics on bulb price after correction for the influence of the other metrics.

Magnitude of the Effects of Individual Performance Characteristics

Since the residuals indicate that valid inferences can be made from the regression estimates, Energy Solutions used the model to predict the magnitude of the impact of each independent variable on bulb price. This was accomplished by implementing the model in a spreadsheet using the following equation:

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

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 spreadsheet was used to estimate the price of bulbs with different combinations of performance characteristics. Figure A.5 shows how CRI and ENERGY STAR qualification status are predicted to affect the price of A-lamps at different wattages. As shown in the figure, ENERGY STAR qualification is predicted to increase the price much more dramatically than 5-unit changes in CRI. For any given wattage, ENERGY STAR qualification increases bulb price by 21%, whereas each 5-unit increase in CRI increases bulb price by only 6%. Each additional watt increases bulb price by 5%. Since the regression model is general and not shape-specific, the model predicts the same relationships among wattage, ENERGY STAR qualification, and CRI for other lamp shapes, but at different price points (see Figures A.6 & A.7).

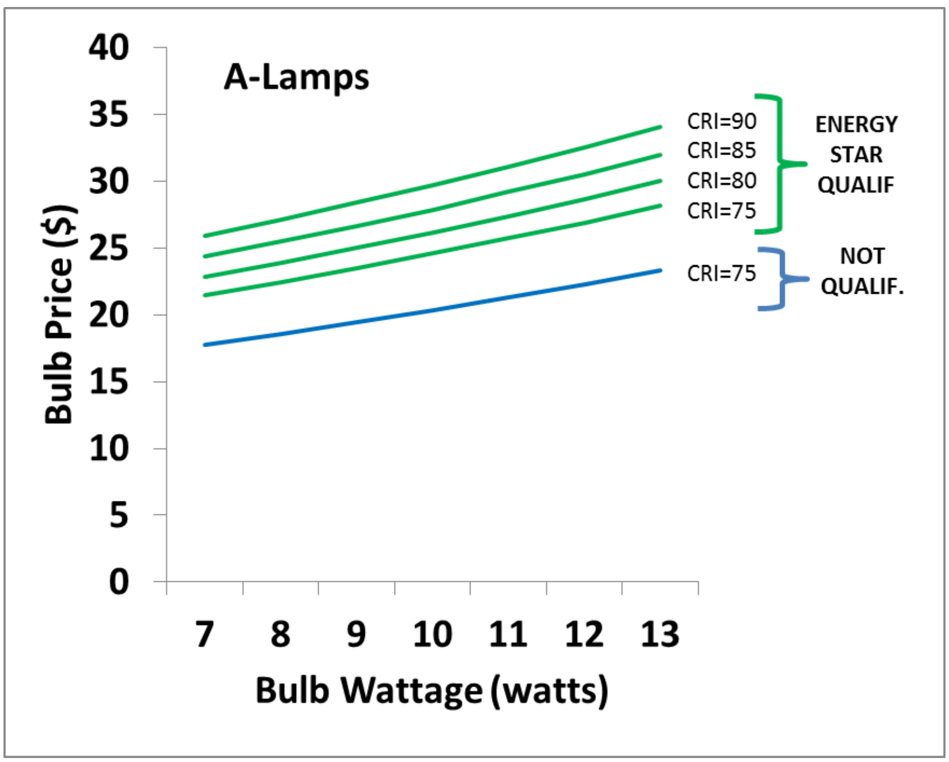


Figure A.5. Relative impact of changes in CRI and ENERGY STAR qualification on price of A-shape LED lamps.

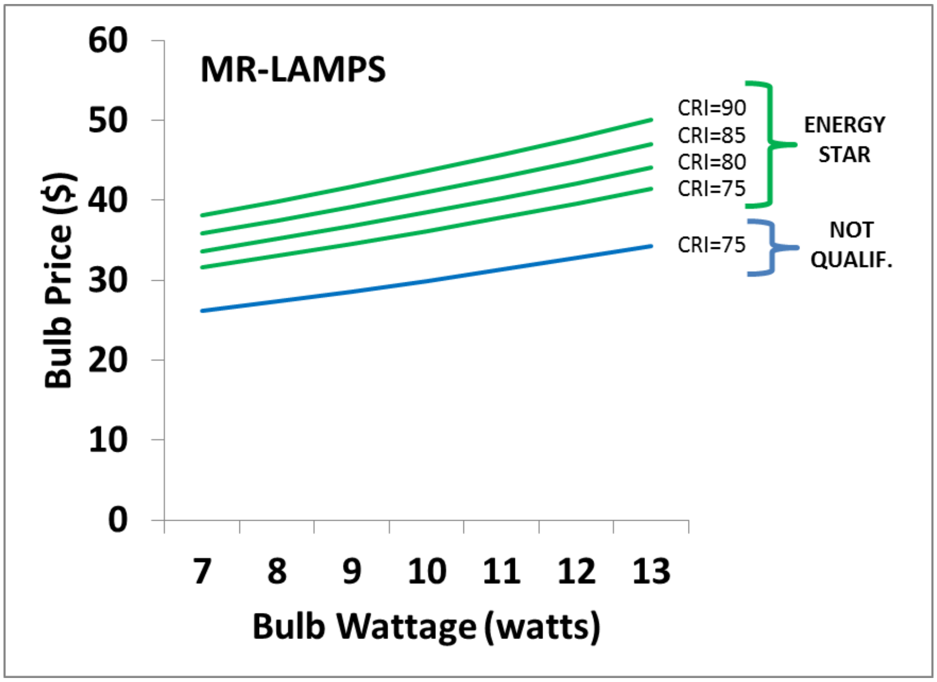


Figure A.6. Relative impact of changes in CRI and ENERGY STAR qualification on price of MR-shape LED lamps.

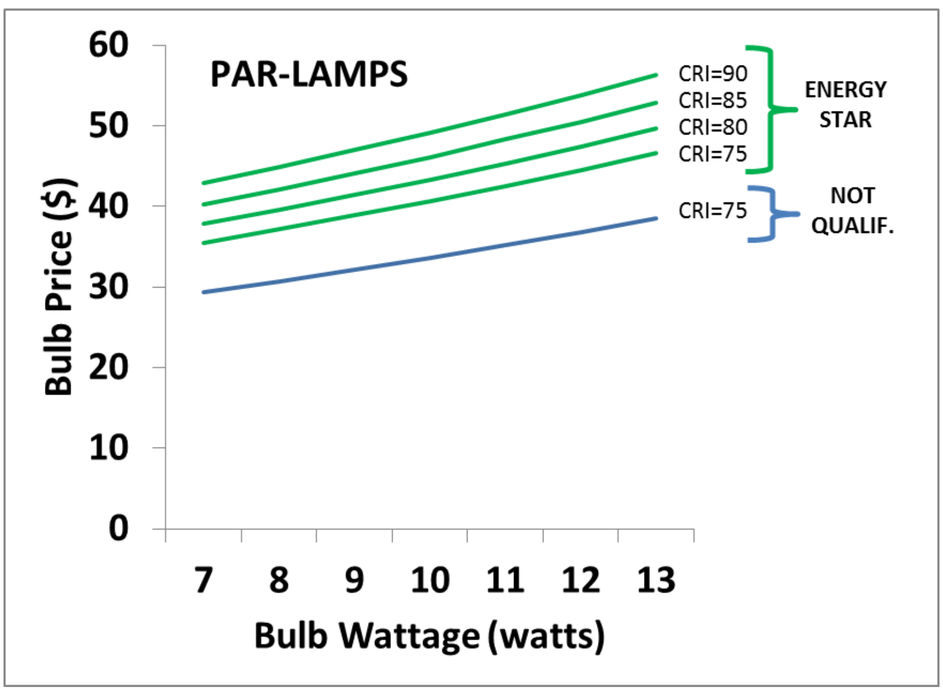


Figure A.7. Relative impact of changes in CRI and ENERGY STAR qualification on price of PAR-shape LED lamps.