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Small Diameter Directional Lamps

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

Analysis *of* Standards Proposal for
Small Diameter Directional Lamps

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1 Executive Summary

The Pacific Gas and Electric Company (PG&E), Southern California Edison (SCE), Southern California Gas (SoCalGas), San Diego Gas & Electric (SDG&E) Codes and Standards Enhancement (CASE) Initiative Program seeks to address energy efficiency opportunities through development of new and updated Title 20 standards. Individual reports document information and data helpful to the California Energy Commission (CEC), and other stakeholders in the development of these new and updated standards. The objective of this Program is to develop CASE Reports that provide comprehensive technical, economic, market, and infrastructure information on each of the potential appliance standards. This CASE Report covers a standard proposal for small diameter directional lamps (SDDL; diameter less than or equal to 2.5 inches), which include some multi-faceted reflector (MR) lamps (MR16s and MR11s) and parabolic aluminized reflector (PAR) lamps (PAR16s and PAR11s).

Given the magnitude of this market and large variance in energy consumption across products that offer very similar utility, establishing a minimum performance through the Title 20 process would yield significant energy savings that are cost effective to the consumer. Moreover, the very large majority of the installed base in California is comprised of the most energy-consumptive lamp type available (e.g., conventional halogen). Substitutes, such as halogen-infrared and light emitting diode (LED) lamps, provide comparable utility, and while slowly growing in market share, a standard is needed to transform and saturate the market with more cost-effective and energy efficient options. At present no Title 20 standard for small diameter directional lamps exists, nor is there a federal standard for small diameter directional lamps less than or equal to 2.5 inches (federal standards exist for incandescent reflector lamps with diameters greater than 2.5 inches).

In the commercial lighting sector one way of comparing the efficiency of two different light sources is by their luminous efficacy, a term which refers to the ratio of the amount of light produced by a lamp, measured in lumens, to the amount of power, measured in watts drawn. In this CASE Report we evaluate efficiency in terms of luminous efficacy (otherwise commonly referred to as efficacy), using the terms interchangeably. We established a baseline (or non-standards case) efficacy level, as well as four other potential efficacy standard levels (ESLs) that are representative of lamps with improved efficiency. Conventional halogen lamps were used to establish the baseline efficacy level, and the following lamps were used to establish the potential ESLs: conventional halogen infrared (HIR) lamps (ESL1), high-performing (HP) HIR lamps (ESL2), technically feasible HIR lamps and conventional LED replacement lamps (ESL3), and HP LED lamps (ESL4). These ESLs were segmented by efficacy and evaluated against typical baseline lamp wattage (W) designations in the small diameter directional lamps market (i.e., 20W, 35W, and 50W). This CASE Report goes into detail about feasibility of design and cost considerations associated with each ESL, as well as how these levels were evaluated.

We recommend a two-tiered approach to implementation. This would result in near immediate realized energy savings in California as well as greater energy savings in the futre, as LED and technically feasible HIR technology for small diameter directional lamps matures. Table 1.1 shows the recommended standard levels for this measure.

Table 1.1 Recommended Standard Levels for Small Diameter Directional Lamps

Tier Level	Voltage (V)	Energy Efficiency Standard (x = lumens)	Minimum Rated Life (hours)
Tier 1 (2015)	≥49	LPW > 0.01 * x + 5.08	4,000
	<49	Lm ≥ 300: LPW > 0.01 * x + 12.07 300< Lm ≤ 200: LPW > 0.05 *x Lm < 200: LPW ≥ 10	
Tier 2 (2018)	All voltages	LPW > 28	

A Tier 1 standard set at ESL1 would effectively require infrared coating on halogen lamps sold in the California market for lamps exceeding 300 lumens in output. HIR technology provides equivalent utility in the small diameter market, compatibility in all use-cases to the conventional halogen technology, already has a sizeable market presence, and serves as a cost-effective alternative without any technical feasibility concerns. The CEC should set this performance standard to be effective as soon as possible.

A Tier 2 standard set at ESL3 is necessary to capture significant savings associated with technically feasible HP HIR and conventional LED performance, allowing both halogen and LED technology to compete against one another within the California market. Small diameter LED products are already commercially proven to provide similar performance to halogen and HIR lamps in many applications. However, issues with high lumen output (e.g., greater than 600 lumens), replication of extreme beam angles (<10 degrees & >40 degrees), and transformer, dimmer, and occupancy sensor incompatibility in certain applications may prevent them from being a viable option for a standard at this time. The rate of LED product improvement, and our testing of prototype products, suggests that LED technology will overcome these compatibility issues and will provide equivalent utility to their halogen and HIR counterparts in all use-cases by 2018. Additionally, there is some growth in the high-performing HIR space which could supplement the variety of products that meet Tier 2.

In total, this approach would yield a net savings of 1,713 gigawatt-hours (GWh) after stock turnover and a reduction of 368 megawatts (MW) in peak demand. We recommend that the Commission adopt the above two-tiered standard, utilizing the same definitions and test procedures as set forth in IESNA LM-20-1994 and IES LM-79-2008 for efficacy, and LM-49-12 and IES LM-80-08 for lifetime.

2 Product Description

Small diameter MR and parabolic aluminized reflector (PAR) lamps are widely used for accent, task, and display lighting in museums, art galleries, retail stores, residential settings, and entertainment venues. MR lamps comprise the large majority (approximately 95 percent[1]) of the small diameter lamp market, while small diameter PAR lamps comprise the remaining portion of the market. For the purpose of this analysis, we assume a 95:5 split between MRs and PARs.

2.1 MR Lamp Market

MR lamps are typically designed for low-voltage operation using shorter, thicker, and more robust filaments which allow the lamp to generate high luminous intensity.[2] More robust filaments can accommodate higher currents, while thinner filaments are needed to limit current higher voltage appplications. In combination with lamp reflector design, the short filament also allows more precise control of light distribution and beam intensity, otherwise known as beam angle and center beam candle power (CBCP). Figure 2.1 below illustrates the relationship between CBCP and beam angle.

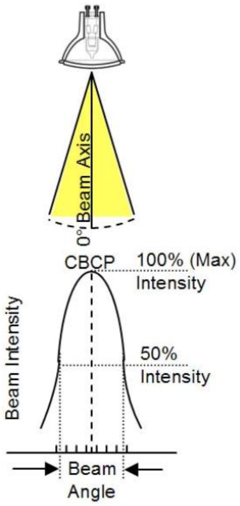

Figure 2.1 Relationship between CBCP and Beam Angle in Directional Lamps

Source: Paget and Lingard 2008

Based on a survey of manufacturers' catalogs, typical MR lamp beam angles range from 10 to 60 degrees.[3] CBCPs range from about 400 to upwards of 7,500 candelas[4], depending on the wattage and beam angle combination (ENERGY STAR® CBCP tool 2013). For directional lamps, CBCP is a useful metric because it helps to characterize how light is distributed, while lumen output is also useful because it helps to characterize how bright a lamp appears. Table 2.1 below describes typical

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[1] Based on phone interviews with lighting experts.

[2] Luminous intensity is a measure of the amount of light that a point source radiates in a given direction, which is particularly relevant to small diameter directional lamps since light is emitted within a specified beam angle. (IES TM-1-12)

[3] Beam angles for halogen products can be +/- 3 degrees, but are required to round to the nearest whole 10, 15, 20, 25, etc degree for the purposes of CBCP calculation with the test procedure.

[4] A candela is the Systeme International d'Unities (SI) unit for luminous intensity. One candela is one lumen per steradian.

CBCP values for commonly sold beam angles and wattages. ENERGY STAR® (ES) uses a CBCP calculator to establish wattage equivalency thresholds for MR and PAR lamps based on diameter, beam angle, and intended wattage equivalency replacement. This tool is the basis for manufacturer marketed claims for ES qualified LED products.

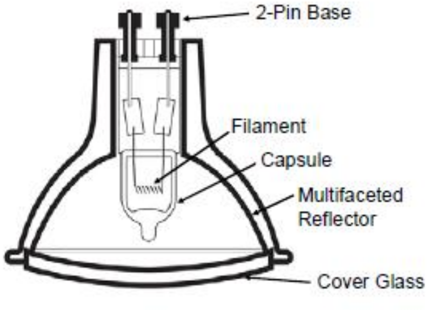
Table 2.1 Center beam candle power (CBCP) and beam angles for Halogen MRs

Lamp Type	Beam Angle	Average Range of CBCP (candelas)
Spot	10°	2,850 – 7,550
Narrow Flood	25°	875 – 2,300
Wide Flood	40°	400 – 1,050

Source: Survey of CBCP ranges from OSRAM/Sylvania 2010

MR lamps are typically sold as MR16s and MR11s, with the appended number referring to the diameter in eighths of an inch. MR lamps are sold in three conventional wattage categories: 50W, 35W, and 20W lamps. Wattage categories such as 37W and 30W are typically HIR and serve to replace 50W and 35W lamps, respectively. For the purposes of this Report, we refer to the 50W, 35W, and 20W lamp designations and 50We, 35We, and 20We as the equivalent lamp for lower wattage replacement lamps. According to Soraa, the market is split roughly 70%, 20%, 10% among 50W, 35W and 20W lamps and their respective replacements.

Many of these lamps operate on low voltage (12V), while some operate at line voltage (120V, for some MR lamps and all PAR lamps). Based on field observations and review of products available in manufacturer catalogs,[5] MR lamps sold in commercial applications tend to be low voltage while MR lamps sold in big box stores for residential applications operate on a mixture of line and low voltage. Low voltage lamps allow for a shorter, thicker, and more robust filament; this design enables the lamps to generate high luminous intensity (see Figure 2.2 for a schematic of a typical MR lamp). Typical bases for these lamps include the two-pin (GU5.3) base for low-voltage applications and a turn-and-lock (GU10) configuration for applications in which line voltage is used. Some MR that have been developed and marketed in the last few years include an integral transformer, which provides low voltage performance while using line voltage supply (see Figure 2.3 below).



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[5] GE 2013a, GE 2013b, Philips 2013a, Philips 2013b, Sylvania 2013a, Sylvania 2013b

Figure 2.2 Conventional Halogen MR Lamp

Source: LRC 2002

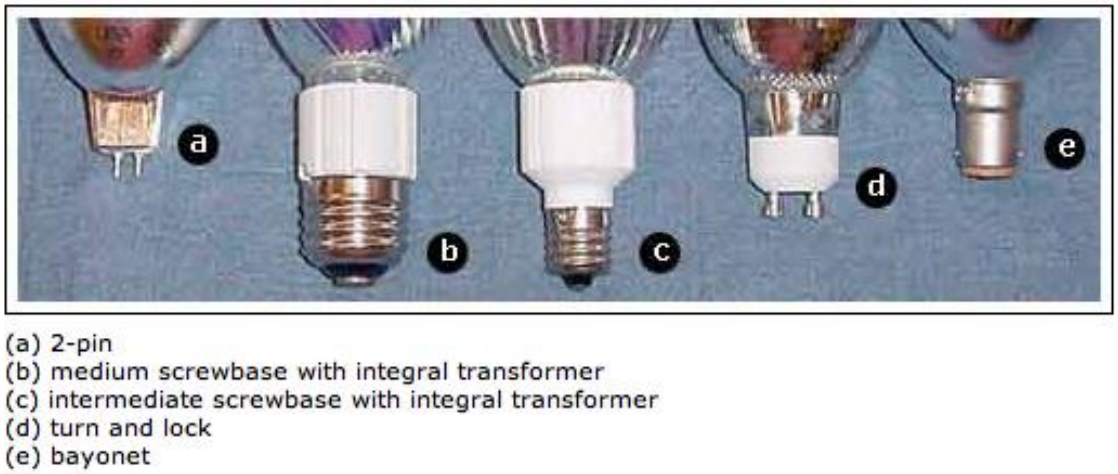

Figure 2.3 MR lamp bases

Source: LRC 2002

Like typical halogen lamps, MR lamps have very high (close to 100) Color Rendering Index (CRI) and Correlated Color Temperature (CCT) ranging from 2600 to 3200 Kelvin.

2.2 Small Diameter PAR Lamp Market

PAR lamps have less control over beam angle, shape, and sharpness relative to MR lamps, and are still widely used in entertainment and venue lighting. Though small diameter PAR lamps (including PAR16 lamps) are much less common, they still available. Similar to MR lamps, small diameter PAR lamps also come in the same range of beam angles (10 degrees to 60 degrees).[6] Additionally, CBCP and lumen output are typically considered in the selection of a PAR16. They operate at line voltage and generally have medium screw bases, medium-skirted bases, or GU-10 bases. PAR16 lamps are sold in three conventional wattage categories: 20W, 35W, and 50W. They are rarely found in 60W and 75W configurations.

2.3 Technologies Considered in this Report

The small diameter directional lamp market is comprised of three main technologies with widely varying efficacy levels. Additionally, there is not a trade-off in utility in switching among these different performance levels. From most to least energy intensive and from largest to smallest market share, these technologies include: (1) conventional halogen lamps, (2) halogen infrared (HIR) lamps and high performing HIR lamps, and (3) technically feasible HIR lamps and LED small diameter lamp replacements and their higher performing LED counterparts. A more detailed description of the performance, design, market saturation, and cost associated with each of the performance levels is discussed in Section 4.3 of this Report.

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[6] Beam angles for halogen products can be +/- 3 degrees, but are required to round to the nearest whole 10, 15, 20, 25, etc degree for the purposes of CBCP calculation with the test procedure.

3 Manufacturing and Market Channel Overview

The “big three” traditional lighting manufacturers, Philips, OSRAM Sylvania, and GE all make a range of halogen and HIR small diameter directional lamp products. Additionally, they act as innovators and drivers in the LED lighting space (e.g., Philips Lumileds and OSRAM Opto Semiconductors, and GE GelCore) making high quality, competitive products. In some instances, they have also responded to opportunities in LED lighting by creating joint ventures or acquiring those in the solid-state lighting space (Sanderson, Simmons and Walsh 2008). Many other companies are focused primarily on LED lighting and do not make halogen or HIR lamps, including CREE, CRS Electronics, SORAA, LEDnovation, and Solais.

In the residential market, small diameter directional lighting products are typically purchased by consumers in Home Improvement stores like Lowe’s, Home Depot, and ACE Hardware. These stores sell conventional halogen lamps, and are increasingly offering a number of LED options. In the non-residential market, commercial lighting designers often select lamps through distributor contacts or lighting catalogs, which provide a wider range of HIR and LED options. According to interviews with experts, halogen-infrared constitute roughly 6 percent of the market, LEDs constitute 2 percent, and halogens constitute the remainder.

4 Energy Usage

4.1 Test Methods

4.1.1 Current Test Methods

For efficacy measurements of incandescent reflector lamps the most relevant test method is IESNA LM-20-1994, “IESNA (Illuminating Engineering Society of North America) Approved Method for Photometric Testing of Reflector-Type Lamps.” For lifetime testing, the most relevant test method is IESNA LM-49-12. Department of Energy (DOE) released a final rule on test procedures for incandescent reflector lamps (IRL), general service incandescent lamps (GSIL), and general service fluorescent lamps (GSFL) on January 27, 2012 (DOE 2012). In the final rule, DOE adopted LM-20-1994, the IES-approved[7] method for the electrical and photometric measurement of reflector type lamps. It should be noted that while a test procedure is in place, DOE does not have standards for small diameter directional lamps.

For measurement of LED lamps, the most relevant test methods are IES LM-79-08, “IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products,” IES LM-80-08, “IES Approved Method for Measuring Lumen Maintenance of LED Light Sources,” and TM-21-11 for “Projecting Long Term Lumen Maintenance of LED Light Sources”.

4.1.2 Proposed Test Methods

We recommend that the CEC adopt the following test procedures, discussed above and reiterated below, since they are the industry standard test procedures for halogen reflector and LED replacement lamps:

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[7] The Illuminating Engineering Society (IES) is the recognized technical authority for lighting test methods in the United States, and works through a consensus process with related organizations to produce jointly published documents and standards.

- *IESNA LM-20-1994,* "IESNA Approved Method for Photometric Testing of Reflector-Type Lamps"
- *LM*-49-12, "IES Approved Method for Life Testing of Incandescent Filament Lamps"
- *IES LM-79-08*, "IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting"
- *IES LM*-80-08, "IES Approved Method for Measuring Lumen Maintenance of LED Light Sources"
- *TM*-21-11, "Projecting Long Term Lumen Maintenance of LED Light Sources"

The following specific data measurements should be collected during the test procedure:

- Luminous flux, measured in lumens (lm)
- Power, measured in watts (W)
- Efficacy, measured in lumens per watt (lm/W)
- Beam angle, (degrees)
- Beam Lumens
- Center beam candle power (CBCP), as defined in LM-20-1994
- Lifetime, as determined by LM-20-1994 or TM-21-11

For LED testing, given that there are multiple methods for the LM-79 test, including sphere-spectroradiometer, sphere-photometer, and goniophotometer, we recommend that the CEC accept any of these methods of testing as permitted by LM-79.

For this standard, the Case Team proposes that performance be measured in terms of efficacy (in lumens per watt). For the Tier 1 standard, we suggest that different efficacy standards apply to low voltage and line voltage lamps. Additionally, we suggest a linear formula for minimum efficacy based on lumen-output and voltage for Tier 1 since halogen lamps have increased performance at higher lumen output and lower voltage. We recommend that manufacturers also report data on lumen output, beam angle, center beam candle power, power, and true power factor, and that this information be maintained in a database by the CEC.

4.2 Other efficiency metrics considered, but not recommended

Two other plausible metrics would be CBCP per watt and beam lumens (or field lumens) per watt could be used in lieu of efficacy, and that are applicable to small diameter directional lamps. Since lighting designers often use CBCP (instead of lumens) for selecting MR lamps, it is more appropriate to evaluate lamp efficiency in terms of this metric. However, since CBCP is a function of beam angle, a CBCP per watt performance metric would necessitate a standard specification for each beam angle, for which there are many. CBCP is also not a conventionally reported value for PAR lamps. We believe CBCP per watt, while an important design consideration, would be overly complicated for lighting designers and consumers and would be difficult to enforce. Thus, we do not recommend using this metric.

Evaluating efficiency of lamps in terms of beam lumens or field lumens per watt could be appropriate. Beam lumens measure only the lumen output within the lamp's designated beam angle, which is particularly relevant to MR lamps because their light output tends to be concentrated within the beam spread (see Figure 4.1 for an illustration of typical MR light distribution). However, since neither field lumen or beam lumen data is readily available, or published in most manufacturer catalogs, little data is available to evaluate standard levels using this metric. Thus, we do not recommend this metric at this time.

20-watt R40 CFL

20-watt 40° MR16 lamp

Figure 4.1 Concentrated Light Output within the Beam Spread for MRs – Comparison

Source: Lighting Research Center 2002

4.3 Market Segmentation & Characterization

We have categorized the market of small diameter directional lamp technologies into five levels, with one baseline, and four efficiency level considerations per standard referred to as Efficacy Standard Levels (ESLs). These categorizations are grouped according to the mean efficacy of a given lamp design, which consists of the technology employed, filament design, capsule design, reflector design, and lens. These ESLs are the basis for evaluating different standard levels and for calculating the savings associated with the CASE Report Proposal, discussed later in this Report.

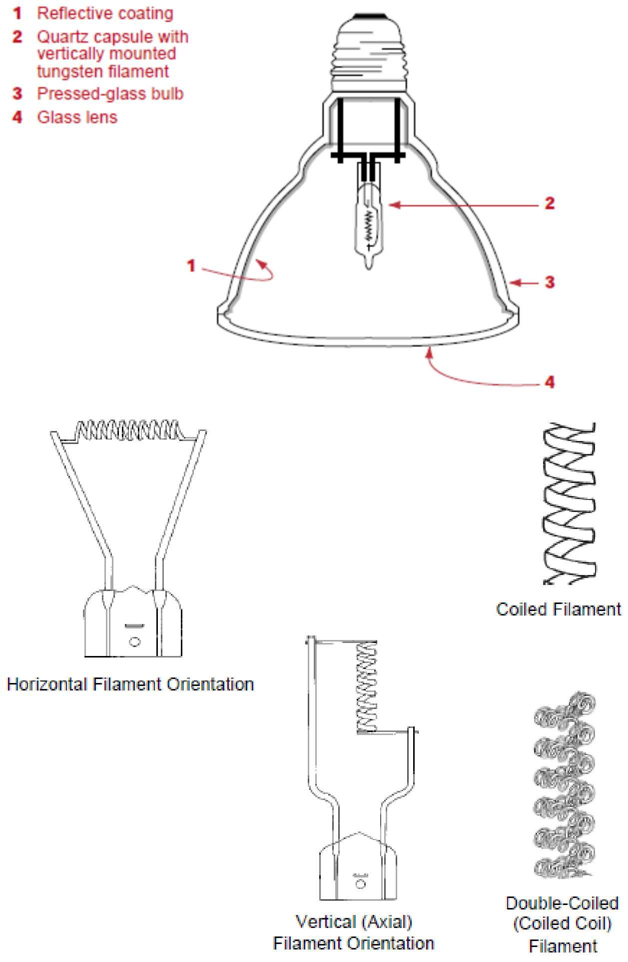
4.3.1 BASELINE - Conventional Halogen Lamps

Conventional halogens are the least efficacious directional lamps, achieving a range of about 5 to 13 lumens per watt (lpw) in three primary wattages: 50W, 35W, and 20W (Walercyzk 2006 & ECEEE 2011). This Report references newer, more efficacious technologies that allow lower wattage lamps to achieve equivalent lumen output to the baseline. These lower wattage lamps will be referred to as "50W-e" (for 50W equivalent), "35W-e", and "20W-e."

Conventional halogens achieve the full range of beam angles and are compatible with magnetic and electronic transformers in low voltage applications, as well as with dimmers and occupancy sensors. These lamps have the shortest lifespans of the efficiency levels evaluated in this CASE

Report (~1,500–3,000 hours), but also have the lowest upfront cost, ranging from $2 to $5 per lamp. This type of lamp constitutes approximately 93 percent of the small diameter market.[8]

With respect to lamp design, halogen filament lamps are usually coiled or double-coiled and oriented vertically, parallel to the center-beam axis of the lamp (see Figure 4.2 below); please note that while a PAR lamp is featured below (not an MR lamp), the representation of filament design and orientation is transferable across. This axial orientation makes it easier to direct the light with reflectors and improves optical control.



(Adapted from IESNA 1993)

Figure 4.2 Conventional Halogen Lamp Filament Design and Orientation

Source: NLPIP 1994

Variance in performance across the spectrum of halogen small diameter lamps is influenced by the filament, Quartz capsule (also called a burner), and reflector design.

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[8] Based on a phone conversation with a Sales Specialist at Deposition Sciences Inc.

4.3.2 ESL 1 – Halogen-IR

HIR lamps contain an infrared reflective coating on the outside of the halogen capsule which reflects infrared energy back onto the filament, causing it to burn at a higher temperature and generate more light. Typical HIR lamps use infrared (IR) coatings with alternating layers of two materials, SiO_2 and either Ta_2O_5 or Nb_2O_5 (DOE 2009b). They are more efficacious than standard halogen lamps (Sylvania 2011) and achieve approximately 13-20 lpw. To this end, a 37W HIR lamp produces equivalent lumen output to a 50W conventional halogen; a 20W HIR lamp produces about the same lumen output as a 30W and some 35W conventional halogen lamps. The CASE Team is unaware of any HIR lamps that are designed to replace 20W conventional halogens. We speculate that 20We is not commercially available because the 20W market segment is already very small and the cost-savings benefits of HIR lamps diminish at these low wattages.

HIRs have a larger variance in useful life though they are typically designed to last longer than conventional halogens; they are generally branded as a higher-performing product. Based on catalog literature from GE, Philips, and OSRAM-Sylvania, these lamps have an average life of 4,000 to 6,000 hours. Based on google shopping results, these lamps cost in the range of $4 to $10. Conventional HIR lamps account for approximately 2.5 percent of the market. While HIR lamps have increased in market share over the past 10 years, the natural market transition from conventional halogen to HIR is occurring slowly. Philips, GE, Osram Sylvania, and other manufacturers already have positions in this market. In Section 7 of this report, we delve into manufacturer impact in greater detail, along with an analysis of impact on manufacturing equipment and capacity to scale deployment of HIR and LED lamps. Impact to consumers is net positive, as discussed further in the savings potential section (see Section 6).

4.3.3 ESL2 – High Performing Halogen-IR

There is also a growing presence of high performing (HP) HIR lamps, which are achieving higher efficacy in the range of 17 to 22 lpw with even longer lifetimes of 8,000 hours. Like typical HIR lamps, these higher performing lamps use IR coatings with alternating layers of two materials, SiO_2 and either Ta_2O_5 or Nb_2O_5 (DOE 2009b), though some models achieve increased efficiency through application of additional layers and/or improved coating formulas. Additionally, they tend to utilize one of the following design options as well as an infrared coating to achieve higher performance: double-ended halogen infrared burner, a higher-efficiency inert fill gas in the surrounding lamp, or a more efficient filament orientation (DOE 2009c). Like conventional halogen and HIR lamps, HP HIR lamps do not have issues with transformer and dimmer compatibility and come in the full range of beam angles. HP HIR lamps range in cost from $10 to $15, and only account for 2.5 percent of the market. Companies such as Venture Lighting and Advanced Lighting Technologies are creating products that have performance specifications in this range.

4.3.4 ESL3 – Technically Feasible HP HIR lamps & Conventional LEDs

Due to the wide range in LED performance, we have divided the LED replacement lamp market into two categories: conventional LEDs and higher performing LEDs. We are also aware of very high performing halogen infrared capsules that can achieve upwards of 45 lumens per watt at larger form factors, and thus, have chosen to include those technically feasible (not yet commercially available) HIR products in ESL3 as well.

In terms of LEDs, ESL3 represents the LED market with efficacy ranging between 35 to 45 lumens per watt. On a lumen output basis, there are a large number of LED products that already achieve 20W and 50W equivalency, and a growing number that claim to achieve 50W equivalency. Several manufacturers have recently released LED replacements for 50W equivalency; these LEDs are currently likely to match 50W small diameter lamps on a CBCP basis. While there is a wide range of variance in CRI and CCT of LED products on the market, they are achieving an average CRI above 80. Many are also in the range of 2600 to 3000 Kelvin, which is typical of halogen lamps.[9]

Conventional LED replacement lamps range in cost from $16 to $30 and typically last around 25,000 hours. These lamps constitute the majority of the 2 percent of the market that represent LED penetration in the small diameter directional lamp market.

In addition to LEDs, the CASE Team expects to see super high efficiency HIR lamps that are on par with conventional LEDs in terms of efficacy. Deposition Sciences Incorporated is in the research and development phase of halogen-IR lamps that achieve 45 lpw. One of the goals of the halogen lamp testing is to build prototype lamps that can achieve higher than commercially available efficacies.

4.3.5 ESL4 – High Performance LEDs

Innovation within the solid-state lighting sector has paved the way for high performing small diameter LED replacements. They achieve efficacies of 45 to 70 lumens per watt, and these have been quickly improving over the last several years, as is the rest of the LED market for replacement lamps. Higher performance LEDs are characterized by more advanced chip designs, fewer LEDs, better optics, and other design improvements. These lamps constitute the smaller portion of the remaining roughly 2 percent of the small diameter lamp market comprised of conventional and high performance LEDs. The cost of these lamps range between $28 to $45.

For the reader's convenience, the CASE Report summarizes basic technical and market information about each ESL in the Table 4.1 below.

Table 4.1 Overview of Baseline and Efficacy Standard Levels Considered in this CASE Report

Standard Level	Baseline	ESL1	ESL2	ESL3	ESL4
Design Option	Halogen - non IR	HIR	HP HIR	Technicall feasible HIR and basic LEDs	HP LEDs - newer chip & electronic configurations
Efficacy (lpw)	12 to 15	15 to 20	17 to 22	30 to 45	45 to 70
Cost per Unit	$4	$6	$8.30	$25	$30
Average Lifetime Hours per Lamp	1,500 - 3,000	3,000 - 6,000	3,000 - 8,000	~25,000	> 35,000
Current Market Share	92.8%	4.5%	1.5%	1%	.7%

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[9] The Title 20 spec on LED quality for directional lamps will largely address issues of color quality and wattage equivalency thresholds for LEDs, which would mitigate most issues surrounding LED performance comparability to conventional halogen and halogen infrared products.

4.4 Trends in Small Diameter Directional Lamp Technology

4.4.1 Factors Influencing Luminous Efficacy of Halogen Lamps

Infrared Coating in HIR lamps can dramatically improve a lamp's efficacy, but other factors also influence the performance of halogen lamps. Some of these factors include:

- Fill gas composition and pressure
- Capsule geometry (relevant to IR coated lamps)
- Filament composition, orientation, and placement
- Reflective coatings applied to the inner surface of the reflector portion of the lamp
- Use of double-ended burners

Fill gas, such as xenon, can improve efficacy. Increasing the pressure of any fill gas that is used can also improve efficacy. This approach also increases explosion hazard, however. Capsule design (elliptical), filament orientation (vertically oriented), and filament type (double-coiled) have greater effects on efficacy in HIR lamps. The most efficacious capsules use a double-ended design with an ellipsoidal capsule shape. Higher reflectance coatings on the inner surface of the reflector, such as aluminum, silver, and gold affect efficacy as well. Silver and gold have higher reflectivity, and thus higher efficacy, but aluminum is the most commonly used due to its lower cost. Silver reflective coatings used in conjunction with Tungsten filaments are also more efficacious than conventional halogens. Figure 4.3 below illustrates some of these design strategies.

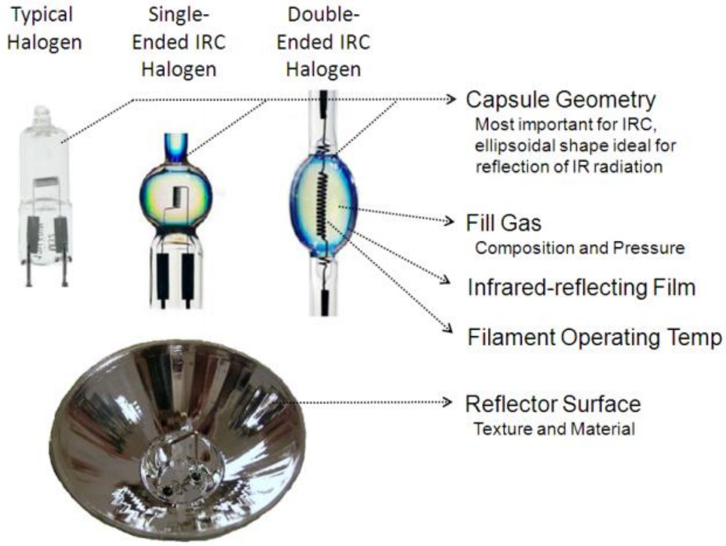

Figure 4.3 Design Strategies for Improving Halogen Performance[10]

Source: ECEEE 2011

Figure 4.4 below illustrates the performance difference between a sample of halogen and halogen-infrared products from General Electric (GE) and Philips. Halogen-infrared lamps are on average 4

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[10] IRC stands for Incandescent reflector lamp.

lumens per watt more efficacious than halogen lamps. Additionally, halogen-infrared can achieve greater light output than halogen lamps.

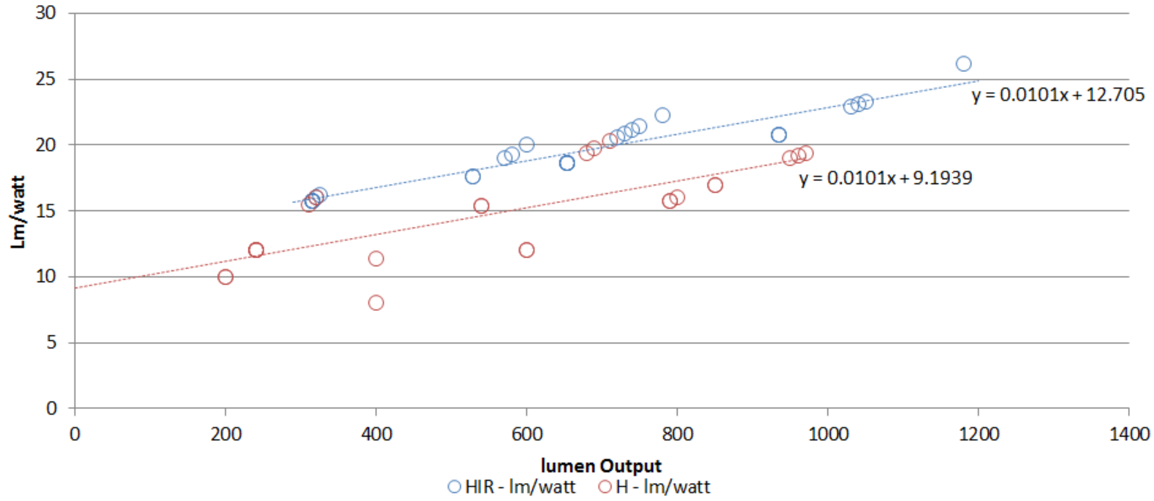


Figure 4.4 Halogen Performance Comparison

Source: ECEEE 2011

One issue associated with making halogen and halogen-infrared lamps more efficacious is the impact on lamp lifetime. Increasing gas pressure or temperature will make the lamp burn more efficaciously; however, lamp life may be compromised.

4.4.2 Trends in LED Replacement Lamps

New products continue to show increased lumen output and CBCP. While LED products claiming to be 50W equivalents are only recent additions to the market (and their performance should be verified with further testing), indications are that LED technology is improving quickly, and that 50W equivalency using ES' CBCP tool are already within reach for LED manufacturers (discussed further in Section 8.2.2). The primary issue is that heat dissipation is limited by the small form factor. As efficacies further increase, higher wattage equivalencies will be achieved.

ENERGY STAR® has qualified over 175 individual LED MR replacement lamps, and the DOE Lighting Facts Program has identified over 434 LED MR replacement lamps (ENERGY STAR® April 2013 & DOE April 2013).

Figure 4.5, Figure 4.6, and Figure 4.7 below show future trends based on historical LED Lighting Facts (LFD) database information and ES data, illustrating current trajectories for LED lamp performance in the small diameter market. The figures demonstrate that efficacy and lumen output have been increasing steadily over the past three years.

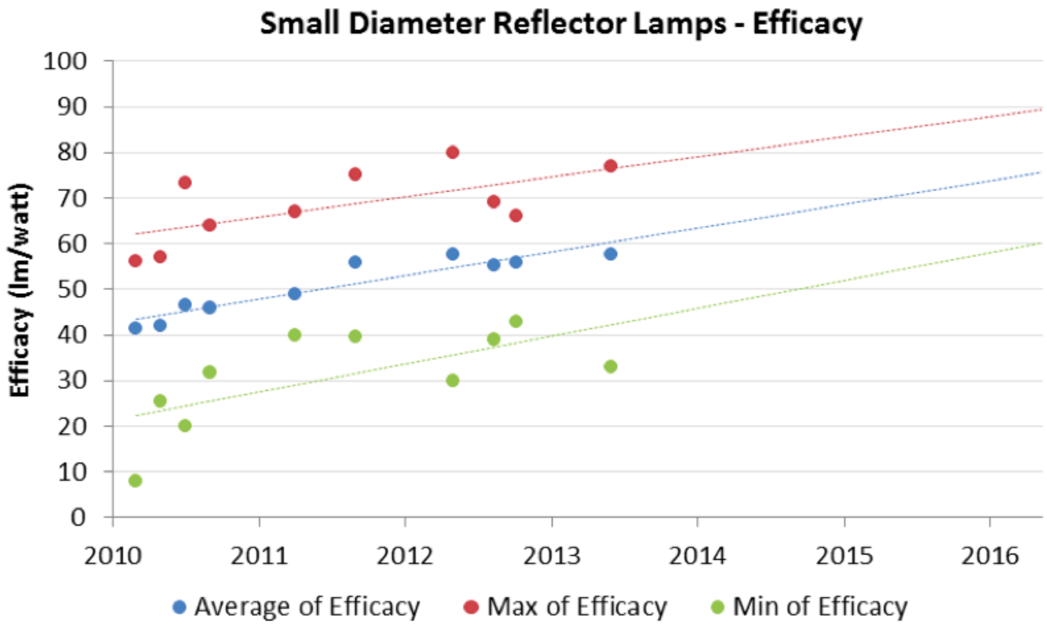


Figure 4.5 Efficacy Trends for Small Diameter Directional LED Lamps

Source: Energy Solutions analysis adapted from Lighting Facts Database (LFD) historical records. Each data point represents max and average lpw from unique records pulled from LFD lists dating back to March 2010.

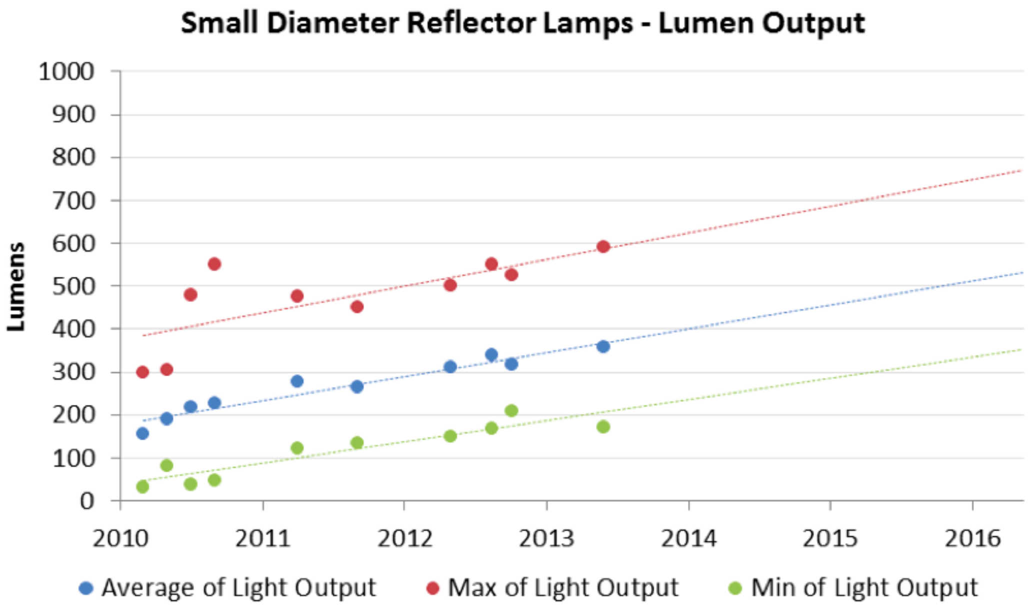
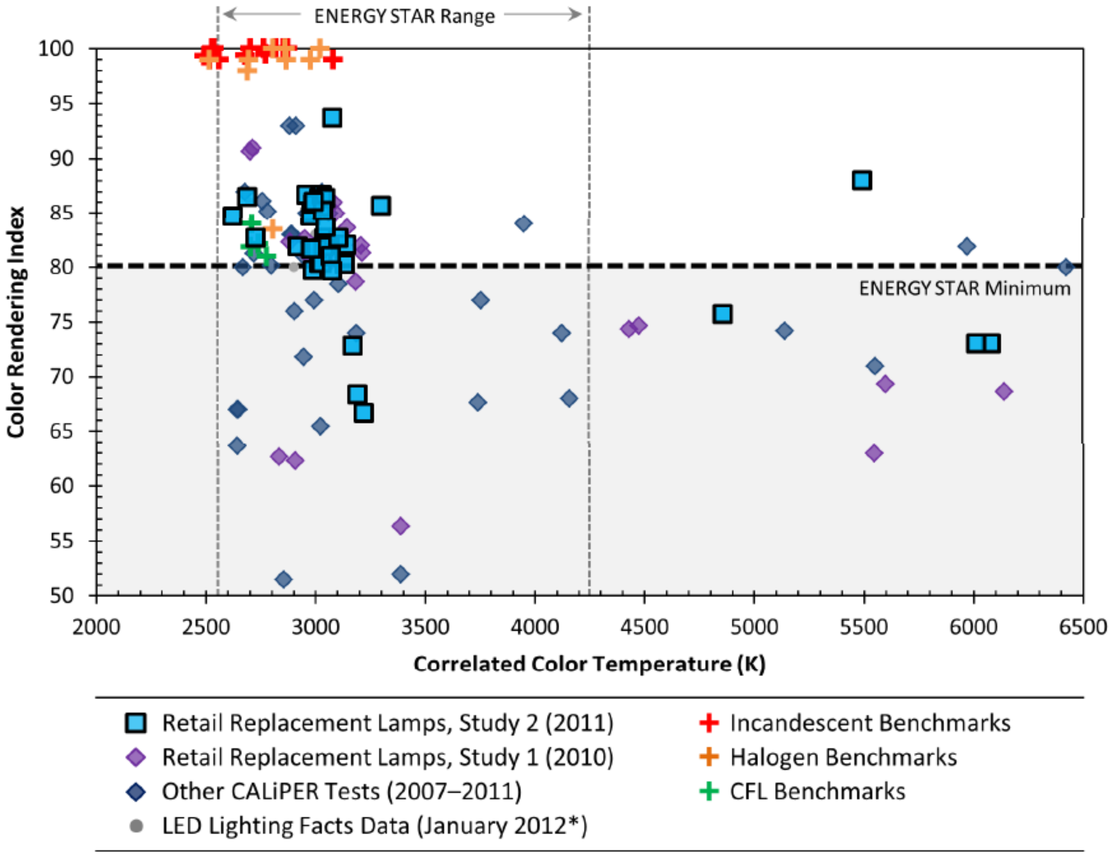


Figure 4.6 Lumen Output Trends for Small Diameter Directional LED Lamps

Source: Energy Solutions analysis adapted from Lighting Facts Database (LFD) historical records. Each data point represents max and average lpw from unique records pulled from LFD lists dating back to March 2010.



*Date of download; actual date of product listing is unknown.

Figure 4.7 Color Characteristics (CRI & CCT) of LED Replacements (Purchased in November 2011) Benchmarked against Incandescent, Halogen, & CFL lamps

Source: CALiPER 2012

4.5 Barriers to LED Adoption in the Small Diameter Directional Lamp Market

LED replacements for small diameter lamps continue to face challenges in gaining market acceptance. The two biggest challenges are: (1) meeting CBCP and lumen output equivalency to higher wattages, and (2) demonstrating compatibility with transformers and dimmers and occupancy sensors.

4.5.1 *Achieving High Wattage Equivalency*

Producing high lumen output and high CBCP equivalency to 50W halogens has been difficult for LED manufacturers. However, in 2013 a growing number of manufacturers have reported 50W equivalent products. These include Philips, Soraa, TCP, Green Creative, and GE Lighting. “The main limitation has been with thermal management, where we needed to combine high lumen output in a very compact form factor,” said Ellen Sizemore, product marketing manager for Osram Sylvania (LEDs Magazine 2012). Nonetheless, based on current market trends, LEDs are projected to easily overcome this barrier (see Figure 4.5 for projections described previously).

ENERGY STAR® has developed a CBCP calculator that specifies a minimum CBCP needed for a manufacturer to claim equivalent lamp wattage for a given lamp diameter and beam angle. Lamps that are ENERGY STAR® listed cannot claim equivalency to 50We, 35We, or 20We unless their lamp meets this minimum calculated CBCP (discussed further in Section 8.2.2).

There are a handful of lamps that already claim equivalency to 50W halogens on a CBCP basis. Figure 4.8 below compares 2012 California Lighting Technology Center (CLTC) tested LED MR replacements against 2013 manufacturer reported claims for wattage equivalency.[11] The red bars show the tested (2012) and reported (2013) CBCP values from different lamps.[12] Note that the sample of lamps in the 2012 set are not included in the 2013 set. In Figure 4.8 beow, the green, purple, and blue horiztonal bars indicate the wattage equivalency thresholds in CBCP that a lamp would have to meet to claim 50W, 35W, and 20W equivalency, respectively. As one can see, in 2013, all lamps meet 35W equivalency and the majority meet 50Wequivalency, whereas in 2012 fewer lamps met 50W and 35W equivalency.

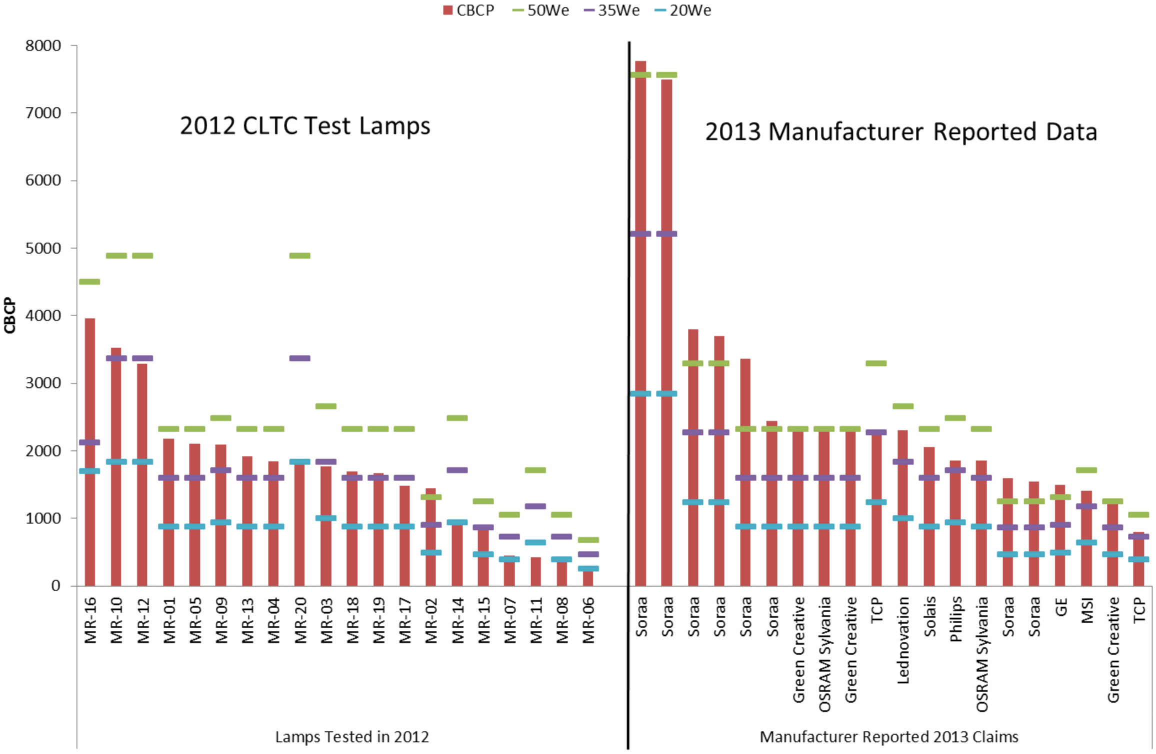


Figure 4.8 Change in MR LED Replacement Lamp Performance between 2013-2013 as indicated by Wattage Equivalency Test Data and Manufaturer Reported Claims

Source: CLTC 2012 Test data & Manufacturer Report Claims from publicly available cut sheets/online

While it is always a possibility that manufacturers could over report claims, a CALiPER 2011 study on retail LED lighting indicated that the majority of tested MR LED products yielded results that

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[11] Publicly available LM-79 data is limited, and as such the CASE Team was unable to report tested values for 2013. However, we believe that manufacturer reported claims are a close proxy to tested data, and as such felt comfortable including it here.

[12] For the time being CLTC will not be sharing the specific make and model number of tested lamps, though this may be released in the future.

had no or very little difference from manufacturer reported claims (CALiPER 2012). Ulimately, the data in Figure 4.8 suggests that lamps are improving in CBCP output and that many more 50W equivalent lamps exist now than compared to a year ago, thus implying that improvements are occurring quickly.

4.5.2 Compatibility with Low Voltage Transformers

Designing a low voltage LED replacement lamp is complicated by the fact that it must often be paired with an existing transformer, which is necessary to step the main AC Voltage (typically 120 root square mean (rms) voltage (V)) down to 12 V direct current (dc). The issue is that existing transformers were designed with higher wattage lamps in mind (i.e., 50W and 35W lamps), which provide higher currents to enable proper and functional operation of the transformer. The power draw of a 9W or 6W lamp (e.g., an LED replacement lamp) may not be enough to operate the transformer in its ideal power range, resulting in a lamp that may flicker, experience shorter than expected useful life, or fail to work altogether.

The installed base of transformers is characterized by magnetic low voltage transformers (MLVTs) and electronic low voltage transformers (ELVTs). MLVTs, the older technology, constitute the majority of the installed base in the United States (U.S.), while ELVTs, the newer technology, constitute the majority of new shipments (LEDs 2011). Hatch and Lightech are the two largest manufacturers of transformers and comprise the lion's share of shipments within the US, providing hundreds of different models and designs (Reynolds 2012).

A drop-in replacement would ideally be designed to work with both types of transformers, since both types are already commonly installed in lamp housings, tracks, or inside walls and ceilings. Some of the electrical challenges stem from the mechanical and thermal limitations of the MR16 form factor (LEDs 2012). In the case of an MLVT, there has been difficulty in designing a capacitor that is small enough to fit within the form factor/shell (which is often consumed by a sizeable heat sink needed to keep the electronics and LED cool) that provides the amount of capacitance needed for a best in class diode-bridge and capacitor circuit (i.e. that maintains functional operation of the MLVT). An alternative option is to use an electrolytic capacitor, but this tends to be bulky and prone to shorter lifetimes when exposed to the heat of the LED.

According to experts at LEDs Magazine, "more issues occur with compatibility with ELVTs, which are further complicated by the fact that they also have many different design schemes" (2012, online article). Use of a self-oscillating ELVT that is designed for a heavy resistive load, but is instead presented with a light load with negative impedance, can result in flickering light, audible buzzing, or a complete failure to start up. Some design work-arounds for lamps include inverting buck-booster regulators, buck converters, boost converters, extra stages in circuitry, and dynamic transformer recognition. These approaches are intended to work on both ELVT and MLVT. There are pros and cons to each of these designs, which are outlined in

Table 4.2 Overview of Transformer compatibility Design Approaches

Design	Description	Performance
Buck Converter	Buck converters cause the stack voltage to be less than the input voltage, which can cause ripple in light varying in intensity between higher and lower values, due to insufficient load being pulled through the transformer to keep it operable. It is a fairly good solution for non-dimmable lamps.	Non-dimming solution. Adding dimmer makes it tough.
Boost Converter	Boost converters have slightly better performance than buck converters due to their ability to boost up to 21V. This design approach also performs poorly under dimming applications.	Works better than buck. Non-dimming solution.
Single Stage Solution - Inverting Buck-Boost Regulator	This is a highly effective approach at reduced cost, with considerable flexibility meaning that LEDs selected for the lamp can operate between 6V and 21V and should function properly. However, there are efficiency losses, which could limit light output. Should work within dimming applications.	Is likely to work the best for dimming and non-dimming applications
Diode Bridge	The Capacity (with diode bridge) would smooth out the AC, making it DC. Capacitor size and longevity are major constraints.	Underperforms
Two-Stage solution - Boost Converter Followed by Buck Converter	Effective with room for R&D to bring design cost down (though cost of materials will remain fairly constant). Two stages allow for a separation of problems.	Performance is better
Dynamic Transformer Recognition	Could be two stage or single stage, or extra circuitry. Lamp recognizes where it's having issues and adds extra load, adding some resistance across transformer, which aids in compatibility. Decreases lamp efficiency.	Bulky solution, but works
Backwards Compatible Transformer	New transformers can be redesigned to work with both high and low wattage lamps. Doesn't have minimum load requirement.	Architecture retrofit (not for lamp)

The two figures below (Figure 4.9 and Figure 4.10) indicate the market prevalence and costs of these solutions based on one Manufacturer/Industry expert highly knowledgeable of the transformer issues and design. The costs are estimates specific to the electronics of the lamp (not the whole lamp).

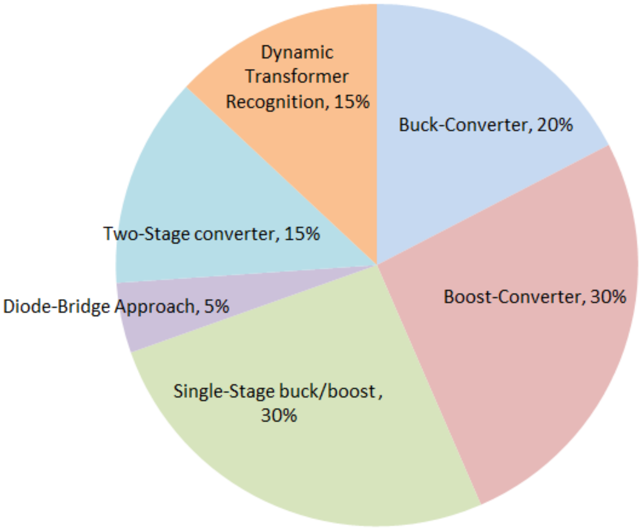

Figure 4.9 Market Prevalence of Different Transformer Designs

Source: Phone Conversation with Engineer at CREE

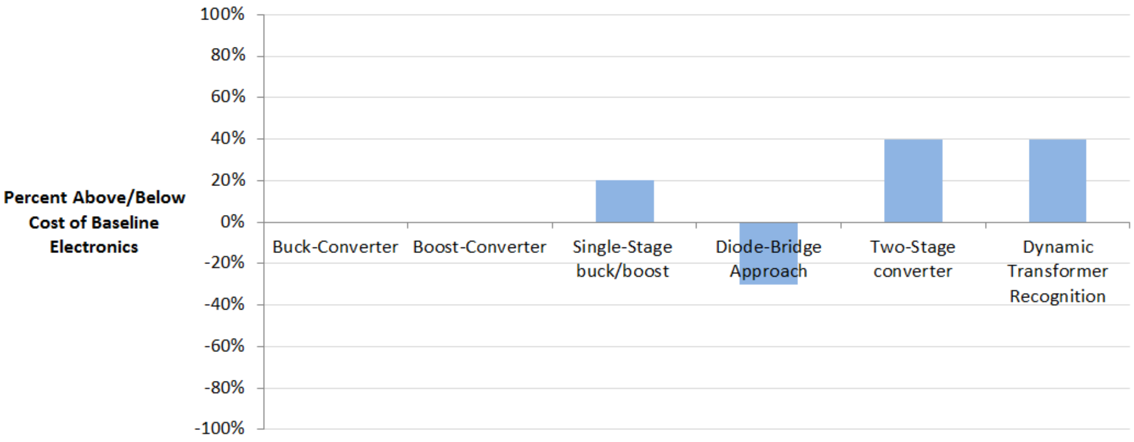

Figure 4.10 LED Solutions for Transformer Compatibility

Source: Phone Conversation with Engineer at CREE

Manufacturers are making headway on providing uniform compatibility with transformers. To further investigate transformer compatibility, the California investor owned utilities (IOUs) have contracted with CLTC to test an array of LED lamps on 1 common magnetic and 6 common electronic transformers. Figure 4.11 below highlights some of the basic results from this testing. If the lamp failed to turn on it would receive a 1 point; if there was noticeable humming associated with the lamp's operation on the transformer, it would receive 1 point. Likewise, if there was noticeable flicker the lamp would receive 1 point. Thus, the lamps that performed to expectation along these three metrics received zeros across the board.

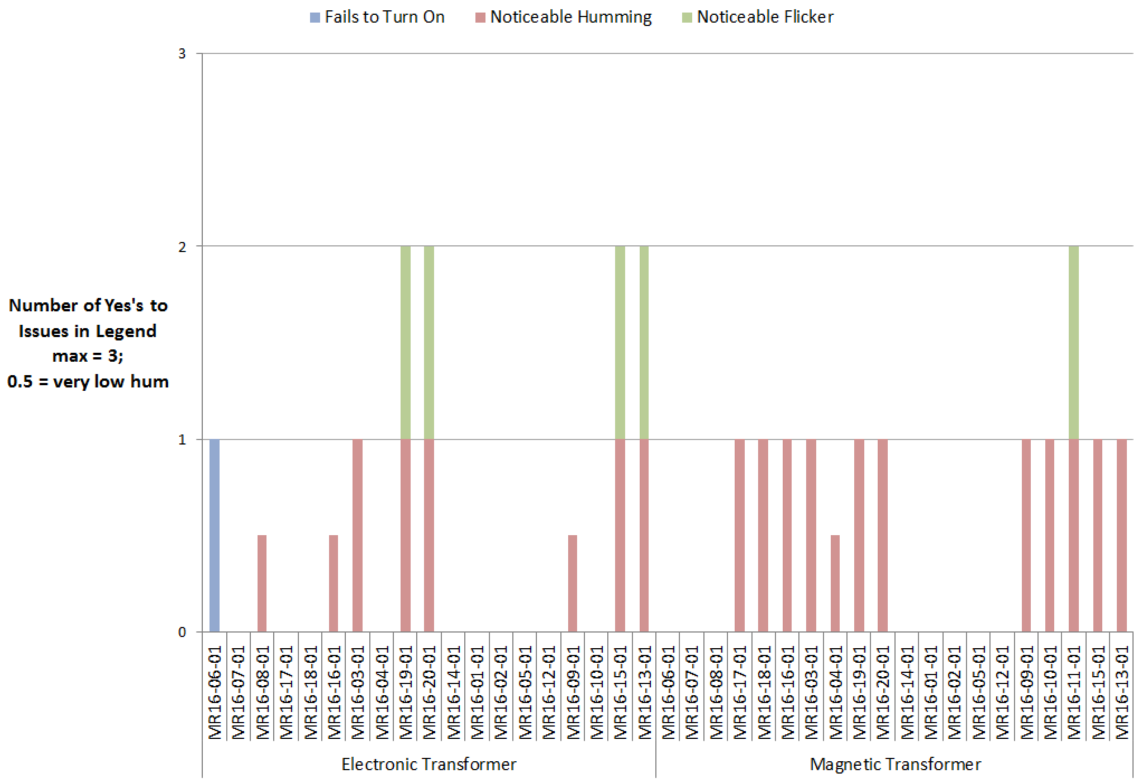

Figure 4.11 CLTC Test Results for Transformer Compatibility

Source: CLTC 2012

Based on the results above, for electronic transformers all but 1 lamp turned, half had no flicker or humming, and 3 other lamps indicated very low humming, with no other negative downsides. For the magnetic transformer, all lamps turned on and 8 out of 20 did not have noticeable humming or flicker. Compatibility with Dimming Systems

In the U.S., the preference, particularly among big box retailers, is to sell dimmable lamps (LEDs 2012). However, not all applications require dimming. For instance, commercial retail and museum applications rarely require dimming, while residential and restaurant down-lights often do (LEDs 2012). Nonetheless, many customers do not distinguish between dimmable and non-dimmable lamps.

Dimming is complicated by low voltage transformer issues, as discussed earlier, and driver electronics. Despite this, dimmable LEDs are readily available (unlike compact fluorescent lamps).

4.5.3 Testing Efforts

Testing was conducted by the CLTC to understand the extent to which LEDs achieve CBCP equivalency and have comparable lumen output. Approximately 20 LED lamps were tested for CBCP, lumen output, beam angle, beam lumens some color quality considerations, and compatibility with prevalent transformers. The LED lamps chosen for testing represent a range of types by wattage equivalency and beam angle, with preference given to high lumen output lamps and those with very narrow or wide angles. These lamps were commercially available in Q1, Q2, and Q3 of 2012. Unfortunately, 2013 lamps were not included in this effort. Published test results should be available in Fall 2013.

5 Assumptions for Savings Calculations

As discussed previously, in order to assess the potential energy and cost implications of a proposed standard, four ESLs were created to segment the market into the range of commercially available performance levels.

5.1 Assumptions about Wattage

To calculate power draw for each of the ESLs, we established lumen criteria for 20W-e, 35W-e, and 50W-e lamps, where (-e) standards for an equivalent lamp of lower wattage that meets specified CBCP or lumen proxy. Using assumptions about efficacy for each of the ESLs laid out in Section 4.2, we the calculated wattage by dividing lumen output by efficacy. We do not assume that every lamp will either produce 750 lumens, 500 lumens, or 240 lumens, but rather used these outputs as a way to establish an apple-to-apple comparison across the different ESLs. Table 5.1 below describes assumptions about wattage, efficacy, and lumens for each of the ESLs.

Table 5.1 Low Voltage Lamp Assumptions about Efficacy, Lumen Output, and Wattage for each ESL

Efficacy Level	Design Option	Assumed Efficacy (lm/watt)			Calculated Wattage (W)		
		750 lm	500 lm	240 lm	50W-e	35W-e	20W-e
Baseline	Halogen - non IR	15	14	12	50	35	20
ESL1	Halogen w/ infrared coating	20	17	15	37	30	20
ESL2	Improved reflector coatings, HIR coatings, or capsule designs	21	20	17	35	25	18
ESL3	Technicaly Feasible HIR & first generation LEDs	35	35	35	21	14	9
ESL4	Secong Gen LEDs - newer chip & electronic configurations	65	65	65	12	8	5

Source: Author created 2013

As shown in Table 5.1, for each halogen technology option efficacy increases with lumen output. For halogen lamps, higher wattage lamps burn more efficiently than low wattage lamps. Note that the relationship between wattage and efficacy is logarithmic and not linear. Efficacy does not decline with lower wattage LEDs as it does with halogen incandescent lamps.

5.2 Assumptions about Annual Operating Hours

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

For cost-effectiveness we evaluated ESL levels in combinations individually (e.g., ESL1, res operation hours, at 50W/35W/20W equivalencies) as well as in a blended manner (e.g., qualifying products, blended operating hours, blended wattages by market share). These cost-effectiveness scenarios are further discussed in Section 7.3.

5.2.1 Calculation of Per Unit Energy Consumption

Estimates of annual per unit energy consumption were calculated by multiplying wattage by assumed annual operating hours. Figure 5.1 below describes the per unit annual energy consumption associated with each efficiency standard level (in blue) and the baseline (in grey).

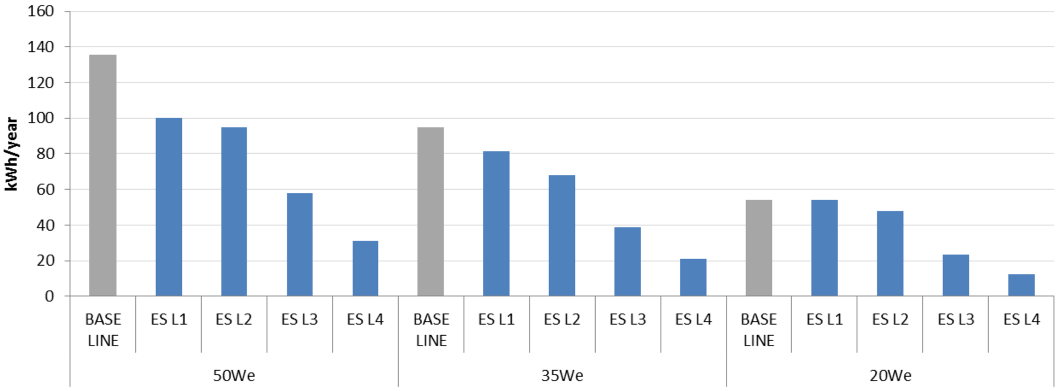

Figure 5.1 Estimated Annual Per Unit Energy Consumption of Efficiency Levels

Source: Author created 2013

5.3 Current Market Saturation & Sales

5.3.1 Installed Base

There are approximately 14.6 million small diameter directional lamps installed in California (Navigant 2011), which is an extrapoloation from an estimate for U.S. installed base (assuming 12 percent[13] of the nationally installed base).

The large majority of these lamps are comprised of the baseline conventional halogen lamps and ESL1 conventional HIR lamps (more than 90 percent), with a combination of ESL2, ESL3, and ESL4 products constituting the remaining amount. These estimates are based partially on the Navigant 2011 study that assumes LEDs account for 1.7 percent of the installed base, with halogen technology constituting the remainder. See Figure 5.2 below for a visual representation of this

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[13] We have chosen to use 12 percent as representative of California's share, relative to the national share. This is based on population data.

market split. Based on Soraa's Invitation to Participate (ITP), we assume a 70 percent, 20 percent, and 10 percent split among 50W-e, 35W-e, and 20W-e products, respectively.

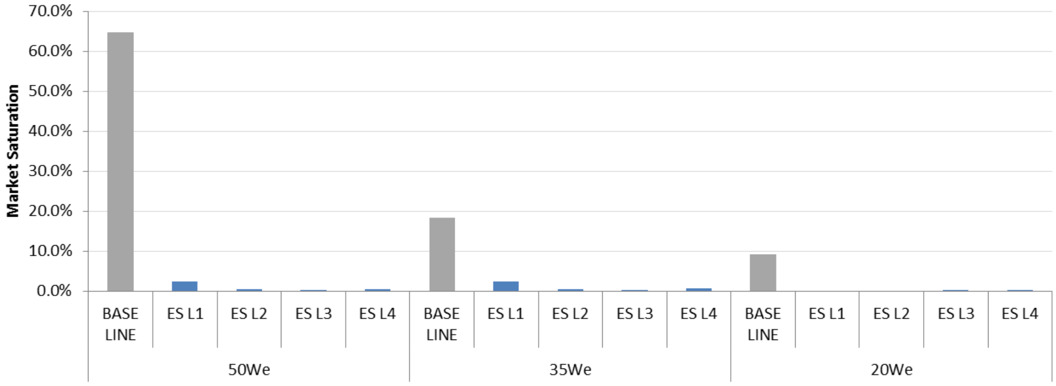

Figure 5.2 Estimated Market Share of Installed Base in California in 2011

Source: Author created 2013

5.3.2 Future Shipments

Future shipments will be based on shipments due to lamp replacement as well as growth. Taking into account shorter average lifetime for the current installed base of halogen lamps (approximately 1 to 2 years), we project average annual shipments around 10 million lamps per year in the non-standards case. As the installed base transitions to more energy efficient, longer life products (ranging from 2 to 13 years), as discussed in Section 4.2, we expect annual sales of replacements to drop.

In general, we expect this market to follow the ebbs and flows of the economy as well as population growth.[14] For the purposes of this CASE Report, we assume a steady 1.3 percent per year increase in installed base.

5.4 Future Market Adoption

While HIR lamps have increased in market share over the past 10 years, the natural market transition from conventional halogen to HIR is occurring slowly.

For LEDs, performance projections highlighted in Section 4.4 show that in the next three years, LED lamp options will be suitable for replacing the full range of halogen products in terms of lumen output, CBCP, and color quality. Furthermore, we believe that as manufacturing experience increases, LED costs will continue to fall sharply. With these projections in mind, we believe that withou standards in place, a portion of the market will still adopt high efficiency LED products within the next few years, but that some portion of the market will likely not adopt high efficiency technology for a number of years.

California legislative policy goals set forth by the California Public Utility Commission (CPUC), and implemented by third party-operated and utility rebate programs are all contributing towards market transformation of advanced solid-state lighting.

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[14] One source projected California population growth to increase by 1 percent annually out to 2030 (WSDOT 2012). This year, the state's economy is expected to grow 1.5 percent (LA Times 2012).

At the federal level, the Energy Independence and Security Act of 2007 established a total phase-out of traditional, low efficiency incandescent lamps by 2019, which California will enact a year earlier in 2018 through California's AB1109 (the "Huffman Bill") (EISA 2007). The CEC also established a goal for net-zero-energy performance in residential buildings by 2020 and in commercial buildings by 2030. Aggressive mandates and goals like these, which make California a leader in energy policy, are intended to be met using all cost-effective energy measures such as low cost appliance performance measures. Specifically related to lighting, the CPUC adopted the Long Term Energy Efficiency Strategic Plan in 2008, with a target reduction of 60 to 80 percent in statewide electrical lighting energy consumption by 2020.

Utility rebate programs are also contributing to this market transformation. These programs are designed to provide attractive rebates to retail and commercial entities who upgrade low efficiency lighting to high performing LEDs that exceed ENERGY STAR® specifications. The California investor owned utilities (IOUs), including PG&E, SCE, SoCalGas, and SDG&E, also offer calculated rebates at $0.08/kWh and $100/kW through customized rebate programs. Additionally, PG&E has formed a working group to tackle transformer compatibility issues and to evaluate various pathways for greater market transformation of LED replacement lamps.

6 Savings Potential

6.1 Statewide California Energy Savings

In order to calculate energy savings, we identified the market for qualifying and non-qualifying lamps for each proposed tier based on which lamps would be prohibited from being sold in California (non-qualifying), and the market share that would qualify with the standard. For instance, in Tier 1 we propose a standard level at ESL1, which effectively requires infrared reflective coating for lamps that have greater than 240 lumens, of which there are no commercially available infrared products. The Tier 2 standard pushes the market to ELS 3, which would enable technically feasible HIR lamps and LEDs to compete in the marketspace.

Using market share assumptions previously described for Baseline through ESL4, we developed market weighted average per unit energy and demand consumption values for qualifying and non-qualifying units, for Tier 1 and Tier 2. Table 6.1 below describes our calculated assumptions about average annual energy use for qualifying and non-qualifying products.

Table 6.1 Estimated Non-qualifying and Qualifying Per Unit Annual Energy Consumption for Tier 1 and Tier 2

`Energy Consumption (kWh/unit)	Tier 1	Tier 2
Non-qualifying Unit	119	89
Qualifying Unit	74	29
Energy Savings per unit	45	60
% Reduction in Energy Consumption from Non-qualifying to Qualifying	38%	67%

Source: Author created 2013

California stands to gain significant energy savings and greenhouse gas emissions reductions from a two-tiered standard. Table 6.2 below and corresponding figures (6.1 and 6.2) report these values numerically and graphically. Coincident peak load is based on a 0.53 Load Factor, which is a weighted average of the coincident load for the commercial and residential sectors associated with interior lighting and cooking, respectively. Both tier levels are necessary to achieve all cost-effective savings (cost-effectiveness is discussed in detail in Section 7).

Table 6.2 Statewide Savings from Tier 1 and Tier 2

	Statewide Savings		
	Tier 1	*Tier 2*	*Total*
1St Year Savings (GWh)	638	235	873
Annual Savings after Stock turnover (GWh)	638	1,011	1,649
Coincident peak demand savings (1st year in MW)	137	50	187
Coincident peak demand savings (after stock turnover in MW)	137	155	292

Source: Author created 2013

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

6.2 State or Local Government Costs and Savings

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

7 Economic Analysis

7.1 Incremental Cost

The costs per lamp, as depicted in Figure 7.1 below, are based on a PG&E Business Fact Sheet from 2010 for the baseline and ESL1, and on numerous data points from Google Shopping internet searches for ESL2–ESL4.

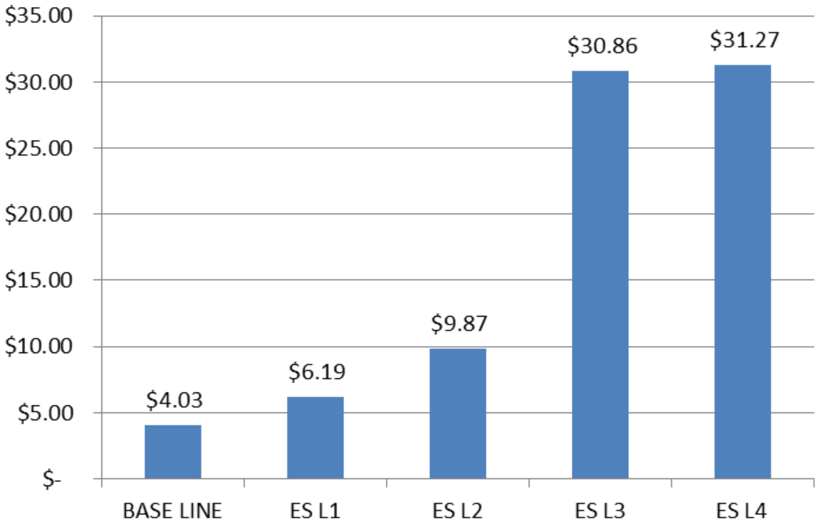

Figure 7.1 Cost Assumptions for Baseline and Efficiency Standard Levels

Source: Author created 2013

For ESL1 and ESL2, a data set of 54 price points for various HIR lamps from Google shopping results were evaluated. For ESL1, the price is based on the average of the minimum price values reported for 37W, 35W, 20W, and 20W HIR lamps. For ESL2, the price is based on the average of the average prices reported from 37W, 35W, 30W, and 20W HIR lamps. For ESL 3 and ESL 4 prices are based on 82 different data points for LEDs based on Google shopping results. For ESL3 the average price of lamps with efficacy less than or equal to 45 lpw was selected. For ESL4, the average price of lamps with efficacy greater than or equal to 45 lpw was selected.

While high performing halogens and LEDs are more costly upfront, they last significantly longer, thus, they need to be replaced less frequently.

7.2 Design Life

Conventional halogen lamps last approximately 2,000 to 6,000 hours, while conventional halogen IR lamps last from 4,000 to 5,000 hours (GE Lighting, OSRAM Sylvania, and Philips Lighting Catalogs 2013). High performing HIR lamps have typical lamp lifetimes between 5,000 and 9,000 hours. Conventional LEDs have useful lifespans of around 25,000 hours, while high performing LEDs can last upwards of 35,000 hours. See Figure 7.2 below for lifetime values in years based upon typical 2,712 annual operating hours for small diameter lamps.

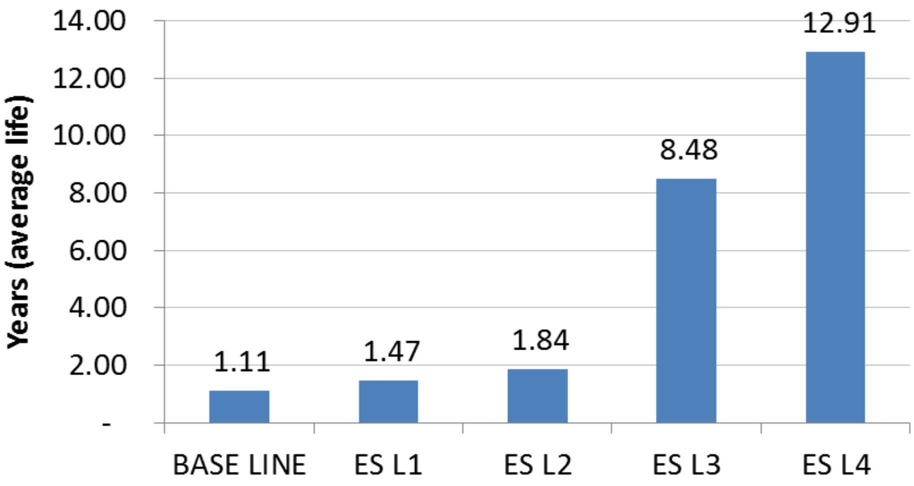

Figure 7.2 Lamp lifetimes based on 2,712 Annual Operating Hours

Source: Author created 2013

7.3 Lifecycle Cost / Net Benefit

The CASE Team evaluated the cost-effectiveness of Tiers 1 and 2, using multiple methodologies, as outlined below.

1. Blended vs. Non-blended Commercial/Residential operating hours

In the blended scenario we assume that the lamp annual operating hours (which influences lifetime and thus replacement costs) is based on a market weighted average split of commercial (3,720 hours at 65 percent) and residential operating hours (840 hours at 35 percent) for a total of 2,712 hours. In the non-blended scenario, we evaluate cost-effectiveness for the residential and commercial markets separately, using their respective annual operating hours to define different measure lives for the qualifying and non-qualifying cases.

2. Blended vs. Non-blended ESL levels

In the blended scenario we assume a market weighted average of the qualifying and non-qualifying ESL annual energy consumption values. In the non-blended scenario, we evaluated the baseline against ESL1 and then against ESL2, not taking into account the blend of ESL3 and ESL4 products since a consumer will either choose to switch between a non-qualifying lamp and an HIR lamp of a given performance or to an LED, which has a large performance difference. The non-blended scenario has the effect of shortening the measure life, which lowers energy-cost savings and avoided replacement lamp costs.

3. Blended vs. Non-blended Wattage equivalency categories

In the blended scenario we take a market weighted average (70 percent 50W-e, 20 percent 35W-e., and 10 percent 20W-e) of the energy consumption associated with each ESL, which is comprised of a 50W-e, 35W-e, and 20W-e lamp, such that each ESL has one representative energy consumption value associated with it. In the non-blended scenario, we evaluate 50W-e, 35W-e, and 20W-e. lamps independently. For halogen lamps, the savings increase at higher wattages and decrease at lower wattages, having the effect of larger net benefits for 50W-e lamps and smaller net benefits for 20W-e.

Cost-Effectiveness Methods: Using combinations of blended and non-blended assumptions for operating hours, ESL levels, and wattage equivalency categories, the CASE Team evaluated the cost-effectiveness of Tier 1 and Tier2. The following two methods below summarize these scenarios and in Table 7.1:

- *First Method*: Upfront incremental costs were calculated in the same fashion as calculations for per unit energy consumption for qualifying and non-qualifying units in each tier (i.e., market weighted values were applied to the qualifying and non-qualifying market segments). Incremental energy costs were also evaluated using market-weighted average lifetime assumptions of qualifying and non-qualifying market. The qualifying products for Tier 1 and Tier 2 had significantly longer measure lives than their non-qualifying counterparts. As such, the energy-cost savings were larger than the compared replacement of a conventional halogen with a conventional HIR lamp. We also blended residential and commercial annual operating hour assumptions.
- *Second Method*: Incremental costs for Tier 1 were calculated using fully non-blended scenarios with combinations of some blending that resulted in a total of 24 different cost-effective evaluations.

Table 7.1 Cost-Effectiveness Scenarios

	Operating Hours	**ESL Levels**	**Wattage equivalency categories**
Method 1	Blended	Blended	Blended
Method 2	Non-blended	Non-blended	Non-blended

The tables below summarize the per unit costs and benefits associated with Tier 1 and Tier 2 in net present value and the societal net benefits, respectively. Energy-cost savings and avoided replacement cost are both benefits that the consumer receives, while the incremental cost is a cost that the customer incurs, and thus is indicated as a negative value by the color red in the table bleow. The column on the right (Per Unit NPV) indicates the sum of benefits net of the costs associated with owning a qualifying lamp. Under both methods, Tier 1 is cost-effective in all scenarios.

Table 7.2 Costs and Benefits per Unit for Qualifying Products

			Enery Cost Savings[a]	**Incremental Cost**[b]	**Avoided Replacement Cost**[c]	**Per Unit NPV**[d]
Method 1	Tier 1	Combined	$ 29.91	$5.80	$5.63	$29.75
Method 1	Tier 2	Combined	$123.56	$7.13	$27.14	$143.57
Method 2	Tier 1	Combined	$4.13	$ 2.11	$ 3.98	$ 6.01
		Res	$ 6.56	$ 2.11	$ 3.98	$ 8.43
		Comm	$ 5.67	$ 2.11	$ 3.98	$ 7.54
	50W-e Tier 1	Combined	$5.32	$ 2.11	$ 3.98	$ 7.19
		Res	$8.44	$ 2.11	$3.98	$10.32

	Comm	$14.68	$2.11	$3.98	$16.56
35W-e Tier 1	Combined	$ 2.05	$ 2.11	$3.98	$3.92
	Res	$ 3.25	$ 2.11	$3.98	$5.12
	Comm	$ 2.81	$2.11	$3.98	$ 4.68
20W-e Tier 1	Not applicable since the standard would allow for quality conventional halogen (non-HIR) products.				

Source: Author created 2013

[a] Energy Cost Savings are calculated over the measure life of the qualifying product. For Method 1, it is blended across the qualifying market of HIR and LED products, which is why it appears larger than the energy costs associated with Method 2, which strictly looks at ESL1 level HIR measure cost life and associated energy savings.

[b] Incremental Cost refers to the cost difference between the non-qualifying and qualifying units. For Method 1, qualifying and non-qualifying per unit costs are blended across the market weighted average of ESL levels that qualify and do not qualify, respectively. These costs take into account learning curves, which forecast lower costs for LED and higher performing HIR products in the future. For Method 2, the incremental cost is the difference between a conventional halogen lamp and a basic halogen infrared product, which is why the incremental cost appears lower for Method 2. Red indicates a negative value

[C] Avoided Replacement cost refers to the cost-savings associated with not having to buy a non-qualifying product because the qualifying product lasts substantially longer.

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

Table 7.3 Lifecycle Costs and Benefits for Qualifying Products

Tier	Lifecycle Benefit/Cost Ratio[a]	Net Present Value[bd]		
		Per Unit	First Year Sales	Stock Turnover[c]
Tier 1	6.13	$29.75	$ 465,288,652	$ 465,288,652
Tier 2	21.13	$143.57	$583,634,435	$2,380,671,885

Source: Author created 2013

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

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

[c] Stock Turnover NPV is calculated by taking the sum of the NPVs for the products purchased each year following the standard's effective date through the stock turnover year, i.e., the NPV of "turning over" the whole stock of less efficient products that were in use at the effective date to more efficient products, plus any additional non-replacement units due to market growth, if applicable. For example, for a standard effective in 2015 applying to a product with a 5 year design life, the NPV of the products purchased in the 5th year (2019) includes lifecycle cost and benefits through 2024, and therefore, so does the Stock Turnover NPV.

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

8 Acceptance Issues

8.1 Infrastructure Issues

A Tier 2 LED standard could face infrastructure issues with existing low voltage magnetic and electronic transformers. These issues are discussed at length in Sections 4.5.2 and **Error! eference source not found.** on barriers to adoption of small diameter directional LED replacement lamps. The designers of these products are working diligently to find solutions that resolve these issues.

8.2 Existing Standards

8.2.1 DOE Established HIR Performance Standard for Incandescent Reflector Lamps (IRLs)

DOE conducted a standards rulemaking on standard spectrum and modified spectrum IRLs with diameters and wattages exceeding 2.5 inches and 40 watts, respectively. The rulemaking, finalized on July 14, 2009 and effective on July 14, 2012, established minimum performance level (efficacy) that can be achieved by halogen infrared (HIR) lamps incorporating improved reflectors, coatings, and filaments. Improved HIR technologies will increase average baseline efficacy from about 14 lpw to 19 lpw, dropping average IRL wattage from 75W to 55W (ASAP 2011).

DOE conducted a full energy and cost-savings analysis which demonstrated that, in the case of IRLs, HIR lamps provided maximized benefits at minimized costs. DOE made the following claims in the Final Rule:

- DOE indicated that it believed manufacturers could maintain production capacity levels and continue to meet market demand at the proposed IRL standard (TSL 4- HIR). DOE stated that manufacturers could install additional coaters, purchase infrared burners from a supplier, and use existing excess capacity.
- DOE did not receive comments that indicated that the energy conservation standards would result in the unavailability of standards-compliant products.
- DOE does not believe manufacturers will have to obtain proprietary technology to meet the energy conservation standards set forth by the final rule.
- DOE did not receive additional information or comments that would indicate that the identified alternative technologies necessary to meet energy conservation standards set forth by today's final rule will lead to any lessening of competition.

In the rulemaking process, DOE received one petition for exemption from the IRL standard on the basis that the HIR lamps did not provide the same quality of light as the halogen lamps that would be eliminated by the proposed standard. DOE responded indicating that it was unaware of any specific light quality of halogen lamps that would necessitate their usage instead of halogen infrared reflector lamps. Although infrared reflector coating causes a reduction in the infrared region of the electromagnetic spectrum, these wavelengths are largely invisible to the human eye. Ultimately, DOE did not grant an extension on the basis that halogen lamps do not present a distinct utility when compared to HIR lamps.

DOE has started conducting a rulemaking on small diameter directional lamps, but MR16s, MR11s, PAR16s, and PAR11s are outside the scope of the rulemaking. Therefore, we believe there will be no major issues in adopting a Title 20 Standard for small diameter directional lamps recommended in this report.

8.2.2 ENERGY STAR® Specifications and Wattage Equivalency Criteria

ENERGY STAR® established specifications for LEDs in Version 1.4, including MR and PAR lamps. For lamps with a diameter less than or equal to 20/8 inch (e.g. MR16 or PAR16), efficacy must be at least 40 lpw. The maximum lamp diameter and maximum overall length (MOL) are not to exceed MOL for the target lamp. For PAR and MR lamps, wattage equivalency is based on CBCP values. ENERGY STAR® provides a tool for PAR and MR lamps to calculate minimum CBCP requirements based on the replacement lamp's beam angle and claims about wattage equivalency. Table 8.1 below describes minimum CBCP values for commonly sold combinations of wattage and beam angles.

Table 8.1 ENERGY STAR® Minimum CBCP for Wattage Equivalency Claims

Wattage	Beam Angle	Minimum Corresponding CBCP
20We	10	2951
	15	1860
	25	855
	35	479
	40	385
35W-e	10	5079
	15	3201
	25	1472
	35	824
	40	663
50W-e	10	7598
	15	4788
	25	2203
	35	1232
	40	992

Source: Energy Solutions Adapted Analysis from ENERGY STAR® CBCP Tool

8.3 Australian Lamp Standard

The Australian commission for lighting standards[15] established lighting standards for low voltage MR16 lamps by establishing a wattage cap at 37W, which became effective on April 14, 2012. This effectively banned 50W halogen lamps from being sold in the market market, leaving the 37W HIR lamp (a 50W equivalent) and LED replacements to compete (AGDRET 2012).

8.4 Manufacturing Impact

Lighting professionals at Deposition Sciences Incorporated (DSI) estimate that Advanced Lighting Technologies (ADLT), AUER Lighting, and DSI, could add capacity at a compounded rate of 60 million capsules per year for IR coated MR 16 and PAR 16 burners. They project that the handful of other producers, all major lighting companies, could also add at a significant rate. Ultimately, industry capacity does not to appear to be a likely problem for CEC considerations.

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[15] Within the Department of Resources, Energy, and Tourism

8.5 Stakeholder Positions

Refer to response to ITP responses (CEC 2013) for stakeholder comments.

9 Environmental Impacts

9.1 Hazardous Materials

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

9.2 Air Quality

This proposed measure is estimated to reduce total criteria pollutant emissions in California by 304,300 lbs/year in 2021, as shown in Table 9.1 due to 1,666 GWh in reduced end user electricity consumption with an estimated value of $13,730,000. Criteria pollutant emission factors for California electricity generation were calculated per MWh based on California Air Resources Board data of emission rates by power plant type and expected generation mix (CARB 2010). The monetization of these criteria pollutant emission reductions is based on CARB power plant air pollution emission rate data times the dollar per ton value of these reductions based on Carl Moyer values where available, and San Joaquin Valley UAPCD "BACT" thresholds for sulfur oxides (SOx). These dollar per ton values vary significantly for fine particulates, as discussed in Appendix B: (CARB 2011a, CARB 2013a and San Joaquin Valley UAPCD).

Table 9.1 Estimated California Criteria Pollutant Reduction Benefits in 2021

	lbs/year	**Carl Moyer $/ton (2013)**	**Monetization**
ROG	45,897	$17,460	$400,679
Nox	156,539	$17,460	$1,366,584
Sox	16,453	$18,300	$150,545
PM2.5	67,653	$349,200	$11,812,201
Total in 2021	**286,500**	**402,400**	**$13,730,000**

9.3 Greenhouse Gases

Table 9.2 shows the annual and stock GHG savings by year and the range of the societal benefits as a result of the standard. In the year 2021, this standard would save 727,907 metric tons of CO2e, equal to between $39 million and $118 million of societal benefits. The total avoided CO2e is based on CARB's estimate of 437 MT CO2e/GWh (and 53 MT CO2e/millon therms) of energy savings from energy efficiency improvements, and includes additional electrical transmission and distribution loses estimated at 7.8% (CARB 2008). The range of societal benefits per year is based on a range of annual $ per metric ton of CO2 (in 2013 dollars) sourced from the U.S. Government's Interagency Working Group on Social Cost of Carbon (SCC) (Interagency Working Group 2013). The low end uses the average SCC, while the high end incorporates SCC values which use climate sensitivity values in the 95th percentile, both with 3% discount rate. It is important to note that this range can be lower and higher, depending on the approach used, so policy judgements should consider this uncertainty. See Appendix C: for more details regarding this and other approaches.

Table 9.2 Estimated California Statewide Greenhouse Gas Savings and Cost Savings for Standards Case

	Stock GHG Savings (MT of CO2e/yr)	**Value of Stock GHG Savings - low ($)**	**Value of Stock GHG Savings - high ($)**
2015	279,016	$13,334,564	$38,249,145
2016	282,643	$18,765,116	$54,370,721
2017	286,317	$24,589,247	$71,923,549
2018	392,590	$30,819,584	$90,955,357
2019	501,577	$37,469,055	$111,515,046
2020	613,332	$38,859,871	$116,579,613
2021	727,907	$40,280,516	$120,841,547
2022	737,370	$41,731,530	$125,194,589
2023	746,956	$43,213,463	$129,640,388
2024	756,666	$44,726,873	$134,180,620
2025	766,503	$46,272,330	$138,816,989

10 Recommendations

10.1 Recommended Standards Proposal

We recommend a two-tiered approach, which would position California to realize some savings almost immediately and realize larger energy savings in a few years when even more suitable LED replacement lamp and technically feasible high-performing HIR options are available. Table 10.1 refers to the recommended standard levels for this measure.

Table 10.1 Recommended Standard Levels for Small Diameter Directional Lamps

Tier Level	Voltage (V)	Energy Efficiency Standard (x = lumens)	Minimum Rated Life (hours)
Tier 1 (2015)	≥49	LPW > 0.01 * x + 5.08	4,000
	<49	Lm ≥ 300: LPW > 0.01 * x + 12.07 300< Lm ≤ 200: LPW > 0.05 *x Lm < 200: LPW ≥ 10	
Tier 2 (2018)	All voltages	LPW > 28	

Figure 10.1 and Figure 10.2 graphically illustrate the proposed standards for Tier 1 line voltage SDDLs and Tier 1 low voltage SDDLs & Tier 2 SDDLs, respectively. They are plotted against

publicly available lamp data for low and line voltage halogen and HIR lamps from GE, OSRAM Sylvania, and Philips. LED data are from the ENERGY STAR® Qualified product list for MR LED replacement lamps.

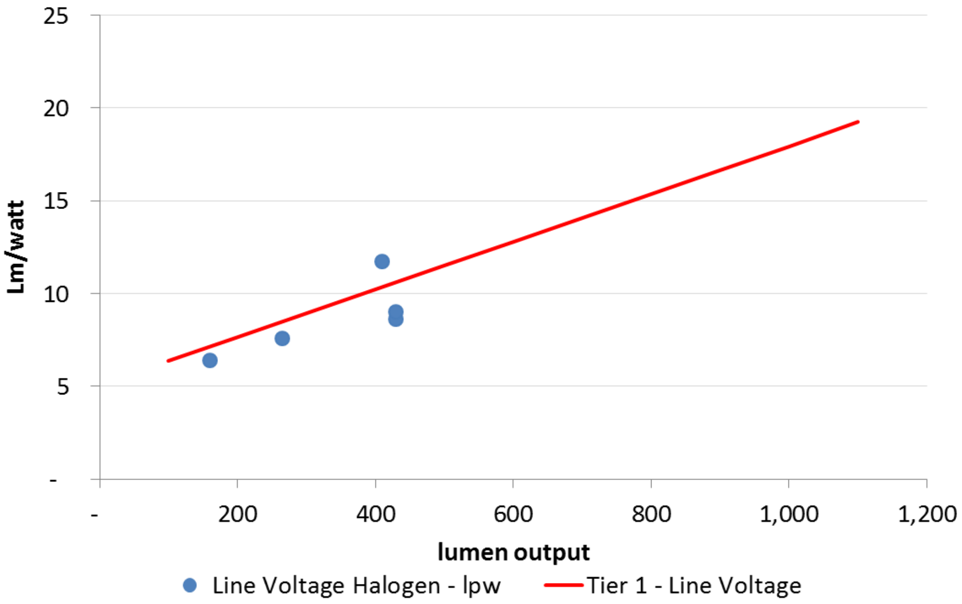

Figure 10.1 Tier 1 Standard for Line Voltage Small Diameter Directional Lamps

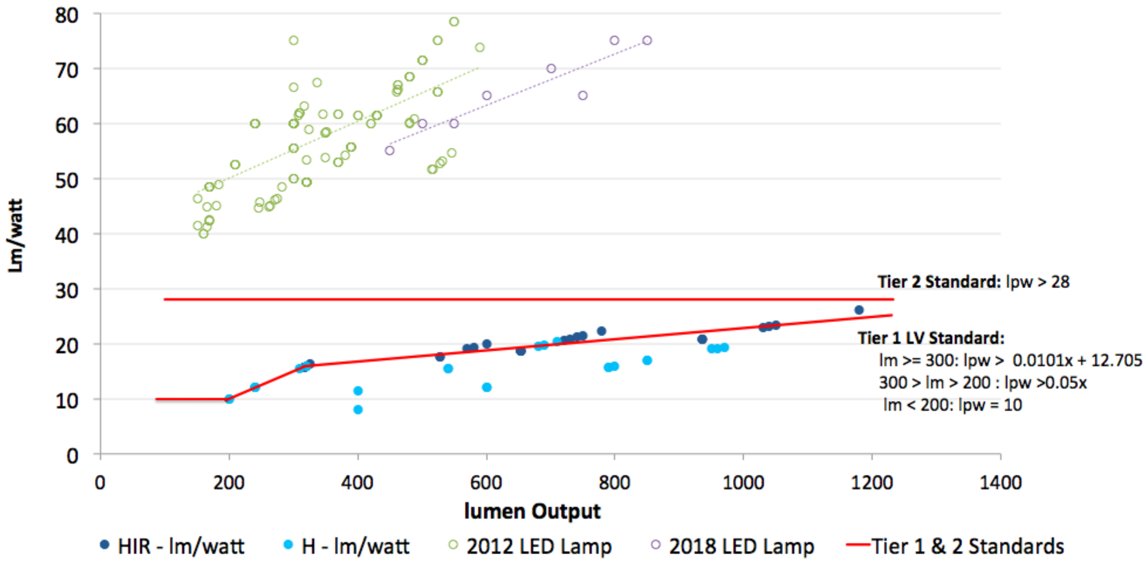

Figure 10.2 Tier 1 Standard for Low Voltage SDDL and Tier 2 for all SDDLs

A Tier 1 standard set at ESL1 would effectively require lamps emitting greater than 300 lumens to have an infrared reflective coating, shifting approximately 90 percent of the market away from the baseline halogen product. For lumen packages less than 300 (equivalent to 20W halogen output), the standard would allow for higher quality halogen products to compete on the market. HIR technology provides equivalent utility in the small diameter market and is compatible in all use cases with the conventional halogen technology. They constitute the large majority of the remaining market share and serve as a cost-effective solution without any feasibility concerns. California should make this performance standard effective as soon as possible.

A Tier 2 ESL3 standard is necessary to capture significant savings associated with LED and HP HIR performance. Small diameter LED products are already commercially proven to provide similar utility to halogen and HIR lamps in many applications. However, we recognize that concerns associated with wattage equivalency and issues with transformer and dimmer compatibility in certain applications may prevent them from being a viable option for a standard at the current time. Nonetheless, the rate of LED product improvement and our testing of prototype products suggest that LED technology will easily overcome these compatibility issues and will prove to provide equivalent utility to their halogen and HIR counterparts in all use cases by 2016.

10.2 Proposed Changes to the Title 20 Code Language

The following is proposed language, by Section, for the Title 20 Appliance Efficiency Regulations.

Section 1601. Scope.

(x) All small diameter directional replacement lamps, which meet the definitions outlined in Section X (Definitions), including both low voltage and line voltage lamps. This also includes halogen, halogen-infrared, and LED technologies, as well as any other lighting technology that falls within the definitions outlined for this standard. This standard establishes minimum performance levels for efficacy and lamp lifetime.

Section 1602. Definitions.

“Small Diameter Directional Lamp” (SDDL) refers to multi-faceted reflector (MR) lamps, parabolic aluminized reflector (PAR) lamps, and directional LED replacement lamps that are less than or equal to 2.5 inches in diameter, also commonly sold as MR16, MR11, PAR16, PAR11 lamps and their LED replacement equivalents that include all wattage, lumen-output, center beam candle power, and color temperature offerings.

“Efficacy” for the purposes of this performance standard refers to the ratio of the amount of light produced by a lamp, measured in lumens, to the amount of power drawn, measured in watts.

“Rated life” refers to the useful effective life of a lamp as measured in hours in which the lamp is left on, regardless of whether or not it is being dimmed. Halogen lamps would need to adhere to LM-49 standards for rated life. The useful life for LEDs is characterized by lumen maintenance within 70% of full output.

“Low voltage” refers to lamps that operate on voltage less than or equal to 49 volts per ANSI C84.1 (240.20(A)), which specifies low voltage distribution (system voltage).

“Line voltage” refers to lamps that operate on voltage that is greater than 49 volts per ANSI C84.1 (240.20(A)), which specifies low voltage distribution (system voltage).

Section 1604. Test Method for Specific Appliances.

(x) Small Diameter Directional Lamps

Table X. Test Procedures for Small Diameter Directional Lamps

Test Method	Description	Application
IESNA LM-20-	“IESNA Approved Method for Photometric	For efficacy measurement for

1994,	Testing of Reflector-Type Lamps”	halogen and halogen-infrared SDDLs
LM-49-12	“IES Approved Method for Life Testing of Incandescent Filament Lamps”	For lamp lifetime measurements for halogen and halogen-infrared
IES LM-79-08	“IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting”	For efficacy measurement for LED SDDLs
IES LM-80-08 & *TM*-21-11	“IES Approved Method for Measuring Lumen Maintenance of LED Light Sources” “Projecting Long Term Lumen Maintenance of LED Light Sources”	For lamp lifetime evaluation for LED SDDLs.

Section 1605.3 State Standards for Non-Federally Regulated Appliances.

(x) Small Diameter Directional lamps

Tier 1: Effective January 1, 2015, SDDLs will have separate minimum efficacy requirements as a function of lumen output for low voltage and line voltage SDDLs. Minimum lifetime is the same for both low and line voltage. Efficacy should be expressed as lumens per watt, per the definition, and rounded to one decimal place (e.g. 20.7), whose value must be greater than the value specificed in the linear formula for efficacy.

Tier 2: Effective January 1, 2018, SDDLs will have one minimum efficacy requirement irrespective of lumen output and voltage. Efficacy should be expressed as lumens per watt, per the definition, and rounded to one decimal place (e.g. 20.7), whose value must be greater than 28 lumens per watt.

Table X. Standards for Small Diameter Directional Lamps

Tier Level	Voltage (V)	Energy Efficiency Standard (x = lumens)	Minimum Rated Life (hours)
Tier 1 (2015)	≥49	$\text{LPW} > 0.01 * x + 5.08$	4,000
	<49	$\text{Lm} \geq 300$: $\text{LPW} > 0.01 * x + 12.07$ $300 < \text{Lm} \leq 200$: $\text{LPW} > 0.05 * x$ $\text{Lm} < 200$: $\text{LPW} \geq 10$	
Tier 2 (2018)	All voltages	$\text{LPW} > 28$	

Section 1606 Filing by Manufacturers; Listing of Appliances in Database

(x) Small Diameter Directional Lamps

Effective Januar 1, 2015, Small Diameter Directinoal Lamp's luminous flux, center beam candle power, beam angle, lifetime, efficacy, power, true power factor, and CRI shall be measured and reported. These metrics are described in greater detail below.

a. Luminous flux: Due to increased awareness of wattage equivalency and importance of data management of available products, manufacturers shall indicate luminous flux of their lamps per IESNA LM-20 and IES LM-79.

b. Center beam candle power: Due increased awareness of wattage equivalency and importance of data management of available products, manufacturers shall indicate center beam candle power of their lamps per IESNA LM-20 and IES LM-79.

c. Beam angle: Due increased of importance of data management of available products, manufacturers shall indicate the beam angle of their lamps per IESNA LM-20 and IES LM-79.

d. Power: Due increased of importance of data management of available products, manufacturers shall indicate the power of their lamps per IESNA LM-20 and IES LM-79.

e. True Power Factor: Due increased awareness of the importance of power quality on the part of EPA and electric utilities, manufacturers shall indicate the true power factor of their lamps during On Mode measurement.

10.3 Implementation Plan

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

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Appendix A: Cost Analysis Assumptions

The electricity rates used in the analysis of this CASE Report were derived from projected future prices for residential, commercial and industrial sectors in the CEC's "Mid-case" projection of the 2012 Demand Forecast (2012), which used a 3% discount rate and provide prices in 2010 dollars. The sales weighted average of the 5 largest utilities in California was converted to 2013 dollars using an inflation adjustment of 1.07 (DOL 2013). A sector weighted average electricity rate was then calculated using 65% commercial, 35% residential, 0% industrial. See the rates by year below in Table A.1.

Table A.1 Statewide Weighted Average Electricity Rates 2015 - 2040 (PG&E, SCE, SDG&E, LADWP and SMUD - 5 largest Utilities) in 2013 cents/kWh

Year	**Residential**	**Commercial**	**Industrial**	**Sector Weighted Average**
2015	16.82	14.67	11.31	15.09
2016	17.02	14.84	11.43	15.28
2017	17.24	15.02	11.56	15.46
2018	17.47	15.22	11.7	15.65
2019	17.71	15.42	11.84	15.86
2020	18	15.67	12.01	16.07
2021	18.34	15.98	12.23	16.33
2022	18.7	16.29	12.45	16.65
2023	19.06	16.61	12.67	16.97
2024	19.43	16.93	12.9	17.30
2025	19.81	17.27	13.13	17.64
2026	20.19	17.6	13.37	17.99
2027	20.59	17.95	13.61	18.34
2028	20.98	18.3	13.86	18.70
2029	21.39	18.66	14.12	19.06
2030	21.81	19.03	14.38	19.43

Appendix B: Criteria Pollutant Emissions and Monetization

B.1 Criteria Pollutant Emissions Calculation

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

B.2 Criteria Pollutant Emissions Monetization

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

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

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

This CASE report relies primarily on the Carl Moyer thresholds due to their state-wide nature and applicability to combustion sources[16]. In addition, the Carl Moyer fine particulate values for fine particulate apply to combustion sources with specific health impacts, while BACT thresholds include both combustion sources and dust. The Carl Moyer values are somewhat more conservative for ozone precursors than San Joaquin Valley UAPCD BACT thresholds, and significantly higher for fine particulate[17].The Carl Moyer program does not address sulfur oxides, however, thus the San Joaquin BACT thresholds were used for this pollutant.

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

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

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

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

Appendix C: Greenhouse Gas Valuation Discussion

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

C.1 Damage Cost Approach

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

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

C.1.1 Interagency Working Group Estimates

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

Table C.1 Social Cost of CO_2 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

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

source: Interagency Working Group on Social Cost of Carbon, United States Government, 2013.

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

C.2 Abatement Cost Approach

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

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

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

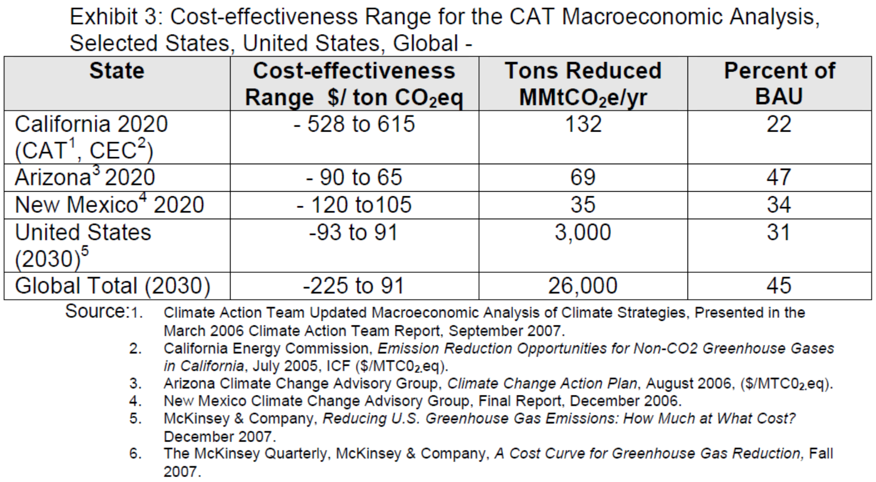

Exhibit 3: Cost-effectiveness Range for the CAT Macroeconomic Analysis, Selected States, United States, Global -

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

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

Source: CARB 2008b

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

C.3 Regulated Carbon Market Approach

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

C.3.1 European Union Emissions Trading System

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

C.3.2 California Cap & Trade

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