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California Energy Commission

STAFF REPORT

Analysis of Small-Diameter Directional Lamp and General Service Light-Emitting Diode (LED) Lamp Efficiency Opportunities

2015 Appliance Efficiency Rulemaking

Docket Number 15-AAER-6

California Energy Commission

Edmund G. Brown Jr., Governor

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Harinder Singh
Ken Rider
Primary Author(s)

Harinder Singh
Project Manager

Kristen Driskell
Supervisor
Appliance Efficiency Program

Dave Ashuckian P.E.
Deputy Director
Efficiency Division

Robert P. Oglesby
Executive Director

PREFACE

On March 14, 2012, the California Energy Commission issued an order instituting rulemaking (OIR) to begin considering standards, test procedures, labeling requirements, and other efficiency measures to amend the *Appliance Efficiency Regulations* (California Code of Regulations, Title 20, Sections 1601 through Section 1609). In this OIR, the Energy Commission identified a variety of appliances with the potential to save energy and/or water. The goal of this pre-rulemaking was to develop the proposed appliance efficiency standards and measures to realize these energy savings opportunities.

On March 25, 2013, the Energy Commission released an “invitation to participate” to provide interested parties the opportunity to inform the Energy Commission about the product, market, and industry characteristics of the appliances identified in the OIR. The Energy Commission reviewed the information and data received in the docket and hosted staff workshops on May 28 through 31, 2013, to vet this information publicly.

On June 13, 2013, the Energy Commission released an “invitation to submit proposals” to seek proposals for standards, test procedures, labeling requirements, and other measures to improve the efficiency and reduce the energy or water consumption of the appliances identified in the OIR.

On September 19, 2014, the Energy Commission released a notice of a staff workshop accompanied by a draft staff report containing draft efficiency regulations for small-diameter directional and general service light-emitting diode (LED) lamps. The staff report also contained an analysis of energy savings, technological feasibility, and cost-effectiveness of the proposal. Stakeholders submitted comments by November 14, 2014.

The Energy Commission reviewed all information received to determine which appliances were strong candidates for the development of efficiency standards and measures. This final staff report proposes regulations for small-diameter directional lamps and general service LED lamps to support the formal rulemaking proceeding.

ABSTRACT

This staff report focuses on two types of lamps. The first type is small-diameter directional lamps, 2.25 inches or less in diameter. Directional lamps illuminate certain specific areas in a particular direction for demanding visual tasks. No Title 20 standard for small-diameter directional lamps exists, nor is there a federal standard. A large majority of the small diameter directional lamps installed in California buildings are also incandescent, halogen, and halogen infrared lamps, which consume the most energy. Until recently, there were no efficient substitutes for incandescent, halogen, and halogen infrared lamps. Light-emitting-diode (LED) small-diameter directional lamps have become available in the market, offering comparable, cost-effective performance for significantly less energy. By replacing the existing inefficient, energy-wasting incandescent and halogen lamp stock with energy-efficient LED lamps, the proposed standard would save California 2,285 gigawatt-hours (GWh) annually by 2029.

The second type is general service LED lamps. These are white light LED replacement lamps and retrofit kits. These LED replacement lamps use as little as one sixth times the energy of incandescent lamps, and the efficiency of these continues to improve rapidly. Average LED efficiency has also outpaced and surpassed that of compact fluorescent lamps (CFLs). There are federal standards for general service incandescent lamps), large-diameter directional incandescent lamps, and general service CFL lamps. However, there are no Title 20 or federal standards for general service LED lamps. To save significant energy in California, it is necessary to develop cost-effective energy efficiency standards for LED lamps. Furthermore, to encourage faster adoption of these energy saving lamps and save significant energy in California, there is a need to ensure a minimum level of quality and performance from these lamps to avoid consumer dissatisfaction that may hinder the adoption of this improved efficiency technology. The proposed standard would save 859 GWh per year in 2029.

Keywords: Appliance Efficiency Regulations, energy efficiency, LEDs, LED lamps, lighting, MR16, general service lamps, light quality, incandescent, halogen, HIR, small-diameter directional lamps

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EXECUTIVE SUMMARY

The California Energy Commission proposes to achieve energy efficiency opportunities for small-diameter directional lamps and general service light-emitting diode (LED) lamps through Title 20 standards. This Commission's Appliance Efficiency Program analysis provides the basis for the proposed standards. Staff's analysis shows that proposed small-diameter directional lamps and LED lamp standards are technically feasible and cost-effective to consumers and would save significant energy in the state. Specifically, the proposed standards combined are estimated to save 3,144 gigawatt-hours (GWh) per year after stock turnover.

Small-diameter directional lamps are often used in retail, hospitality, residential, and museum applications. However, their popularity in residential use is also growing. Incandescent-based small-diameter directional lamps are practical and relatively inexpensive, but higher efficacy LED replacements are dramatically more efficient, and the efficacy continues to improve. The proposed standard for small-diameter directional lamps covers lamps of diameter 2.25 inches or less, which include some multifaceted reflector lamps and parabolic aluminized reflector lamps. Staff's proposal requires small-diameter directional lamps to have either an efficacy greater than or equal to 80 lumens per watt or a color rendering index +*Efficiency* score of at least 165 with a minimum efficiency of at least 70 lumens per watt. Small-diameter directional lamps must also have a minimum lifetime of 25,000 hours. This lifetime would effectively eliminate new incandescent, halogen, and halogen infrared technologies from the market after the proposed standard takes effect on January 1, 2018. At an incremental cost of roughly $4 per lamp and average per-lamp savings of $248.80 over the life of lamp in both reduced energy and reduced replacement costs, the proposal is extremely cost-effective. The proposed standards would result in an estimated 1,978 GWh in first-year savings and an estimated 2,285 GWh in statewide energy savings after full stock turnover.

This staff report also proposes LED lamp standards for general-purpose lighting. The scope of the standards includes omnidirectional, directional, and decorative lamps, as well as LED lamps designed for retrofitting the covered socket types. Staff proposes a standard that requires improvements to lamps on the market, yet allows for tradeoffs between the efficiency and color rendering index of a lamp. The proposed Tier I standard would take effect January 1, 2017, and Proposed Tier II standard would take effect on January 1, 2019. The proposed standards require omnidirectional lamps to produce a light distribution pattern that aligns with requirements adopted by the U.S. Environmental Protection Agency's (EPA) ENERGY STAR® program for lamps. The staff also proposes labeling standards that require manufacturers to meet minimum thresholds before making claims about dimmability or applicability to retrofits of traditionally incandescent sockets. Lastly, staff proposes to set a limit to the amount of power a connected LED lamp can use in a connected standby mode. As LED prices continue to decrease with improvements in efficiency, staff expects to see even greater per-lamp savings at a low purchase price. Total estimated statewide savings are 28 GWh in the first year, 185 GWh after Tier 2, and 859 GWh annual savings in 2029.

CHAPTER 1: Legislative Criteria

Section 25402(c)(1) of the California Public Resources Code mandates that the California Energy Commission reduce the inefficient consumption of energy and water by prescribing efficiency standards and other cost-effective measures[1] for appliances that require a significant amount of energy or water to operate on a statewide basis. Such standards must be technologically feasible and attainable and must not result in any added total cost to the consumer over the designed life of the appliance.

In determining cost-effectiveness, the Energy Commission considers the value of the energy and water saved, the effect on product efficacy for the consumer, and the life-cycle cost to the consumer of complying with the standard. The Energy Commission also considers other relevant factors, including but not limited to the effect on housing costs, the total statewide costs and benefits of the standard over the lifetime of the standard, the economic impact on California businesses, and alternative approaches and the associated costs.

In addition, the California Lighting Efficiency and Toxics Reductions Act of 2007[2] requires the Energy Commission to adopt minimum energy efficiency standards for general service lighting. These standards, in combination with other programs and activities, must be structured to reduce average statewide electrical energy consumption by not less than 50 percent from 2007 levels for indoor residential lighting and not less than 25 percent from the 2007 levels for indoor commercial and outdoor lighting by 2018.

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1 These include energy and water consumption labeling, fleet averaging, incentive programs, and consumer education programs.

2 Assembly Bill 1109 (Huffman, Chapter 534, Statutes of 2007), codified in relevant part at Pub. Resources Code, § 25402.5.4.

CHAPTER 2: Efficiency Policy

The Warren-Alquist Act[3] establishes the California Energy Commission as California's primary energy policy and planning agency and mandates that the Commission reduce the wasteful and inefficient consumption of energy and water in the state by prescribing standards for minimum levels of operating efficiency for appliances that consume a significant amount of energy or water statewide.

For nearly four decades, appliance standards have shifted the marketplace toward more efficient products and practices, reaping large benefits for California's consumers. The state's *Appliance Efficiency Regulations* saved an estimated 22,923 gigawatt hours (GWh) of electricity and 1,626 million therms of natural gas in 2012[4] alone, resulting in about $5.24 billion in savings to California consumers in 2012 from these regulations.[5] Since the mid-1970s, California has regularly increased the energy efficiency requirements for new appliances sold and new buildings constructed in the state. In addition, the CPUC in the 1990s decoupled the utilities' financial results from their direct energy sales, promoting utility support for efficiency programs. These efforts have reduced peak load needs by more than 12,000 MW and continue to save about 45,519 GWh per year of electricity.[6] Still, there remains a huge potential for additional savings by increasing the energy efficiency and improving the use of appliances.

Reducing Electrical Energy Consumption to Address Climate Change

Appliance energy efficiency is identified as a key to achieving the greenhouse gas (GHG) emission reduction goals of Assembly Bill 32 (the Global Warming Solutions Act, Núñez, Chapter 488, Statutes of 2006)[7] (AB 32), as well as the recommendations contained in the California Air

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3 The Warren-Alquist State Energy Resources Conservation and Development Act, Division 15 of the Public Resources Code, § 25000 et seq available at http://www.energy.ca.gov/2015publications/CEC-140-2015-002/CEC-140-2015-002.pdf.

4 California Energy Commission. *California Energy Demand 2014-2024 Revised Forecast,* September 2013, available at

http://www.energy.ca.gov/2013publications/CEC-200-2013-004/CEC-200-2013-004-V2-CMF.pdf.

5 Using current average electric power and natural gas rates of: residential electric rate of $0.164 per kilowatt-hour, commercial electric rate of $0.147 per kilowatt-hour, residential gas rate of $0.98 per therm and commercial gas rate of $0.75 per therm. This estimate does not incorporate any costs associated with developing or complying with appliance standards.

6 *California Energy Demand 2014-2024 Final Forecast*, available at

http://www.energy.ca.gov/2013publications/CEC-200-2013-004/CEC-200-2013-004-V2-CMF.pdf Page 86.

7 Assembly Bill 32, California Global Warming Solutions Act of 2006, available at http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.html

Resources Board's *Climate Change Scoping Plan*.[8] Energy efficiency regulations are also identified as key components in reducing electrical energy consumption in the Energy Commission's *2013 Integrated Energy Policy Report (IEPR)*[9] and the California Public Utilities Commission's (CPUC) 2011 update to its *Energy Efficiency Strategic Plan.*[10] Finally, Governor Edmund G. Brown Jr. identified reduced energy consumption through efficiency standards as a key strategy for achieving his 2030 GHG reduction goals.[11]

Loading Order for Meeting the State's Energy Needs

California's loading order places energy efficiency as the top priority for meeting the state's energy needs. *Energy Action Plan II* continues the strong support for the loading order, which describes the priority sequence for actions to address increasing energy needs. The loading order identifies energy efficiency and demand response as the state's preferred means of meeting growing energy needs.[12]

For the past 30 years, while per capita electricity consumption in the United States has increased by nearly 50 percent, California electricity use per capita has been nearly flat. Continued progress in cost-effective building and appliance standards and ongoing enhancements to efficiency programs implemented by investor-owned utilities (IOUs), publicly owned utilities, and other entities have significantly contributed to this achievement.[13]

Zero-Net-Energy Goals

The *California Long-Term Energy Efficiency Strategic Plan*,[14] adopted in 2008 by the CPUC, and developed with the Energy Commission, the California Air Resource Board, the state's utilities, and other key stakeholders, is California's roadmap to achieving maximum energy savings in the

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8 *Climate Change Scoping Plan* available at http://www.arb.ca.gov/cc/scopingplan/2013_update/first_update_climate_change_scoping_plan.pdf.

9 California Energy Commission, *2013 Integrated Energy Policy Report*, January 2014, available at http://www.energy.ca.gov/2013publications/CEC-100-2013-001/CEC-100-2013-001-CMF .

10 California Public Utilities Commission, *Energy Efficiency Strategic Plan,* updated January 2011, *available at*

http://www.cpuc.ca.gov/NR/rdonlyres/A54B59C2-D571-440D-9477-3363726F573A/0/CAEnergyEfficiencyStrategicPlan_Jan2011.pdf .

11 Gov. Edmund G. Brown Jr., 2015 Inaugural Address, available at http://gov.ca.gov/news.php?id=18828

12 *Energy Action Plan II,* available at http://www.energy.ca.gov/energy_action_plan/2005-09-21_EAP2_FINAL.PDF , page 2.

13 *Energy Action Plan II,* available at

http://www.energy.ca.gov/energy_action_plan/2005-09-21_EAP2_FINAL.PDF , page 3.

14 California Energy Commission and California Public Utilities Commission, *Long-Term Energy Efficiency Strategic Plan,* updated January 2011, available at http://www.cpuc.ca.gov/NR/rdonlyres/A54B59C2-D571-440D-9477-3363726F573A/0/CAEnergyEfficiencyStrategicPlan_Jan2011.pdf.

state between 2009 and 2020, and beyond. It includes four "big bold strategies" as cornerstones for significant energy savings with widespread benefit for all Californians:[15]

- All new residential construction in California will be zero-net-energy [16]by 2020.
- All new commercial construction in California will be zero-net-energy by 2030.
- Heating, ventilation, and air conditioning (HVAC) will be transformed to ensure that the energy performance is optimal for California's climate.
- All eligible low-income customers will be given the opportunity to participate in the low-income energy efficiency program by 2020.

These strategies were selected based on the ability to achieve significant energy efficiency savings and bring energy-efficient technologies and products into the market.

On April 25, 2012, Governor Brown further targeted zero-net-energy consumption for state-owned buildings. Executive Order B-18-12[17] requires zero-net-energy consumption for 50 percent of the square footage of existing state-owned buildings by 2025 and zero-net-energy consumption from all new or renovated state buildings beginning design after 2025.

To achieve these zero-net-energy goals, the Energy Commission has committed to adopting and implementing building and appliance regulations that reduce wasteful energy and water consumption. The *Long-Term Energy Efficiency Strategic Plan* calls on the Energy Commission to develop a phased and accelerated "top-down" approach to more stringent codes and standards.[18] It also calls for expanding the scope of appliance standards to plug loads, process loads, and water use. The Energy Commission adopted its detailed plan for fulfilling these zero-net-energy objectives in its *2013 IEPR*.[19]

Governor's Clean Energy Jobs Plan

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15 California Energy Commission and California Public Utilities Commission, *Long-Term Energy Efficiency Strategic Plan*, available at

http://www.cpuc.ca.gov/NR/rdonlyres/14D34133-4741-4EBC-85EA-8AE8CF69D36F/0/EESP_onepager.pdf , page 1.

16 A zero net energy (ZNE) is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site.

17 Office of Edmund G. Brown Jr., Executive Order B-18-12, April 25, 2012, available at

http://www.gov.ca.gov/news.php?id=17506http://gov.ca.gov/news.php?id=17506.

18 California Energy Commission and California Public Utilities Commission, *Long-Term Energy Efficiency Strategic Plan*, p. 64.

19 California Energy Commission, *2013 IEPR*, pp. 21-26.

On June 15, 2010, as a part of his election campaign, Governor Brown proposed a *Clean Energy Jobs Plan*,[20] which called on the Energy Commission to strengthen appliance efficiency standards for lighting, consumer electronics, and other products. Governor Brown noted that energy efficiency is the cheapest, fastest, and most reliable way to create jobs, save consumers money, and cut pollution from the power sector. He stated that California's efficiency standards and programs have triggered innovation and creativity in the market. Today's appliances are not only more efficient, but they are cheaper and more versatile than ever.

20 Office of Edmund G. Brown Jr., *Clean Energy Jobs Plan,* available http://gov.ca.gov/docs/Clean_Energy_Plan.pdf

PART A: SMALL-DIAMETER DIRECTIONAL LAMPS

CHAPTER 3: Background

Product Description

Lighting applications can be categorized as general, directional, or aesthetic. General lighting consists of ambient light and is designed to produce consistent level of illumination over an entire area.. Directional lighting is used to illuminate the work area in a particular direction. Directional lighting provides more light on a particular object than the surrounding area and is used when high levels of light are required for accenting purposes or for demanding visual tasks. Directional lighting includes accent lighting, down lighting, and track lighting. Aesthetic lighting provides illumination effects on an object in an area around the lamp but does not illuminate surrounding objects or area.

Small-diameter directional lamps (SDDLs) are a class of lamps that are less than or equal to 2.25 inches in diameter. Small-diameter directional lamps are used for accent, task, and display lighting in museums, art galleries, retail stores, residential buildings, and entertainment venues.

Small-diameter directional lamps can be made from a variety of technologies. Filament-based directional lamps, which include incandescent, halogen, and halogen infrared (HIR) technologies, are the most common technology type for directional lamps. There are two types of small diameter directional lamps available in filament base technology: (a) multifaceted reflector (MR) lamps and (b) parabolic aluminized reflector (PAR) lamps. The California investor-owned utilities' (IOUs) 2013 Codes and Standards Enhancement (CASE) study estimates that 95 percent of the small-diameter directional lamps installed the California buildings are MR types, and only 5 percent lamps are PAR type.[21]

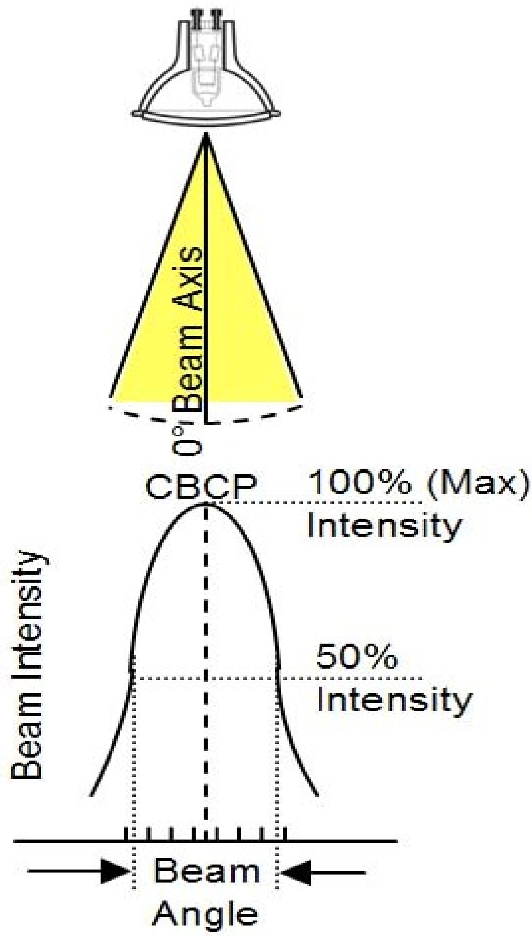
About 80 percent of SDDLs operate on low voltage (12V), while 20 percent operate at line voltage (120V, for some MR lamps and all PAR lamps). "Low voltage" refers to lamps that operate on voltage less than or equal to 49 volts per American National Standards Institute (ANSI) C84.1 (240.20[A]), which specifies low voltage distribution (system voltage). "Line voltage" refers to lamps that operate on voltage that is greater than 49 volts per the same standard. IOUs in their CASE study discussed line and low voltage SDDLs based on field observations and review of products available in manufacturer catalogs.[22] MR lamps sold in commercial applications tend to

21*IOU CASE Report: Small Diameter Directional Lamps,* July 29, 2013 available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf Page 3.

22 http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf page 4.

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 1.) 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.[23] However, a small number of MR 16 lamps may be screw-based. Some MR lamps 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. Figure 1 also shows the relationship between center beam candle power (CBCP) and beam angle in directional lamps.

Figure 1: Low-Voltage Lamps Generate High Luminous Intensity



23 Low-voltage lamps operate with a low-voltage transformer of voltage 6-24 volts, whereas line-voltage lamps operate at 110 volts.

Incandescent, Halogen, HIR MR, and Extended MR (MRX) Lamps

MR lamps are typically either incandescent, halogen, or HIR technology. Halogen MR 16 lamps are available in different wattage ranges, such as 20W, 35W, or 50W conventional wattages. HIR MR lamps come in lower wattages (for example, 37W), intended to replace higher wattages (for example, 50W), but have a lower market penetration.

Halogen, HIR, or incandescent MR lamps provide optical control by collecting the light from the filament to create a concentrated beam of light. This is usually done through faceted surfaces within the lamp, although some MR lamps contain smooth rather than faceted surfaces.

One of the most common types of MR lamp is the MR 16, which is a multifaceted reflector with a 16 x 1/8" diameter or 2 inches. MRX 16 lamp is an extended MR 16 that is also available in the market. The MR 16 lamp typically contains a light source consisting of a single-ended quartz halogen or tungsten halogen filament capsule mounted within a pressed glass reflector. The reflective coating of MR 16 lamps can either be dichroic[24] or aluminum.

The quartz halogen filament capsule in MR lamps is designed to operate at significantly higher pressure than a standard incandescent lamp. Because the capsule can rupture under certain end-of-life conditions, MR 16 lamps must have either an integrated cover glass or be used in an enclosed fixture.

Small-diameter directional MR 16 lamps are designed for low-voltage operation (12 or 24 volts) and have a shorter and thicker filament that allows halogen MR lamps to generate high luminous intensities.

Since small-diameter directional lamps operate at a low voltage (typically 12 V, but can be 6 V or 24 V), a transformer is used to reduce a line voltage of 120 V to an appropriate level that small-diameter directional lamps can withstand. There are two major types of low-voltage transformers, magnetic and electronic. Transformers generally need to meet a minimum load requirement to work properly without causing lamp flickering. Electronic transformers can achieve lower minimum load requirements, as low as 2.5 watts. Transformer types for small-diameter directional lamps are discussed in more detail in the section Small Diameter Directional Lamp Systems and in the section Overview of Transformer Compatibility Design Approaches of this staff report.

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24 Dichroic coating will cause visible light to split up into distinct beams of different wavelengths (colors) or the coating >I will result in light rays of different polarization plans to be absorbed by different amounts.

Dichroic reflectors are commonly used behind a light source to reflect visible light forward while allowing the invisible infrared light (radiated heat) to pass from the rear of the fixture, resulting in a beam of light that is literally cooler (of lower thermal temperature). Such an arrangement allows a given light to dramatically increase the forward intensity while allowing the heat generated by the backward-facing part of the fixture to escape.

In small-diameter directional lamps, beam angle is critical in delivering the light at the precise point to illuminate the desired object, increasing brightness from general area to accent area. High levels of light are needed to accentuate dark objects. *Beam angle* is the angle at which the beam intensity is 50 percent of the *center beam candlepower* (CBCP). CBCP is the intensity in candelas emitted at the center of a directional lamp beam (0°). CBCPs range from about 230 to upward of 16,000 candelas and are affected by the lamp wattage and the beam angle.[25] One of the factors that determine the beam intensity is field angle: the angle at which the beam intensity is 10 percent of the CBCP. Halogen MR lamps offer a variety of light distribution ranging from narrow pin spots with a beam angle of 7° to beam angles of 60° or greater (wide flood distribution).[26] A lamp with a large beam angle will have a lower CBCP than a lamp with narrow distribution. MR lamps with greater range offerings are continuously reaching the market.

Incandescent, Halogen, and HIR R and PAR Lamps

Reflector (R) and parabolic aluminized reflector (PAR) lamps of diameter 2.25 inches or less are categorized as small-diameter directional lamps. A small diameter directional PAR lamp is a spot light that uses a parabolic (U-shaped) reflector to collect and reflect the light from the front of the bulb. Small-diameter directional PAR lamps come in two sizes: PAR 11 and PAR 16. PAR lamps have less control over beam angle, shape, and sharpness relative to MR lamps. Though small-diameter PAR lamps are far less common than MR lamps, they are still available and used in entertainment and venue lighting. PAR lamps operate at line voltage and generally have medium-screw bases or GU-10 bases. PAR 16 lamps are made with incandescent, halogen, and HIR technologies, and are sold in three conventional wattage categories: 20W, 35W, and 50W.

LED MR, MRX, R, and PAR Lamps

Small-diameter directional LED lamps are similar in shape and size to conventional MR and PAR incandescent, halogen, and HIR lamps, and can be used in most fixtures designed for halogen MR lamps. There are a wide variety of designs, varying significantly with regard to beam width, light color, efficiency, and luminous intensity. The beam width of the LED MR lamps can be controlled by using the optical lenses. Some designs may have simple cut-off apertures that limit beam width, or even reflectors for each LED.[27] A few LED MR 16 lamps with the multifaceted surface are available in the market.[28]

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25 A *candela* is the unit for luminous intensity. One candela is one lumen per steradian.

26 *Performance of Halogen Incandescent MR16 Lamps and LED Replacements,* prepared for the U.S. Department of Energy by Pacific Northwest National Laboratory, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/mr16_benchmark_11-08.pdf, page 3.

27 Global information Premium Market Research Reports, *LED Multifaceted Reflector (MR) Lamps Global Market Forecast,* available at http://www.giiresearch.com/report/el306109-led-multifaceted-reflector-mr-lamps-global-market.html.

28 *Superbrightled.com 5 Watt MR16 LED bulb* - Multifaceted Lens with High Power Epistar COB LED, available at https://www.superbrightleds.com/moreinfo/mr-series/3-watt-mr16-led-bulb--multifaceted-lens-with-high-power-epistar-cob-led/1395/#.

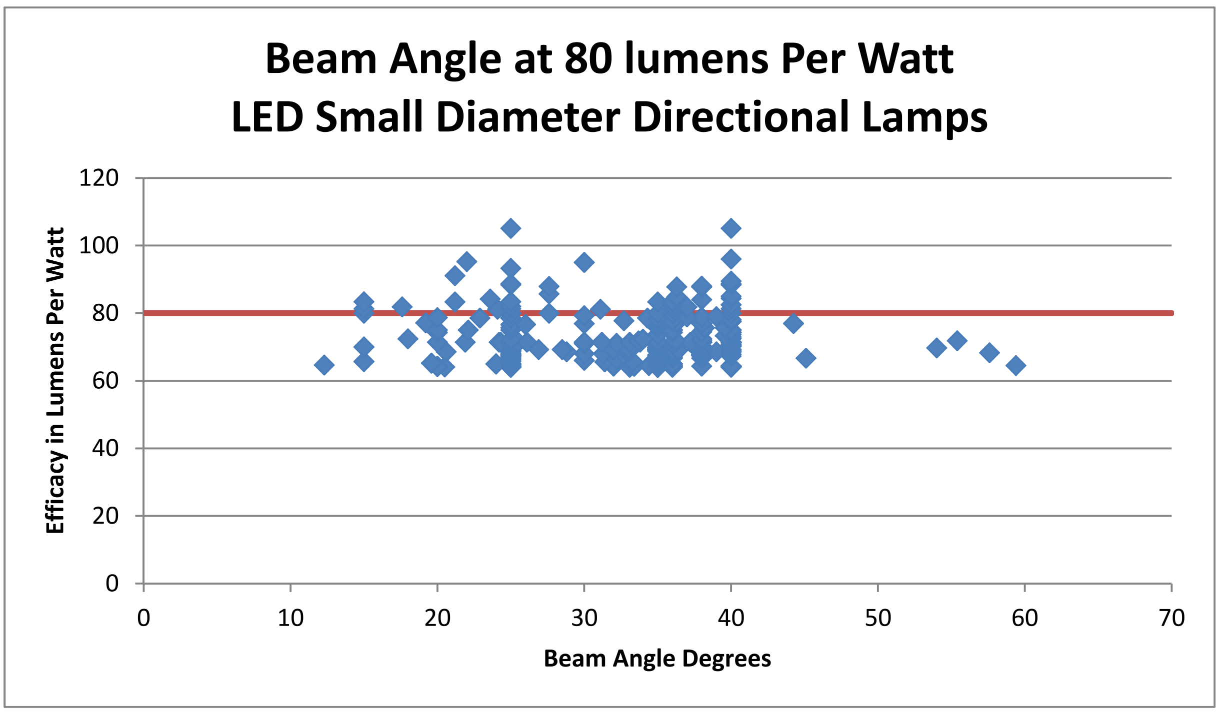
Beam Angle

In terms of beam angle, LED manufacturers are continuously working to provide lamp options with narrow spot, spot, narrow flood, and flood angles. Many LED manufacturers now offer MR 16 lamps with 15-degree and 40-degree beam angles and the range of beam angles in between. A 12-degree and a 60-degree beam angle lamp is also available in the market at 65 lumens per watt, suggesting that improvements in beam angles does not affect the efficiency of the lamp.

LED small-diameter directional lamp beam angles use different optics than MR, PAR, and reflective (R) lamps to provide narrow spot and wide flood beams. The optics has a limited effect on the efficacy of the lamp, due to relatively thin optical thicknesses and clear lenses. Since technical feasibility does not appear to be a barrier, consumers can anticipate a variety of products with spot and flood beam angles as LED lamp demand grows in the market.

Staff has analyzed and plotted the beam angle against efficacy for listed ENERGY STAR® and Lighting Facts data for LED small diameter directional lamps. While there is a limited data set for reported beam angle, the data show that lamps at 80 lumens per watt are capable of achieving narrow beam angles.

Figure 2: Beam Angle vs. Efficacy



Source: California Energy Commission

Flicker and Dimmablity

Replacing high–wattage, small-diameter directional halogen lamps with low-wattage LED lamps can result in flicker in some existing low-voltage applications, specifically when the lamp is dimmed or when otherwise operated at very low wattage. Transformers require a minimum power load for proper operation. LED lamps are extremely energy-efficient when compared to incandescent, halogen, or HIR lamps that operate at much higher wattages. Transformer and LED drivers technology has progressed substantially in the past few years. New transformers and drivers that are specifically designed for compatibility have the ability to run low-voltage LEDs while avoiding flicker.

Electronic transformers typically require a higher minimum load for the LED lamps to maintain the dimming abilities, which is often higher than the minimum required load for a transformer to run. This minimum load can vary from as low as 2.5 W (low-wattage start) to as high as 20 W (for dimming capabilities). Switching to an LED-compatible transformer allows for LED dimming.

Dimming problems in LED lamps can also be resolved by the use of LED drivers that are compatible with electronic transformers.[29] Compatible LED drivers will keep most electronic transformers operating smoothly with MR 16 LED lamps. The current drawn by the MR 16 lamps is adjusted with the root mean square (RMS) voltage applied to the lamp. When the voltage is low, MR 16 lamp draws certain amount of current. This current will keep the lamp dim without interruption. To keep the input power constant, this current will reduce when RMS input voltage is increased.

Small-Diameter Directional Lamp Systems

Small-diameter directional lamp systems are designed to operate between 1 and 10 lamps; about 60 percent of the systems use three to five lamps.

The system power requirements are based on the assumption that 30 percent of the lighting load is a transformer load. Use of highly efficient lamps would significantly reduce the system power consumption and reduce the energy used by the transformer.

Overview of Transformer Compatibility Design Approaches

Transformer compatibility is occasionally an issue for low-voltage LED lamps that are installed on high-wattage transformers. These issues are increasingly less prevalent based on evidence from utility rebate programs that suggest the incidence of compatibility issues is decreasing. [30] Manufacturers recognize that transformer compatibility for low-wattage lamps has been a concern and have therefore invested resources to improve the LED driver and lamp designs. In most cases, low-voltage/low-wattage LED lamp/transformer compatibility challenges can be resolved either by changing the higher-wattage transformer with a low-wattage transformer or by changing out the LED lamp with one with a different driver or circuitry design. Replacing a high-

29 Available at http://www.digikey.com/en/articles/techzone/2013/jul/mr16-led-driver-makes-mr16-led-lamps-compatible-with-most-electronic-transformers.

30 Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf Page 13.

wattage transformer with a low-wattage transformer will reduce the power conversion losses as well help resolve the dimmer and flicker issue. For remaining compatibility challenges, the low-voltage transformer can be swapped out for another low-voltage system, or the system could be converted to line voltage. There are number of transformer technology that SDDL system designers use. Transformer technologies are discussed in detail in the IOUs' CASE study.[31]

31 Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf , page 18.

CHAPTER 4: Regulatory Approaches

Objectives

A study conducted by Navigant Consulting[32] estimates that there will be about 15.8 million small diameter directional lamps installed in residential and commercial buildings in California in 2018 and that this stock will grow to about 18 million lamps by 2028. Based on the numbers estimated in this study, staff estimates that small-diameter directional lamps will consume about 2,349 GWh/year statewide in 2018 and that this consumption will grow to 2,673 GWh/year statewide in 2028 in the absence of any regulation. The significant statewide energy consumption is the result of two things: (1) Most small-diameter directional lamp stock is energy-inefficient, filament-based incandescent, halogen, and HIR lamps[33] and (2) small-diameter directional lamp sales and stock are continuously increasing.

Consumers do not have sufficient information related to the energy consumption of small-diameter directional lamps. These lamps are not regulated by the State of California, the U.S. Department of Energy (DOE), or the Federal Trade Commission. There are no Energy Guide[34] labeling requirements for these lamps, and manufacturers of small-diameter directional lamps are not required to disclose energy consumption information, although some voluntarily do so through the ENERGY STAR and Lighting Facts programs. Moreover, there is no mandatory test procedure prescribed to disclose the energy rating of these lamps.

It is the Energy Commission's objective to ensure that the 15.8 million small-diameter directional lamps expected to be installed in 2018, and those installed thereafter, are as energy-efficient as is feasible and cost-effective, and to minimize the amount of effort by purchasers trying to identify the small-diameter directional lamps with the desired characteristics. As discussed below, regulations that set an efficiency floor are the best method for achieving these objectives.

Small-diameter directional lamps are available in four technologies – incandescent, halogen, HIR, and LED. Table 1 summarizes performance characterizations for halogen and LED:

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32 These numbers are calculated based on the Navigant Consulting. 2011, "*Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications,*" available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf.

33 *Codes and Standards Enhancement (CASE) Initiative For PY 2013: Title 20 Standards Development Small Diameter Directional Lamps* available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf (page 11).

34 The Federal Trade Commission requires yellow-and-black Energy Guide labels to help consumers to compare and shop for energy-efficient appliances. The labels show the highest and lowest energy consumption or efficiency estimates of similar appliance models. The labels provide the yearly cost of that energy, based on national average price for the fuel (electricity or gas).

Table 1: Summary of Ranges for Typical Performance by Lamp Technology

Lamp Performance Characterization	Halogen (Noninfrared)	LED Replacement Lamps
Lumen Output	200-950 lumens	200-680 lumens
Wattage Availability	20W, 35W, 50W	3W to 10W
Beam Angle Availability	10-60 degrees	12-60 degrees
Efficacy LPW	5-25 LPW	35-105 LPW
Average Lifetime Hours per Lamp	1,500-3,000 hours	25,000-35,000 hours
Low and Line Voltage	12 V & 120 V	12 V & 120 V

Sources: GE 2013a/b, Phillips 3a/b, Sylvania 2013a/b, ENERGY STAR QPL 2013, PG&E 2010

LED lamps have an estimated life of more than 25,000 hours, while filament lamps have a life span of only 2,000-4,000 hours. This means that, on average, the life of one LED lamp is about five times the life of one halogen, HIR, or incandescent lamp. The average price of an LED lamp is about $10.00 whereas halogen lamps sell for about $6.[35] As a result, when a consumer replaces a halogen lamp with an LED lamp, consumers will save a minimum of ($6*5)-$10.00=$20.00 in lamp replacement costs alone due to the longer life of these LED bulbs.

The majority of filament–based, small-diameter directional HIR or halogen lamps produce light in the range of 10-15 lumens per watt of power consumed. Staff assumed that these lamps have about 30 percent[36] of power loss in transformer power conversion, whereas an average LED small-diameter directional lamp produces more than 60-105 lumens of light per watt of power. Transformer power conversion loss for LED lamps is much smaller because of the low wattage needed to operate the LED lamps. Thus, LED SDDLs consume 80-84 percent less power than an incandescent, halogen, or HIR lamp, resulting in a lower operating cost, which means more energy bill savings for consumers.

To avoid further waste of electricity, environmental damage associated with the building and operation of power plants, and increases in greenhouse gas emissions, and to save water used in power generation, it is necessary to transform the small-diameter directional lamp market by

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35 Available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf. Page 4 and page 6; Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf Page 11 and 26.

36 *MR-16 LED Replacement Lamps: Electrical Compatibility And Performance***,** Available at http://cltc.ucdavis.edu/sites/default/files/files/publication/201505-electrical-compatibility-mr16-led-replacements.pdf page 20, http://cltc.ucdavis.edu/sites/default/files/files/publication/lda-may2015-electrical-compatibility-mr16-led-replacements.pdf Page 88.

setting cost-effective and feasible energy efficiency standards for small-diameter directional lamps. Standards will ensure that Californians purchase efficient and cost-effective lamps.

DOE's Activity and Status

There are no existing DOE standards for small-diameter directional lamps. DOE has established HIR performance standards for incandescent reflector lamps (IRLs) of diameter greater than 2.25 inches that use 40 watts or more. MR 16s, MR 11s, PAR 16s, and PAR 11s are not regulated by the DOE.

ENERGY STAR® Specifications and Wattage Equivalency Criteria

ENERGY STAR® established voluntary specifications for LEDs in Version 1.4, including MR and PAR lamps.[37] For lamps with a diameter less than or equal to 2.25 inches, efficacy must be at least 40 lumens per watt. ENERGY STAR provides a tool for PAR and MR lamps to calculate minimum CBCP requirements based on the beam angle and claims about wattage equivalency of the replacement lamp.

Australian Lamp Standard

The Australian Department of Resources, Energy and Tourism[38] established lighting standards for low-voltage MR16 lamps by establishing a wattage cap at 37W, which became effective on April 14, 2012. This cap effectively banned 50W halogen lamps from being sold in the market, leaving the 37W HIR lamp (a 50W equivalent) and LED replacements to compete.

Proposals for Small-Diameter Directional Lamp Efficiency Standards

Seoul Semiconductors' Proposal

Seoul Semiconductors proposed that California should harmonize with ENERGY STAR specifications. The ENERGY STAR program provides a framework of standards and testing that California can adopt. Harmonizing with ENERGY STAR test procedures would mean manufacturers would need to test only their equipment once and therefore reduce testing costs. Based on the data and information staff has reviewed, staff finds that the 40-lumens-per-watt efficiency level is too low and not reflective of the state of lighting technology or the potential cost-effective savings.

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37 *ENERGY STAR® Program Requirements for Integral LED Lamps*, available at http://www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf

38 Now the Australian Department of Industry and Science. Available at https://www.comlaw.gov.au/Details/F2012L02122,

IOU Proposal

The California IOUs CASE team supported a high-efficacy standard for small-diameter directional lamps effective in 2018.[39]

Natural Resources Defense Council Proposal

NRDC supports an energy efficiency standard of 80 lumens per watt (LPW) by January 1, 2018, but suggests scaling the efficiency standard with CRI. As a result, lamps with higher CRI could meet lower minimum efficiency requirements. NRDC's alternate proposal is as shown in Table 2 below.

Table 2: NRDC's Proposed Standard

Color Rendering Index	Minimum Efficacy (Lumens per Watt)
CRI 80-85	LPW > 80
CRI 85-90	LPW > 70
CRI 90-95	LPW > 60
CRI > 95	LPW < 50

SORRA Proposal

SORRA also proposed a standard that scaled with CRI. The following proposal is based on the forecasted average efficacies for SSDL based on analysis of Lighting Facts® database (as of September 2014) and assumed 10 percent annual improvement.[40]

Table 3: SORRA's Proposed Standard

Color Rendering Group	2018 Efficacy
80-85 CRI	78 lumens per watt
90-100 CRI	58 lumens per watt

National Electrical Manufacturer's Association (NEMA) Proposal

NEMA proposed that the scope include all small diameter directional lamps of a diameter less than or equal to 2.25 inches, that operate satisfactorily at 120 volts or 12 volts, and that have an

39 Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf Page 8.

40 SORRA Comment Letter dated October 24, 2014, is available at http://www.energy.ca.gov/appliances/2014-AAER-01/prerulemaking/documents/2014-09-29_workshop/comments/Soraa_comments_related_to_title_20_rulemaking_for_Small_Diameter_Directional_Lamps_and_LED_lamps_2014-10-24_TN-73901.pdf Page 2.

MR16 or MRX 16 lamp shape with a GU-5.3 bi-pin or GU-10 lamp base, or have a PAR16, R16 or R14 lamp shape with a medium screw base.

NEMA's proposed standard for these lamp types, effective January 1, 2018, is a luminous efficiency of 60 LPW per watt or greater, a CRI greater than or equal to 80, a power factor of 0.7 or greater, and a minimum rated life of 10,000 hours.[41]

Phillips' Proposal

Phillips, noting that different lighting applications require different color quality and efficiency, suggested that the Energy Commission specify a minimum for each parameter:

- CRI of at least 80
- Efficacy of at least 60 LPW
- Color accuracy of at least 7 McAdam Steps,[42] consistent with ENERGY STAR

This would allow customers to choose products for a range of applications and prices[43]

41 NEMA comment letter available at http://www.energy.ca.gov/appliances/2014-AAER-01/prerulemaking/documents/2014-09 -29_workshop/comments/NEMA_Cooments_on_Staff_Analysis_of_Small_Diameter_Directional_Lamp_and_LightEmitting_Diode_Lamp_Efficiency_Opportunities_2014-11-14_TN-740012.pdf29_workshop/comments/NEMA_Cooments_on_Staff_Analysis_of_Small_Diameter_Directional_Lamp_and_Light Emitting_Diode_Lamp_Efficiency_Opportunities_2014-11-14_TN-740012.pdf Page 15.

42 MacAdam steps are deviations in MacAdam ellipse. A MacAdams ellipse is a region on a chromaticity diagram which contains all colors which are indistinguishable, to the average human eye, from the color at the center of the ellipse. The contour of the ellipse therefore represents the just noticeable differences of chromaticity

43 Phillips comment letter is available at http://www.energy.ca.gov/appliances/2014-AAER-01/prerulemaking/documents/2014-09-29_workshop/comments/Philips_Lighting_Comments_on_Small_Diameter_Directional_Lamp_and_Light_Emitting_Diode_LED_Lamps_2014-11-11_TN-74008.pdf Page 11.

CHAPTER 5: Staff Proposal

Proposed Standards

Energy Commission staff analyzed the SDDL market data and researched the design and technology development. Staff observed significant improvement over the last year in the LED lamp efficacy, quality, beam angle, and color temperature compared to earlier generations of LED lamps. Based on the data and information provided by stakeholders, as well ENERGY STAR and Lighting Facts® latest data and staff research of numerous studies and reports, staff proposes the following standard for small diameter directional lamps, effective January 1, 2018:

- Meet one of the following:
  - Minimum efficacy ≥ 80 lumens per watt
  - CRI + *Efficiency* ≥ 165 and a minimum required *Efficiency* ≥ 70 LPW
- Have a minimum rated life of 25,000 hours.

The staff-proposed standards for small-diameter directional lamps would result in significant energy savings in California in 2018 and beyond.

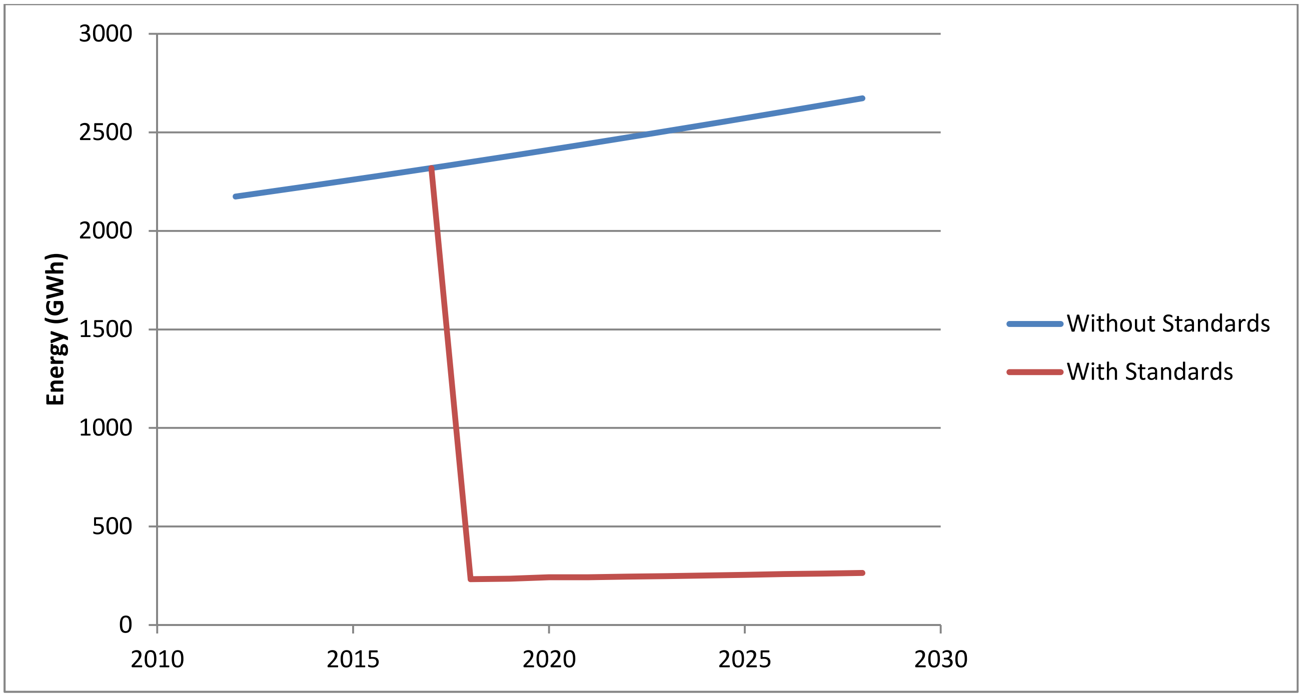
Table 4: Summary of Proposed Standards

Effective date	Voltage (V)	Energy Efficiency Standard (x = lumens)	Minimum Rated Life (hours)
January 1, 2018	All voltages	≥ 80 lumens per watt or a CRI +*Efficiency* ≥ 165 and a minimum required *Efficiency* ≥ 70 LPW	25,000

Source: California Energy Commission

Figure 3 below shows estimated energy use decrease with and without the proposed regulations (in California). Figure 3 shows a significant decrease in power consumption after the standard takes effect. There will be sharp drop in energy consumption due to replacement of inefficient filament base lamps with highly efficient LED lamps in the commercial buildings and residential buildings. filament base lamp has an average life cycle of 4,000 hours whereas the LED lamp life cycle is more than 25,000 hours. Filament base lamp in commercial buildings lasts a little more than a year. Commercial stock is 65 percent of the installed base with an average duty cycle of 3,720 hours a year and consumes about 85 percent of the total power consumed by small-diameter directional lamps. Residential stock is 35 percent, and the duty cycle is about 840 hours a year and consumes only 12 percent of the total power consumed by small-diameter directional lamps.

Figure 3: Energy Consumption vs. Time



Source: Appliance Efficiency Staff, California Energy Commission Legend: The blue line shows the energy consumed by small diameter directional lamps without regulations, in other words, business as usual, for Incandescent, halogen, and HIR lamps. The red line shows the energy consumed after stock replacement with 80 lumens/watt lamps.

Proposed Test Procedures

Staff proposes that manufacturers use IES LM-79-08 for Electrical and Photometric Measurement of Solid State Lighting Products with additional guidance provided in 80 Fed. Reg. 39665-39666 (July 9, 2015), §430.23(dd) and Appendix BB to Subpart B of Part 430, to test the efficacy of small-diameter directional LED lamps. To test small-diameter directional lamps with an incandescent filament, manufacturers shall use 10 C.F.R. Section 430.23(r) (Appendix R to Subpart B of part 430), in case this technology is able to develop in a way that meets the proposed standards. To test for lumen maintenance and time to failure, manufacturers can use the IES LM-84 (2014) and TM-28 (2014) with additional guidance provided in 80 Fed. Reg. 39665-39667 (July 9, 2015), §430.23(dd), and Appendix BB to Subpart B of Part 430.

CHAPTER 6:
Energy Savings and Cost Analysis

Staff conducted an energy savings and cost benefit analysis for the proposed standard. The proposed small diameter directional lamp requirements represent a significant energy and cost savings opportunity for commercial and residential buildings in California.

Stock and Sales

IOUs estimated that there are about 15.8 million small-diameter directional lamps installed in California in 2018.[44] The 2018 stock estimate is based on the total national installed stock and the assumption that California stock is about 12 percent of the national installed stock. IOUs report further estimated that 70 percent of the California stock is 50-watt lamps, 20 percent are 35-watt lamps, and 10 percent are 20-watt lamps. The CASE study points out that 80 percent of the small-diameter directional lamps in stock are low voltage that operates from 6-24 volts whereas 20 percent of the lamps are line voltage that operates at 110 volts. The CASE study does not find any cost difference between low-voltage and line-voltage lamps. Based on the market, IOUs estimated that the current stock is growing at a compound annual growth rate (CAGR) of 1.3 percent.[45] Staff used 2015 California stock and a CAGR of 1.3 percent per year to calculate total California stock for 2018 through 2028, as shown in Table 5 below.

Table 5: Projected Residential and Commercial Stock

Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Residential	5.5	5.6	5.7	5.7	5.8	5.9	6.0	6.0	6.1	6.2	6.3
Commercial	10.3	10.4	10.5	10.7	10.8	10.9	11.1	11.2	11.4	11.5	11.7
Total	15.8	16.0	16.2	16.4	16.6	16.8	17.0	17.3	17.5	17.7	18.0

44 *Small Diameter Directional Lamps Codes and Standards Enhancement (CASE) Initiative*, August 6, 2014, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf, Appendix Overview of small diameter directional lamp class, page 2.

45 Available http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf Page 22 and 23.

Annual Operating Hours/Duty Cycle

The IOUs CASE study assumptions for annual operating hours are based on a 2011 Navigant Study on MR lamps.[46] 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 roughly 35 percent of sales, while the commercial sector accounts for 65 percent of sales.[47] Applying a weighted average to these values, staff estimates that a typical small diameter lamp is used on average 2,712 hours per year.[48]

Incremental Cost

Staff developed the incremental cost of making a small-diameter directional lamp that would comply with the proposed standards by reviewing IOU data on the retail price of existing LED small-diameter directional lamps that would meet the standard and baseline halogen lamps that would not, then applying appropriate "experience" or "learning" curves to each lamp type based on historical price drops resulting from improvements in manufacturing. Staff then considered the incremental cost between a noncompliant LED lamp and a compliant LED lamp, as well as potential additional costs for new transformers where transformer compatibility might be an issue.

Halogen-to-LED Incremental Costs

Learning curves are a method to account for historical changes in product prices and energy efficiency in product price forecasting. Learning curves are especially appropriate for newer technologies that are expected to come down significantly in cost as manufacturers determine how to make the products more efficiently; however, they are also applicable to more mature products where some level of improvement remains. Figure 4, below, shows the inflation-adjusted price histories of various products over the past four decades. The universal decrease in price across all products even as energy efficiency improves as a result of standards and other programs demonstrates why learning curves are a reasonable approach to projecting future prices for appliances.[49]

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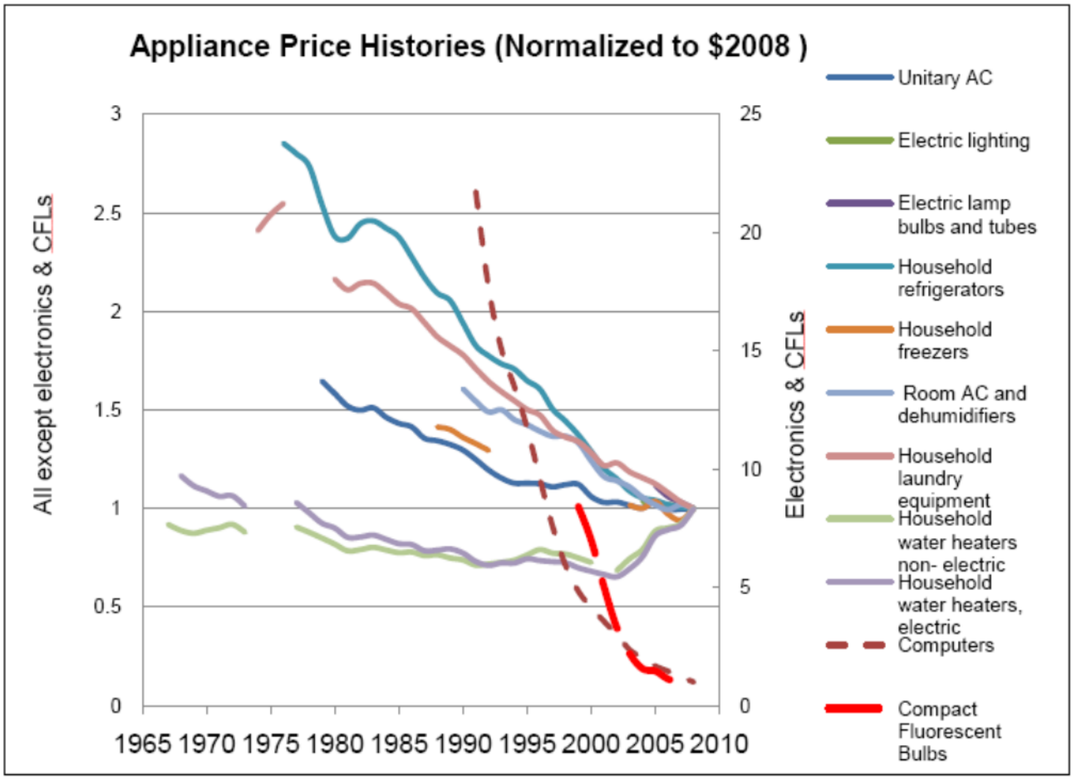
46 *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications* Prepared for: Building Technologies Program Office of Energy Efficiency and Renewable Energy U.S. Department of Energy, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf.

47 Ibid.

48 *Small Diameter Directional Lamps Codes and Standards Enhancement (CASE) Initiative*, July 29,2013, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf, page 22.

49 *Using the Experience Curve Approach for Appliance Price Forecasting*, February 2011, available at https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/experience_curve_appliance_price_forecasting_3-16-11.pdf.

Figure 4: Product Price Histories



Source: Producer Price Index (PPI) data from Bureau of Labor Statistics, except Compact Fluorescent Lamp (CFL) Bulbs (Pulliam, R., 2008).

The cost of LED lamps generally has been improving rapidly according to what has been called Haitz's law, analogous to Moore's law for semiconductor devices.[50] Haitz's Law asserts that LEDs will become exponentially more efficient and more affordable over time.

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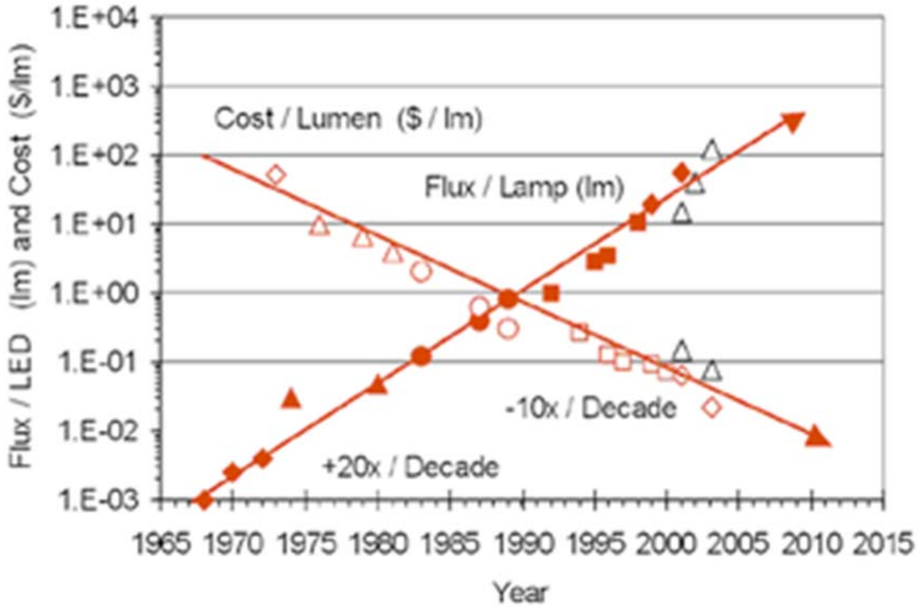
50 Available at http://www.elementalled.com/academy/blog/led-news/haitzs-law-asserts-leds-will-become-exponentially-more-efficient%E2%80%94and-more-affordable%E2%80%94over-time/.

Figure 5: Increase in LED Lumens/Watt and Decrease in Cost per Year



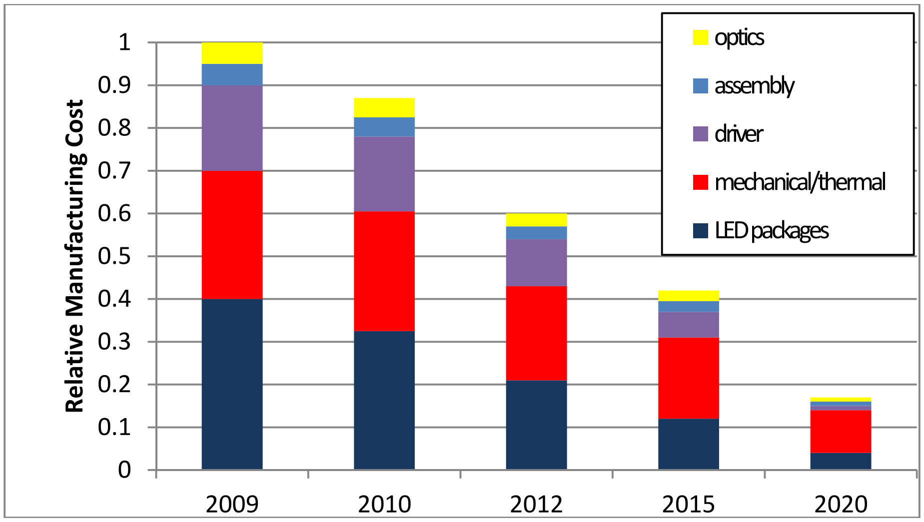
Source*:* Elemental LED, Haitz's law asserts LEDs will become exponentially more efficient and more affordable over time.

The implications of Haitz's Law for LED retailers and consumers are significant: LEDs will continue to get brighter and more efficient, LEDs will continue to get cheaper, LEDs will eventually dominate the lighting market, and over time they will completely replace the less-efficient counterparts, such as incandescent lamps. Despite this trend, effective policy coupled with appropriate efficiency regulations are needed to accelerate the energy- and money-saving potential of energy efficient lamps.

Figure 6 below shows that the relative manufacturing cost of LED packages (cluster of LEDs on a circuit board) is on a continuous decline.[51]

51 *http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf* , Prepared for: Lighting Research and Development Building Technologies Program Office of Energy Efficiency and Renewable Energy U.S. Department of Energy, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_manuf-roadmap_july2010.pdf

Figure 6: Relative Manufacturing Cost Per Year



Source: California Energy Commission

Manufacturers have developed highly efficient LED lighting technologies, and great achievements and breakthroughs have been made in this area. LED manufacturers have made claims to develop LEDs of light intensity tenfold, that is, from 50 lumens per watt to 500 lumens per watt.[52]

To verify these drops in cost for small-diameter directional lamps specifically, the IOUs surveyed small-diameter directional LED lamp price data. Results of that survey show LED lamp retail price dropping from 2013 to 2014. IOUs also conducted a price drop analysis based using an Experience Curve Approach for Appliance Price Forecasting method used by the DOE.[53] The average lamp price in the data set of LED MR 16 and PAR 16 replacements was $24.67 in 2014. By 2015, the prices have decreased significantly, with the most efficient LED lamps averaging around $10, and the average price of all LED small-diameter directional lamps around $21, as shown in Table 5, below:

52 "Seoul Semi Quintuples LED Brightness With New Technology," *EE Times*, available at http://www.ledlighting-eetimes.com/en/seoul-semi-quintuples-led-brightness-with-new-technology.html?cmp_id=7&news_id=222908002

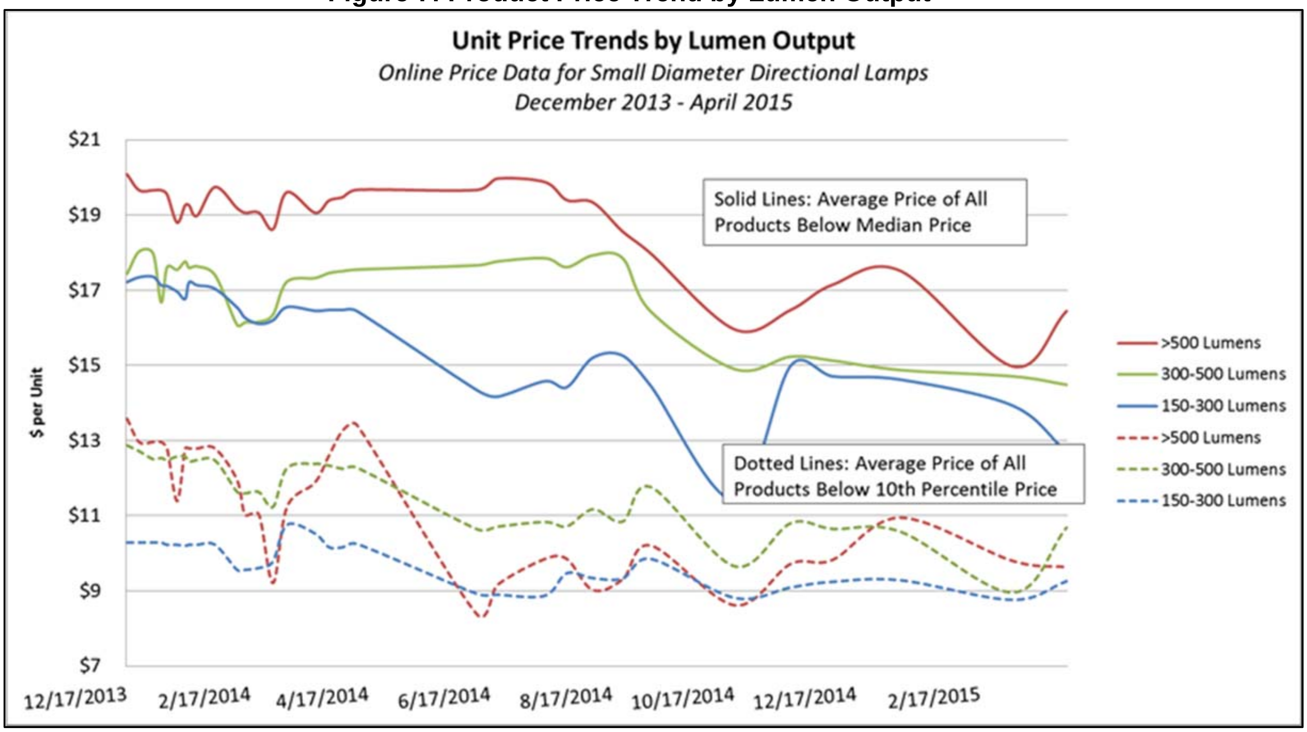
53Available at https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/experience_curve_appliance_price_forecasting_3-16-11.pdf

Table 6 Current Small-Diameter Directional Lamps Pricing[54, 55]

	Halogen Baseline (No Change Since CASE Report)	2015 Average price of LED SDDLs Below 10th Percentile Price (Most Aggressive)	2015 Average Price of LED SDDLs Below the Median Price	2015 Average Price of All LED SDDLs Collected Online (Most Conservative)
Average Price per unit	$6	$9.31	$14.50	$20.39

The following figures provide unit price trends by lumen output and by efficacy.

Figure 7: Product Price Trend by Lumen Output[56]

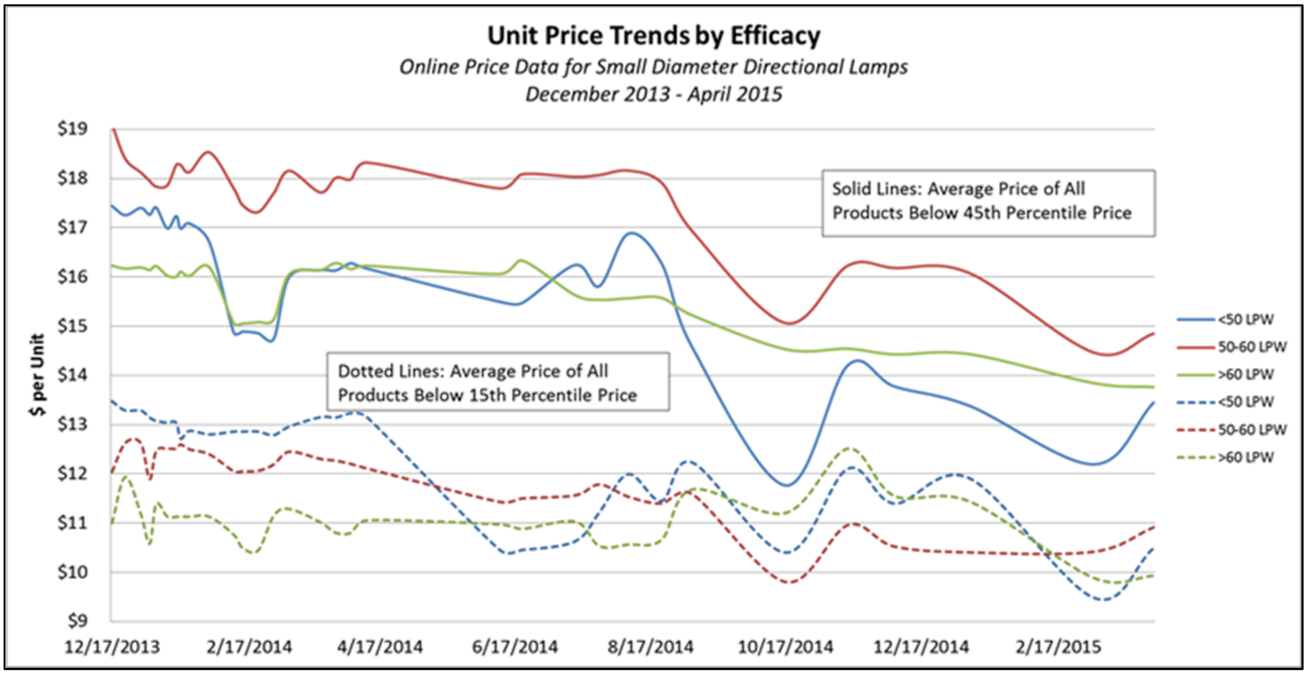


54 Pricing shown for lamps that have lumen output above 150 lumens.

55 Available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf . Page 4 and page 6.

56 Product price trend figure is available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf Page 5.

Figure 8: Product Price Trend by Efficacy[57]



Both Figures 7 and 8 demonstrate a decreasing retail price over time. Typically, lumen pricing is directly proportional (the greater the lumens, the greater the average price) – this is clear in Figure 7. However, lumens per watt and price do not bear a proportional relationship. As Figure 8 shows, lamps with an efficacy greater than 60 LPW have a lower retail price than lamps between 50 and 60 LPW. Thus, efficacy does not appear to be directly correlated with price.

Figure 9 below shows trends of average online prices of products below median price projected through 2018. The IOU CASE report cites a 2014 LBNL study from December 2013 to June 2015 that found that lamp prices dropped at an average of 23 percent.[58] This finding results in lamp prices averaging $14.99 today, and, if they continue to decrease at the same rate, to less than $10 in 2018. Together, these figures and data show that learning curves are appropriate for small-diameter directional LED lamps, which are rapidly dropping in cost even as efficacy improves.

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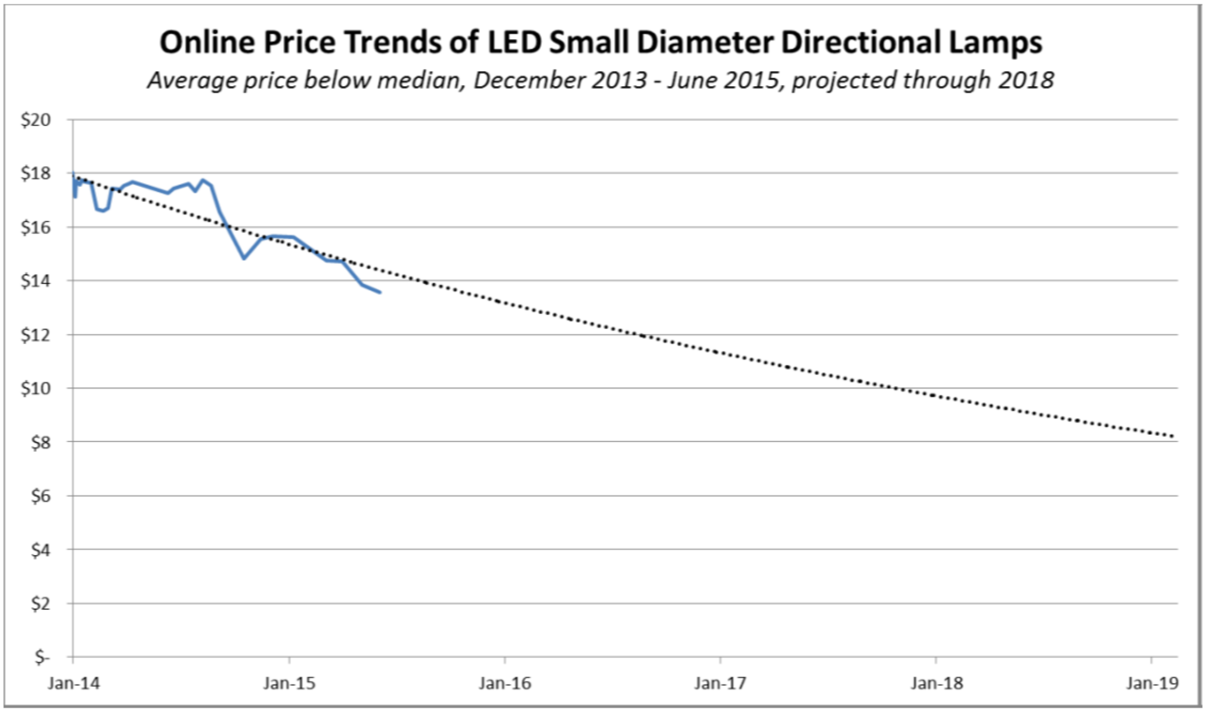
57 Product price trend figure is available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf Page 5.

58 Available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf.

Figure 9: Unit Price Trends Projected Through 2018



The IOUs applied learning curves to existing average prices for both baseline lamp products (halogen, HIR, and incandescent) and compliant LED products. For baseline technologies, the IOUs assumed a slower learning curve than for LED technology, since LED technology is newer and innovation is still taking place to bring prices down. Table 7 below shows the resulting prices in 2018 and beyond after applying these learning curves.

Table 7: Price Drop Based on Learning Curve

Lamp Cost w/Learning curves	Baseline	80 lumens/watt
2014	$6.68	$30.25
2015	$6.64	$23.22
2016	$6.59	$15.00
2017	$6.55	$12.00
2018	$6.51	$10.00
2019	$6.48	$10.00
2020	$6.44	$10.00
2021	$6.40	$10.00
2022	$6.37	$10.00
2023	$6.34	$10.00
2024	$6.31	$10.00
2025	$6.28	$10.00
2026	$6.25	$10.00
2027	$6.22	$10.00
2028	$6.19	$10.00

Source: *Small Diameter Directional Lamps Codes and Standards Enhancement (CASE) Initiative* August 6, 2014. Changes to table have been made starting in 2015, to reflect the recent drop in price of the lamps.

Staff has reviewed the IOUs' price survey and data and agrees with the predicted learning curve analysis. The IOUs' assumptions on price drop trend are conservative; therefore, it is reasonable to assume the average price of LED small diameter directional lamps in 2018 will be about $10.00. Staff notes that there are compliant small-diameter directional LED lamps today that meet the proposed standards available at around $10.[59] The average price of a filament-based incandescent, halogen, and HIR lamp is about $6.00. Replacement cost of filament based lamp with a LED lamps is in 2018 will be $10.00-$6.00 = $4.00.

59 Price information is provided in IOUs update on SDDL market trends, performance proposal, and hazardous/toxic contents available at http://docketpublic.energy.ca.gov/PublicDocuments/15-AAER-06/TN206027_20150909T111542_Codes_and_Standards_Enhancement_CASE_Initiative_For_2015.pdf on page 6.

LED-to-LED Incremental Costs

As shown in Figures 7 and 8, above, there is little to no correlation between efficacy and the retail cost of a small-diameter directional lamp. This is also true when comparing LED technologies only. Staff collected sales data on pricing and efficacy (lumens/watt) to verify this effect in the LED market. The data shows a 50 lumens/watt, a 63 lumens/watt, a 72 lumens/watt lamp, and an 80 lumens/watt lamp selling at about $15.00 each. Staff also researched and collected LED cluster data from the DIGIKEY, an LED component distributor.[60] The LED price and efficacy analysis shows that there is no cost difference between a high-efficacy LED cluster and low-efficacy LED cluster. Because there is no price correlation between high- and low-efficacy LED lamps, staff assumes $0 incremental cost between the base case 40 lumens per watt LED and the LED lamp that could meet the proposed standard.

Transformer Incremental Costs

The Energy Commission is not requiring the use of a dimmer with small-diameter directional LED lamps, so there is no requirement to upgrade the transformer to accommodate dimmable LEDs. As a result, the cost of the transformer (and the energy savings from dimming lamps) was not included in this analysis. However, staff notes that the price for these LED-compatible transformers is reasonable. Standard 12 V, 60 W transformers can be found in the market for less than $20. LED lamps can save significant energy and money, and switching to an LED-compatible transformer will be the easiest way to accommodate lamps with dimming capabilities. Staff analysis of the cost-effectiveness of the proposed LED lamp standard shows that LED lamp will save about $200 over the entire life cycle. (See below.) Most small-diameter directional lamp systems have three to five lamps installed. As a result, replacing all the existing incandescent, halogen, and HIR lamps with LED lamps will generate savings of about $600-$1000. With the average cost of a new compatible transformer ranging from $20-$80 ($80 transformer for higher-end products), this is sufficient savings to replace the existing inefficient high-wattage transformer with a low-wattage compatible transformer. Thus, even if the cost to replace the transformer were included in the incremental cost of the lamp, the savings would still vastly exceed the costs.

Energy Savings

The energy savings achieved by moving from an inefficient incandescent, halogen, or HIR bulb to an efficient LED bulb depend on power draw, hours of use, and lifetime of the bulb. Staff conducted calculations for energy savings, and the results of the calculations are presented in the tables in Appendix A.

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60 Available at http://www.digikey.com/en/articles/techzone/2011/nov/led-efficacy-improvement-shows-no-signs-of-slowing

Inputs

Power Draw

The common wattage incandescent, halogen, and HIR lamps that are sold on the market are 50-watt, 35-watt, and 20-watt lamps. A 50-watt lamp produces about 600 lumens of light, a 35-watt lamp produces 385 lumens, and a 20-watt lamp produces 200 lumens. Table 8 below shows lamp wattage, light intensity, and lumens per watt for filament based lamps:

Table 8: Wattages, Light Output, and Efficacy

Lamp Wattage	Light Output (Lumens)	Efficacy (Lumens/Watt)
50 Watt	≥600Lumens	≥9
35 Watt	≥385 Lumens	≥8
20 Watt	≥200Lumens	≥7

Source: California Energy Commission

Table 9 shows the equivalent wattages of 80-lumens-per-watt lamps.

Table 9: Wattages and Lamp Efficacy

Lamp Wattage	Light Output	Efficacy (Lumens/Watt)
50 Watt equivalent ≥7.5 W	≥600Lumens	80
35 Watt equivalent ≥4.8 W	≥385 Lumens	80
20 Watt equivalent ≥3W	≥240 Lumens	80

Source: California Energy Commission

Hours of Use

Table 10 below shows the estimated hours of use (duty cycle) and market share for small-diameter directional lamps, based on information provided in the IOUs' CASE study.[61]

Table 10: Annual Operating Hours

Annual Energy Consumption	Hours/year	Market share
Commercial	3720	65 percent
Residential	840	35 percent

Source: California Energy Commission

Lifetime

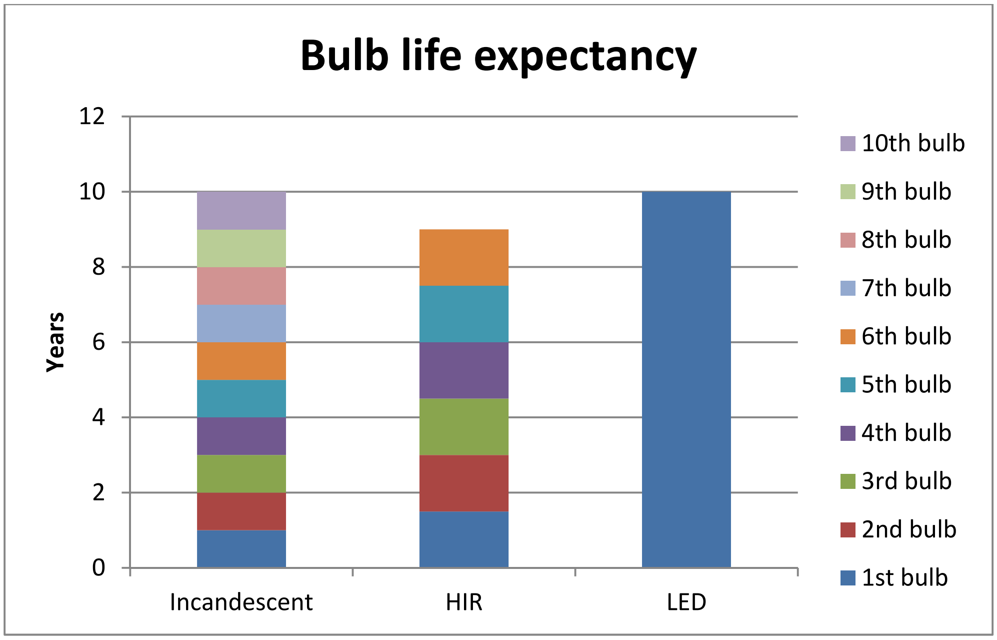
Conventional LEDs have useful lifespans of around 25,000 hours, while high-performing LEDs can last upward of 35,000 hours.[62] Figure 10 below was plotted by the staff to illustrate the lamp life expectancy for incandescent, halogen, HIR, and LED lamps. Staff collected lamp price data from the Internet and used pricing information from the IOUs' CASE study.[63]

61 Reference to duty cycle is available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf. page 22

62 Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf. page 27

63 *Small Diameter Directional Lamps Codes and Standards Enhancement (CASE) Initiative*, August 6, 2014, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf, page 2.

Figure 10: Bulb Life Expectancy Comparison and Price Over Time



Source: California Energy Commission

The life expectancy is calculated based on the average duty cycle or hours of usage (2712 hours) in commercial and residential buildings and manufacturer-rated lifetime hours of usage (3,000 hours for incandescent and 4,000 hours for halogen and HIR lamps) assumptions.[64] Figure 10 above illustrates that the life cycle of one LED lamp is roughly equal to 6 halogen or HIR lamps and about 10 incandescent lamps.

Replacement Savings

Applying the learning curve estimates above, the predicted price for a LED lamp in 2018 is about $10.00. An LED lamp is estimated to last for about 10 years, or 25,000 hours.[65] The predicted price for an incandescent, halogen, or HIR lamp in 2018 is about $6.00. Halogen small-diameter directional lamps have a typical rated life of 4,000 hours. A consumer would have to buy 6.25 halogen lamps over the lifetime of 1 LED lamp. By purchasing LED lamps, consumers will buy 5.25 fewer lamps over a 25,000-hour operational period. Halogen lamps cost about $6, leading to avoided lamp replacement costs of $31.50 worth of halogens per LED replacement. However, LED lamps are expected to be $4 more expensive (see above), at $10 per lamp, making the net replacement savings $27.50.

64 *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications* Prepared for: Building Technologies Program Office of Energy Efficiency and Renewable Energy U.S. Department of Energy, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf.

65 Twenty-five thousand hours is the most common rating in Lighting Facts and ENERGY STAR data.

Energy Savings

Staff analysis of energy savings shows that an LED lamp will save, on average, $221.30 per lamp over the lifetime of the lamp in conserved electricity by switching from an incandescent or halogen lamp to an LED lamp. The calculations for these energy savings are presented in Appendix A.

Cost-Effectiveness

According to staff analysis, the proposed standards are cost-effective, as the energy and replacement savings greatly exceed the incremental cost of moving from a halogen, incandescent, or HIR lamp to an efficient LED lamp. The cost-effectiveness calculations are expanded upon in Appendix A. Table 11, below, summarizes the costs and benefits per unit of improving the efficiency of small-diameter directional lamps. The total savings to consumers after replacing an incandescent, halogen, or HIR bulb with an LED lamp is about $221.30+$27.50= $248.80.

Table 11 Lamp Cost and Cost-Effectiveness

Incremental Cost[66]	Avoided Replacement Savings[67]	Annual Energy Savings per Unit per Year	Total Energy Savings per Unit Over the Lifetime of the Unit[68]	Per Unit Savings Over the Lifetime of the Lamp[69]
$0.00	$27.50	133.39 KWh/year	1333.9 KWh	$221.30

Source: Appliance Efficiency Program, California Energy Commission

66 Explained in LED-to-LED Incremental Costs section above in this chapter.

67 Based on longer lifetime of LED lamp compared to halogen lamp.

68 Assumes 11-year life.

69 Applying a rate of 15¢/kWh for commercial and 17¢/kWh for residential.

Statewide Energy and Cost Impact

Staff conducted statewide energy savings calculations and cost impact analysis and the conclusions are in Table 12.

Table 12: Statewide Energy and Cost Impact

Proposed Standard`	Incremental Cost for Improving LED Lamp Efficacy	Replacement Cost of Filament Base Lamp to LED Lamp	Annual Energy Savings/Unit kWh/year	First-Year Unit Energy Cost Savings	Total Savings per Unit Over the Design Life($)	Simple Payback Period	Statewide Energy Savings After Stock Replacement in 2029
≥ 80 lumens per watt or a CRI +*Efficiency* ≥ 165 and a minimum required *Efficiency* ≥ 70 LPW	$0.00	$4.00	133.39 kWh/year	$22.13	Energy Saving $221.30+Avoided Replacement Cost 27.50= $248.80	<1 year	About 2,286 GWh

Source: California Energy Commission

CHAPTER 7: Technological Feasibility

Electric power consumption for residential lighting in California is about 20 percent of the total electricity consumed in the state[70] and lighting power in commercial buildings is 29 percent.[71] Inefficient incandescent and halogen lamps consume significant electric power. Most of the power consumed is wasted as heat in the filament that produces the light. To reduce lighting power consumption in the state, inefficient incandescent, halogen, and HIR small-diameter directional lamps must be replaced with highly efficient small-diameter directional lamps that are cost-effective and are available in the market. LED small-diameter directional lamps have the advantages of increased efficiency, color specificity, size, response time, and lifetime. The total cost of electricity used over the short lifetime of a single incandescent or halogen lamp costs significantly higher than the original purchase price of the lamp itself.

Lumen Output and Efficacy

LED lighting is closely tied with the semiconductor industry, which makes the design, production, and innovation on a time scale and flexibility that is far different from traditional lamps. LED chip-on-board architecture serves as the basis for improving light quality and color control, lowering the production cost and time to market for a wide variety of lighting applications. LED lamps have a lifespan and electrical efficiency that is several times better than incandescent lamps and halogen lamps. Many LED chips are able to emit more than 100 lumens per watt.[72]

In terms of lumen output, LED small-diameter directional lamps are steadily increasing in output as LED efficiency improvements are continuously increasing the efficacy of the lamps. Based on staff analysis of the May 2015 Lighting Facts® database and ENERGY STAR data, 80 LPW lamps are able to achieve more than 600 lumens in output, which is equivalent to 50W halogen lamps. There are more than 70 models of LED MR and PAR lamps already available in the market that exceed the Energy Commission-proposed standard of 80 lumens per watt. Data plotted in the graph below show that lamps are available in the market that produce light output that exceeds 600 lumens at or above 80 lumens per watt.

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70 *2009 California Residential Appliance Saturation Study*, available at

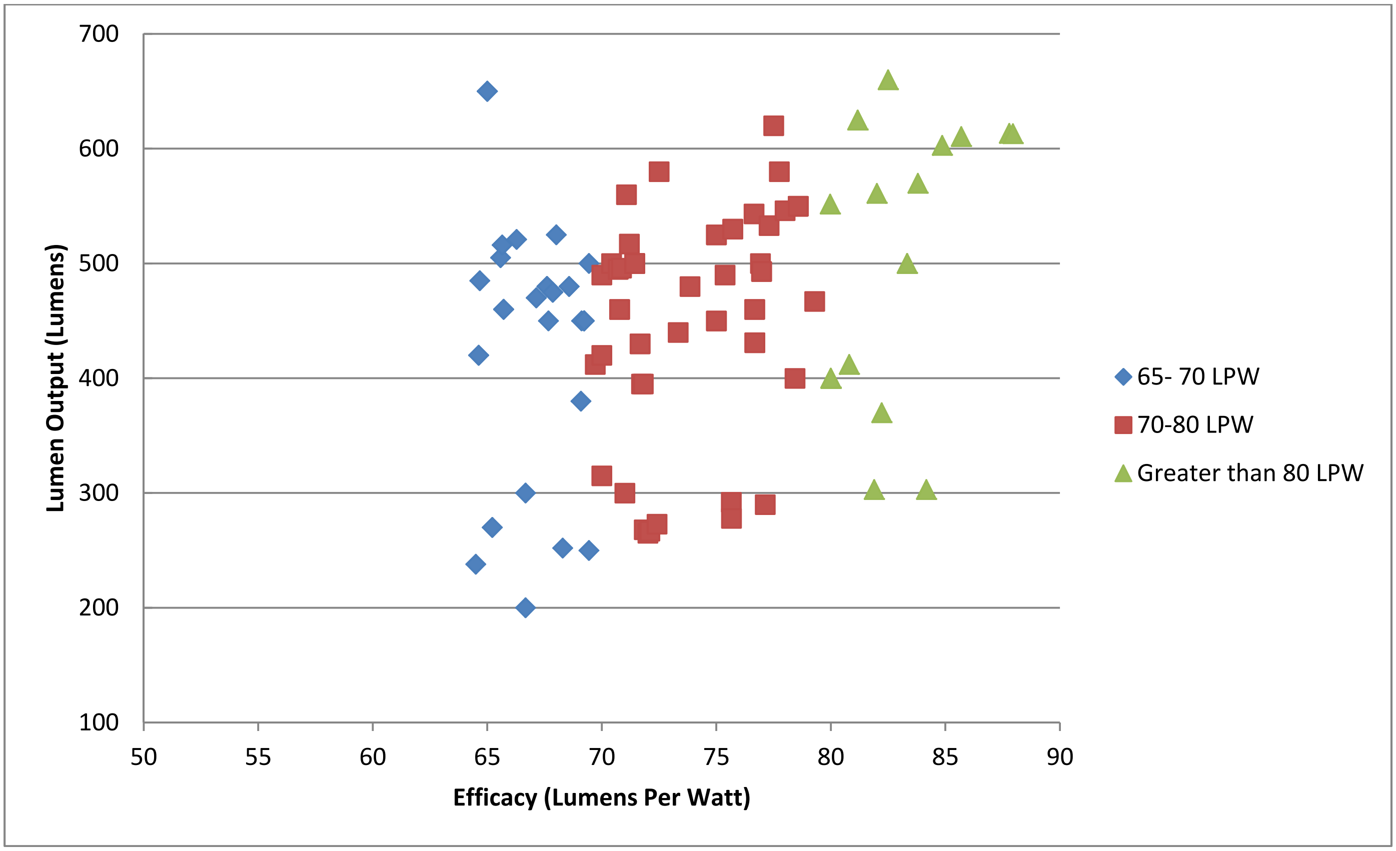
http://www.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-ES.PDF, page 3.

71*2006 California Commercial End-Use Survey*, available athttp://www.energy.ca.gov/2006publications/CEC-400-2006-005/CEC-400-2006-005.PDF, page 9.

72 "DigiKey Electronics, LED Efficacy Improvement Shows No Signs of Slowing," available at http://www.digikey.com/en/articles/techzone/2011/nov/led-efficacy-improvement-shows-no-signs-of-slowing.

In addition, according to a recent DOE CALiPER report, LED small-diameter directional lamps up to 700 lumens are widely available (CALiPER 2014).[73]The efficacy of these lamps range for 60 to 90 lumens per watt.

Figure 11: Lumen Output vs. Luminous Efficacy



Source: California Energy Commission, Appliance Efficiency Program Staff. Data used in the graph above are from Lighting Facts and ENERGY STAR.

The U.S. DOE-issued CALiPER report studied Series 22 LED MR16 lamps that had measured output ranging from 197 lumens to 640 lumens, with a mean of 436 lumens.[74] The study shows a more general trend of increasing lumen output and increased efficacy. Both the lumen output and efficacy of the Series 22 CALiPER products represent the higher end of the LED Lighting

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73 *CALiPER Application Summary Report 22 LED MR 16 Lamps*, June 2014, *available at* http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_22_summary.pdf
Lighting/CaliforniaIOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps August 6, 2014 available at

2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf Page 10.

74 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/postings_08-20-14.pdf

Facts® and ENERGY STAR datasets, although the CALiPER dataset is much smaller, but it illustrates the rapid improvements in the lamp lumen output and gains in the lamp efficacy. Staff has plotted the lumen output versus efficacy by using the latest ENERGY STAR and Lighting Facts® data. The result of the latest data, shown in Figure 11 above, shows the efficacy of LED lamps continuously increasing. The gains in efficiency are resulting from use of better phosphors, more efficient driver design, and better chip design, packaging, and heat dissipation. Figure 11 above shows that the efficiency of majority of small-diameter directional LED lamps far exceeds 65 lumens per watt.

Consumer Efficacy

LED MR lamps provide uniformity across the beam, have fewer hotspots, have no filament images, and have no ragged edges.[75] These attributes make LED directional lamps better products in some ways than incandescent, halogens, and HIR. However, LEDs are still developing greater ranges of beam angles and CBCP, higher color rendering, and improvements to avoid flicker and allow dimmability to match incandescent, halogen, and HIR technologies.

LEDs contribute far less to heat buildup in a room because of their significantly higher efficiency.

High-quality and highly efficient LED lamps for hundreds of applications are readily available at major retail stores. California utilities also started an aggressive rebate program based on the California Quality Light Emitting Diode (LED) Lamp Specification to promote high-efficacy and high-quality LED lamps.[76]

Color Rendering Index (CRI) and Efficacy

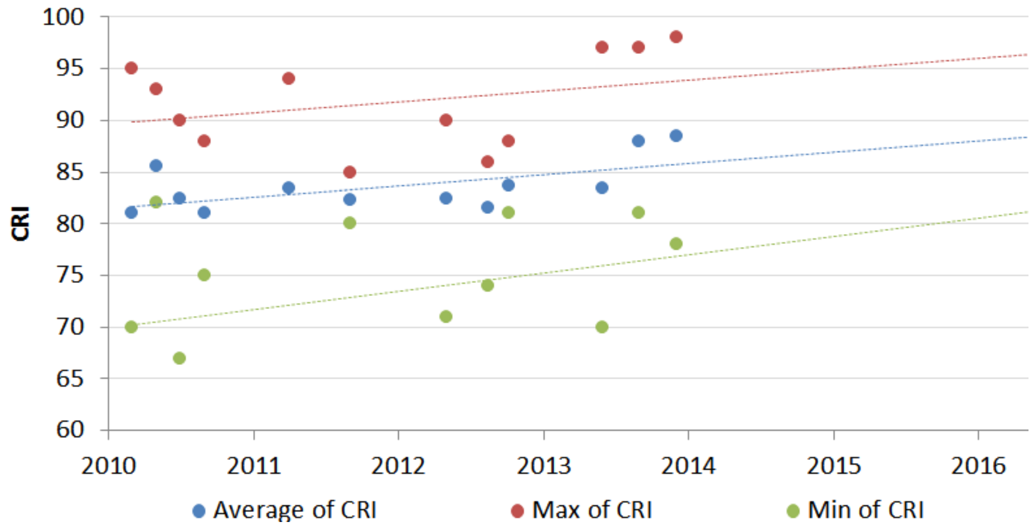
CRI is a quantitative measure of the ability of a light source to render the colors of objects as natural light would. While halogen lamps yield close to 100 CRI, LED lamps average around 80-85 CRI. (See Figure 12 below.) About 65 percent of the small-diameter directional lamps are used in commercial buildings. In many commercial applications, customers prefer to have lamps with higher CRI so that all the true colors of the object are displayed. Higher CRI lamps can render the true colors of objects more accurately. The highest performing LED lamps achieve CRI above 95; in the recent CALiPER report, one LED yielded a measured CRI of 98 (2014).

75U.*S. Department of Energy, Building Technologies Program Solid-State Lighting Technology Fact Sheet*, available at

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_mr16-lamps.pdf .

76 *Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification* is available at: http://www.energy.ca.gov/2015publications/CEC-400-2015-001/CEC-400-2015-001.pdf

Figure 12: CRI Improvement Over Time



Source: IOU's *CASE Report Appendix: Small Diameter Directional Lamps* | August 6, 2014, Page 13

To succeed as replacement lamps, LED lamps must be available with high CRI in the comparable color temperature range as halogen lamps. Halogen lamps such as MR16 lamps provide light that appears whiter (2800 K to 3200 K) compared to the yellowish white light provided by nonhalogen incandescent lamps (normally 2700 K). In certain applications such as in retail or museums, whiter light may be more desirable. Halogen incandescent lamps have a higher color rendering index (CRI of 95 to100). A higher CRI means that the light source will most likely render the color of objects more naturally and in some cases more vividly.

The white LEDs with a higher CRI tend to have a lower efficacy. There are two primary methods for generating high-color-quality white light with the LEDs. The first method is phosphor conversion (PC), and the second method is color mixing. The PC-LED approach is the most energy-efficient, providing package efficacy greater than 130 lumens per watt. They are also by far the most common type available. Due to additional inefficiencies related to phosphor conversion, PC-LED packages have a lower efficacy than color-mixed systems. To achieve the high efficacy and higher color quality in LEDs, PC and color-mixing or hybrid systems are helpful. Manufacturers are already taking this approach in some new products.[77] Another factor that is likely to affect LED package efficacy of a higher-color-quality LED is spectral power distribution.[78] Higher CRI requirements are more restrictive of spectral content and generally require a broader spectral power distribution.[79]

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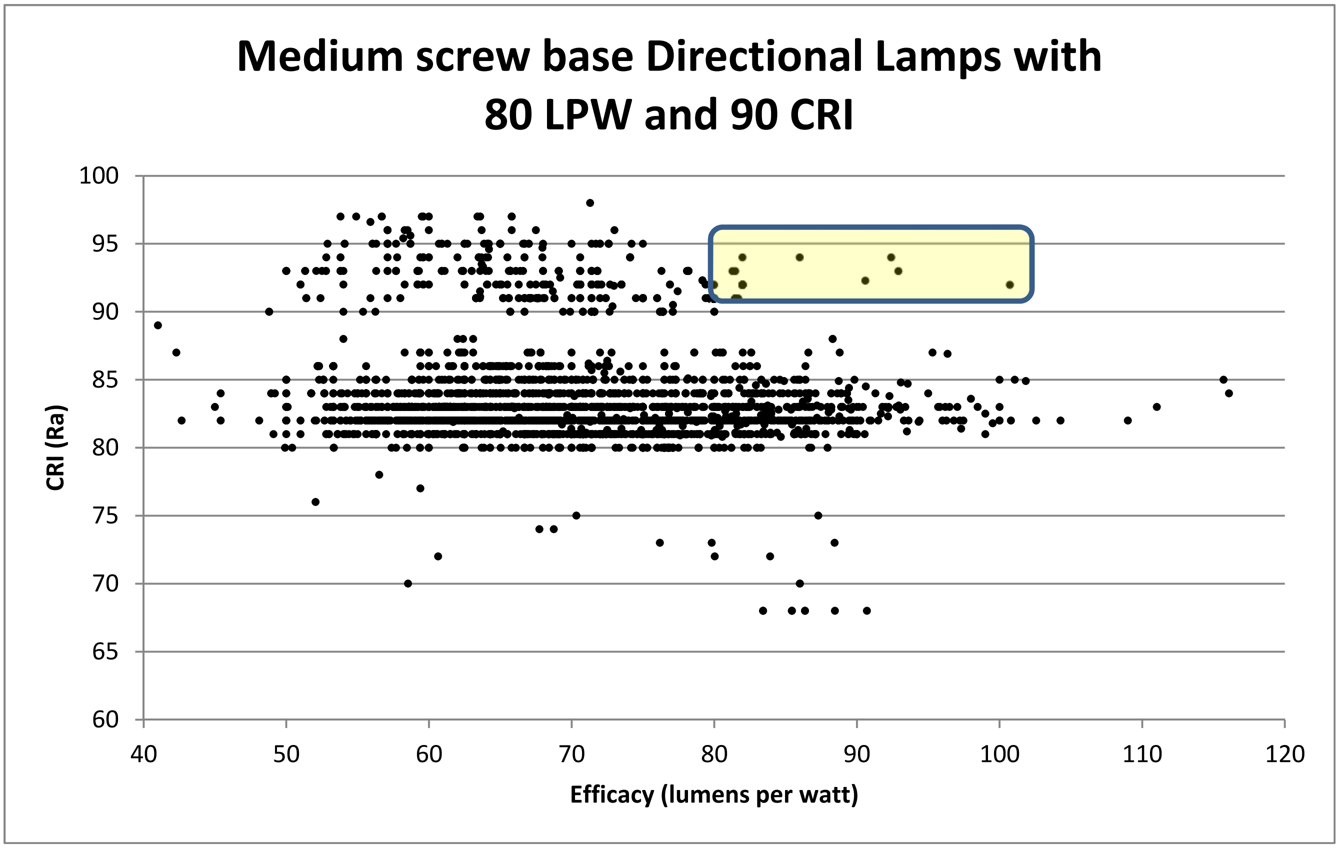
77 Information available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_energy_efficiency.pdf, page 1.

78 A *spectral power distribution (SPD) measurement* describes the power per unit area per unit wavelength of an illumination (radiant exitance). Radiant exitance is the radiant flux *emitted* by a *surface* per unit area.

79 Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_energy_efficiency.pdf, page 1.

Small-diameter directional lamps of CRI of 97 that are available in the market have an efficacy of about 60 lumens per watt. To achieve higher CRI and high efficacy, small-diameter directional lamps can use the same LED chips, drivers, and controllers as are being used in general service LED lamps. Stakeholders have not shown that there are any technical barriers that would limit the use of high-efficacy and high-CRI LEDs, controllers, and drivers in small-diameter directional lamps as they are used in the general service lamps. Figure 13 below shows the number of general service, medium screw base directional lamps with high CRI and high efficacy, demonstrating that the LED chips, drivers, and controllers exist and simply need to be included in small-diameter directional lamps.

Figure 13: CRI vs. Efficacy



Source: California Energy Commission, Appliance Efficiency Staff

Therefore, staff finds that there are no significant impacts to CRI as a result of higher-efficacy lamps. High-CRI lamps are being made today with high efficacy, and incorporating technologies from other lamp types can help small-diameter directional lamps achieve even higher CRI levels at high efficacy.

LEDs and Power Factor

Power factor is the ratio of real power to apparent power. A LED lamp driver can collect the energy it needs by drawing power from the grid while perfectly in sync with the utility waveform, or larger bursts of energy while only partially in sync with the utility waveform. Many appliances draw a large amount of power from the grid, store it, use it, and then draw another surge of power. While the power consumption within the LED driver (referred to as *real power*) is the same in the each case, the power draw from the grid (apparent power) is very different. Shorter, but more intense current draws increase energy losses in building wiring. These wire losses are proportional to the square of the current. Therefore, an appliance that draws double the current would result in quadruple the wiring loss of power.

Low power factor in non-linear LED drivers send power back to the grid and generates harmonic waves in the power line. As the number of LED lamps increases, these harmonics may cause issues in electrical transmission and require expensive utility equipment to correct the harmonic waves generated by the low power factor. Sometimes, the harmonics remain uncorrected, and the quality of power in the building is reduced, resulting in poor quality power availability for other electronic equipment. The most common SDDL lamps are incandescent and halogen technologies, which have a power factor of 1. A power factor of 1 is ideal. The proposed regulations do not include power factor requirements, but it is reasonable to expect manufacturers of LED small-diameter directional lamp systems supply power transformers and high-power LED drivers with a power factor of 0.9 or greater as a means to maintaining performance that is similar to the products they are displacing..

Dimmability

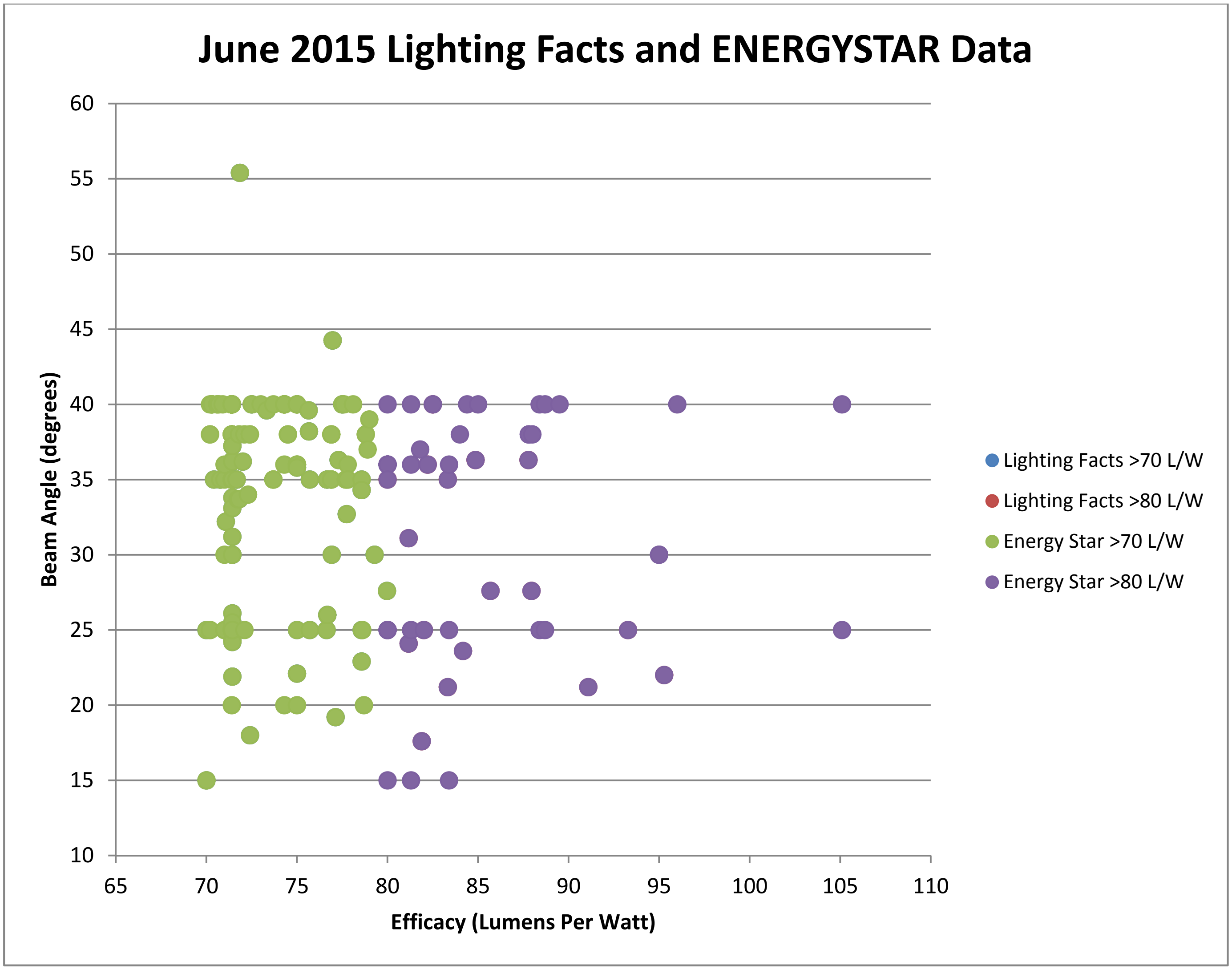
As discussed above, consumers may experience flicker when using dimmable LED small-diameter directional lamps, due to the lower power draw from these lamps. This is a problem only if the LED lamp is dimmed and does not have a compatible transformer or LED driver. This issue can be resolved by installing an appropriate transformer that can handle lower minimum load requirements, as low as 2.5 watts, or by manufacturers producing LED lamps with LED drivers that overcome this compatibility issue. Most manufacturers have resolved the low-voltage LED transformer compatibility issues, once considered a barrier. Under either approach, the consumer still reaps significant cost savings by switching from halogen lamps to LEDs.

Efficacy and Beam Angle

LEDs are ideal for track lighting lamps because they produce directional light. A significant feature of LEDs is that the light produce is directed at a narrow angle, as opposed to halogen or incandescent lamps, which spread the light more spherically. This is an advantage with recessed lighting or undercabinet lighting and directional lighting. For wide-angle directional applications, LED lamp designs address the directional limitation by using more diffuse lenses and reflectors to disperse the light more like a halogen or incandescent lamp.

Staff analysis of the existing data shows that LED lamps with a beam angle of 15° to 40° angle of 80 lumens or greater are available in the market. There is a significant improvement made in the small-diameter directional lamp optics. Figure 14 below shows the beam angle versus efficacy.

Figure 14: Beam Angle vs. Efficacy



Source: California Energy Commission, Appliance Efficiency Staff

Therefore, staff finds that there are no barriers to achieving high light output (lumens) with a highly efficient bulb.

CHAPTER 8: Safety and Environmental Issues

Staff has evaluated the potential safety or negative environmental impacts of improving small-diameter directional lamp efficiency. The technical feasibility section acknowledges the use of more efficient LED, driver, and controller components. Use of efficient components means that the lamps will last longer than the incandescent and halogen counterparts, thereby reducing the amount of waste associated with the lamps. The standard would also save significant energy statewide.

The majority of the existing installed products are incandescent or halogen technologies. These products last about 4,000 hours.[80] The new, more efficient SDDLs will last 25,000 hours or more. This long life will result in fewer lamps being disposed as more long-lasting products are installed.

The proposed standards will also improve environmental quality in California. Saved energy translates to fewer power plants built and less pressure on the limited energy resources, land, and water use associated with it. Saved energy also relieves pressure on transmission infrastructure, thereby enhancing grid reliability. Implementation of the proposed regulations will result in an estimated reduction of 2,285 GWh per year in electricity consumption in 2029. In addition, lower electricity consumption results in reduced greenhouse gas and criteria pollutant emissions, primarily from lower generation in hydrocarbon-burning power plants, such as natural gas power plants.

Staff estimated that the concomitant reduction in power plant operation in California would reduce criteria air pollutants, including nitrous oxides (NO_x) between 820 and 6,558 tons, sulfur oxides (SO_x) between 66 and 116 tons from 2017 to 2029, and particulate matter of less than 2.5 microns (PM2.5) between 492 and 1,148 tons from 2017 to 2029. The proposed regulations are estimated to avoid 10.3 million metric tons of carbon dioxide (CO_2) between 2017 and 2029.[81] Reduction in emissions translates to improved health and safety to the people in the state. The proposed standards are estimated to avoid annual public health losses of between $3.3 million

80 Available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf. Page 4, Table 2.1.

81 Available at http://www.dof.ca.gov/research/economic_research_unit/SB617_regulation/Major_Regulations/documents/SRIA-CEC-LED-regs.pdf page 31. Staff assumed that energy efficiency reduces carbon emissions by 690 pounds of carbon dioxide per megawatt hour avoided.

and $22.2 million. Over a 10-year period, public health benefits are estimated to range between $33 million and $222 million.[82]

LED lamps do not contain any hazardous materials not already handled by existing laws. The Eurepean union Restriction of Hazardous Substances (ROHS) Directive requires manufacturer of LED lamps to comply with their products under category 5.[83] Manufacturers provide ROHs compliance declarations either on their website or on specifications sheets. For example, Cree lighting provides ROHS compliance information under product ecology.[84] GE provides ROHS information on specifications sheets.[85]

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82 Available at http://www.dof.ca.gov/research/economic_research_unit/SB617_regulation/Major_Regulations/documents/SRIA-CEC-LED-regs.pdf Page 32.

83 Available at http://www.rohsguide.com/rohs-categories.htm.

84 Available at http://www.cree.com/support/product-ecology.

85 Available at http://www.gelighting.com/LightingWeb/na/images/63557_GE_LED_PAR16_SellSheet_tcm201-20391.pdf.

PART B:
General Service Light-Emitting Diode (LED) Lamps

CHAPTER 9: LED Lamps Background

Product Description

General service omnidirectional, reflector, and decorative lamps are used to provide general illumination in buildings. These lamps produce white light and are designed to either emit light in every direction or have built-in reflectors to provide directional light. Primarily the light is generated using incandescent, fluorescent, or light-emitting diode (LED) technologies.

LED lamps are the most efficient general service lamps available in the market today, reaching efficacies as high as 130 lumens per watt.[86] This efficiency is far superior to incandescent lamps, which are around 14 lumens per watt. This shows the potential for a nearly tenfold improvement in efficiency. The screw-base market has been shifting and continues to shift from traditional incandescent lamps toward more efficient halogen-incandescent lamps, compact fluorescent lamps (CFLs), and LEDs. This has a large effect on residential electricity use in particular – lighting was estimated to consume 22 percent of residential electricity in 2009, according to the *2009 Residential Appliance Saturation Survey* (RASS).[87] Moving to high-efficiency LED lamps could cut that consumption to less than half. LED technology can also benefit businesses, which tend to reap faster payback than residential applications.

LED lamps are sold in a variety of shapes and sizes, just like the CFL and incandescent counterparts. The LEDs within the scope of this section of the report are limited to those that have a candelabra, intermediate, medium, or GU-24 base or that are meant to retrofit these sockets without removing the socket itself. LEDs can produce white light but also can produce colored light and even transition between the two. The regulations considered in this report are meant to cover LED lamps that produce white light, thereby focusing on general service lighting.

Existing Standards

There are several standards for LED lamps in the United States. These standards are under development and maintained by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency's ENERGY STAR program, and the U.S. Federal Trade Commission (FTC). There are also LED-specific regulations in the Energy Commission's regulations for portable luminaires. In addition, there is a voluntary LED performance specification created by the Energy Commission and recognized by the California Public Utilities Commission (CPUC).

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86 Nanoleaf model NL02-1600WN120E26 has an efficacy of 134 LPW in the Lighting Facts database.

87 KEMA, Inc. 2010. *2009 California Residential Appliance Saturation Study.* California Energy Commission. Publication Number: CEC-200-2010-004-ES.

The DOE has two rulemakings underway that will affect LED lamps, one for a new test procedure and one for mandatory performance standards. The test procedure is in the "supplemental notice of proposed rulemaking" phase, which was published July 9, 2015.[88] This test procedure will eventually preempt any energy efficiency measurement procedure for LED lamps adopted by the Energy Commission. In addition, the DOE is in the preliminary analysis stage of a "general service lamp" performance standard that would, as currently proposed, cover medium screw base LED omnidirectional lamps. The performance standards that would be finalized through this process would also eventually replace state-specific standards where the scopes overlap. The standards, however, are not likely to take effect until 2020, leaving a significant amount of energy and cost savings opportunity unrealized in the meantime. Lastly, the DOE has sponsored an LED certification and information website called "Lighting Facts®," which makes available the efficiency data for a large number of LED lamps.[89]

The ENERGY STAR program has specifications for lamps with a scope that includes medium screw base, candelabra, intermediate, and GU-based CFLs and LEDs. The most recent version of the specification is Version 1.1. The number of criteria that a LED lamp must meet to qualify with ENERGY STAR includes correlated color temperature (CCT), color maintenance, color rendering index (CRI), warranty, power factor, minimum operating temperature, LED operating frequency, electromagnetic and radio frequency interference, audible noise, transient protection, operating voltage, safety requirements, package language, equivalency claims, efficacy, minimum lumen output, lumen maintenance, and rapid-cycle stress testing. As of July 15, 2015, there were 5,634 LED lamp models certified in the ENERGY STAR qualified product database. The efficacy of qualified lamps ranges from 40 lumens per watt to 127 lumens per watt.

The ENERGY STAR program is revising its specification to Version 2.0 and is in the third draft.[90] The revision, in the current draft, will slightly increase the minimum efficacy levels for LED lamps and introduce a maximum connected standby power of 0.5 watts. In addition, ENERGY STAR is working to harmonize with the new standards, such as the DOE test procedure, and address color-tunable lamps.

The FTC has mandatory labeling for medium screw base general service lamps, requiring disclosure of lamp brightness, estimated annual energy cost, lamp life, color temperature, and power.[91] These are required to be provided on product packaging and available through online retailers.

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88 80 Fed. Reg. 39644, 39664 (July 9, 2015).

89 Lighting Facts is a program of the Department of Energy. http://www.lightingfacts.com/.

90 The ENERGY STAR Product Specification for Lamps Version 2.0 Draft 3 is available online at the ENERGY STAR website http://www.energystar.gov/sites/default/files/ENERGY%20STAR%20Lamps%20V2.0%20Draft%203%20Specification.pdf.

91 16 CFR Part 305 Section 305.15.

The Energy Commission also has existing standards and specifications for LED lamps. The Energy Commission has specified minimum performance levels for LEDs that are sold with portable luminaires (for example, table or floor lamps) that have been effective since 2010.[92] The Energy Commission also has existing minimum efficiency standards of 45 lumens per watt for general service lamps, as defined in the Energy Security and Independence Act of 2007 (EISA), effective January 1, 2018. The 45-lumen-per-watt standard will affect LED, CFL, and incandescent general service lamps, effectively moving the market toward more efficient LEDs and CFLs.[93]

In addition, the Commission released a voluntary performance specification for quality LEDs in December 2012.[94] This specification built upon the ENERGY STAR specification to further enhance quality. The specification has since become the fulcrum of residential LED lamp utility rebates in California.

Lessons Learned From the CFL Market

The history of competition between higher-efficiency CFL lamps and lower-efficiency incandescent lamps provide important lessons that are applicable to the LED marketplace. Efforts to drive consumers to CFL lighting have met significant resistance driven mainly by factors beyond first cost and operating costs. These factors include aesthetic quality of the illumination (such as harshness), humming, dimming issues, flicker, slow start, hazardous mercury contained in CFLs, and poor product performance.[95] In fact, despite very low CFL costs, market penetration appears stagnant.[96] The relatively stable line between incandescent/halogen and LED/CFL market penetration implies that the large amount of initial momentum in the LED market was from the replacement of CFLs, not incandescent lamps.

The resistance to moving from lower-efficiency lamps to higher-efficiency lamps is tied to incremental costs, real and perceived differences in utility, and familiarity. Trends in LED lamps, as was also true in CFL lamps, are that incremental costs are dropping over time, along with increased sales. Buyers' familiarity with CFLs and LEDs is improving through typical market adoption curves. However, in CFLs the early adopter curve was heavily frustrated by poor product

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92 The existing standards for portable luminaires can be found in the California Code of Regulations, Title 20, Division 2, Chapter 4, Article 4, Section 1605.3(n)(3).

93 The existing standards for general service lamps can be found in the California Code of Regulations, Title 20, Division 2, Chapter 4, Article 4, Section 1605.3(k)(2).

94 Flamm, Gary, Owen Howlett, Gabriel D. Taylor, 2012. *Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification.* California Energy Commission, High Performance Buildings and Standards Development Office. Publication Number: CEC-400-2012-016-SD.

95 *LED Lamp Quality Codes and Standards Enhancement (CASE) Initiative,* available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/PG_and_E_and_SDG_and_Es_Responses_to_the_Invitation_for_Standards_Proposals_for_LED_Quality_Lamps_2013-07-29_TN-71758.pdf, page 10-11.

96 "Halogen A-Line Lamp Shipments Continue to Rise During Fourth Quarter," *NEMA*, March 27, 2014, http://www.nema.org/News/Pages/Halogen-A-line-Lamp-Shipments-Continue-to-Rise-During-Fourth-Quarter.aspx.

performance. Product performance and utility have a large effect on the technology adoption curve.

To incorporate these lessons, the proposal includes considerations of product efficacy beyond simply the amount of light output. The color quality of the light, distribution pattern, and color temperature are incorporated. In addition several labeling cues are incorporated into the proposal to help ensure expectations of product performance better match actual performance. The improved market acceptance of LED lamps will cause energy savings as they replace less efficient forms of lighting.

CHAPTER 10: Analysis of LED Characteristics and Regulatory Potential

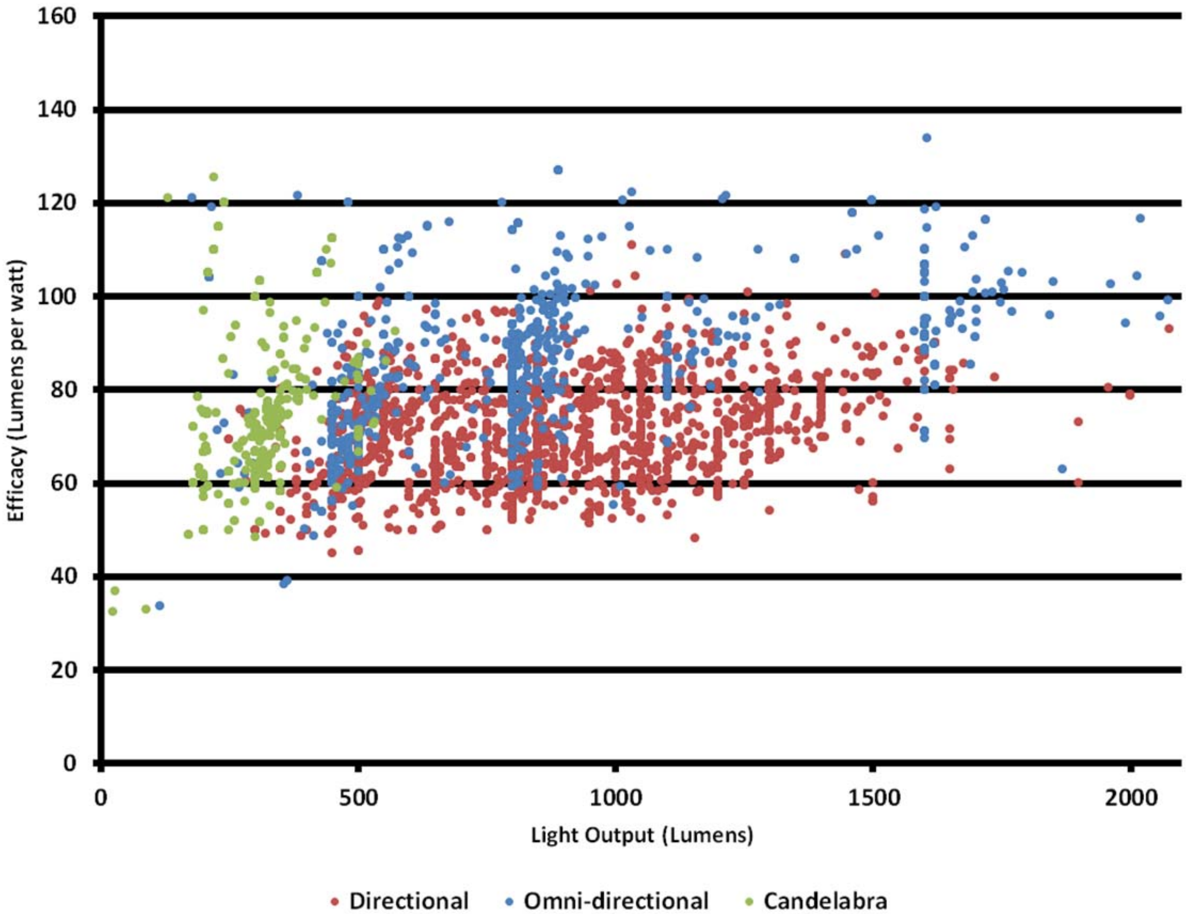
Lamp Efficiency

Efficiency is broadly defined as the amount of work output per work input. In the context of general service lamps, the amount of input work is easy to identify from the electrical power in watts. Traditionally when discussing the efficiency of general service lamps, the rating of lumens per watt is used. While this is a measure of the amount of light output for an amount of electrical input, it is not a raw measure of efficiency. Lumens are a function of the total light output weighted by the eye's sensitivity to each wavelength/color. For example, the human eye is more sensitive to yellow wavelengths than red wavelengths, so a lamp gets more lumen credit for producing yellow than red. The lumen per watt therefore is a measure of how much perceived light is emitted per watt, not the actual amount of physical light per watt. This is why lumens per watt is often referred to as *efficacy* and not efficiency.

The efficacy of a general service light is, however, even more complex than just the lumen-per-watt rating. The job of a general service light goes beyond simply filling an area with perceptible light; it must also provide color differentiation. Monochromatic light, for example, would not be sufficient for general service lighting in either residential or commercial spaces. A second metric is therefore necessary to determine the amount of "white light" produced per lumen. The ideal color content of "white light" is defined by correlated color temperatures and scored by the color rendering index. A lamp that increases lumens per watt but decreases CRI is therefore not necessarily more efficacious. Correspondingly, a lamp that decreases the lumens per watt but increases the CRI is not necessarily less efficacious.

Industry benchmarks are based on fixed lumen output bins. When looking at a fixed lumen output, increasing the lumens per watt will reduce the power draw of the lamp and therefore save energy. Improving lamp efficacy will lead to direct energy savings in LED-to-LED replacements as well as in LED replacements for other technology lamps. The efficacy of LED lamps in the current market varies widely. It is possible to purchase LED lamps that use almost double the power than that of other LED lamps while producing the same amount of lumens.

Figure 15: ENERGY STAR and Lighting Facts Lamp Data



Source: Energy Commission staff

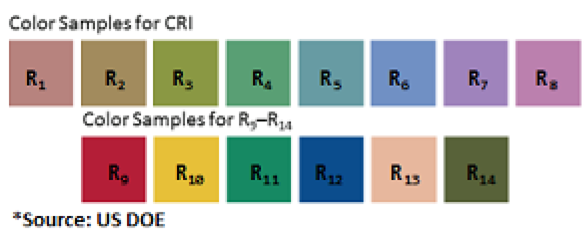
Figure 15 presents data made up of more than 5,500 Lighting Facts® and ENERGY STAR lamps certified in 2014 and 2015. Of these lamps, 1,627 models are available at more than 80 lumens per watt, and many lamps are available across lumen output and lamp type at more than 100 lumens per watt. Unlike trends seen in other lighting technologies, there is no strong trend between lumen output and efficacy. The one exception to this seems to be lamps above 1,500 lumen output, essentially 100-watt incandescent replacements. Lower efficacy lamps do not appear in this region likely due to a combination of thermal and space constraints.

While a snapshot of today's efficiencies is interesting, it is also important to understand the trajectory and potential efficacy of LED lamps over time. General service LED lamps have been on an upward efficiency trend. In fact, the average medium-screw base omnidirectional lamp efficacy in data analyzed for the draft staff report was 69.6 lumens per watt, whereas updated data from less than a year later show an average efficacy of 81.3 lumens per watt. These numbers closely match the IOU projections presented in their 2013 CASE study, which projects steady improvement in lumen-per-watt values across multiple LED lamp categories.[97] Other entities have similarly projected continued advances in lamp efficacy.[98] Interestingly, as also seen in the CASE study, the spread between lowest efficacy and highest efficacy is also increasing. This means that although the average efficacy across all models is improving, lamps with significantly lower efficacy remain in the market.

Color Rendering

The color rendering index (CRI) is the international standardized rating for color content and quality and has been since the 1970s. The CRI score, referred to as R_a, is the average of eight measured color distortions. A score of 100 indicates no distortion. The scale has no lower limit, and extreme color distortion yields negative scores. (Low-pressure sodium yields negative scores for example.) The scores are all made relative to a reference source, which in most cases is a black-body radiator like an incandescent bulb. The color samples are a set of eight pastels with reflectance spectrums that span the visible spectrum.

Figure 16: Color Samples Used to Determine CRI



A purpose of a general service lamp is to provide generic white light to a space. This illumination should generally be able to render the colors in a room accurately for the perception of the occupants. There are differing opinions regarding the exact level of accuracy needed; however, the CRI provides a score of that rendering and therefore how well a lamp is doing the job of "providing white light." The incumbent incandescent lamp in screw base sockets typically have a CRI of 100 or close to 100. LED lamps are available at a broad range of CRI.

As with CRI value R_a, individual color scores of 100 indicates no distortion. High CRI lamps have high individual color scores, minimizing the noticeable distortion of different colors. However, lower CRI lamps, even those at 80-85, may have low individual color scores, particularly with

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97 *Codes and Standards Enhancement (CASE) Initiative For PY 2013: Title 20 Standards Development Analysis of Standards Proposals for LED Replacement Lamp Quality,* PG&E and SDG&E, July 29, 2013, pages 38-40.

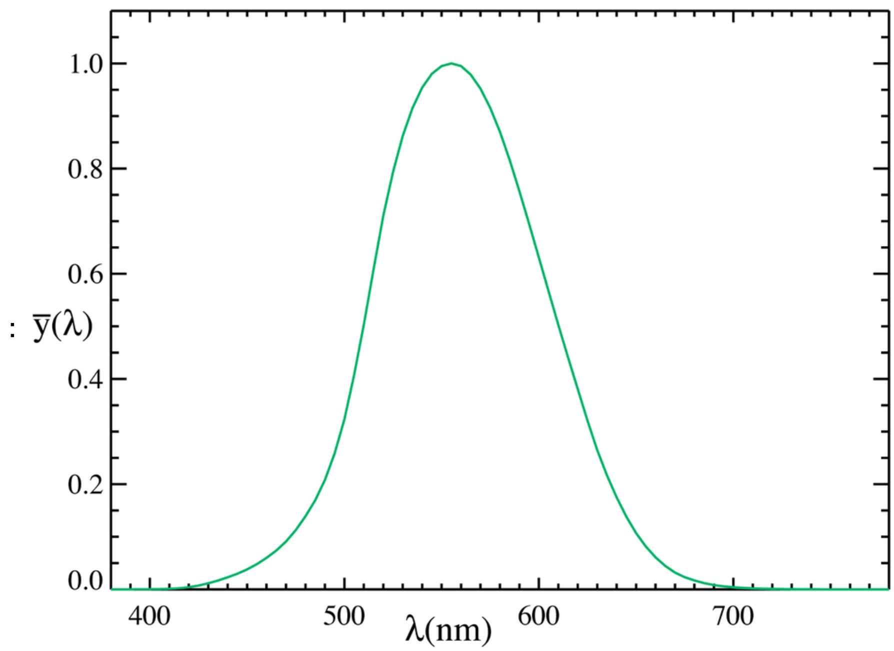
98 "CALiPER Snapshot 'Light Bulbs'," U.S. DOE, October 1, 2013, page 4, available online at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/snapshot2013_a-lamp.pdf; *Solid-State Lighting R&D Plan,* U.S. DOE, May 2015, page 49, available online at http://energy.gov/sites/prod/files/2015/06/f22/ssl_rd-plan_may2015_0.pdf; *Preliminary Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: General Service Lamps*, U.S. DOE, Page 3-55 available online at http://www.regulations.gov/contentStreamer?documentId=EERE-2013-BT-STD-0051-0022&disposition=attachment&contentType=pdf.

respect to showing red color content (R_8). Some specifications address this issue by requiring a minimum R_9 color score. However, this requirement doesn't address distortions of colors other than red.

Increasing color rendering index can have an effect on the amount of energy consumed by a lamp. The issue must be cautiously approached, however, because in one sense trading color rendering index for lower power consumption is more of a conservation effort than an efficiency effort. As discussed in the first section of this paper, the "work" performed by a general service lamp is to both illuminate a room and provide the ability to discern colors.

Because the lumen is not an unbiased measure of spectral power and is instead targeted to the sensitivities of the human eye, amber wavelengths (592 nm) get far more lumen credit than violet (425 nm for example) or red wavelengths (635 nm for example).

Figure 17: Luminous Flux Transform of Radiant Flux



Source: Wikipedia.99 The curve demonstrates the eye's sensitivity to various wavelengths of light, with higher y values representing greater sensitivity.

This inherently means that a lamp with a fuller color gamut and high color rendering cannot have as many lumens per watt as a monochromatic source at the peak of the curve. This speaks to the need to combine both the lumen and CRI to fully describe the work performed by a general service lamp.

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99 Wikipedia public domain graphic from its article on photopic vision, available at https://en.wikipedia.org/wiki/Photopic_vision

Correlated Color Temperature

The correlated color temperature (CCT) measures how "warm" or "cool" a light appears to be. CCT is based around lamps that create white light. CCT is used in the proposed regulation in two ways. First, it determines scope. (Colored lights are not within the scope.) Second, for products within the scope, CCT is used to ensure lamps are producing consistent white light and to improve brand to brand compatibility. Lamps with very high (beyond 7000K) and very low (less than 2000K) CCT are not in the scope of the proposed regulation.

Standby Mode Power

Most screw-base lamps operate in either an active state of providing light or an "off" state, where electrical power is not applied to the lamp. However, there are a growing number of LED lamps that are designed to be connected to power at all times so that they may be controlled via a network. These lamps, therefore, have a third mode of operation referred to as "standby mode" not found in other lamps. The network standby mode functionality contributes to the power consumption of the lamp nearly 24 hours per day as the lamp listens for commands both when the lamp is on and off. Because of this constant usage, even small amounts of power can contribute significantly to the annual energy consumption of a lamp.

A nonconnected LED lamp that uses 8.5 watts while on and 0 watts while off consumes 7.8 kWh per year if used 2.5 hours per day. If a network standby circuit were added that used an additional 1 watt all day long, this energy consumption would more than double to 16.5 kWh per year. This means that the majority of the energy use of a lamp would no longer be from producing light, but rather from waiting for network commands. However, if a more energy conserving network circuit were added that consumed 0.2 watts, the energy consumption would increase only to 9.5 kWh per year.

The International Energy Agency conducted research under their Electronic Devices and Networks Annex on smart-connected lamps and the current levels of standby mode power in 2014.[100] The models tested were all commercially available in the United States. The network standby mode power of lamps in the market varied from 0.17 watts up to 2.7 watts. In addition, the study measured further energy consumption in some devices where a gateway device was required for functionality.

The incremental cost to purchase a connected lamp versus a standard lamp is shrinking, with lamps already available for around $15 each.[101] The incremental costs for connectivity is dominated by increased operating costs, not purchase cost. With relatively low prices, a significant number of the more than 600 million screw base sockets in California could be occupied by connected lamps. If all screw-base sockets contained lamps with a network standby

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100 Results are available online at http://edna.iea-4e.org/files/otherfiles/0000/0100/Smart_Lights_Paper_for_EDNA_Website_v3.pdf.

101 Both GE and CREE products were available for $14.97 at Amazon.com and Homedepot.com as of September 25, 2015.

mode, statewide electricity consumption would increase by about 526 GWh per year per 0.1 watts of standby power. DOE, in its general service lamp preliminary technical support document, noted that "while such GSLs currently represent a very small fraction of the GSL market, the market share for GSLs that can operate in standby mode will increase" and in fact assumed that more than 30 percent of lamp shipments would have standby mode by 2020.[102]

Staff's proposed regulations include limits for standby mode because it makes up a significant percentage of the energy use of connected lamps today and because of the large potential statewide energy impacts with market saturation. This is consistent with the legislative mandate for appliance efficiency which states, "The minimum levels of operating efficiency shall be based on feasible and attainable efficiencies or feasible improved efficiencies that will reduce the energy or water consumption growth rates."[103]

102 *Preliminary Technical Support Document for General Service Lamps*, U.S. Department of Energy, December 1, 2014, page 2-28 . The shipment assumptions can be seen in the National Impacts Analysis spreadsheet that accompanies the Preliminary Technical Support Document on the "controls and smart lamp incursion" tab.

103 California Public Resources Code Section 25402(c)(1).

CHAPTER 11: Staff Proposal

Scope

Staff's proposed standards are designed to improve the efficiency of LED lamps and ensure that they produce a certain grade of white light. For the standards, staff proposes a scope of coverage that includes all LED lamps that produce light within 0.012 Duv of the black-body locus,[104] with a CCT of 2,000 through 7,000, and that have an E12, E17, E26, or GU-24 socket. In addition, the standards apply only to lamps with maximum brightness of 2,000 lumens or less.

Test Procedures

The primary test procedure for the proposed requirements is IES LM 79 (2008). This procedure gathers the necessary data to calculate CCT, CRI, and efficiency. Adopting LM 79 as the test procedure aligns with other Energy Commission lighting regulations, the voluntary specification, ENERGY STAR and the proposed DOE test procedure. To calculate the CCT and CRI, the Energy Commission proposes CIE 15.2004 and CIE 13.3 (1995), respectively, which are also referenced in IES LM 79.

The Commission also reviewed the most DOE's recent, July 9, 2015, supplemental notice of proposed rulemaking (SNOPR), which offers additional minor guidance and testing requirements relative to LM 79. To the extent possible, staff's proposal aligns with the SNOPR. The Commission expects that, consistent with the Federal Office of Information and Regulatory Affairs' schedule for a final rule in November 2015,[105] that the DOE rule will be finalized before the proposed regulations would become effective. Once the rule is finalized, the Energy Commission will revise the regulations to match the newly finalized federal test procedure.

The proposed regulations match the SNOPR test procedure by referencing the draft language. In addition, the proposed regulations rely on ENERGY STAR test procedures for audible noise and the Energy Commission's adopted 2016 Title 24 Building Energy Code, Joint Appendix 10 for flicker testing because the DOE test method does not include measurement of these metrics.

In addition, there are a series of test procedures included in the regulations for demonstrating performance with the optional California Quality LED Lamp Specification or Title 24 Building Energy Code, Joint Appendix 8, levels of performance.

104 The "black-body locus" refers to the radiation spectra of a body at different temperatures. This curve lies at the core of the standardization of white light.

105 The schedule for the DOE LED test procedure is available online at http://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201504&RIN=1904-AC67.

Mandatory Standards

Phased-In Timing

The proposed regulations would become effective at two dates to address two specific needs in the California market. The earlier set of standards, proposed to be effective January 1, 2017, will set the baseline of LED performance in preparation for the early implementation of EISA's minimum 45 lumens-per-watt standard in California in 2018. The Energy Commission expects a large increase in LED sales from consumers who are no longer able to find general service incandescent lamps as a result of the standard. To be effective at this purpose, the LED standard must be effective in advance of January 1, 2018, because compliance is based on manufacture date. This means that time for distribution and retailer stock turnover should be factored in. However, setting a near-term standard limits how aggressive the energy efficiency standard can be, potentially leaving important energy efficiency opportunities behind. Therefore, a separate longer-term standard is proposed to achieve the potential of higher-efficiency LEDs.

Minimum CRI and Efficacy

Staff proposes three aspects of lamps to be regulated on a mandatory basis: the efficiency, color rendering index, and color correlated temperature. The efficiency and CRI requirements will allow for tradeoffs between one another, and proposed implementation is in two tiers, with more stringent requirements in Tier 2. Each tier is composed of a minimum compliance equation and bounding conditions on how low efficiency and CRI can be.

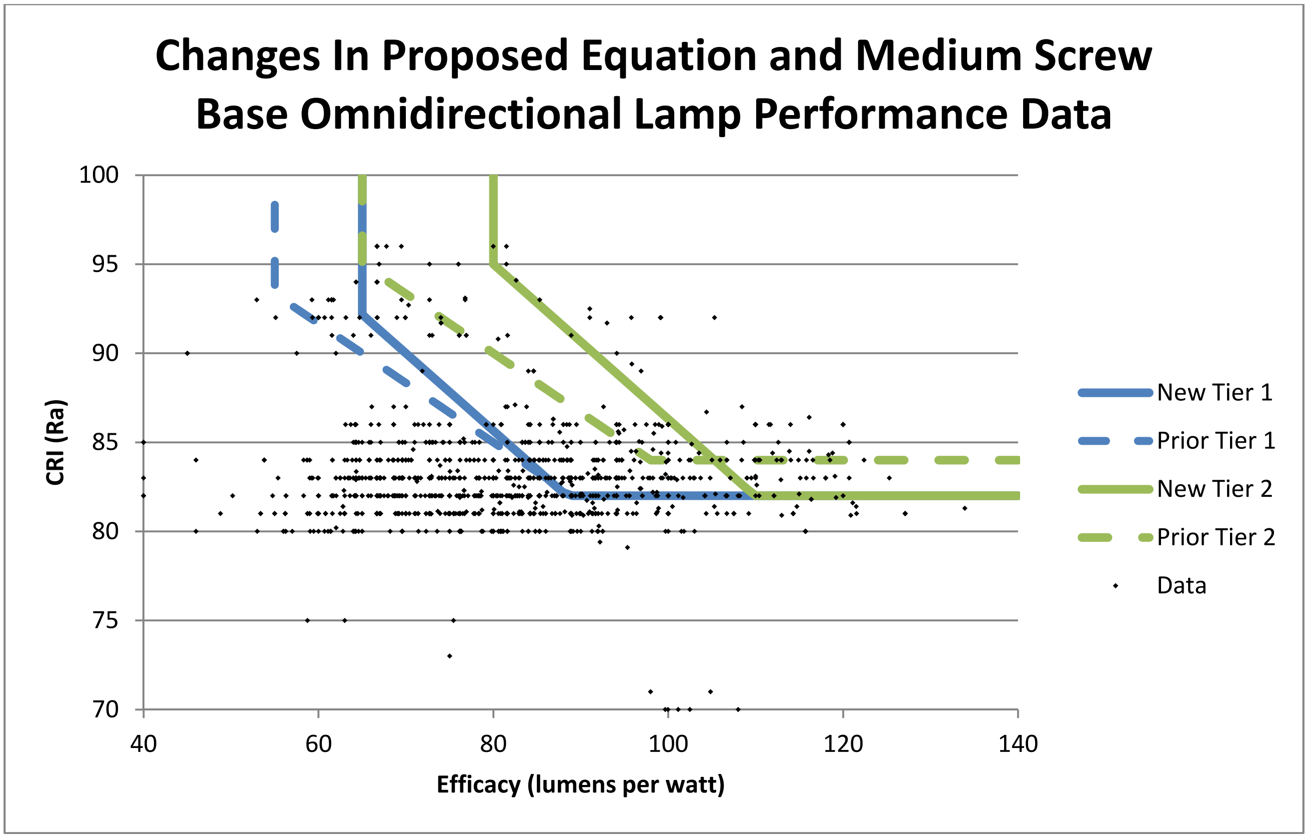
Tier 1 standard: $2.3 \times CRI + Efficiency \geq 277 \ and \ CRI \geq 82, Efficiency \geq 65 \ lpw$

Tier 2 standard: $2.3 \times CRI + Efficiency \geq 297 \ and \ CRI \geq 82, Efficiency \geq 80 \ lpw$

The first tier would be effective January 1, 2017, and the second tier would be effective January 1, 2019. The proposed formulas have been adjusted from those originally proposed in the draft staff report published on September 2014. The relative ratio of CRI to efficacy has been decreased from 3:1, down to 2.3:1. The original ratio is altered to better represent the observed efficacy differences between higher and lower CRI lamps.

Adjustments were also made to the "compliance score" portion of the equation. For Tier 1, the compliance score was adjusted such that the efficacy requirements for 82 CRI lamps remain unchanged. The Tier 2 standard was similarly adjusted; however, the overall efficiency requirement was adjusted to be around 6 lumens per watt more stringent. The adjustment to higher efficiency is to achieve additional energy savings apparent in new products in the market that appeared after the last draft proposal was released. The difference in the equations is expected to be met through improved efficacy, increasing the stringency of the standard by 20 lumens per watt after two years. Figure 18 below shows the standards proposed in this staff report compared to the originally proposed levels, with ENERGY STAR and Lighting Facts datasets.

Figure 18: Omnidirectional Lamp Changes in Tiers



Source: California Energy Commission. The source of the data points is ENERGY STAR and Lighting Facts.

Maximum Color Distortion

The proposed standards would require that lamps achieve a minimum score of 72 or greater for each of the eight color samples, R1 through R8, used to calculate CRI. In addition, lamps would have to have an average CRI (Ra) of 82 or greater. These requirements are proposed to be effective January 1, 2017.

Unlike the CRI metric R_a, which is the average score of R1 through R8, color scores have a direct correlation with noticeable changes in color content. The color scores are designed such that every 4.6 difference in score is roughly equivalent to the "just noticeable difference" of a human observer. The minimum level that would be established by the proposed regulation is therefore about 6 "delta error" or "just noticeable differences" from an ideal light source. These requirements are to reduce and limit color distortion.

Correlated Color Temperature

The correlated color temperature tolerance proposal is set using Duv rather than MacAdam steps for consistency with Title 24 specifications. In addition, the Energy Commission also changed the regulations to allow lamps to alternatively show compliance by using the ANSI white curve in substitute of the black-body locus. This primarily allows for variation at higher color temperatures where the value of adhering to the black body curve is less. This option is incorporated into the proposal in equation form by allowing Duv to vary on the positive side by 0.0033 plus the distance between the two curves. The 0.0033 levels are roughly equivalent to setting a four-MacAdam-step requirement. These requirements are proposed to be effective January 1, 2017.

Omnidirectional Light Distribution

In addition, staff proposes requirements for a subset of covered lamps that are traditionally expected to produce light in all directions (omnidirectional). The ENERGY STAR lamps specification and California Quality LED specification both incorporate light distribution requirements for omnidirectional lamps to avoid consumer dissatisfaction and, therefore, avoidance of efficient LED technologies due to poor light distribution. Warnings of potential negative consumer reactions to this feature have also been clearly incorporated into DOE's CALiPER application reports for replacement lamps. Staff proposes that omnidirectional lamps meet the light distribution specified in the ENERGY STAR lamp specification Version 1.1. This level of light distribution performance is also harmonized with the California Voluntary LED Specification. The proposal regulations differentiates the light distribution pattern by ANSI bulb shape, as done in Section 9.5 of the ENERGY STAR specification, meaning that an A-shape lamp has a different requirement than a C-shape lamp. The requirements do not limit manufacture of directional lamps in general but limit them for shapes traditionally considered omnidirectional, such as the classic A-shape. These requirements are proposed to be effective January 1, 2017.

For general omnidirectional lamps, the requirement is that "90% of the luminous intensity measured values (candelas) shall vary by no more than 25% from the average of all measured values. All measured values (candelas) shall vary by no more than 50% from the average of all measured values. No less than 5% of total flux (zonal lumens) shall be emitted in the 135° to 180° zone."

For decorative omnidirectional lamps the requirements are that "no less than 5% of total flux (lumens) shall be emitted in the 110° to 180° zone."

Product Life Requirements

The proposed standards would require lamps to meet or exceed a lumen maintenance rating of 10,000 hours. This requirement provides a level of certainty around the efficiency of the product over a length of time. Lumen depreciation often causes fewer lumens to be produced for a similar amount of wattage, thereby degrading the efficiency rating of lumen per watt over the life of the bulb. While this degradation is inevitable, design of LED heat dissipation and phosphor stability can provide efficiencies similar to the initial efficiency over long periods. This proposed level is consistent with the NEMA's proposed requirements from the Energy Commission's request for proposals.[106] These requirements are proposed to be effective January 1, 2017.

Connected Standby Requirements

The proposed standards would require lamps to meet maximum standby power requirements of 0.2 watts or less. This requirement saves energy by ensuring that lamps do not consume large amounts of energy while not in use or waiting for a signaled or command. These requirements are proposed to be effective January 1, 2019.

Power Factor

The proposed standards would require lamps to have a power factor of 0.7 or greater. Improved power factor reduces excessive current draw in building electrical distribution and energy wasted from associated resistive losses.

Labeling Standards

The proposed labeling standards do not affect all lamps offered for sale in California. However, if manufacturers want to make certain claims about the performance of an LED lamp, that performance must be tested and certified. The proposed regulations would require manufacturers to demonstrate performance before making claims about dimmability, incandescent equivalence, and meeting the Voluntary California Quality LED Lamp Specification. The proposed regulations also include the optional ability to demonstrate compliance with the requirements of the 2016 California Title 24 Building Energy Code, Joint Appendix 8 (JA-8).[107] Finally, lamps that produce very low lumen output must be labeled as "for decorative purposes."

To make claims of being "dimmable," lamps must pass a flicker test and must be dimmable to 10 percent. Further, they must not exceed a threshold of audible noise. Lamps may claim to be dimmable if the lamp can pass the test using a standard phase-cut dimmer. Alternatively, lamps may claim to be "dimmable with LED dimmer" if the lamp cannot be dimmed using a standard phase-cut dimmer but can be dimmed with another dimmer, such as one that complies with NEMA SSL7. Lamps that are "dimmable with LED dimmer" must include instructions with the lamp describing the compatible/recommended dimmers.

To make claims of being an "incandescent equivalent," lamps must have a color temperature of 3000K or less and must be dimmable. The proposed standards also contain minimum initial lamp output for claims of equivalence for various wattages of incandescent lamps, as shown in Table 13.

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106 "Proposal for Standards – LED Lamps," NEMA, July 29, 2013, page 7, available online at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/NEMAs_Proposal_for_Standards_-_LED_Lamps_2013-07-29_TN-71922.pdf.

107 The adopted Joint Appendix 8 is available online here: http://www.energy.ca.gov/title24/2016standards/rulemaking/documents/15-day_language/revised_express_terms/2016_Joint_Appendix_15-Day_Language.pdf .

Table 13: Incandescent Equivalences

Incandescent Equivalence	Lumen Minimum
Medium screw base and GU-24 Base Omnidirectional Lamps	
40 W	310
60 W	750
75 W	1050
100 W	1490
150 W	2500

Source: California Energy Commission, based on lumen bin values contained in EISA for general service incandescent lamps.

To make claims of meeting the Voluntary California Quality LED Lamp Specification, a lamp must be certified as such with the California Energy Commission. Finally, any lamp that provides fewer than 200 lumens for lamp bases other than a candelabra and 150 lumens for candelabra bases must be labeled as "for decorative purposes."

These requirements are proposed to be effective January 1, 2017.

California Building Code Screw-Base Lamps

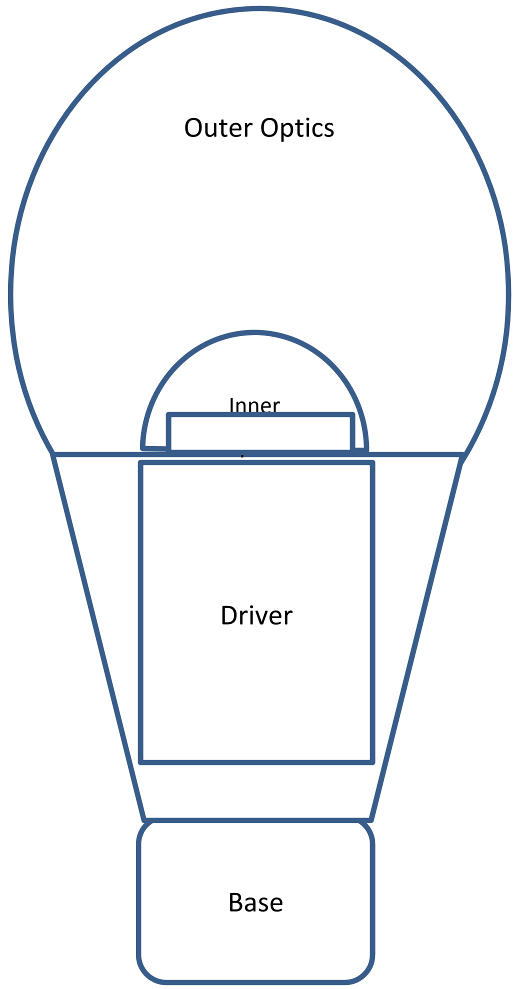
On June 10, 2015, the California Energy Commission adopted new regulations for new construction and alterations in California. One of the changes allows installation of screw-base sockets and fixtures to be considered "high-efficacy" if lamps are installed that meet the requirements contained in JA-8. Because the LED lamps in the scope of these proposed regulations are likely the same lamps to be used with this building code, the Energy Commission proposes to allow certification of compliance to this specification. The proposed regulations do not require compliance with JA-8. They merely provide a method to demonstrate compliance with JA-8 using the same certification process used to demonstrate minimum compliance levels.

CHAPTER 12: Technical Feasibility

CRI-Efficiency Tradeoff Equation

The proposed mandatory standards are feasible as there are already products in the marketplace today that comply with and meet both tiers of the proposed standards. The efficiency of a lamp is driven by three primary components: the lamp driver, the LED chip(s), and the optics. The location of these components can be seen in Figure 19 below.

Figure 19: Typical Layout of an LED lamp



Source: California Energy Commission

The efficiency can also be driven to some extent by the thermal management of the lamp, depending on how quickly the waste heat can be rejected from the lamp. The driver of an LED lamp converts AC power provided in the distribution and wiring system of a building to a voltage and waveform suitable for LED lamps. This conversion comes at an efficiency cost, but the amount can vary by how efficient the design and subcomponents are. The AC-DC power conversion efficiency of the driver is determined by the topology, or configuration, and parts incorporated. The DC voltage is then passed to the lamp controller, which adjusts the power to the LED package.

The efficiency of drivers can vary, and staff found performances at 85 percent,[108] 90 percent,[109] and 95 percent.[110] One strategy to improve the efficiency of a LED lamp would therefore be to improve the efficiency of the lamp driver from 85 percent to 95 percent. That level of driver efficiency improvement would increase the efficiency of a lamp from 55 LPW to 62 LPW. The driver has little, if any, effect on the CRI of an LED.

The LED package also plays a critical role, if not the most critical role, in the performance of the lamp. The LED package contains a series of LED devices that handle all of the conversion of electrical energy into photonic energy. LED devices are monochromatic, with the photonic energy released equal to the band gap caused by the junction of dissimilarly doped semiconductors. To achieve a white light, which includes a full spectrum of colors, an array of LEDs of many different colors must be used, or a secondary emission/conversion must be achieved through a series of phosphors.

In phosphor based LEDs, the monochromatic light selected is of short wavelength, in the deep blue, violet, or ultraviolet wavelength. The efficacy of the device is driven by the diode efficiency, the difference between the diode wavelength and the phosphor wavelength, and the phosphor characteristics.

The efficiency of an LED device itself can be very high, and devices have been demonstrated at performance levels above 200 LPW. The device efficiency can be improved through material science engineering, selection of semiconductor, selection of dopants, and by making the LED thinner. A large contribution to energy loss in the device is the recombination of photons before

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108 Marvell Single-Stage Flyback (A19) TRIAC-Dimmable LED Driver Evaluation Kit For Evaluation of the Marvell 88EM8183 LED Driver IC, available at

http://www.marvell.com/led-lighting/assets/Marvell_Flybackpercent20LED_Driverpercent20Eval_Kit-04_PB_v1.pdf.

109 Marvell 88EM8187 Shimmerless, Flicker-free, Deep Dimming Single-Stage AC/DC LED Driver IC for Replacement LED Lamps and Luminaires, available at http://www.marvell.com/led-lighting/assets/Marvell_88EM8187_IC-02_product_brief_final.pdf.

110 Marvell 88EM8803 Dual-string Intelligent PWM Dimming DC/DC Buck LED Driver Integrated I2C Interface for LED Lighting with Wireless Network, available at

http://www.marvell.com/led-lighting/assets/Marvell_88EM8803_IC-01_product_brief_final2.pdf;

See also Fairchild Single stage fly back boundary mode PFC controller for lighting, available at

http://www.fairchildsemi.com/ds/FL/FL7930C.pdf.

they are able to escape from the material, particularly in the junction area that is beneath the surface of the device.

The CRI is driven by the LED device and, if applicable, the phosphors. To improve CRI, the phosphor types and relative amounts of phosphors must be changed relative to a low-CRI lamp. For LED lamps that do not use phosphors, additional band-gap LED devices must be added to the LED chip to better fill the visible light spectrum. High-efficiency and high-CRI LED chips are commercially available today.

Generally, high-CRI LED devices will suffer from lower efficacy when adding violet, blue, and red spectral content. For warm color temperatures such as 2700 K, the ideal source has strong red color content. However, the red color content created from phosphors suffers from the largest stokes shift in LED lamps of any of the visible spectrum; therefore higher red content leads to lower efficacy. In addition, the longer wavelength red content from wide-band phosphors offers little lumen credit as the emissions of the phosphors bleed into infrared, again lowering efficacy. There are technologies that reduce the extent to which high CRI causes decreases in efficacy. The incorporation of a second set of red-emitting LEDs allows a lamp to avoid stokes shift losses, while the narrow emission band also avoids infrared spectrum. The use of narrow band red phosphors allows for high red content while minimizing production of longer wavelength red light that provides little lumen value. These losses, however, can never be fully avoided, particularly where gains in CRI require gains in gamut. Recognizing this, the Energy Commission has incorporated CRI in consideration with efficacy, allowing lamps closer to ideal color content to be less efficacious corresponding to these physical limitations.

Compliance with the proposed Tier 1 and Tier 2 efficacy-CRI equations is feasible and attainable as many commercially available products already comply. In examining active models in the lighting facts and ENERGY STAR databases as of June 15, 2015, there were 573 models of medium screw base omnidirectional lamps, 658 models of medium screw base directional lamps, and 85 models of candelabra-base omnidirectional lamps that meet the Tier 1 equation standards, including the 82 CRI minimum. There are several products that already meet the Tier 2 levels that are commercially available today, more than three years in advance of the standard, including 113 models of medium screw base omnidirectional lamps, 18 models of medium screw base directional lamps, and 42 models of candelabra-base omnidirectional lamps from the same dataset. The compliant models are available across a range of manufacturers and the full range of CRI levels. Compliance analysis is based upon reported and certified numbers that have been shown to be significantly below actual performance.[111] The actual number of models that meet the tradeoff equation are likely greater, making the estimates presented in this section conservative.

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111 *Omni-Directional LED Replacement Lamp Performance Testing Final Report,* California Lighting Technology Center, August 7, 2014, pages 57-58 available online at: http://cltc.ucdavis.edu/sites/default/files/files/publication/140609-report-omni-directional-led-replacement-lamps_rev140807.pdf.

Minimum Color Scores

The proposed regulations would require each of the color scores, R_1 through R_8, that are generated during the CRI test procedure to meet a minimum score of 72. This is because, as discussed above, color scores directly correlate with noticeable changes in how the user perceives color. The vast majority of lamps covered under the proposed color score regulation are used in residential buildings. Several residential room types demand color accuracy, including the kitchen and bathroom, where grooming and food preparation/consumption occur.[112]

LED technology today is capable of producing general purpose lighting that well exceeds the minimum scores proposed. Lamps that would not comply with the proposed regulation generally meet a minimum of 72 for each color sample except for R_8. These lamps are generally blue LEDs with white phosphor. One lamp scoring more than 81 average CRI has color scores as low as 55[113], which amounts to 12 "delta errors" versus the 6 allowed by the proposal. Unfortunately, neither the minimum CRI level of 82 nor the industry proposed levels of 80 can resolve this error. Instead, color scores must be held to a standard or much higher CRI levels must be set to achieve the error correction.

The Energy Commission proposes to set minimum color scores rather than a higher overall CRI to allow greater flexibility in LED design. This is technically feasible as demonstrated from the simple fact that it is possible to reach CRIs below 90 and comply with the 72 color score metric across all the common LED technologies today. Lamps that do not comply will most commonly need to add red to the associated spectral power distribution. This will require red phosphors or red LEDs to achieve.

Omnidirectional Light Distribution

LED packages are inherently directional, producing a direct beam of light dictated by the shape of the package and immediate primary optics. There are thousands of lamp models certified to the ENERGY STAR program that meet the omnidirectional light distribution requirements proposed in the regulations. These lamps are able to achieve high efficiencies as well as omnidirectionality.

Manufacturers have met the design challenge of omnidirectionality in a variety of ways. Some of these approaches have minimal impacts on light output, others do not. The use of multiple LED packages means that these packages can be arranged to face different directions and thereby fulfill a broader light distribution pattern. Other lamps use secondary optics to redirect the directional light from the LED packages toward areas that would not otherwise be lit. Some lamps use a combination of LED position and optics. Lastly, some lamps use bidirectional LED strips

112 *The IESNA Lighting Handbook, Reference & Application*, Ninth Edition, Illuminating Engineering Society of North America, copyright 2000, pages 18-6 et seq.

113 *Omni-Directional LED Replacement Lamp Performance Testing Final Report,* California Lighting Technology Center, August 7, 2014, see photometry data for product E.

surrounded in phosphor to emulate a "filament" that produces light in multiple directions, and then angle multiple filaments to achieve omnidirectional light distributions.

Lamp designs that are not likely to meet the omnidirectional requirements consist of a printed circuit board (PCB) with a single plane of LED packages. Without modification, this design is semidirectional or directional and not omnidirectional. The design, popularly referred to as a "snow-cone," is still readily found on store shelves, and these are the products that most likely will need alteration to comply with this requirement.

The technical feasibility of the proposed light distribution requirements is evident by the fact that thousands of models are certified as meeting this requirement under the ENERGY STAR program. Although the ENERGY STAR-certified list does not represent the entire market, it does represent the majority of LEDs sold in the United States.[114]

Standby Mode Power

The standby mode requirement that a connected lamp use 0.2 watts or less is feasible as there are products for sale today that would comply. While products on the market today have a wide variety of functionality and use different communication protocols, most spend the majority of the time waiting for commands in standby mode. The most common communication protocols found in medium screw-base lamps are ZigBee, Bluetooth, and Wi-Fi. Fortunately, wireless communication protocols have already been developed for low power consumption in standby mode, mostly by the mobile and battery-constrained consumer electronics industry. In addition, low-power mesh networking and standby mode power are key characteristics of the "internet of things" ecosystem where sensors may not have access to AC power.

Achieving lower standby mode power is a matter of both hardware and firmware design. Power consumption by wireless network hardware is related to the bit-rate as well as intended range. The communication in standby mode requires only very small amounts of information to be passed and, therefore, only a low average bitrate and, therefore, bandwidth. Staff found implementations in the market claiming as low as 0.1 watt[115] and measured as low as 0.17 watt[116]. In addition, staff found feasibility white papers discussing connected standby power levels as low as 0.05 watt.[117] The proposed standard levels are consistent with technologies available today and

114 "ENERGY STAR® Unit Shipment and Market Penetration Report Calendar Year 2014 Summary," US EPA, page 6, available online at https://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2014_USD_Summary_Report.pdf?11da-2e48

115 Energy Commission staff research of manufacturers' claims of standby power for their connected lamps.

116 *Smart Lamp Testing – Initial Results,* Electronic Devices and Networks Annex, November 2014.

117 *Make Internet-Enabled, Energy-Efficient Lighting Networks a Reality,* NXP Semiconductors, May 2011, available online at http://www.nxp.com/documents/brochure/75017123.pdf.

as discussed in *FINAL REPORT: Power Requirements for Functions,* a level of 0.2 watt is feasible and attainable.[118]

While the hardware that enables this technology is generic and generally third party, the software and function set of current connected lamps are specific to each manufacturer. Therefore, the requirement is set to a longer timeline to allow manufacturers to develop specific solutions for their connected products. The proposed regulations for standby mode power are proposed to come into effect January 1, 2019, roughly three years after potential adoption.

Power Factor

The power factor levels proposed of 0.7 are readily achievable, and the majority of LED lamps that would be covered by the regulations already comply. In fact, because it is also a minimum level required for LEDs by the ENERGY STAR program for lamps, every LED in the qualified product list database meets this level. In 2014, this made up 75 percent of shipments in the United States. The average power factor for non-ENERGY STAR lamps, as certified in the Lighting Facts database, is over 0.8. There were some Lighting Facts models that had a power factor between 0.5 and 0.6. These products would need to improve the LED drivers to include power factor correction or switch to widely available drivers already on the market that provide such functionality.

Product Lifetime

The proposal for a minimum product lifetime of 10,000 hours is technically feasible. In fact, staff could not find an LED lamp for sale and that would fit the scope of the proposed regulation that does not meet the level including within ENERGY STAR and Lighting Facts databases.

Correlated Color Temperature

The proposed tolerance levels for correlated color temperature are feasible, demonstrated clearly by the fact that current products meet the requirement. There are two primary reasons why a lamp would not comply with the proposed standard. The first is too strong of a colored tint (usually greenish or pinkish) from the established locus. For these lamps, the phosphor mix must be slightly adjusted to remove the tint. The second reason is large variance from loose manufacturing controls or internal lamp controls. The control over manufacturing variance is expected to improve over time, and as pointed out in the IOU CASE report. Many major manufacturers such as Cree and Philips are already making lamps to this tolerance.[119] While the

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118 *Final Report: Power Requirements for Functions,* Xergy Consulting, September 8, 2013, pages 20-24, available online at http://standby.iea-4e.org/files/otherfiles/0000/0103/PFF_Final_Report_FINAL_v2_Xergy_17Sep2013.pdf#sthash.Vu0Lo7Gl.dpuf.

119 *LED Lamp Quality Codes and Standards Enhancement (CASE) Initiative: Analysis of Standards Proposals for LED Replacement Lamp Quality*, PG&E and SDG&E, July 29, 2013, Page 31 available online at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/PG_and_E_and_SDG_and_Es_Responses_to_the_Invitation_for_Standards_Proposals_for_LED_Quality_Lamps_2013-07-29_TN-71758.pdf.

Duv is not commonly reported by manufacturers; the Lighting Facts database did contain Duv data for 186 medium screw-base omnidirectional LED lamps, of which 162 fell within a tolerance of plus or minus 0.0033 Duv.[120]

120 Note analysis was conducted on Lighting Facts data collected June 15, 2015.

CHAPTER 13: Savings and Cost Analysis

Stock and Sales

The total stock of general service and reflector lamps in California was about 622 million sockets in 2010.[121] At that time, LED lamps made up less than 1 percent of the total stock of general service lamp sockets, but this value is predicted to increase over the next 10 years as manufacturing processes and technology continue to improve and as less efficient lamps are displaced due to existing federal and state regulations. The majority of current lamp stock consists of incandescent/halogen lamps or CFLs.

Incremental Cost

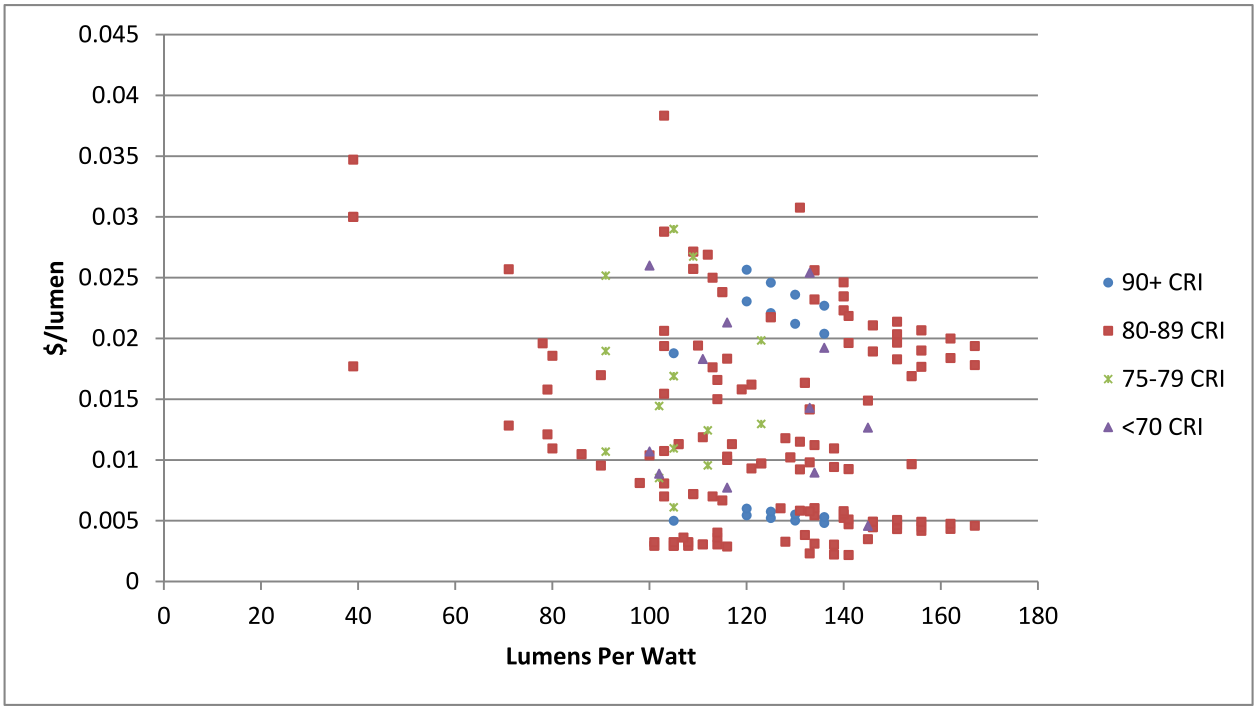
There is little to no correlation between efficacy and the retail cost of a lamp; for example, staff found a 50-lumens-per-watt, a 63–-lumens-per-watt, a 72-lumens-per-watt, and an 80-lumens-per-watt lamp each selling for about $23.00. This lack of correlation in retail prices versus efficiency is further supported by market research conducted by DOE that shows poor correlation among efficacy, quality, and price, as well as overall downward trends in the cost of these attributes.[122] Furthermore, staff has collected LED chip data from DIGIKEY, a major distributor of electronic devices with more than 15,000 white LED chip offerings.[123] The DIGIKEY data are plotted in Figure 20. This figure shows no relationship between cost and efficacy. This same relationship seems to hold for cost versus CRI as well.

121 Analysis of US DOE's *2010 U.S. Lighting Market Characterization* study Table 4.1 using a population scaling factor of 12 percent across appropriate incandescent, halogen, and CFL categories. This figure does not include linear fluorescent general service lamps, as those are outside the scope of the proposed regulation available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf.

122 U.S. DOE, *CALiPER Retail Study 3*, February 2014, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_retail-lamps-study3.pdf.

123 These offerings can be found online at http://www.digikey.com/product-search/en/optoelectronics/led-lighting-white/ .

Figure 20: Efficacy vs. Cost of Light



Source: California Energy Commission. Only products that had quantities available of 5,000 units or greater are plotted.

As newer LED chips and efficient drivers come into the market, the price continues to decrease even further. This trend is well characterized by the DOE,[124] as well as analysis contained in the California IOUs CASE study.[125] All this information suggests that the incremental cost for improved efficacy to reach compliance with the proposed regulations is very small relative to the life-cycle savings. In addition, the trend toward lower cost and simultaneously higher efficiency over time has been strong and projected to continue at a fixed CRI as seen in Figure 21.

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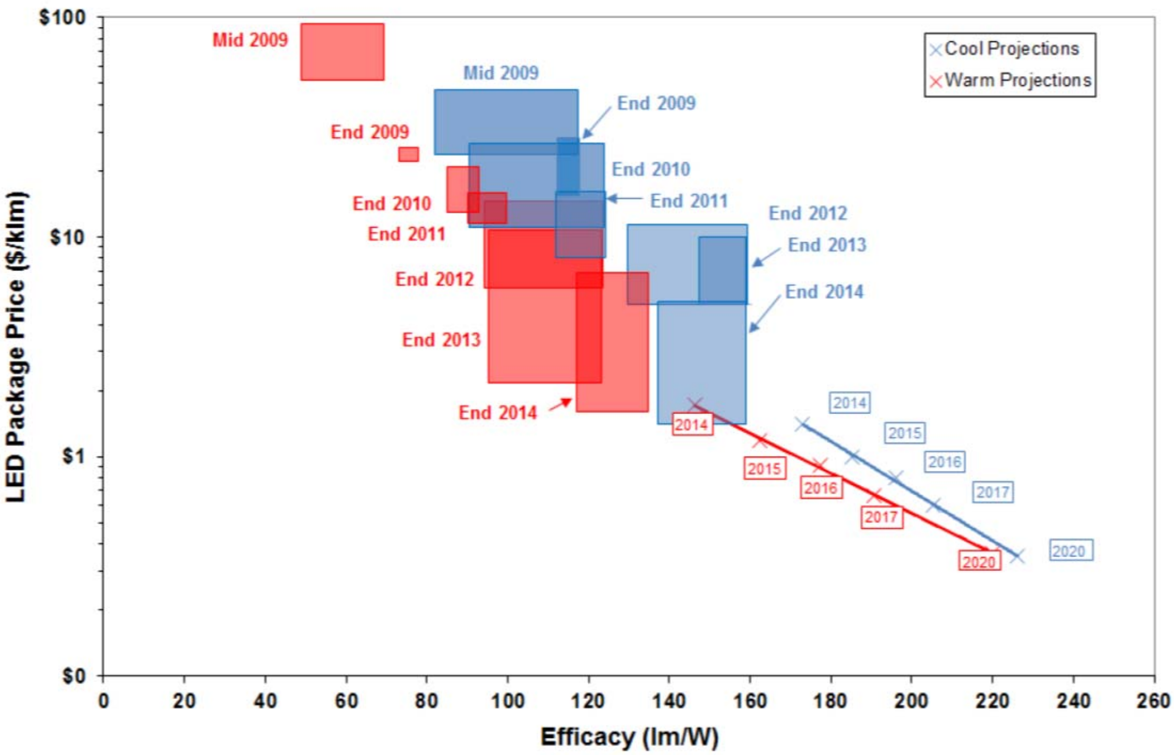
124 U.S. DOE, *Manufacturing Roadmap Solid-State Lighting Research and Development*, August 2014, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

125 California IOUs, *Codes and Standards Enhancement Initiative for LED Lamp Quality*, July 29, 2013, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/PG_and_E_and_SDG_and_Es_Responses_to_the_Invitation_for_Standards_Proposals_for_LED_Quality_Lamps_2013-07-29_TN-71758.pdf.

Figure 21: Price-Efficacy Trade-Off for LED Packages at 1 W/mm^2 (equiv. 35 A/cm^2) and 25^{oC}



Source: *Solid-State Lighting R&D Plan*, DOE, May 2015, Figure 5.17 Page 79. Cool-white packages assume CCT=5700K and CRI=70; warm-white packages assume CCT=3000K and CR=80. Rectangles represent region mapped by maximum efficacy and lowest price for each period.

Staff found several estimates relating to the potential incremental cost of a standard. The California IOUs submitted incremental costs to improve the CRI of general service LED lamps to 90 at $1.84 per unit.[126] While the IOU proposal differs from staff's proposal, improvement in CRI also provides a pathway to compliance because of the nature of the tradeoff equation. Staff expects that improving the efficacy will be less expensive than improving the CRI of LED lamps because of existing strong trends of improved efficacy in the industry, and because improvements in efficacy have counterbalancing cost savings in thermal dissipation components such as heat sinks and LED drivers.

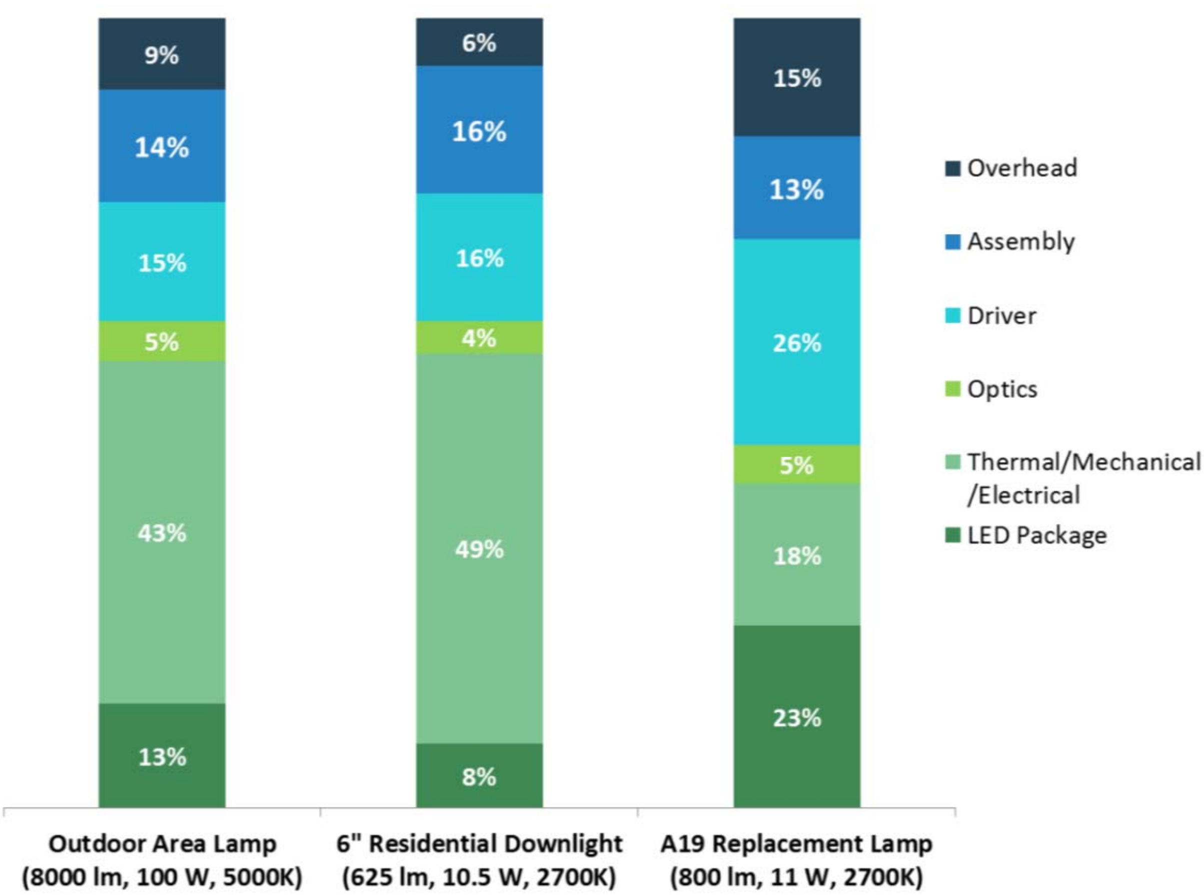
The constantly changing price of LED lamps leads to the need to talk about costs in a temporal context. The incremental cost in 2017 will be different in 2019 and so on as the manufacturing techniques of LED bulbs mature and develop. A clear historical example of this is the price of California Quality LED Specification-compliant lamps. Initially the price of these "quality" lamps

126 California IOUs, *Codes and Standards Enhancement Initiative for LED Lamp Quality*, July 29, 2013, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/PG_and_E_and_SDG_and_Es_Responses_to_the_Invitation_for_Standards_Proposals_for_LED_Quality_Lamps_2013-07-29_TN-71758.pdf

were significantly higher than the price of other ENERGY STAR lamps. Now the compliant lamps have reached comparable prices.

The DOE maintains a research and development plan that summarizes the state of current technologies and associated cost and predicts future developments and changes in LED pricing.[127] Figure 22 shows the cost breakdown of lamps in 2014, and Figure 23 shows changes in absolute and relative cost over the next five years.

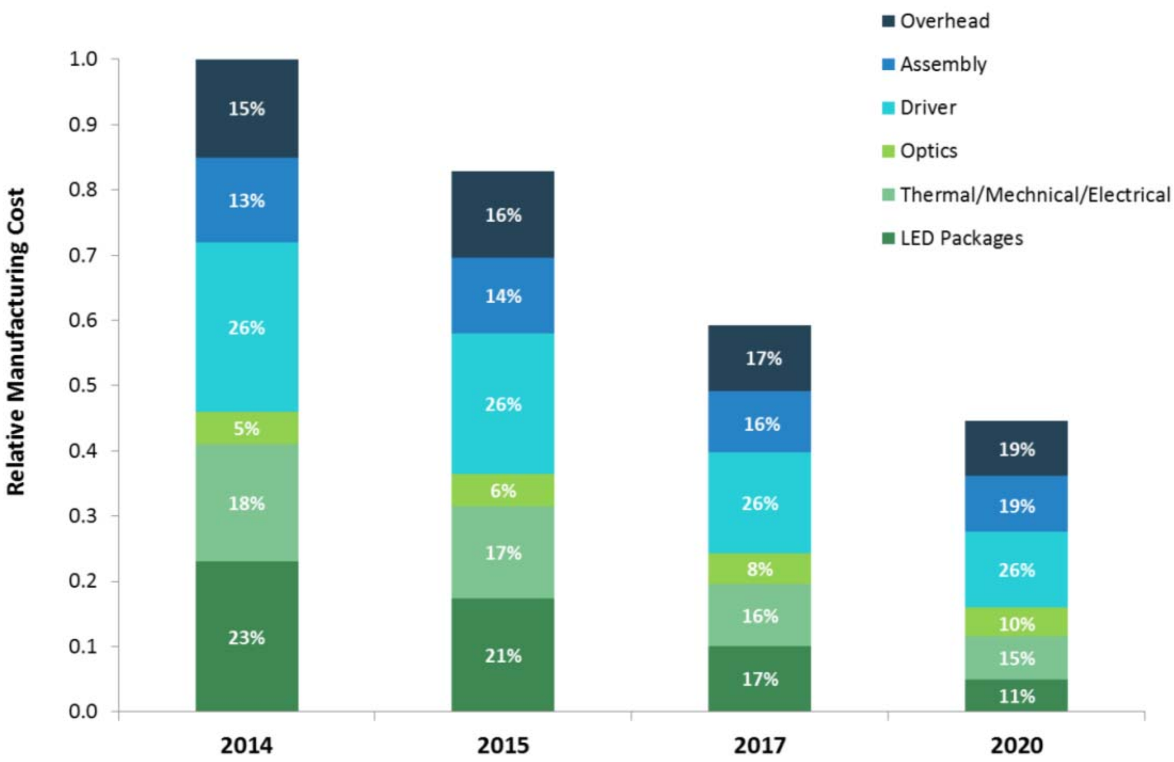
Figure 22: Comparison of Cost Breakdown for Different Lighting Applications



Source: *Solid-State Lighting R&D Plan*, DOE, May 2015, Figure 5.11 Page 70. Developed from DOE SSL Roundtable and Workshop attendees and industrial partners.

127 *Solid-State Lighting R&D Plan*, DOE, May 2015, available online at http://energy.gov/sites/prod/files/2015/06/f22/ssl_rd-plan_may2015_0.pdf.

Figure 23: Cost Breakdown Projection for a Typical A19 Replacement Lamp



Source: *Solid-State Lighting R&D Plan*, DOE, May 2015, Figure 5.12 Page 71. Developed from DOE SSL Roundtable and Workshop attendees.

Table 14 summarizes the estimated incremental cost by component type in a manner consistent with the DOE R&D cost breakdown.

Table 14: Cost Impact of Proposed Regulation

Requirement	Lamp Component Affected	Cost Impact
Efficacy/CRI tradeoff	LED packages/chips	Minimal, general trend toward both lower cost and higher efficacy. Costs incurred are from accelerating the trend.
Minimum 72 R1 through R8	LED packages/chips	Addition of red phosphor, narrow band red phosphor, or red LED. Affects cost for lower CRI LEDs.
CCT	LED packages/chips	In most LED lamps CCT and CCT variance are almost entirely determined by the LED packages. Current production lines are marketed at different MacAdam step or Duv tolerances. Small incremental cost will be incurred for manufacturers

		transferring from large tolerances to small tolerances.
Light Distribution	Optics, Thermal/Mechanical/Electrical, Assembly	Improved geometry of package layout, better optics. Minority of market does not meet this specification. Snow cones product lines would need revision or be altered to directional lamp shapes.
Product Life	LED packages/chips, Thermal/Mechanical/Electrical	None, all lamps on the market already meet this level.
Standby Power	Driver	Improved communications chips and firmware could increase costs; 3-year timeline to comply will minimize these costs.
Power Factor	Driver	Most drivers already hit this target. No expected incremental cost over standard drivers available.
Labeling	Overhead	Incremental costs for performance verification for existing products. Performance testing and verification are generally already part of design processes, so little cost is expected for future products.

Source: California Energy Commission

The exact cost of revising a noncompliant lamp design depends on what aspect does not comply. To a large extent, the feasible incremental cost to consumers will be limited by the cost of lamps that already comply with the proposed regulations as lamps with significantly higher prices would compete poorly in the market. Consumers are most likely to see incremental cost incurred in the LED package portion of the lamp to achieve better color rendering, and the driver in connected lamps.

The LED package is estimated to make up 17 percent of a typical A19 LED lamp in 2017 as seen in Figure 23. If a benchmark consumer purchase price of $5 is applied, this equates to the LED package contributing roughly $0.85 to that cost. Phosphors make up roughly 18 percent[128] of the cost of an LED package, translating to about $0.15. In the extreme case that phosphor costs double in designing to the CRI standards or to improve efficacy, this would lead to a retail incremental cost of $0.15.

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128 *Solid-State Lighting R&D Plan*, DOE, May 2015, Figure 5.9, page 67.

An alternative approach would be to add a red LED. Not only does this approach require two types of LED emitters rather than one, but it also requires a color mixing control system to ensure proper output across a range of lamp temperatures. This could lead to an incremental lamp cost of $1.04[129] and improve CRI and efficacy in a standard lamp. This incremental approach would likely lead to additional features such as tunable colors and a CRI in excess of 90.

Staff estimated the incremental cost to be $0.50 for medium screw-base omnidirectional lamps in consideration of these two approaches and continued downward prices for LED lamps and packages. In researching the LED lamp market, the best technologies and lowest prices seem to occur in medium screw base omnidirectional lamps, indicating an industry focus on A19 lamp replacements. These lamps constitute a significantly larger demand than candelabra base lamps or medium screw base directional LEDs combined. These lamps are more expensive per kilo-lumen output. The incremental costs were adjusted to these higher base costs, yielding an incremental cost of $1.50 for medium screw base reflector lamps and $1.00 for candelabra lamps.

The standby power improvements for connected standby come at little, if any, incremental cost. The network connectivity is provided by a system on a chip (SoC) that is integrated into the LED driver. Every smart bulb requires such a chip, and therefore energy savings are achieved either by swapping a less efficient chip with a more efficient chip, or by reprogramming and enhancing the implementation of a currently used chip. The firmware, or software, used in the SoCs is configurable. In some cases, they are reconfigurable even after manufacture due to the network connectivity, which allows them to be "updated."

The most efficient chip that staff could identify is a solution provided by NXP in its JN5169 ZigBee SoC. This device costs nearly $2.00 at quantity. One of the least expensive connected lamps on the market today is GE's, which uses Marvell's ZigBee 88MZ100 SoC. While pricing could not be obtained for the 88MZ100, it is expected to be comparable with the NXP chip and certainly not more than $1.00. The incremental cost is therefore $1.00 or less for chip-to-chip replacement. Power consumption statistics for the 88MZ100 were difficult to find, but it claims to be below 500 milliwatts. At a power reduction of 0.3 watts then, the discounted[130] savings are worth $3.68 in the first 10 years, providing payback to the consumer.

Cost-Effectiveness

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129 Using a $5 benchmark consumer cost for an LED lamp, the cost of LED packages was doubled to account for the addition of red LED packages. This incremental cost is equal to $5 x 0.17 or $0.85. Phosphor cost was removed as red LEDs do not need phosphors, giving an incremental cost of $0.85 x (1-0.18) or $0.70. The driver cost was increased by 20 percent to account for the control complexity of driving multiple LED types, adding an additional $0.26 to cost. Further, another 10 percent cost was added to thermal/mechanical/electrical to account for more complex LED layout, adding $0.08 for a total incremental cost of $1.04.

130 Using a 3 percent discount rate.

The proposed standards are cost-effective, as the energy savings greatly outweigh both the incremental cost of improvements and the price of compliant product with payback within one to three-and-a-half years, depending on lamp type. The year-by-year breakdown of unit costs and savings is shown in Appendix B. Table 14 summarizes the unit costs, benefits, and cost-benefit ratio of improved efficiency in general service, directional, and decorative LED lamps.

Table 15: Energy Savings Summary

Lamp Type	Incremental Cost per Unit	Lifetime Savings per Unit[131]	Cost-to-Benefit Ratio	Payback Period (years)
Omni-directional	$0.50	$7.80	15.6	1
Directional	$1.50	$11.57	7.7	2
Candelabra	$1.00	$4.47	4.5	3.5

Source: California Energy Commission, specifically calculations contained in Appendix B

The lifetime savings per unit is significantly higher than the estimated incremental cost, indicating that much higher incremental costs would still yield cost-effective results. While the lifetime savings were calculated over a 20-year period, the payback occurs significantly faster, giving an overall positive return on investment.

Table 15 presents the cost-effectiveness of the proposed standby mode regulation across a variety of baseline consumptions. In all cases, the proposed standby mode standard is cost-effective even against the high-range estimate of a $1.00 incremental cost.

131 Lifetime savings were calculated using a 3 percent annual discount to the value of bill savings at an electricity rate of $0.17 per kWh, the rounded forecast average residential electricity rate for 2017 and 2019.

Table 16: Energy Savings Summary

	Energy Savings Compared to 1 Watt Standby[132]	First 10 Years $ Savings Compared to 1 Watt[133] Standby	Energy Savings Compared to 0.5 Watt Standby	First 10 Years $ Savings Compared to 0.5 Watt Standby	Energy Savings Compared to 0.3 Watt Standby	First 10 Years $ Savings Compared to 0.3 Watt Standby
0.2 Watt Standby Lamp	7 kWh/yr	$10.42	2.6 kWh/yr	$3.87	0.9 kWh/yr	$1.34

Source: California Energy Commission

Energy Savings

Staff calculated energy savings by adjusting products that do not comply with the proposed standard to a point where they would just barely meet the standard. This forms a conservative estimate of the savings from improvements because, in reality, those products would most likely improve to a point beyond compliance. The savings numbers presented (with the exception of the 12,000 GWh/yr figure) account only for incremental savings between noncompliant LEDs and compliant LEDs and do not account for savings that would occur from LED replacement of CFL or incandescent lamps. For detailed information about assumptions and calculations used to determine energy savings, see Appendix B of this report.

Table 17 contains the expected first-year energy savings, as well as the energy savings that would occur in 2029. The energy savings estimates are lower than in the draft staff report, despite an increase in stringency, because the assumptions of baseline efficacy were significantly increased in line with improvements observed in the market. For example, the average medium screw base omnidirectional LED was estimated to have an efficacy of 65 lumens per watt, whereas the average of more recent LED data shows efficacy of about 80 lumens per watt. Similar gains were observed for reflector and candelabra market segments.

132 Calculated under the assumption that the lamp is always in standby mode, or 8,760 hours of operation. The network portion of the lamp would likely also be in active mode at various points, but the effect of this consumption would be negligible in a power-managed connected lamp.

133 Ten-year savings were calculated using a 3 percent annual discount to the value of bill savings at an electricity rate of $0.17 per kWh, the rounded forecast average residential electricity rate for 2017 and 2019.

Table 17: Statewide Energy Savings Summary

Scenario	Statewide Energy Savings (GWh/yr)	Statewide Utility Bill Savings[134] (million)
First Year of Tier 1	28	$4.8
First Year of Tier 2*	185	$31.5
Projected Savings 2029**	859	$146.0
Projected Savings 2029 Relative to Today's Usage***	12,000	$2,040.0

Source: California Energy Commission, more details about the calculations are available in Appendix B.

*This is the incremental savings for 2019 shipments and does not include savings from previously regulated shipments

** Calculated using stock and shipment scenarios shown in Appendix B.

*** Total effect of migration from current stock of LED, CFL, halogen, and incandescent lamps

134 These savings were calculated using an electricity rate of $0.17 per kWh, the rounded forecast average residential electricity rate for 2017 and 2019.

CHAPTER 14: Safety and Environmental Issues

Staff did not identify negative safety or environmental impacts from improving general service LED lamp efficiency. While the technical feasibility section acknowledges the use of different, more efficient components, and perhaps some additional control circuitry, those improvements would not create a particular waste hazard.

The proposed standards will, however, lead to improved environmental quality in California. Saved energy translates to fewer power plants built and less pressure on the limited energy resources, land, and water use associated with it. In addition, lower electricity consumption results in reduced greenhouse gas and criteria pollutant emissions, primarily from lower generation in hydrocarbon-burning power plants, such as natural gas power plants. The energy saved by this proposal would reduce greenhouse gas emissions by 0.268 million metric tons of carbon dioxide equivalentsMMTCO_2e. annually after stock turnover[135]

135 Million metric tons of carbon dioxide equivalents are calculated by using conversion of 690 pounds per MWh to metric scale, using the rate estimated by the *Energy Aware Planning Guide,* CEC-600-2009-013, February 2011, Section II: Overview, page 5.

APPENDIX A

Model for Small-Diameter Directional Lamps

Appendix A discusses the information and calculations used to characterize small-diameter directional lamps in California, the effect of the current energy use impact, and potential savings.

Existing Stock and Market Share and Future Stock Projections

The IOUs' CASE Study estimates that in 2018 there were about 15.8 million small-diameter directional lamps installed in California.[136] This estimate is based on the assumption that California stock is about 12 percent of the national installed stock. The IOUs further estimated that 70 percent of the California stock is of 50-watt lamps, 20 percent are 35-watt lamps, and 10 percent are 20-watt lamps. The first row in the table below shows the existing residential stock, and the second row in the same table shows existing commercial stock. Total stock is the sum of all the existing stock in the third row of the table below.

Based on the market, IOUs also estimated that the current stock is growing at a compound annual growth rate (CAGR) of 1.3 percent. Calculations for total stock for 2018 through 2028 are shown in the table below.

Variables for calculations are as follows:

ES = Existing Stock

Existing Stock + Stock Projections = (Commercial Stock* CAGR) + (Residential Stock*CAGR)

Table A-1: Existing Stock and Stock Projections

Existing Stock											
Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Residential	5.5	5.6	5.7	5.7	5.8	5.9	6.0	6.0	6.1	6.2	6.3
Commercial	10.3	10.4	10.5	10.7	10.8	10.9	11.1	11.2	11.4	11.5	11.7
Total Stock	15.8	16.0	16.2	16.4	16.6	16.8	17.0	17.3	17.5	17.7	18.0

Source: California Energy Commission

136 *Small Diameter Directional Lamps Codes and Standards Enhancement (CASE) Initiative*, August 6, 2014, available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Small_Diameter_Directional_Lamps_Addendum_to_CASE_Report_2014-08-06_TN-73551.pdf, page 2.

The IOUs' CASE report also estimated that 80 percent of the existing stock is low-voltage lamps, and 20 percent of the stock is line voltage. Low-voltage lamps are connected via a transformer, whereas line voltage lamps directly connect to 110 volts. The IOUs' CASE report also estimates that low-voltage transformers consume an additional 30 percent of power.

Formula for calculating the low voltage lamps:

$$\text{Low Voltage Stock} = ES*LO*CAGR$$

LO= Low wattage Bin=80 percent of the total stock

Formula for calculating the line voltage lamps:

$$\text{Line Voltage Stock} = ES*LN*CAGR$$

LN= Line wattage Bin=20 percent of the total stock

Table A-2: Low-Voltage and Line-Voltage Stock and Projections

Existing Low-Voltage and Line-Voltage Stock											
Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Low-Voltage Stock= 80 percent	12.6	12.8	13.0	13.1	13.3	13.5	13.6	13.8	14.0	14.2	14.4
Line-Voltage Stock 20 percent	3.2	3.2	3.2	3.3	3.3	3.4	3.43	3.5	3.5	3.5	3.6
Total Stock in Millions	15.8	16.0	16.2	16.4	16.6	16.8	17.0	17.3	17.5	17.7	18.0

Source: California Energy Commission

The IOUs CASE study was used to estimate that commercial lamps make 65 percent of the total installed stock, whereas 35 percent of the stock is residential lamps.[137]

Annual Energy Consumption

Annual operating hour estimates are based on usage of 840 hours/year for residential and 3,720 hours/year for commercial sectors. The annual operating hours are based on the 2002 lighting market characterization study conducted by Navigant, which states that the commercial low-voltage lamps operate roughly 3,720 hours per year, while residential general service halogen lamps operate 840 hours per year.[138]

137 Reference to market share is available at http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/California_IOUs_Response_to_the_Invitation_for_Standards_Proposals_for_Small_Diameter_Directional_Lamps_2013-07-29_TN-71763.pdf. page 22.

138 Operating hours are calculated based on the Navigant Consulting 2011 report *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*," available at

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf, page 17.

Table A-3: Annual Operating Hours

Market Sector	Hours/year	Market share
Commercial	3720	65 percent
Residential	840	35 percent

Source: California Energy Commission

Table A-4 below shows the total yearly energy consumption for small-diameter directional lamps without any standards. The annual energy consumption after the standard is also shown in Table A-4.

LN Consumption=[3720*(NW50 or NW35 or NW20)*0.2/1000*.65 KWh] + [3840*(NW50 or NW35 or NW20)*0.2/1000*.35] KWh

LO Consumption= [3720*(NW50 or NW35 or NW20)*0.8/0.9/1000*.65+ 840*(NW50 or NW35 or NW20)*0.8/0.9/1000*.35]KWh

BECPL= LN Consumption + LO Consumption KWh

LN =Line Voltage lamp, LO=Low Voltage Lamp, Nominal Wattage, and Baseline Energy Consumption per Lamp=BECPL

Table A-4: Annual Energy Consumption per Lamp

Annual Energy Consumption Per Lamp		
No Standard	≥ 80 lumens per watt or a CRI +*Efficiency* ≥ 165 and a minimum required *Efficiency* ≥ 70 LPW	Savings per year from proposed standards
158.43 KWh/year	25.04KWh/year	133.39 KWh/year
Annual Operating Cost		**$ Savings/year**
No Standards	80 lumens/watt	
$25.94	$3.81	$22.14

Source: California Energy Commission

Baseline Energy Consumption

Statewide baseline energy consumption is the projected energy consumption from the product without a standard. Ninety percent of the existing stock is filament lamps of average efficacy 8 lumens per watt, while 10 percent is LED lamps of average efficacy of 40 lumens per watt.

SBEC=ES*BECPL*CAGR KWh

ES = Existing Stock

Statewide Baseline Energy Consumption=SBEC

Statewide Energy Consumption with ≥ 80 lumens per watt or a CRI +*Efficiency* ≥ 165 and a minimum required *Efficiency* ≥ 70 LPW with standard in effect:

LN Consumption =[{(Commercial Duty cycle*Lamp Wattage*.9/80*0.2*.65)+(Residential Duty Cycle* Lamp Wattage*.9/80*0.2*.35)} +{(Commercial Duty cycle*40 LPW*.1/80*0.2*.65)+(Residential Duty Cycle* 40LPW*.1/80*0.2*.35)}/1000] KWh

LO Consumption= [{(Commercial Duty cycle*Lamp wattage*.9/80*0.8*.65)} + {(Residential Duty Cycle* Lamp Wattage*.1/80*0.8*.35)} + [(Commercial Duty cycle*40 LPW*.1/80*0.8*.65) + (Residential Duty Cycle* 40LPW*.1/80*0.8*.35)}/1000] KWh

BECPL= LN Consumption + LO Consumption KWh

Annual energy consumption per lamp is calculated by multiplying annual operating hours with the average lamp wattage of low-voltage and line-voltage lamps.

Table A-5: Annual Energy Consumption (Baseline and With Standards)

Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Annual Energy Consumption Without Standards (GWh)	2528	2561	2594	2628	2662	2697	2732	2767	2803	2840	2877	2914
Annual Energy Consumption with Standards (GWh)	371	376	381	386	391	396	401	406	412	417	422	428

Source: California Energy Commission

Energy Savings

Table A-6 below shows the total annual statewide monetary savings per year from 2018 to 2029. These savings are calculated by multiplying the total statewide energy savings with the average per kWh rate of 16 cents in 2018 to 18.59 cents in 2029 for commercial buildings and 17 cents in 2018 and 20.51 cents in 2029 for residential buildings. Total electricity bill savings to consumers in today's dollars are about $4.3 billion. In addition to electric bill savings, consumers will also save $694 million in lamp purchase cost over the life of the product.

Table A-6: Annual Energy Savings

Annual $ savings												
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Savings (in Millions)	$310	$318	$326	$333	$341	$349	$357	$389	$399	$409	$419	$430

Source: California Energy Commission

Table A-7: Statewide Energy and Cost Impact

Design Life	Annual Energy Savings/Unit	Incremental Cost of LED Improvement/Unit+ Replacement Cost	2018 Stock	First year Unit Energy Savings	Total unit savings over the design life	Simple payback period	Annual sales in millions	1st year statewide energy savings
11 years	133.39 KWh/year	$0.00+$4.00	15.8 Million	$22	$221.301	<1 year	15.8	1978 GWH

Source: California Energy Commission

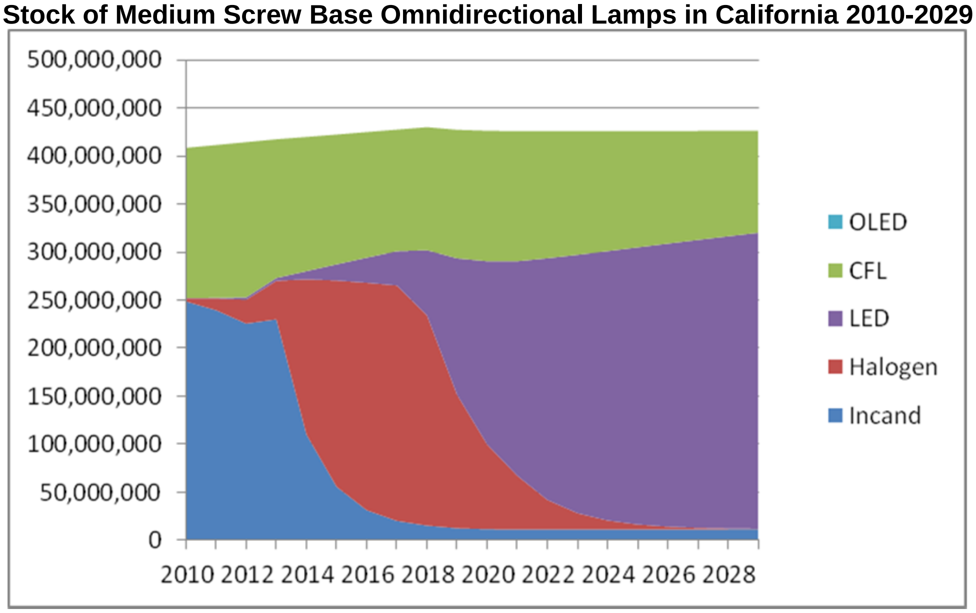
APPENDIX B

Appendix B discusses the information used to characterize LED lamp energy use and potential savings.

Existing Stock, Market Share, and Future Stock Projections

Energy Commission staff constructed a complex model of omnidirectional medium screw base market share based on NEMA and DOE data.[139] The model also incorporated EISA standards for incandescent general service lamps and the 45-lumen-per-watt backstop standard adopted by the Energy Commission and effective January 1, 2018. The effects of EISA can be seen as incandescent lamp stock declines in 2013 and then halogen lamp stock declines rapidly after 2018. The stock and shipment distributions were generated are shown in Figures B-1 through B-6 below. These models illustrate anticipated increases in LED stocks by hundreds of millions of lamps. While unit energy savings are in the 1 to 5 kWh per year range, when multiplied by a factor of 10^8, the savings become quite significant. The statewide savings over a set period or specific year were derived using these projections.

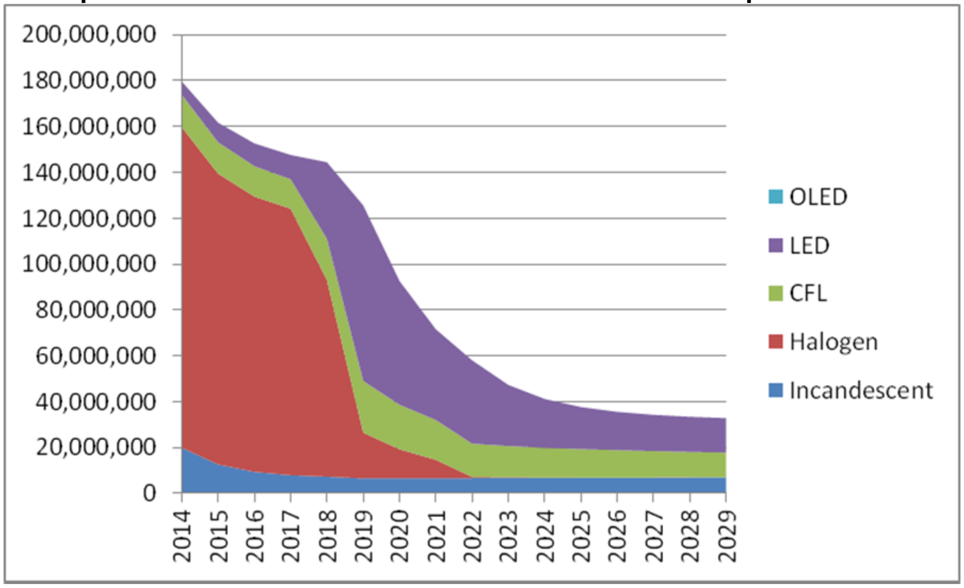
Figure B-1:
Stock of Medium Screw Base Omnidirectional Lamps in California 2010-2029



Source: Energy Commission Staff – Appliances and Existing Buildings Office

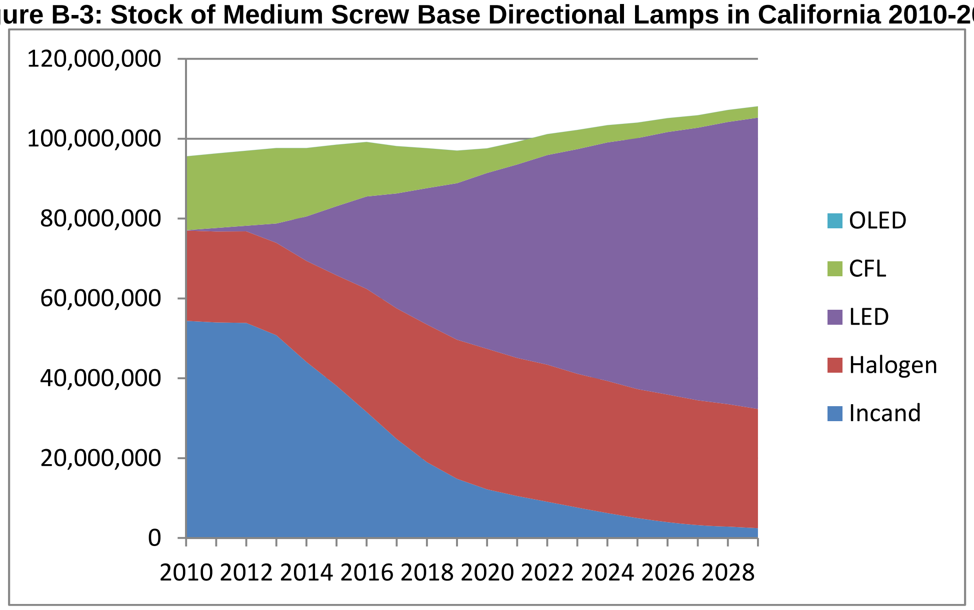
139 NEMA, "LED A-line Replacement Lamps Begin Making Inroads into the Market," December 20, 2013, available at http://www.nema.org/news/Pages/LED-A-line-Replacement-Lamps-Begin-Making-Inroads-into-the-Market.aspx; DOE, *2010 U.S. Lighting Market Characterization,* January 2012, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf; DOE, *Adoption of Light-Emitting Diodes in Common Lighting Applications*, May 2013, available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-adoption-report_2013.pdf.

Figure B-2: Shipments of Medium Screw Base Omnidirectional Lamps in California 2014-2029



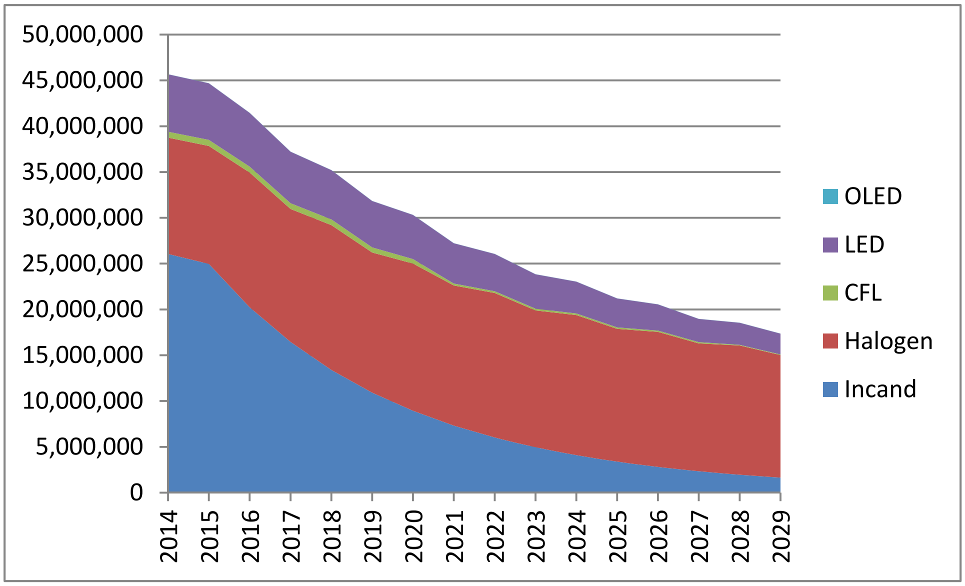
Source: Energy Commission Staff – Appliances and Existing Buildings Office

Figure B-3: Stock of Medium Screw Base Directional Lamps in California 2010-2029



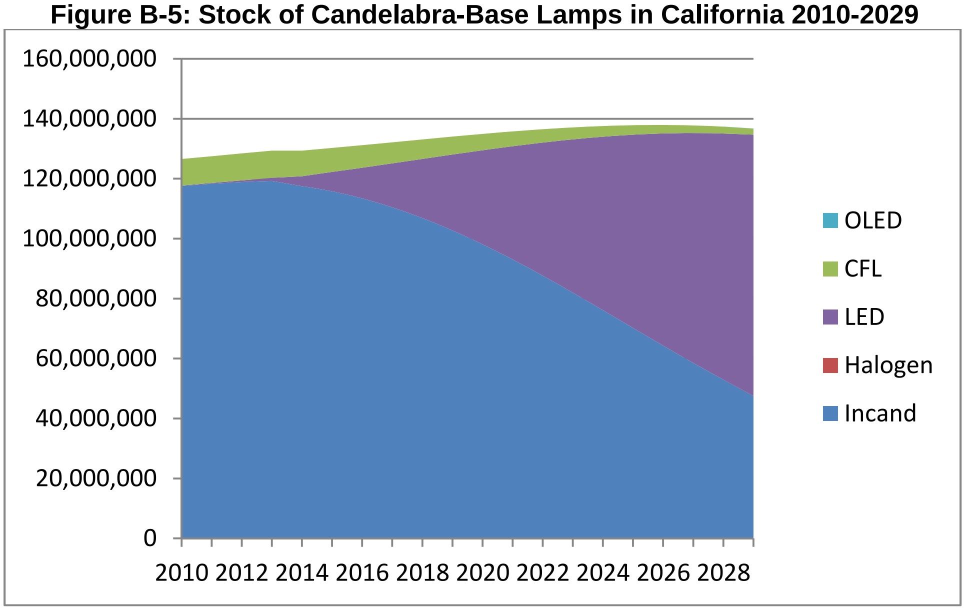
Source: Energy Commission Staff – Appliances and Existing Buildings Office

Figure B-4: Shipments of Medium Screw Base Directional Lamps in California 2014-2029



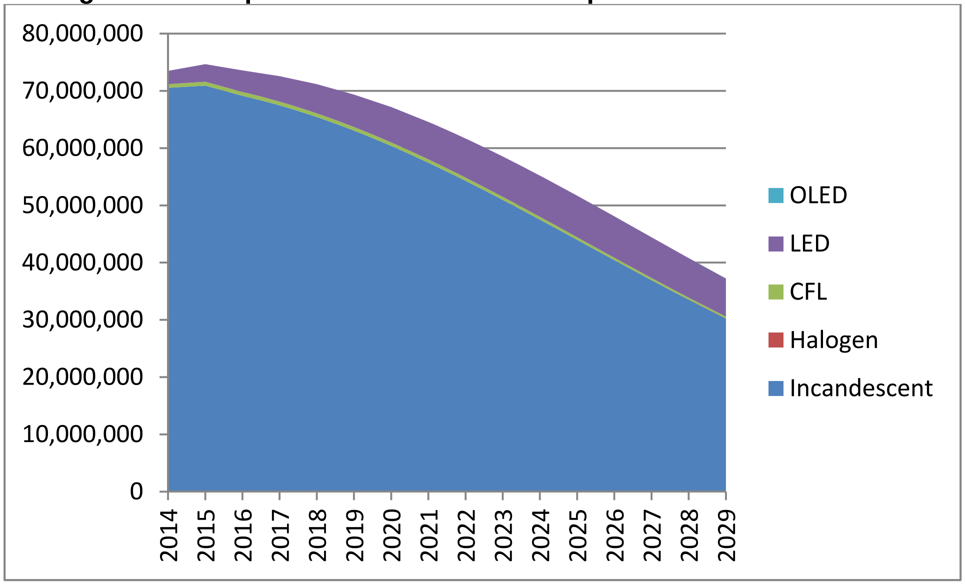
Source: Energy Commission Staff – Appliances and Existing Buildings Office

Figure B-5: Stock of Candelabra-Base Lamps in California 2010-2029



Source: Energy Commission Staff – Appliances and Existing Buildings Office

Figure B-6: Shipments of Candelabra Lamps in California 2014-2029



Source: Energy Commission Staff – Appliances and Existing Buildings Office

Energy Savings

Average LED lamp efficacy would increase in both Tier 1 and Tier 2, saving energy in the process. The quality aspects of the regulation in additional to the reduced operating costs would also accelerate market share growth of LED lamps relative to less efficient technologies such as halogen lamps and CFLs. Table B-1 summarizes the energy savings potential of omnidirectional, directional, and candelabra LED lamps.

Table B-1: Stock Energy Savings

Lamp Type	Potential Future LED Stock (Millions)	Average Baseline Efficacy (LPW)	Average Tier 2 Efficacy (LPW)	Energy Savings (GWh for the YEAR 2030)
Omni-directional	308.1	81.3	106.8	552
Directional	47.8	69	104.2	190
Candelabra	110.6	72.3	107.8	69

Source: California Energy Commission

The average baseline efficacy was developed by taking the average efficacy of all lamp data available for each lamp type and giving each model even weighting. The efficacy data for the lamps that would not comply with the data were then changed to be just efficacious enough to pass. The new average of the altered dataset was taken and used to represent the average efficacy of the Tier 1 and Tier 2 regulatory scenarios. These efficacy changes were used to model the unit energy savings. Statewide energy savings were calculated by multiplying unit energy savings by shipments. The annual savings of the proposed regulations in 2030 would be 812 GWh without adjusting for commercial usages and 862 GWh with the adjustment. Tables B-2, B-3, and B-4 display a typical life cycle cost/payback for each type of lamp.

Table B-2: Single Lamp Savings, Directional Lamp

Year	Energy Savings (kWh)	Value Of kWh	$ Savings	Lifetime Savings	Lifetime Cost
2019	4.5	$0.170	$0.76	$0.76	$1.50
2020	4.5	$0.165	$0.74	$1.50	$1.50
2021	4.5	$0.160	$0.72	$2.21	$1.50
2022	4.5	$0.155	$0.69	$2.91	$1.50
2023	4.5	$0.150	$0.67	$3.58	$1.50
2024	4.5	$0.146	$0.65	$4.24	$1.50
2025	4.5	$0.142	$0.63	$4.87	$1.50
2026	4.5	$0.137	$0.61	$5.49	$1.50
2027	4.5	$0.133	$0.60	$6.08	$1.50
2028	4.5	$0.129	$0.58	$6.66	$1.50
2029	4.5	$0.125	$0.56	$7.22	$1.50
2030	4.5	$0.122	$0.54	$7.77	$1.50
2031	4.5	$0.118	$0.53	$8.29	$1.50
2032	4.5	$0.114	$0.51	$8.81	$1.50
2033	4.5	$0.111	$0.50	$9.30	$1.50
2034	4.5	$0.108	$0.48	$9.78	$1.50
2035	4.5	$0.104	$0.47	$10.25	$1.50
2036	4.5	$0.101	$0.45	$10.70	$1.50
2037	4.5	$0.098	$0.44	$11.14	$1.50
2038	4.5	$0.095	$0.43	$11.57	$1.50

Source: California Energy Commission

Table B-3: Single Lamp Savings, Candelabra Lamp

Year	Energy Savings (kWh)	Value Of kWh	$ Savings	Lifetime Savings	Lifetime Cost
2019	1.7	$0.170	$0.29	$0.29	$1.00
2020	1.7	$0.165	$0.29	$0.58	$1.00
2021	1.7	$0.160	$0.28	$0.86	$1.00
2022	1.7	$0.155	$0.27	$1.12	$1.00
2023	1.7	$0.150	$0.26	$1.38	$1.00
2024	1.7	$0.146	$0.25	$1.64	$1.00
2025	1.7	$0.142	$0.24	$1.88	$1.00
2026	1.7	$0.137	$0.24	$2.12	$1.00
2027	1.7	$0.133	$0.23	$2.35	$1.00
2028	1.7	$0.129	$0.22	$2.57	$1.00
2029	1.7	$0.125	$0.22	$2.79	$1.00
2030	1.7	$0.122	$0.21	$3.00	$1.00
2031	1.7	$0.118	$0.20	$3.20	$1.00
2032	1.7	$0.114	$0.20	$3.40	$1.00
2033	1.7	$0.111	$0.19	$3.59	$1.00
2034	1.7	$0.108	$0.19	$3.78	$1.00
2035	1.7	$0.104	$0.18	$3.96	$1.00
2036	1.7	$0.101	$0.18	$4.13	$1.00
2037	1.7	$0.098	$0.17	$4.30	$1.00
2038	1.7	$0.095	$0.16	$4.47	$1.00

Source: California Energy Commission

Table B-4: Single Lamp Savings, Omnidirectional Lamp

Year	Energy Savings (kWh)	Value Of kWh	$ Savings	Lifetime Savings	Lifetime Cost
2019	3.0	$0.170	$0.51	$0.51	$0.50
2020	3.0	$0.165	$0.50	$1.01	$0.50
2021	3.0	$0.160	$0.48	$1.49	$0.50
2022	3.0	$0.155	$0.47	$1.96	$0.50
2023	3.0	$0.150	$0.45	$2.42	$0.50
2024	3.0	$0.146	$0.44	$2.86	$0.50
2025	3.0	$0.142	$0.43	$3.28	$0.50
2026	3.0	$0.137	$0.41	$3.70	$0.50
2027	3.0	$0.133	$0.40	$4.10	$0.50
2028	3.0	$0.129	$0.39	$4.49	$0.50
2029	3.0	$0.125	$0.38	$4.87	$0.50
2030	3.0	$0.122	$0.37	$5.24	$0.50
2031	3.0	$0.118	$0.36	$5.59	$0.50
2032	3.0	$0.114	$0.35	$5.94	$0.50
2033	3.0	$0.111	$0.33	$6.27	$0.50
2034	3.0	$0.108	$0.32	$6.60	$0.50
2035	3.0	$0.104	$0.32	$6.91	$0.50
2036	3.0	$0.101	$0.31	$7.22	$0.50
2037	3.0	$0.098	$0.30	$7.51	$0.50
2038	3.0	$0.095	$0.29	$7.80	$0.50

Source: California Energy Commission