Codes and Standards Enhancement Initiative
For PY2004: Title 20 Standards Development

Analysis of Standards Options
for
General Service Incandescent Lamps

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1 Introduction

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

Energy efficient lighting advocates have called for the use of compact fluorescent lamps (CFLs) for years, pointing out their high efficacy (lumens/watt), decreased size, rapid paybacks, improved color rendition and variety of color temperatures. Despite the above advantages and the continuous improvement of CFLs, some applications remain best suited to incandescent lamps. Estimates from Lawrence Berkeley National Laboratories found that only about one-third of the three billion residential lamp sockets nation-wide could operate CFLs cost effectively,[1] though continuing declines in CFL prices have likely increased that fraction. Reasons why incandescent lamps may continue to be preferred for particular applications include:

- CFLs will not fit in all fixtures
- the color rendition may be inadequate for the task
- dimming is not possible with many CFL/fixture combinations
- need for instant starting or rapid cycling
- unusually high or low temperature operating environment
- the hours of operation are too little to justify a lamp with a high initial cost
- fixture design requires a specialty lamp type
- application requires a point source of light

For most applications of ambient lighting, fluorescent or HID lighting are recommended on a lifecycle cost basis. The pace of that market transformation, though steady, still leaves incandescents as the dominant light source in the residential sector.

Given that there is a wide range of efficacies for general service incandescent lamps producing the same light output, it is appropriate as part of a comprehensive effort to lower electricity consumption statewide, to limit the low efficacy lamps from entering the California market. This can be done without unnecessarily limiting the choice of incandescent lighting products or their utility.

2 Product Description

Incandescent lamp technology has undergone evolutionary and incremental improvement since Thomas Edison first patented his carbon filament version in 1879, but few revolutionary breakthroughs have occurred.[2] Modern incandescent lamps use a tungsten filament and gas fill instead of a carbon filament in a partially evacuated envelope, but the basic technology remains the same: heat a thin wire with an electrical current until it glows. Most of the energy consumed by incandescent lamps produces waste heat (infrared radiation), as shown in Figure 1.

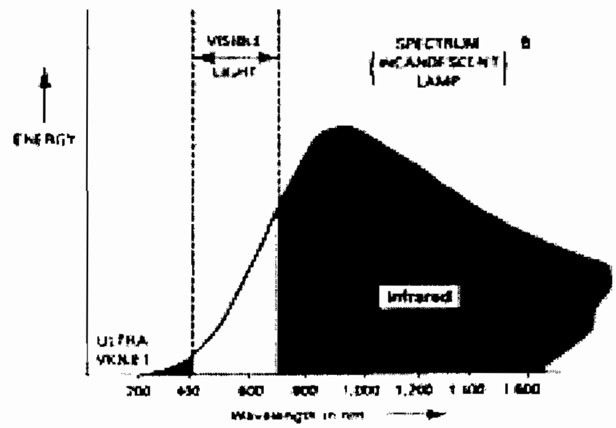


Figure 1 – Illustration of Spectral Distribution of Incandescent Lamp Output[3]

The efficiency of a lamp is measured in lumens per watt (lm/W) and is referred to as efficacy. The need for greater efficacy has been an important aspect of incandescent lighting since its earliest production. Edison's original incandescent lamp had an efficacy of about 1 lm/W. Modern incandescent and tungsten halogen lamp types within the proposed scope of this research have an efficacy in the range of 7 to 20 lm/W.[4] The theoretical maximum efficacy of an incandescent source is 53 lm/w. As a result, the standards levels proposed in this document seek not to force a dramatic technological breakthrough, but merely to accelerate usage of the efficient technologies already well understood and established.

Many factors affect the efficacy of a lamp. In general, a lamp's efficacy increases with the operating temperature of its filament, because higher temperature operation shifts the peak of the spectral curve in Figure 1 toward shorter wavelengths (closer to the visible spectrum). Tungsten filaments reach their maximum efficacy immediately before their melting point. However, high temperature operation also shortens lamp life.

The proposed scope would include non-reflector incandescent lamps intended for general lighting applications. This standard would be limited to incandescent medium screw-based lamps intended for general ambient lighting, including: A-lamps, PS-lamps, and halogen BT and MB-lamps (not pictured) with wattages between 25 and 150 Watts in power. See Figure 2 below for examples of these lamp shapes and types.

Globe-shaped or "G" lamps are also recommended for consideration (though savings from them are not yet included in the estimated impacts discussed here). These products are widely used in bathroom vanity fixtures and some types of open fixture lighting in other rooms. The 40-watt version appears to be the most popular, though some manufacturers offer the products in versions from 25 watts up to 150 watts. Many appear to use filament designs with multiple support wires (suggesting lower-than-average efficiency). None of the products discloses lumen output on packaging or in manufacturer catalogs. As a result, their efficiency is completely unknown to their purchasers.

Recommended exclusions from standards coverage include: rough service, decorative, three-way, and colored lamps except full spectrum. Conspicuously not excluded are lamps with a blue coloring designed to imitate daylight but intended for general lighting applications. Vibration service and "soft white" lamps are included with a slightly more lenient standard than clear lamps to allow for the implicit reduction of efficacy required to build these lamps to their design specifications. Three-way lamps are excluded only because of the limited scope of this research, but we believe they are promising candidates for efficiency standards as well. Some reflector lamps such as the common PAR lamp are already regulated at a federal level. Other shapes of reflector lamps are not federally regulated and could be good candidates for future standards, such as the BR, ER, and R20 lamps which are the subject of a separate CASE study.

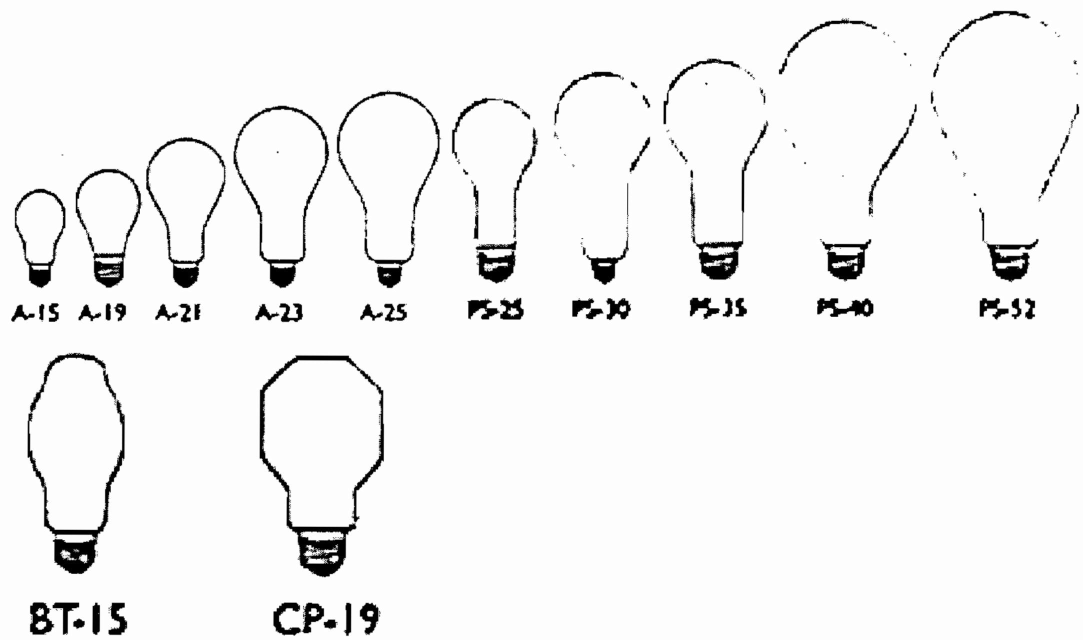


Figure 2 – Proposed Standard Lamp Shapes and Types[5]

3 Market Status

3.1 Market Penetration

Incandescent lamps are among the most prevalent products found in American homes. The average home contains 20 to 30 lamps, with 86% of those being incandescent.[3] Including residential, commercial, industrial, and institutional applications, the total number of incandescent lamps installed in California likely exceeds 300 million.

3.2 Sales Volume

Annual sales of screw-based incandescent lamps through major national retailers in California are approximately 82 million standard and 740,000 halogen units.[6] This estimate does not include decorative, three-way, or reflector screw-based lamp types. An unknown but significant additional quantity of lamps is sold through electrical distributors and small retailers. Thus the 74.3 million unit sales estimate of covered lamps in Table 1 should be seen as conservative. The true number could be 100 million units or more.

Table 1: California sales of included lamp types in 2000[7]

Watts	Soft White	Vibration Resistant	Standard Clear	Total
40	6,913,961	327,785	2,807,771	10,049,516
60	25,402,783	435,953	6,312,060	32,150,796
75	15,131,053		3,196,726	18,327,780
100	9,338,296		4,071,127	13,409,422
150	283,948	24,601	70,824	379,373
	57,070,041	788,339	16,458,507	74,316,888

Table 2: National sales of included lamp types in 2000[8]

Watts	Soft White	Vibration Resistant	Standard Clear	Total
40	104,756,984	5,471,256	42,037,158	152,265,398
60	384,890,653	6,605,354	95,637,271	487,133,278
75	229,258,382		48,435,249	277,693,631
100	141,489,328		61,683,736	203,173,064
150	4,302,245	372,746	1,073,085	5,748,076
	864,697,592	12,449,356	248,866,499	1,126,013,447

3.3 Market Penetration of High Efficiency Options

Standard performance, incandescent, general service lamps represent over 85% of general service lamp sales. Compact fluorescent lamps likely comprise an additional 6 to 10%,[9] with high performance incandescent lamps (halogen, coiled-coil, and other technologies described in section 4.3 below) comprising the remaining fraction.

4 Savings Potential

4.1 Baseline Energy Estimates

The baseline energy use of incandescent lamps covered by this standard in California is nearly 6.5 TWh per year. Potential savings estimates by lamp type are found in Table 3.

Table 3 – Baseline and Energy Savings Estimate for Incandescent Lamp Standards in California[10]

Bulb Type	Total Annual Energy Savings (GWh)	Total Annual Energy Cost Savings Total (millions)	Total Lifetime Energy Savings (GWh)	Total Lifetime Energy Cost Savings Total (millions)
Tier 1				
Soft White	122.14	$14	132.12	$15
VR	1.30	$0	1.66	$0
Frost or Clear	35.74	$4	38.81	$4
TOTAL	159.18	$18	172.59	$20
Tier 2				
Soft White	339.04	$39	471.31	$54
VR	2.85	$0	4.67	$1
Frost or Clear	99.21	$11	138.45	$16
TOTAL	441.10	$51	614.43	$71

4.2 Proposed Test Method

Test methods can be a controversial issue with any energy efficiency measure. However, for lighting, two test methods are already widely accepted in the industry and should be the required test methods for an incandescent lamp standard. Illuminating Engineering Society of North America (IESNA) publications clearly explain the test methods for both lamp life and lumens.[11]

4.3 Efficiency Measures

Numerous materials and design strategies to increase the efficiency of standard incandescent lamps are in use and under development. Brief summaries of the promising measures are shown below. Many of these may be combined with others to accomplish various cost, efficacy and performance goals.

Measures already in use

Krypton or xenon gas fill
Anything that can be done to help retain heat within an incandescent filament will allow it to maintain a given operating temperature with lower power input, improving efficiency. Using krypton or xenon gas fill can increase efficacy, hours of life, or both by thermally insulating the filament and reducing its vaporization rate. Some extremely long life screw-base incandescent lamps currently employ this strategy. Likewise, krypton and xenon are fairly common in low voltage DC flashlight bulbs, where the higher efficacy and light output confer a significant market advantage.

Coiled-coil filaments
Coiled-coil filaments (figure 3) increase efficacy by reducing convective cooling of the filament. The more compact the filament, the less gas can circulate around it.

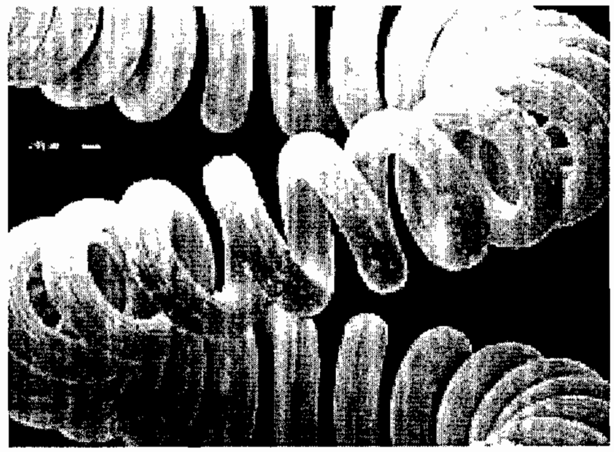


Figure 3: Coiled-coil filament at 500X magnification with an electron microscope[12]

Filament support wires
Using fewer support wires increases efficacy by reducing conductive heat loss from the filament.

Lamp enclosure ("bulb") diffusion
Increasing bulb transparency allows more visible light to be emitted. Diffuse ("soft white") bulb coatings are often redundant when used in fixtures with built-in diffusers or translucent globes. Likewise, the use of a very thick glass envelope on some halogen lamp styles may reduce light output (and increase cost) relative to other designs with thinner enclosures, though associated changes in the design of inner lamp envelope may counteract that effect.

Halogen
Use of a halogen gas fill within an interior quartz or hard-glass encasement prevents the slowly evaporating tungsten from depositing on the inner surface of the bulb and instead deposits the tungsten back on the filament. This tungsten cycle allows the filament to be operated at a higher temperature without depleting the filament, thereby increasing efficacy without sacrificing life. Most halogen lamps are optimized for life with little change in efficacy. Because the bulb does not blacken as much with use, halogen lamps suffer less lumen depreciation than standard incandescent lamps.

Filament temperature
Increasing the operating temperature of the filament also increases the efficacy. The temperature of the filament can be increased by adjusting the filament's resistance (through changes to the length, diameter, coil spacing, and/or the inside diameter of the coils). Increasing the efficacy of the filament using these methods alone will often come at the cost of decreasing the life of the lamp.

Halogen infrared reflecting
A dichroic (i.e. spectrally reflective) coating can be applied to the inner wall of the halogen capsule, which reflects long wave radiation (heat) back to the filament while allowing radiation in the visible spectrum (light) to pass through. The reflected heat is directed back to the filament to increase its temperature for a given amount of power input.

Future Technologies
3D crystalline photonic lattice
Future efficacy increases to the incandescent lamp may be achieved by heating a tungsten 3D crystalline photonic lattice to >1,500 deg C., shifting the emission into the visible region.[13] These lattices act like a sieve at the molecular level, increasing the percentage of energy emitted in the visible spectrum.

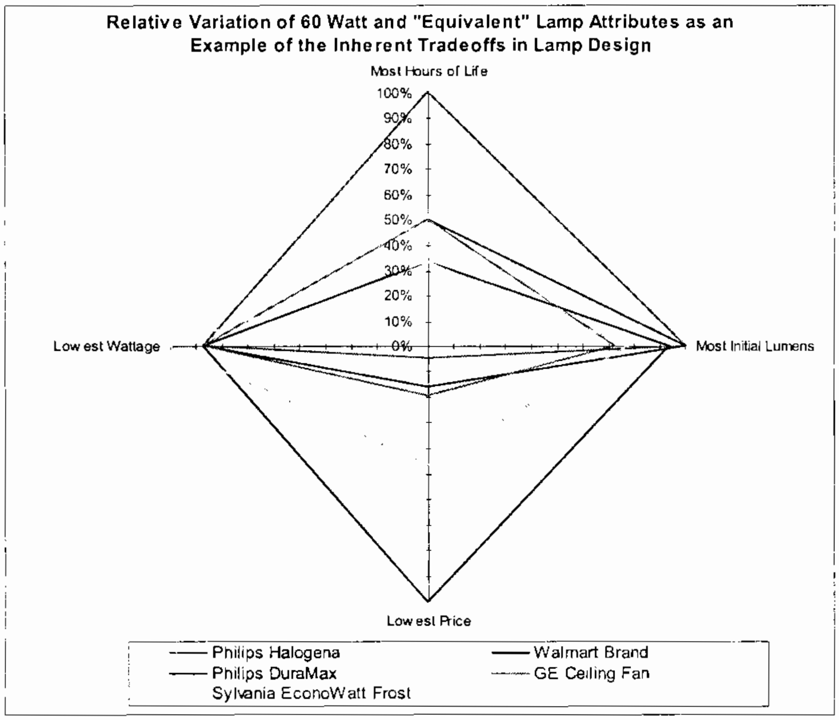
Metal oxide coated filament
The filament can be coated with a metal oxide to trap infrared radiation and emit more visible light.

Hafnium carbide ceramic filament
A filament material like hafnium carbide ceramic can be substituted for tungsten, yielding a higher melting temperature and greater efficacy.[14] The U.S. Department of Energy's Inventions and Innovations program recently provided grant funding to Sonsight, a company developing a "multi-element selective emitter" of similar design.[15]

Considerations of Technology and Construction in the Standards Development Process

Incandescent lamp design is a balance between watts, volts, lumens, efficacy (lm/w), hours of life, color temperature, and cost. Most incandescent lamps are optimized for low cost first and hours of life second. Efficacy and lumens, both poorly understood by consumers, are a distant third and forth. Rough service and vibration resistant lamps have lower efficacies than standard lamps, because additional metal filament supports are employed, conducting heat away from the filament. Long life lamps have oversized filaments or are designed for a higher voltage than expected, but tend to sacrifice efficacy and light output as a result (see Figure 3a)

For a given product cost or technology type, there tend to be significant tradeoffs among these variables, such that increasing light output increases power use and efficacy but reduces longevity. However, it is possible to make simultaneous gains in many of the



desired attributes of an incandescent lamp when product cost rises, as has been demonstrated in many of the halogen and krypton-filled products.

Figure 3a – Examples of Lamp Design Tradeoffs

4.4 Standards Options

4.4.1 Standards Levels

We considered four scenarios in which savings of 3.6%, 6.0%, 10%, or 15.5% of total energy consumption could be realized by a combination of preventing sale of the least efficient technologies and spurring increased sales of advanced technologies that are more efficient than typical units in use today. As efficiencies rise with the various options, we would expect a near term market response of shortened lamp life at similar cost and a longer term response of steady or increased lamp life at higher cost.

Some methods for increasing incandescent lamp efficacy are commonly used today, while others are still a few years away, are still in the development stage, or may never become cost effective. This standard analysis focuses on four design options and sets forth a two tiered approach based on the expected savings of the most cost effective design improvements over today's average incandescent lamp. The standards recommended are reasonable based on presently available technology that is both cost effective and produced by a variety of manufacturers.

4.4.1.1 Design Modification One: Reduce lamp wattage by 3.6%, achievable by lowering the average hours of life by approximately 22%

Lighting designers have used a simple method for gaining long life from incandescent lamps by under-driving the lamp and sacrificing efficacy. Conversely, a lamp's efficacy and light output could be increased by slightly over-driving the lamp (see Figure 5 below). Well know equations in the lighting design world are used to estimate lamp life when other variables are known. For example, a lamp rated at 120 volts and 1000 hours would last an estimated 350 hours if operated at 130 volts.[16] Alterations in lumens, power, and other attributes can be calculated by equations available to lighting engineers. For design modifications one and two, we are proposing to lower lamp wattage while maintaining lumens. To keep the cost constant, the additional efficacy comes at the expense of some of the lamp life. As shown in Figures 5-7, many lamps already meet the standard proposed. Many of these lamps are rated at 1000-1500 hours. By reducing lamp wattage by 3.6% (an average of 2.2 watts) in standard one and maintaining lumens, it is reasonable to estimate the effect on the hours of life.

To calculate the average hours of operation if average power is reduced by 3.6% the following equation was used, based on a 60-watt lamp:

$$\text{Estimated Lamp Life} = 1000\ \text{hours} * ((840\ \text{lumens}/60\ \text{watts})/(840\ \text{lumens}/57.8\ \text{watts}))^{6.8} = 778\text{hrs.}$$

We analyzed lamps with standard coatings, vibration resistance, and soft white coatings separately because of the innate efficacy differences for these lamp types. Costs for this design modification are from the cost of additional lamp replacements in the residential market and from the cost of additional lamp replacements plus a $1.00 per lamp labor charge for commercial and industrial. The vast majority of incandescent lamps are sold to residential customers. The average life of an incandescent lamp for a given efficacy can be predicted using formulas found in the IESNA Lighting Reference and Applications Book. Note in Figure 6 that the observed variation in light output at a given wattage with vibration resistant lamps tends to be smaller than with the other types.

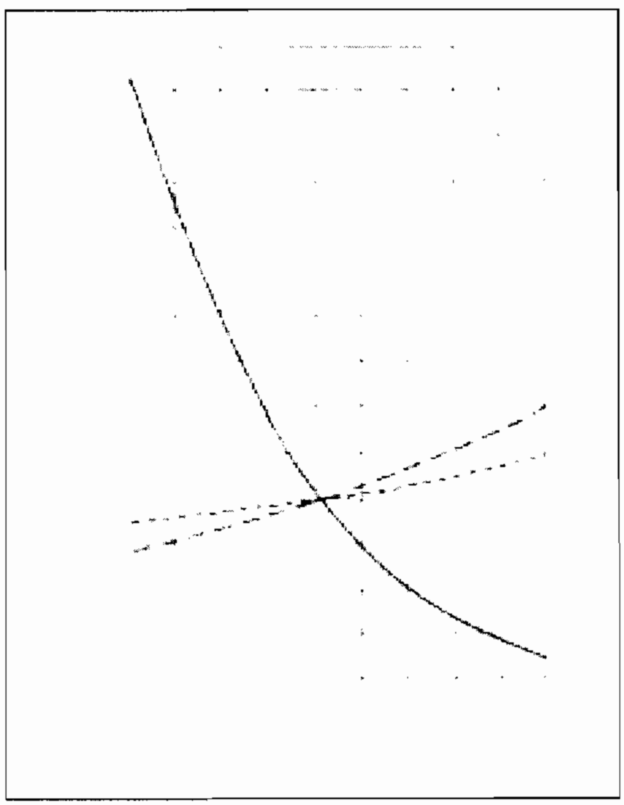


Figure 4: Relationships between lumens, life, power, and rated power (IESNA)

4.4.1.2 Design Modification Two: Reduce lamp wattage by 6%, achievable by lowering the average hours of life by approximately 35%

This Design Modification is essentially the same as Design Modification One, but it requires a greater reduction of hours of life if standard incandescent lamps are used. However, this option significantly reduces the lamp life, which would amplify the difference in longevity between incandescent and compact fluorescent lamps. While the obvious result is that consumers purchase more lamps, another possibility is that the reduced lamp life will encourage consumers to use the incandescent lamps only in locations with very limited hours of use or where CFLs are not otherwise appropriate. The fact that some long life incandescent lamps claim lifetimes of 20,000 hours suggests that it might be possible to offset some of these reductions in lifetime through straightforward technology upgrades as well.

4.4.1.3 Design Modification Three: Use krypton-filled lamps to reduce wattage by 10% with an increased cost per lamp and constant lamp life

Krypton gas has a larger molecular size than argon, so it retards tungsten vaporization, increasing lamp life by 50% or more.[17] It also provides better insulation, allowing higher operating temperatures, and increasing the efficacy by 7 to 20% according to ESOURCE and IES. According to Osram Sylvania Lighting, "Krypton, which is heavier than [argon] but has characteristics similar to argon, is an excellent fill gas. Using krypton produces an increase up to 10% in efficacy (l/W) without a decrease in lamp life."[18] As promising as this technology is, manufacturers do not appear to use it widely at present, possibly from a desire to minimize first cost in a largely undifferentiated commodity product. Krypton is widely used in very small DC incandescent bulbs intended for the flashlight market, where highly efficient LED technology is putting pressure on conventional flashlight manufacturers to boost efficiency to provide competitive battery lifetimes and brightness levels.

Current prices for krypton gas fill lamps vary widely and are affected by multiple variables, confounding efforts to precisely estimate incremental cost. Most 120-volt AC krypton-filled lamps are usually optimized for long life, and to this end they also employ other features that increase life while decreasing efficacy and increasing the lamp cost. Currently produced krypton-filled lamps range in price from $0.75[19] to $1.00. This price could be significantly reduced if the lamps were produced in greater volume. Many lamp manufactures make specialty krypton lamps for long life in traffic signals or long-life decorative lamps for the European market, but this technology is not widely used in the United States.

4.4.1.4 Design Modification Four: Increase efficiency by 15.5%, with infrared reflecting halogen technology already used in reflector lamps

This option has the highest energy savings of the analyzed measures. Energy savings for incandescent lamps are obtainable by utilizing technology already common for PAR and other reflector lamps. This option would increase life and efficacy, but would increase the cost of general service lamps considerably. Averaging the cost of a standard halogen general service lamp and increasing it by the difference in cost between a standard reflector halogen and a halogen IR reflector yields estimated individual lamp costs. For this calculation it is assumed that a general service halogen IR lamp could be created for the same incremental cost associated with reflector lamps undergoing the same technological improvement. Increases in efficacy were also estimates based on halogen IR and reflector lamps.

Unfortunately, this design modification is not cost effective at this time. Future improvements in manufacturing techniques and increased sales volumes could bring the cost down, but given current market conditions, halogen IR lamps' high initial cost yields lower cost effectiveness than other options. Other issues relating to halogen IR general service lamps are discussed in recent DOE appliance standards program documents.[20]

4.4.2 Standards Levels Approach

Several standards approaches would prevent the least efficient general service incandescent lamps from being sold in the California market and increase the efficacy of future lamps. Lamps can be divided into "bins" by lumens or by watts with appropriate efficacy standards for each. Efficiency can also be stated as a function of watts or lumens, allowing a more continuous set of standards levels.

The "bin" model -- federal standards for reflector lamps

An approach similar to the federal standard for reflector lamps (see Existing Standards) is suitable for general service lamps. As the wattage of a lamp increases, all other factors being equal, the efficacy increases. For this reason, it is convenient to divide lamps into categories of wattages, setting a higher efficacy standard for higher wattage groups.

Drawbacks of this approach are that the lower wattage lamps in a given bin are at a distinct disadvantage when compared to higher wattage lamps in the same bin. This could encourage lamp manufacturers to produce more lamps near the high wattage end of each bin. A second disadvantage to this approach is that it furthers the confusion for consumers on how to select a lamp. Consumers are accustomed to selecting lamps based on their rated wattage. In effect, wattage can be a proxy in their minds for luminance, even though incandescent lamps of a given wattage can provide widely varying amounts of light output. Federally required labeling for lumen output is a step in the right direction, but a standard correlated to lumens is likely to yield greater efficiency improvement than one simply scaled to wattage.

Line slope method
Another approach to the standard is to define the slope of a line on a chart of lumens (x-axis) and watts (y-axis), so that for any desired light output level, a maximum allowable wattage can be calculated by the formula for the line. This approach solves the problem stated above of favoring low wattages within a bin because no bins are needed. Unfortunately, wattage is often still the most prominent characteristic of the lamp on its package, so consumer education would be an important adjunct to the introduction of such a standard.

Watts per lumen
A third approach is to keep the bin approach, but divide the lamps into bins based on their lumens rather than wattage. For a given amount of light emitted, the lamp must use no more than a specified amount of power. Alternatively, for a given amount of light emitted, the lamp must reach a specified threshold of efficacy in lumens per watt. This method has the advantage of more accurately categorizing the lamps by their useful output. A lamp's purpose is to produce light, and so it is appropriate to evaluate them by their ability to produce lumens. The amount of power consumed is not a very precise way to purchase a given amount of functionality in a lamp when a wide range of efficacies exists.

The primary challenge with employing a lumens-based standard is to overcome the inertia of existing practice. This approach has not been used before, so it would be more challenging to track sales based on lumens. With the proper education and marketing, such an approach might also increase consumer awareness of lumens as the most useful measure of lamp functionality. However, it would be a substantial departure from current practice.

Given all of these considerations, we recommend the line slope method. For any given light output level, a maximum allowable wattage can be calculated. Although a seemingly complex formula is sometimes needed to closely mirror the efficacy of lamps across a range of power inputs, even the most complex formula can automatically determine, through a spreadsheet, if a lamp complies. The standards recommended are based on the formula for a straight line, stating the y-intercept and slope. Any standard will require either a reduction of average wattage or a substantial effort to educate consumers and update labeling protocols.

4.5 Energy Savings

Ecos Consulting gathered data on a wide variety of incandescent and halogen lamps sold through major retailers. By plotting watts vs. initial lumens for each type of incandescent lamp, we were able to determine equations that explain most of the observed relationship between light output and power use, representing an average for each lamp type. The equations are shown in Table 4 below:

Table 4: Average light output versus power use

Lamp Type	Power Use (Watts)
Frost or Clear	Watts = 0.05 * Lumens + 19.04
Soft White	Watts = 0.05 * Lumens + 21.38
Vibration Service Lamps	Watts = 0.07 * Lumens + 15.24

The R^2 values for these equations range from 0.94 to 0.96, indicating very high correlations between the equations and actual lamp performance. About half of the models analyzed in each category fall above each line (less efficient than average) and half fall below each line (more efficient than average). The proposed standards for each of the categories are equations that reduce the average wattage by 3.6% for Tier 1 (based on efficient existing practice – the first option discussed above) and 10% for Tier 2 (based on using krypton gas fill – the third option discussed above), as follows in Table 5 below:

Table 5: Proposed standards levels

Lamp Type	Maximum Power Use (Watts)	Average Savings (Watts)
Tier-1 Frost or Clear	Watts = 0.0500 * Lumens + 21	2.1 watts
Tier-1 Soft White	Watts = 0.0480 * Lumens + 23	2.2 watts
Tier-1 Vibration Lamps	Watts = 0.0730 * Lumens + 13.5	2.0 watts
Tier-2 Frost or Clear	Watts = 0.0485 * Lumens + 15	6.2 watts
Tier-2 Soft White	Watts = 0.0490 * Lumens + 15.5	5.8 watts
Tier-2 Vibration Lamps	Watts = 0.0740 * Lumens + 9	5.1 watts

Current models from a variety of manufactures meet each standard. Scatter plots of all sampled lamps are shown in Figures 5, 6, and 7. The proposed standards are shown as

Figure 5: Distribution of Watt/Lumen & Proposed Standard Cutoff, Frosted or Clear General Service

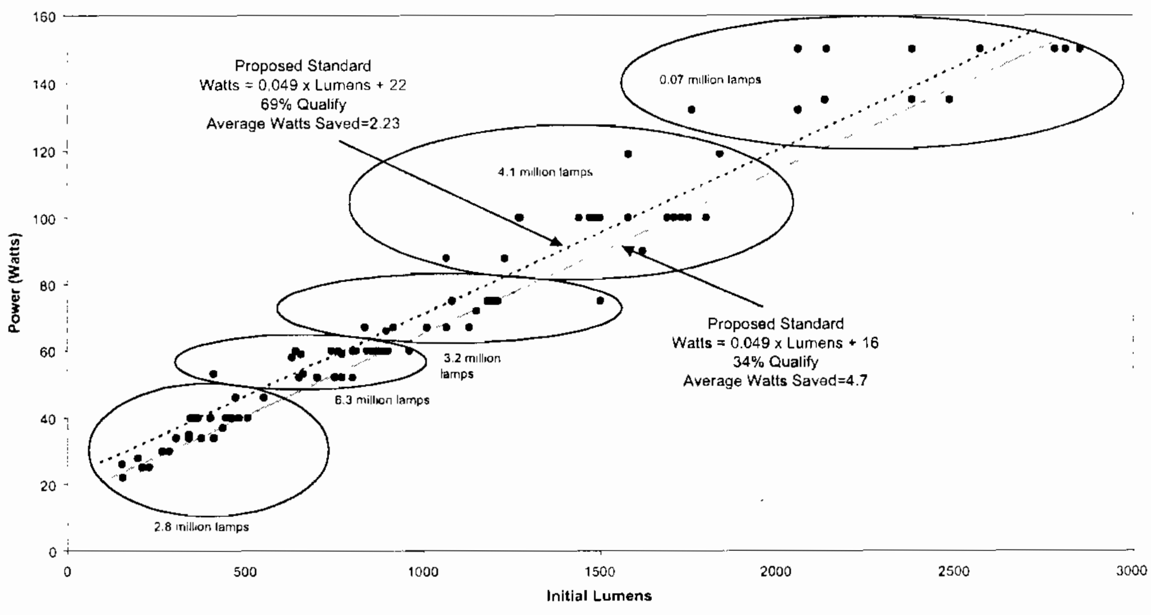


Figure 6: Distribution of Watt per Lumen and Proposed Standard Cutoff, Vibration Service A-Lamps

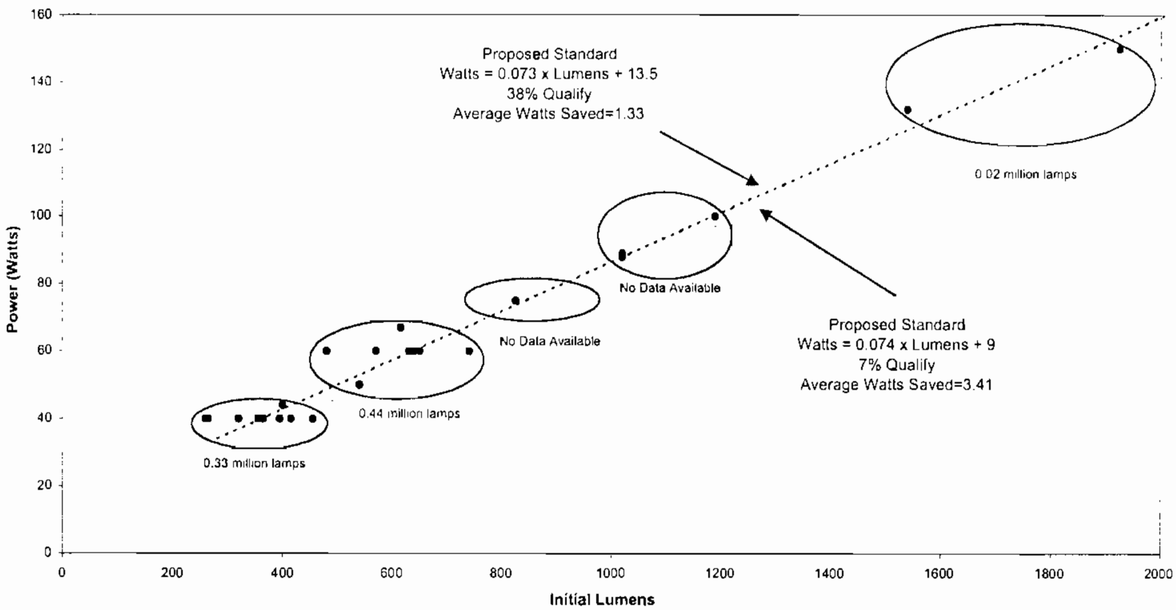
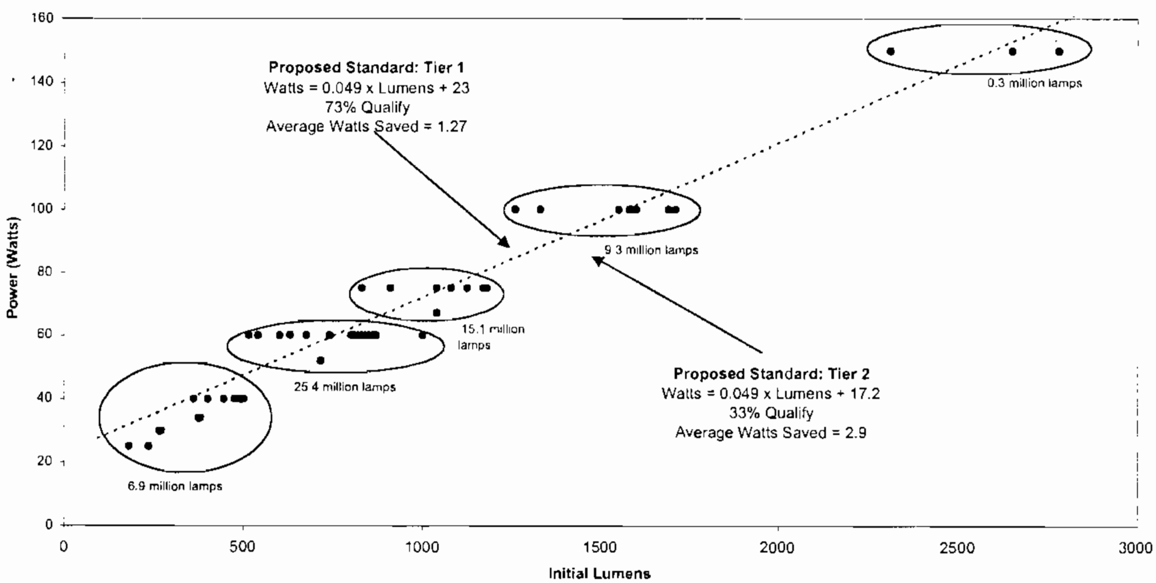


Figure 7: Distribution of Watt per Lumen and Proposed Standard Cutoff, Soft White General Service



lines, with Tier 1 standards higher on the charts and Tier 2 standards lower. Lamp models falling on or below the proposed standards lines would qualify. Note the slightly different standards for each lamp type. Vibration service lamps and soft white lamps have an intrinsically lower efficacy due to the added support wires and thicker filament in vibration lamps and the additional diffusive coating used on a soft white lamp. More on this topic appears below.

Annual savings resulting from one year's worth of covered lamp sales could be as much as 159 GWh for Tier 1 and 441GWh for Tier 2. Actual savings are likely to be less, but it is very difficult to estimate by how much. Manufacturers that generally respond by increasing the light output of existing lamp wattages will bring about smaller energy savings than those that seek to maintain lumen levels of current lamp models at lower wattages. The Tier 2 standard improves efficacies to the point in many cases where a consumer that formerly purchased a 75-watt lamp would find a new qualifying 60-watt model virtually equivalent in light output. This is most readily apparent in Figure 5 and Figure 7, where the most efficient lamp models in each wattage bin tend to be brighter than the least efficient models in the next-highest wattage bin. It may be reasonable to assume that Tier 1 savings will be 25 to 50% less than expected because of light output "takeback," while Tier 2 savings would be much closer to the expected amount (see Table 6 below). Thus, we estimate that expected first year savings would be 80 GWh for Tier 1 and 441 GWh for Tier 2.

Demand impacts are very difficult to estimate, because the majority of incandescent lamp demand is residential and can occur later in the day than the traditional commercial sector peak. If all incandescent lamp use were coincident, demand impacts could be up to 1.5 GW. Coincidence factors of 10% have been documented in the literature, but we are not aware of any recent studies matching incandescent lamp load factors to demand peaks in California specifically. Internal estimates suggest demand impacts of perhaps 10 to 55 MW.

In discussing the preliminary draft of this standards proposal with representatives of the lighting industry, some manufacturers alleged that certain high efficacy incandescent products depicted in the figures above may overstate their light output or understate power consumption. If true, these assertions would suggest that higher levels of efficiency are relatively more difficult to achieve than our analysis suggests. To determine whether there was in fact a substantive difference between nominal and measured efficacy in these or a representative sample of other more typical, nominal efficacy general service lamps (drawn from the models depicted in figures 5, 6, and 7 above), PG&E retained the Lighting Research Center to test 31 different incandescent general service lamp models (20 clear lamps, 3 soft white lamps, 2 vibration resistant lamps, 2 lamps from categories not included in standards legislation, and 4 lamps that did not have nominal ratings) according to accepted IESNA test methods.

The percentage of independently tested lamps that qualify is compared to the percentage of nominal rated lamps that qualify, in the case of both Tier 1 and Tier 2. Figure 8 and 9 show the results of watt and lumen measurements conducted by LRC. Samples were taken for a wide rage of wattages and lumens. The category labeled "other" refers to lamp types that are not included in savings estimates.

Figure 8. Variation Between Nominal Watts and Average Measured Watts for Each Lamp Type

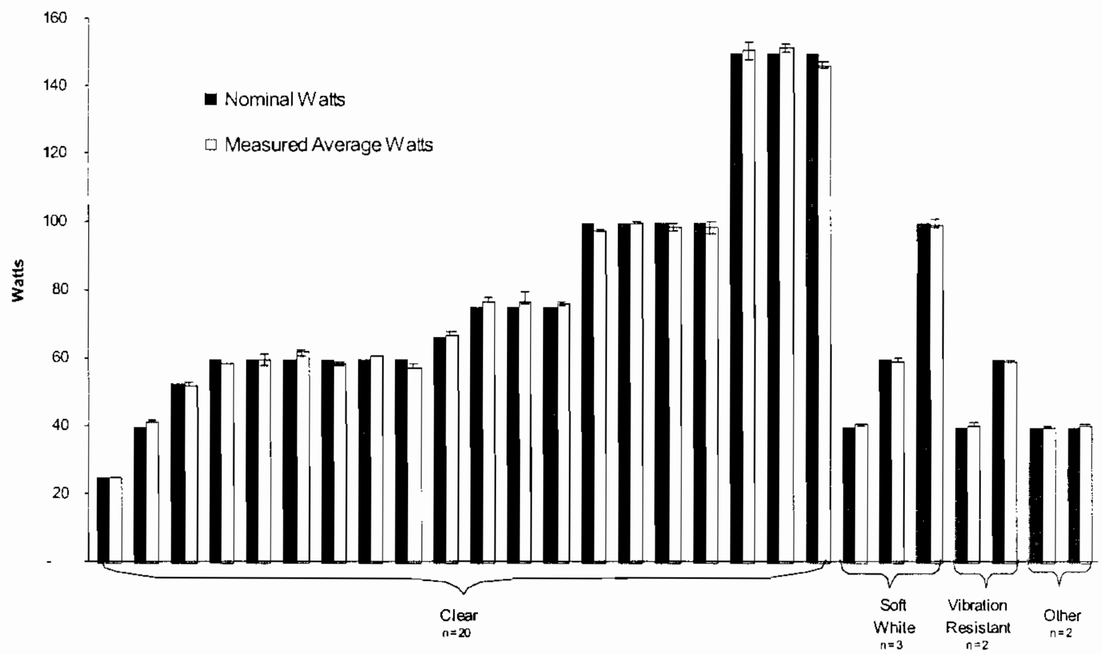


Figure 9. Variation Between Nominal Lumens and Average Measured Lumens for Each Lamp Type

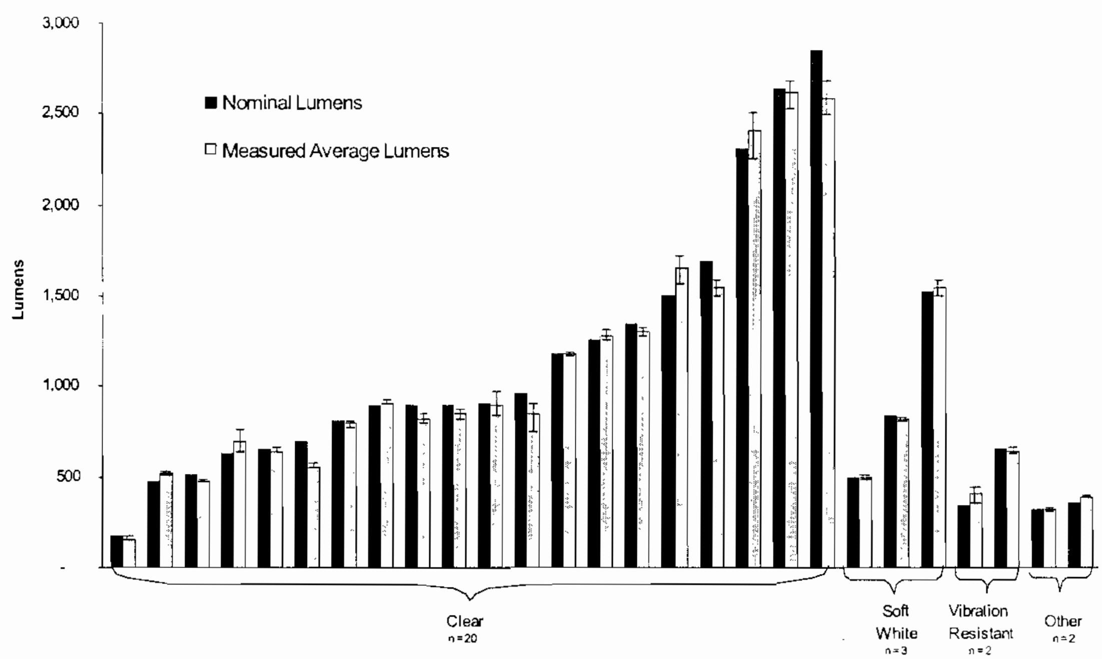


Figure 10 and 11 summarize the variation between nominal and average measured watts for each type of bulb. The measured watts range from 96% to 104% of nominal watts across the population of samples. The average for each type of bulb was 100%, indicating that current testing and reporting methods for nominal watts are accurate.

Figure 10. Variation Between Nominal and Average Measured Watts for Each Type of Bulb

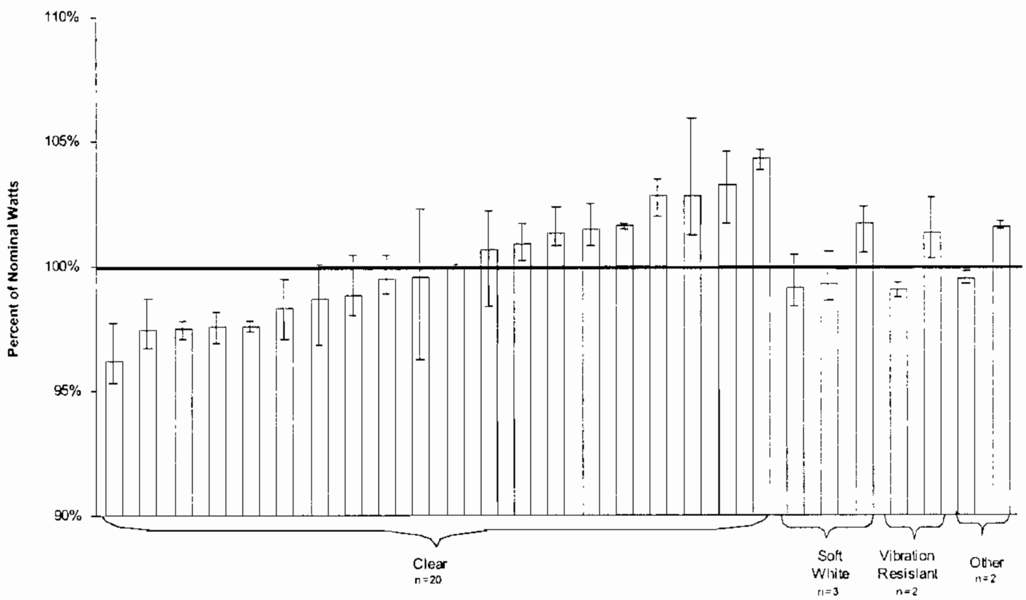


Figure 11. Variation Between Nominal and Average Measured Watts for Each Type of Bulb

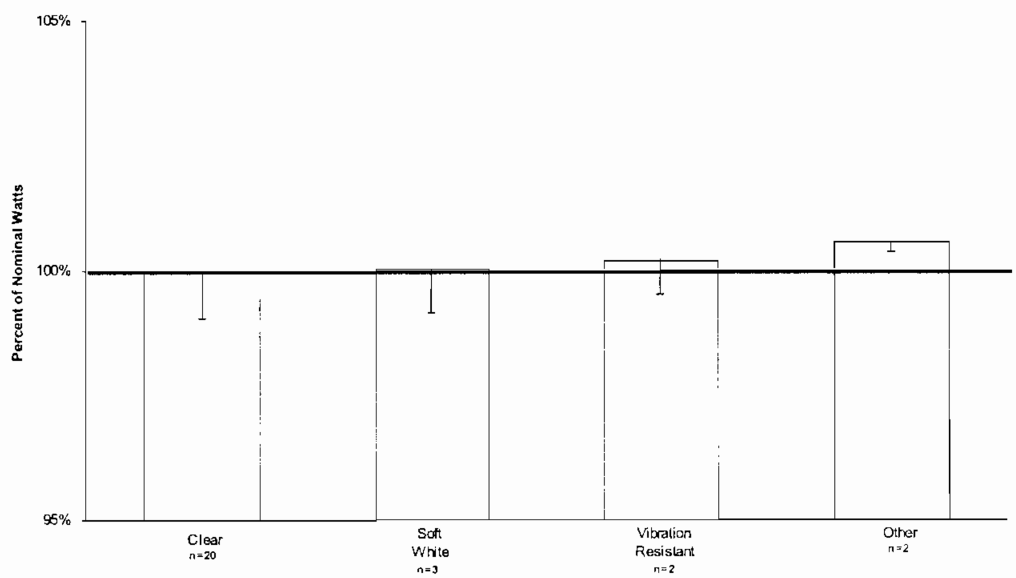


Figure 12 and 13 summarize the variation between nominal and average measured lumens for each type of bulb. The measured lumens range from 80% to 119% of nominal lumens across the population of samples. The average for each type of bulb ranged from 98% to 109% of nominal lumens. While this is more variable than watt measurements, these findings continue to suggest that current testing and reporting methods for nominal lumens are accurate.

Figure 12. Variation Between Nominal and Average Measured Lumens for Each Type of Bulb

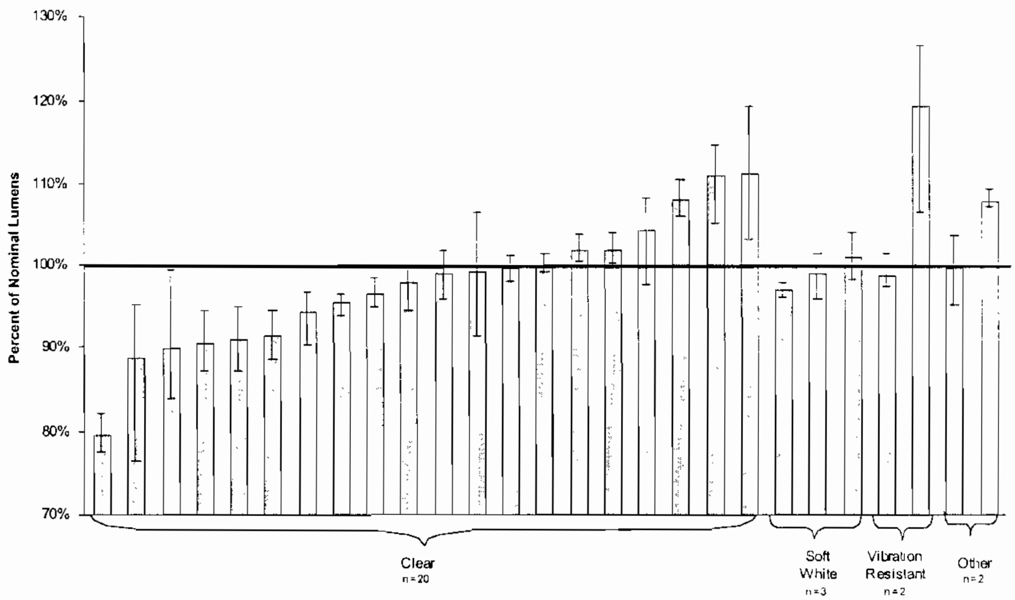
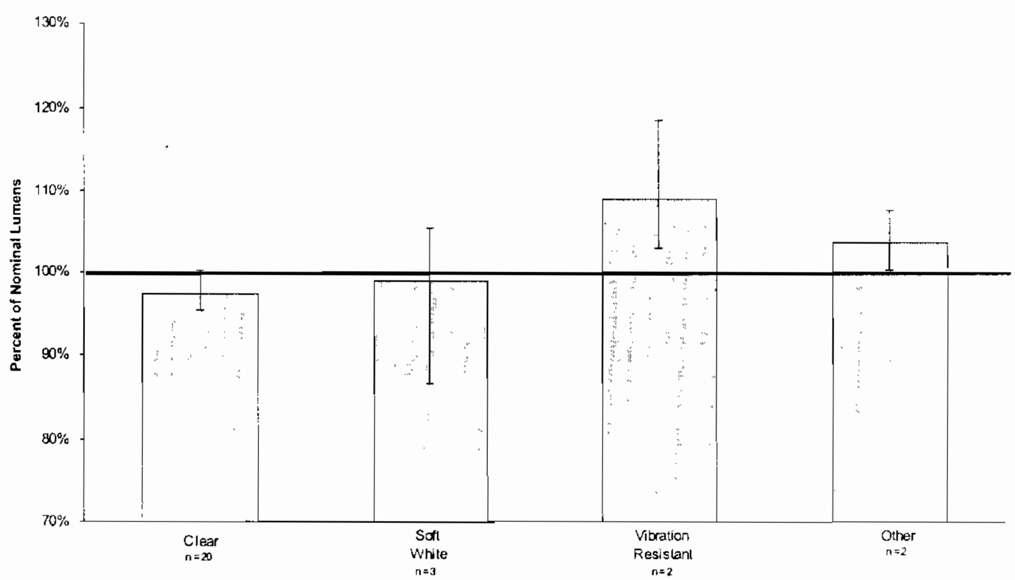


Figure 13. Variation Between Nominal and Average Measured Lumens for Each Type of Bulb



We conclude that the measured results *do not* suggest that the proposed Tier 1 or Teir 2 standard would be more difficult to achieve than claimed. In other words, the percentage of qualifying lamps when measured is largely consistent with the percentage of qualifying lamps when using nominal light output values. Manufacturers have at their disposal a range of technological options for achieving the proposed efficacy levels. The proposed standards levels are achievable and the design changes envisioned are sufficiently robust to meet the proposed efficacy levels.

5 Economic Analysis

5.1 Incremental Cost

We estimate that there will be virtually no net incremental cost associated with meeting Tier 1, since current filament materials and designs optimized for long life can be optimized for higher efficiency instead. The value of the additional energy savings exceeds any consumer losses associated with replacing lamps more frequently. Compliance with Tier 2 would likely yield incremental costs of roughly $0.25 to $0.50 per lamp, which would vary from a modest to substantial price premium depending on the base cost of the particular lamp model in question. The primary driver of uncertainty in the incremental cost is the difficulty of determining the wholesale cost of krypton gas at the purity, quantity, and pressure required to fill a typical incandescent lamp's volume.

Wal-Mart currently sells generic 60-watt soft white incandescent bulbs for as little as $0.19 apiece with identical nominal light output and lifetimes to lamp models from the major manufacturers that retail for $0.24 to $0.29 apiece from mass market discount retailers like Wal-Mart and Home Depot. However, many of the current models that would not comply with the Tier 2 specification are specialized lamps that sell for $0.50 to about $2.00 apiece or more, causing the incremental cost to represent a smaller proportion of total lamp cost. The fact that many models already comply with the proposed standards at competitive prices suggests that manufacturers will find very cost competitive means of compliance over successive design iterations, with the most cost effective approaches rapidly gaining market share. Determining actual incremental cost impacts on a percentage basis for each model is complex for a number of reasons:

- Percentage markups can be very large (200 to 300%) in the incandescent lamp business, in part, because three manufacturers dominate most of the production and two retailers account for about half of all sales. As a result, modest increases in the cost of materials could yield larger retail price increases unless competitive forces reduce markup percentages.
- The base retail price of current incandescent bulbs can range from as little as $0.20 to as much as $10.00, so percentage markups resulting from a fixed incremental cost increase can vary widely.
- Numerous technologies could be employed to improve efficiency, and their costs vary significantly.

5.2 Design Life

Based on an average of 1,000 hours of life and three hours of operation per day, an incandescent lamp will last about one year.

5.3 Life Cycle Cost

Due to this short life, it is not useful to calculate a present value for energy savings. If the average lamp purchase cost increases by $0.25 to $0.50 to improve its efficiency by 10% with constant lamp life of 1000 hours, average lifetime lamp energy consumption would drop from 60 kWh to 55 kWh, saving 5 kWh or about $0.55 to $0.70 worth of electricity per lamp. Net lifecycle savings could be as much as $0.45 per lamp or as little as $0.05 per lamp, with the most likely value in the range of $0.25.

6 Acceptance Issues

6.1 Infrastructure Issues

The proposed efficiency improvement for non-qualifying products is equivalent to a roughly 6 to 10% gain in lumens per watt. Incandescent efficiency gains of 10% can be met through at least two different non-proprietary means – krypton gas fill and infrared-reflective (dichroic) coatings. Other technologies can be employed incrementally and in combination to achieve particular combinations of improved lamp efficiency and longevity, including halogen or xenon gas fill, coiled-coil filaments, increased lamp transparency, reduced number of support wires, and higher temperature ceramic filaments.

6.2 Existing Standards

Current federal standards for incandescent reflector lamps divide the lamps into wattage bins and then use the lamps' rated efficacy as the cutoff.[21] See Table 6 below. Note that these data were collected before the standard took effect, so the typical efficacy at the time was sometimes below the standard efficacy:

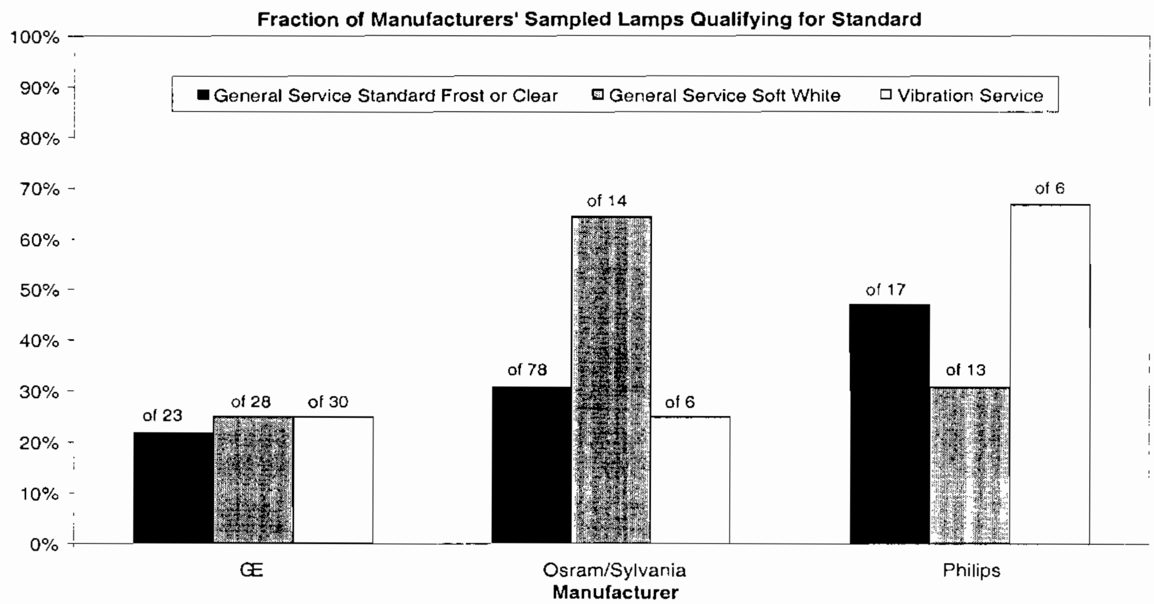
Table 6: EPACT minimum efficacies for incandescent reflector lamps[22]

Nominal lamp wattage	EPACT minimum required efficacy (lumens/watt	Typical efficacy of current models (lumens/watt)
40-50	10.5	10.5
51-66	11.0	10.4
67-85	12.0	10.2-12.0
86-115	14.0	12.0
116-155	14.0	11.4-13.3
156-205	15.0	11.3

The U.S. DOE has no minimum efficiency standards for non-reflectorized GSILs. EPCA in 42 U.S.C 6295 (i4) required DOE to initiate a rulemaking between October 2000 and April 2002 to determine if federal standards should be promulgated for general service incandescent lamps other than the reflectorized ones mandated by EPCA. DOE never initiated that rulemaking. There do not appear to be other applicable state or international standards and specifications.

The effect of the proposed Tier 1 standard on specific manufacturers is displayed below. Note that Philips and Osram/Sylvania tend to offer a greater percentage of qualifying models than General Electric does.

Figure 14.



7 Recommendations

7.1 Proposed Standards

Increased efficiency of incandescent lamps is a significant opportunity for energy savings in California. While efforts should continue to transform the lighting market to higher efficiency fluorescent sources with rebates and other programs, incandescent lamps are excellent candidates for mandatory efficiency standards. To put the energy savings opportunities from incandescent standards into some perspective, it is useful to compare potential energy savings from efficient incandescent lamps to the achieved energy savings from CFLs in California.

The year 2001 was momentous for the sale of CFLs in California.[23] In that year, sales may have been as high as 10 million screw-based CFLs[24] with total energy savings of roughly 700 GWh/year.[25] Estimated annual energy savings for Tier 2, a 10% increase in average efficiency, would yield an equivalent amount of annual energy savings -- 648 GWh/year – with no rebate payments or utility promotion. While a single CFL will save more energy than a single efficient incandescent lamp, incandescent lamps currently sell over 84 million units per year in California and will continue to outsell CFLs for the foreseeable future, providing excellent savings potential for a proposed standard. The main disadvantage to standards, the slight increase in initial cost, may prove to be a benefit, encouraging more customers to consider CFLs and increasing average revenue per lamp sold for lamp manufactures and storeowners, while saving the consumer money over the life of the lamps.

Specifically, we propose that the following language be added to Section 1605.3 (k):

Energy Design Standards for State-Regulated General Service Incandescent Lamps
The power use of state-regulated general service incandescent lamps manufactured on or after the applicable dates shown in Table K, shall be no greater than the applicable values shown in Table K.

Lamp Type	***Maximum Power Use (Watts)***
Tier 1: Effective January 1, 2006	
Frost or Clear	*Watts = 0.0500 * Lumens + 21*
Soft White	*Watts = 0.0480 * Lumens + 23*
Vibration Lamps	*Watts = 0.0730 * Lumens + 13.5*
Tier 2: Effective January 1, 2007	
Frost or Clear	*Watts = 0.0485 * Lumens + 15*
Soft White	*Watts = 0.0490 * Lumens + 15.5*
Vibration Lamps	*Watts = 0.0740 * Lumens + 9*

7.2 Importance of consumer education

Product packaging already includes instructions to "select the lamp with the amount of light needed." This could potentially be improved by indicating the standard incandescent wattage equivalent of the product or by calling much greater attention to lumens as the measure of product utility on the package. In addition to any of the above approaches, it would be useful to require manufacturers to report efficacy on the lamp packaging. This would create a simple scale that consumers could use to quickly and accurately judge lamp efficiency. Efficacy is a particularly useful metric because a bigger number is better, which is easy for consumers to understand. Likewise, some utilities are moving to offer varying rebates for efficient lighting within ranges of lumens, instead of ranges of wattages, helping to further shift consumer mindsets. This topic is discussed in greater detail in a previous report prepared by Ecos Consulting for NRDC entitled *Lighting the Way to Energy Savings: How Can We Transform Residential Lighting Markets?*[26]

7.3 Other needed research

RER/Itron has been collecting detailed retail sales data by lamp model number for the California and national marketplaces since 2000. These data were included in aggregate wattage families for the basic energy savings estimates made in this report. However, we recommend that the California Energy Commission work with RER/Itron to match specific lamp model efficacies and sales numbers as part of its final analysis. Such a process would make it possible to determine with significant precision how many units at which wattages would and would not qualify for proposed standards.

7.4 "Full-spectrum" or "daylight" lamps

A lamp of particular concern is the daylight lamp utilizing a bluish frost or translucent blue finish. These coatings filter out some of the long wavelength visible light to create a higher color temperature.[27] The manufacturers often make claims of more visible color when the lamps are actually filtering color out of the light transmitted. One example is this advertisement text, "Chromalux creates a pleasing, colorful and relaxing atmosphere that is shown to enhance people's sense of comfort and well being." Another example is: "GE Reveal light bulbs uncover what's been hiding under ordinary light!"[28] Unfortunately, the claimed advantage of these lamps comes from a reduction of total light output of approximately 35%. What these lamps actually provide is a color temperature of between 3500 and 4000K, achieved by blocking some of the output of particular colors.[29]

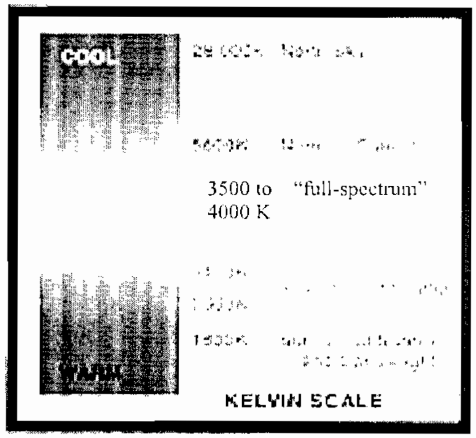


Figure 15: "The spectral distribution of the TBB [Theoretical Black Body] is continuous as it varies from 1800K (candlelight) to 28,000K (north sky)."

This lamp type is a curious anomaly from a lighting design standpoint. Before fluorescent lamps developed into the wide array of color temperature choices we have today, one of the common complaints occupants made of fluorescent light was the "cold" color. Before the use of rare earth phosphors, most fluorescent lamps were the "cool white" variety, having a color temperature of about 4100 K, closer to natural daylight than the incandescent daylight lamps. For those who prefer a high color temperature, fluorescent light sources are a far better option. This highly efficacious light source is available in color temperatures anywhere between 2700 and 6500 K.

While it is clear that "full spectrum" lamps are rising in popularity in spite of their very significant price premiums, it is less clear that scientific evidence supports claims that such lamps yield medical or psychological benefits for users. One common claim is that full spectrum lighting prevents or treats Seasonal Affective Disorder (SAD). While exposure to very bright white light has been proven effective in treating this condition, the type of white light seems to be much less important.[30] What is important is the quantity of light administered at the right period of the day.[31] Full spectrum light does provide better color rendition than some other light sources. However, the color-rendering index of full spectrum lamps is no higher than any other incandescent source, and the efficiency penalty is substantial. Thus, the effect the proposed standards could have on reducing availability of full spectrum incandescent lamps still leaves consumers with viable and more cost effective alternatives, whether the benefits they seek are aesthetic, medical, or psychological.

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[8] RER, Personal communication and database querying, October 2003.
[9] CFL market share on a unit sales basis in California is likely between 3 and 6% at present. Socket share is likely higher, given the longer average lifetime of CFLs than incandescents. See Vicki Fulbright, Andria Jacob, and Chris Calwell, *Compact Fluorescent Light Programs Shine Through the West Coast Power Crisis,* ER-03-11, report prepared by Ecos Consulting for Platts Research and Consulting, July 2003.
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[22] Energy Policy Act of 1992, Public Law 102-486.

[23] Calwell, Chris and John Zugel, Ecos Consulting and Peter Banwell and Wendy Reed, US Environmental Protection Agency. *2001: A CFL Odyssey, What Went Right?*, presented at 2002 ACEEE Summer Study.
[24] Regional Economic Research, *California lamp report 2001*, Vol. 2. Prepared for Southern California Edison, April 30, 2002.
[25] Assumes an annual energy savings per CFL of 71 kWh/year.
[26] Chris Calwell, Chris Granda, Lois Gordon, and My Ton, *Lighting the way to energy savings: how can we transform residential lighting markets?*, prepared by Ecos Consulting for the Natural Resources Defense Council, Volume 1, December 1999, pp. 26-27.
[27] Paradoxically, a high color temperature corresponds to a cool blue light while a low color temperature corresponds to a warm red-orange light.
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NEMA Rationales for Proposed Incandescent Reflector Lamp Regulations
Based on the NEMA-ACEEE Proposal Submitted October 20, 2005 to the CEC

Lamp Type	Change	Rationale
BPAR	Add BPAR (blown PAR) lamps with a diameter of 2.25 inches or more to the definition of "Incandescent Reflector Lamp"	It is unclear from the current definition whether these types are covered or not. Including them in the definition removes ambiguity.
BR30	Exempt 65W and ≤50W	65W BR30 lamps are affordable directional lamps used primarily in residential applications. They have replaced the old style 75W R30 lamps as a result of federal regulations prohibiting BR30 lamp wattage from exceeding 65W. If we regulate them, manufacturers can still produce 65 W products that just meet the standards. This would increase lamp costs but not save any energy. For similar light output, the other options for replacing 65W BR lamps include: much more expensive compact fluorescent lamps that cannot be dimmed; higher wattage inexpensive general service incandescent lamps with no directionality; or more expensive halogen PAR lamps with significantly narrower beam spreads that illuminate less surface area in the home. When these options are considered, study and experience show that consumers would choose inexpensive higher wattage general service lamps often enough that in the best case, no energy will be saved, or in the worst case, more energy will be used. Additionally exempting 50W BR30 lamps allows this low wattage version to remain as an energy-saving alternative to higher wattages.
BR40	Exempt 65W and ≤50W	The most popular BR40 lamps sold today are 120W, 100W and 75W and are used primarily in commercial applications. With the regulation, we expect the majority of consumers to purchase halogen lamps using from 60-100W. By allowing a 65W version, as well as versions of 50W or less, commercial users will also have access to affordable energy-saving directional lamps of a size that fits into their existing light fixtures but use substantially less energy.

ER40	Exempt 65W and ≤50W	ER40 lamps are very low volume types—primarily 120W--used primarily in commercial applications in deeply recessed downlights, where the lamp's optical design helps decrease the amount of light trapped in the fixture. By allowing a 65W version, as well as 50W or less, commercial users will have access to affordable energy-saving directional lamps that fit into their existing installations but use substantially less energy and provide the unique light distribution for the application
ER30	Exempt ≤50W	ER30 lamps, sold primarily in 50W and 75W versions in commercial installations, are also used in deeply recessed downlights. By allowing 50W versions or less, commercial users will have access to affordable energy saving directional lamps that fit into their existing installations and provide the unique light distribution for the application. This exemption is included in the CEC proposal.
R20	Exempt ≤45W	R20 lamps are used in both commercial and residential niche applications, with the 50W version being predominant. An energy saving 45W version is available, and this exemption would guarantee a 5W savings in this category. Eliminating this lamp altogether would drive users to more expensive alternatives, many of which are higher wattage.