Dimming Fluorescent Lamp Ballasts

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1 Executive Summary

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

Dimming fluorescent lamp ballasts serve the same purpose as non-dimming (also known as fixed output) fluorescent lamp ballasts, but with the additional feature that they are able to operate the lamp(s) at a lower light output level. This allows for smarter control of lamp light output, which can lead to significant energy savings over fixtures operated with fixed output ballasts. Interest in dimmable lighting systems is increasing rapidly, and beginning in 2014, new Title 24 building regulations will drive increased adoption of dimming ballasts in new commercial installations in California (CA). And with the absence of state or federal appliance standards to regulate the efficiency of fluorescent ballasts to allow lamp(s) to be dimmed below 50 percent full output, it is imperative that a standard be developed to ensure that dimming ballasts perform efficiently and that energy savings from Title 24 do not fall short of expectations.

There is a broad range of efficiencies among dimming ballasts, most of which are not currently regulated by federal efficiency standards.[1] Higher efficiency dimming ballasts can perform the same operation as lower efficiency dimming ballasts while consuming on the order of 5-10 percent less energy. Given the lack of an existing performance metric useful for evaluating these products, particularly when they operate in dimmed settings, consumers are unable to easily identify high efficiency products. Furthermore, as there is no observable correlation between product efficiency and other key purchase drivers, such as cost, there is unlikely to be significant natural market adoption of higher efficiency products. California, therefore, has a significant opportunity to generate substantial energy savings through an efficiency standard for dimming ballasts.

This CASE Report assesses the potential opportunities for such standards in California. The standards option considered in this report consists of a performance standard requiring minimum energy efficiency at full power and dimmed modes, as well as power quality reporting requirements. Additionally the proposed standard specifies a maximum standby mode power consumption level for bi-way communications-enabled ballasts. The savings associated with the proposed performance standard are estimated to be 300 gigawatt-hours (GWh) per year with a demand reduction of 53 megawatts (MW) after stock turnover.

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[1] Federal standards only apply to dimming ballasts that are not capable of dimming below 50% full output.

2 Product Description

Fluorescent lamp and ballast systems are commonly used to light commercial office space, but can also be found in residential, industrial manufacturing, warehouse, and sign lighting applications. In order to operate, all fluorescent lamps require a ballast. Figure 2.1 below illustrates the key components of a fluorescent lamp. To start the lamp, the ballast provides a high initial voltage to the lamp electrodes (sometimes referred to as cathodes) at each end of the lamp. These electrodes are used to initiate the electrical arc through the tube. The electrical arc excites mercury atoms which produce short-wave ultraviolet light that then causes wall phosphors to fluoresce, producing visible light. The ballast then rapidly limits the lamp current to safely sustain the discharge and keep the lamp lit. Figure 2.2 provides an image of typical fluorescent ballasts.

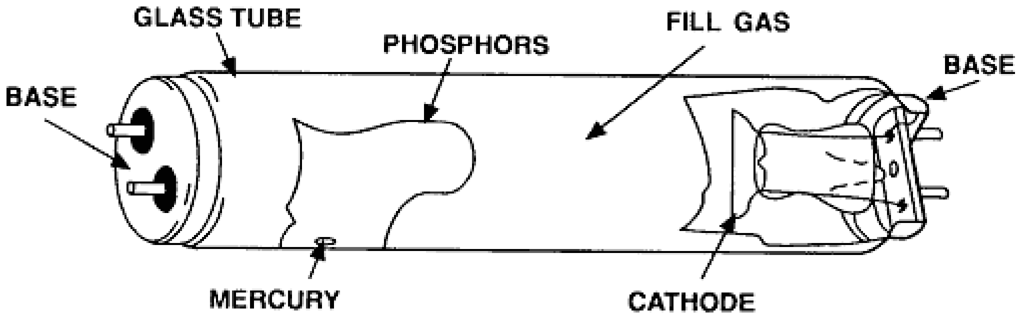

Figure 2.1 Diagram of a Fluorescent Lamp

Source: (Sedlak & Smith 2008)

Figure 2.2 Typical Fluorescent Ballasts

Source: Google Images

For a fluorescent lamp to be dimmed, it must be driven by a dimming ballast, as fluorescent lamps driven by fixed output ballasts cannot be dimmed.

Dimming ballasts are capable of reducing the lamp light output to at least one intermediate light level between 100 percent full output and off mode. Some ballasts known as "step dimming" ballasts, can achieve only one or more specific intermediate light levels, while "continuously-dimming" ballasts can dim gradually to any level from 100 percent down to a specified minimum percent light output. Continuously-dimming ballasts are the focus of this proposed measure, though step dimming ballasts that dim below 50 percent full output are also considered.

The ability to dim light fixtures via the ballast and with the appropriate controls can save significant energy relative to fixed output ballasts by adjusting lamp light output to adaptively meet specific lighting needs in varying conditions (e.g., availability of daylight) and activity levels. For indoor spaces with available daylight, fixtures can be gradually dimmed automatically in response to ambient light conditions (known as daylight harvesting). Manual controls can also be used in parallel to supplement and/or override automatic controls. Common daylight harvesting mechanisms include commercial spaces with windows, skylights, light tubes, and other similar fenestrations. Additionally, dimming ballasts can be used to finely adjust light levels to be better suited to their desired applications. Lighting designers typically specify lighting levels to ensure that minimum illuminance specifications are met while accounting for lamp lumen depreciation and fixture dirt depreciation over the life of the lamp. The process of using dimming ballasts to customize lighting systems to more precisely meet desired levels, known as tuning, improves lighting performance and can also lead to significant energy savings, particularly when combined with the other dimming strategies described previously.

2.1 Ballast Starting Method

Most dimming ballasts today are electronic ballasts, which operate at over 20 kilohertz (kHz), using electronic components to provide for safe operation of the lamp. Electronic ballasts use significantly less energy (on the order of 10 to 30 percent less) than magnetic ballasts (DOE 2011d).

Ballasts are also classified according to the manner by which they start the lamp: rapid start (RS), programmed-rapid start (commonly referred to as programmed start or program start) (PS), and instant start (IS), as defined by American National Standards Institute (ANSI) C82.11-2002. The starting method impacts both lamp life and ballast efficiency.

- Instant start (IS) – These ballasts use a higher voltage to start the lamp but do not provide electrode heating, thereby reducing operating energy consumption. However, the higher voltage used to start the lamp results in decreased lamp life. This is particularly true when lamps are frequently cycled on and off, such as when they are used with occupancy sensors.

- Rapid start (RS) – These ballasts heat the electrodes in the lamp simultaneously during ignition, reducing the voltage required to start the lamp. Although rapid start ballasts take slightly longer (0.5-1.0 seconds) to start the lamp, this results in slightly longer lamp life, due to the reduced stress on the lamp electrodes, compared to IS ballasts.

- Programmed-rapid start (PS) – These are advanced versions of RS ballasts, providing more precise pre-heating of the starting electrodes before igniting the lamp. Stress on the cathodes is minimized resulting in significantly longer lamp life compared to both RS and IS ballasts. Some programmed-rapid start ballasts utilize “cathode cut-out” to remove power to the lamp electrodes after ignition, which saves energy over RS or other non-cathode cut-out PS systems during lamp operation.

IS ballasts are generally more efficient, while RS ballasts offer slightly longer lamp life; neither IS ballasts nor RS ballasts are particularly well suited for use with sensors that increase the number of on/off cycles. PS ballasts, however, are better suited for these applications, as PS ballasts’ treatment of lamp electrodes offers the longest lamp lifetime (DOE 2011d). The vast majority of dimming ballasts are programmed start, though some step dimming ballasts (typically limited to 50 percent or greater minimum power) are instant start.

2.2 Ballast Factor

Ballast factor (BF) is defined by ANSI as the measure of the lumen output of a reference lamp being driven by the ballast in question relative to the output of the same lamp driven by a reference ballast. BF determines the light output for a given lamp-ballast system, and is an important parameter useful to lighting designers and engineers. BF is particularly critical in retrofit applications, where fixture spacing cannot be easily altered, and replacement components (lamps and/or ballasts) may have different performance than the original equipment. For dimming ballasts, BF changes according to the level of light output reduction. Lower BF means lower lamp arc power, corresponding to dimmer lamp operation.

2.3 Ballast Operation

Once the lamp has been lit, the ballast must regulate the electric current flowing through the lamp to control the arc discharge. Fixed output ballasts generally do not require the lamp electrodes to continue to be heated after the arc has been ignited. Ballasts that dim lamps such that they are operating at low lamp arc power levels (below 0.7 BF), however, need to provide electrode heating. This electrode heating is necessary to compensate for the reduced current flowing into the lamp in order to keep the lamp lit at lower lamp arc power levels.

Dimming ballasts are often dimmable far below 0.7 BF, and below this threshold of low lamp arc power, electrode heating decreases the efficiency of these ballasts. Figure 2.3 plots ballast luminous efficiency (BLE) as a function of lamp arc power for a continuously dimmable ballast that utilizes cathode cutout at higher light output levels. BLE is an efficiency metric for fluorescent ballasts defined as the lamp arc power divided by the ballast input power. A more thorough explanation of the BLE metric is provided in Section 4.1. Reading from right to left along the graph in Figure 2.3, the lamp is dimmed from 100 percent full output down to the point where the lamp no longer remains lit in 5 percent increments. The gentle stair-step decrease in efficiency, occurring about midway down the dimming curve, illustrates the point at which cathode heating re-engages.

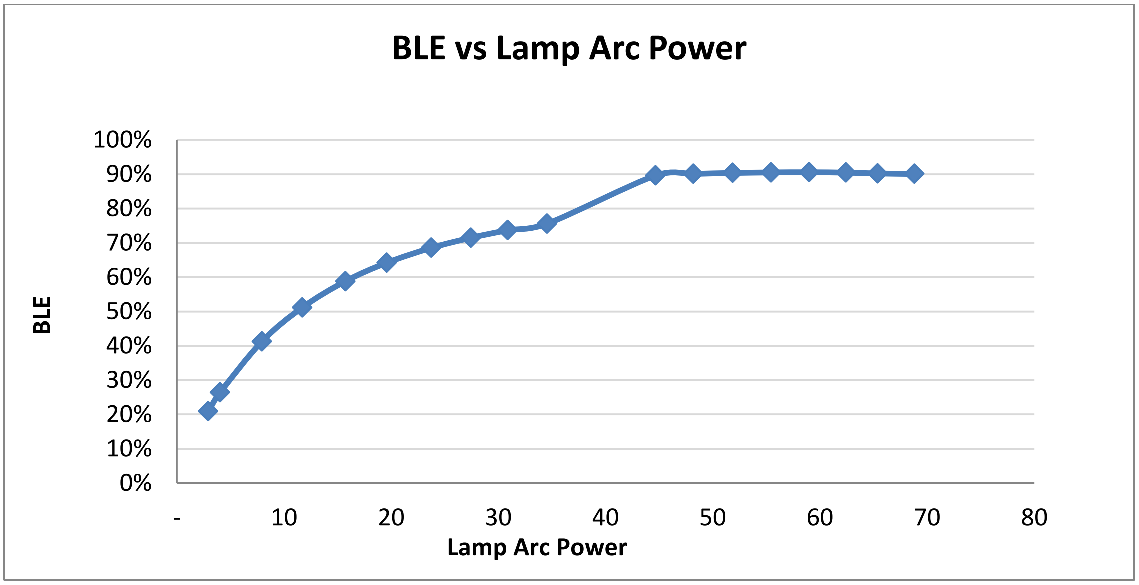

Figure 2.3 BLE as a function of lamp arc power for a dimming ballast that utilizes cathode cutout above 0.7 BF

Source: CASE Team analysis

This process can also be illustrated by examining the relative light output of the ballast as a function of the relative input power, as in Figure 2.4 below. Again, for the same ballast as in Figure 2.3, reading from right to left, the lamp is dimmed down from 100 percent full output in 5 percent increments. The otherwise roughly linear relationship between relative input power and relative light output is broken up by the point of cathode heating re-igniting. Not all dimming ballasts utilize cathode cutout at full light output; though less efficient at full output, many dimming ballast simply use cathode heating in all operating modes.

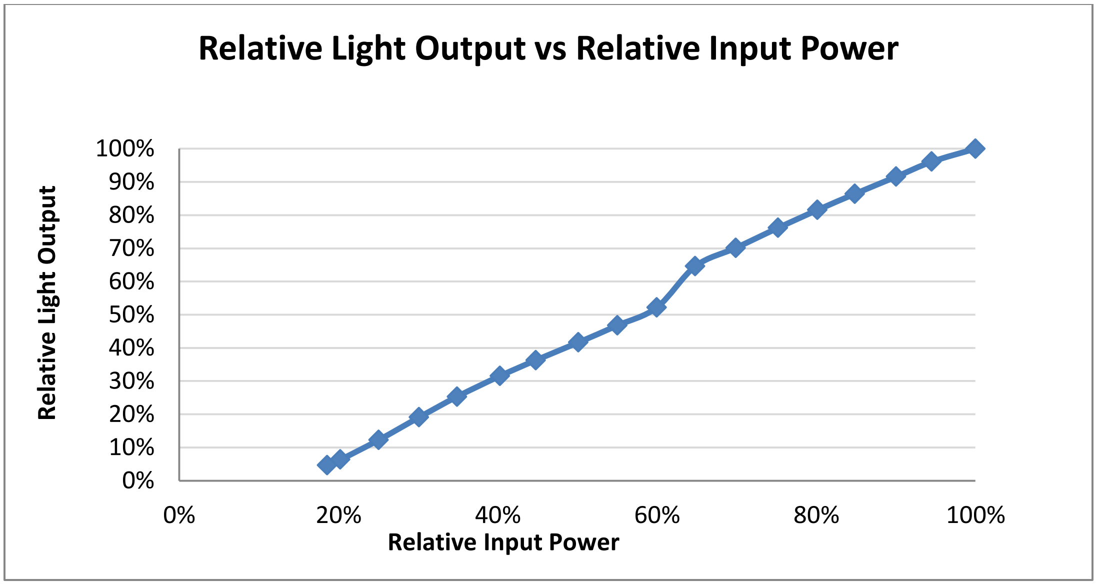

Figure 2.4 Relative light output as a function of relative ballast input power for a dimming ballast that utilizes cathode cutout above 0.7 BF

Source: CASE Team analysis

2.4 Controls

There are three common non-proprietary methods for controlling continuously dimmable ballasts: (1) phase control, (2) 0-10V, and (3) digital addressable lighting interface (DALI). Phase control is most common in dimmable ballasts intended for residential installations. Phase control ballasts typically work with standard incandescent dimmer switches, and are therefore compatible with many existing residential lighting circuits. The biggest advantage to phase control ballasts is their simplicity in terms of installation and operation. The ballast is dimmed by chopping the 60 hertz (Hz) voltage waveform, which the ballast interprets as a command to dim. This requires no extra wiring (other than the hot and neutral power wires), and uses relatively inexpensive control devices. On/off control is achieved by the dimmer switch, which severs all power to the ballast in off mode. The disadvantage to standard phase control is its limited dimming range, due to the fact that the ballast must deal with a non-sinusoidal voltage waveform with decreasing power, as the dimmer switch continues to trim the amount of energy delivered to the ballast. While this works naturally for incandescent technology, it is not an ideal way to control fluorescent technology.

In commercial lighting installations, 0-10V and DALI are much more common. 0-10V ballasts are controlled by a signal that varies between approximately one and ten volts direct current (V DC), where higher voltage tells the ballast to product full light output and lower voltage instructs the ballast to go to minimum light output (i.e. not off mode). On/off control is achieved by a switch or relay built into the 0-10V control device, which severs all power to the ballast in off mode. 0-10V ballasts are simple to control but require dedicated low-voltage control wiring in addition to the power wiring, which can increase installation labor and material costs.

DALI is the most sophisticated of these three methods. Again, the ballasts require dedicated low-voltage control wiring in addition to the power wiring, which can increase installation and labor costs. Furthermore, DALI control systems are typically more complex and expensive. However, DALI has the capability to individually address ballasts in a system (i.e., each ballast can be handled separately even though they are all connected to the same power and control wiring). This allows for bi-directional communication between the ballast and control system, easily reconfigurable lighting zones, status monitoring, and diagnostics, in addition to dimming. On/off control of the lamps is achieved by a switch built into the ballast itself, which is controlled by signals received over the control wiring. The ballast is typically connected to a constant voltage waveform that is never switched off. This constant power supply is needed to keep the ballast's internal DALI controls active so the ballast can communicate with the control system over the control wiring and receive commands for on/off or status queries. As a result, the ballast consumes power even when the lamps are off (known as standby mode). While some manufacturers claim that standby mode power consumption is typically less than one watt,[2] CASE Team test results show a range between 0.3 to 1.9 watts (explained in greater detail in Section 4.7).

Some manufacturers design their own proprietary implementations based on non-proprietary control methods. Examples include Lutron TuWire and 3-wire (modified phase control), and Lutron EcoSystem (modified DALI). Another proprietary strategy is power line carrier (PLC), where a relatively low-amplitude control signal is superimposed on top of the higher voltage 60 Hz waveform for the branch lighting circuit. Using PLC, dimmable ballasts receive power and control signals over the same two wires. Like phase control, this has the advantage of not requiring standalone control wires, which can reduce installation labor and material costs. However, this method requires a power line injector to superimpose the control signal on top of the 60 Hz voltage waveform for each branch lighting circuit.

2.5 Ballast Efficiency

Energy efficiency of dimming ballasts can be quantified in terms of ballast efficacy factor (BEF) or the ballast luminous efficiency (BLE) metric newly developed by DOE, which has been used to set new federal energy efficiency standards for fixed output ballasts and ballasts that do not dim below 50 percent full output. BEF and BLE have traditionally only been measured and reported at full output operation.

Though ballast efficiency has not historically been a major selling point for dimming ballasts, and manufacturers do not have product lines distinctly differentiated by efficiency, there are organizations that attempt to identify efficient products on the market. The Consortium for Energy Efficiency (CEE) maintains a list of "High-Performance Dimming Ballasts," which represent dimming ballasts that meet the programmed-rapid start requirements of the "High Performance T8 Specification" (originally developed for fixed output ballasts) at full light output. This list is partially provided in Appendix A:. The National Electric Manufacturers Association (NEMA) also maintains a list of "Premium" efficiency dimming ballasts.

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[2] Osram lists standby power consumption as 200mW for 1-/2-lamp systems, 500mW for 3-/4- lamp systems. http://www.osram.de/media/resource/HIRES/333539/2037986/OSRAM-DALI-Pro---FAQ.pdf.

3 Manufacturing and Market Channel Overview

Major manufacturers of dimming ballasts include the following five companies:

- Advance Transformer of Philips Lighting
- GE Consumer and Industrial of General Electric, Inc.
- Lutron Electronics Company, Inc.
- OSRAM Sylvania of Siemens AG
- Universal Lighting Technologies

Other manufacturers of dimming ballasts found on CEE's list of "High-Performance Dimming Ballasts" include the following companies:

- ELB Electronics, Inc.
- Espen Technology, Inc.
- Fifth Light Technology
- iDim
- LUMEnergi
- Pure Spectrum
- Robertson Worldwide
- Sage Lighting Ltd.
- Sunpark Electronics
- Ultrasave Lighting Ltd.

Fluorescent ballasts are typically purchased either as part of new fluorescent fixtures or as replacement ballasts for existing fixtures. New fluorescent fixtures are commonly specified and purchased by architects, lighting designers, building engineers, or electrical contractors. Commercial customers, including building managers and engineers, or other design and engineering professionals are also commonly responsible for the purchase of fluorescent fixtures or replacement ballasts. Both fluorescent lamp fixtures and ballasts are generally purchased either from lighting distributors, or in some cases, directly from the manufacturing companies themselves.

Though less common, residential customers, and some commercial customers, also purchase fixtures through retail channels including home improvement centers, hardware chains, and other mass merchandisers.

4 Energy Usage

4.1 Test Methods

4.1.1 Current Test Methods

Ballast efficiency has historically been measured using the BEF metric. BEF is defined as the ratio of the ballast factor (percent) to the ballast input power (W); ballasts with higher BEFs are more efficient. ANSI National Standard C82.2-1984 sets forth the test conditions required for measuring BEF. For dimming ballasts, BEF is generally only measured and reported at full light output.

There are some inherent shortcomings to the BEF metric. For instance, BEF cannot be scaled across ballasts designed to operate different lamp wattages or lamp quantities; a 4-lamp ballast and a 2-lamp ballast with comparable efficiencies will have very different BEFs. Past efficiency standards therefore required multiple product classes to be able to provide even coverage of different ballasts.

In the most recent rulemaking to revise federal ballast standards (which take effect November 14, 2014), DOE -- informed by many months of research as well as input from industry representatives and energy efficiency advocate groups -- developed a new metric and test method to measure ballast efficiency. This metric is known as "ballast luminous efficiency" (BLE), and is defined by the following equation:

Equation 4.1 Equation that defines ballast luminous efficiency (BLE)

$$BLE = \frac{Measured\ Lamp\ Arc\ Power}{Ballast\ Input\ Power} * 100 * \beta$$

Where β is defined as an adjustment factor used to account for the lamp efficacy advantages of high frequency operation.

BLE scales between ballasts designed to operate lamps of different wattages and different lamp quantities, allowing for greatly simplified product class breakdowns. This in turn facilitates more complete and uniform standards coverage of different ballast types.

DOE provides the complete test procedure in *10CFR Part 430: Test Procedures for Fluorescent Lamp Ballasts, Final Rule*. It includes a procedure for measuring standby power consumption, though this measurement is not required for compliance with the federal standard. Additionally, DOE provides guidance to account for variation in test results among ballasts of the same model in *10CFR Parts 429, 430, and 431: Certification, Compliance, and Enforcement for Consumer Products and Commercial and Industrial Equipment; Final Rule*. This rule requires a minimum of four samples of a single ballast model be tested, and relies on statistical analysis to determine a representative result for the model.

4.1.2 Proposed Test Methods

Though BLE was originally designed for use with fixed output ballasts, we propose to apply the test procedure to dimming ballasts as well, with a slight modification. We propose that manufacturers must measure and report BLE per the test procedure outlined in *10CFR Part 430* at dimmed settings in addition to at 100 percent full power. For continuously dimming ballasts, we propose to require three total measurements: 100 percent full power, 80 percent of the manufacturer's full rated ballast input power, and 50 percent of the manufacturer's full rated ballast input power. To achieve the dimmed operating modes, ballasts must be connected to a single, generic, commercially available, compatible controls device. If the product does not operate with a generic controls device, it shall be tested with the manufacturer recommended, commercially available, compatible controls device connected in a single configuration. The controls device will then be adjusted by the testing technician such that the ballast input power being measured by the connected test equipment is equal to the desired percent of full rated ballast input power for each test. At this point, the BLE test measurements are recorded, as they normally would be at full output. For step dimming ballasts, we propose to require BLE measurements only at steps where the ballast is able to operate.

In addition to BLE, we also propose to require the measurement and reporting of power factor (PF) and total harmonic distortion (THD) on the ballast input current at each of these three operating modes. For step dimming ballasts, we propose to require measurements at 100 percent full power and each dimming step. Finally, for DALI and other communications-enabled ballasts, manufacturers will also be required to measure and report standby power consumption per the test procedure outlined in *10CFR Part 430*, with a slight modification. In Section 3.2.1, DOE specifies that these products “shall be tested with all commercially available compatible control devices connected in all possible configurations” (DOE 2011b). However, we believe this to be unnecessarily burdensome and propose that fluorescent lamp ballasts capable of connections to controls devices be tested with a single, generic, commercially available, compatible controls device connected in a single configuration, as described above in the BLE measurement for dimmed operating modes.

For all measurement points, it is necessary to apply, DOE methodology for accounting for variation in test results among ballasts of the same model, as defined in *10CFR Parts 429, 430, and 431: Certification, Compliance, and Enforcement for Consumer Products and Commercial and Industrial Equipment; Final Rule*.

4.2 Energy Efficiency Testing

The CASE Team conducted independent testing on 88 ballasts (including multiple samples of 34 unique ballasts) to evaluate their energy efficiency, applying DOE’s BLE test procedure at full output and throughout their dimming ranges. The ballasts were chosen from the CEE list of qualifying high performance dimming ballasts, with a focus on product lines from major manufacturers. However, two of the selected ballast models were unavailable at the time of procurement, so replacement ballasts suggested by the distributor were ordered in their place. These replacement ballasts were not CEE-listed products.

A mix of ballast factors, lamp numbers, dimming ranges, and control methods were selected to evaluate the full range of dimming ballasts. Figure 4.1 below illustrates the results of the testing for the 34 unique ballasts. Each line represents the tested dimming performance of a single ballast. The test results demonstrate a wide range of performance at full output, as well as throughout the dimming range.

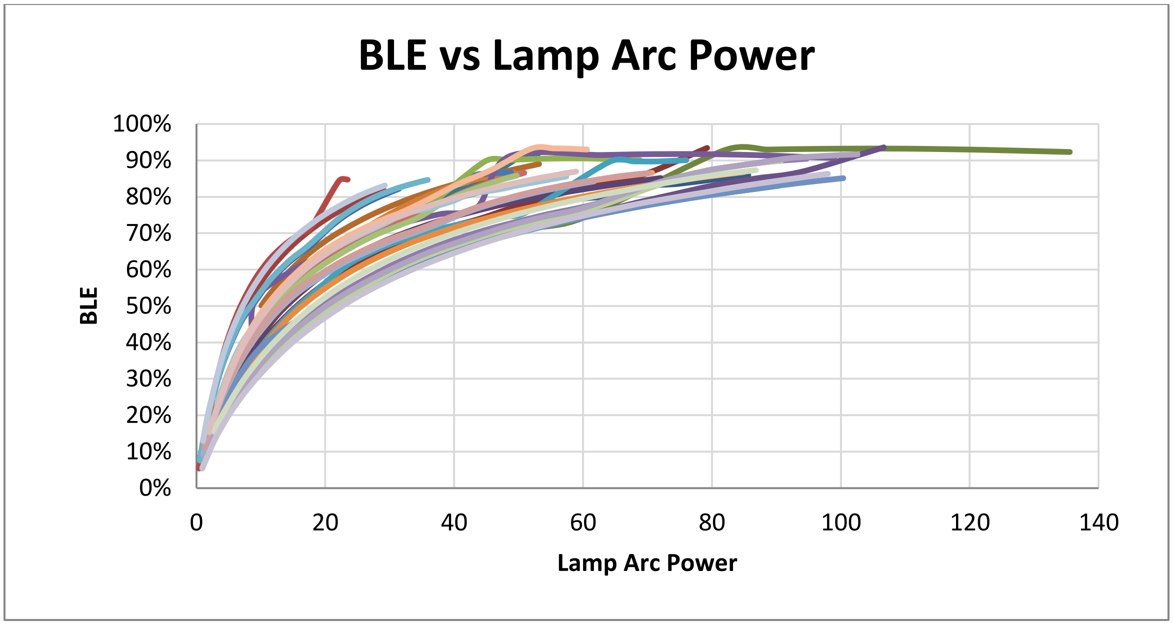

Figure 4.1 Complete test results from CASE Team's independent testing of 34 unique dimming ballasts throughout their dimming range

Source: CASE Team analysis

All of the tested ballasts follow a similar performance curve in that efficiency decreased as they were dimmed. However, not all ballasts suffered the same decrease in efficiency at the same rate. In other words, some ballasts were better performers in dimmed states relative to their full output performance. In addition, from examining the test data, it was clear that not all dimming ballasts are using cathode cutout at full output, as all ballasts did not exhibit a stair-step efficiency decrease at around 0.7BF. Interestingly, dimming ballasts that did use cathode cutout at full output where not always more efficient than ballasts that did not use cathode cutout, even when near full output operating levels.

As all but two unique ballasts were CEE-listed products from major manufacturers, we expect that the range of efficiencies being evaluated is towards the top end of the full dimming ballast market. Figure 4.2 below presents the full output measurement points for each of the ballasts tested (after removing the dimming curves that drop off from each of these high points). This simplified graph allows for easier analysis of the full output performance of the tested ballasts and has been color coded by the number of lamps the ballasts operate. As with fixed output ballasts, dimming ballasts that operate fewer lamps are generally less efficient than those that operate more lamps. This figure also clearly shows that the non-CEE-listed ballasts are underperforming the majority of the CEE-listed ballasts at full output.

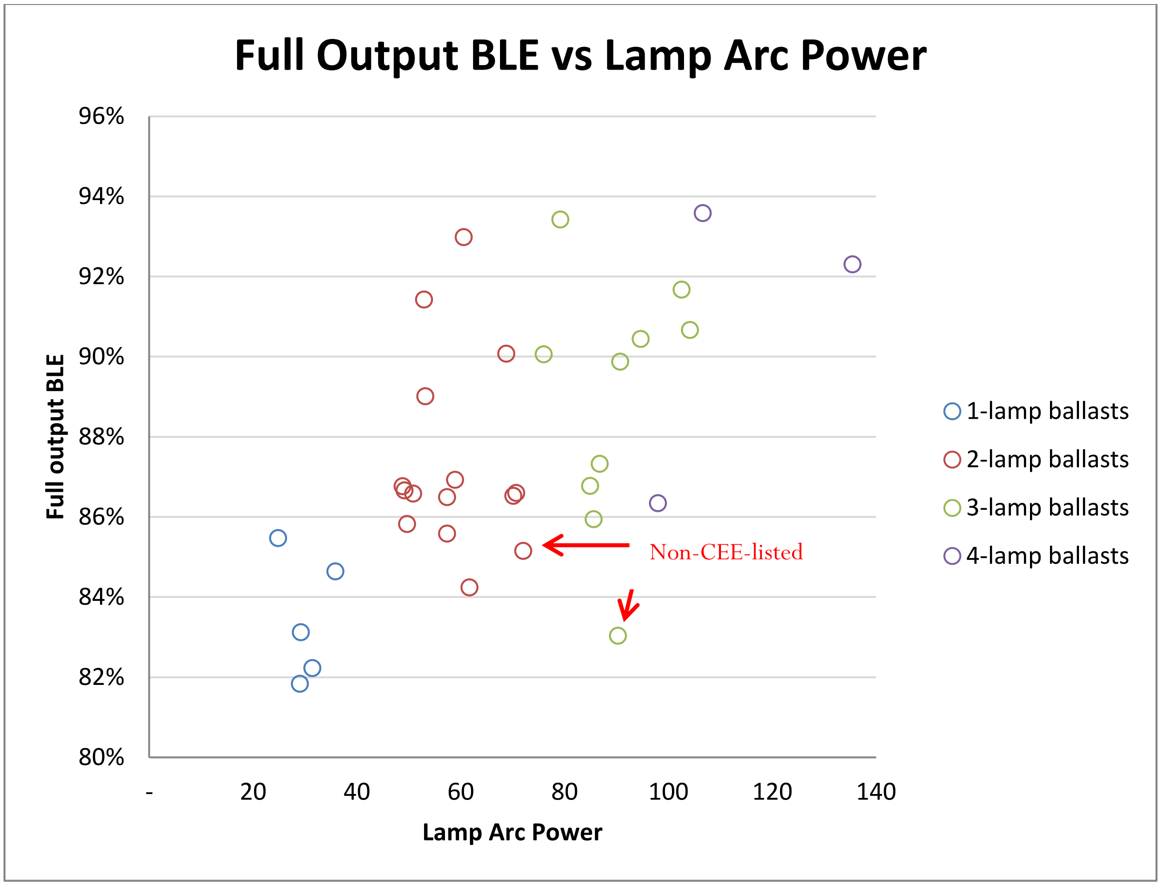

Figure 4.2 Full output BLE vs Lamp Arc Power for all tested ballasts, highlighting low performing non-CEE-listed ballasts

Source: CASE Team analysis

Outside of the set of ballasts SCE tested, no other BLE-based data exists or has been reported for dimming ballasts, particularly when considering dimmed operating states. Therefore, we could rely only on this dataset to draw conclusions about the performance of high, medium, and low efficiency products.

4.3 Energy Use Per Unit for Non-Qualifying Products

The most direct path to energy savings is to require minimum BLE levels for dimming ballasts at full output and in dimmed modes.

Energy use for tested non-qualifying products, products that do not meet the proposed minimum BLE levels described in Section 10.1 of this report,[3] is presented in Table 4.1 Average Energy Use for Non-Qualifying Products below.

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[3] See Section 10.

Table 4.1 Average Energy Use for Non-Qualifying Products

Operating Cycle	**Power Draw (W)**	**Annual Operating Hours[a]**	**Unit Electricity Consumption (kWh/yr)**
Full output	69.9	637	44
Mid-dimmed	57.3	1,592	91
Low-dimmed	35.5	955	34
Total		3,184	209

Source: CASE Team analysis

[a] Hours spent in standby mode not included.

To develop a representative performance curve as a function of lamp arc power, power draw at full and dimmed outputs was estimated by finding the average efficiency at each measurement point for all non-qualifying products. The dashed red line in Figure 4.3 provides an example of this curve at full output.

Based on California utility best estimates, the CASE Team assumes that the average total annual operating hours for fluorescent ballasts in commercial buildings is 3,184 hours (see Appendix C). This analysis also assumes a dimming profile, where ballasts spend 20 percent of their operating hours at 100 percent full output, 50 percent of their operating hours at 80 percent of full output, and the remaining 30 percent at 50 percent full output. The assumed dimming profile results in 25 percent energy savings over operation at 100 percent full output only. This falls within the range of expected energy savings from different control types, as compiled in a meta-analysis conducted by Lawrence Berkeley National Laboratory (Williams et al. 2011). This dimming profile assumption is used to weight the importance of savings at different stages along the dimming curve and to provide a more realistic estimate of total annual energy use for these products.

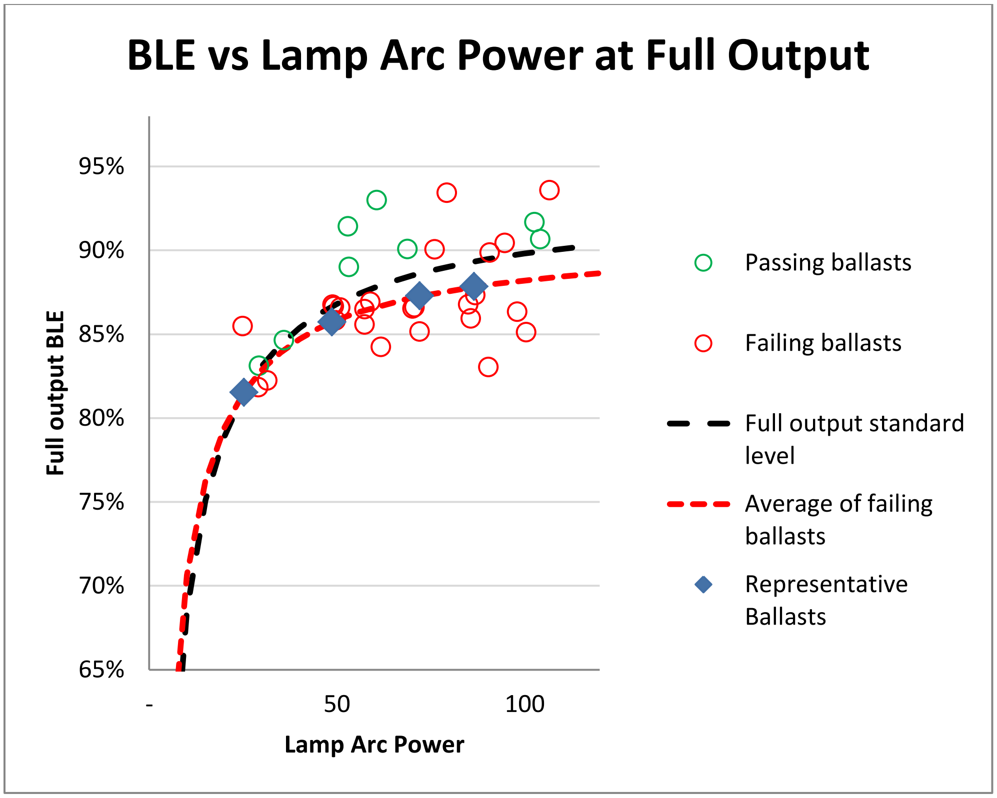

Figure 4.3 Using representative lamp arc powers to calculate non-qualifying product energy use

Source: CASE Team analysis

Figure 4.3 illustrates how the energy use of non-qualifying products is calculated through the use of a representative performance curve. Similar to Figure 4.2, this figure only shows the full output points for each of the ballasts tested. The dotted black line represents the proposed standard level at full output as a function of the lamp arc power. The red dotted line represents the average performance in terms of BLE and as a function of lamp arc power of all non-qualifying products.

As also evident in Figure 4.2, ballasts that operate different numbers of lamps require different amounts of power, and drive different lamp arc powers. 4-lamp ballasts require more power than 3-lamp ballasts, which require more power than 2-lamp ballasts, etc. Relying on the test data, the CASE Team took the median lamp arc power for 1-, 2-, 3-, and 4-lamp ballasts as representative of each type of ballast. These representative lamp arc powers are used to determine average efficiency and ballast input power of non-qualifying 1-, 2-, 3-, and 4-lamp ballasts.

To determine the representative ballast input power for each type of non-qualifying ballast at full output, we use the median lamp arc powers in the formula represented by the dotted red line in Figure 4.3 for the average full output ballast efficiencies of non-qualifying products. This yields the average non-qualifying product BLE at each representative lamp arc power (represented by the blue diamonds in the figure), which can be easily converted to ballast input powers. In order to develop representative non-qualifying product energy use, the CASE Team used a historical shipments analysis from DOE to create a weighted average of 1-, 2-, 3-, and 4-lamp ballasts.

Table 4.2 presents the assumed market breakdown of shipments for these four types of fluorescent ballasts and their respective median lamp arc powers.

Table 4.2 Representative lamp arc power and market share for different ballast types

Ballast Type	**Representative Lamp Arc Power**	**Market Share**
1-lamp	25W	11%
2-lamp	49W	43%
3-lamp	72W	19%
4-lamp	87W	27%

Source: CASE Team analysis

This entire process must be repeated to find the representative product energy use in each dimmed operating mode, at 80 percent of full rated output and 50 percent of full rated output. Finally, the assumed duty cycle is used to weight the total average energy use of the representative ballast across the different operating modes.

The final estimates for non-qualifying product average energy use are expected to be low, given that our dataset was constructed almost exclusively from the CEE list of the highest performing products on the market. The measured BLE of the two non-CEE-listed ballasts highlighted in the previous section suggests that the actual market average non-qualifying product energy use is likely to be significantly higher.

4.4 Efficiency Measures

Though commonly defined tiers of efficiency levels within the dimming ballast market do not exist, there is in fact a wide range of efficiency among dimming ballasts. As with fixed output ballasts, dimming ballast efficiency can be improved through the use of higher quality electrical components. DOE research into fluorescent ballast technology showed that four specific component types could be upgraded to improve ballast efficiency:

- Magnetics (transformers and inductors) – these components influence the efficiency of the electromagnetic interference, power factor correction, and output stages of ballast operation.
- Diodes – diodes with lower voltage drop consume less power and contribute to more efficient ballasts.
- Capacitors – use of capacitors with low effective series resistance improves efficiency and reliability of the power factor correction, DC filtering, and output stages of ballast operation.
- Transistors – improved transistor efficiency impacts both the power factor correction and DC-AC inversion stages of ballast operation (DOE 2011d).

Additionally, RS and PS ballasts that provide electrode heating prior to starting the lamp can employ “cathode cut-out” technology, removing the electrode power once the lamp has been started. This can reduce ballast power consumption by as much as 2 watts per lamp. However, below a certain level of dimming, electrode heating must be re-engaged to ensure that the lamp remains lit. Efficient dimming ballasts should be capable of scaling the cathode heating as needed, inversely to the light output.

4.5 Energy Use per Unit for Qualifying Products

Energy use for qualifying products that meet or exceed the proposed minimum BLE levels described in Section 10.1 of this report is presented in the table below.[4] The same methodology and set of assumptions described in Section 4.3 regarding representative lamp arc powers and market shares of 1-, 2-, 3-, and 4-lamp ballasts were applied for qualifying products' energy use calculations as well. As with the non-qualifying products, representative lamp arc powers were used in conjunction with a representative ballast performance curve for qualifying products to determine BLE and energy use for each ballast type. The results of these calculations are presented in Table 4.3 below.

Table 4.3 Average Energy Use for Qualifying Products

Operating Cycle	**Power Draw (W)**	**Annual Operating Hours[a]**	**Unit Electricity Consumption (kWh/yr)**
Full output	67.4	637	43
Mid-dimmed	52.8	1592	84
Low-dimmed	33.15	955	32
Total		3,184	159

Source: CASE Team analysis

[a] Hours spent in standby mode not included.

4.6 Impact of Dimming Standard

To date, efforts to evaluate the efficiency of dimming ballasts have centered on the full output efficiency of these products, without consideration of their performance when dimmed. The following figures plot the full output, 80 percent output, and 50 percent output BLE versus lamp arc power for each dimming ballast tested. The following set of plots, Figure 4.4 and Figure 4.5, illustrate the consequences of setting a standard for full output performance only.

In Figure 4.4 and Figure 4.5, the red circles represent ballasts that fail the proposed efficiency standards (non-qualifying products) and the green circles represent ballasts that pass the standards (qualifying products). Figure 4.4 defines a standard level only for full output efficiency, while Figure 4.5 defines standard levels for full output and dimming efficiency. In both figures the dashed black lines represent the proposed standard level for ballasts operating at full output. This line is provided on all graphs for reference, as the scale for each graph was modified to present the data more clearly.

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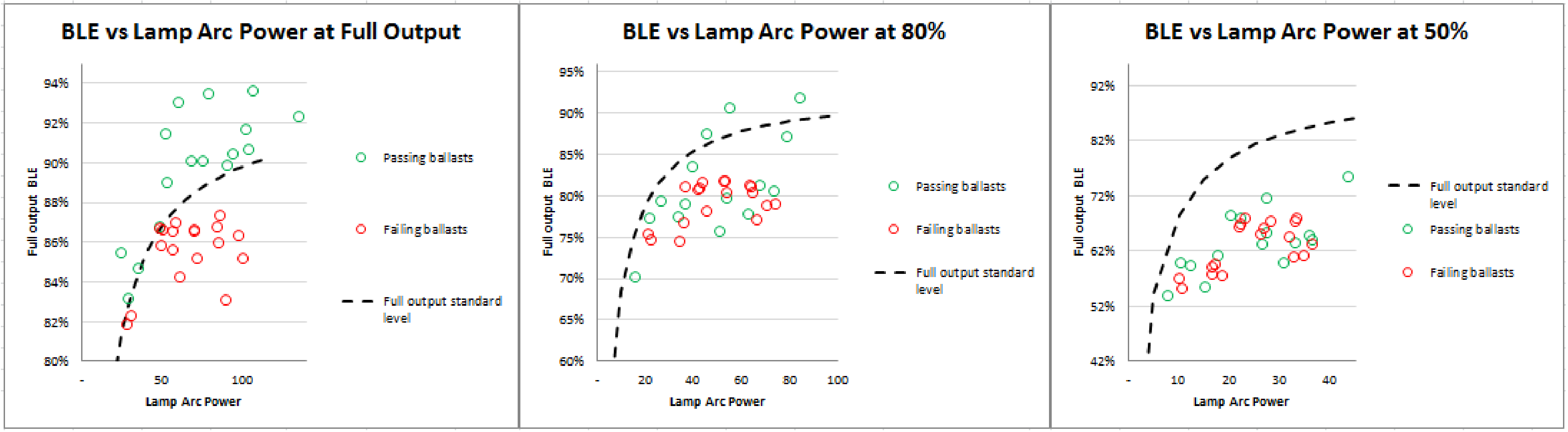
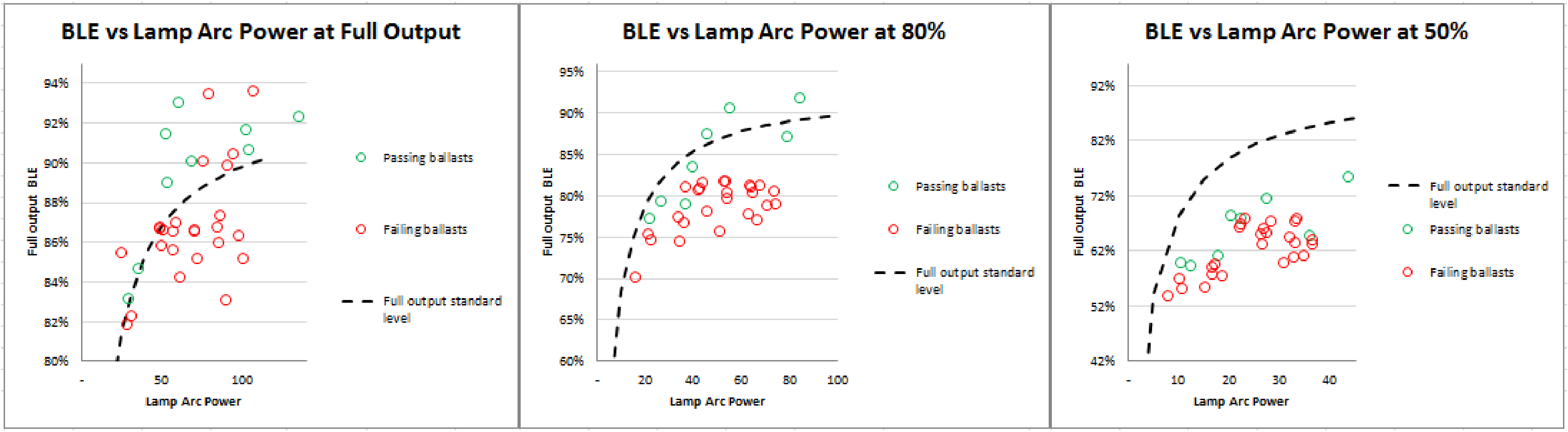
[4] See Section 10.


BLE vs Lamp Arc Power at Full Output

BLE vs Lamp Arc Power at 80%

BLE vs Lamp Arc Power at 50%

Figure 4.4 Passing and failing ballasts at full output, 80%, and 50% of full output, with a standard set based on full output efficiency only


BLE vs Lamp Arc Power at Full Output

BLE vs Lamp Arc Power at 80%

BLE vs Lamp Arc Power at 50%

Figure 4.5 Passing and failing ballasts at full output, 80%, and 50% of full output, with a standard set based on full output efficiency as well as a minimum standard for dimming performance

As described above, in Figure 4.4, a standard has been set only for full output efficiency, ignoring ballast performance at dimmed states. As these figures indicate, many ballasts that pass the standard levels set at full output are not necessarily the best performers when dimmed. The mix of passing and failing ballasts at 80 percent and 50 percent of full output appears almost as random. Given that most dimming ballasts are expected to be operating in dimmed states most of the time, efficiency when dimming is as important as efficiency at full light output. Therefore, it is imperative to apply a standard that addresses dimmed state efficiency as well. Figure 4.5 is based on the same full output standard level combined with a modest standard for dimming performance. As indicated, some ballasts that meet the standard at full output are no longer considered passing ballasts, as they underperform when dimmed. However, the plots at 80 percent and 50 percent of full output look very different compared to Figure 4.4. With the moderate dimming standard in place, the passing ballasts generally outperform the failing ballasts at the dimmed operating modes, so the mix of green and red circles appears much more organized. Together, these two sets of figures show that a standard that includes minimum requirements for dimming performance is absolutely necessary to ensure that qualifying products are best performers, not only at full output but also throughout the expected range of dimming.

4.7 Standby Mode Energy Use

As previously discussed, many dimming ballasts are equipped with electronics that allow for digital addressing and two way communication between the ballast and a central control system. These communications-enabled ballasts consume energy even when they are not operating lamps for the purpose of being ready to accept commands from the central control system. The CASE Team measured standby mode energy use for 15 unique communications-enabled ballasts and found a range of standby mode energy use for these products. As shown in Figure 4.6 below, standby power use varied significantly, from around 0.3W to 1.9W.

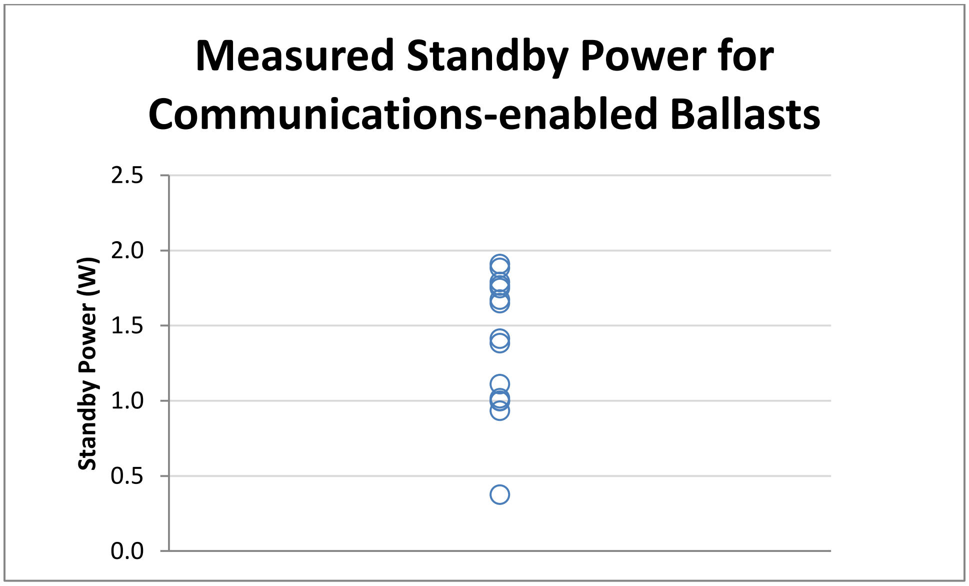


Figure 4.6 Graphical representation of measured range of standby power for communications-enabled ballasts

Source: CASE Team analysis

This significant variation in standby power for communications-enabled ballasts represents an excellent opportunity for energy savings. There could be a potential difference of 1 W or more between qualifying and non-qualifying products.

5 Market Saturation & Sales

5.1 Current Market Situation

5.1.1 Impact of New Building Codes

Currently, annual sales and existing stock of dimming ballasts in California are relatively small compared to fixed output ballasts. However, changes to the California Building Efficiency Standards (Title 24), adopted by the CEC in 2012, will greatly impact future fluorescent ballast sales; the new version of the code will take effect in January 2014.

In the newly adopted building standards, Section 130.1(b) “Multi-Level Lighting Controls” states that all fluorescent lighting systems installed in any enclosed area 100 square feet or larger,[5] with a connected lighting load that exceeds 0.5 watts per square foot be capable of the number of control steps detailed in Table 5.1. These requirements will likely result in a very large increase in annual sales of dimmable fluorescent ballasts in California.

Table 5.1 Control requirements for linear fluorescent lamps; modified from Title 24: TABLE 130.1-A MULTI-LEVEL LIGHTING CONTROLS AND UNIFORMITY REQUIREMENTS

Luminaire Wattage	Minimum Required Control Steps (% full rated power)				Uniform level of illuminance shall be achieved by:
<13 Watts	Minimum one step between 30-70%				Step dimming; or Continuous dimming; or Switching alternate lamps in a luminaire
>13 Watts	Minimum one step in each range:				Stepped dimming; or Continuous dimming; or switching alternate lamps in each luminaire, having a minimum of 4 lamps per luminaire, illuminating the same area and in the same manner
	20-40%	50-70%	80-85%	100%	

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[5] Exceptions to this requirement are classrooms with a connected general lighting load of 0.7 watts per square foot or less (which are required to have at least one control step between 30-70 percent of full rated power), and areas enclosed by ceiling height partitions with only one luminaire consisting of no more than two lamps.

5.1.2 Total Stock and Annual Sales

DOE analyses in support of federal ballast standards provide a foundation for determining annual shipments and total stock in California for fixed output ballasts (DOE 2011d). The DOE documentation includes estimates of annual national fluorescent ballast shipments from 2006 through 2045, broken up by product class and purchase type. DOE's estimates for IS, RS, and PS ballasts that operate commercial medium bi-pin lamps are most relevant to this measure, so only shipments of these ballast types have been included in the analysis. Additionally, Title 24 primarily impacts the retrofit and new construction markets (as opposed to replace on burnout), so only retrofit and new construction shipments need to be counted.

The CASE Team estimates that California represents 10.8 percent of national fluorescent ballast sales, based on the percentage of national commercial floor area in the Pacific West census region (EIA 2003) and the portion of the Pacific West population that resides in California (Census Bureau 2010). Applying this assumption regarding the fraction of national ballast shipments in California, along with the expected impact of Title 24 on the market penetration of dimming ballasts in retrofit and new construction, results in estimated annual shipments of 2.3 million units in California in 2015.

For this measure, the CASE Team estimates the installed stock of dimming ballasts in California (not including fixed output ballasts) to be on the order of 3.7 million at the start of 2014. However, shipments are expected to grow dramatically in 2014 with the implementation of the new controllable lighting requirements in Title 24, with stock also increasing beginning in 2014. The CASE Team estimates the current total stock of fluorescent ballasts in California (including both dimming and fixed output) to be over 100 million, which represents the upper bound of the potential impact of this standard.

Table 5.2 provides an indication of the annual sales and total stock of fluorescent dimming ballasts in 2015.

Table 5.2 California Stock and Sales - 2015

Product Class	**Annual Sales**	**Stock**[a]
Dimming Ballasts	2.3 million	100 million

Source: CASE Team analysis

[a] 2015 stock of all fluorescent ballasts, including fixed output ballasts. Currently this stock is largely comprised of fixed output ballasts. After new Title 24 standards become effective in 2014, the stock of dimming ballasts is expected to increase substantially.

To determine the peak demand and peak demand reduction potential associated with fluorescent ballasts, the CASE Team used the coincident diversity factors reported by the California Public Utility Commission's Energy Division to utilities in BaseCamp on January 26, 2011 (see Appendix C). The CASE Team has preliminarily used the average value, 0.64, across all commercial building types.

5.1.3 Market Shares of High Efficiency Options

The precise market share of high efficiency dimming ballasts is not well known. The primary factors being considered in ballast purchases include a range of different product features independent of efficiency. These features include ballast control type, communications capability, and cost. As product cost and functionality are likely to be the key factors influencing most purchasing decisions, this report assumes an equally weighted distribution of market share for ballasts of different efficiencies (product cost and functionality have not been shown to be directly correlated to ballast efficiency, absent sales data for specific dimming ballast product lines). Therefore, given that the chosen standard level represents qualifies roughly 26 percent of all products tested, the CASE Team has determined that total annual sales of qualifying products are currently 26 percent of total dimming ballast sales.

5.2 Future Market Adoption of High Efficiency Products

In current practice, most dimming ballasts are specified because they are assumed to be energy saving products (relative to fixed output ballasts) capable of light level tuning and/or adaptive dimming. Though energy conservation may be a priority for these customers, the industry does not provide an easy way to distinguish between dimming ballasts of different efficiency levels. No federal energy efficiency standards currently exist or are in development for dimming ballasts, nor is there a federally recognized test procedure or metric dedicated to dimming ballasts. Though the BEF metric can and has been used to evaluate a dimming ballast's full output efficiency, manufacturers do not typically report BEF at operating modes below 100 percent, where most dimming ballasts can be expected to operate. Furthermore, unlike for fixed output ballasts, manufacturers do not generally offer product lines clearly and specifically delineated by efficiency. For these reasons, it is currently very difficult for consumers to distinguish between high and low efficiency products.

Standards would ensure that energy efficiency performance data for these products, throughout their ranges of operation, will be available to consumers. Furthermore, accurate and representative energy efficiency performance data for these products will be available so that consumers can conduct informed purchases. Without minimum efficiency standards, a natural shift towards high efficiency products beyond current market saturation does not appear to be likely.

6 Savings Potential

Savings estimates are based on differences in energy use between qualifying products and non-qualifying products under the assumed operating cycle described previously. Annual statewide savings were estimated for the 13-year stock turnover period and are presented in the following sections. These savings are assumed to be conservative, given that our data consisted almost entirely of CEE-listed ballasts, which are claimed to be the highest performing ballasts on the market. The actual market average energy use for non-qualifying products is likely to be much higher than what was presented in Section 4.3. Additionally, savings from a standby mode standard are considered separately and have not been included in the following tables.

6.1 Statewide California Energy Savings

Table 6.1 California Statewide Non-Standards Case Energy Use[A]

	Annual Sales		Stock	
Year	Energy Use (GWh/yr)	Peak Demand (MW)	Energy Use (GWh/yr)	Peak Demand (MW)
2013	340	61	4,424	789
2015 (Effective Year)	385	69	4,489	801
2027 (Stock turnover)	560	100	6,252	1,115

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

Table 6.2 California Statewide Standards Case Energy Use[A]

	Annual Sales		Stock	
Year	Energy Use (GWh/yr)	Peak Demand (MW)	Energy Use (GWh/yr)	Peak Demand (MW)
2013	340	61	4,424	789
2015 (Effective Year)	367	65	4,471	797
2027 (Stock turnover)	533	95	5,952	1,062

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

Table 6.3 California Statewide Energy Savings for Standards Case[A]

	Annual Sales		Stock	
Year	Energy Use (GWh/yr)	Peak Demand (MW)	Energy Use (GWh/yr)	Peak Demand (MW)
2015 (Effective Year)	18.5	3.3	18.5	3.3
2027 (Stock turnover)	27	5	300	53

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

6.1 State or Local Government Costs and Savings

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

7 Economic Analysis

7.1 Incremental Cost

Initial conversations with industry experts suggested that incremental costs are expected to be very low, if not negligible in many cases. Phone conversations with manufacturers also revealed that there was virtually no price difference among the various efficiency levels for dimming ballasts, but rather, price differences were overwhelmingly dictated by the specific features of the product (Burjansky, 2007; Walma; 2007; Williams, 2007).

These general impressions from industry experts and manufacturers were calibrated with the pricing data the CASE Team collected on the 34 unique ballasts that were tested for efficiency. Relying on multiple regression analysis, we were able to understand the relationships of different product characteristics, including brand, efficiency, control type, number of lamps, and model how these parameters impact product cost.

This analysis indicated that the efficiency of a dimming ballast, and whether or not it meets the proposed standard, does not contribute to determining the price of the ballast. In other words, more efficient dimming ballasts and/or dimming ballasts that meet the proposed standard are not more expensive than less efficient dimming ballasts and/or dimming ballasts that do not meet the proposed standard. The CASE Team therefore concludes that there is no incremental cost to this standard.

The regression analysis performed on our dataset is discussed in more detail in Appendix B:.

7.2 Design Life

DOE analyzed the design life for fluorescent ballasts in its 2012 standards rulemaking (DOE 2011c). Their research indicated an estimated useful life of 13 years in commercial applications. DOE's estimate does not distinguish dimming from fixed output ballasts, but since both fixed output and dimming ballasts perform similar functions and rely on similar electrical components, the useful lives for both are assumed to be roughly equivalent.

7.3 Lifecycle Cost / Net Benefit

Table 7.2 shows the lifecycle costs and benefits for the standards option under consideration. The energy savings benefits are estimated using the CEC methodology which includes a 3 percent discount rate. Table 7.2 shows the net present value for both first year sales and for the turnover of the entire existing stock. Since the CASE Team found no incremental cost for this measure, the lifecycle cost/benefit ratio is not applicable. The proposed energy efficiency standards are not expected to have any impact on ballast maintenance costs or any other factors that may impact cost-effectiveness.

Table 7.1 Costs and Benefits per Unit for Qualifying Products

Product Class	Design Life (years)	Lifecycle Costs per Unit (Present Value $)			Lifecycle Benefits per Unit (Present Value $)		
		Incremental Cost	Add'l Costs	**Total PV Costs**	Energy Savings[a]	Add'l Benefits	**Total PV Benefits**
Dimming Ballasts	13	$0	$0	**$0**	$22.17	$0	**$22.17**

PV = Present Value

[a] For price of electricity, average annual rates were used, starting in the effective year (see Appendix D: for more details

Table 7.2 Lifecycle Costs and Benefits for Qualifying Products

Product Class	Lifecycle Benefit / Cost Ratio[a]	Net Present Value ($)[b]		
		Per Unit	First Year Sales ($ million)	Stock Turnover ($ million)[c]
Dimming Ballasts	N/A	$22.17	$38	$505

Source: CASE Team analysis

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

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

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

[d] It should be noted that while the proposed standard is cost-effective, it may be more cost-effective if using alternative rate structures. For example, marginal utility rates may more accurately reflect what customers save on utility bills as result of the standard.

This standard is shown to be highly cost effective, with a total Net Present Value (NPV) of $38 million for the first year that the standard is effective, and an NPV of over $505 million after the stock has turned over. This is a function of the high number of annual shipments for these products, the assumed zero incremental measure cost, and long product lifetimes.

8 Acceptance Issues

8.1 Infrastructure Issues

As previously mentioned, dimming ballasts are currently not sold in separate tiers of efficiency. There have been limited efforts made to characterize the efficiency of these products, particularly when considering dimmed mode operation. Manufacturers have therefore not been properly incentivized to create higher efficiency products. The presence of several products that meet the proposed standard levels, however, demonstrates that the efficiency levels being considered are technically feasible at zero incremental cost.

The absence of a metric for evaluating dimming ballast efficiency is also a barrier for utility incentive programs. The CA investor owned utilities (IOUs) do not currently offer rebates for the purchase of higher efficiency dimming ballasts. Should California adopt the test procedure and standard levels proposed in this report, CA IOUs will be better positioned to develop rebate programs in the future.

8.2 Existing Standards

While DOE completed a rulemaking in 2011 to update standards for fixed output ballasts and ballasts that do not dim below 50 percent full output, there are currently no state or federal standards which cover ballasts that dim to below 50 percent full output. Although all ballasts (including all dimming ballasts) are technically defined in the Energy Policy and Conservation Act (EPCA) as "covered products," language in Sections 327(b) and 327(c) of EPCA, which define preemption for federally covered products, provides special exemptions for fluorescent ballasts for which standards have not been set. In subsequent updates to ballast standards, scope definitions have explicitly excluded ballasts that dim below 50 percent full output from the scope of coverage. Furthermore, no new federal rulemakings have been planned to cover these products.

As previously discussed, the 2013 revision of Title 24 is expected to drastically increase the sales and installation of dimming ballasts in California. As these products would otherwise be exempted from efficiency standards, an excellent opportunity exists to capture significant energy savings.

8.3 Stakeholder Positions

Refer to Invitation To Participate responses (CEC 2013) for stakeholder comments.

8.3.1 New Test Procedure

Though the proposed test procedure is an extension of the currently approved and accepted test procedure for fixed output ballasts, industry stakeholders may be wary of relying upon a test method that has not yet been officially accepted by DOE or other national standards-setting bodies (e.g., ANSI) for measuring efficiency of ballasts operating below 100 percent full output. Industry stakeholders may also object to certain provisions in the proposed test procedure if they perceive it as placing an additional testing burden on manufacturers (e.g., such as requirements for ballasts to be tested at multiple operating modes in addition to full output).

The CASE Team has recently learned that the National Electrical Manufacturers Association (NEMA) is considering the development of a test procedure to measure the efficiency of dimming ballasts based on DOE's recently adopted BLE test procedure. The CASE Team will continue to engage with NEMA as they move forward with this effort.

8.3.2 Proposed Standard Levels

During federal standard-setting proceedings for fixed output fluorescent lamp ballasts, manufacturers were strongly opposed to adopting stringent standard levels. Manufacturers had considered their products to be very efficient and believed that higher standard levels would be difficult to meet. Though significant differences in performance exist without comparable price differentiation, manufacturers are expected to be similarly resistant to standards for dimming ballasts; these ballasts are generally installed with energy savings in mind and are therefore already perceived to be high efficiency products, though significant differences in performance exist.

9 Environmental Impacts

9.1 Hazardous Materials

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

9.2 Air Quality

This proposed measure is estimated to reduce total criteria pollutant emissions in California by 51,600 lbs/year in 2027, after stock turnover, as shown in Table 9.1 due to 300 GWh in reduced end user electricity consumption with an estimated value of $2,472,400. Criteria pollutant emission factors for California electricity generation were calculated per MWh based on California Air Resources Board data of emission rates by power plant type and expected generation mix (CARB 2010). The monetization of these criteria pollutant emission reductions is based on CARB power plant air pollution emission rate data times the dollar per ton value of these reductions based on Carl Moyer values where available, and San Joaquin Valley UAPCD "BACT" thresholds for sulfur oxides (SOx). These dollar per ton values vary significantly for fine particulates, as discussed in Appendix E: (CARB 2011a, CARB 2013a and San Joaquin Valley UAPCD).

Table 9.1 Estimated California Criteria Pollutant Reduction Benefits (lbs/year) After Stock Turnover

	lbs/year	**Carl Moyer $/ton (2013)**	**Monetization**
ROG	8,265	$17,460	$72,151
Nox	28,188	$17,460	$246,083
Sox	2,963	$18,300	$27,109
PM2.5	12,182	$349,200	$2,127,047
Total			**$2,472,400**

9.3 Greenhouse Gases

Table 9.2 shows the annual and stock GHG savings by year and the range of the societal benefits as a result of the standard. By stock turnover in 2027, this standard would save 131,000 metric tons of CO2e annually, equal to between $7,960,000 and $24,000,000 of societal benefits. The total avoided CO2e is based on CARB's estimate of 437 MT CO2e/GWh of energy savings from energy efficiency improvements, and includes additional electrical transmission and distribution loses estimated at 7.8% (CARB 2008a). The range of societal benefits per year is based on a range of annual dollar per metric ton of CO2 (in 2013 dollars) sourced from the U.S. Government's Interagency Working Group on Social Cost of Carbon (SCC) (Interagency Working Group 2013). The low end uses the average SCC, while the high end incorporates SCC values which use climate sensitivity values in the 95th percentile, both with 3% discount rate. It is important to note that this range can be lower and higher, depending on the approach used, so policy judgments should consider this uncertainty. See Appendix F: for more details regarding this and other approaches.

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

Year	Annual GHG Savings (MT of CO2e/yr)	Stock GHG Savings (MT of CO2e/yr)	Value of Stock GHG Savings - low ($)	Value of Stock GHG Savings - high ($)
2015	8,071	8,071	375,888	1,078,205
2027	11,719	130,941	7,959,849	24,072,125

10 Recommendations

10.1 Recommended Standards Proposal

The CASE Team recommends that the CEC set energy efficiency requirements for fluorescent dimming ballasts based on BLE at full light output and dimmed operating modes. Minimum BLE levels that a continuously dimming ballast must meet at 100 percent, 80 percent, and 50 percent of full output are defined by the three equations below:

$$Minimum\ BLE_{Full\ Output} = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{Full\ Output} + C}$$

$$Minimum\ BLE_{80\%} = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{80\%} + C}$$

$$Minimum\ BLE_{50\%} = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{50\%} + C}$$

Where A = 0.84, B = 0.235, and C = 3.85.

These standard levels were determined based on the results of testing approximately 88 ballasts of varying types and efficiency (covering 34 unique ballasts, with multiple samples of each) that were primarily drawn from the CEE qualified products list. Factors for A, B, and C were chosen such that nine of the 34 total unique ballasts that were tested qualify at the proposed levels. For 1-, 2-, and 3- lamp ballasts, products from multiple manufacturers qualify for the proposed standard.

For step dimming ballasts, measurement points at 80 percent and 50 percent of full output power are substituted by measurements at each step the ballast is capable of dimming. For all ballasts, manufacturers must also test and list THD and PF on the ballast input current.

Additionally, the CASE Team recommends that the CEC set maximum standby power consumption limits at no more than 1W.

Manufacturers should be required to test a minimum of four samples of each ballast model to demonstrate compliance. At each measurement point, manufacturers should refer to the guidelines provided by DOE to account for measurement and testing variations when certifying compliance with federal efficiency standards. These guidelines are outlined in *10CFR430 Subpart B, § 429.26*.

Finally, dimming ballasts should comply with flicker requirements set forth in Title 20 for dimmer controls, and allow for reduced flicker operation through the dimming range so that the light output has an amplitude modulation of less than 30 percent for frequencies less than 200 Hz without causing premature lamp failure.

10.2 Proposed Changes to the Title 20 Code Language

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

Section 1601. Scope.

(x) Dimming fluorescent ballasts that meet the product type definition in Section 1602.

Section 1602. Definitions.

"Dimming fluorescent ballast" means a fluorescent ballast that is capable of operating 1, 2, 3, or 4 lamps in dimmed operating modes below 50 percent of full output.

"Continuously dimming fluorescent ballast" means a dimming fluorescent ballast that can dim to any level between 100 percent full output and a minimum percentage of full output.

"Step dimming fluorescent ballast" means a dimming fluorescent ballast that can dim to limited specific fixed output levels below 100 percent full output.

"Communications-enabled dimming fluorescent ballast" means a fluorescent ballast that is capable of two-way communication with a central management system.

"Fluorescent ballast" means a device which is used to start and operate fluorescent lamps by providing a starting voltage and current and limiting the current during normal operation.

"Ballast Luminous Efficacy (BLE)" means the total fluorescent lamp arc power divided by the fluorescent lamp ballast input power.

"Standby mode" means the condition in which an energy-using product-

1) Is connected to a main power source; and

2) Offers one or more of the following user-oriented or protective functions:

i) To facilitate the activation or deactivation of other functions (including active mode) by remote switch (including remote control), internal sensor or timer; or

ii) Continuous functions, including information or status displays (including clocks) or sensor-based functions

"Total harmonic distortion (THD)" means the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

"Power factor" means the ratio of the real power to the apparent power.

Section 1604. Test Method for Specific Appliances.

(x) Dimming Fluorescent Ballasts

Table X: Test Procedures for Dimming Fluorescent Ballasts

Specification Requirement	**Test Protocol**	**Source**
Full output	*10CFR Part 430: Test Procedures for Fluorescent Lamp Ballasts, with modification*	US DOE
80% of Rated Full Output	*10CFR Part 430: Test Procedures for Fluorescent Lamp Ballasts, with modification*	US DOE
50% of Rated Full Output	*10CFR Part 430: Test Procedures for Fluorescent Lamp Ballasts, with modification*	US DOE
Standby Mode	*10CFR Part 430: Test Procedures for Fluorescent Lamp Ballasts, with modification*	US DOE
Measurement Accuracy	*10CFR Parts 429, 430, and 431: Certification, Compliance, and Enforcement for Consumer Products and Commercial and Industrial Equipment*	US DOE

Guidance on Implementation of 10CFR Part 430 for dimming fluorescent ballasts: Below, the CEC provides guidance on using 10CFR Part 430 for measuring dimming fluorescent ballast BLE.

a. Controls device: Ballasts must be connected to a single generic commercially available compatible controls device; if the product does not operate with a generic controls device, it shall be tested with the manufacturer recommended, commercially available, compatible controls device connected in a single configuration. This applies to full output BLE measurements as well as standby mode measurements.

b. Determination of dimmed operating modes: Target ballast input power equal to 80 percent of full output and 50 percent of full output must be calculated based on manufacturer rated full output. BLE measurements at dimmed operating modes shall be obtained when the measured ballast input power is equal to the target ballast input power as determined by these calculations. The measurements at dimmed operating modes shall then be performed in accordance with the guidance provided in 10CFR Part 430.

c. 0-10V ballasts: Ballasts that determine the dimming mode based on a 0-10V signal may not always operate at full output when connected to a controls device. For this reason, the full output BLE measurement for 0-10V dimming shall be taken with the control lead open circuited.

d. Step dimming ballasts: BLE for step dimming ballasts shall be measured only at the steps at which the ballast is capable of operating.

e. Measurement accuracy: Testing and sample variation is accounted for through the application of *10CFR Parts 429, 430, and 431: Certification, Compliance, and Enforcement for Consumer Products and Commercial and Industrial Equipment* for each measurement point.

Section 1605.3 State Standards for Non-Federally Regulated Appliances.

(x) Dimming Fluorescent Ballasts

Effective January 1, 2015, measured BLE for continuously dimming fluorescent ballasts shall exceed the standard level BLE defined in Table X below at three discrete operating modes: full output, 80 percent of manufacturer's rated full output, and 50 percent of manufacturer's rated full output. The equation takes as input the measured lamp arc power at full output and the measured lamp arc power at the operating mode to be evaluated.

Table X. Standards for Dimming Fluorescent Ballasts

Operating Mode	**Minimum BLE Level**
Full output	$Min\ BLE = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{Full\ Output} + C}$
80% of rated full output	$Min\ BLE = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{80\%} + C}$
50% of rated full output	$Min\ BLE = \frac{Arc\ Power_{Full\ Output}}{Arc\ Power_{Full\ Output} * A + B * Arc\ Power_{50\%} + C}$

Where A = 0.84, B = 0.235, and C = 3.85.

Step dimming fluorescent ballasts shall meet the minimum BLE levels defined by the same formulas provided in Table X, but only applicable at the discrete dimmed modes the ballast is designed to operate in.

Communications enabled dimming fluorescent ballasts must not exceed 1W in total standby mode power consumption.

Dimming fluorescent ballasts shall allow for reduced flicker operation through the dimming range so that the light output has an amplitude modulation of less than 30 percent for frequencies less than 200 Hz without causing premature lamp failure.

Section 1606 Filing by Manufacturers; Listing of Appliances in Database

Effective January 1, 2015, dimming fluorescent ballasts' power factor and total harmonic distortion on the ballast input current shall be measured and reported.

10.3 Implementation Plan

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

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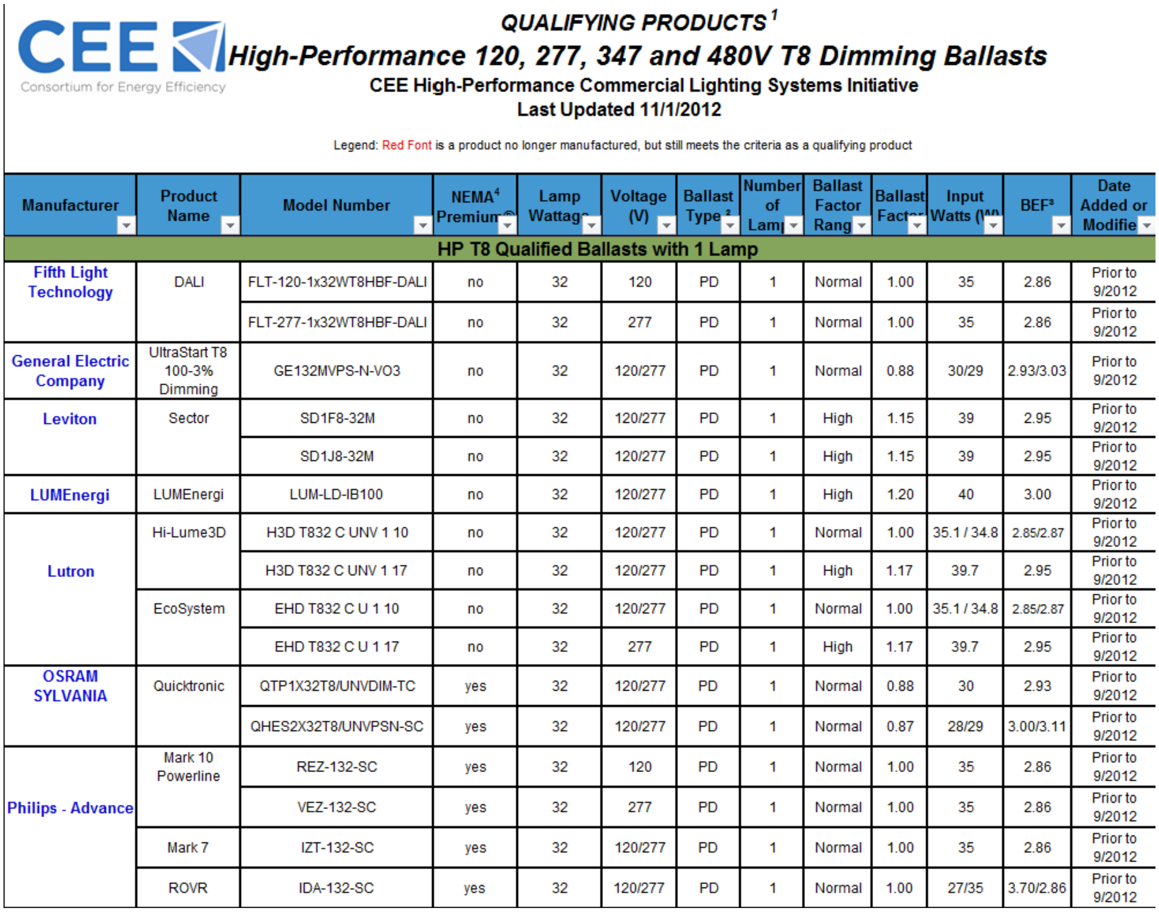
Appendix A: CEE Qualified Products List



QUALIFYING PRODUCTS[1]

High-Performance 120, 277, 347 and 480V T8 Dimming Ballasts

CEE High-Performance Commercial Lighting Systems Initiative

Last Updated 11/1/2012

Legend: Red Font is a product no longer manufactured, but still meets the criteria as a qualifying product

Manufacturer	Product Name	Model Number	NEMA[4] Premium	Lamp Wattag	Voltage (V)	Ballast Type [2]	Number of Lamp	Ballast Factor Rang	Ballast Fact	Input Watts (W	BEF[3]	Date Added or Modifie
HP T8 Qualified Ballasts with 1 Lamp												
Fifth Light Technology	DALI	FLT-120-1x32WT8HBF-DALI	no	32	120	PD	1	Normal	1.00	35	2.86	Prior to 9/2012
		FLT-277-1x32WT8HBF-DALI	no	32	277	PD	1	Normal	1.00	35	2.86	Prior to 9/2012
General Electric Company	UltraStart T8 100-3% Dimming	GE132MVPS-N-VO3	no	32	120/277	PD	1	Normal	0.88	30/29	2.93/3.03	Prior to 9/2012
Leviton	Sector	SD1F8-32M	no	32	120/277	PD	1	High	1.15	39	2.95	Prior to 9/2012
		SD1J8-32M	no	32	120/277	PD	1	High	1.15	39	2.95	Prior to 9/2012
LUMEnergi	LUMEnergi	LUM-LD-IB100	no	32	120/277	PD	1	High	1.20	40	3.00	Prior to 9/2012
Lutron	Hi-Lume3D	H3D T832 C UNV 1 10	no	32	120/277	PD	1	Normal	1.00	35.1 / 34.8	2.85/2.87	Prior to 9/2012
		H3D T832 C UNV 1 17	no	32	120/277	PD	1	High	1.17	39.7	2.95	Prior to 9/2012
	EcoSystem	EHD T832 C U 1 10	no	32	120/277	PD	1	Normal	1.00	35.1 / 34.8	2.85/2.87	Prior to 9/2012
		EHD T832 C U 1 17	no	32	277	PD	1	High	1.17	39.7	2.95	Prior to 9/2012
OSRAM SYLVANIA	Quicktronic	QTP1X32T8/UNVDIM-TC	yes	32	120/277	PD	1	Normal	0.88	30	2.93	Prior to 9/2012
		QHES2X32T8/UNVPSN-SC	yes	32	120/277	PD	1	Normal	0.87	28/29	3.00/3.11	Prior to 9/2012
Philips - Advance	Mark 10 Powerline	REZ-132-SC	yes	32	120	PD	1	Normal	1.00	35	2.86	Prior to 9/2012
		VEZ-132-SC	yes	32	277	PD	1	Normal	1.00	35	2.86	Prior to 9/2012
	Mark 7	IZT-132-SC	yes	32	120/277	PD	1	Normal	1.00	35	2.86	Prior to 9/2012
	ROVR	IDA-132-SC	yes	32	120/277	PD	1	Normal	1.00	27/35	3.70/2.86	Prior to 9/2012

Only a snapshot of the CEE Qualified Products List is provided here. The full list is available for download at http://www.cee1.org/content/cee-program-resources.

Appendix B: Incremental Cost Multiple Regression Analysis

The CASE Team conducted a multi-variable regression analysis on dimming fluorescent ballasts to analyze price as a function of five basic ballast characteristics, efficiency, brand, controls type, lamp number, and maximum dimmability. The variables included in the model are defined as follows:

- Price: The price, in dollars, of the ballast as determined through internet research performed by the CASE Team.
- Efficiency: Binary variable indicating whether or not the ballast passes the proposed standard level. Nine of the 34 ballasts in the model pass.
- Brand: Categorical variable representing the manufacturer of the ballast. Each manufacturer was assigned an arbitrary letter from a-f.
- Controls type: Binary variable indicating whether or not the ballast control type is communications enabled. Communications enabled ballasts include DALI and other proprietary systems. Non-communications enabled ballasts include 0-10V and phase control ballasts.
- Lamp number: Integer variable representing the total number of lamps the ballast is designed to operate, from one to four.
- Maximum Dimmability: Percentage, representing the maximum depth of dimming of ballast input power, as observed during testing. This is the lowest operating mode at which lamps were still functioning normally.

The resulting regression model that was established was a good fit to the data; it explained 78% of the observed variability in ballast price (R^2 value of 0.782), had a statistically significant slope ($p<0.001$), and yielded roughly normally distributed residuals, though limited by a relatively low number of samples (34). Figure B.1 presents the results of the multiple regression analysis, and Table B.1 lists the effects of individual terms in the model.

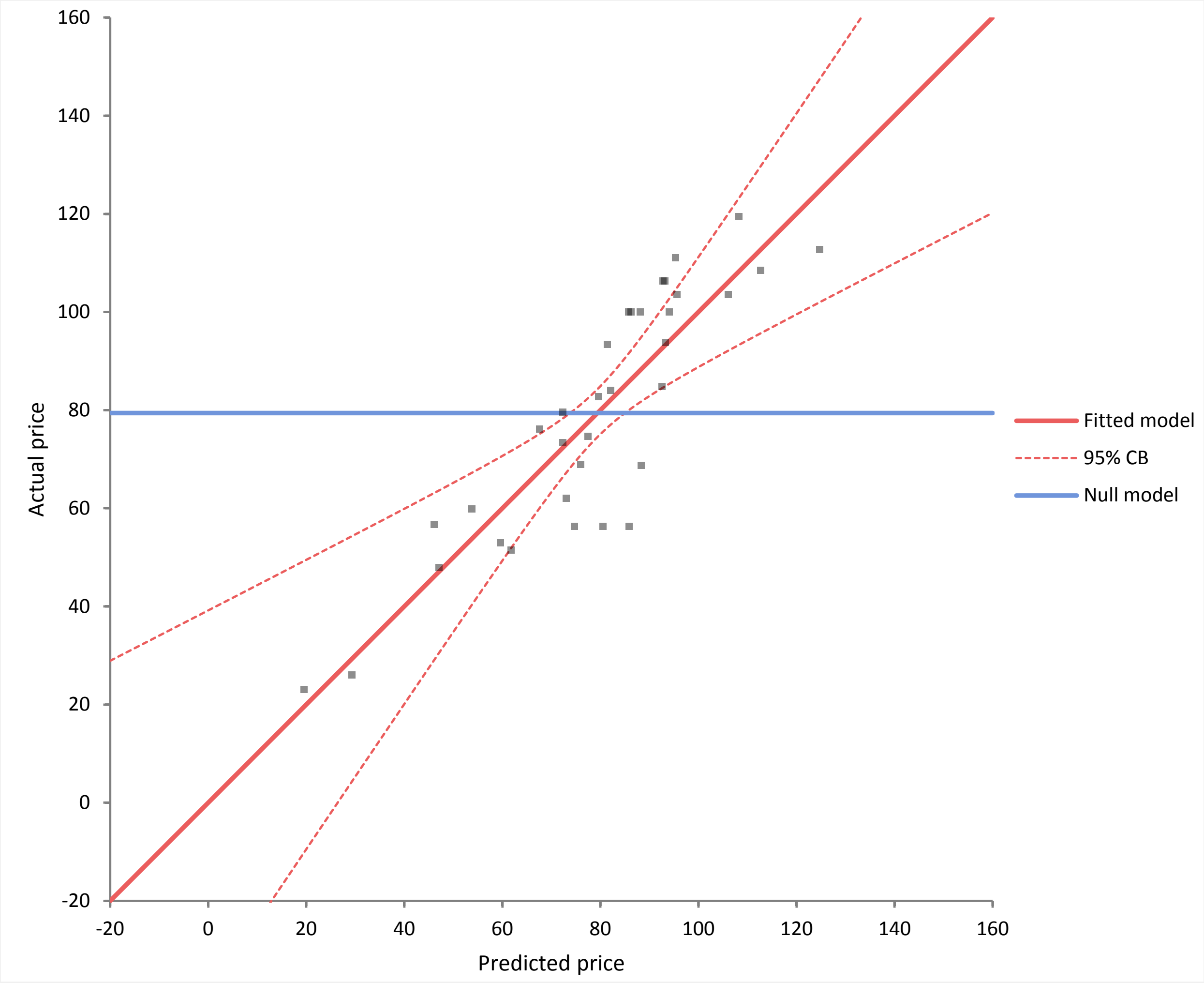


Figure B.1 Multiple Regression Model of Ballast Price as a Function of Ballast Efficiency, Brand, Dimming Type, and Lamp Number.

Table B.1 Effects of Terms

Term	SS	DF	MS	F	p-value
Brand	7.18 E+03	5	1.44 E+03	7.57	0.0002
Lamp Number	1.13 E+03	1	1.13 E+03	5.96	0.0224
Efficiency	1.24 E+02	1	1.24 E+02	0.65	0.4264
Maximum Dimmability	1.31 E+02	1	1.31 E+02	0.69	0.4146
Controls Type	3.47 E+03	1	3.47 E+03	18.29	0.0003

Some of the ballast characteristics studied did not demonstrate statistically significant independent effects on price when corrected for the influence of other metrics. The p-values indicate that only "Controls Type," "Brand," and "Lamp Number" have a statistically significant impact on price (p-value <0.05). Both "Efficiency" and "Maximum Dimmability" have very high p-values, indicating that they do not exert statistically significant independent effects on price in the model. Removing both of these variables completely had little effect on the overall model, with the R^2 value only decreasing very slightly.

The results of this analysis suggest that whether or not a given ballast passes the proposed standard is not statistically linked to the price of the ballast. In other words, passing ballasts are not shown by the model to be more expensive than failing ballasts. Rather, ballast price is more dependent on whether or not the ballast is communications enabled, which manufacturer produced the ballast, and how many lamps the ballast is designed to operate. The CASE Team therefore concludes that the model shows no incremental cost for the proposed energy efficiency standard levels.

Appendix C: DEER Tables

Non-CFL Energy Impacts for: Pacific Gas & Electric

Location: IOU Territory, Building Vintage: Existing

				Lighting	Energy Impacts per ΔWatt Lighting					HVAC Factors		
Measure	Building	Building	Lighting	Coincident	Direct (End-Use)		Whole Building			Energy	Demand	Gas
Type	Type	Vintage	EFLH	Demand	kWh/ΔW	Watt/ΔW	kWh/ΔW	Watt/ΔW	kBTU/ΔW	kWh/kWh	kW/kW	therm/kWh
Non-CFL	Asm	Existing	2614	0.53	2.61	0.53	2.73	0.62	-2.35	1.05	1.16	-0.0090
Non-CFL	EPr	Existing	2140	0.04	2.14	0.04	2.31	0.04	-1.86	1.08	1.10	-0.0087
Non-CFL	ESe	Existing	2285	0.04	2.28	0.04	2.45	0.04	-2.44	1.07	1.10	-0.0107
Non-CFL	ECC	Existing	2423	0.45	2.42	0.45	2.68	0.57	-2.61	1.11	1.25	-0.0108
Non-CFL	EUn	Existing	2353	0.41	2.35	0.41	2.62	0.50	-1.77	1.12	1.22	-0.0075
Non-CFL	ERC	Existing	2475	0.04	2.48	0.04	2.56	0.05	-2.41	1.03	1.11	-0.0097
Non-CFL	Gro	Existing	4907	0.69	4.91	0.69	4.58	0.88	-6.24	0.93	1.27	-0.0127
Non-CFL	Hsp	Existing	5258	0.83	5.26	0.83	5.85	1.02	-3.23	1.11	1.23	-0.0061
Non-CFL	Nrs	Existing	4158	0.68	4.16	0.68	4.38	0.85	-5.42	1.05	1.26	-0.0130
Non-CFL	Htl	Existing	1947	0.24	1.95	0.24	2.00	0.30	-1.08	1.03	1.25	-0.0055
Non-CFL	Mtl	Existing	1550	0.17	1.55	0.17	1.61	0.21	-0.91	1.04	1.23	-0.0059
Non-CFL	MBT	Existing	3528	0.85	3.53	0.85	3.96	1.03	-0.20	1.12	1.21	-0.0006
Non-CFL	MLI	Existing	3216	0.92	3.22	0.92	3.38	1.08	-1.70	1.05	1.17	-0.0053
Non-CFL	OfL	Existing	2641	0.71	2.64	0.71	2.97	0.93	-1.67	1.12	1.32	-0.0063
Non-CFL	OfS	Existing	2594	0.69	2.59	0.69	2.79	0.85	-0.92	1.08	1.22	-0.0036
Non-CFL	RSD	Existing	4826	0.80	4.83	0.80	4.95	0.93	-4.12	1.03	1.17	-0.0085
Non-CFL	RFF	Existing	4835	0.81	4.84	0.81	5.02	0.95	-3.62	1.04	1.17	-0.0075
Non-CFL	Rt3	Existing	3375	0.76	3.38	0.76	3.66	0.90	-1.65	1.08	1.18	-0.0049
Non-CFL	RtL	Existing	4269	0.85	4.27	0.85	4.59	1.01	-2.54	1.08	1.20	-0.0060
Non-CFL	RtS	Existing	3376	0.88	3.38	0.88	3.62	1.04	-1.74	1.07	1.18	-0.0052
Non-CFL	SCn	Existing	3422	0.70	3.42	0.70	3.31	0.89	-2.81	0.97	1.27	-0.0082
Non-CFL	SUn	Existing	3422	0.70	3.42	0.70	3.42	0.70	0.00	1.00	1.00	0.0000
Non-CFL	WRf	Existing	4766	0.56	4.77	0.56	4.77	0.56	0.00	1.00	1.00	0.0000
Non-CFL	Wtd-Com	Existing	3184	0.64	3.18	0.64	3.38	0.76	-1.93	1.06	1.20	-0.0061
Non-CFL	SFM	Existing	na	na	na	na	na	na	na	na	na	na
Non-CFL	MFM	Existing	na	na	na	na	na	na	na	na	na	na
Non-CFL	DMO	Existing	na	na	na	na	na	na	na	na	na	na
Non-CFL	Wtd-Res	Existing	na	na	na	na	na	na	na	na	na	na

Appendix D: Cost Analysis Assumptions

The electricity rates used in the analysis of this CASE Report were derived from projected future prices for residential, commercial and industrial sectors in the CEC's "Mid-case" projection of the 2012 Demand Forecast (2012), which used a 3% discount rate and provide prices in 2010 dollars. The sales weighted average of the 5 largest utilities in California was converted to 2013 dollars using an inflation adjustment of 1.07 (DOL 2013). A sector weighted average electricity rate was then calculated using 100% commercial, 0% residential, 0% industrial, as fluorescent ballasts are most commonly found in the commercial sector, and the multi-level lighting controls requirements in Title 24 apply to commercial installations. See the rates by year below in Table D.1.

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

Year	**Residential**	**Commercial**	**Industrial**	**Sector Weighted Average**
2015	16.82	14.67	11.31	14.67
2016	17.02	14.84	11.43	14.84
2017	17.24	15.02	11.56	15.02
2018	17.47	15.22	11.70	15.22
2019	17.71	15.42	11.84	15.42
2020	18.00	15.67	12.01	15.67
2021	18.34	15.98	12.23	15.98
2022	18.70	16.29	12.45	16.29
2023	19.06	16.61	12.67	16.61
2024	19.43	16.93	12.90	16.93
2025	19.81	17.27	13.13	17.27
2026	20.19	17.60	13.37	17.60
2027	20.59	17.95	13.61	17.95
2028	20.98	18.30	13.86	18.30
2029	21.39	18.66	14.12	18.66
2030	21.81	19.03	14.38	19.03
2031	22.23	19.40	14.64	19.40
2032	22.66	19.78	14.92	19.78
2033	23.10	20.17	15.19	20.17
2034	23.55	20.57	15.48	20.57
2035	24.01	20.97	15.77	20.97
2036	24.48	21.38	16.06	21.38
2037	24.96	21.80	16.37	21.80
2038	25.44	22.23	16.68	22.23
2039	25.94	22.67	16.99	22.67
2040	26.44	23.12	17.32	23.12

Appendix E: Criteria Pollutant Emissions and Monetization

E.1 Criteria Pollutant Emissions Calculation

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

E.2 Criteria Pollutant Emissions Monetization

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

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

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

This CASE report relies primarily on the Carl Moyer thresholds due to their state-wide nature and applicability to combustion sources[6]. In addition, the Carl Moyer fine particulate values for fine particulate apply to combustion sources with specific health impacts, while BACT thresholds include both combustion sources and dust. The Carl Moyer values are somewhat more conservative for ozone precursors than San Joaquin Valley UAPCD BACT thresholds, and significantly higher for fine particulate[7].The Carl Moyer program does not address sulfur oxides, however, thus the San Joaquin BACT thresholds were used for this pollutant.

Price reports for California Emission Reduction Credit (ERCs, i.e. air pollution credits purchased to offset regulated emission increases) for 2011 and 2012 were also compared to the values selected in this CASE report. For each pollutant there is a wide range of ERC values per ton that are both

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

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

higher and lower than the values per ton used in this CASE report [CARB 2011b and 2012]. Due to wide variability and low trading volumes, ERC values were evaluated for comparative purposes only.

Appendix F: Greenhouse Gas Valuation Discussion

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

F.1 Damage Cost Approach

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

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

F.1.1 Interagency Working Group Estimates

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

Table F.1 Social Cost of CO2 2010 – 2050 (in 2007 dollars per metric ton of CO2)

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

Source: Interagency Working Group 2013

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

F.2 Abatement Cost Approach

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

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

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

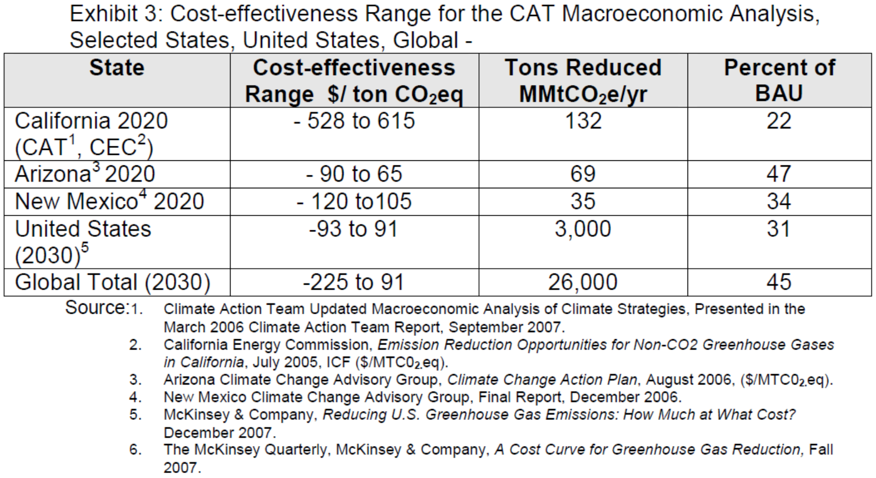

Exhibit 3: Cost-effectiveness Range for the CAT Macroeconomic Analysis, Selected States, United States, Global -

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

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

Source: CARB 2008b

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

F.3 Regulated Carbon Market Approach

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

F.3.1 European Union Emissions Trading System

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

F.3.2 California Cap & Trade

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