Linear LED Lamps: Application and Interoperability Evaluation

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LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

BF	Ballast Factor
CCT	Correlated Color Temperature
CEE	Consortium for Energy Efficiency
CLTC	California Lighting Technology Center
CRI	Color Rendering Index
CSS	California Commercial Saturation Survey Report (Itron 2014)
DLC	DesignLights Consortium
GWh	Gigawatt Hour
IEC	International Electrotechnical Commission
IOU	Investor-Owned Utility
LED	Light Emitting Diode
LFL	Linear Fluorescent Lamp
LMC	Lighting Market Characterization report (DOE 2012)
lm	Lumen
PG&E	Pacific Gas and Electric Company
QPL	Qualified Products List
TWh	Terawatt Hour
W	Watt

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EXECUTIVE SUMMARY

PROJECT GOAL

The goal of this project is to evaluate linear light-emitting diode (LED) lamps intended to replace equivalent linear fluorescent systems when operating under real-world conditions expected of commercial retrofits and in fixtures other than recessed troffers. Project objectives include evaluation and documentation of product performance as compared to a standard linear fluorescent baseline in terms of photometrics, energy use, and cross-compatibility of products within linear LED lamp type categories A and C.

PROJECT DESCRIPTION

LED lamps marketed to replace linear fluorescent products are an emerging product category with the potential to deliver significant energy and maintenance cost savings. Three primary types of linear LED products have emerged on the market.

- Type A: Linear LED lamp with internal driver that is designed to operate on a linear fluorescent lamp ballast.
- Type B: Linear LED lamp with internal driver that must be connected directly to line voltage for power.
- Type C: Linear LED lamp with external driver that is designed to replace both the linear fluorescent lamp and fluorescent lamp ballast.

In addition, some products can operate under multiple scenarios such as with a fluorescent ballast and also when the ballast is replaced with a compatible LED driver. These hybrid products, also called dual-mode products, are currently available in Types AB and AC.

The diversity of replacement options and associated compatibility/interchangeability issues have limited broad utility program investment in this product category. While customers gravitate towards these products due to their potential benefits, information on product performance under real-world conditions and in less than ideal configurations is sparse. In particular, data on linear LED product performance in fixtures other than recessed troffers is very limited.

To help fill these gaps and provide data to support development of targeted efficiency programs, this project assesses a cross-section of typical linear LED products operating in non-troffer fixtures and under specific scenarios expected of commercial building retrofits. Work includes evaluation of multiple LED products' photometric and electrical performance when paired with a variety of fluorescent lamp ballasts and/or electronic drivers. A standard 2-lamp fluorescent system is used as the baseline for comparison in terms of both photometric performance and energy use. Selection of specific LED technologies for evaluation was based on an assessment of publically available market data in order to identify the most prevalent linear products along with expected performance characteristics.

PROJECT FINDINGS/RESULTS

In California, approximately 80 percent of linear lamps are found in office, school, retail and miscellaneous businesses such as services, laboratories and assembly spaces. Common lighting design practice calls for use of direct or indirect lighting methods with recessed or surfaced-mounted troffers, surface-mounted wraps and suspended direct/indirect pendants being the most prevalent luminaire types. Within these businesses, on average, linear fixtures contain 2.5 lamps, with the four-foot, base efficiency, T8 fluorescent lamp being most common. On average, these installed fluorescent consume 31.5 W per lamp, and their LED counterparts 17.8 W per lamp. A statewide conversion to linear LED lamps could deliver approximately a 43 percent reduction in lighting energy use and result in as much as 3.2 TWh of savings annually.

Currently, linear LED lamps constitute less than one percent of the total installed base[1], however the breadth of commercially available linear LED alternatives continues to grow. More than 15,000 linear LED lamp products have been added to the DesignLights Consortium's Qualified Products List in the past three years. A sample of 4' T8 replacements qualified in the last three months shows that manufacturers continue to bring products to market in all three product type categories with the majority of newly added products being Type A, B or AB hybrids.

TECHNICAL ASSESSMENT

In light of these findings, this assessment focused on photometric and electrical evaluation of 13 commercially available linear LED lamps and one standard, 700 series linear fluorescent. Selected products are all 4' lamps operating in a 2-lamp fixture with a 2-lamp ballast or driver. Selected LED products include Type A, Type B, Type C, Type AB and Type AC. The selected fluorescent system represents the most common linear system installed in California buildings today and is used as a baseline of comparison for tested LED products. Characterization was conducted for each selected product operating in a bare-lamp strip fixture, a suspended pendant, and a surface-mounted wrap. Troffers were excluded from the assessment because significant data already exists on LED performance in this fixture type.

Test results for Type A products show a wide range of performance in terms of light output and system efficacy when comparing data for lamps operating in the same fixture and on the same fluorescent ballast. As compared to the fluorescent baseline, Type A LED products delivered significantly less light in all three fixtures tested. System efficacy, across all fixture types, however, was much higher for the LED products as compared to the fluorescent.

Type B linear LED lamps also provide less light than the standard, 700 series fluorescent baseline. For the bare-lamp fixture, linear LED lamps delivered 13 to 35 percent less light than the fluorescent baseline. In the pendant, light output was reduced by 17 to 51 percent. LEDs performed best in the wrap fixture as compared to the fluorescent because the fluorescent experienced degraded performance due to the elevated temperature present within the fixture. For the wrap, LEDs delivered two to 31 percent less light as compared to the fluorescent.

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[1] California Commercial Saturation Survey, 2014.

Linear LED Type C products performed best of all products tested. Type C products utilize an external LED driver, which is often optimized for a particular linear LED lamp. This leads to improved overall performance and increased light output. On average, Type C LED products delivered about 10 percent more light in the wrap as compared to the fluorescent, 10 percent less in the pendant and about the same in the bare-lamp fixture.

Light output of hybrid products varied significantly across manufacturers and products. For most Type AB products tested, light output did not vary significantly between output in operating mode A versus operating mode B. One Type AB product demonstrated slightly reduced light output operating as in a Type B configuration as compared to Type A. Of the two Type AC products tested, one demonstrated significantly increased light output operating as a Type C, while the other showed no significant difference in light output between operating mode C and A.

INTEROPERABILITY TESTING

Testing examined two common Type A linear LED lamps operating on three common electronic linear fluorescent lamp ballasts designed for use with a maximum of two lamps. Tests were conducted for lamps operating in a fully lamped, 2-lamp scenario and in a delamped, 1-lamp scenario.

As expected, the fluorescent lamp performed well in both the instant-start and programmed start ballasts, but experienced some degradation when operating on the T12 rapid start ballast. T8 lamps operating on a T12 ballast will also shorten the life of the lamp.

Product LED J worked well with the instant-start ballast and rapid-start ballast, but suffered severe degradation in power and light output operating on the programmed start ballast – approximately 40 percent. Product LED I worked well on the instant-start ballast. It did not perform well on either the rapid-start or the programmed start ballast. When operating with the rapid start ballast, performance was degraded by approximately 33 percent.

To understand performance in delamped fixtures, testing included operation of the same two, common, linear LED products on the same three ballasts. However, installed lamps were reduced from two to one. The linear fluorescent performed as expected under the delamped scenario for both the instant-start and programmed start ballasts. Input power and light output were reduced by roughly half. When operating with the rapid-start ballast, which requires lamps to be wired in series, a delamped scenario does not work.

For linear LED products, delamping may or may not be suitable. For product LED J, delamping with an instant-start ballast appeared to be compatible. The programmed start scenario showed about 50 percent degradation in power and light output as compared to that expected for a one-lamp configuration, which can be viewed as insufficient for most environments. As with the fluorescent, delamping on a rapid-start ballast results in a nonfunctioning system.

Testing examined five common Type C linear LED lamps operating on five linear LED drivers, each designed for use with two lamps. One of the five combinations included the LED lamp with a driver recommended by the LED lamp manufacturer. The remaining four combinations represent alternate operating cases, each composed of the LED lamp powered by the drivers recommended for the other LED lamps included in the testing. Tests were conducted for lamps operating in a fully lamped, 2-lamp scenario and in a delamped, 1-lamp scenario.

Overall, none of the alternate lamp and driver combinations resulted in a properly functioning system as characterized by power consumption and light output values in the range expected. In all cases, alternative drivers either overdrove the lamp (too much current) which caused light output values to jump significantly or created a situation where lamps were only producing about half the expected light output. Two combinations met this result. The remaining alternate combinations all drew substantially less power and produced substantially less light than under normal conditions where the lamp is wired to the manufacturer-recommended driver.

Under delamped conditions, some LED combinations performed as expected with respect to input power when operating on the manufacturer's recommended driver. For two combinations, input power values were within the range specified for one-lamp operation on driver specifications sheets. For alternative lamp/driver combinations, results varied from combinations that did not turn ON to those that produced very elevated power and light output values. Six product combinations failed to turn ON, while three others delivered approximately 25 percent of values expected for a properly functioning system (50 percent of that expected under a delamped scenario).

OPTICAL DISTRIBUTION

When comparing performance among Type A, Type B, Type C and hybrid products, no significant difference in optical distribution was found for products with the same beam angle. Linear LED lamps utilize heat sinks located along the length of the lamp. The arc length of the heat sink limits the beam angle of the lamp. This is a significant difference as compared to linear fluorescents, which emit light in all 360 degrees. The linear LEDs tested have beam angles between 160 and 310 degrees.

The wrap fixture is designed to deliver general ambient lighting with no up light component. The opaque, acrylic diffuser wraps around the sides of the fixture and essentially creates a 180° aperture. This also creates a fully enclosed lamp cavity that retains heat during operation. For fluorescent and LED sources, increased ambient temperature can lead to decreased light output. In the wrap tested, it appears that the elevated temperature operating environment reduced linear fluorescent performance by roughly 13 percent. LED performance, in contrast, was not as significantly impacted and LED products, on average, experienced only a five percent degradation in light output. Results indicate that some LEDs may perform better and deliver more light than fluorescents due to these elevated temperature impacts. LED product performance relative to fluorescent improved by six to 10 percent when operating in the wrap fixture.

The most challenging fixture type for linear LEDs is the direct/indirect, because the fixture is designed to distribute a portion of light up onto the ceiling where it is reflected back down to the work plane. Linear LED lamps, as previously discussed, have limited beam angles. A portion or all of the upper lamp hemisphere is utilized by the heat sink and no light is emitted along this surface. This directly impacts the performance of indirect lighting components. Direct/indirect lighting designs rely on a full 360 degrees of lamp distribution and they will deliver lower overall light output when using LED lamps as compared to fluorescents.

Average relative light output of tested linear LED products as compared to fluorescent performance between the bare-lamp and pendant fixtures was reduced from four percent less than fluorescent to 21 percent less than fluorescent. This difference between the LED and fluorescent systems jumped to 47 percent less light for the LED as compared to the fluorescent when operating in the pendant. For all tested LED products, relative performance decreased as compared to the fluorescent. On average, linear LED lamps saw an additional 28 percent reduction in light output as compared to the fluorescent baseline when operating in the direct/indirect pendent.

PROJECT RECOMMENDATIONS

Based on project test results, it's evident that linear LED lamps marketed to replace standard 4' linear fluorescents cannot compete in terms of total light output. While the tested LED products are very efficacious at both the source and system level, overall energy savings are achieved, in part, by reducing light output, not just power. Type A and Type B LED products, including hybrid Type AB, consistently demonstrated significantly reduced light output as compared to the fluorescent baseline. While Type A lamps may appear to be a simple, energy saving product, based on test results, these products are best only considered for retrofits where the space is currently over lit or reduced light levels will not negatively impact occupants or operations.

A potentially better alternative to Type A products is Type AC hybrid LED lamps. Type C lamps demonstrated the highest light output and system efficacy of all tested products. These lamps, when paired with recommended drivers consistently deliver light levels that are generally equivalent to or better than the selected fluorescent system used as a baseline for comparison. Initial installation is as quick as a Type A. When fluorescent ballasts fail, they can be replaced with LED drivers that will maximize light output and energy savings.

Light distribution is also a critical factor to consider when selecting linear LED lamps. Fixtures with indirect lighting / distribution components may not deliver suitable distribution or appropriate light levels when operating with linear LED products. While most linear LED products tested underperformed in terms of light output as compared to the fluorescent baseline, performance reductions were magnified when products were operated in the tested direct/indirect pendant. Very little light was available for indirect distribution because of the LED heat sink geometry and location along the length of the lamp. When considering a linear LED retrofit in existing linear direct/indirect fixtures, consumers should seek products with the largest beam angle to maximize performance or consider alternative energy-saving measures utilizing fluorescent lamp technology.

For fixtures with direct distribution, however, linear LED products may be a good alternative looking at distribution alone. In the wrap fixture tested, LED products performed much better as compared to the linear fluorescent and more closely matched its distribution pattern. Products of all beam angles performed well.

Whether Type A, C or Type AC products are used, products must be paired with manufacturer recommended control gear. Compatibility testing proved that most products suffer severe performance degradation when paired with nonstandard ballasts and drivers. Consumers must seek out ballast compatibility information to ensure proper operation and performance. Many manufacturers do not provide easy-to-obtain compatibility information. Manufacturers should improve their product literature to better ensure consumers match linear LED lamps with compatible fluorescent ballasts.

For LED lamps operating with external LED drivers, consumers should never pair a lamp with driver that is not explicitly recommended by the manufacturer. Interoperability testing showed that most Type C products only performed as promoted when operating on the manufacturer-recommended product. In some cases, an improper match between lamp and driver produced clearly visible, negative results and consumers will quickly be able to tell there is a problem. For other cases, however, light output increased and consumers may be left thinking the system is fully functional, when in fact, the system is being overdriven and will most likely exhibit a shortened life.

Last, consumers should avoid using linear LED lamps in delamped configurations. Most combinations of lamps and ballasts or drivers experienced severe performance degradation in a delamped scenario. Few manufacturers include delamping information on product specification sheets. Manufacturer's should explicitly call out information on delamping and bring that information out of the footnotes and into the main body of publications.

INTRODUCTION

LED lamps marketed to replace linear fluorescent products are an emerging product category with the potential to deliver significant energy savings and maintenance benefits. In recent years, many major lighting manufacturers have introduced products for the commercial market and some industry consortiums, such as the DesignLights® Consortium (DLC), now offer qualification tiers for some types of linear LED lamps and retrofit kits. Overall, the linear LED product category continues to expand and improve in terms of performance and cost-effectiveness. However, the diversity of existing linear fixture types and potential operating scenarios for LED replacements creates a significant number of applications for which little or no independent data of LED replacement performance exists.

To help fill these gaps and provide data to support development of targeted efficiency programs, this project assesses a cross-section of typical linear LED products operating in non-troffer fixtures and under specific scenarios expected of commercial building retrofits. Work addresses evaluation of 4' T8 LED products, the alternative for the most common type of linear fluorescent installed in California buildings. Evaluations include photometric and electrical performance of 4' linear LED lamps when paired with a variety of fluorescent lamp ballasts and/or electronic drivers. A standard 4' T8 2-lamp fluorescent system is used as the baseline for comparison in terms of both photometric performance and energy savings. Selection of specific products for evaluation is based on a market assessment, which identified the most prevalent linear fluorescent products and their LED replacements along with expected performance metrics, energy use and costs.

BACKGROUND

Linear fluorescent and LED sources emit light in different, distinct ways. These differences affect the interchangeability of the LED and fluorescent products, restricting compatibility based on the product's electrical architecture and power requirements. Because of these restrictions, three different types of linear LED products have emerged on the market, each with its own unique installation and operational requirements. In addition, the availability of some hybrid products, which can operate under multiple configurations, further diversifies replacement operating scenarios.

- Type A: Linear LED lamp with internal driver that is designed to operate on a linear fluorescent lamp ballast.
- Type B: Linear LED lamp with internal driver that must be connected directly to line voltage for power.
- Type C: Linear LED lamp with external driver that is designed to replace both the linear fluorescent lamp and fluorescent lamp ballast.

To better understand why these product types have emerged and how compatibility with fluorescents is affected, the following information on fluorescent technology is presented. Background information includes details on light source technology, lighting system compatibility (use of ballast or driver), lamp base type and lamp fixture types' descriptions, which is necessary for a better understanding of this emerging technology evaluation.

LIGHT SOURCE TECHNOLOGY

Linear fluorescent and LED technologies emit light in different, distinct ways. Fluorescent lamps rely on its phosphor-coated glass tube filled with low-pressure argon gas to act as a conductive pathway for electric discharge created during the start-up process. The charge continuously vaporizes a small amount of mercury present in the tube. This vaporized mercury, or plasma, emits photons in the ultra-violet (UV) range that is converted to visible light as it encounters the phosphor coating. This method of light emission results in a diffuse, isotropic source that is prevalent in common commercial and residential applications.

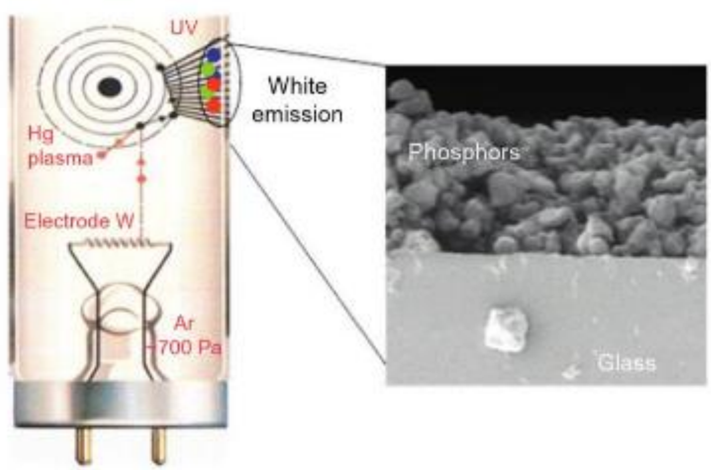


FIGURE 1. FLUORESCENT TECHNOLOGY OVERVIEW[2]

An LED is a solid-state technology, meaning it does not utilize a gas like fluorescent. Instead, the semi-conductor diode conducts electrons from the positive (p) to the negative (n) side of the semiconductor material, through the p-n junction. When the electron flows through the p-n junction, it releases energy is in the form of a photon. Photons are emitted from only one location, which creates a highly directional source of visible light.

[2] Lucas, Jacques, et al. "Rare Earths: Science, Technology, Production, Use". Page 289. 2015.

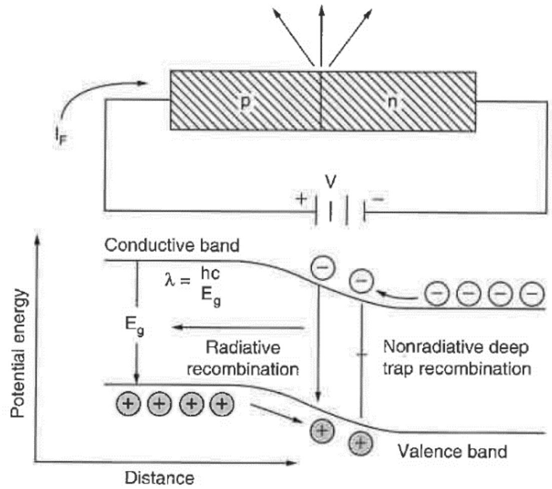


FIGURE 2. LED P-N JUNCTION OPERATION (PHOTO CREDIT: IES LIGHTING HANDBOOK, 9TH EDITION)[3]

BALLAST COMPATIBILITY

Linear fluorescent lamps require an external ballast to provide the initial voltage required for start-up and current regulation during lamp operation. There are a variety of ballasts marketed for use with linear fluorescent lamps. The two main ballast types are magnetic and electronic. Electronic ballasts dominate the market and magnetic ballasts are becoming less and less common as federal energy conservation standards have essentially dictated their phase out and replacement with electronic equivalents. Overall, to ensure quality performance and reduce visible flicker and/or audible noise, linear fluorescent lamps must be paired with fluorescent ballasts identified as 'compatible' per the manufacturer's recommendations, or by third-party testing.

The diversity of linear fluorescent systems also affects the potential compatibility of an LED replacement. There are several different types of electronic fluorescent ballasts – instant start or programmed start, for example, which can influence the selection and/or performance of LED lamp replacement alternatives. Some LED products are designed to operate on linear fluorescent ballasts, while others must be wired directly to line voltage. Each configuration has its own set of benefits and limitations and compatibility of products across or even within types is not common.

LAMP BASE TYPES

Standard lamp bases and caps are defined by the International Electrotechnical Commission (IEC). Types defined by the IEC include bayonet, screw-cap (Edison), single-pin, multi-pin, pre-focus, recessed, and other specialty base types such as the 'flashcube' for photography. This evaluation is focused on lamp base type systems employed with linear fluorescent and linear LED lamps, which includes the following: Fa6, Fa8, G5, G13, 2G13, G20, R17d, and W4.3x8.5d.

[3] Illuminating Engineering Society. IES The Lighting Handbook – 9th Edition. 2000. Figure 1-18.

Linear fluorescent and linear LED lamps are manufactured in base type systems, which are grouped into 4 different categories.

- Single pin base, denoted by an 'F' in the system name.
- Multiple pin base, denoted by a 'G' in the system name.
- Recessed base, denoted by an 'R' in the system name.
- Wedge base, denoted by a 'W' in the system name.

Each of the base type system categories contains a variety of base and cap shapes and sizes. Size is denoted by the dimension in millimeters, or 'D1', between the pins. An additional notation of 'd' or 'q' is added if the shape type can be equipped with a dual or quad pin configuration. Specifically with regards to the multiple pin base system category, if there is no 'd' or 'q' notation of a 'G' type lamp, it is assumed there are two pins.

Table 1 summarizes the base and cap systems acknowledged by the IEC along with the linear lamps to which they correspond based on current commercially available products, including system name, type and description.

TABLE 1. CAP SYSTEMS FOR LINEAR FLUORESCENT AND LINEAR LED LAMPS[4]

SYSTEM NAME	TYPE	DESCRIPTION	STANDARD SHEET
Fa6	Cap	Single Pin	7004-55-3
Fa8	Cap	Single Pin for Tubular Lamps	7004-57-1
G5	Cap	Miniature Bi-Pin	7004-52-5
G13	Cap	Medium Bi-Pin	7004-51-8
2G13	Cap	U-Shaped Fluorescent Base with Bi-Pins	7004-33-2
G20	Cap	Mogul Bi-Pin	7004-53-2
R17d	Cap	Recessed Double Contact	7004-56-2
W4.3x8.5d	Cap	Wedge	7004-115-1

LINEAR FIXTURES

With regards to indoor linear luminaires, there are two main lighting applications, four main fixture categories, and eight fixture types commonly associated with linear products. These are listed and a sample is shown in Table 2. These common fixture categories and types were determined as part of the inventory and product review process described later in this report.

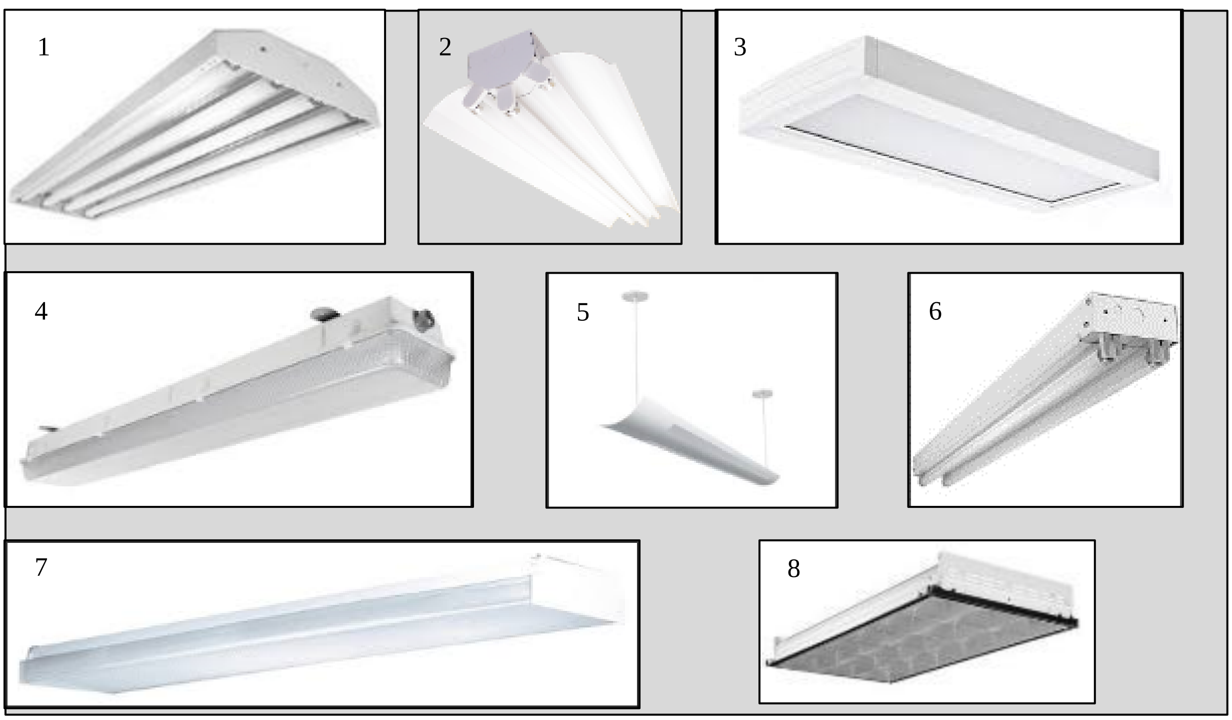
For the purposes of this project assessment, the recessed troffer is excluded because existing performance data and product qualification processes are currently available from other entities. For more information on linear LED product performance and qualified products lists in recessed troffer applications, for example, refer to the U.S. Department of

[4] IEC 60061-1 ed.3.0

Energy's Caliper program, the DLC or the Consortium for Energy Efficiency (CEE) qualified product lists.

Table 2. Linear Fluorescent Luminaire Applications and Fixture Types

Item #	Lighting Application	Fixture Category	Fixture Type
1	Direct Ambient	High Bay	High Bay
2	Direct Ambient	Low Bay	Low Bay
3	Direct Ambient	Non-recessed	Surface-mounted troffer/coffer
4	Direct Ambient	Non-recessed	Industrial-grade fixture for hazardous areas
5	Direct/Indirect Ambient	Non-recessed	Pendant with direct and/or indirect component
6	Direct Ambient	Non-recessed	Surface-mounted strip
7	Direct Ambient	Non-recessed	Surface-mounted wrap
8	Direct Ambient	Recessed	Troffer



EMERGING TECHNOLOGY

The inherent differences in linear fluorescent and linear LED technology require distinct design changes to accommodate and overcome the challenges of molding a highly directional, solid-state light source into a suitable replacement for omnidirectional fluorescent tubes. These changes are necessary to accommodate proper thermal management and transfer heat away from individual LED emitters, which ensures the LED product can better deliver on longevity and lumen output claims.

As important, linear fluorescent lamps are, by nature, an omnidirectional source. The luminaires in which they are housed are most often designed to leverage this omnidirectionality. When an array of directional point sources is used as their replacement, design consideration must be given to ensure that replacement LED linear lamps can deliver the same optical distribution or provide adequate light out of the fixture by other means.

Apart from these elements, products have been developed to address the way in which the LED replacement receives the necessary power to operate. Intrinsically, LEDs do not require or operate with a ballast. They require a DC power supply and driver to regulate their light output. In this regard, currently, linear LED lamps are recognized by Underwriters Laboratory and categorized as one of three product types: Type A, Type B or Type C.

LINEAR LED LAMPS – TYPE A

Type A products contain an internal driver and are designed to operate on a linear fluorescent lamp ballast. They utilize existing fluorescent lamp sockets for power and support. Type A products require shunted sockets. These products are available to replace T5, T8 and T12 fluorescent lamps.

Type A products are simple to retrofit assuming they are compatible with the existing fluorescent ballast, however, compatibility is not guaranteed. Type A products are often only compatible with instant-start fluorescent ballasts, yet because they're considered "plug and play" from the consumer's perspective, products can easily become paired with a ballast type for which they are not compatible. Consumers must read all literature carefully to match lamps with compatible ballasts.

Other issues can arise, which also affect the performance of Type A products. Delamping, for example, can negatively impact LED product life. On the surface, a Type A replacement may be compatible with a 2-lamp ballast, but a fluorescent luminaire may actually contain a 3-lamp ballast and only appear to be a 2-lamp system. A linear fluorescent luminaire, which has been delamped, can create an environment where LED replacements receive too much current and fail prematurely. Again, Type A products can become paired with ballasts for which they are not compatible.

Type A products are also the least efficient option of the three replacement categories because energy is consumed by the ballast in addition to the lamp. In addition, the lifespan of the LED retrofit system is often dictated by the remaining life of the fluorescent ballast. Owners must maintain a replacement ballast inventory and ensure replacement products, whether LED lamp or fluorescent ballast, are compatible.

FIGURE 3. UL TYPE A LINEAR LED LAMP

LINEAR LED LAMPS – TYPE B

Type B LED lamps utilize an internal driver and must be connected directly to line voltage for power. These products rely on the fluorescent sockets for support and may receive power through the component, as well. Type B products are often more efficient than Type A products because ballast losses are eliminated, but clear markings / labeling is paramount to ensure technicians understand that line power is being supplied directly to the socket/lamp and avoid shock hazards. Some products do offer safety mechanisms to reduce this risk. When the internal driver fails, most Type B products must be replaced in their entirety, making driver life the life of the product, not the LED. In addition, type B products are UL certified as a component only, and their use may void the UL certification of the luminaire as a whole.

FIGURE 4. UL TYPE B LINEAR LED LAMP - END CAP SHOWING LINE AND NEUTRAL PIN LABELING (LEFT) AND LAMP WITH END CAP REMOVED SHOWING LED ARRAY (RIGHT)

LINEAR LED LAMPS – TYPE C

Type C lamps utilize an external driver and systems are designed to replace both the linear fluorescent lamp and fluorescent lamp ballast. This type of product is usually the most efficient of the three options. However, the interchangeability of any two Type C products is not guaranteed, as each may require a different type of driver to operate, even though both products are considered part of the same type category. Drivers designed for one LED lamp may not automatically be compatible with another Type C lamp. Type C products may be powered from one or both ends of the lamp. They may use fluorescent lamp sockets for support or they may rely on their own mounting hardware.

FIGURE 5. UL TYPE C LINEAR LED LAMP WITH DRIVER

LINEAR LED LAMPS – HYBRIDS

Some commercial linear LED products can operate under multiple configurations. They are essentially hybrids of Type A, B and C. Two types of hybrids are currently available – Type AB and Type AC. With Type AB products, lamps can be installed as a simple plug-and-play replacement of linear fluorescents. Then, when the ballast fails, instead of replacing it, the Type AB hybrid can be wired directly to line voltage. Type AC products are designed to work either with a fluorescent ballast or with an electronic driver. When used as a Type A product, retrofits can be quick and simple. When used as a Type C product, energy efficiency and performance are optimized.

FIGURE 6. THREE DIFFERENT COMMERCIALLY AVAILABLE HYBRID LED LAMPS – UL TYPE AB (UPPER LEFT), UL TYPE AC (UPPER RIGHT AND BOTTOM)

TECHNICAL APPROACH

This project's technical approach consists of a market and technology assessment developed to determine if LED replacement lamps intended to replace linear fluorescent lamps can provide a reliable replacement alternative, deliver sufficient energy savings and offer equivalent or better photometric performance, specifically with regards to non-recessed troffer applications. In addition, this assessment evaluates the electrical compatibility and related performance issues associated with the diversity of operating scenarios expected in today's commercial buildings.

From the consumer's perspective, linear LED lamps will be treated like their fluorescent counterparts. When a lamp fails, for example, it will be replaced, but it's not expected that consumers will ensure that the same linear LED product is used as a replacement. How will products perform when connected to a driver or ballast left in place from a previous system? To answer questions like this, the assessment includes evaluation of various Type A products when paired with a cross-section of typical fluorescent ballasts; as well as the interchangeability of Type C products operating on a variety of LED drivers.

MARKET ASSESSMENT

This market assessment contains three key parts. First, the assessment contains an estimate of the installed linear lamp baseline in California and PG&E territory. Second, it includes an inventory and literature review of linear lamps, ballast and fixtures, which was used to determine the most relevant non-troffer fixture types to include as part of laboratory evaluations. Last, the assessment provides an estimate of the energy reduction potential of linear LED lamps intended to replace the most common linear fluorescents in key commercial applications.

INSTALLED BASELINE

Commercial, publically available market surveys and reports are referenced to estimate the number of buildings and associated, installed, linear fluorescent lamps for the US, California and PG&E markets. This information is coupled with commercial lighting design principles to identify the most common linear fixtures in use today in California. This information served as the foundation for selection of specific products included in the laboratory evaluation phase of the project.

MARKET INVENTORY

To assess the market for linear fluorescent systems (lamp, ballast and fixture) and their LED replacements (lamp, ballast/driver and fixture), both incumbent and replacement technologies available for purchase in the United States were identified and catalogued in a product inventory. Market data was collected from the DLC Qualified Product's List (QPL), the CEE QPL for 4' T8 replacements, as well as an online survey of major manufacturers offering these products.

Lamp characteristics identified include lamp manufacturer, lamp model, base type, light source technology, nominal power consumption (Watts), rated lifetime (hours), warranty (years), maximum overall length (inches), correlated color temperature (CCT), color rendering index (CRI), maximum light output (lumens), dimmability rating and ballast compatibility.

Due to the prevalence of four-foot T8s in commercial buildings, comparative data on LED replacements focuses on products marketed as equivalents for this product category. Information on this product sector has been extracted from QPLs that address LED lamps serving the T8 replacement market as well as a variety of other categories such as T5 and eight-foot T8 replacements.

POTENTIAL LOAD AND ENERGY USE REDUCTION

Lamp inventory information includes the average installed wattage of common 4' T8 linear fluorescents and their LED counterparts. This information was coupled with an estimate of the number of installed 4' T8 fluorescent lamps and average hours of use for commercial buildings in order to calculate the energy reduction potential of linear LED lamp technology.

TECHNOLOGY ASSESSMENT

The technology assessment consists of two evaluations. The first, application testing, is designed to test LED product performance in various fixture types. The second, interoperability testing, is designed to test performance of LED products operating on various manufacturer's ballasts and drivers. In total, one fluorescent and thirteen LED linear lamps were tested as part of this evaluation.

TEST EQUIPMENT AND TEST STANDARDS

Photometric measurements were made with a SphereOptics SMS-500 spectrometer in a 2-meter integrating sphere. Power provided by a California Instruments 2253ix power supply. Power measurements were taken with a Yokogawa PZ4000. Total harmonic distortion (THD) measurements were taken with PZ4000's harmonics mode. Auxiliary correction applied for fixture self-absorptions. Lamps were seasoned for 100 hours and allowed to stabilize before each test.

All tests were completed in accordance with industry standard test procedures:

- LED tests: IES LM-79-08
- Fluorescent tests: IES LM-09-09

FIGURE 7. BARE-LAMP TEST SET-UP IN INTEGRATING SPHERE

Optical distribution data was collected with a T-10A Konica Minolta illuminance meter and a CL-200A Konica Minolta chromameter in a dark room with a Type C Goniophotometer. The goniophotometer was used to collect data for each product in each fixture and for each electrical configuration (Type A, B or C), as applicable. Power provided by a California Instruments 751ix. Stray light correction applied for fixture self-absorptions. Lower and Upper hemisphere characterizations was taken separately and then combined in post processing to create full hemisphere characterization.

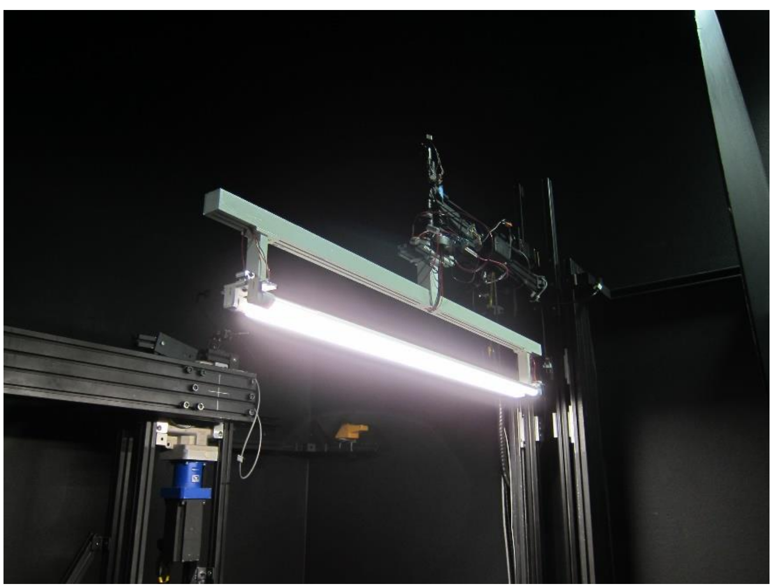


FIGURE 8. BARE-LAMP TEST SET-UP IN GONIOPHOTOMETER

TESTED PRODUCTS

Selected products are all 4' lamps operating in a 2-lamp fixture with a 2-lamp ballast or driver. For the linear fluorescent, Type A and Type AB hybrids, lamps were powered on a standard instant-start ballast with 0.88 ballast factor in the application testing and on three different ballast types as part of the interoperability testing. Ballast and lamp compatibility was verified for applicable LED products used in the application testing. Type B products were powered directly by line voltage, 120V. Type C and Type AC products operating in the Type C configuration were powered by the manufacturer's recommended driver in the application testing and on a variety of different manufacturer's drivers for the interoperability testing.

Table 3 lists all tested products along with their manufacturer-listed performance attributes. For LED hybrid products, performance in both operating modes (A and B or A and C) is provided. The fluorescent system represents the most common linear system installed in California buildings today and is used as a baseline of comparison for tested LED products.

TABLE 3. TESTED PRODUCTS WITH MANUFACTURER LISTED PERFORMANCE

Product ID	Operating Mode	Beam Angle (degrees)	CCT (K)	CRI (Ra)	Input Power (W)	Light Output (lm)	System Efficacy (lm/W)
Fluorescent	-	360	3500	>70	59.0	4484	76.0
LED B	A	180	4000	>80	30.0	3200	106.7
LED B	B	180	4000	>80	30.0	3200	106.7
LED C	A	220	4000	>80	34.0	3600	105.9
LED C	B	220	4000	>80	30.0	3600	120.0
LED D	A	Not stated	4000	>80	33.2	3750	113.0
LED D	B	Not stated	4000	>80	30.0	3600	120.0
LED E	B	Not stated	4000	>80	26.0	3120	120.0
LED F	C	Not stated	4000	83	36.0	4400	122.2
LED G	B	310	4000	80	29.0	3400	117.2
LED H	B	Not stated	3500-5000	Not stated	36.0	5040	140.0
LED I	A	120	4100	82	36.0	Not stated	121.0
LED J	A	160	4000	82	34.0	4200	123.5
LED J	C	160	4000	82	33.0	4200	127.3
LED L	A	220	4100	82	36.0	4400	122.2
LED L	C	220	4100	82	36.0	4400	122.2
LED N	C	Not stated	4000	80	44.0	4500	102.3
LED O	C	Not stated	4000	>80	30.0	3600	120.0
LED P	C	Not stated	3700-4300	>80	30.0	3700	123.3

Application Testing

Application testing is intended to quantify the effects of using an array of point sources with a highly directional beam angle (LEDs) in fixtures designed to distribute light from a source with a 360 degree beam angle (fluorescent). Impacts on delivered light output, system efficacy and overall light distribution are examined. Assessments focus on non-troffer fixtures.

Based on market assessment results, two common fixtures were utilized for application testing along with characterization of bare lamp performance, which is used as the baseline for comparison. More information on how these fixtures were selected is provided in the Results section of this report. Characterization was conducted for each selected product operating in a bare-lamp strip fixture, a suspended pendant, and a surface-mounted wrap. All fixtures utilized a two-lamp configuration. Details on selected fixtures are provided in Table 4.

TABLE 4. FIXTURES USED FOR TESTING

Fixture Type	Bare-Lamp Strip	Wrap	Pendant
Description	Fixture provided by sphere manufacturer for bare lamp characterization	Ceiling, surface mount	Suspended, direct/indirect (34% direct/66% indirect)
Lens/Reflector	None	Acrylic, white opal, fully enclosed	Aluminum, diffuse reflector
Fixture Efficiency	~100% (estimate based on fluorescent bare lamp test)	75.7%	79.5%

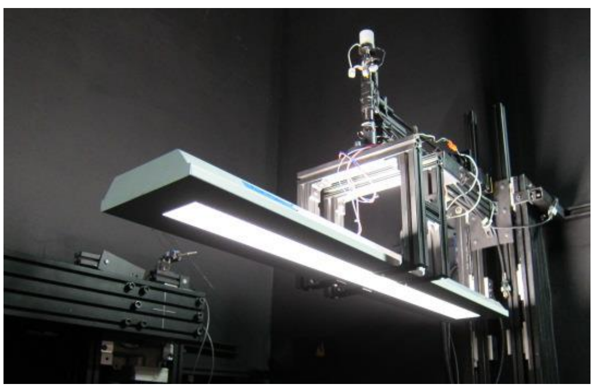


FIGURE 9. LINEAR SUSPENDED PENDANT (LEFT), LINEAR WRAP (RIGHT)

Interoperability Testing

The second goal of this project is to characterize lamp performance and document compatibility issues for products operating in configurations that may not be recommended by manufacturers, but that may be unknowingly instituted by consumers in common repair and replacement situations.

For Type A LED products, two such scenarios are expected to be most common:

1. Products installed in fixtures with incompatible fluorescent ballasts. For this project, testing includes operating two representative, Type A LED lamps on the following ballast types:
   a. Instant-start: 2-lamp, electronic, 0.88 ballast factor (BF), parallel wiring
   b. Rapid start: 2-lamp, electronic, 0.85 BF, series wiring
   c. Programmed rapid start: 2-lamp, 0.85 BF, parallel wiring
2. Products replacing fluorescent lamps in a delamped fixture where the ballast is rated for use with more lamps than are replaced by LED. Because this project examines LED lamp performance in a 2-lamp fixture, this interoperability testing will examine a 2-lamp fluorescent ballast operating only one LED lamp.

For Type C LED lamps, when lamps fail, consumers may choose to replace them with a different Type C LED lamp and leave the existing driver in place. Under this scenario, the lamp may not be compatible with the existing driver. This project examines five Type C LED lamp/driver combinations and includes performance data for each LED lamp operating on each of the five drivers.

A list of all test combinations is provided in Table 5. Each test combination was completed for the product combination using a fully lamped, 2-lamp configuration and again under a delamped, 1-lamp configuration.

TABLE 5. INTEROPERABILITY TEST MATRIX

Control Gear	Lamp Product Tested							
	Type A			Type C				
	Fluorescent	LED J	LED I	LED N	LED F	LED L	LED O	LED P
Ballast A: Instant-start, High BF ballast	X	X	X					
Ballast B: Rapid start ballast	X	X	X					
Ballast C: Programmed start ballast	X	X	X					
Driver - LED N				X	X	X	X	X
Driver - LED F				X	X	X	X	X
Driver - LED L				X	X	X	X	X
Driver - LED O				X	X	X	X	X
Driver - LED P				X	X	X	X	X

RESULTS

Results show that linear LED lamps have the potential to significantly reduce lighting electricity use locally and nationwide. A complete conversion of indoor linear fluorescent to LED technology in the PG&E service territory has the potential to cut lighting electricity use by nearly 20 percent. However, consumers must be cautious when converting to linear LED solutions. In nearly all configurations and fixtures tested, LED lamps delivered significantly less light than the fluorescents they were marketed to replace. In the bare lamp fixture, where fixture efficiency and effects of beam angle on distribution do not impact light exiting the fixture, the LED products produced, on average, 15 percent less light than the fluorescent baseline. In addition, as LED products age and fail, consumers must ensure that they replace the entire linear LED system – both lamp and ballast/driver to ensure continued successful operation. As expected, test results show that most Type A linear LED lamps experience significant performance degradation when operating on ballasts that are not recommended by the lamp manufacturer. For Type C LED lamps, care must be taken to operate only on manufacturer-recommended drivers. Most products are not compatible with other manufacturer's drivers even though on paper, the drivers may appear very similar or even identical.

The following section details results of the market assessment; laboratory evaluation of commercially available linear LED lamps operating in common fixtures; and interoperability of multiple linear LED lamp, ballast and driver combinations.

MARKET ASSESSMENT

In California, approximately 80 percent of linear lamps are found in office, school, retail and miscellaneous businesses such as services, laboratories and assembly spaces. With these businesses, on average, linear fixtures contain 2.5 lamps, with the four-foot, base-efficiency (700 series, 32W) T8 fluorescent lamp being most common. Common lighting design practice calls for use of direct or indirect lighting methods with recessed or surfaced-mounted troffers, surface-mounted wraps and suspended direct/indirect pendants being the most prevalent fixture types. The next most common fixture category for linears is the highbay, which accounts for 13 percent of all installed linears in the state. Additional details regarding the installed base of linear lamps, ballasts and fixtures is provide below.

INSTALLED BASELINE

LINEAR LAMPS

TABLE 6. ESTIMATED INSTALLED LINEAR FLUORESCENT LAMPS BY REGION (2014) – COMMERCIAL AND RESIDENTIAL

Lamp Type	United States	California	PG&E Territory
Linear Fluorescent	2,540,000,000	171,000,000	69,000,000

As of 2010, there was a total of 2,385,399,000 linear fluorescent lamps installed in the United States.[5] According to the report issued by the U.S. Department of Energy, on average, there were 5.1 linear fluorescent lamps per residential building, 301 linear fluorescent lamps per commercial building, and 283 linear fluorescent lamps per building in the industrial sector.[6]

According to the same report, the growth in overall linear fluorescent lamp inventory for the residential, commercial and industrial sectors between 2001 and 2010 was 26%, 13% and -54%, respectively. The decline in growth in the industrial sector was attributed to the increased availability and use of high-wattage HID alternatives. At these growth rates, we estimate the total installed linear fluorescent baseline in the U.S is approximately 2,540,000,000 lamps as of 2014. Note, we are using 2014 as a basis for comparison so that national level data is better aligned with the most recent California-level data, which is discussed in detail below.

Using California commercial building data published in the 2014 California Commercial Saturation Survey Report (CSS), we estimate that there are approximately 719,500 commercial buildings in the state. In total, these buildings contain nearly 106 million linear lamps. Roughly ninety-three percent of this baseline is composed of four-foot fluorescents, which is approximately six percent of all commercial linear fluorescent lamps installed in the U.S. Table 7 contains details on the installed base of linear lamps in California commercial buildings.

With respect to residential buildings, California homes contain approximately 65 million linear fluorescent lamps, however the distribution of lamps by lamp length is unknown. For the purposes of this report, we estimate the residential linear lamp distributions using the commercial sector distribution data, which states 93 percent of installed linear fluorescents are four-foot lamps.

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[5] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf. Table 4.1, page 35 of 100.

[6] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf. Table 4.3, page 39 of 100.

TABLE 7. ESTIMATED INSTALLED LINEAR FLUORESCENT LAMPS IN CALIFORNIA COMMERCIAL BUILDINGS (2014)

					4' Linear Lamps				
Business Type	Total Commercial Floorspace (1000s sq. ft.)	Total Number of Buildings	Average No. of Linear lamps per 1000 sf	Total No. of Linear Lamps (All lengths, all types)	% of Total Installed Lamps - 4' Linears	Total No. of 4' Linear Fluorescent Lamps	% of Total Lamps - LED	Total No. of 4' Linear LED Lamps	Total No. of Other Linear Lamps (Other lengths/types)
Food/Liquor	135,296	21,921	25.7	3,477,107	85%	2,943,719	0.40%	11,822	521,566
Health/Medical - Clinic	254,814	52,954	28	7,134,792	94%	6,706,704	0.00%	-	428,088
Miscellaneous	1,325,202	220,830	19.5	25,841,439	92%	23,750,350	0.10%	23,774	2,067,315
Office	1,438,667	144,881	7.9	11,365,469	96%	10,910,851	0.00%	-	454,619
Restaurant	197,856	74,776	15.4	3,046,982	96%	2,925,103	0.00%	-	121,879
Retail	825,124	119,983	22	18,152,728	88%	15,958,426	0.10%	15,974	2,178,327
School	711,206	14,906	30.3	21,549,542	99%	21,334,046	0.00%	-	215,495
Warehouse	1,996,311	69,275	7.7	15,371,595	88%	13,527,003	0.00%	-	1,844,591
Total	6,884,476	719,526		105,939,654		98,056,203		51,571	7,831,881

Table based on data provided by 2014 CSS and 2010 LMC reports.

As of 2006, commercial floor stock within PG&E territory comprised 1,969,884,000 square feet - 40 percent of California commercial buildings. Assuming this percentage has not significantly changed between 2006 and 2014, we estimate there is approximately 2.7 million square feet of commercial floor space in PG&E service territory.

The 2014 CSS report shows that the average commercial building size varies among California IOU service territories, which directly impacts the number of linear fluorescent lamps and luminaires installed. Adjusting average building size based on available data, we estimate there is approximately 42.3 million linear lamps installed in commercial buildings within PG&E territory.

Residential buildings represent another significant base of installed linear fluorescent lamps. There are approximately 5.2 million households within the PG&E service area. Assuming an average of 5.1 lamps per residence, as estimated by U.S. DOE, these buildings add another 26,520,000 linears to the baseline. In total, we estimate there are nearly 69 million installed linear lamps within the PG&E service area.

Four foot, base-efficiency (700 series, 32W) T8 fluorescent lamps are the most common type of linear lamp installed in California buildings. Within California and PG&E territory, there are 81.6 and 32.9 million installed 4' T8 fluorescent lamps, respectively. Approximately 83 percent of all installed 4' linear fluorescent lamps are 4' T8s. The remaining 17 percent of 4' linears are comprised of T12, T5 and LED products. Table 8 contains data from the CSS report on the indoor lighting length distribution of 4' fluorescents by business type. Figure 11 and Table 9 contains data on the linear lamp efficiency distribution by business type within PG&E territory.

TABLE 8. INDOOR LIGHTING LENGTH DISTRIBUTION OF LINEAR LAMPS BY BUSINESS TYPE IN CALIFORNIA [7]

Lamp Length	Food/ Liquor	Health/ Medical - Clinic	Misc.	Office	Restaurant	Retail	School	Warehouse
4' Linear	85%	94%	92%	96%	96%	88%	99%	88%
8' Linear	15%	1.0%	7%	0.4%	2.2%	9%	0.6%	11%
Other Length	0.6%	4.5%	1.6%	3.8%	1.8%	2.9%	0.5%	1.0%
Total	100%	100%	100%	100%	100%	100%	100%	100%

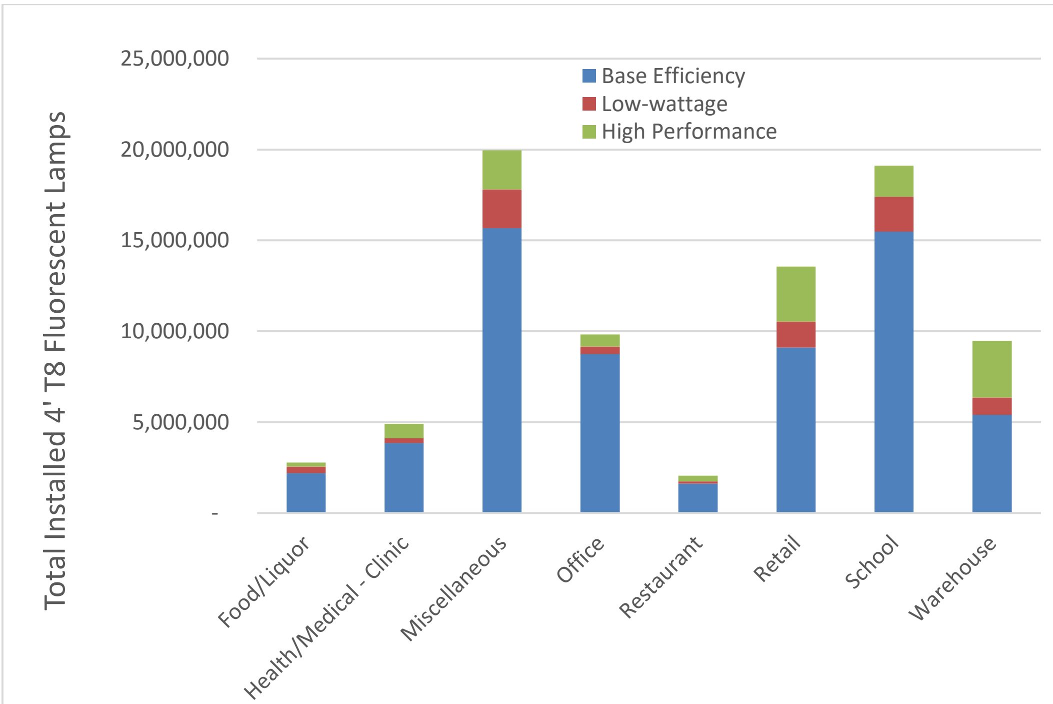

FIGURE 10. DISTRIBUTION OF 4' T8 FLUORESCENT LAMPS IN CALIFORNIA BY COMMERCIAL BUSINESS TYPE

[7] http://www.calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf. Table 5-13, page 153 of 397.

TABLE 9. INDOOR LIGHTING – 4' T8 LINEAR LAMP EFFICIENCY DISTRIBUTION BY BUSINESS TYPE IN THE PG&E TERRITORY [8]

Performance Group	Food/ Liquor	Health/ Medical - Clinic	Misc.	Office	Restaurant	Retail	School	Warehouse
Base Efficiency	86%	83%	85%	94%	96%	72%	86%	41%
High Efficiency	14%	17%	15%	6%	4.4%	28%	14%	59%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Base Efficiency Tiers Distribution								
4' Other	0%	0%	0%	0%	0%	0%	0%	0%
4' Unknown T8	2.9%	2.0%	3.8%	4.0%	2.6%	17%	3.2%	6%
4' Std 700 T8	47%	50%	38%	78%	49%	25%	61%	9%
4' Std 800 T8	33%	14%	23%	6%	8%	23%	14%	3.9%
High Efficiency Tiers Distribution								
4' High Performance T8	2.2%	17%	7%	2.7%	4.4%	9%	6%	38%
4' Reduced Wattage T8	11%	0%	6%	2.9%	0%	14%	7%	15%

LINEAR FLUORESCENT BALLASTS

Electronic linear fluorescent lamp ballasts are the most common ballast installed in California buildings. High-efficiency electronic ballasts, which meet the CEE top-tier requirements, constitutes approximately 10 percent of all installed ballasts, while base efficiency products represent between 70 to 80 percent of all ballasts depending on the business type. In California, restaurants and medical clinics have the highest percentage of magnetic ballasts still in use. Figure 11 and Figure 12 show the distribution, as of 2014, of ballasts installed in California and PG&E commercial buildings by business type and light source type, respectively.

It is important to note that both the instant start electronic ballast and the programmed start electronic ballast are the most widely recommended compatible ballasts for use with linear fluorescent lamps. These are also the two most commonly referenced compatible ballasts for Type A linear products.

[8] http://www.calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf. Table 5-16, page 159 of 397.

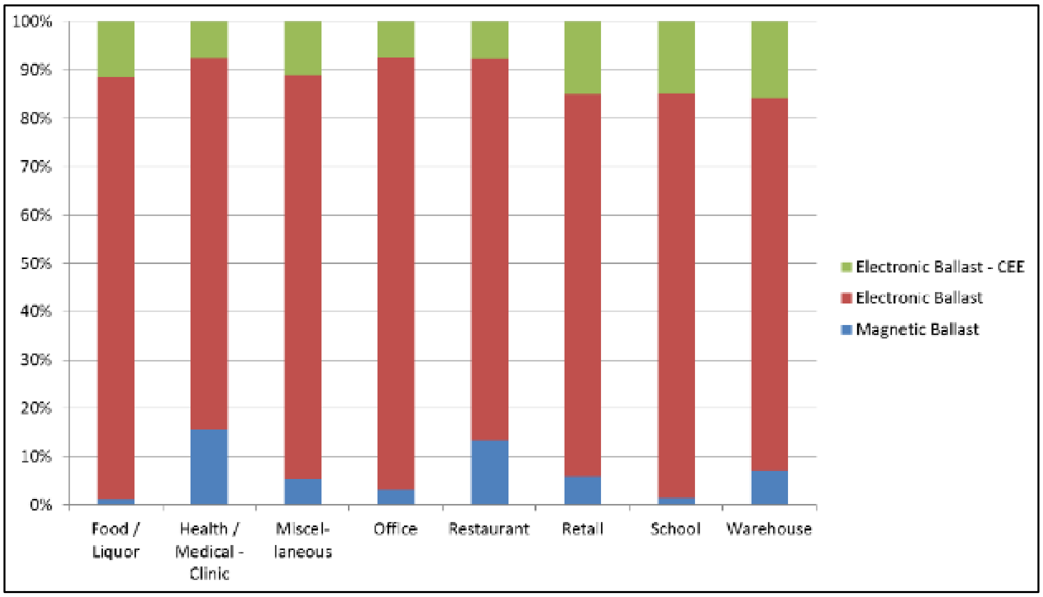

FIGURE 11. INDOOR LIGHTING LINEAR BALLAST EFFICIENCY DISTRIBUTION BY BUSINESS TYPE IN CALIFORNIA [9]

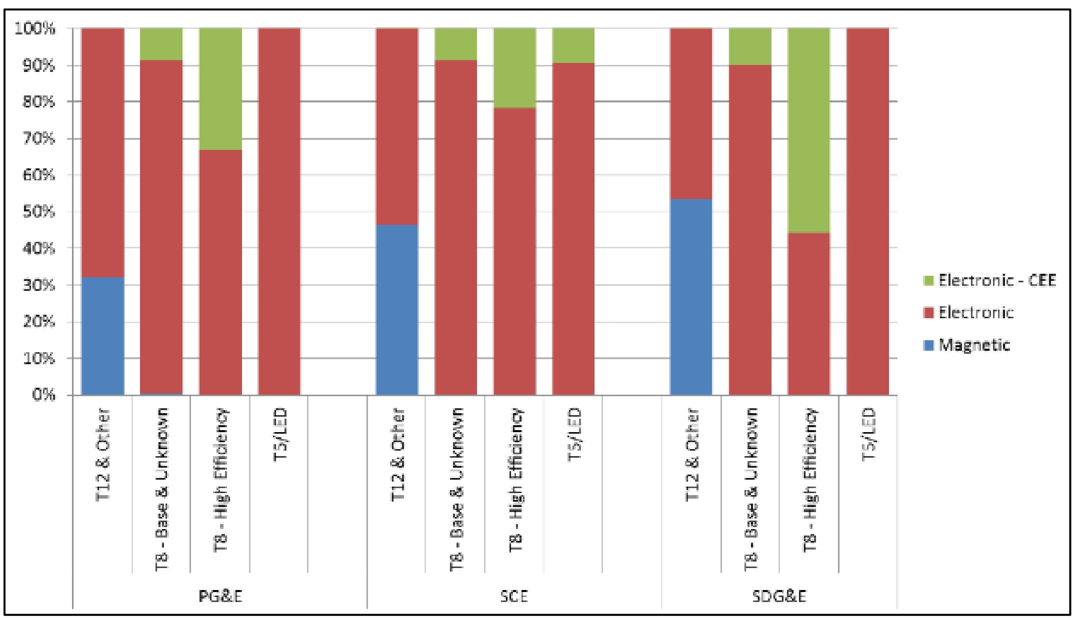

FIGURE 12. INDOOR LIGHTING LINEAR BALLAST EFFICIENCY DISTRIBUTION BY LAMP TECHNOLOGY AND BUSINESS SIZE IN CALIFORNIA [10]

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[9] http://www.calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf. Figure 5-16, page 184 of 397.

[10] http://www.calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf. Figure 5-17, page 185 of 397.

LINEAR FIXTURES

Comprehensive estimates of installed linear fixture types at the national or state level is not available as part of publically available databases or reports, beyond some limited data for high bay luminaires. However, an estimate of the installed linear fixture baseline can be made indirectly by examining lamp data and considering this information in combination with common commercial lighting design practice.

In California, the largest portion of linear lamps are found in office spaces. Looking at the top business types, sixty percent of linear lamps are found in offices, schools and retail buildings. Miscellaneous buildings utilize the second largest number of linear lamps in California at 19 percent. Miscellaneous buildings include businesses such as services, laboratories, multifamily common areas and assembly spaces. Figure 13 contains the indoor lighting distribution of linear lamps by business type (data taken from 2014 CSS).

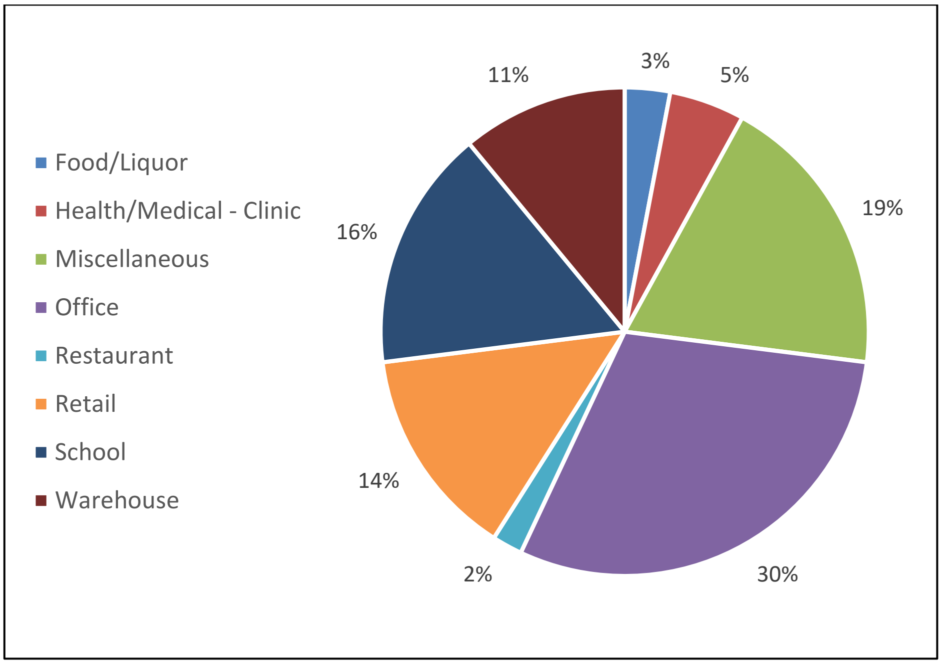


FIGURE 13. DISTRIBUTION OF LINEAR LAMPS BY BUSINESS TYPE IN CALIFORNIA COMMERCIAL BUILDINGS (2014)

Because data is unavailable on the actual distribution of specific fixture types within California commercial buildings, we can justify a reasonable estimation of the most prevalent types by considering general lighting design principles for commercial applications using the largest percentage of California's installed linear lamps. As shown in Figure 8, these applications are offices, retail businesses, schools and miscellaneous spaces.

From a design perspective, lighting in these applications follows one of two approaches: generalized or localized illumination. The intent of generalized illumination is to provide uniform light levels throughout the space, while localized illumination provides targeted lighting for work areas and displays.

Within the offices, schools and the miscellaneous businesses that most often employ linear lighting, several factors contribute to the prevalence of two types of lighting, direct or indirect lighting, to achieve these design goals. Spaces that change configurations with respect to furniture, work areas or occupants most often follow a generalized lighting approach achieved through use of luminaires that deliver direct lighting. This is because direct luminaires are mounted or recessed in the ceiling, away from occupants, furniture and other items. Direct general lighting does not interfere with or obstruct movement of objects within the space and it provides adequate light levels to all areas of the building independent of space configurations.

When changes within the space can be kept to a minimum, indirect lighting becomes more common. Indirect lighting or direct/indirect for general illumination is achieved through the use of suspended linear pendants. These luminaries direct lighting up onto the ceiling, where it is reflected back to the work space, created a low-glare, uniform lighted environment. In addition, because luminaries are suspended from the ceiling and therefore closer to the work plane, required light levels can often be achieved with an overall lower lighting power density as compared to a design that utilizes direct lighting mounted at the ceiling level.

Regardless of the approach, the most common linear luminaires available to achieve these design goals are recessed and surface mounted troffers, suspended direct/indirect pendants and surface mounted wraps. Warehouses, which account for 11 percent of all installed linears utilize high and low-bay luminaires, another type of direct general illumination luminaire, as do some types of retail spaces and school buildings.

Performance data is available on recessed troffers as well as qualified product lists for this fixture type, as previously discussed, from groups such as DLC and CEE. This study seeks to better understand performance of linear LED lamps installed in other types of common fixtures. Considering the lighting design practices of the business types that most commonly use linear lamps (offices, schools, retail and miscellaneous), the next most common fixtures are surface-mounted troffers, surface-mounted wraps and high/low bay luminaires.

From a photometric perspective, linear LED lamps installed in surface mounted troffers – also commonly called coffers – will perform nearly identical to their recessed counterparts. The aperture size of the same product surface-mounted as compared to recessed does not change. Some variance in thermal conditions between the two could impact lamp performance overtime, however this type of testing is not considered as part of this work.

Therefore, looking beyond the troffer, the next most common luminaire is the surface-mounted wrap and the suspended linear pendant. By considering these two fixture types, the study, when combined with existing data on recessed troffers from other sources, will address up to 80 percent of the installed linears in California commercial buildings.

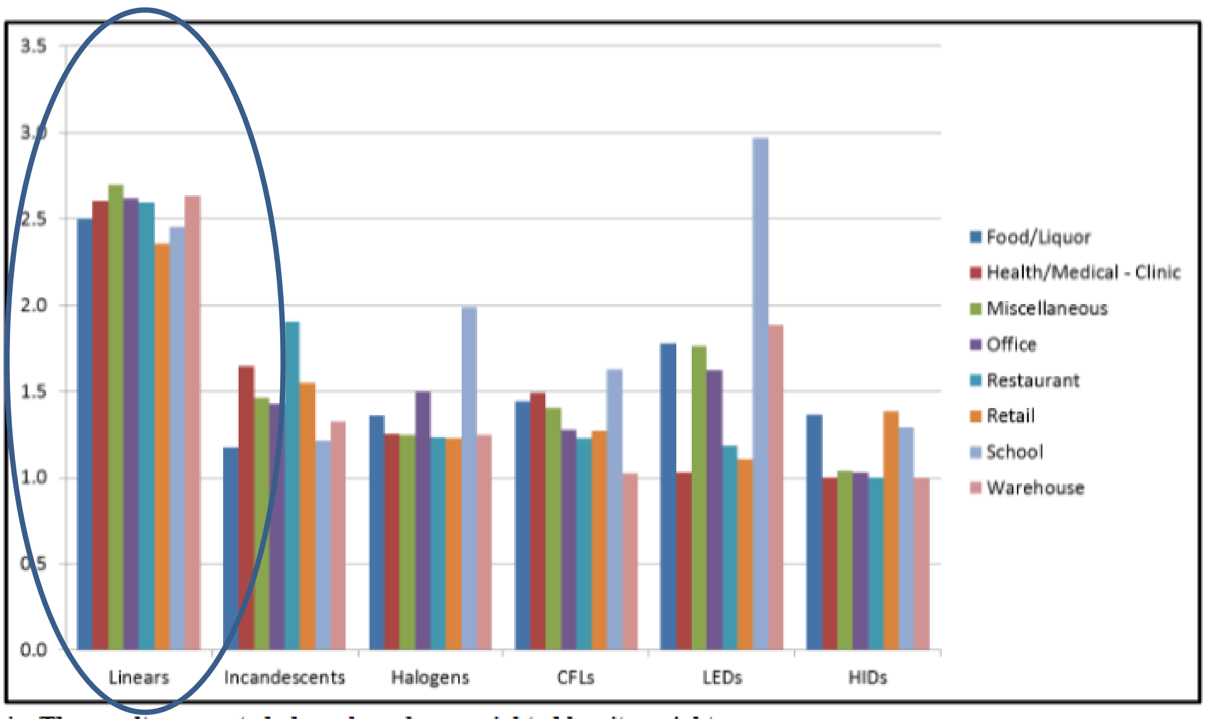
The next largest segment of the installed linear fixture market is highbay luminaires. Highbay luminaires are defined as luminaire mounted 15′ or above grade. These luminaires are primarily used in warehouse applications, however a portion of the previously mentioned target business types do utilize these luminaires. According to the CSS report, 13 percent of linear lamps reside in highbay luminaires.

Last, the scope of the assessment can be further limited to address 2 or 3 lamp fixtures. The majority of linear fixtures installed in California utilize two or three lamps according the CSS report. An excerpted graph from the CSS report, Figure 14 below, shows that on average, there are approximately 2.5 lamps per linear fixture in California. Given the total number of installed linear lamps, and assuming 2.5 lamps per fixture, results in approximately 27,600,000 linear fixtures in PG&E service territory.

TABLE 10. ESTIMATED INSTALLED LINEAR FLUORESCENT FIXTURES BY REGION (2014) – COMMERCIAL AND RESIDENTIAL

Lamp Type	United States	California	PG&E Territory
Linear Fluorescent	1,016,000,000	68,400,000	27,600,000

When used in the application of interest, one and four lamp configurations can be disregarded. Four linears per fixture in a non-high bay application would commonly over light a space, while a one-lamp linear fixture becomes insufficient to achieve general illumination under most conditions.



* **The results presented above have been weighted by site weight.**

FIGURE 14. Average Number of Lamps per Linear Fixture in California Commercial Buildings

To summarize, approximately 80 percent of installed linear lamps reside in office, retail, school and miscellaneous businesses. Within these businesses, three types of fixtures are most common: troffers, suspended pendants and surfaced-mounted wraps. Another 13 percent of linears are installed in highbay luminaires. Regardless of the application or fixture type, two and three lamp configurations are most common, with the four-foot, standard efficiency T8 lamp being most prevalent.

LINEAR LAMP MARKET SURVEY

To better understand individual performance attributes of existing 4' T8 fluorescent and LED lamps, a survey of 3rd party certified product data was completed and results catalogued. Detailed product data was collected from two primary sources, shown in Table 11Due to the size of the DLC QPL (15,000+ products as of 10/5/2016), analysis includes only recent products submitted since July 1, 2016. This results in a data subset of approximately 3,000 products. All products on the CEE QPL were included.

TABLE 11. PRODUCT DATA SOURCES

Source	Date QPL Accessed	Product Submittals Considered
DesignLights Consortium	October 2016	July 1, 2016 – October 5, 2016
Consortium for Energy Efficiency	October 2016	ALL

Based on surveyed products, roughly one third of linear LED products are Type A, one third type B, with the remaining one third split between Type C and Type AB hybrids. The distribution of linear LED products by product Type (A, B, C, hybrid) is shown in Table 12.

TABLE 12. LINEAR LED LAMPS - BALLAST COMPATIBILITY MARKET SHARE

	UL Type A	UL Type B	UL Type C	Type AB - Hybrid	Type AC – Hybrid
LED	33%	35%	14%	18%	<1%

Catalogued lamp attributes include manufacturer, model, base type, light source technology, nominal power consumption (Watts), rated lifetime (hours), warranty (years), maximum overall length (inches), correlated color temperature (CCT), color rendering index (CRI), full light output (lumens), dimmability rating and ballast compatibility. A summary of linear fluorescent and linear LED lamp performance is shown in Table 13 to Table 17. A copy of the QPLs utilized for this work is provided in Appendix A.

Focusing on four-foot T8 lamps, the most common linear fluorescent installed in California buildings, surveyed LED linears show an average load reduction of 43 percent as compared to the average fluorescent system . This value has been weighted to account for the portion of the installed inventory attributed to low-wattage T8 lamps (25W, 28W, 30W) and high performance T8s (3100 or more lumens and 4000+ hours of extended life). Assuming the selected linear LED lamp products are compatible with existing components, this product category allows system owners the flexibility to keep existing fixtures and reduce system load.

TABLE 13. 4' T8 LINEAR FLUORESCENT (LFL) AND LINEAR LED LAMPS - GENERAL MARKET CHARACTERISTICS

	Number of Lamps Surveyed	Average Rated Power (W)	Average Efficacy (lm/W)	Average Light Output (lm)	Avg. Rated Life (Hrs.)	Average Warranty (Yrs.)
LFL	774	31.5	94	2970	33,000	Unknown
LED	3537	17.8	119	2120	50,000	4.5

On average, however, linear LEDs marketed to replace 4' T8s deliver about 28 percent less light per lamp. As shown in Table 11, a majority of linear replacements deliver light output significantly lower than the majority of linear fluorescents.

With respect to light output, 89 percent of the inventoried linear fluorescent lamps produce between 2,400 and 3,099 lumens. Typical retrofit applications are suited for 'one-to-one' lamp replacements. For this approach, only 28 percent of the inventoried linear LED replacement lamps produce light within the 2,400 to 3,099 lumen range. Based only on a lumen comparison, the number of products that are actually 'equivalent' in terms of light output is limited.

TABLE 14. 4' T8 LINEAR FLUORESCENT (LFL) AND LINEAR LED LAMPS - LUMEN OUTPUT MARKET SHARE

Lumen Range	0 - 699	700 - 899	900 - 1199	1,200 - 1,599	1,600 - 1,999	2,000 - 2,399	2,400 - 3,099	3,100 - 5,199	5,200 - 10,000	Unknown
LFL	0%	0%	0%	0%	0%	2%	89%	3%	0%	6%
LED	0%	0%	0%	3%	35%	34%	15%	13%	0%	0%

Dimmable products allow for additional savings when paired with appropriate lighting controls. Twenty-one percent of surveyed 4' linear LED lamps are dimmable. Note, for Type A and Type C LED products, dimming is only achievable when the product is paired with a dimming ballast or driver. Based on surveyed products, Type C LED replacements have the highest occurrence of dimming functionality. Very few Type A or Type B products are dimmable. Dimmability ratings for the majority of linear fluorescent lamps listed with surveyed QPLs was not provided, however most base efficiency fluorescents are dimmable, when paired with a dimming ballast.

TABLE 15. 4' T8 LINEAR FLUORESCENT (LFL) AND LINEAR LED LAMPS - DIMMABILITY MARKET SHARE PER MANUFACTURER RATING

Source Type	Dimmable? Yes	Dimmable? No	Unknown/Not Yet Tested
LFL	4%	2%	94%
LED - Total	21%	74%	5%
LED – Type A	4%	96%	<1%
LED – Type B	7%	86%	7%
LED – Type C	79%	17%	4%

Based on data from the CEE QPL, 91 percent of the listed linear fluorescent lamps have a CCT between 3,000 Kelvin (K) and 6,500 K. Typical commercial applications specify a CCT between 3,000 K and 4,200 K. Fifty-six percent of the inventoried linear fluorescent lamps fall within this range. Sixty-two percent of the inventoried LED products had a CCT between 3,000 K and 4,200 K.

TABLE 16. 4' T8 LINEAR FLUORESCENT (LFL) AND LINEAR LED LAMPS - CCT MARKET SHARE

Nominal CCT (K) Rating	2,200	2,500	2,700	3,000	3,500	4,000	4,500	5,000	5,700	6,500	Unknown
LFL*	0%	0%	0%	13%	20%	23%	0%	29%	1%	5%	8%
LED*	0%	0%	1%	19%	19%	24%	12%	23%	1%	1%	1%

*Note: Values contain round-off errors due to the number of nominal CCT ratings.

With respect to color rendering, 50 percent of installed linear fluorescent lamps have a color rendering index (CRI) between 80 and 100. Approximately 47 percent of installed linear fluorescents are 700 series lamps with a CRI between 70 and 79. Most indoor applications require a CRI of at least 80.[11] Most linear LED replacement lamps fall in the 80+ range with 98 percent of the inventoried lamps falling in this category.

TABLE 17. 4' T8 LINEAR FLUORESCENT (LFL) AND LINEAR LED LAMPS - CRI MARKET SHARE

CRI Range	70-79	80-100	Unknown
LFL	47%	50%	3%
LED	0%	98%	2%

MANUFACTURERS SERVING THE LINEAR LUMINAIRE SYSTEM MARKET

Nearly all major domestic lighting manufactures now offer LED products including dedicated LED luminaires, LED retrofit kits and replacement lamps. In addition, a plethora of new companies focused on private labeling and distribution of LED products manufactured by others have joined the market. Table 18 contains a sample of manufacturers who offer linear fluorescent lamps, linear LEDs, ballast, drivers, and/or linear fixtures.

[11] DesignLights Consortium. Technical Requirements Table V4.0. June 1, 2016.

TABLE 18. LIST OF MAJOR LIGHTING INDUSTRY MANUFACTURERS

Manufacturer	Lamps		Ballast/ Drivers	Fixtures and Retrofit Kits
	LED	LFL		
3M	X			
Acuity			X	X
Aleddra	X			X
All Green Lighting, Inc.				X
Cree, Inc.	X		X	X
Deco Lighting				X
Eaton			X	X
Eiko		X		
Espen	X			
Feit Electric Co., Inc.	X			
Finelite, Inc				X
GE	X	X	X	X
Green Creative LTD	X			X
Halco Lighting Technologies			X	
Hatch Transformers			X	
Howard Lighting		X		
James Industry Group	X			X
LEDTRONICS, INC	X			X
Leviton			X	
Linmore LED Labs	X			
Lunera	X			
Lutron			X	
Luxul Technology Inc.	X			
Maxlite	X		X	X
Osram Sylvania	X	X	X	X
Philips		X	X	X
Philips Advance			X	
Philips Day-Brite				X
Philips Emergency Lighting (Bodine)			X	
Philips Ledalite				X
Plusrite		X		
Shydee	X			
TCP			X	
Thomas Lighting			X	
Ushio		X		

Potential Savings – Commercial Sector

The most common type of linear lamp found in California buildings is the 4' T8 fluorescent lamp. These lamps comprise 83 percent of all installed linears. The distribution of 4' T8 fluorescent lamps installed in California by lamp efficiency is shown in Table 19[12]. Lamps are categorized as base efficiency (32W standard), low-wattage (less than 32W) or high performance (32W plus extended life and lumen output).

Table 19. Distribution of 4' T8 Fluorescent Lamps by Lamp Type

Lamp Type	Percent of 4' T8 Baseline California	Average Lamp Power (W) California	Percent of 4' T8 Baseline PG&E Territory	Average Lamp Power (W) PG&E Territory
4' T8 – Base Efficiency	63.3 %	32	64.5%	32
4' T8 – Low Wattage	7.7%	27	8.0%	27
4' T8 – High Performance	12.2%	32	11.4%	32
Average		31.5		31.5

Based on the weighted average lamp wattage of these linear fluorescent (31.5 W) and linear LED lamps (17.8 W) found in the lamp inventory, linear LED retrofit products allow for an estimated 43 percent load reduction over the fluorescent baseline.

As of 2010, the average daily operating hours for linear fluorescent lamps in commercial buildings was 11.1 hours.[13] Assuming 260 annual days of use, linears operate approximately 2,886 hours each year. Given the installed 4' T8 linear lamp baseline per the CSS report, shown in Table 20, the total technical savings potential of a fluorescent to LED retrofit results in substantial energy savings.

Table 20. Estimated Installed 4' T8 Linear Fluorescent Lamps by Region (2014) – Commercial Sector

Lamp Type	California	PG&E Territory
4' T8 linear fluorescent	81,667,200	32,873,500

For California, 100 percent market saturation of this technology results in an opportunity to reduce annual energy use by 3.2 TWh based on lamp wattage reductions only. Interior lighting, as of 2010, consumes 25.7 TWh of electricity.[14] A full conversion of 4' T8 linear fluorescents to linear LED equivalents would result in a 12 percent reduction in lighting energy use in California.

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[12] http://www.calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf. Table 5-15, page 156 of 397.

[13] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf. Table 4.20, page 59 of 100.

[14] http://www.energy.ca.gov/2014publications/CEC-500-2014-039/CEC-500-2014-039.pdf. Table 4, page 16 of 44.

Within the PG&E territory, 100 percent market saturation of this technology results in an opportunity to reduce annual energy use by 1.3 TWh based on lamp wattage reductions only. Based on the interior lighting energy use for the commercial sector in 2006 for the PG&E territory being 7.4 TWh[15], 100 percent market saturation of this technology in the commercial sector would result in an 18 percent annual interior lighting energy use reduction.

TABLE 21. ESTIMATED SAVINGS POTENTIAL OF CONVERSION FROM 4' T8 LINEAR FLUORESCENT TO LINEAR LED LAMPS

	California Energy Use (TWh)	PG&E Territory Energy Use (TWh)
Total Indoor Lighting Energy Use	25.7	7.4
Fluorescent linears – 4' T8	7.4	3.0
LED linears – 4' T8	4.2	1.7
Total Savings Potential	3.2	1.3
Commercial Indoor Lighting Savings	12%	18%

TECHNOLOGY ASSESSMENT – APPLICATION TESTING

Application testing utilized a bare-lamp fixture and two common, indoor, linear fixtures - a surface-mounted wrap and a suspended, direct/indirect pendent. Testing including characterization of 11 linear LED lamps and one linear fluorescent, which was used as the baseline for comparison. LED lamps included a range of products spanning all UL Types (A, B, C and hybrids). Products were selected based on the following criteria:

- Range of wattages marketed as replacements for standard, 4', 32W T8 linear fluorescent
- CCT: ~4000 K
- Frosted lamp tube
- Dimmable, if available

FLUORESCENT BASELINE

The fluorescent baseline consists of standard 4', 32W, 700 series, T8 lamps operating on a standard electronic, normal ballast factor (BF) ballast. The system utilizes a 2-lamp configuration and a 2-lamp ballast with 0.88 BF. Baseline system performance characteristics are provided in Table 22.

[15] http://www.energy.ca.gov/2006publications/CEC-400-2006-005/CEC-400-2006-005.PDF. Table 9-2, page 201 of 339.

TABLE 22. PERFORMANCE CHARACTERISTICS: LINEAR FLUORESCENT LAMPS USED FOR BASELINE

	Bare-lamp Strip	Wrap	Pendant
Input Power (W)	57.1	52.4	56.8
Initial Light Output (lm)	4675	3092	4196
Mean Light Output (lm)	4441	2937	3986
Initial System Efficacy (lm/W)	81.9	59.0	73.9
Mean System Efficacy (lm/W)	77.7	56.0	70.2
CCT (K)	3500		
CRI (R_a)	78		
Life (hrs.)	24,000 (3-hr start); 30,000 (12-hr start)		

Initial light output values represent performance after 100 hours of operation. Output is expected to depreciate approximately five percent over the first 35,000 hours of operation. The lumen depreciation curve for the fluorescent product tested is provided below. Mean light output and mean system efficacy are calculated as 95 percent of initial values.

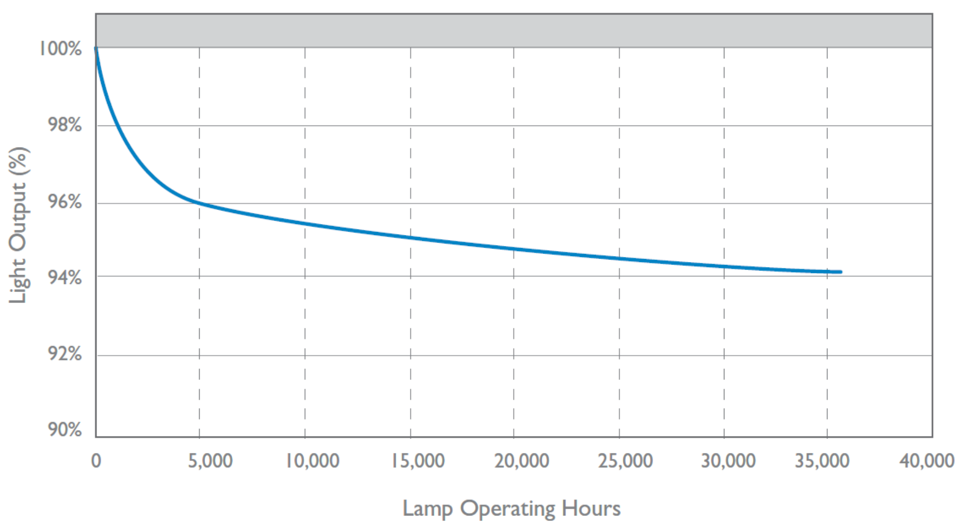
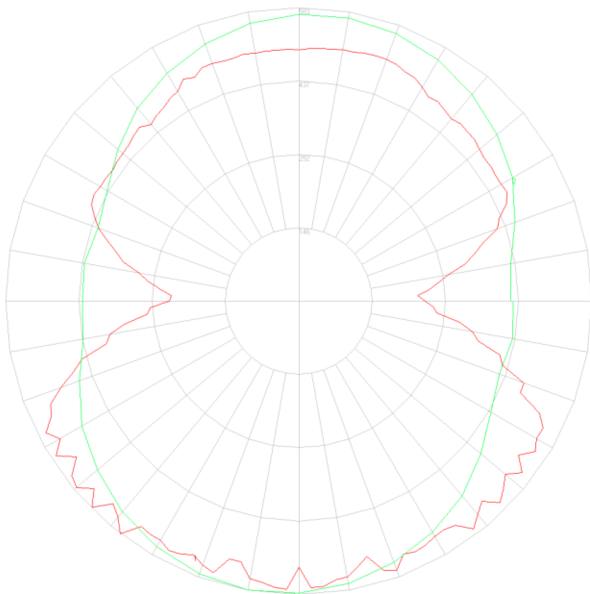


FIGURE 15. LUMEN DEPRECIATION CURVE FOR STANDARD LINEAR FLUORESCENT LAMPS USED AS BASELINE

DISTRIBUTION

Linear fluorescents are characterized by a 360° beam angle. Most existing fixtures designed for use with linear lamps, are designed around the linear fluorescent. In a bare-lamp configuration, where fixture efficiency is very high, system light output should be very near to the product of the rated light output of the lamp itself and the ballast factor. The measured light output of the fluorescent in the bare-lamp fixture is 4675 lumens. This demonstrates that the bare-lamp fixture efficiency is effectively 100 percent when considering measurement error. Figure 16 shows the photometric diagram of the linear fluorescent operating in the bare-lamp strip fixture. The transverse plane plot is shown in red and the axial plane plot in green. The diagram shows that light is directed out, nearly uniform in all directions (360° beam pattern).

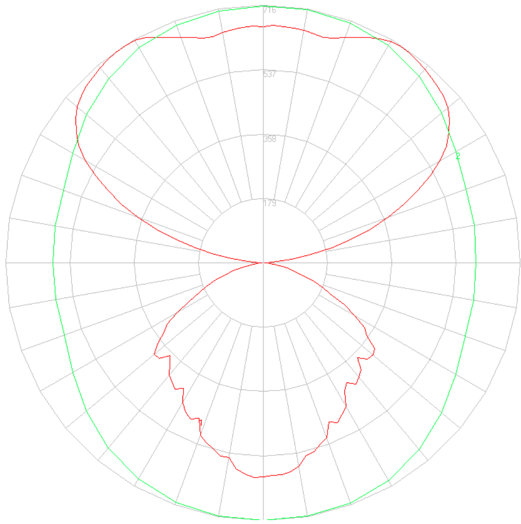


Red line with #1 label on Plot:
Transverse Plane: Vertical plane through horizontal angles. 80˚ - 260˚ (Through Maximum Candela)
Green line with #2 label on Plot:
Axial Plane: Horizontal cone through vertical angle. 37.5˚ (Through Maximum Candela)

FIGURE 16. LINEAR FLUORESCENT IN BARE-LAMP FIXTURE – POLAR LUMINOUS INTENSITY DIAGRAM

For direct/indirect fixtures, where a portion of light is directed up and a portion down, linear fluorescent systems should exhibit a total system light output that is at or nearly equal to the product of the rated lamp light output, ballast factor and the fixture's rated fixture efficiency (%). The same is true for wraps, troffers and other linear fixtures.

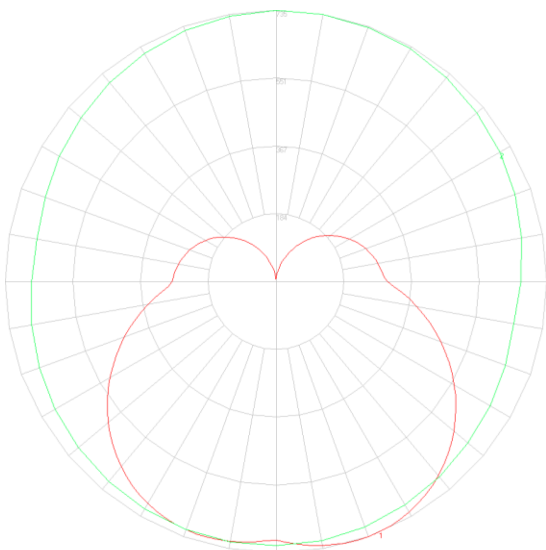
Figure 17 shows a photometric diagram of the linear fluorescent lamp in the Pendant fixture. The transverse plane plot is shown in red and the axial plane plot in green. The vertical plane plot confirms the fixture manufacturer's claimed indirect/direct ratio of 66/34.



Red line with #1 label on Plot:
Transverse Plane: Vertical plane through horizontal angles.
80˚ - 260˚ (Through Maximum Candela)
Green line with #2 label on Plot:
Axial Plane: Horizontal cone through vertical angle.
147˚ (Through Maximum Candela)

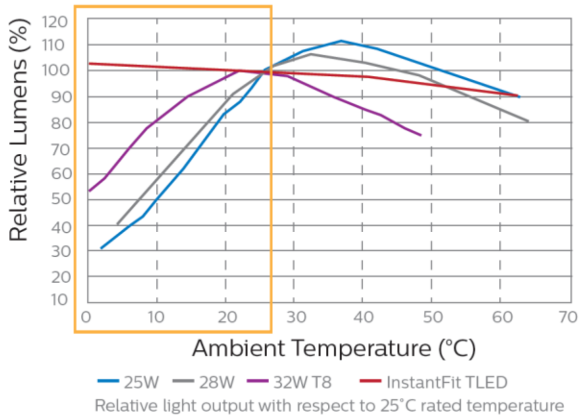
FIGURE 17. LINEAR FLUORESCENT IN PENDANT FIXTURE – POLAR LUMINOUS INTENSITY DIAGRAM

The wrap fixture is the least efficient with a manufacturer's stated fixture efficiency of 75.7 percent. Figure 18 shows the photometric diagram for the linear fluorescent operating in the wrap. In addition, the fixture is fully enclosed, which creates an elevated temperature operating environment that negatively impacts fluorescent lamp performance. Under increased temperatures, those in excess of 25° C, linear fluorescent lamps exhibit decreased power consumption and light output. Figure 19 show a typical depreciation curve for light output with respect to temperature. Test results show that linear fluorescent light output degrades by approximately 10 percent when operating in the wrap fixture.



Red line with #1 label on Plot:
Transverse Plane: Vertical plane through horizontal angles.
80˚ - 260˚ (Through Maximum Candela)
Green line with #2 label on Plot:
Axial Plane: Horizontal cone through vertical angle.
25˚ (Through Maximum Candela)

FIGURE 18. LINEAR FLUORESCENT IN WRAP FIXTURE – POLAR LUMINOUS INTENSITY DIAGRAM



*Source: Philips

FIGURE 19. LIGHT OUTPUT VS TEMPERATURE CURVE EXAMPLE

TYPE A CONFIGURATION

Test results for Type A products show a wide range of performance in terms of light output and system efficacy when comparing data for lamps operating in the same fixture and on the same fluorescent ballast. As compared to the fluorescent baseline and considering the total light exiting the fixture, Type A LED replacements delivered significantly less light in all three fixtures tested.

Only one LED Type A product, Product LED L, delivered more light than the fluorescent system. This occurred in the wrap fixture where fluorescent performance was significantly degraded as compared to its performance in the bare-strip or pendant fixtures. Because the fluorescent system was impacted by the elevated temperature conditions created by the enclosed, wrap fixture, the LED solutions were able to compete better in terms of light output with five of six tested products delivering total light output within 10 percent of the fluorescent baseline. At these levels, most observers will not notice the reduced light output. Across all three fixtures, Product LED L performed best of all tested linear LED lamps. Table 23 shows the total initial light output and total initial light output relative to the fluorescent baseline for all LED products tested in a Type A configuration.

TABLE 23. LED LAMPS – TYPE A: LIGHT OUTPUT COMPARED TO FLUORESCENT BASELINE

Product ID	Bare-Lamp Strip		Wrap		Pendant	
	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent
Fluorescent	4675	-	3092	-	4196	-
LED B	3251	-30%	2295	-26%	2235	-47%
LED C	4017	-14%	3032	-2%	3466	-17%
LED D	3974	-15%	2840	-8%	2679	-36%
LED I	4064	-13%	2905	-6%	2764	-34%
LED J	3792	-19%	2926	-5%	2955	-30%
LED L	4404	-6%	3229	4%	3748	-11%

For the bare-lamp fixture, system efficacy for a two-lamp system operating on a standard instant start ballast ranged from approximately 100 lm/W to 128 lm/W, a range of 25 percent. For the wrap and pendant fixtures, the percent difference between minimum and maximum system efficacy of tested LED products was 33 and 40 percent, respectively.

While all products were marketed as an energy-efficient alternative to standard 4', T8 fluorescents, the actual performance as compared to a linear fluorescent baseline was highly variable in terms of energy use and system efficacy. Energy savings ranged from 36 to 48 percent for operation in both the bare strip fixture and suspended pendant. Savings were somewhat less for operation in the wrap due in part to the reduced performance of the fluorescent itself. The input power and light output of the fluorescent system operating in the wrap was roughly 8 percent lower than in the other two fixtures due to the elevated temperature present inside the fixture. Because of this, energy savings was also reduced between the LED systems and the fluorescent.

In terms of system efficacy, however, the LED solutions outperformed the fluorescent baseline in 20 of 21 cases. One LED product operating in the suspended pendant had lower system efficacy as compared to the fluorescent system. In that case, the LED lamps on the instant start ballast were approximately seven percent less efficacious than the fluorescent baseline.

TABLE 24. LED LAMPS - TYPE A: INPUT POWER, LIGHT OUTPUT AND SYSTEM EFFICACY FOR 2-LAMP CONFIGURATION

Product ID	Bare-Lamp Strip			Wrap			Pendant		
	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)
Fluorescent	57.1	4675	81.9	52.4	3092	59.0	56.8	4196	73.9
LED B	32.6	3251	99.7	32.2	2295	71.3	32.4	2235	69.0
LED C	34.9	4017	115.1	34.6	3032	87.6	34.9	3466	99.3
LED D	33.6	3974	118.3	33.3	2840	85.3	33.9	2679	79.0
LED I	33.7	4064	120.6	33.4	2905	87.0	33.6	2764	82.3
LED J	29.6	3792	128.1	29.5	2926	99.2	29.6	2955	99.8
LED L	36.3	4404	121.3	36	3229	89.7	36.2	3748	103.5

TYPE B CONFIGURATION

Type B linear LED lamps provide less light than a standard, 700 series fluorescent baseline. For the bare-lamp fixture, linear LED lamps delivered 13 to 35 percent less light than the fluorescent baseline. In the Pendant, light output was reduced by 17 to 51 percent. LEDs performed best in the wrap fixture as compared to the fluorescent, again, because the fluorescent experienced degraded performance due to the elevated temperature present within the fixture. For the wrap, LEDs delivered two to 31 percent less light as compared to the fluorescent.

Looking at individual linear LED results, product LED C performed best of all tested LED products in all three fixtures. While LED C never delivered more light than the fluorescent, the reduced output was sufficiently low as to likely not be noticeable to most observers. Table 25 shows the total initial light output and total initial light output relative to the fluorescent baseline for all LED products tested in a Type B configuration.

TABLE 25. LED LAMPS - TYPE B: LIGHT OUTPUT COMPARED TO FLUORESCENT BASELINE

Product ID	Bare-Lamp Strip		Wrap		Pendant	
	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent
Fluorescent	4675	-	3092	-	4196	-
LED B	3302	-29%	2325	-25%	2299	-45%
LED C	4087	-13%	3045	-2%	3476	-17%
LED D	3612	-23%	2550	-18%	2446	-42%
LED E	3038	-35%	2148	-31%	2060	-51%
LED G	3586	-23%	2610	-16%	2997	-29%
LED H	3757	-20%	2627	-15%	2527	-40%

Type B products consistently outperformed the fluorescent baseline in terms of system efficacy. The only fixture where fluorescent was able to compete with LED in terms of system efficacy was in the pendant. In the pendant fixture, the fluorescent baseline was on par with 50 percent of tested LED products (3 of 18 combinations tested)

TABLE 26. LED LAMPS - TYPE B: INPUT POWER, LIGHT OUTPUT AND SYSTEM EFFICACY FOR 2-LAMP CONFIGURATION

Product ID	Bare-Lamp Strip			Wrap			Pendant		
	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)
Fluorescent	57.1	4675	81.9	52.4	3092	59.0	56.8	4196	73.9
LED B	29.3	3302	112.7	28.9	2325	80.4	29.2	2299	78.7
LED C	29.5	4087	138.5	29.2	3045	104.3	29.4	3476	118.2
LED D	28.6	3612	126.3	28.1	2550	90.7	28.5	2446	85.8
LED E	26.1	3038	116.4	25.9	2148	82.9	28.5	2060	72.3
LED G	30.7	3586	116.8	30.5	2610	85.6	30.6	2997	97.9
LED H	35.4	3757	106.1	35.1	2627	74.8	35.3	2527	71.6

Type C Configuration

Type C LED products performed best of all tested linear LED systems. Type C products utilize an external LED driver, which is often optimized for a particular linear LED lamp. This leads to improved overall performance and increased light output. On average, Type C LED products delivered about 10 percent more light in the wrap as compared to the fluorescent, 10 percent less in the pendant and about the same in the bare-lamp fixture.

In the bare-lamp fixture, Type C products delivered light output on par with fluorescents. Three of four tested products delivered more light than the fluorescent. In the wrap fixture, all tested LEDs performed better than the fluorescent. LEDs operating in the Pendant fixture delivered the least amount light. Product LED F performed best of all tested LED products. It consumed less energy and delivered more light resulting in a higher system efficacy as compared to the fluorescent baseline for all fixtures tested. Also, one product, Product LED N, utilized special mounting hardware that was not compatible with the pendant and it could not be installed in this fixture.

Table 27. LED Lamps - Type C: Light Output Compared to Fluorescent Baseline

Product ID	Bare-Lamp Strip		Wrap		Pendant	
	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent
Fluorescent	4675	-	3092	-	4196	-
LED F	5054	8%	3711	20%	4284	2%
LED J	4716	1%	3453	12%	3483	-17%
LED L	4315	-8%	3178	3%	3693	-12%
LED N	4703	1%	3284	6%	N/A	N/A

Consistent with Type A and Type B products, Type C products are characterized by higher system efficacy as compared to the fluorescent system. In all fixtures tested, Type C products outperformed fluorescents with respect to system efficacy by an average of 45 percent in the bare-lamp fixture, 48 percent in the wrap and 33 percent in the pendant. Product LED J demonstrated the highest overall system efficacy at 135 lm/W.

TABLE 28. LED LAMPS - TYPE C: INPUT POWER, LIGHT OUTPUT AND SYSTEM EFFICACY FOR 2-LAMP CONFIGURATION

Product ID	Bare-Lamp Strip			Wrap			Pendant		
	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)
Fluorescent	57.1	4675	81.9	52.4	3092	59.0	56.8	4196	73.9
LED F	42.4	5054	119.2	42	3711	88.4	42.2	4284	101.5
LED J	34.9	4716	135.1	34.1	3453	101.3	34.9	3483	99.8
LED L	35.7	4315	120.9	35.4	3178	89.8	35.6	3693	103.7
LED N	47.2	4703	99.6	46.8	3284	70.2	N/A	N/A	NA

HYBRIDS

Light output of hybrid products varied significantly across manufacturers and products. For most Type AB products tested, light output did not vary significantly between output in operating mode A versus operating mode B. One Type AB product, Product D, demonstrated slightly reduced light output operating as in a Type B configuration as compared to Type A. Of the two Type AC products tested, one demonstrated significantly increased light output operating as a Type C, while the other showed no significant difference in light output between operating mode C and A.

TABLE 29. LED LAMPS - HYBRIDS: LIGHT OUTPUT COMPARED TO FLUORESCENT BASELINE

Product ID	Operating Mode (Type A, B or C)	Bare-Lamp Strip		Wrap		Pendant	
		Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent	Light Output (lm)	Relative Light Output vs. Fluorescent
Fluorescent		4675	-	3092	-	4196	-
LED B	A	3251	-30%	2295	-26%	2235	-47%
LED B	B	3302	-29%	2325	-25%	2299	-45%
LED C	A	4017	-14%	3032	-2%	3466	-17%
LED C	B	4087	-13%	3045	-2%	3476	-17%
LED D	A	3974	-15%	2840	-8%	2679	-36%
LED D	B	3612	-23%	2550	-18%	2446	-42%
LED J	A	3792	-19%	2926	-5%	2955	-30%
LED J	C	4716	1%	3453	12%	3483	-17%
LED L	A	4404	-6%	3229	4%	3748	-11%
LED L	C	4315	-8%	3178	3%	3693	-12%

Type AB products varied significantly between Mode A and Mode B in terms of input power and system efficacy. Type AC products tested, in contrast, demonstrated fairly consistent performance between Type A and Type C operating modes.

TABLE 30. LINEAR LED LAMPS - HYBRIDS: INPUT POWER, LIGHT OUTPUT AND SYSTEM EFFICACY FOR TWO-LAMP CONFIGURATION

Product ID	Operating Mode (Type A, B or C)	Bare-Lamp Strip			Wrap			Pendant		
		Power (W)	Light Output (lm)	System Efficacy (lm/W)	Power (W)	Light Output (lm)*	System Efficacy (lm/W)	Power (W)	Light Output (lm)	System Efficacy (lm/W)
Fluorescent	-	57.1	4675	81.9	52.4	3092	59.0	56.8	4196	73.9
LED B	A	32.6	3251	99.7	32.2	2295	71.3	32.4	2235	69.0
LED B	B	29.3	3302	112.7	28.9	2325	80.4	29.2	2299	78.7
LED C	A	34.9	4017	115.1	34.6	3032	87.6	34.9	3466	99.3
LED C	B	29.5	4087	138.5	29.2	3045	104.3	29.4	3476	118.2
LED D	A	33.6	3974	118.3	33.3	2840	85.3	33.9	2679	79.0
LED D	B	28.6	3612	126.3	28.1	2550	90.7	28.5	2446	85.8
LED J	A	29.6	3792	128.1	29.5	2926	99.2	29.6	2955	99.8
LED J	C	34.9	4716	135.1	34.1	3453	101.3	34.9	3483	99.8
LED L	A	36.3	4404	121.3	36	3229	89.7	36.2	3748	103.5
LED L	C	35.7	4315	120.9	35.4	3178	89.8	35.6	3693	103.7

LIGHT DISTRIBUTION – BARE LAMPS

When comparing performance among Type A, Type B, Type C and hybrid products, no significant difference in optical distribution was found for products with the same beam angle. Linear LED lamps utilize heat sinks located along the length of the lamp. The arc length of the heat sink limits the beam angle of the lamp. This is a significant difference as compared to linear fluorescents, which emit light in all 360 degrees. Figure 20 shows a linear LED with exposed end. The heat sink located along the upper hemisphere of the lamp (highlighted with a red arrow) limits the lamp aperture (bottom hemisphere of the lamp only in the figure) and reduces the beam angle.

FIGURE 20. LINEAR LED SHOWING ITS 180° HEAT SINK, WHICH LIMITS THE LAMP APERTURE AND LAMP BEAM ANGLE

The linear LEDs tested have beam angles between 160 and 310 degrees. Details are shown in Table 31. Photometric diagrams showing the distribution differences between fluorescent (360 degrees) and various linear LED lamps are shown in Figure 21.

TABLE 31. TESTED PRODUCTS: BEAM ANGLE

Product ID	Type	Beam Angle (degrees)	Product ID	Type	Beam Angle (degrees)
Fluorescent	-	360	**LED H**	B	Not stated
LED B	AB	180	**LED I**	A	120
LED C	AB	220	**LED J**	AC	160
LED D	AB	Not stated	**LED L**	AC	220
LED E	B	Not stated	**LED N**	C	Not stated
LED F	C	Not stated	**LED O**	C	Not stated
LED G	B	310	**LED P**	C	Not stated

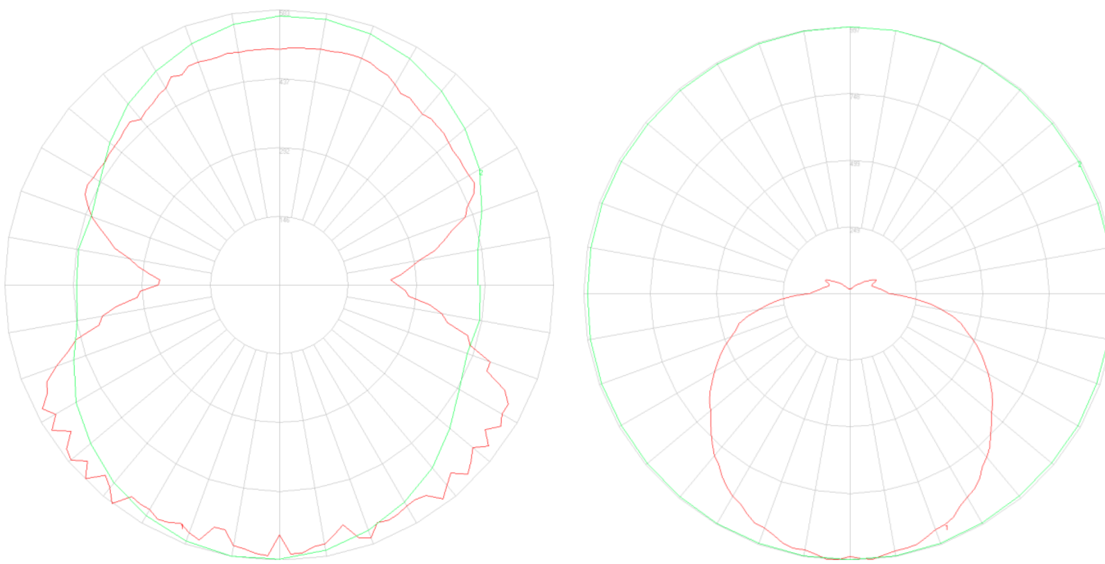


FIGURE 21. PHOTOMETRIC DIAGRAM SHOWING DIFFERENCES IN OPTICAL DISTRIBUTION PATTERNS BETWEEN A LINEAR FLUORESCENT LAMP WITH 360° BEAM ANGLE (LEFT) AND A LINEAR LED WITH 180° BEAM ANGLE (RIGHT)

LIGHT OUTPUT AND DISTRIBUTION – WRAP

The wrap fixture is designed to deliver general ambient lighting with no up light component. The opaque, acrylic diffuser wraps around the sides of the fixture and essentially creates a 180° aperture. This is important for two reasons.

First, the diffuser creates a fully enclosed lamp cavity that retains heat during operation. For fluorescent and LED sources, increased ambient temperature can lead to decreased light output. In the case of the fluorescent, as previously discussed, this resulted in approximately a 13 percent decrease in light output and power consumption as compared to the light levels expected (product of bare-lamp output and wrap fixture efficiency vs. measured value).

For the linear LED lamps, increased ambient temperature impacts LED junction temperature, which, if not properly managed, can also lead to the same negative effect on light output. However, in the case of the wrap tested, the elevated temperatures do not appear to have impacted tested LED product performance as much as the fluorescent. This suggests that the tested LED lamps experience depreciation at higher temperatures as compared to the fluorescent. On average, LED products experienced only a five percent decrease in light output resulting from temperature impacts.

As an example, Figure 22 shows how a linear LED lamp compares to various linear fluorescents in terms of relative light output versus ambient temperature. The LED in this example has more stable relative light output at elevated operating temperatures as compared to a standard, 32 W fluorescent.

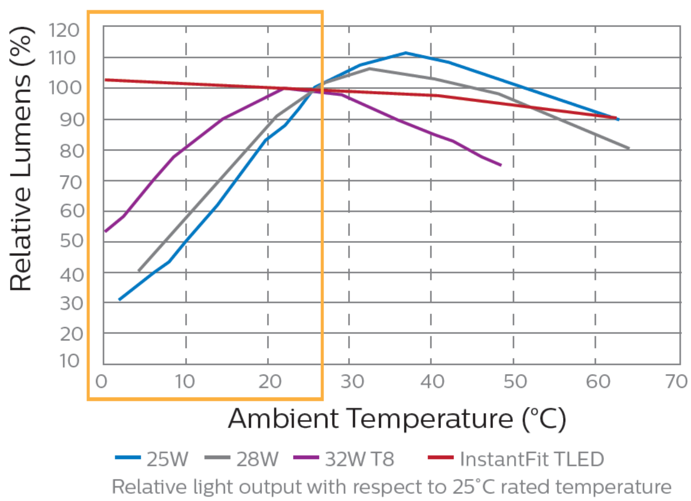


FIGURE 22. LIGHT OUTPUT VS TEMPERATURE CURVE EXAMPLE FOR LINEAR FLUORESCENT AND LINEAR LED LAMPS

Test results show that the linear LEDs delivered total light output that was closer to fluorescent values because the linear fluorescent experienced more degradation in the wrap as compared to its operation in the bare-lamp or pendant fixtures. Table 32 shows a comparison of product performance in both the wrap fixture and the bare-lamp fixture. On average, for every LED Type (A, B, C), the LED products showed better performance in the wrap as compared to the fluorescent than in the bare strip. For the Type A products, relative light output improved nine percent. Type B products showed a six percent relative improvement. Type C products, while already comparable in the bare-lamp strip, delivered 10 percent more light than the fluorescent when operating in the wrap.

TABLE 32. WRAP - TOTAL LIGHT OUTPUT

Product ID	Operating Mode (A, B, C)	WRAP		BARE-LAMP STRIP	
		Light Output (lm)	% Difference as Compared to Fluorescent	Light Output (lm)	% Difference as Compared to Fluorescent
Fluorescent	-	**3092**		**4675**	
LED B	A	2295	-26%	3251	-30%
LED B	B	2325	-25%	3302	-29%
LED C	A	3032	-2%	4017	-14%
LED C	B	3045	-2%	4087	-13%
LED D	A	2840	-8%	3974	-15%
LED D	B	2550	-18%	3612	-23%
LED E	B	2148	-31%	3038	-35%
LED F	C	3711	20%	5054	8%
LED G	B	2610	-16%	3586	-23%
LED H	B	2627	-15%	3757	-20%
LED I	A	2905	-6%	4064	-13%
LED J	A	2926	-5%	3792	-19%
LED J	C	3453	12%	4716	1%
LED L	A	3229	4%	4404	-6%
LED L	C	3178	3%	4315	-8%
LED N	C	3284	6%	4703	1%
Average – Operating Mode A		**2871.2**	**-7%**	**3917.0**	**-16%**
Average – Operating Mode B		**2550.8**	**-18%**	**3563.7**	**-24%**
Average – Operating Mode C		**3406.5**	**10%**	**4697.0**	**0%**

The second impact of the 180 degree aperture (no up light) is that LED products, which have reduced beam angles as compared to the fluorescent, are naturally better able to direct their light out of the fixture as compared to operation in direct/indirect fixtures. Because the LED heat sink reduces light distribution along a portion of the lamp's circumference, fixtures that rely on a full 360 degrees of distribution will deliver lower overall light output when using LED lamps as compared to fluorescents.

In the wrap, the heat sink geometry does not appear to significantly reduce overall performance relative to fluorescent performance. Figure 23 shows two photometric diagrams of tested products operating in the wrap fixture. The left diagram shows the linear fluorescent and the right shows product LED B. The distribution patterns and magnitude of measured candela are very similar even though the LED product only has a 180° beam angle – half that of the fluorescent. Figure 24 shows two additional diagrams for LED Products with a 220° beam angle (left) and 310° beam angle (right). Again, the patterns are very similar. Detailed diagrams for each product tested in the wrap fixture are provided in Attachment A.

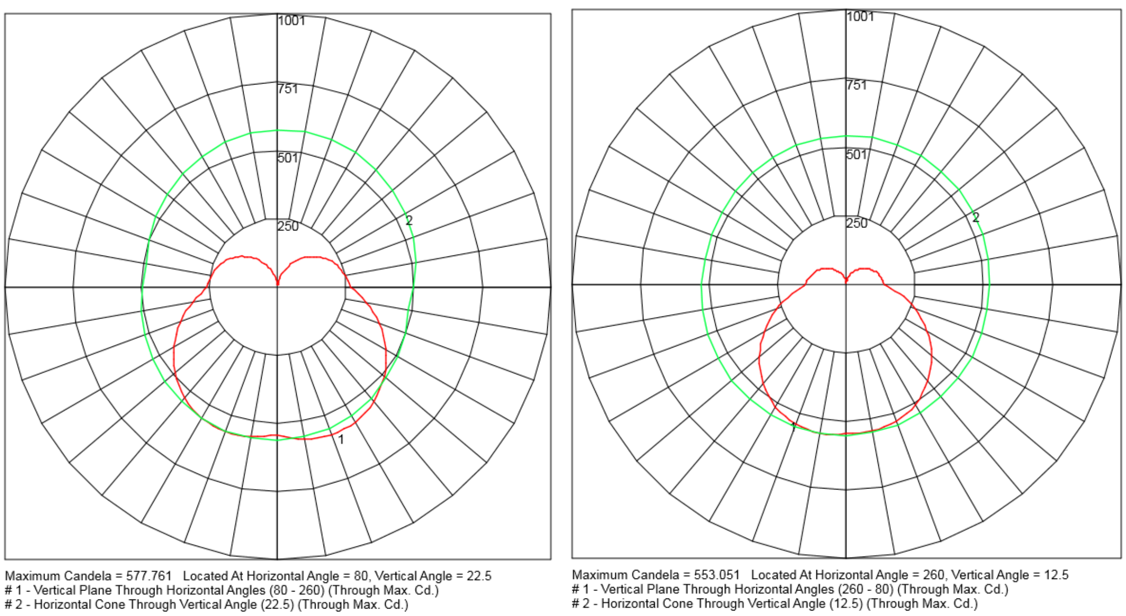


FIGURE 23. PHOTOMETRIC DIAGRAMS COMPARING PERFORMANCE OF THE LINEAR FLUORESCENT WITH 360° BEAM ANGLE (LEFT) AND LED B WITH 180° BEAM ANGLE (RIGHT) IN THE WRAP FIXTURE

Pacific Gas and Electric Company®

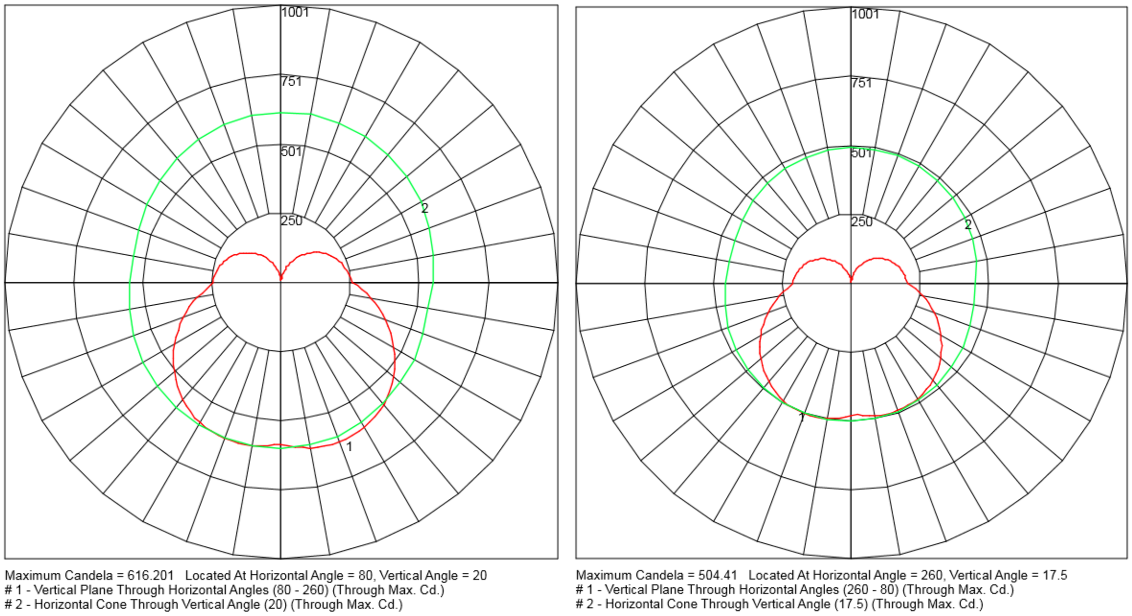


FIGURE 24. PHOTOMETRIC DIAGRAMS COMPARING PERFORMANCE OF PRODUCT LED L WITH 220° BEAM ANGLE (LEFT) TO PRODUCT LED G WITH 310° BEAM ANGLE (RIGHT)

LIGHT OUTPUT AND DISTRIBUTION – PENDANT

Pendant fixtures are available in a variety of distribution patterns, from 100 percent direct lighting to direct/indirect to 100 percent indirect. The most challenging type for linear LEDs is the direct/indirect, because the fixture is designed to distribute a portion of light up onto the ceiling where it is reflected back down to the work plane. Linear LED lamps, as previously discussed, have limited beam angles. A portion or all of the upper lamp hemisphere is utilized by the heat sink and no light is emitted along this surface. This directly impacts the performance of indirect lighting components. Direct/indirect lighting designs rely on a full 360 degrees of lamp distribution and they will deliver lower overall light output when using LED lamps as compared to fluorescents.

These facts are evident based on test results. Relative light output of tested linear LED products as compared to fluorescent performance between the bare-lamp and pendant fixtures was reduced from -4 to -21 percent. For example, looking at Table 33, product LED B delivered 30 percent less light than the fluorescent when operating in the bare-strip fixture. This difference jumped to 47 percent when operating in the pendant. For all tested LED products, relative performance decreased as compared to the fluorescent. On average, linear LED lamps saw an additional 28 percent reduction in light output as compared to the fluorescent baseline when operating in the direct/indirect pendent.

TABLE 33. PENDANT - TOTAL LIGHT OUTPUT

Product ID	Beam Angle	Operating Mode (A, B, C)	PENDANT (Direct/Indirect: 34/66)		BARE-LAMP STRIP	
			Light Output (lm)	% Difference as compared to fluorescent	Light Output (lm)	% Difference as compared to fluorescent
Fluorescent	**360**	-	**4196**	-	**4675**	-
LED B	180	A	2235	-47%	3251	-30%
LED B	180	B	2299	-45%	3302	-29%
LED C	220	A	3466	-17%	4017	-14%
LED C	220	B	3476	-17%	4087	-13%
LED D	Not stated	A	2679	-36%	3974	-15%
LED D	Not stated	B	2446	-42%	3612	-23%
LED E	Not stated	B	2060	-51%	3038	-35%
LED F	Not stated	C	4284	2%	5054	8%
LED G	310	B	2997	-29%	3586	-23%
LED H	Not stated	B	2527	-40%	3757	-20%
LED I	120	A	2764	-34%	4064	-13%
LED J	160	A	2955	-30%	3792	-19%
LED J	160	C	3483	-17%	4716	1%
LED L	220	A	3748	-11%	4404	-6%
LED L	220	C	3693	-12%	4315	-8%
LED N	Not stated	C	N/A	N/A	4703	1%
Average – Operating Mode A			**2974.5**	**-29%**	**3917.0**	**-16%**
Average – Operating Mode B			**2634.2**	**-37%**	**3563.7**	**-24%**
Average – Operating Mode C			**3820.0**	**-9%**	**4697.0**	**0%**

Looking, again, at the impact of reduced source aperture size, Figure 25 shows two photometric diagrams. On the left is the linear fluorescent. The distribution pattern shows the effect of the direct/indirect fixture design. Approximately 66 percent of the light is directed up and 34 percent down. On the right, the linear LED photometric diagram shows a much different distribution. The linear LED shown in Figure 25 has a 180° beam angle. Nearly all the light is emitted down. The value of the indirect/direct fixture design is lost and overall performance is reduced. Linear LED products with 220° and 310° beam angles are shown in Figure 26. As compared to the linear LED shown in Figure 25, these products more closely replicate the distribution of a linear fluorescent in the axial plane and also more closely match the distribution of the fluorescent when operating in the pendant fixture. Detailed diagrams for each product tested in the pendant fixture are provided in Attachment A.

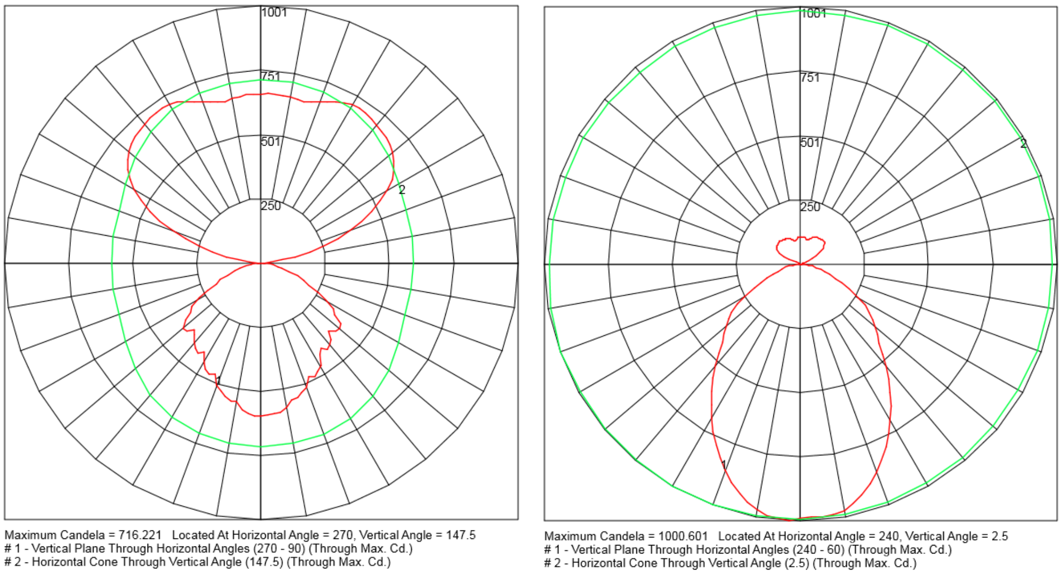


FIGURE 25. PHOTOMETRIC DIAGRAMS SHOWING THE LINEAR FLUORESCENT WITH 360° BEAM ANGLE (LEFT) AND PRODUCT LED B WITH 180° BEAM ANGLE (RIGHT) OPERATING IN THE SAME PENDANT FIXTURE

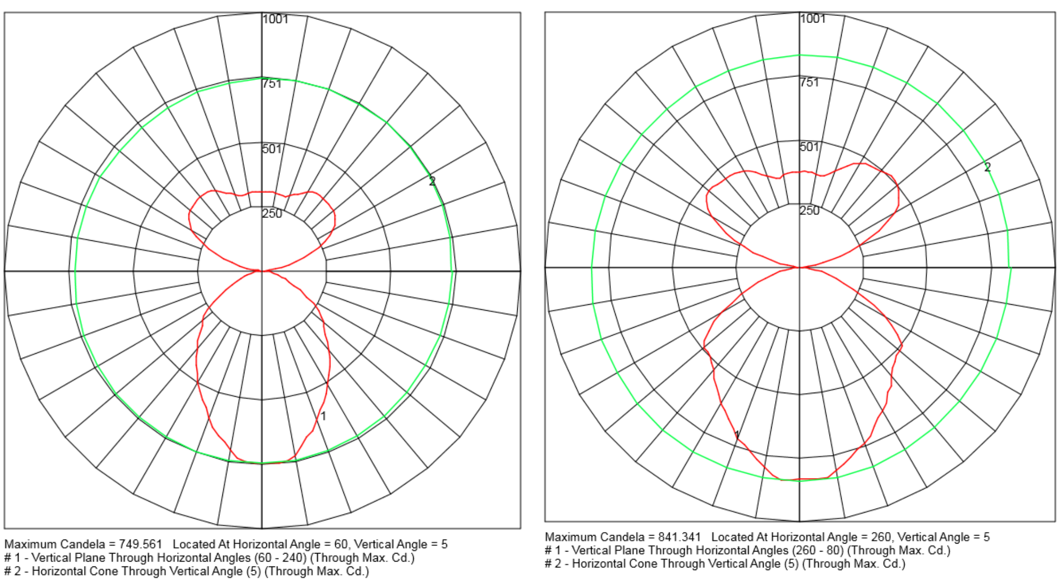


FIGURE 26. PHOTOMETRIC DIAGRAMS SHOWING PRODUCT LED L WITH 220° BEAM ANGLE (LEFT) AND PRODUCT LED G WITH 220° BEAM ANGLE (RIGHT)

TECHNOLOGY ASSESSMENT – INTEROPERABILITY

Interoperability testing is intended to characterize lamp performance and document compatibility issues for products operating in configurations that may not be recommended by manufacturers, but that may be unknowingly instituted by consumers in common repair and replacement situations.

For Type A LED products, two such scenarios are expected to be most common:

1. Products installed in fixtures with incompatible fluorescent ballasts. For this project, testing includes operating two representative, Type A LED lamps on the following ballast types:
    a. Instant-start: 2-lamp, T8, electronic, 0.88 BF, parallel wiring
    b. Rapid start: 2-lamp, T12, electronic, 0.85 BF, series wiring
    c. Programmed start: 2-lamp, T8, electronic, 0.85 BF, parallel wiring
2. Products replacing fluorescent lamps in a delamped fixture where the ballast is rated for use with more lamps than are replaced by LED. Because this project examines LED lamp performance in a 2-lamp fixture, this interoperability testing will examine a 2-lamp fluorescent ballast operating only one LED lamp.

For Type C LED lamps, this project examines five Type C LED lamp/driver combinations and includes performance data for each LED lamp operating on each of the five drivers. A list of all test combinations is provided in the Approach section of this report. Each test combination was completed for the product combination using a fully lamped, 2-lamp configuration and again under a delamped, 1-lamp configuration.

TYPE A CONFIGURATIONS

Testing examined two common Type A linear LED lamps operating on three common electronic linear fluorescent lamp ballasts designed for use with a maximum of two lamps. Tests were conducted for lamps operating in a fully lamped, 2-lamp scenario and in a delamped, 1-lamp scenario. Results for the 2-lamp test are show in Table 34.

As expected, the fluorescent lamp performed well in both the instant-start and programmed start ballasts, but experienced some degradation when operating on the T12 rapid start ballast. T8 lamps operating on a T12 ballast will also shorten the life of the lamp.

Product LED J worked well with the instant-start ballast and rapid-start ballast, but suffered severe degradation in power and light output operating on the programmed start ballast – approximately 40 percent. The lamp specification sheet for LED J indicates the ballast works on a large number of different fluorescent lamp ballasts, but no other details are provided. Consumers are asked to consult a separate ballast compatibility guide available for download on the manufacturer's website. The ballast compatibility guide does not list the programmed start ballast as compatible. It does list the lamp as compatible with the rapid start ballast.

Product LED I worked well on the instant-start ballast. It did not perform well on either the rapid-start or the programmed start ballast. The LED I lamp specification sheet does not indicate the type or number of ballasts with which the product is compatible. Literature does state the lamp is a suitable replacement of T8 and T12 fluorescent lamps, which would indicate compatibility with the T12 rapid-start ballast. However, when operating with the rapid start ballast, performance was degraded by approximately 33 percent.

TABLE 34. INTEROPERABILITY TEST RESULTS FOR TYPE A LED LAMPS ON THREE COMMON LINEAR FLUORESCENT BALLASTS – FULLY LAMPED FIXTURE – TWO LAMPS WITH A TWO LAMP BALLAST

Ballast Type	Ballast Notes	Fluorescent (2 Lamps)		LED J (2 Lamps)		LED I (2 Lamps)	
		Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (W)
Ballast A: Instant-start	0.88 BF Parallel wiring 120-277 V	57.3	4679	29.5	3800	33.8	4199
Ballast B: Rapid start (T12)	0.85 BF Series wiring 120 V	81.6	3432	33.9	4018	28.5	2835
Ballast C: Programmed start	0.85 BF Parallel wiring 120-277 V	55.6	4414	18	2279	11.9	1303

DELAMPING

Some linear LED lamps can operate in a delamped scenario; others cannot. Product literature may or may not speak to this point. In a delamped scenario, ballast factors will increase resulting in slightly increased input power and light output for the remaining lamps left in a system as compared to the lamps under a fully lamped scenario. However, delamping is often used as an energy-savings measure because the energy saved by lamp removal substantially outweighs the increased power consumption of the remaining lamps.

To understand performance in delamped fixtures, testing included operation of the same two, common, linear LED products on the same three ballasts. However, installed lamps were reduced from two to one. Results are shown in Table 35.

The linear fluorescent performed as expected under the delamped scenario for both the instant-start and programmed start ballasts. Input power and light output were reduced by roughly half. When operating with the rapid-start ballast, which requires lamps to be wired in series, a delamped scenario does not work.

For linear LED products, delamping may or may not be suitable. For product LED J, delamping with an instant-start ballast appeared to be compatible. The programmed start scenario showed about 50 percent degradation in power and light output as compared to that expected for a one-lamp configuration, which can be viewed as insufficient for most environments. As with the fluorescent, delamping on a rapid-start ballast results in a nonfunctioning system.

For product LED I, delamped worked on an instant-start ballast, but both the rapid-start and programmed start ballast scenarios resulted in a nonfunctioning system that delivered only minimal light output.

Looking at product literature for both LED J and LED I, delamping information is not provided. However, on at least one other linear LED lamp specification sheet, delamping scenarios are provided along with warnings and a list of configurations for which delamping may be suitable.

TABLE 35. INTEROPERABILITY TEST RESULTS FOR TYPE A LED LAMPS ON THREE COMMON LINEAR FLUORESCENT BALLASTS – DELAMPED FROM TWO LAMPS TO ONE

Ballast Type	Ballast Notes	Fluorescent (1 Lamp Only)		LED J (1 Lamp Only)		LED I (1 Lamp Only)	
		Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (W)
Ballast A: Instant-start	0.88 BF Parallel wiring 120-277 V	35.7	2885	19.5	2376	20.6	2470
Ballast B: Rapid start (T12)	0.85 BF Series wiring 120 V	7.5	15.42	7.4	219.3	9.5	226.7
Ballast C: Programmed start	0.85 BF Parallel wiring 120-277 V	30.7	2393	11.2	1254	7.8	693.7

TYPE C CONFIGURATIONS

Testing examined five common Type C linear LED lamps operating on five linear LED drivers, each designed for use with two lamps. Tests were conducted for lamps operating in a fully lamped, 2-lamp scenario and in a delamped, 1-lamp scenario. Results for the 2-lamp test are show in Table 34. Lamps that did not turn ON with certain drivers are noted as '0' in both light output and input power. One system had a proprietary connector and did not allow for different manufacturers lamps to be connected to the driver or for different drivers to be connected to the lamps. Values in this case are marked with 'NA'. Manufacturer recommended driver and lamp combinations are noted in bold font.

Overall, none of the alternate lamp and driver combinations resulted in a properly functioning system characterized by power consumption and light output values in the range expected. In all cases, alternative drivers either overdrove the lamp (too much current) which caused light output values to jump significantly or created a situation where lamps were only producing about half the expected light levels. When too much current is supplied to the lamp it significantly shortens lamp life. Combinations LED L/Driver F and LED O/Driver P fall in this category. The remaining alternate combinations all drew substantially less power and produced substantially less light than under normal conditions where the lamp is wired to the manufacturer recommended driver.

TABLE 36. INTEROPERABILITY TEST RESULTS FOR TYPE C LED LAMPS ON FIVE COMMON LINEAR LED DRIVERS – FULLY LAMPED FIXTURE – TWO LAMPS WITH A TWO-LAMP DRIVER

Driver	LED F (2 Lamps)		LED L (2 Lamps)		LED N (2 Lamps)		LED O (2 Lamps)		LED P (2 Lamps)	
	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (W)	Input Power (W)	Light Output (W)	Input Power (W)	Light Output (W)
Driver F: **120-277V, Parallel, Dimming**	**42.4**	**4400**	42.2	5170	NA	NA	14.2	1676	21.8	327.6
Driver L: **Universal voltage, Parallel, Dimming**	33.8	4141	**36.1**	**4460**	NA	NA	13.3	1423	24.5	374.5
Driver N: **120-277V, Parallel, Dimming**	NA	NA	NA	NA	**47.3**	**4922**	NA	NA	NA	NA
Driver O: **120-277V, Parallel, Dimming**	0	0	0	0	NA	NA	**30.3**	**3541**	0	0
Driver P: **120-277V, Parallel**	0	0	0	0	NA	NA	49	5442	**59.2**	**5096**

DELAMPING

Under delamped conditions, some LED combinations performed as expected with respect to input power when operating on the manufacturer's recommended driver. LED L and LED P fell into this category. Input power values were within the range specified for one-lamp operation on driver specifications sheets. While not noted in its specification sheet, LED N also produced results in a range expected of one-lamp operation on a two-lamp ballast. Light output, however, for these combinations was substantially higher than expected for one-lamp operation.

For alternative lamp/driver combinations, results varied from combinations that did not turn ON to those that produced very elevated power and light output values. Six product combinations failed to turn ON, while three others delivered approximately 25 percent of values expected for a properly functioning system (50 percent of that expected under a delamped scenario). All results for Type C driver interoperability testing are provided in Table 35.

TABLE 37. INTEROPERABILITY TEST RESULTS FOR TYPE C LED LAMPS ON FIVE COMMON LINEAR LED DRIVERS – DELAMPED FIXTURE – ONE LAMP WITH A TWO-LAMP DRIVER

Driver	LED F (1 Lamp)		LED L (1 Lamp)		LED N (1 Lamp)		LED O (1 Lamp)		LED P (1 Lamp)	
	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (lm)	Input Power (W)	Light Output (W)	Input Power (W)	Light Output (W)	Input Power (W)	Light Output (W)
Driver F: **120-277V, Parallel, Dimming**	**33.1**	**3279**	22.2	2608	NA	NA	8.3	863.4	12.9	171.6
Driver L: **Universal voltage, Parallel, Dimming**	21.4	2372	**23.5**	**3670**	NA	NA	9.6	920.4	0	0
Driver N: **120-277V, Parallel, Dimming**	NA	NA	NA	NA	**25.3**	**2494**	NA	NA	NA	NA
Driver O: **120-277V, Parallel, Dimming**	0	0	0	0	NA	NA	**15.6**	**1803**	0	0
Driver P: **120-277V,**	0	0	0	0	NA	NA	24.2	2712	**29.4**	**2667**

RECOMMENDATIONS

Based on project test results, it's evident that linear LED lamps marketed to replace standard 4' linear fluorescents cannot compete in terms of total light output. While the tested LED products are very efficacious at both the source and system level, overall energy savings are achieved, in part, by reducing light output, not just power. Type A and Type B LED products, including hybrid Type AB, consistently demonstrated significantly reduced light output as compared to the fluorescent baseline. While Type A lamps may appear to be a simple, energy saving product, based on test results, these products are best only considered for retrofits where the space is currently over lit or reduced light levels will not negatively impact occupants or operations. In addition, Type A products require the use of a fluorescent lamp ballast and consumers must understand that they will be required to stock both LED lamps and compatible ballasts in order to replace failed components.

A potentially better alternative to Type A products is Type AC hybrid LED lamps. Type C lamps demonstrated the highest light output and system efficacy of all tested products. These lamps, when paired with recommended drivers consistently deliver light levels that are generally equivalent to or better than the selected fluorescent system used as a baseline for comparison. For consumers who wish to make a quick and easy change to linear LED from linear fluorescent, Type AC products can fit those requirements. Initial installation is quick as a Type A. When fluorescent ballasts fail, they can be replaced with LED drivers that will maximize light output and energy savings.

Light distribution is a critical factor to consider when selecting linear LED lamps. Fixtures with indirect lighting / distribution components may not deliver suitable distribution or appropriate light levels when operating with linear LED products. While most linear LED products tested underperformed in terms of light output as compared to the fluorescent baseline, performance reductions were magnified when products were operated in the tested direct/indirect pendant. Very little light was available for indirect distribution because of the LED heat sink geometry and its location along the length of the lamp, which reduces the lamp's beam angle and limits the product's overall light distribution as compared to fluorescent When considering a linear LED retrofit in existing linear direct/indirect fixtures, consumers should seek products with the largest beam angle to maximize performance or consider alternative energy-saving measures utilizing fluorescent lamp technology.

For fixtures with direct distribution, linear LED products may be a good alternative looking at distribution alone. In the wrap fixture tested, LED products performed much better as compared to the linear fluorescent and more closely matched its distribution pattern. Products of all beam angles performed well, because the wrap fixture did not include an indirect distribution component.

In addition, in the wrap tested, it appears that the elevated temperature operating environment reduced linear fluorescent performance by roughly 13 percent. LED performance, in contrast, was not as significantly impacted and LED products, on average, experienced only a five percent degradation in light output. Results indicate that some LEDs may perform better and deliver more light than fluorescents due to these elevated temperature impacts. LED product performance relative to fluorescent improved by six to 10 percent when operating in the wrap fixture.

Overall, for direct and enclosed fixtures like the wrap tested, consumers should focus on total light output as a basis for comparison in applications where light levels should be maintained. When doing so, retrofits will achieve energy savings and deliver expected lighting performance. For projects where light levels can be reduced, energy savings may range as high as 50 percent when using some linear LED products.

Whether Type A, C or Type AC products are used, products must be paired with manufacturer recommended control gear. Compatibility testing proved that most products suffer severe performance degradation when paired with nonstandard ballasts and drivers.

In the case of Type A products, interoperability of LED lamps with all types of fluorescent ballasts is not guaranteed. For the two products tested, both were deemed compatible with the rapid-start ballast, and neither was deemed compatible with the programmed start ballast. Consumers must seek out ballast compatibility information to ensure proper operation and performance. In some cases, certain vintages of the same ballast product were listed by manufacturers as having different compatibility ratings for their LED lamps. Single character differences in a 10-20 character product code were the only difference that distinguished a fully compatible ballast from a incompatible ballast.

Many manufacturers do not provide easy-to-obtain compatibility information. Manufacturers should improve their product literature to better ensure consumers match linear LED lamps with compatible fluorescent ballasts.

For LED lamps operating with external LED drivers, consumers should never pair a lamp with driver that is not explicitly recommended by the manufacturer. Interoperability testing showed that most Type C products only performed as promoted when operating on the manufacturer-recommended product. In some cases, an improper match between lamp and driver produced clearly visible, negative results and consumers will quickly be able to tell there is a problem. For other cases, however, light output increased and consumers may be left thinking the system is fully functional, when in fact, the system is being overdriven and will most likely exhibit a shortened life. For type C products, manufactures should improve product specification sheets and literature to include explicit specification of compatible drivers.

Last, consumers should avoid using linear LED lamps in delamped configurations. Most combinations of lamps and ballasts or drivers experienced severe performance degradation in a delamped scenario. Few manufacturers include delamping information on product specification sheets. Manufacturer's should explicitly call out information on delamping and bring that information out of the footnotes and into the main body of publications. Delamped fixtures are a common situation in today's commercial buildings. Consumers making a change could easily replace fluorescent lamps with LED in a delamped configuration, which could quickly damage the new lamp.

APPENDIX A

The lamp and fixture inventory data that was used to support this report is located in the following files, which are presented as attachments:

1. Appendix A - CEE_LFL-LED_Inventory_2016.10.03.xlsx
2. Appendix A - DLC-QPL_Lamp Inventory_2016.10.05.xlsx

ATTACHMENT A

Attachment A contains individual test results for each product and fixture combination tested. Test reports are provided in PDF format (.pdf).