Performance and Energy Efficiency Evaluation of Residential LED Under-Cabinet Lighting

ET 07.03 Report

Prepared by:

Design & Engineering Services
Customer Service Business Unit
Southern California Edison

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Southern California Edison's Design & Engineering Services (D&ES) group is responsible for this project. It was developed as part of Southern California Edison's Emerging Technology program under internal project number ET 07.03. D&ES project manager Vireak Ly conducted this technology evaluation with overall guidance and management from Dr. Henry Lau. Technical analysis and reporting was conducted by SEED Inc. under the direction of Michael Jones, CEM. For more information on this project, contact *Vireak.Ly*@sce.com.

Disclaimer

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
CCT	Correlated Color Temperature
CRI	Color Rendering Index
DC	Direct Current
kW	Kilowatt
kWh	Kilowatt Hour
LED	Light Emitting Diode
lm	Lumens
SCE	Southern California Edison
SCLTC	Southern California Lighting Technology Center
SSL	Solid State Lighting
VA	Volt-Amperes
W	Watt

FIGURES

TABLES

EQUATIONS

CONTENTS

EXECUTIVE SUMMARY

The objective of this study was to assess the status of the light-emitting diode (LED) under-cabinet lighting and measure incremental energy and demand savings over their T8 linear fluorescent and incandescent counterparts. Photometric and power tests conducted in the Southern California Lighting Technology Center (SCLTC) demonstrate the differences and similarities of the baseline (fluorescent and incandescent) vs. measure (LED) cases. To supplement tests conducted at the SCLTC, a field study was conducted to understand how residences use their kitchen under-cabinet lighting. This study consisted of monitoring 26 houses in Southern California Edison (SCE) service territory, Sierra Pacific service territory, and Truckee-Donner Public Utilities District service territory. The data was used to help gain an understanding of the yearly operation of under-cabinet lighting. The focus of the study was the use of under-cabinet lighting in kitchen applications.

The photometric and power data obtained through lab testing was combined with hourly usage figures to obtain energy savings, demand savings, and efficacy figures for the technology.

Recent advances in LED technology have made them brighter and more efficient, thereby expanding the application of LED to the under-cabinet lighting market. In addition, some manufacturers have improved efficiency of the required AC-DC conversion process. This study assumes that the operation of the LED under-cabinet light is the same as that of the fluorescent and incandescent under-cabinet light from the perspective of the end-user.

The measurements taken in the laboratory verify the energy and demand figures for baseline and measure cases. Measurements were also taken to compare other lighting characteristics of the LED vs. the fluorescent and incandescent under-cabinet lights. Since under-cabinet lighting is typically sold in different lengths, measurements are presented on a “per foot” basis.

The total lumen (lm)/foot (ft) output of LED under-cabinet lamps range from 63 lm/ft to 291 lm/ft, which is below that of a T8 linear fluorescent at 320 lm/ft. Since the incandescent fixture tested at 145 lm/ft, some of the LED fixtures can be considered equivalent. The lm/foot output does not account for overall application efficiency.

Since the LED tested products did not have similar lumen output as the T8 linear fluorescent, it is difficult to consider them equivalent using this metric. However, there were a few LED products that were comparable to the incandescent lamp. In addition, most of the LEDs had a greater efficacy than the incandescent lamp. Based on the tested LEDs and using hourly usage figures developed during this project, an annual savings of 22.97 kWh per linear foot of under-cabinet lighting was realized over the incandescent technology tested.

Lab assessment included:

- Lumen output
- Correlated Color Temperature
- Color Rendering Index
- Power (kW)
- Efficacy

Field assessment included tracking kitchen under-cabinet lighting usage.

Assessment integration included combining power and under-cabinet lighting usage to determine energy savings.

INTRODUCTION

Solid-state lighting (SSL) technology is continually progressing in terms of efficiency and quality. Consumers are becoming more interested in lighting that uses less energy, as well as delivering lighting that meets or exceeds current market products. Research and development performed by the Department of Energy and manufacturers of SSL and light-emitting diode (LED) technology has shown that LEDs are good candidates for an efficient general lighting source. This study was meant to assess whether or not this technology could be applied to residential kitchen under-cabinet lighting.

As new residential homes are built in Southern California, under-cabinet lighting is becoming an increasingly popular way to meet the requirements of 2005 Title 24. Since under-cabinet lighting typically utilizes linear fluorescent lights, they qualify as high efficacy. The use of high efficacy under-cabinet lighting for 50% of the total kitchen lighting wattage gives the homebuilder flexibility when choosing the kitchen's overall lighting strategy. It is expected that the use of LED under-cabinet lighting will provide the same, if not higher efficacy with a longer life.

The focus of this project is to evaluate various types of hard-wired under-cabinet lighting available on the market in terms of demand and energy use, as well as photometry. This includes popular incandescent and linear fluorescent options as the baseline case, compared to popular LED alternatives as the measure case.

Incandescent bulbs use a tungsten filament which is heated and begins to glow in a low pressure inert gas-filled bulb. Most of the energy required to operate an incandescent light bulb is wasted in the form of heat.

Linear fluorescent lamps work on a different principle than incandescent bulbs. Using a ballast to regulate the flow of power through the lamp, the electricity is used to excite mercury vapor. The excited mercury atoms produce short-wave ultraviolet light that causes phosphor located in the fluorescent tube to fluoresce. As a result, visible light is produced. This process has proven to be more efficient than the incandescent method of lighting.

LED lamps work differently from their traditional counterparts since they use a semiconductor diode. An LED lamp consists of a chip of semiconductor material treated to create a structure called a P-N (positive-negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side, or cathode, but not in the reverse direction. Charge-carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light)[1]. Different semiconductor materials are used to create different colors. There are typically two ways white light is created. The first is to combine red, green, and blue LED's to make white. The second is to coat a blue or ultraviolet LED with phosphors.

MARKET DESCRIPTION

Under-cabinet lighting has become popular in residential kitchen applications. Nearly every residential customer in SCE service territory has a kitchen. Under-cabinet lighting is a popular retrofit for existing kitchens, and a viable code compliant lighting method in new construction applications. As with compact fluorescents when they were first introduced, the availability and cost of the LED under-cabinet light are perhaps the most significant market barriers for this energy efficient option.

2005 Title 24 considers all screw-type fixtures to be low efficacy. This gives home builders the option to leverage the high efficacy of LED under-cabinet lighting. If 50% of the total wattage is allocated towards LED under-cabinet lighting, this allows for flexibility in selecting other lighting throughout the kitchen. The expected long life of the LED is also a tremendous advantage over fluorescent and incandescent lighting.

Due to changes in the residential building code over the years, different vintage houses may have different kitchen lighting configurations. For retrofit applications, there are two alternate scenarios, kitchens with or without under-cabinet lighting. If kitchens already have under-cabinet lighting, the switch to LED is slightly less difficult because electrical wiring is already in place. If the kitchen does not have under-cabinet lighting, wiring and fixture mounting are both required, making the installation more difficult. Both scenarios require a fixture change.

Considering the various installation opportunities for under-cabinet lighting in residential kitchen settings, the LED under-cabinet light is most appropriate for applications in this order:

1. New-Construction Applications
2. Retrofit Applications (Kitchens with existing under-cabinet lighting)
3. Retrofit Applications (Kitchens without existing under-cabinet lighting)

BUILDING ENERGY CODE

The 2005 California Building Energy Code (Title 24) requirement for kitchen lighting states that fixtures and lamps must be high efficacy OR have up to 50% of the total wattage as low efficacy. Typically, pin-based recessed can-type compact fluorescent lamps used for overhead downlighting are employed to satisfy the high efficacy requirements, but high efficacy under-cabinet lighting may also be considered. The 2005 code allows up to 50% of kitchen lighting to be low efficacy, as long as these luminaries are switched separately from the high efficacy luminaries. Though uncommon, this creates a code-compliant case where high efficacy fluorescent overhead lighting is paired with low efficacy incandescent under-cabinet lighting. A more popular approach is to use high efficacy under-cabinet lighting to allow for flexibility in selecting other kitchen lighting while remaining code compliant.

Since different types of kitchen under-cabinet lighting are permitted by code, the two most popular types of under-cabinet lighting were investigated for this report. Furthermore, consumers purchasing under-cabinet lights for retrofit applications have the option to purchase any type of under-cabinet lighting. For this reason both incandescent and fluorescent type under-cabinet lighting were selected as the baseline case. Figure 1 shows the Title 24 language[2].

Title 24 SECTION 150 – MANDATORY FEATURES AND DEVICES

(k) **Residential Lighting.**

1. **High Efficacy Luminaires.** High Efficacy Luminaires for residential lighting shall contain only high efficacy lamps and shall not contain a medium screw base socket (E24/E26). A high efficacy lamp has a lamp efficacy that is no lower than the efficacies contained in TABLE 150-C. Ballasts for lamps rated 13 Watts or greater shall be electronic and shall have an output frequency no less than 20 kHz.

   EXCEPTION to Section 150 (k) 1: High intensity discharge luminaires containing hardwired electromagnetic ballasts in medium screw base sockets shall be considered high efficacy luminaires for the purposes of meeting Section 150 (k) 6, provided they meet the efficacies contained in TABLE 150-C.

NOTE: To determine the minimum lamp efficacy category only the watts of the lamp (not the ballast) are to be considered.

2. **Lighting in Kitchens.** Permanently installed luminaires in kitchens shall be high efficacy luminaires.

   EXCEPTION to Section 150 (k) 2 Up to 50 percent of the total rated wattage of permanently installed luminaires in kitchens may be in luminaires that are not high efficacy luminaires, provided that these luminaires are controlled by switches separate from those controlling the high efficacy luminaires. The wattage of high efficacy luminaires shall be the total nominal rated wattage of the installed high efficacy lamp(s). The wattage of luminaires shall be determined as specified by Section 130 (c).

FIGURE 1. 2005 TITLE 24 LIGHTING REQUIREMENTS FOR KITCHEN LIGHTING

Since the goal of this project is to determine the energy and demand savings as well as photometry of the LED under-cabinet light, it is considered the measure case. Using the information determined in the lab evaluation on energy use and photometry, the efficacy of the lamp can be determined.

Efficacy is a measure of light output to power input. Typically, efficacy is measured in lumens/Watt, where a lumen is a measure of light emitted by a lamp and a Watt represents the unit of power required to operate the lamp. High efficacy fixtures produce high lm/W. To be considered high efficacy per table 150-C in the 2005 Title 24, the lamp must meet the requirements listed in Table 1.

LAMP POWER RATING	MINIMUM LAMP EFFICACY
15 watts or less	40 lumens per Watt
Over 15 watts to 40 watts	50 lumens per Watt
Over 40 watts	60 lumens per Watt

TABLE 1. EFFICACY STANDARDS AS DEFINED IN TABLE 150-C FROM 2005 TITLE 24.

Baseline cases investigated during the lab assessment included an incandescent under-cabinet lamp, and T8 linear fluorescent lamp.

To determine energy demand and consumption savings of LED technology over the mentioned baseline cases, kilowatt (kW) and kilowatt hour (kWh) figures must be compared to a measure case. Since multiple LED kitchen under-cabinet lighting options were analyzed in the lab, multiple LED measure cases were presented and compared against each of the baseline cases.

OBJECTIVES

The goal of this project is to determine the photometry, energy, and demand savings associated with under-cabinet LED technology in kitchen applications when compared to fluorescent and incandescent kitchen under-cabinet lighting. To do this, the project was broken into the following three phases: field assessment, lab assessment, and assessment integration.

The field assessment was performed by a third party consultant firm. This field evaluation included contacting residential customers and homebuilders to obtain sites in order to implement the technology and track usage. The focus of this phase was to develop the under-cabinet lighting usage profiles for various households. Sites used to develop these profiles were located throughout California and Northern Nevada and varied by the number of occupants and their ages as well as square footage. Twenty six residences were monitored for this phase. Though the focus of this study was on residential under-cabinet lighting, it was important to also track overhead lighting to understand how the two are used collectively. A popular 2005 Title 24 compliant kitchen lighting configuration can consist of a combination of both under-cabinet and overhead lighting.

The second phase consisted of a lab evaluation performed by SCE at the Southern California Lighting Technology Center (SCLTC). This lab assessment included the procurement of LED under-cabinet lighting from multiple manufacturers. This phase has two objectives. The first objective was to develop the power demand (kW) figures for the measure (LED technology) and baseline (incandescent and fluorescent) cases. The second objective was to perform a photometric test to verify light output which was used to confirm baseline measure case efficacies.

These two phases were then integrated to develop the power consumption (kWh) figures of the measure and baseline cases. The end result was documenting information on kW and kWh savings for the measure case vs. baseline case, which was the goal of this project.

At the time this study was performed, SCE offered rebates for LED installations in commercial applications through SCE's Standard Performance Contract rebate program. This rebate program requires the residential customer to provide calculations on energy savings based on the installation. It is expected that results from this study will be used as a resource for utility programs to help make informed decisions for this technology in other market sectors, such as commercial.

METHODOLOGY AND INSTRUMENTATION

FIELD ASSESSMENT

In order to determine the energy savings of the technology, it is necessary to understand how often kitchen under-cabinet lighting is used in residential settings. Kitchen lighting can include a combination of one or more downlights, under-cabinets, over-cabinets, pendants, and/or wall sconces. Based on interviews with homebuilders in SCE service territory and observations made during the field assessment, the most popular kitchen lighting consisted solely of overhead lighting (recessed-can type downlights or well-type linear fluorescents). Another lighting strategy becoming increasingly popular and found during this evaluation was a combination of overhead lighting and under-cabinet lighting. These two kitchen lighting strategies were selected for monitoring in order to develop two separate usage profiles and to obtain the necessary hour figure used to determine potential energy savings supplied by the measure case.

For this evaluation, sites in SCE service territory were preferred. To obtain an acceptable number of sites, SCE and the third party consultant worked with homebuilders in the area to connect with recent buyers and homeowners associations whose members may be willing to participate.

To supplement data from SCE sites, a variety of locations outside of SCE service territory were also examined to understand if kitchen lighting use varies by location. Additional participants were located in the following service territories:

- Truckee-Donner Public Utilities District
- Sierra Pacific Power Company

In order to track usage at these sites, the Onset HOBO® U9-002 light on/off sensor was used. This adjustable sensor contains a photocell that captures light and records a time and date stamp when the light turns on or off. This sensor provides the amount of time per day homeowners use their kitchen lighting.

Installation of this logger includes mounting the logger close to the under-cabinet lamp with a hook and loop fastener. The installation requires field calibration that includes adjusting the sensitivity of the device to ensure that state changes are accurately tracked and to mitigate daylight and other light sources from interfering.

The field assessment started in February 2009 with homes in the Southern California area. Ten homes were found through industry contacts. This includes individuals and single-families that have participated in previous studies and those acquainted with the members of the project team who were willing to volunteer their home. A significant roadblock was encountered early in the project. As with many residential studies, most people were not willing to participate without a significant incentive. This was most likely due to privacy and security issues. Of the 10 residents who initially participated in this project, all were acquainted in some way to the project team. Even with a small incentive, many people were not willing to give up their privacy and security to participate in a study that did not benefit them in some way.

As a result, the project team contacted 12 homebuilders in the Southern California service territory through SCE account managers. Of the 12 homebuilders, two were interested in participating. The goal was to use the homebuilder’s own housing developments as a potential connection to more participants. The homebuilder provided labor for the LED conversion and SCE provided the installation of the LED technology. The idea behind this incentive is that the customers would allow the project team to monitor their usage and provide feedback on the technology while receiving high efficiency lighting.

It should be noted that the housing market in California during the time of this study was rapidly declining and homebuilders were having trouble selling new models. As a result of the declining housing market, the homebuilders shifted their efforts to reducing costs. Despite efforts to keep them interested, both homebuilders eventually backed out. According to the California Building Industry Organization, the number of new homes being built in California has been declining drastically since 2005. In 2005, 155,322 new single family homes were built. In 2008, only 33,050 new homes were built, roughly 1/5th the number built in 2005[3]. This situation not only makes it difficult for homebuilders to participate in the project, but it also has a significant impact on attainable kWh savings in new construction applications.

After targeting homebuilders, the project team's focus shifted to investigating the use of a third party energy efficiency contractor who specializes in utility programs and installations. The goal was to use their expertise to find homes interested in participating. The caveat is that the customer would pay labor to the contractor while SCE provides the technology. In addition, the customer would allow the project team to monitor their usage and provide feedback on the technology. Initially, the contractor seemed interested but then declined participation in the project.

In an effort to obtain more homes in SCE territory, the project team continued installing loggers in houses outside of SCE territory. This effort was conducted by contacting homeowners associations and walking door-to-door in certain communities. This lead to 26 homes participating spread over three electric utility service territories: three from SCE, seven from Sierra Pacific, 16 from Truckee-Donner PUD.

Households varied in size from 1000 ft^2 to 10,000 ft^2 and ranged from one occupant to five occupants with varying living situations. Figure 2 shows the breakdown of participating households by square footage.

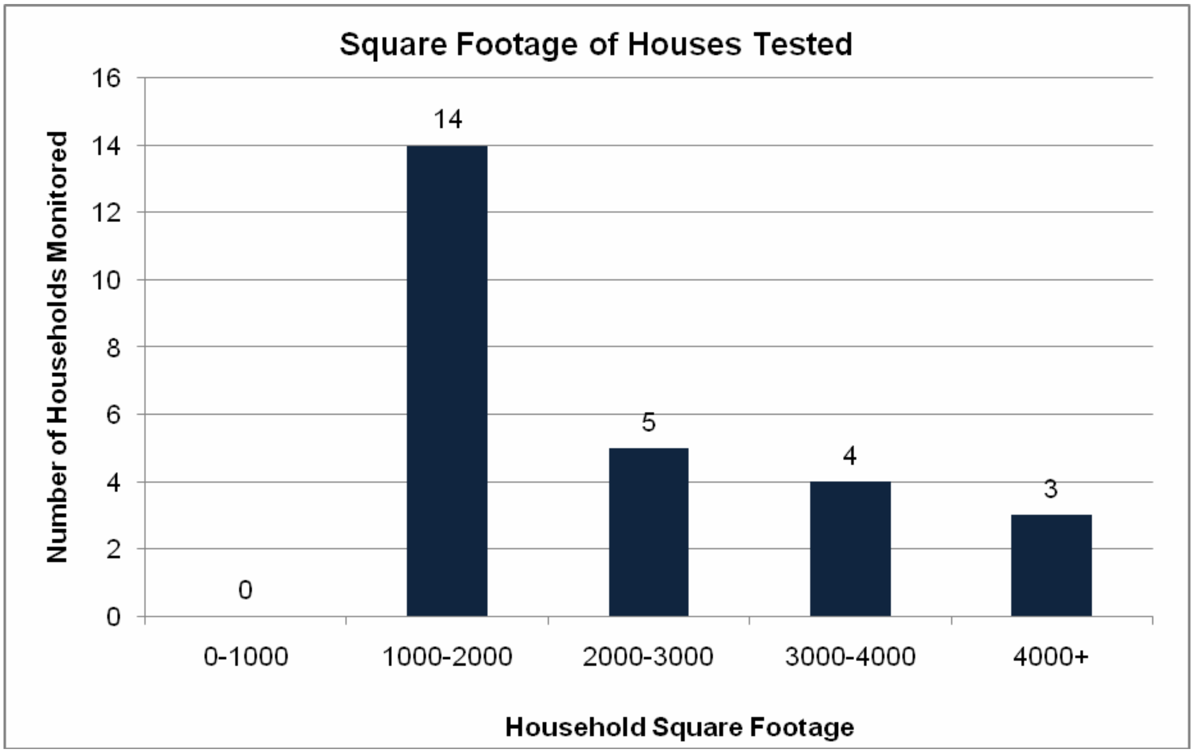

FIGURE 2 . SQUARE FOOTAGE BY HOUSEHOLD

Living situations include:

- One occupant living alone
- Two-occupants non-related shared-living situation
- Two-occupants married couple
- Two-occupants single parent with child
- Three-occupants non-related shared-living situation
- Three-occupants married couple with child
- Four-occupants non-related shared-living situation
- Four-occupants married couples with children
- Five-occupants married couples with children

Figure 3 shows the breakdown of participating households by the number of occupants. Occupants ranged in age from 8 to 70 years old. Each household was instructed to complete a brief survey about their home that included square footage, hours of occupancy, whether or not they have under-cabinet lighting, and information about the location and size of their kitchen windows.

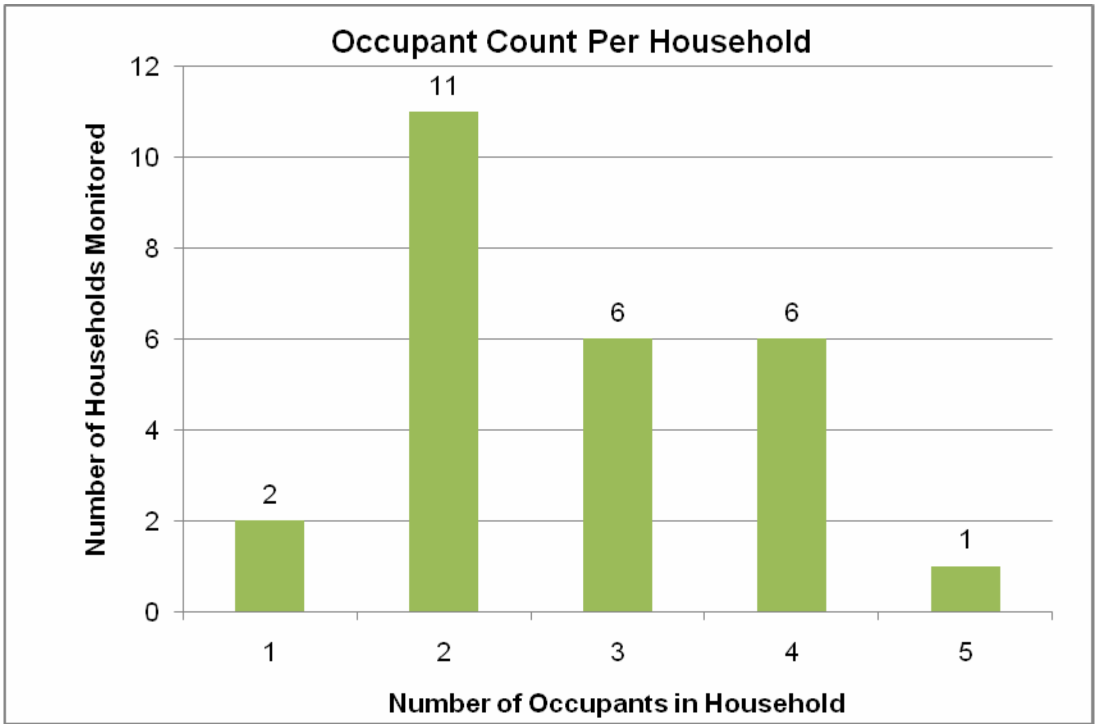

FIGURE 3. OCCUPANT COUNT PER HOUSEHOLD

LAB ASSESSMENT

The lab assessment was conducted concurrently with the field assessment. All lab tests were performed at the SCLTC in Irwindale, CA. Though energy savings figures are important for this evaluation, baseline and measure cases must be tested in terms of light output and quality to ensure the baseline and measure cases are similar. For the lab assessment, 13 LED measure cases were compared to two baseline cases. The baseline cases for this evaluation were a T8 linear fluorescent fixture and an incandescent fixture. The following variables were tested in controlled environments to understand how baseline and measure cases compare.

LIGHT OUTPUT

Light output is the measure of light that a source can provide in lumens. Light output data was obtained from the Integrating Sphere test discussed in the Lab Equipment section of this report.

COLOR RENDERING INDEX

The color quality, measured as Color Rendering Index (CRI), affects visual perception. The CRI is directly related to the colors or spectral characteristics that the lamp gives off. CRI data was obtained from the Integrating Sphere test discussed in the Lab Equipment section of this report.

CRI is an index that describes how well a light source renders color compared to a reference light source of similar color temperature. This index is scaled from 0-100.

CORRELATED COLOR TEMPERATURE

The Correlated Color Temperature (CCT) describes the overall appearance of light. This figure indicates whether a white light source appears yellow with warmer temperatures or lower CCT, or bluer with colder temperatures or higher CCT. CCT refers to how the color of a theoretical black body appears when heated to high temperatures. The CCT of a light source is the temperature in Kelvin at which the heated black body matches the color of the light source in question. CCT data was obtained from the Integrating Sphere test discussed in the Lab Equipment section of this report.

CONNECTED LOAD

Power requirements for all test cases are determined by measuring current and voltage. Since LED's are typically direct current (DC), both voltage and amperage are measured between the driver and the lamp to understand DC Power when possible. Measurements for both current and voltage are taken between the driver and power source to understand alternating current (AC) power. This provides information on driver losses, power requirements of the driver, and AC to DC conversion efficiency. This information is used to understand demand (kW) savings of the measure cases when compared to the baseline cases.

EFFICACY

An important indication of overall lamp performance is efficacy. This value, in lumens per Watt, is a measure of light output over power input. A higher efficacy lamp provides more lumens of light output per Watt than a lower efficacy lamp. Though LED wattage may be lower than their fluorescent counterpart, it must do so while providing the same amount of light. A lamp with a higher efficacy has the most energy savings potential.

LAB EQUIPMENT

LIGHT OUTPUT, CRI, AND CCT MEASUREMENTS

INTEGRATING SPHERE

The integrating sphere is used to measure the light output of a lamp, the CRI, and CCT. The inner surface of the integrating sphere and all internal components are coated with a highly reflective white paint. This paint is engineered to reflect all wavelengths equally which allows for an accurate measurement. The calibrated power supply is connected to the lamps outside of the sphere. The lamps were mounted in the sphere facing downward; the same way they would be installed underneath a cabinet in order to simulate the actual environment. The temperature was regulated to approximately 77 degrees. Measurements were taken every 15 minutes until three consecutive measurements were within 0.5 percent of each other.

FIGURE 4. THE INTEGRATING SPHERE

DEMAND DATA

Power was measured using meter Fluke 435 and meter Fluke 289. The AC power aspects of the driver and LED under-cabinet lights were measured using meter Fluke 435 between regulated 120V power and the driver of the under-cabinet lights. The DC power aspects were measured using meter Fluke 289 between the driver and the LED under-cabinet lights.

ASSESSMENT INTEGRATION

After completion of the field and lab studies, it was necessary to integrate the two assessments to obtain energy savings (kWh). Demand figures for multiple baseline and measure cases were determined through the lab testing. Usage profiles were obtained through the field assessment and tabulated for analysis. When combining demand savings with the amount of hours that the typical household uses their kitchen under-cabinet lights, energy savings could be determined. This integration was based on the assumption that the baseline case was replaced with the measure case.

RESULTS AND DISCUSSION

FIELD ASSESSMENT

The field assessment for homes with under-cabinet lighting consisted of a seven month period which began in mid-February of 2009 and concluded in mid-September of 2009. This field assessment consisted of tracking usage during the data acquisition period. Though 26 houses participated, problems with daylighting and installation of the instrumentation resulted in 20 good data sets. Six of the 20 data sets had to be discarded. Figure 5 shows how often different socioeconomic groups in different locations used their under-cabinet lighting during this study.

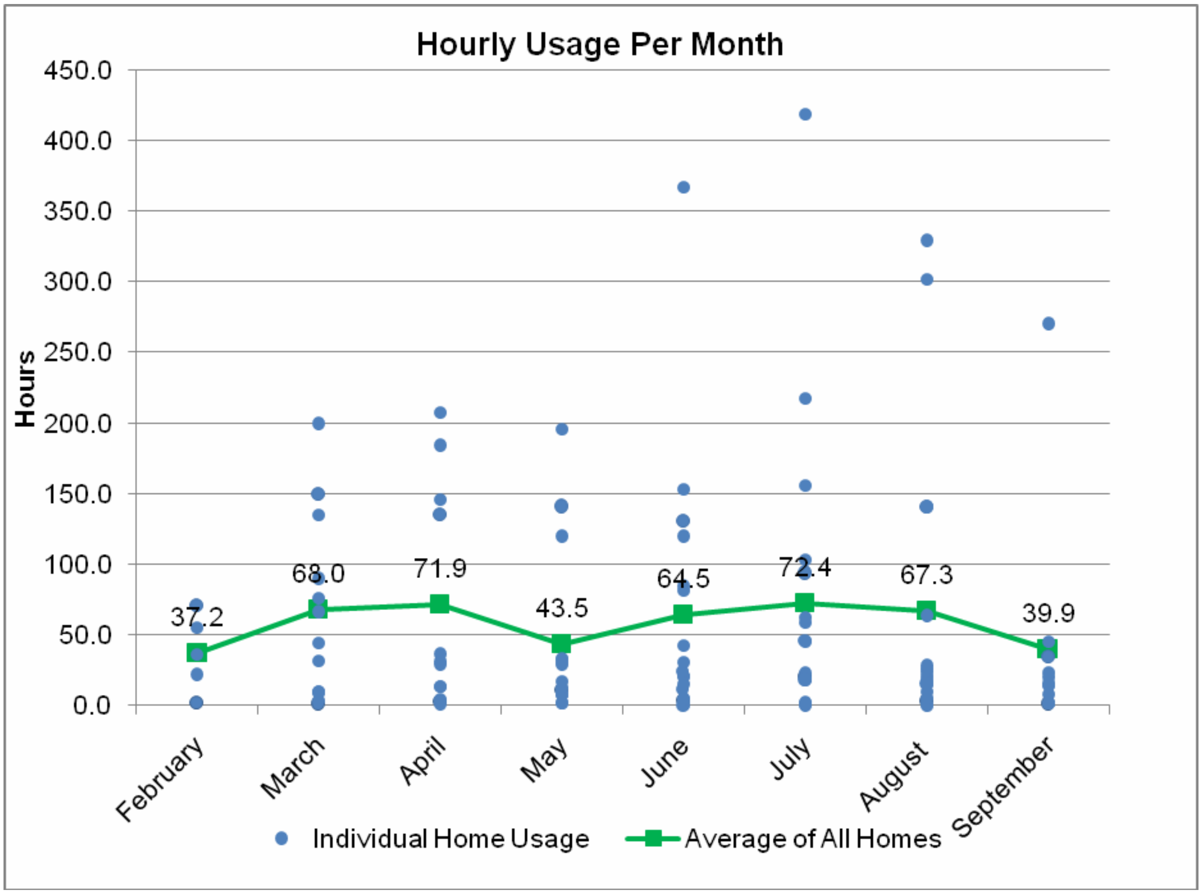

FIGURE 5. MEASURED HOURLY USAGE PER MONTH

Though this information is useful, February and September had only half of the month tracked. To address this, an average usage per day for the year was calculated over the entire data set. Since data from mid-September to mid-February was not available for this study, measured data from the data set was averaged and applied to months where data was not available. This estimate should be considered conservative since it is expected that usage will be higher in the winter months.

The hourly usage of each house can be correlated to that of a percentage per hour for the data set. This percentage is useful to understand how often and during what time of the day participants used their under-cabinet lighting. For example, the month of April has 31 days. Twenty-two days are weekdays, which means there are 22 12:00 A.M. - 1:00 A.M. periods. If the participant has their under-cabinet lighting on the full hour for 11 of those 22 days, then the percentage for that hour for the data set will be 50%. Figure 6 shows an average percentage for the each hour over the entire data set for all houses participating in the study. Most of the usage is during off-peak hours.

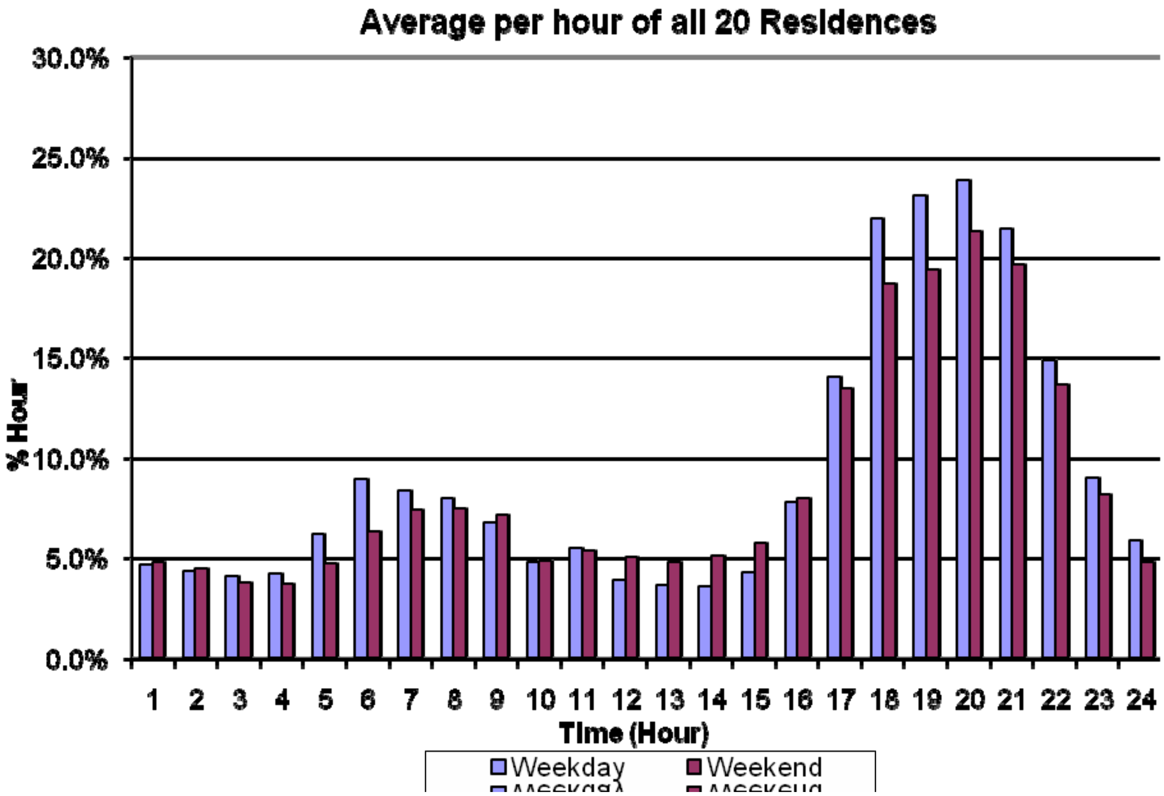

FIGURE 6. USAGE PROFILE OF KITCHEN UNDER-CABINET LIGHTING

Since the households participating in this study varied in occupants and size, an average was taken for all households for hours per day for weekday peak, weekday off-peak, and weekend off-peak periods. Based on results of this study, it was concluded that the average household uses their under-cabinet lights 0.69 hours/day during on-peak periods, 1.53 hours/day during weekday off-peak periods and 2.07 hours/day during weekend off-peak hours as shown is Figure 7.

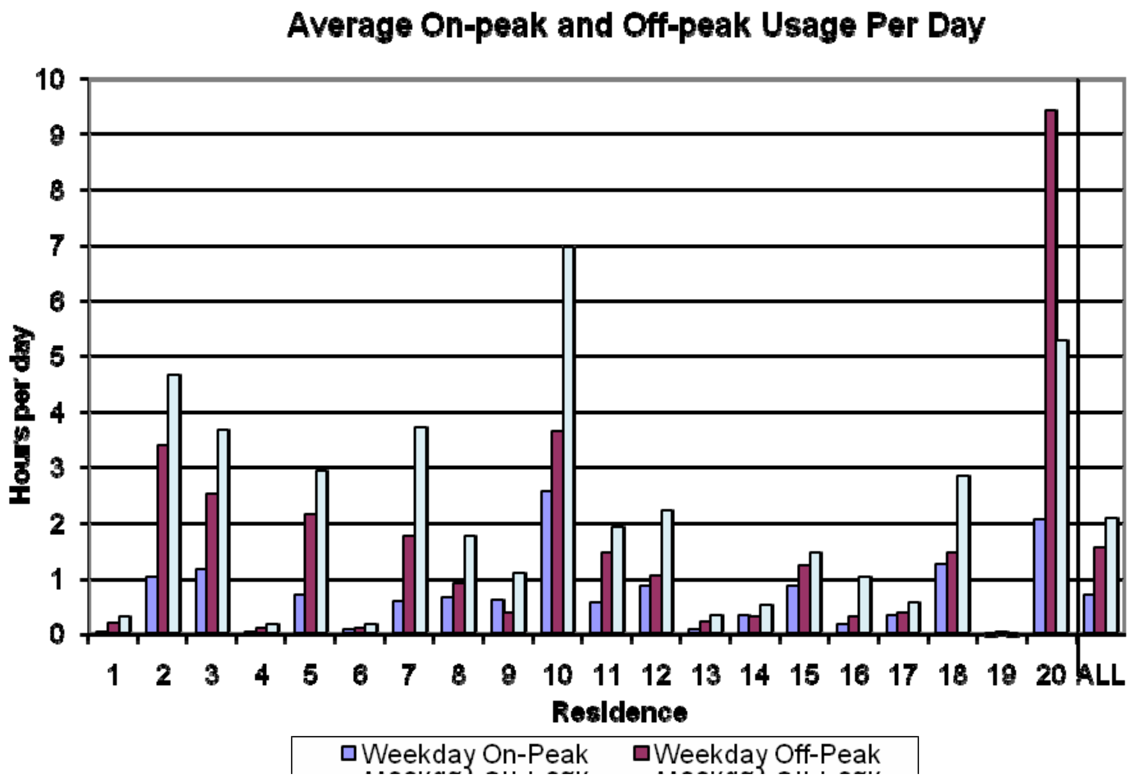

FIGURE 7. HOURLY USAGE PER DAY FOR EACH MONTH

Based on the figures for the hourly usage per day figures in Figure 6, it is estimated that under-cabinet lighting is used approximately 794.4 hours per year. Year shows the breakdown of estimated usage for each month.

UTILITY PERIOD	HOURLY USAGE / YEAR
Weekday On-Peak	180.1
Weekday Off-Peak	398.8
Weekend Off-Peak	215.5
Total	794.4

TABLE 2. ESTIMATED UNDER-CABINET LIGHTING HOURLY USAGE PER YEAR

Though participants in this study were spread throughout California and Northern Nevada, location did not seem to affect the usage of the under-cabinet light. Under-cabinet lighting usage seemed to be most dependent on the amount of people in the house and the square footage of the home.

LAB ASSESSMENT

INTEGRATING SPHERE

LAMP LUMENS

The lumens for each of the under-cabinet baseline and measure cases were recorded at the intervals mentioned in the lab equipment section of this report. This measurement captures the total amount of light coming out of the fixtures and does not account for directionality of the light source. Figure 8 shows the measured lumen output per linear foot of under-cabinet lighting for all the fixtures investigated for this study. The LED lamps are arranged from high to low for easy comparison between the technologies and among the individual lamps.

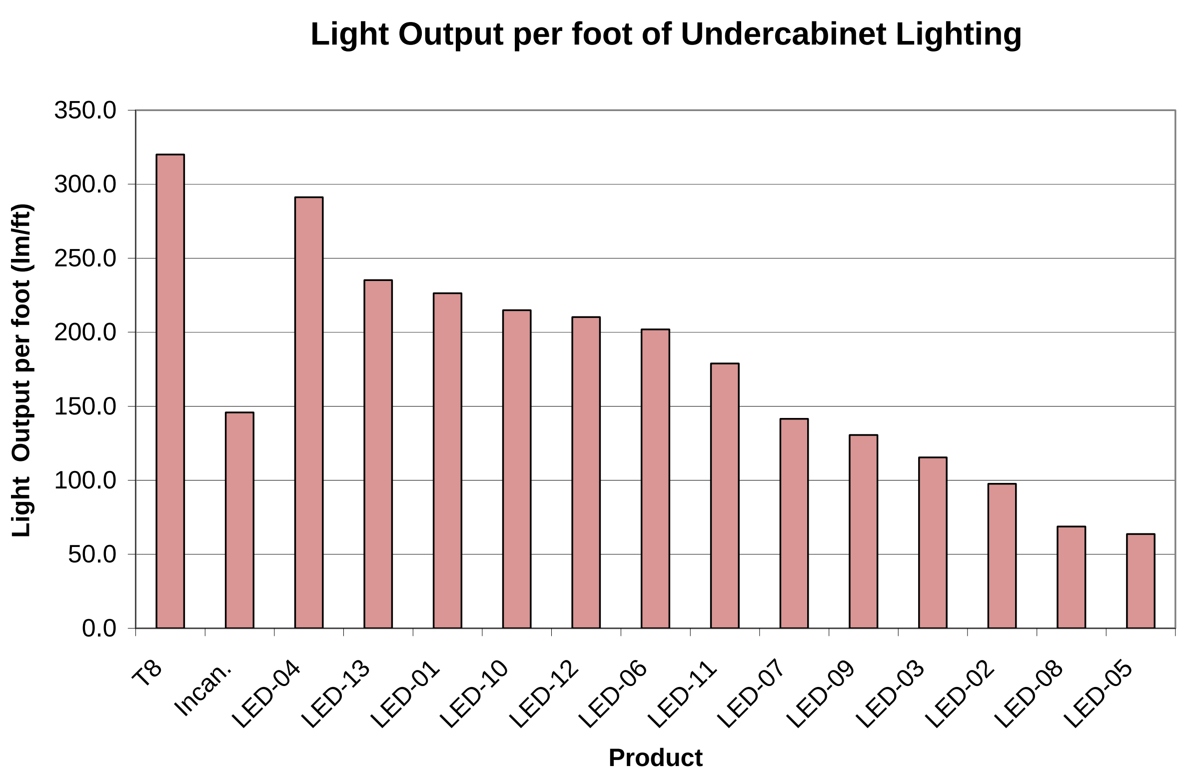

FIGURE 8. LUMEN OUTPUT RESULTS

There is a wide range of light output for available LED under-cabinet lighting products. Most tested LED products did not have the same lumen output as the T8 linear fluorescent product but, in most cases, exceed that of the incandescent baseline case. Because of the directional nature of under-cabinet lighting application, this total lumen output measurement does not account for the application efficiency of the product in getting light onto the work surface or countertops.

CORRELATED COLOR TEMPERATURE

The Correlated Color Temperature (CCT) for the LED under-cabinet lamps can vary. It can range from warm white, meaning the light appears more yellow, similar to incandescent, to a very cool white, meaning the light source appears bluer. There is no "correct" CCT for displaying objects. Depending on the application, different color temperatures are preferred more than others.

CCT was measured for the fluorescent, incandescent, and LED under-cabinet lamps. Figure 9 shows the measured CCT for all tested LED, fluorescent, and incandescent lamps. The values are arranged in increasing CCT to allow for easier comparison of the incandescent and fluorescent lamps.

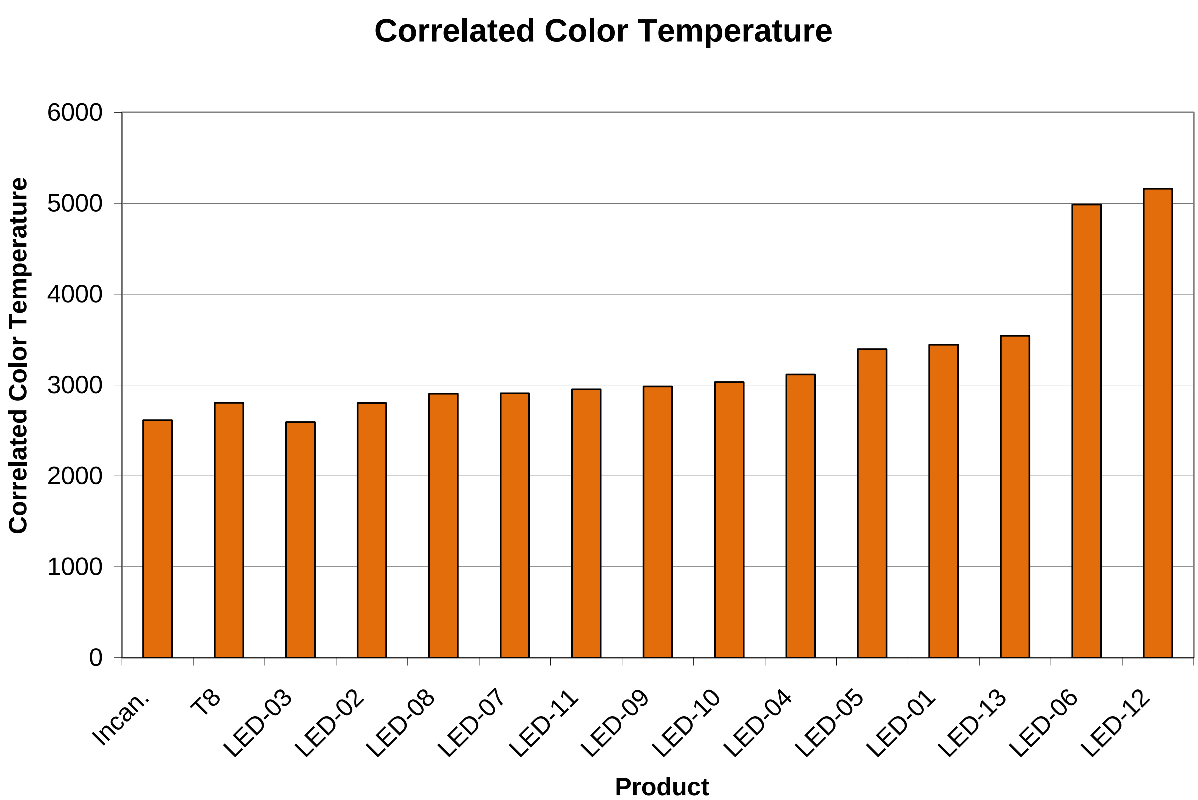

FIGURE 9. CCT RESULTS

Both baseline cases have a slight variance in CCT, with a range of 2600K to 2800K. These cooler Kelvin temperatures are correlated to the warm white (yellow-orange) end of the CCT scale. The LEDs range from an equivalent-to-baseline 2,600K and a cooler blue white at 5,000K. These hotter Kelvin temperatures are correlated to the cooler white (bluer) end of the CCT scale.

The LED under-cabinet products come in a wide array of color temperatures, ranging from warm white on the left to very cool white on the right. Several of the tested LED under-cabinet lights have comparable CCT to the baseline, with higher temperature products available.

COLOR RENDERING INDEX

The color rendering index (CRI) was measured and is shown with the same criteria as the CCT test. Figure 10 shows the measured CRI for all LED and baseline lamps tested. The values are arranged in decreasing CRI for easy comparison of the baseline lamps.

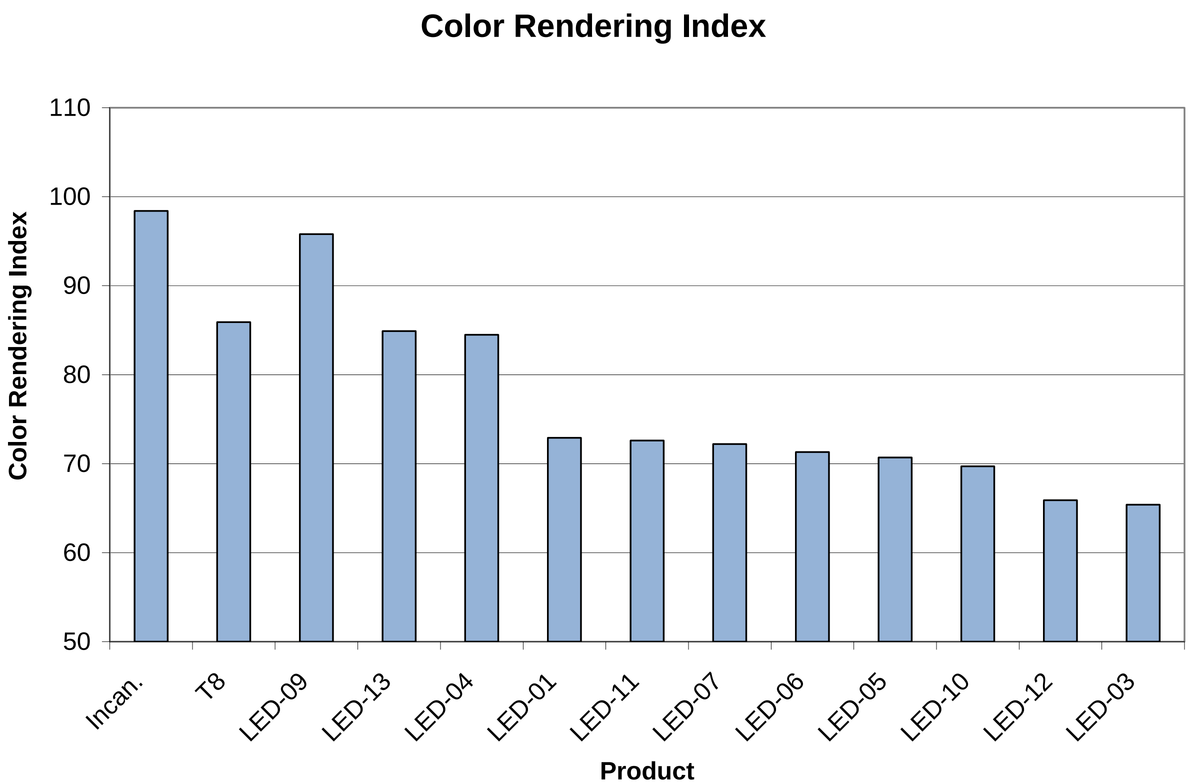

FIGURE 10. CRI RESULTS

The incandescent lamp has the highest CRI value of 98.4. As displayed in Figure 10 the most comparable LED in terms of CRI is LED-09. The linear fluorescent lamp has a CRI value of 85.9. A comparable LED in terms of CRI is LED-09. This shows that there are some LED lamps available that have similar CRI values as popular market options. The largest variance in CRI is between the incandescent baseline at 98.4 and LED-08 at 56.7, a variance of 42%. This demonstrates that there are some LED products on the market that are not comparable in terms of CRI.

POWER MEASUREMENTS

One of the objectives of the LED under-cabinet tests was to determine if replacing fluorescent or incandescent under-cabinet lighting with LED style fixtures would result in energy savings without compromising light quality. The efficacy comparison provides information to help to answer this question.

POWER

The advantage of the LED under-cabinet lighting products over the fluorescent and incandescent products is their lower demand use. Figure 11 shows the measured DC and AC power (in watts) for LED, fluorescent, and incandescent under-cabinet fixtures. Since LED's require an AC-DC driver, there are power requirements separate from the lamp. The DC power measurement excludes the power required by the driver. For this evaluation, three of the LED under-cabinet lighting products could not be tested for DC power due to their integrated driver design.

Because a consumer will typically be changing the entire fixture, the AC Power Demand results are important. It is still beneficial to consider how much power is lost in the conversion process from AC to DC. Energy savings can be achieved if manufacturers consider efficient driver design to compliment the LED's efficient light source.

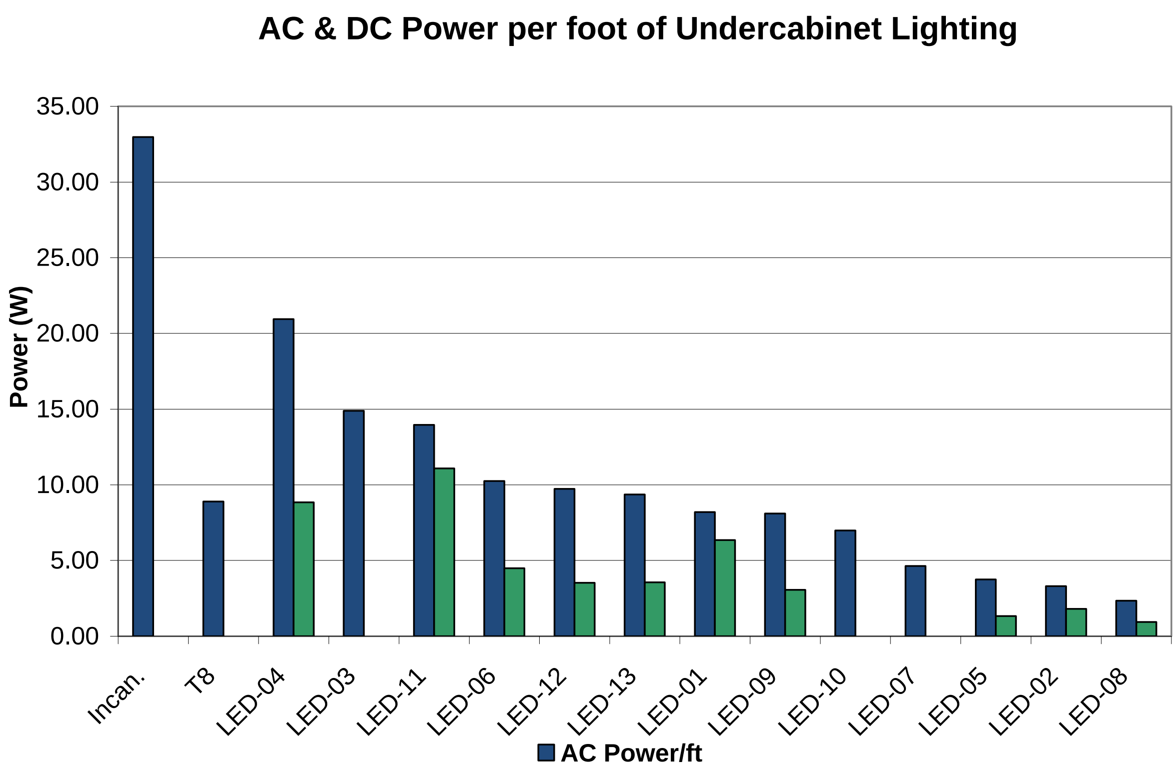

FIGURE 11. AC AND DC POWER DEMAND RESULTS

The incandescent baseline requires the most power. Seven of the 11 LED fixtures tested at a lower overall power demand per foot of under-cabinet lighting than the tested T8 baseline, leaving the remaining four testing higher than the T8 baseline. A larger gap between DC compared to AC power is due to higher driver power requirements and other fixture inefficiencies and losses. For example, LED-04 clearly shows a large difference between the AC and DC power required.

AC-DC EFFICIENCY

The AC to DC power efficiency is defined as the amount of DC Power required to power the lamp divided by the overall AC Power required to power the fixture. This takes into account AC-DC conversion losses. For example, LED-11 is 79% efficient which means that the DC power requirement for the LED itself is 79% of the fixtures total AC power requirement and 21% of the AC power requirement is lost in the conversion from AC to DC. Figure 12 shows these efficiencies.

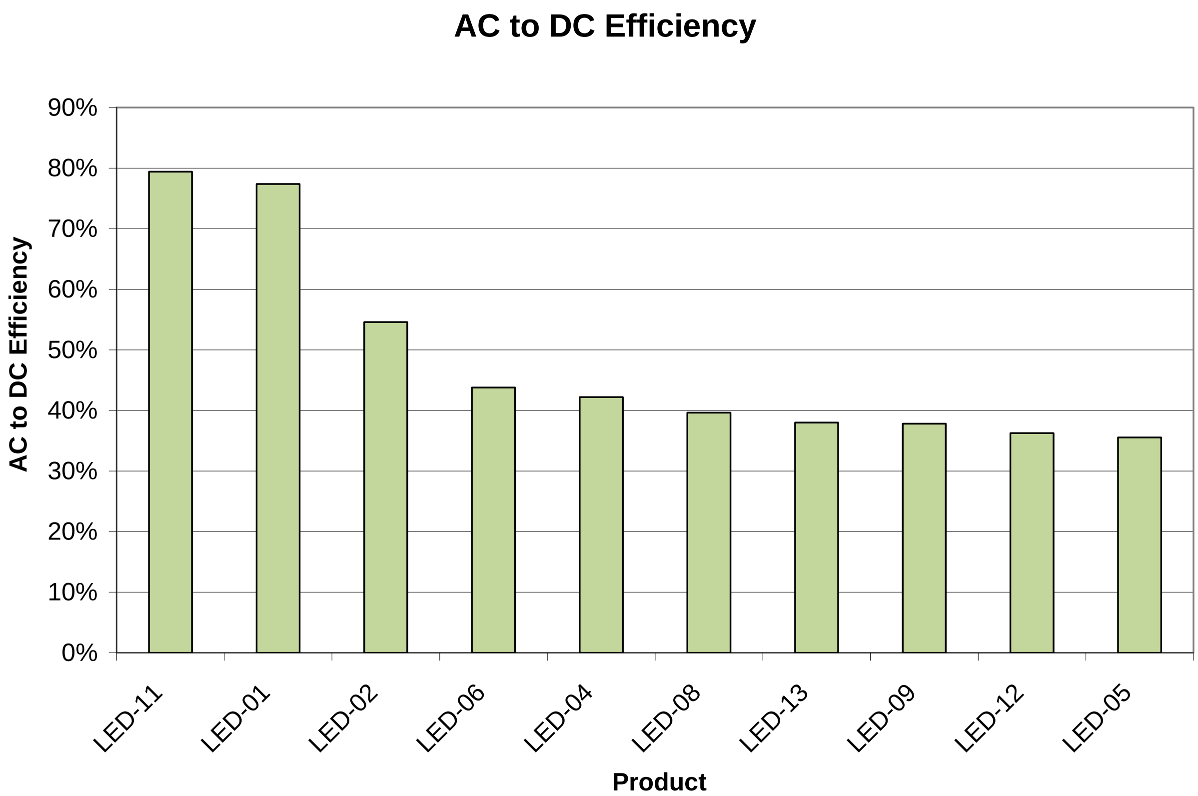

FIGURE 12. AC- DC POWER EFFICIENCY RESULTS

More than half of the tested LED products have AC-DC conversion efficiencies below 50%. This means that more than half the power requirement of the fixture goes to the AC-DC conversion process which includes driver losses. These poor efficiencies are related to poor power factor.

POWER FACTOR

The power factors of each of the lamps were also measured. Power factor is an indication of how efficiently a load is using its power in the form of Volt-Amperes (VA) to Watts. For example, a power factor of 0.92 means that though a connected load requires 92 VA it is pulling 100 watts to operate. This could be due to poor electrical circuit design or a poor operating efficiency. Figure 13 shows the power factor measurements; a power factor of one is optimal.

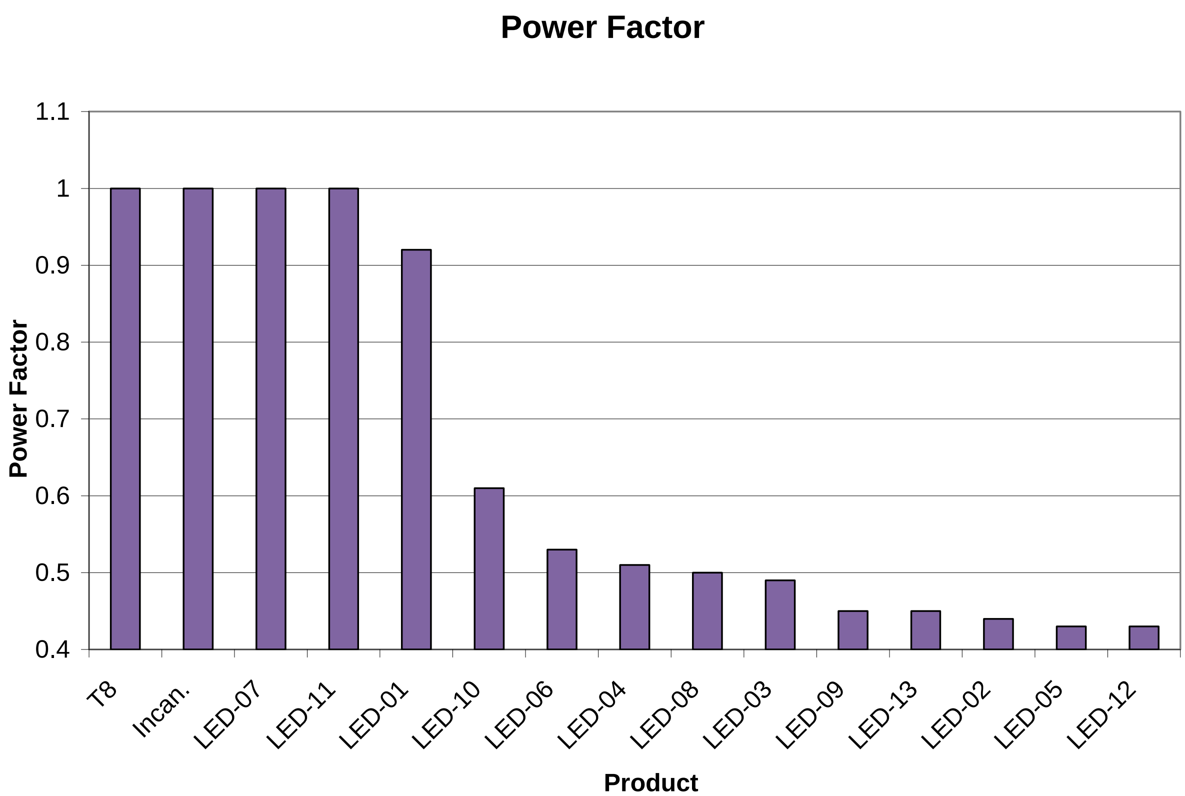

FIGURE 13. POWER FACTOR RESULTS

AC EFFICACY

Efficacy is defined as the lumen output per Watt of power, and provides a common unit for comparison between products. The under-cabinet fixtures' power data was calculated during the Integrating Sphere test, and is the product of the measured lamp current and the lamp voltage. The lamp power data was then combined with the sphere lumen data to determine initial efficacy. Figure 14 shows the range of measured AC efficacy values for the fluorescent, incandescent, and LED under-cabinet products. A higher efficacy is optimal.

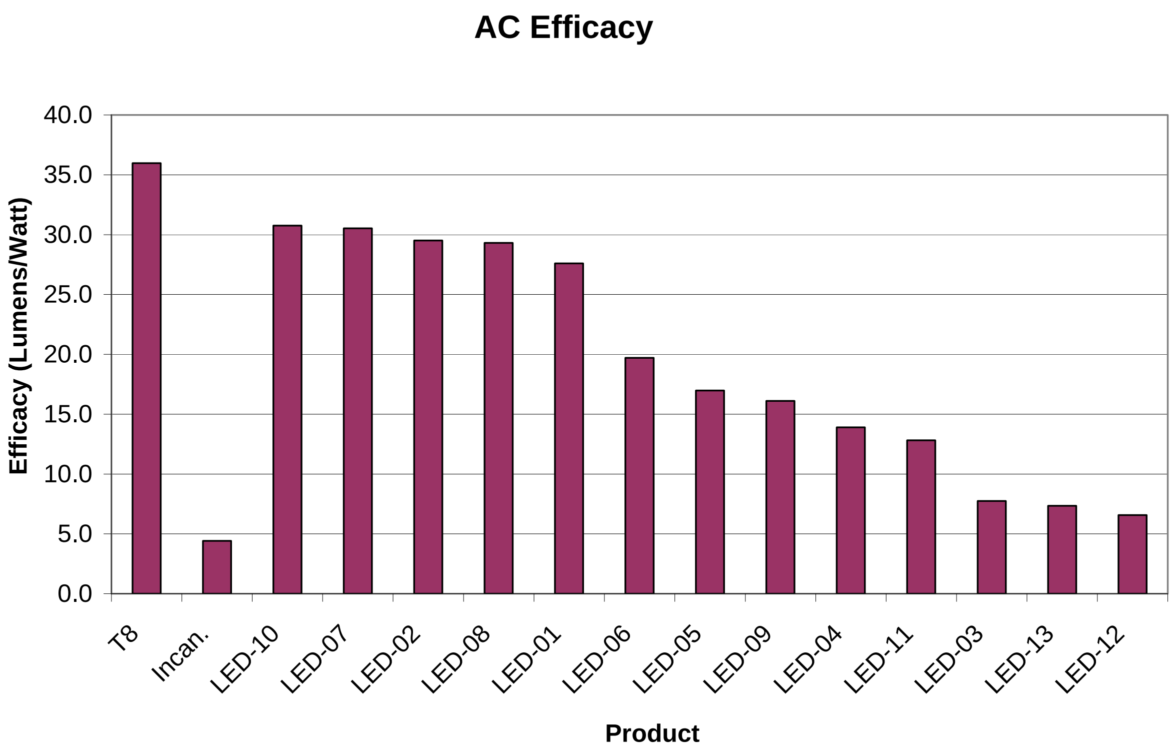

FIGURE 14. MEASURED AC EFFICACY VALUES

Comparing the efficacy of the fluorescent baseline, all LED under-cabinet lamps measured lower. The highest LED product efficacies tested are LED-10 and LED-07 with 31 lm/W, which is six times more efficient than the incandescent baseline but slightly less efficient than the T8 baseline.

Although none of the tested LED under-cabinet lights surpassed the efficacy of the T8 fluorescent baseline in terms of light output per Watt, the application efficiency of the LED products are expected to exceed that of the fluorescent. This means that though the units may output slightly less light per Watt, the light output is more efficiently directed towards the work surface and not lost underneath the cabinet.

DC EFFICACY

Though the AC efficacy is lower than the T8 baseline, the DC efficacy of most of the tested LED lamps is much higher. Figure 15 shows the DC efficacy of the tested LED under-cabinet products.

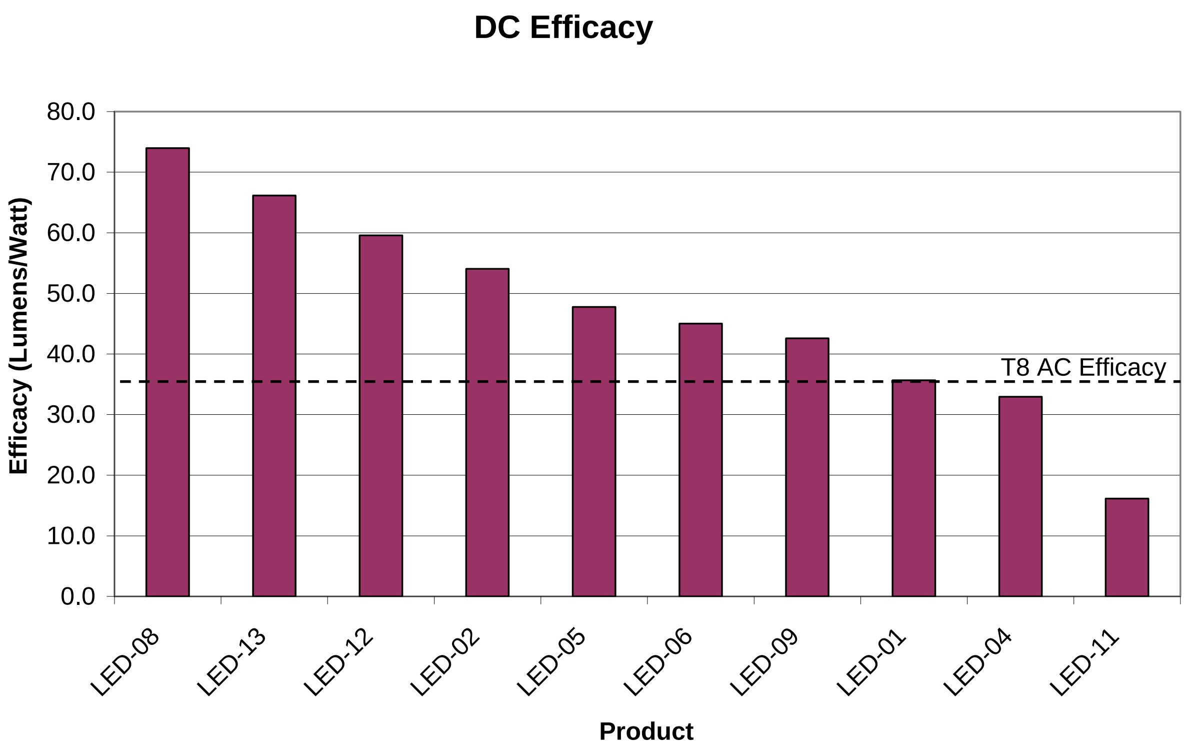

FIGURE 15. MEASURED DC EFFICACY VALUES

The T8 linear fluorescent baseline has an efficacy of 36 lm/W. Only LED-01, LED-04, and LED-11 have worse DC efficacies than the T8 baseline AC efficacy. This indicates that if LED under-cabinet lighting manufacturers can improve their overall fixture design and improve AC-DC efficiencies, the AC efficacy of the LED fixture can easily exceed that of the T8 linear fluorescent.

Actual measured values for AC efficacy vs. lumen output were found to be between the T8 baseline and the incandescent baseline. Figure 16 shows a plot of the efficacy and lumen output of LED, fluorescent, and incandescent products. Points further to the right are more efficacious and points higher up provide higher light output.

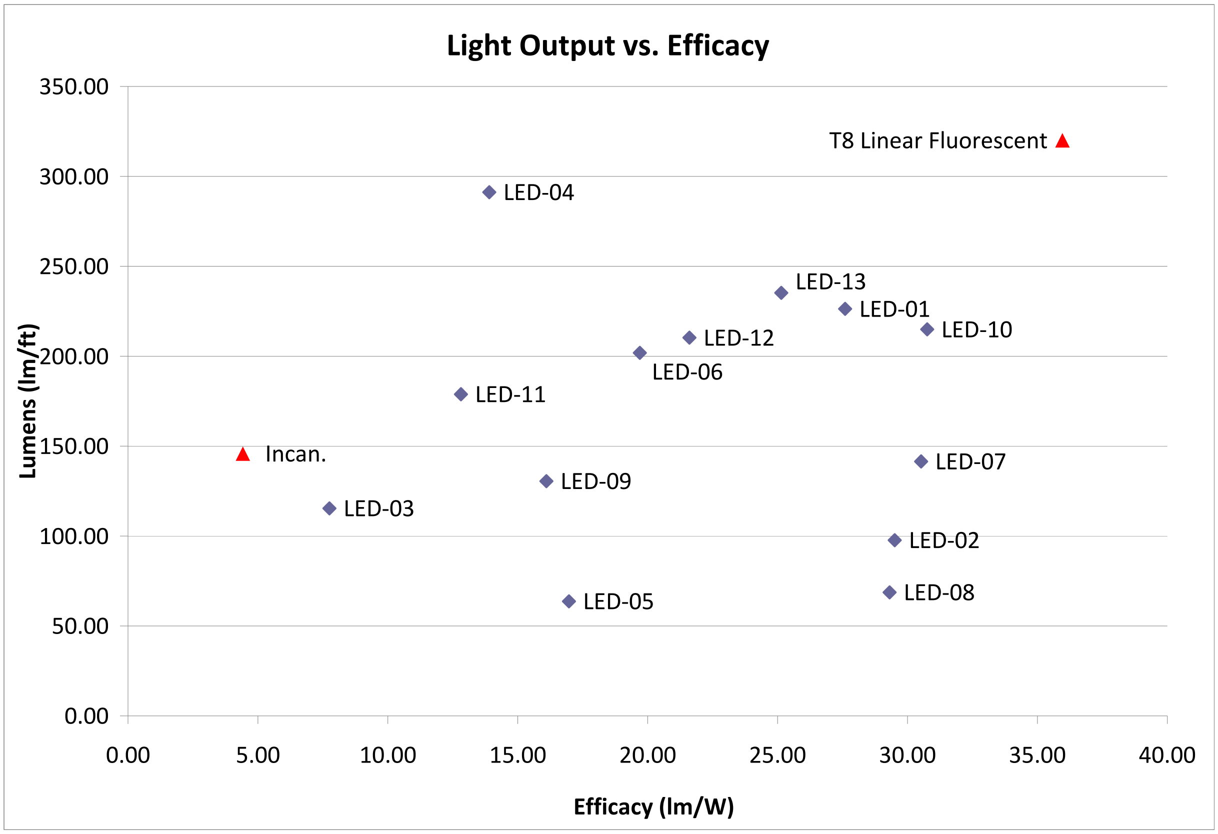

FIGURE 16. LIGHT OUTPUT PER FOOT OF UNDER-CABINET LIGHT VS. EFFICACY

The LED-04 product has a light output similar to the T8 linear fluorescent under-cabinet lamp. Though the light output is comparable, the AC efficacies of all LED products remain below the T8 linear fluorescent baseline.

With other LED products there has been a noticeable trend that an increase in efficacy results in an increase of light output. This is because more efficient LED chips can deliver more lumens at the same power. It is expected that if LED under-cabinet lighting manufacturers can combine efficient LED chips with efficient driver/fixture design, LED under-cabinet lights will easily outperform the T8 linear fluorescent.

ASSESSMENT INTEGRATION

The purpose of the assessment integration was to estimate the annual energy savings. This figure is directly dependent on the lamps' annual operating hours. For purposes of this study, the annual operating hours will be the figure determined through the field assessment which is set at 794.4 hours per year.

Since there are very few LED lamps that can be directly compared to the T8 linear fluorescent baseline, the wattage of the fluorescent has been normalized to equal the light level of the LEDs. The lumen output of the LED was divided by the average efficacy of the T8 linear fluorescent of 36 lm/W as shown in Equation 1. The equivalent AC watts/ft reflects how much power is needed from the T8 linear fluorescent to meet the lumen output of the LED under-cabinet light. Since the efficacy was considerably higher for the T8 baseline case than the LED measure case, a negative energy savings is realized. This was not the case for the incandescent baseline case because its efficacy was considerably lower.

EQUATION 1. EQUIVALENT WATTS CALCULATION

$$EquivalentWatts = \frac{(LEDMeasuredLumens)}{(T8Efficacy)}$$

The example below shows the equivalent Watts of Item 01.

$$EquivalentWatts = \frac{(226.31 lm/ft)}{(36 lm/W)}$$

$$EquivalentWatts = 6.29 Watts/ft$$

After the fluorescent equivalent watts were determined, demand savings could be calculated. Assuming a 794.4 hour annual operation, the energy savings was calculated as shown in Table 3. The same process was performed for the incandescent fixture as shown in Table 4.

Table 3. Energy Savings LED vs. Linear Fluorescent.

LED #	LM / FT	Measured AC Watts / FT	Equivalent AC Watts / FT	Watts / FT Saved	Operating Hours	kWh / FT Saved
LED-01	226.31	8.20	6.29	-1.91	794.4	-1.52
LED-02	97.68	3.31	2.71	-0.06	794.4	-0.05
LED-03	115.43	14.89	3.21	-11.68	794.4	-9.28
LED-04	291.21	20.95	8.09	-12.86	794.4	-10.22
LED-05	63.69	3.75	1.77	-1.98	794.4	-1.57
LED-06	201.93	10.25	5.61	-4.64	794.4	-3.69
LED-07	141.51	4.64	3.93	-0.71	794.4	-0.56
LED-08	68.70	2.34	1.91	-0.44	794.4	-0.35
LED-09	130.54	8.11	3.63	-4.48	794.4	-3.56
LED-10	214.90	6.99	5.97	-1.02	794.4	-0.81
LED-11	178.88	13.96	4.97	-8.99	794.4	-7.14
LED-12	210.29	9.73	5.84	-3.89	794.4	-3.09
LED-13	235.26	9.36	6.54	-2.82	794.4	-2.24
Averages	167.41	8.96	4.65	**-4.27**		**-3.49**

Table 4. Energy Savings LED vs. Incadescent

LED #	LM / FT	Measured AC Watts / FT	Equivalent AC Watts / FT	Watts / FT Saved	Operating Hours	kWh / FT Saved
LED-01	226.31	8.20	51.20	43.00	794.4	34.16
LED-02	97.68	3.31	22.10	18.79	794.4	14.93
LED-03	115.43	14.89	26.11	11.23	794.4	8.92
LED-04	291.21	20.95	65.88	44.93	794.4	35.69
LED-05	63.69	3.75	14.41	10.66	794.4	8.47
LED-06	201.93	10.25	45.69	35.43	794.4	28.15
LED-07	141.51	4.64	32.02	27.38	794.4	21.75
LED-08	68.70	2.34	15.54	13.20	794.4	10.49
LED-09	130.54	8.11	29.53	21.43	794.4	17.02
LED-10	214.90	6.99	48.62	41.63	794.4	33.07
LED-11	178.88	13.96	40.47	26.51	794.4	21.06
LED-12	210.29	9.73	47.57	37.84	794.4	30.06
LED-13	235.26	9.36	53.22	43.86	794.4	34.84
Averages	167.41	8.96	37.87	**28.91**		**22.97**

CONCLUSION

The field results of the study provide a usage profile that allows an approximate understanding of potential energy savings from under-cabinet lighting.

The lighting quality of LED technology in under-cabinet applications is acceptable compared to both incandescent and fluorescent lighting. There are products that have the same CRI and CCT values as that of incandescent and linear fluorescent lights. There are more color varieties in LED technology than the baseline case technologies. These varieties can be options for the end-use customer; however, the variation can be a concern if not understood. The baseline case expectation is that typical under-cabinet lights have a certain CCT and CRI.

All LED under-cabinet lighting products tested during this study had higher efficacy than the incandescent baseline case. Compared to linear fluorescent, the LED under-cabinet lighting products did not perform as well. Though many of the LED lighting products require less AC power, they do not perform on the same level as the linear fluorescent in terms of lumen output and efficacy. However, because of the directional nature of under-cabinet lighting and LED technology, the metric of total lumen output does not account for the application efficiency of the technology. This means that although the technology output is slightly less light per Watt, the light output is more efficiently directed towards the work surface with less light loss under the cabinet.

One concern discovered during this evaluation was that none of the tested LED fixtures outperformed the linear fluorescent baseline when looking at overall system efficacy. Results of this study show that most of the fixtures have very poor AC-DC conversion efficiencies. As a result, seven of the ten LED products that could be tested for DC power had efficiencies less than 50%. This means that it takes more electricity to convert to direct current than it does to power the lamp. It is expected that if measures are taken to correct power factor and reduce driver losses, LED under-cabinet lighting will outperform their fluorescent counterpart. If evaluating at the full system AC efficacy, it should be noted that none of the tested fixtures meet the 40 lm/W required for minimum efficacies per 2005 Title 24.

RECOMMENDATION

The field results of the study were limited in scope. It is recommended that a larger scale evaluation of usage profile be conducted to have a more reliable data set for the 'hour' portion of the energy savings calculations.

LED under-cabinet lights can be used as a replacement for baseline case incandescent and fluorescent under-cabinet lights. The results of this study show that the current state of LED under-cabinet technology can meet the technical requirements of the baseline incandescent and fluorescent under-cabinet lights. There are LED products that have sufficient light output to replace a baseline under-cabinet fixture with similar CCT and CRI characteristics.

LED under-cabinet light fixtures are efficient light sources with up to over 70 lumens per Watt. However, the AC-DC power conversion for the fixtures is not efficient. Seventy percent of the tested fixtures have AC-DC efficiencies of less than 50%. It is recommended that the utility work with the lighting industry to help improve AC-DC conversion efficiency for LED technology.

There are large variations in many aspects of LED under-cabinet technology. The light output of LED under-cabinet lights range from a level that is close to the tested fluorescent system, about 300 lm/ft, down to about 60 lm/ft. The CRI and CCT variation can be easily perceived. The power ranges from about 60 watts to approximately 7 watts. There is much less variation in the standard halogen incandescent lamps. This variation between the technologies can pose a threat to the acceptability of more energy efficient LED technology because of the expectation of minimal variation.

It is recommended that a set of criteria be established to reduce the risk of rejection in the market due to negative product variation. The criteria should include minimum efficacy and light output values as well as acceptable CRI and CCT ranges. The key to the long-term success of energy efficient LED technology is high quality product that meets or exceeds end-user expectation from the lighting quantity and quality standpoint. Concurrently, the technology should have a high level of efficiency to maximize energy savings and demand reduction.

LED technology progresses rapidly. It is recommended that a similar evaluation be conducted at a later time to understand the potential improvements in efficacy and efficiency. The results from a future study will potentially allow for additional energy savings and a better understanding of the advancement in the technology.

APPENDIX A: EQUIPMENT

The following instruments were used in the collection of test data. See the Technical Approach section for details.

Manufacturer	Model	Calibration	Description	Used for	Specifications
Labsphere	SLMS LED 7650	Monthly	Spectral light measurement system (integrating sphere)	Luminous flux, correlated color temperature, color rendering index	Sphere-spectroradiometer method, 76" diameter, 4pi geometry, 350-850 nm spectroradiometer bandwidth, auxiliary compensation, D65 white point
Onset Computer Corporation	H06-002-02	N/A	HOBO light on/off data logger	Light on/off logging	64 kb, 43,000 state changes, +/- 1 minute/month time accuracy, 1 year battery life, 10-100 lm/m2 adjustable light sensitivity threshold
Fluke	435	9/29/2008	Power quality analyzer	AC-side electrical logging, voltage, current, power, frequency, power factor, current THD	1-1000 V (0.1%), 0-20 kA (.5%), 40-70 Hz (.01 Hz), 1-20 MVA (1%), more specifications at www.fluke.com

APPENDIX B: EQUIPMENT

The following instruments were used in the collection of test data. See the Technical Approach section for details.

Manufacturer	Model	Calibration	Description	Used for	Specifications
Labsphere	SLMS LED 7650	Monthly	Spectral light measurement system (integrating sphere)	Luminous flux, correlated color temperature, color rendering index	Sphere-spectroradiometer method, 76” diameter, 4pi geometry, 350-850 nm spectroradiometer bandwidth, auxiliary compensation, D65 white point
Onset Computer Corporation	H06-002-02	N/A	HOBO light on/off data logger	Light on/off logging	64 kb, 43,000 state changes, +/- 1 minute/month time accuracy, 1 year battery life, 10-100 lm/m2 adjustable light sensitivity threshold
Fluke	435	9/29/2008	Power quality analyzer	AC-side electrical logging, voltage, current, power, frequency, power factor, current THD	1-1000 V (0.1%), 0-20 kA (.5%), 40-70 Hz (.01 Hz), 1-20 MVA (1%), more specifications at www.fluke.com
Fluke	289	12/1/2008	True-rms industrial logging multimeter	DC-side electrical measurement, voltage, current	50 mV-1000 V (.025%), 500 uA-10 A (.06%), more specifications at www.fluke.com

REFERENCES

[1] US Department of Energy – How LEDs Work
http://www1.eere.energy.gov/buildings/ssl/how.html

[2] Building Energy Code 2005 Title 24

[3] California Building Industry Association – Housing Statistics

http://www.cbia.org/go/cbia/?LinkServID=FE5ED931-F09E-44C7-96836630388F21F7&showMeta=0