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CALiPER

Report 21.3:

Cost-Effectiveness of Linear (T8) LED Lamps

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Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08[1]) conducted by accredited, independent laboratories.[2] Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.[3] Increasingly, CALiPER investigations also rely on new test procedures that are not industry standards; these experiments provide data that is essential for understanding the most current issues facing the SSL industry.

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Instead, CALiPER focuses on specific groups of products that are relevant to important issues being investigated. The products are selected with the intent of capturing the current state of the market at a given point in time, representing a broad range of performance characteristics. However, the selection does not represent a statistical sample of all available products in the identified group. All selected products are shown as currently available on the manufacturer's web page at the time of purchase.

CALiPER purchases products through standard distribution channels, acting in a similar manner to a typical specifier. CALiPER does not accept or purchase samples directly from manufacturers to ensure that all tested products are representative of a typical manufacturing run and not hand-picked for superior performance. CALiPER cannot control for the age of products in the distribution system, or account for any differences in products that carry the same model number.

Selecting, purchasing, documenting, and testing products can take considerable time. Some products described in CALiPER reports may no longer be sold or may have been updated since the time of purchase. However, each CALiPER dataset represents a snapshot of product performance at a given time, with comparisons only between products that were available at the same time. Further, CALiPER reports seek to investigate market trends and performance relative to benchmarks, rather than as a measure of the suitability of any specific lamp model. Thus, the results should not be taken as a verdict on any product line or manufacturer. Especially given the rapid development cycle for LED products, specifiers and purchasers should always seek current information from manufacturers when evaluating products.

To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,[4] ENERGY STAR® performance criteria,[5] technical requirements for the DesignLights Consortium® (DLC) Qualified Products

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1 IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit http://www.iesna.org/.

2 CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

3 CALiPER summary reports are available at http://www.ssl.energy.gov/reports.html. Detailed test reports for individual products can be obtained from http://www.ssl.energy.gov/search.html.

4 LED Lighting Facts® is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see http://www.lightingfacts.com.

5 ENERGY STAR is a federal program promoting energy efficiency. For more information, visit http://www.energystar.gov.

List (QPL),[6] or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, photometric testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully. In the end, the best product is the one that best meets the needs of the specific application.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

[6] The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit http://www.designlights.org/.

Outline of CALiPER Reports on Linear (T8) LED Lamps

This report is part of a series of investigations performed by the CALiPER program on linear LED lamps. Each report in the series covers the performance of up to 31 linear LED lamps, which were purchased in late 2012 or 2013. Summaries of the evaluations covered in each report are as follows:

Application Summary Report 21: Linear (T8) LED Lamps (March 2014)[7]
This report focused on the bare-lamp performance of 31 linear LED lamps intended as alternatives to T8 fluorescent lamps. Data obtained in accordance with IES LM-79-08 indicated that the mean efficacy of the group was slightly higher than that of fluorescent lamps (with ballast), but that lumen output was often lower. The color quality of the linear LED lamps varied substantially, with many of the products having worse color quality than a typical fluorescent T8 lamp (e.g., CRI less than 80). One important finding was the range in luminous intensity distribution, with clear-optic lamps all having a beam angle less than 120°, and diffuse-optic lamps all having a beam angle above 126°. None of the lamps had an omnidirectional luminous intensity distribution similar to that of a linear fluorescent lamp.

Report 21.1: Linear (T8) LED Lamps in a 2×4 K12-Lensed Troffer (April 2014)[7]
This report focused on the performance of the 31 linear LED lamps operated in a typical troffer with a K12 prismatic lens. In general, luminaire efficacy was strongly dictated by lamp efficacy, but the optical system of the luminaire substantially reduced the differences between the luminous intensity distributions of the lamps. While the distributions in the luminaire were similar, the differences remained large enough that workplane illuminance uniformity could be reduced if linear LED lamps with a narrow distribution were used. At the same time, linear LED lamps with a narrower distribution resulted in slightly higher luminaire efficiency.

Report 21.2: Linear (T8) LED Lamp Performance in Five Types of Recessed Troffers (May 2014)[7]
Although lensed troffers are numerous, there are many other types of optical systems as well. This report looked at the performance of three linear (T8) LED lamps—chosen primarily based on their luminous intensity distributions (narrow, medium, and wide beam angles)—as well as a benchmark fluorescent lamp, in five different troffer types. Also included are the results of a subjective evaluation. Results show that linear (T8) LED lamps can improve luminaire efficiency in K12-lensed and parabolic-louvered troffers, effect little change in volumetric and high-performance diffuse-lensed type luminaires, but reduce efficiency in recessed indirect troffers. These changes can be accompanied by visual appearance and visual comfort consequences, especially when LED lamps with clear lenses and narrow distributions are installed. Linear (T8) LED lamps with diffuse apertures exhibited wider beam angles, performed more similarly to fluorescent lamps, and received better ratings from observers. Guidance is provided on which luminaires are the best candidates for retrofitting with linear (T8) LED lamps.

Report 21.3: Cost-Effectiveness of Linear (T8) LED Lamps
Meeting performance expectations is important for driving adoption of linear LED lamps, but cost-effectiveness may be an overriding factor in many cases. Linear LED lamps cost more initially than

[7] Available at: http://www1.eere.energy.gov/buildings/ssl/application-troffer.html

fluorescent lamps, but energy and maintenance savings may mean that the life-cycle cost is lower. This report details a series of life-cycle cost simulations that compared a two-lamp troffer using LED lamps (38 W total power draw) or fluorescent lamps (51 W total power draw) over a 10-year study period. Variables included LED system cost ($40, $80, or $120), annual operating hours (2,000 hours or 4,000 hours), LED installation time (15 minutes or 30 minutes), and melded electricity rate ($0.06/kWh, $0.12/kWh, $0.18/kWh, or $0.24/kWh). A full factorial of simulations allows users to interpolate between these values to aid in making rough estimates of economic feasibility for their own projects. In general, while their initial cost premium remains high, linear LED lamps are more likely to be cost-effective when electric utility rates are higher than average and hours of operation are long, and if their installation time is shorter.

In addition to these four technical reports, CALiPER will offer a concise guidance document that describes the findings of these studies and provides practical advice to manufacturers, specifiers, and consumers. As always, the applicability of general guidance to any specific application may vary. Further, the LED market is rapidly changing, meaning today's conclusions may or may not apply to products in the future. The performance and effectiveness of each lighting system should be evaluated on its own merits.

1 Background

The higher upfront costs of LED lamps may be offset by reduced electricity and maintenance costs over the long life of the LED lamps, eventually providing long-term savings. This report explores the life-cycle cost (LCC) and payback for linear (T8) LED lamps used as retrofit products in existing fluorescent troffers, which is likely the most frequent use scenario. The analysis considers multiple equipment costs, melded electricity rates, annual operating hours, and installation costs; although these cannot cover every application, they provide a framework where the financial benefit can be estimated for a wide variety of installations.

This economic analysis uses an LCC methodology consistent with that described in the National Institute of Standards and Technology's (NIST) Handbook 135, and energy price escalation rates from NIST's 2013 edition of its Annual Supplement to Handbook 135.[8] The analysis was used to model the present value life-cycle cost of a retrofit installation using an existing 2×4 troffer luminaire with new linear LED lamps, in comparison to a benchmark of a retrofit using a new high-efficiency T8 fluorescent lamp-and-ballast system. Both the fluorescent and LED scenarios are based on a 10-year analysis of each system's respective costs, including annualized spot-relamping costs. Their projected 10-year energy costs take into account projected real fluctuations in energy prices, and the analysis assumes a 3.0% real discount rate.

Life-Cycle Cost Analysis Assumptions

It is impossible to generate an analysis that applies to all scenarios where linear LED lamps might be used. Consequently, CALiPER established a hypothetical installation and made a series of assumptions for the comparison, including performance equivalency, equipment cost per two-lamp troffer, required labor, product lifetimes, annual hours of use, and electricity rate. Readers are encouraged to interpolate among the results to find the set of conditions that is most applicable to their specific application.

The LCC simulation was based on a retrofit project in an existing building, such as a school or commercial office. Labor and material costs were based on a project size of 200 T12- or T8-lamped troffers of the same type, although the results are reported for a single troffer; this allows for easier scaling of the data. Each two-lamp troffer was assumed to be in good working order, including the optical system and door frame.

There are four existing troffer lamp/ballast combinations likely to be found on such a project:

1. T12 fluorescent lamps and rapid-start ballast, either magnetic or electronic
2. T8 fluorescent lamps and rapid-start ballast, either magnetic or electronic[9]
3. T8 fluorescent lamps and older, standard-efficiency, instant-start electronic ballast
4. T8 fluorescent lamps and newer, high-efficiency, instant-start electronic ballast

In the first two cases, the rapid-start wiring and poor energy-efficiency performance of the older ballasts is likely to make a lamp/ballast or LED lamp retrofit economically viable. Although the older instant-start ballast of the third combination could be used in conjunction with new linear LED lamps, the inefficiency of the ballast could add 4 or more watts to the troffer's power draw. This may not be critical in areas where the cost of electricity is very low or in a facility with low operating hours, but in most applications it is wise to consider upgrading to a

[8] Available online at http://www.nist.gov/customcf/get_pdf.cfm?pub_id=907459, and https://www.nist.gov/node/579001, respectively.

[9] Rapid-start or programmed rapid-start electronic ballasts may have been originally specified for reasons such as prolonging lamp life when operated on circuits with frequent switching, or in dimming applications. In these cases, a satisfactory retrofit will require more extensive engineering.

higher efficiency ballast and T8 lamps, or an LED system. The least likely combination to be found is the fourth case, where a change to premium lower-wattage fluorescent lamps (if 32 W lamps are currently installed) is a simple and cost-effective option. The low initial cost of fluorescent lamps and minimal labor is likely to yield rapid energy savings with little change in appearance or function.

This LCC analysis focuses on the first three troffer lamp/ballast combinations because they are most common, and these offer the best opportunities for energy savings. This report examines both fluorescent and LED alternatives.

Performance Equivalency

For this BLCC study, CALiPER assumed the performance of the linear LED lamps was equivalent *in the troffer* to that of 28 W T8 fluorescent lamps operated on a high-efficiency (HE) electronic instant-start (IS) ballast. However, CALiPER Reports 21, 21.1, and 21.2 show that this is not yet the case for most of the LED lamps tested, although the performance of the linear LED lamps is expected to improve in the near future. For equivalent performance in most troffer types, an LED lamp would need to emit at least 1,800–1,900 lumens and exhibit a CRI in the 80s. Other performance qualities, such as a specific luminous intensity distribution, may be necessary for LED lamps to result in similar photometric performance and appearance in certain luminaire types.

For a truly accurate economic analysis, performance equivalency is required. However, perfectly equivalent performance is unlikely in any real installation. There are tradeoffs between costs and benefits, as well as advantages and disadvantages for any alternatives considered for a lighting retrofit. A product that reduces lighting quality or negatively affects light levels may not be appropriate, even if it is economically viable. For this evaluation, a two-lamp fluorescent system, with ballast, was assumed to consume 51 W with an approximate lamp/ballast system efficacy of 88 lm/W. In contrast, a two-lamp LED system was assumed to consume 38 W, which equates to an approximate lamp/driver system efficacy of 100 lm/W. These values were based on data from Application Summary Report 21. While other parameters in the analysis were variable, input power was not. A greater differential between the power draw of the LED and fluorescent systems will improve the relative cost-effectiveness of the LEDs, whereas a smaller differential will have the opposite effect.

Lamp and System Costs

Lamp costs vary widely according to how and through whom the lamps are purchased. Prices also vary regionally. LED lamp prices have been declining substantially, and are expected to continue declining for some time. For this analysis, CALiPER chose to assume tiers of linear LED lamp costs: $20, $40, and $60 per lamp, *including the external driver (or fluorescent ballast), if needed*. This covers a wide range of current and future scenarios. Fluorescent lamp and ballast costs were based on average commercial pricing information from Platt Electric in Tualatin, OR, for quantities of 100 or more, and including a 25% overhead and profit markup. Fluorescent lamp and ballast costs were then rounded up to the nearest $0.50, for a total of $6.50 per lamp, including $1/lamp end-of-life recycling fee, and $17 per ballast. Because the simulation assumed a two-lamp troffer, the initial system equipment costs are $30 for the fluorescent benchmark, and $40, $80, or $120 for the LED options.

This calculation assumes that after the initial equipment installation, a percentage of the products will have to be replaced per year, based on the estimated component life and hours of operation. The costs of the fluorescent ballasts and lamps were annualized individually, with each having a different rated lifetime. In contrast, the total LED cost was annualized as a system with a single lifetime. In some cases, such as remote driver products, the driver may be replaceable; this is not represented in this study, because replacement driver costs and lifetimes are difficult to determine, and future replaceability is not guaranteed. This calculation assumes that LED lamp and driver (whether integral, separate, or used in conjunction with a fluorescent ballast) will have the same rated life, and that they will be replaced at the same time.

Required Labor and Labor Rate

The electrical work was assumed to include any necessary wiring changes to accommodate the new lamps, including the rewiring of the original fluorescent sockets. For the fluorescent system, it was assumed that the existing system would be replaced with new, high-efficiency instant-start ballast and two F28/T8/XL/ECO fluorescent lamps, requiring approximately 15 minutes for installation.

As documented in CALiPER Application Summary Report 21, there are numerous configurations for linear LED lamps, and installation times can vary based on the required work and the contractor. Four LED retrofit scenarios were considered in order to establish an appropriate range of installation times for use in the LCC calculations. Labor hour estimates were received from a commercial electrical contractor in Richland, WA. Electrical labor costs vary widely, but CALiPER assumed an average rate of $65/hour for an electrician to perform the retrofit work.[10] The configurations considered include:

- Two linear LED lamps designed to operate on an instant-start fluorescent ballast. If a new instant-start high-efficiency ballast is required, the material cost is included in the cost of the LED lamps (approximately 15 minutes labor)
- Two linear LED lamps with integral drivers, that are wired directly with mains voltage, either replacing sockets or rewiring existing sockets for the appropriate wiring configuration (approximately 30 minutes labor)
- Two linear LED lamps with remote drivers, either replacing sockets or rewiring existing sockets for the appropriate wiring configuration (approximately 30 minutes labor)
- Two linear LED lamps that are supported and powered without fluorescent sockets (approximately 30 minutes labor).

Note that the simulation assumes that the ballast of the existing troffer is not reused. In the event that the existing troffer uses T12 lamps, the ballast could not be used for either T8 fluorescent or LED options. In the event the existing troffer uses a rapid-start ballast or an inefficient, older T8 instant-start ballast, the ballast would have to be replaced to achieve a high level of efficiency. If the ballast is fairly new and is a high-efficiency instant-start T8 fluorescent ballast, then no new ballast would be required if using 28 W T8 fluorescent lamps or linear LED lamps that operate on an instant-start fluorescent ballast. This LCC simulation assumes a new ballast is required for the fluorescent option, and if a new ballast is required for a linear LED lamp, the material cost is included in the total system cost.

Although CALiPER considered four unique types of LED retrofit in addition to the fluorescent lamp and ballast retrofit, the approximations for labor time listed above were all either 30 minutes or 15 minutes, and these values were used in the LCC simulations. The actual labor time will vary according to the type of existing system (T8 versus T12, type and efficiency level of ballast, instant-start versus rapid-start wiring to sockets, the accessibility of the socket wiring, etc.) and the exact configuration and wiring requirements of the linear LED lamps.

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[10] Source: RS Means Electrical Data, 2013. Average hourly rate for an electrician, including 25% overhead and profit. No site or location factors have been applied.

Lifetime

The fluorescent lamps were assumed to have an average rated lamp life of 36,000 hours at 3 hours per start, and ballast life was assumed to be 60,000 hours, both with spot-relamping of failures. The proposed linear LED lamps and remote electronics, if applicable, were assumed to have an average life of 50,000 hours and be spot-replaced together when they fail, including any electronics included in the LED system. There is no recycling fee associated with the linear LED lamps. Replacement lamp and relamping labor costs were annualized for both LED and fluorescent alternatives over the 10-year study period. No residual value was assumed at the end of the analysis period.

Annual Hours of Use and Annual Lamp Replacement Assumptions

In order to test economic viability, this LCC analysis assumed 2,000 annual operating hours (similar to usage in many schools), or 4,000 annual operating hours (similar to usage in some offices and factories). While the LED lamps are not expected to require any maintenance or to fail during the 10 years of life-cycle analysis, CALiPER conservatively assumed the number of annual lamp replacements using the following equation:

$$\text{Annual number of lamp replacements} = \frac{\text{Number lamps per troffer} \times 2{,}000 \text{ or } 4{,}000 \text{ hours operation per year}}{\text{Rated lamp life}}$$

At 2,000 hours, this resulted in 0.11 fluorescent lamps and 0.08 linear LED lamps required per year. At 4,000 operating hours, the number of replacements was 0.22 fluorescent lamps and 0.16 linear LED lamps required per year.

Electricity Rates

In the United States, commercial electricity prices vary greatly from state to state and region to region. As a reference point, the U.S. Energy Information Administration publishes the *Average Retail Price of Electricity to Ultimate Customers by End-Use Sector by State*.[11] The national average retail price of electricity to ultimate commercial customers in January 2014 was approximately $0.1034/kWh, and commercial electricity prices ranged from a high of $0.3492/kWh in Hawaii to a low of $0.0726/kWh in Idaho.[12] CALiPER ran LCC models at low, average, moderately high, and high melded rates of $0.06/kWh, $0.12/kWh, $0.18/kWh, and $0.24/kWh. In general, LEDs are more likely to be economically viable in places where electricity costs are high enough that the energy savings they generate contribute significantly to paying back the high initial cost of LED products. Readers are encouraged to run LCC analyses with their specific local electric rates, taking demand charges and peak rates into account, rather than a melded rate. This requires making assumptions on how many hours of operation will take place during peak demand hours, often for both winter and summer.

[11] Available online at http://www.eia.gov/cneaf/electricity/epm/chap5.pdf.

[12] Available online at http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

2 Results and Analysis

Appendix A shows a spreadsheet of cost and energy use data that was input for the benchmark T8 fluorescent option, compared to a linear LED alternative estimated at 15 minutes labor. Similarly, Appendix B shows the same type of data, but for a linear LED alternative estimated at 30 minutes of installation labor. Not all permutations of labor hours, annual operating hours, linear LED lamp cost, and melded electric rates are shown in Appendices A and B, but all were included in the LCC calculations.

Table 1 summarizes the initial component costs for the benchmark fluorescent alternative and the linear LED options, which vary based on equipment cost and installation time but are the same regardless of the annual operating hours. As shown, the initial capital costs are higher for any of the LED options than for the fluorescent option. Table 2 summarizes maintenance costs, which vary based on the equipment cost and annual operating hours, but not based on the initial installation time. That is, maintenance costs include the annualized lamp and ballast cost for fluorescent, or the annualized LED system cost, with a 10-minute labor time spot-replacement cost for each fluorescent lamp, fluorescent ballast, or LED system change. At higher LED equipment prices ($80 and $120 per two-lamp troffer), the LEDs exhibited present value maintenance costs ranging from roughly 46% to 105% higher than the fluorescent. However, at $40 per troffer, the linear LED maintenance costs are equivalent or lower, thanks to the longer lifetime of the LED systems.

Table 3 summarizes the annual energy use and 10-year totals for the theoretical fluorescent and LED systems, based on 2,000 and 4,000 annual operating hours. In both cases, the linear LED (assumed to draw 38 W total per luminaire) reduces energy use, and energy cost compared to the fluorescent benchmark (assumed to draw 51 W per luminaire), because of its lower power draw.

Based on the annual energy use shown in Table 3, Table 4 summarizes energy costs for the benchmark fluorescent and linear LED options at electricity rates of $0.06, $0.12, $0.18, and $0.24 per kWh, and at 2,000 and 4,000 annual operating hours. The table includes both the first-year and 10-year costs per troffer.

Table 1. Initial capital costs based on equipment cost and labor time. In all cases, the LED systems have a higher initial cost than the fluorescent benchmark (FL). Red indicates a higher cost than the fluorescent (FL) benchmark.

Source Type:	**FL**	**LED**					
Equipment Cost Per Troffer:	**$30**	**$40**		**$80**		**$120**	
Installation Labor Time (minutes):	**15**	**15**	**30**	**15**	**30**	**15**	**30**
Initial Capital Costs for All Components:	$46.25	$56.25	$72.50	$96.25	$112.50	$136.25	$152.50

Table 2. Maintenance costs based on annual operating hours and equipment replacement cost. At higher costs ($80 and $120 per fixture), the linear LEDs have higher maintenance costs than the benchmark fluorescent (FL); these values are indicated in red. However, at lower costs ($40 per troffer), linear LED systems have a lower maintenance cost than the comparable fluorescent system; these values are shown in green.

Source Type:	**FL**		**LED**					
Equipment Cost Per Fixture:	**$30**		**$40**		**$80**		**$120**	
Annual Operating Hours:	**2,000**	**4,000**	**2,000**	**4,000**	**2,000**	**4,000**	**2,000**	**4,000**
Present Value:	$23.32	$46.63	$20.47	$40.94	$34.12	$68.24	$47.77	$95.54
Annual Value:	$2.73	$5.47	$2.40	$4.80	$4.00	$8.00	$5.60	$11.20

Table 3. **Annual energy use, 10-year energy savings.** Discount rate is 3%, discounting convention is end-of-year, and study period is 10 years.

Annual Operating Hours:	2,000		4,000	
Source Type:	**FL**	**LED**	**FL**	**LED**
Average Annual Electrical Energy Usage:	102 kWh	76 kWh	204 kWh	152 kWh
Total (10-year) Energy Savings from LED Lamping:	-	260 kWh	-	520 kWh

Table 4. **Energy costs based on electricity rate and annual operating hours.** At all electric rates, ranging from $0.06 to $0.24 per kWh, the average linear LED system shows lower energy costs, approximately 25% less than the present value energy costs of the fluorescent (FL) system.

	Melded Electricity Rate:	0.06/kWh		0.12/kWh		0.18/kWh		0.24/kWh	
	Source Type:	**FL**	**LED**	**FL**	**LED**	**FL**	**LED**	**FL**	**LED**
2,000 hours	First Year:	$6.12	$4.56	$12.24	$9.12	$18.36	$13.68	$24.48	$18.24
	Present Value:	$52.99	$39.48	$105.98	$78.96	$158.97	$118.45	$211.96	$157.93
4,000 hours	First Year:	$12.24	$9.12	$24.48	$18.24	$36.72	$27.36	$48.96	$36.48
	Present Value:	$105.98	$78.96	$211.96	$157.93	$317.94	$236.89	$423.91	$315.86

Tables 5 and 6 summarize life-cycle cost calculations for 2,000 annual operating hours and 4,000 annual operating hours, respectively. Each table is further subdivided into four groups, based on melded electric rates of $0.06, $0.12, $0.18, and $0.24 per kWh. The tables compare four basic economic metrics for the baseline fluorescent and linear LED options. Red values indicate that the LED option is less economical over the 10-year study period than the fluorescent benchmark. If the Savings-to-Investment Ratio (SIR) is greater than 1, then the linear T8 LED option is considered more economical.

At 2,000 annual operating hours, a $40 per two-lamp troffer LED system consuming 38 W is cost-effective versus the alternative of a new high-efficiency fluorescent system for all but one combination of electric rates and installation times. For the cost-effective cases, simple payback ranges from 1 to just under 7 years. At $80 or more per two-lamp troffer LED system, the life-cycle cost analysis does not show economic benefit, even at the highest electric rates. The LED system saved at most 17% in present-value total life-cycle cost, compared to the benchmark T8 fluorescent system, and increased the present value LCC cost by as much as 96%.

At 4,000 annual operating hours, the results are more favorable for the LED lamps. At $40 per two-lamp troffer, for an LED system consuming 38 W, simple payback occurs within the 10-year study period for all combinations of electric rates and installation times, versus the alternative of a new high-efficiency fluorescent system. At $80 per two-lamp troffer, electric rates need to be at least $0.18/kWh to achieve life-cycle cost-effectiveness. At $120 per two-lamp troffer, there is no cost-effective case when rates are at $0.24/kWh or below. The LED system saved at most 20% in present-value total life-cycle cost compared to the benchmark T8 fluorescent system, and increased the present value LCC system cost by up to 64%.

Table 5. Life-cycle cost analysis based on 2,000 annual operating hours. Red indicates worse economic performance than the fluorescent (FL) benchmark, green indicates better economic performance.

Melded Electricity Rate:	**$0.06/kWh**							**$0.12/kWh**						
Source Type:	**FL**	**LED**						**FL**	**LED**					
Equipment Cost Per Fixture:	**$30**	**$40**		**$80**		**$120**		**$30**	**$40**		**$80**		**$120**	
Installation Time (minutes):	**15**	**15**	**30**	**15**	**30**	**15**	**30**	**15**	**15**	**30**	**15**	**30**	**15**	**30**
Present Value, Total LCC:	$122.56	$116.20	$132.45	$169.85	$186.10	$223.50	$239.75	$175.54	$155.69	$171.94	$209.34	$225.59	$262.98	$279.23
Annual Value, Total LCC:	$14.37	$13.62	$15.53	$19.91	$21.82	$26.20	$28.11	$20.58	$18.25	$20.16	$24.54	$26.45	$30.83	$32.73
SIR:	-	1.64	0.62	0.05	0.04	-0.12	-0.10	-	2.99	1.14	0.32	0.24	0.03	0.02
Simple Payback (Years):	-	5.28	>10	>10	>10	>10	>10	-	2.90	7.60	>10	>10	>10	>10

Melded Electricity Rate:	**$0.18/kWh**							**$0.24/kWh**						
Source Type:	**FL**	**LED**						**FL**	**LED**					
Equipment Cost Per Fixture:	**$30**	**$40**		**$80**		**$120**		**$30**	**$40**		**$80**		**$120**	
Installation Time (minutes):	**15**	**15**	**30**	**15**	**30**	**15**	**30**	**15**	**15**	**30**	**15**	**30**	**15**	**30**
Present Value, Total LCC:	$228.53	$195.17	$211.42	$248.82	$265.07	$302.47	$318.72	$281.52	$234.65	$250.90	$288.30	$304.55	$341.95	$358.20
Annual Value, Total LCC:	$26.79	$22.88	$24.78	$29.17	$31.07	$35.46	$37.36	$33.00	$27.51	$29.41	$33.80	$35.70	$40.09	$41.99
SIR:	-	4.34	1.65	0.59	0.45	0.18	0.15	-	5.69	2.17	0.86	0.65	0.33	0.28
Simple Payback (Years):	-	1.99	5.24	>10	>10	>10	>10	-	1.52	3.99	>10	>10	>10	>10

Table 6. Life-cycle cost analysis based on 4,000 annual operating hours. Red indicates worse economic performance than the fluorescent (FL) benchmark, green indicates better economic performance.

Melded Electricity Rate:	**$0.06/kWh**							**$0.12/kWh**						
Source Type:	**FL**	**LED**						**FL**	**LED**					
Equipment Cost Per Fixture:	**$30**	**$40**		**$80**		**$120**		**$30**	**$40**		**$80**		**$120**	
Installation Time (minutes):	**15**	**15**	**30**	**15**	**30**	**15**	**30**	**15**	**15**	**30**	**15**	**30**	**15**	**30**
Present Value, Total LCC:	$198.86	$176.16	$192.41	$243.46	$259.71	$310.75	$327.00	$304.84	$255.12	$271.37	$322.42	$338.67	$389.72	$405.97
Annual Value, Total LCC:	$23.31	$20.65	$22.56	$28.54	$30.45	$36.43	$38.33	$35.74	$29.91	$31.81	$37.80	$39.70	$45.69	$47.59
SIR:	-	3.27	1.25	0.11	0.08	-0.24	-0.21	-	5.97	2.27	0.65	0.49	0.06	0.05
Simple Payback (Years):	-	2.64	6.93	>10	>10	>10	>10	-	1.45	3.80	>10	>10	>10	>10

Melded Electricity Rate:	**$0.18/kWh**							**$0.24/kWh**						
Source Type:	**FL**	**LED**						**FL**	**LED**					
Equipment Cost Per Fixture:	**$30**	**$40**		**$80**		**$120**		**$30**	**$40**		**$80**		**$120**	
Installation Time (minutes):	**15**	**15**	**30**	**15**	**30**	**15**	**30**	**15**	**15**	**30**	**15**	**30**	**15**	**30**
Present Value, Total LCC:	$410.82	$334.09	$350.34	$401.38	$417.63	$468.68	$484.93	$516.80	$413.05	$429.30	$480.35	$496.60	$547.65	$563.90
Annual Value, Total LCC:	$48.16	$39.17	$41.07	$47.05	$48.96	$54.94	$56.85	$60.58	$48.42	$50.33	$56.31	$58.22	$64.20	$66.11
SIR:	-	8.67	3.30	1.19	0.90	0.36	0.30	-	11.37	4.33	1.73	1.30	0.66	0.56
Simple Payback (Years):	-	1.00	2.62	7.32	9.70	>10	>10	-	0.76	2.00	5.03	6.66	>10	>10

How to use this LCC information

The reader is encouraged to use the following steps to apply this information to a specific retrofit project:

- Determine the characteristics of the existing troffers (make and model of the troffer, T8 or T12, type and efficiency level of ballast, instant-start or rapid-start wiring to sockets, the accessibility of the socket wiring, etc.). This information is often needed to identify linear LED lamps that are compatible for the retrofit, and to determine whether the ballast can be reused for the retrofit system.
- Identify the make and model of the candidate linear LED lamps (or new fluorescent lamps) for evaluation. It is important to know the exact configuration and wiring requirements of the linear LED lamps. Request an equipment cost for the project, including lamp, driver, and ballast (if required)..
- Procure enough samples of the candidate lamp for an electrician to modify at least two troffers in the facility.
- Hire an experienced electrical contractor or experienced facility electrician to retrofit the two troffers, and estimate the time required per troffer when the total labor time is averaged across the total number of troffers to be modified. Use the labor estimate column that most closely matches the per-troffer labor estimate (either 15 minutes or 30 minutes).
- Using a recent electric utility bill, determine the facility's melded electric rate.
- Estimate the hours of use in the facility.
- Using the per-fixture lamp price, annual operation hours, estimated installation labor time, and melded electric rate, use Table 5 or 6 to estimate per-troffer LCC economic metrics. Some interpolation may be required. If values such as power draw for an equivalent-performance LED system are substantially different, a new analysis may be necessary.

3 Conclusions

There are many factors to take into account in determining whether an LED system is cost-effective for a given site. This report focused only on the initial investment, energy use, energy price, and system lifetime/replacement needs. In general, while their initial cost premium remains high, linear LED lamps are more likely to be cost-effective when electric utility rates are higher than average and hours of operation are long, and if their installation time is shorter. Linear LED lamps may also be more cost-effective if maintenance costs are high, such as occurs when the luminaires are difficult to access, but this was not a variable in this analysis. Other factors could also affect the calculation of value and payback, such as embedded energy cost or the cost of increased waste. At this point, these factors are difficult to quantify and vary according to location, so most were not included in this analysis.

Although it was not a variable in this analysis, reducing the system power draw would increase the cost-effectiveness of the LED system compared to the fluorescent system. On the other hand, reusing existing fluorescent ballasts, or installing longer-life T8 fluorescent lamps, would reduce the amount of savings provided by using linear LED lamps. In short, the cost-effectiveness of retrofits should always be considered on a case-by-case basis.

In the specific scenarios evaluated by CALiPER, at 2,000 annual operating hours, a $40 per two-lamp troffer LED system consuming 38 W was cost-effective at all electric rates as long as the installation time is 15 minutes or less, versus the alternative of a new high-efficiency fluorescent system. (At 30 minutes installation time, the LED lamps were only cost effective at the higher melded electric rates.) At $80 to $120 per two-lamp LED troffer system, the life-cycle cost analysis did not show economic benefit. The LED system saved at most 17% in present-value total life-cycle cost compared to the benchmark T8 fluorescent system, and increased the present value LCC system cost by up to 96%.

At 4,000 annual operating hours, the results were more favorable for the LED lamps. At $40 per two-lamp troffer, for an LED system consuming 38 W, simple payback occurred within the 10-year study period for all four electric rates, versus the alternative of a new high-efficiency fluorescent system. At $80 per two-lamp troffer, electric rates need to be at least $0.18/kWh to achieve life-cycle cost-effectiveness. At $120 per two-lamp troffer, there is no cost-effective case when electric rates are at or below $0.24/kWh. The LED system saved at most 20% in present-value total life-cycle cost compared to the benchmark T8 fluorescent system, and increased the present value LCC system cost by up to 64%.

Appendix A: Input Cost and Energy Use Data (15 Minute LED Installation)

Replacing existing fluorescent troffer's lamps and ballast with either 2F28T8 premium lamps with HE IS electronic ballast (15 min labor) OR with linear (T8) LED lamps with HE IS ballast (15 min labor)

	Fluorescent baseline and Linear LED lamp and ballast/driver components for costs	Lamp Qty	Ballast Qty	Lamp and ballast designation	Rated Life (hours)	Watts	Operating hours per year	Total Annual Energy Use (kWh)	Lamp Cost	Initial cost for lamps	Initial ballast cost at $17 per ballast	Labor cost for initial installation ($65/hr)	Initial installation cost, components + labor	Number of replacement lamps needed per year	Number of replacement ballasts needed per year	Annualized lamp and ballast replacement cost	Annual spot replacement labor cost, at $10 per lamp or ballast	Annual spot relamping, and lamp and ballast cost	Annual energy cost
$0.06/kWh, 2000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	2000	102.00	$6.50	$ 13.00		$8.13	$ 21.13	0.11		$ 0.72	$ 1.11	$ 1.83	$ 6.12
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		2000				$ 17.00	$8.13	$ 25.13		0.03	$ 0.57	$ 0.33	$ 0.90	
	TOTALS	**2**	**1**					**102.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 2.73**	**$ 6.12**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	2000	76.00	$20.00	$ 40.00		$ 16.25	$ 56.25	0.08		$ 1.60	$ 0.80	$ 2.40	$ 4.56
	TOTALS	**2**	**1**					**76.00**		**$ 40.00**	**$ -**	**$ 16.25**	**$ 56.25**					**$ 2.40**	**$ 4.56**
$0.06/kWh, 4000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	4000	204.00	$6.50	$ 13.00		$8.13	$ 21.13	0.22		$ 1.44	$ 2.22	$ 3.67	$ 12.24
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		4000				$ 17.00	$8.13	$ 25.13		0.07	$ 1.13	$ 0.67	$ 1.80	
	TOTALS	**2**	**1**					**204.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 5.47**	**$ 12.24**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	4000	152.00	$20.00	$ 40.00		$ 16.25	$ 56.25	0.16		$ 3.20	$ 1.60	$ 4.80	$ 9.12
	TOTALS	**2**	**1**					**152.00**		**$ 40.00**	**$ -**	**$ 16.25**	**$ 56.25**					**$ 4.80**	**$ 9.12**
$0.12/kWh, 2000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	2000	102.00	$6.50	$ 13.00		$8.13	$ 21.13	0.11		$ 0.72	$ 1.11	$ 1.83	$ 12.24
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		2000				$ 17.00	$8.13	$ 25.13		0.03	$ 0.57	$ 0.33	$ 0.90	
	TOTALS	**2**	**1**					**102.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 2.73**	**$ 12.24**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	2000	76.00	$20.00	$ 40.00		$ 16.25	$ 56.25	0.08		$ 1.60	$ 0.80	$ 2.40	$ 9.12
	TOTALS	**2**	**1**					**76.00**		**$ 40.00**	**$ -**	**$ 16.25**	**$ 56.25**					**$ 2.40**	**$ 9.12**
$0.12/kWh, 4000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	4000	204.00	$6.50	$ 13.00		$8.13	$ 21.13	0.22		$ 1.44	$ 2.22	$ 3.67	$ 24.48
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		4000				$ 17.00	$8.13	$ 25.13		0.07	$ 1.13	$ 0.67	$ 1.80	
	TOTALS	**2**	**1**					**204.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 5.47**	**$ 24.48**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	4000	152.00	$20.00	$ 40.00		$ 16.25	$ 56.25	0.16		$ 3.20	$ 1.60	$ 4.80	$ 18.24
	TOTALS	**2**	**1**					**152.00**		**$ 40.00**	**$ -**	**$ 16.25**	**$ 56.25**					**$ 4.80**	**$ 18.24**

Figure 1. Cost and energy use data of a benchmark 28 W T8 fluorescent lamp and linear LED system, estimated to have an installation time of 15 minutes, used in the LCC analysis. Installation labor time is estimated at 15 minutes for both options. The cost of any electronics associated with the initial installation of the LED system is assumed to be included in the lamp cost.

Appendix B: Input Cost and Energy Use Data (30 Minute LED Installation)

Replacing existing fluorescent troffer's lamps and ballast with either 2F28T8 premium lamps with HE IS electronic ballast (15 min labor) OR linear (T8) LED lamps with mains voltage wiring, remote drivers, or LED lamp kit with no reuse of sockets (30 min labor)

Scenario	Fluorescent baseline and Linear LED lamp and ballast/driver components for costs	Lamp Qty	Ballast Qty	Lamp and ballast designation	Rated Life (hours)	Watts	Operating hours per year	Total Annual Energy Use (kWh)	Lamp Cost	Initial cost for lamps	Initial ballast cost at $17 per ballast	Labor cost for initial installation ($65/hr)	Initial installation cost, components + labor	Number of replacement lamps needed per year	Number of replacement ballasts needed per year	Annualized lamp and ballast replacement cost	Annual spot replacement labor cost, at $10 per lamp or ballast	Annual spot relamping, and lamp and ballast cost	Annual energy cost
$0.06/kWh, 2000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	2000	102.00	$6.50	$ 13.00		$8.13	$ 21.13	0.11		$ 0.72	$ 1.11	$ 1.83	$ 6.12
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		2000				$ 17.00	$8.13	$ 25.13		0.03	$ 0.57	$ 0.33	$ 0.90	
	TOTALS	**2**	**1**					**102.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 2.73**	**$ 6.12**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	2000	76.00	$20.00	$ 40.00		$ 32.50	$ 72.50	0.08		$ 1.60	$ 0.80	$ 2.40	$ 4.56
	TOTALS	**2**	**1**					**76.00**		**$ 40.00**		**$ 32.50**	**$ 72.50**					**$ 2.40**	**$ 4.56**
$0.06/kWh, 4000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	4000	204.00	$6.50	$ 13.00		$8.13	$ 21.13	0.22		$ 1.44	$ 2.22	$ 3.67	$ 12.24
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		4000				$ 17.00	$8.13	$ 25.13		0.07	$ 1.13	$ 0.67	$ 1.80	
	TOTALS	**2**	**1**					**204.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 5.47**	**$ 12.24**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	4000	152.00	$20.00	$ 40.00		$ 32.50	$ 72.50	0.16		$ 3.20	$ 1.60	$ 4.80	$ 9.12
	TOTALS	**2**	**1**					**152.00**		**$ 40.00**		**$ 32.50**	**$ 72.50**					**$ 4.80**	**$ 9.12**
$0.12/kWh, 2000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	2000	102.00	$6.50	$ 13.00		$8.13	$ 21.13	0.11		$ 0.72	$ 1.11	$ 1.83	$ 12.24
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		2000				$ 17.00	$8.13	$ 25.13		0.03	$ 0.57	$ 0.33	$ 0.90	
	TOTALS	**2**	**1**					**102.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 2.73**	**$ 12.24**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	2000	76.00	$20.00	$ 40.00		$ 32.50	$ 72.50	0.08		$ 1.60	$ 0.80	$ 2.40	$ 9.12
	TOTALS	**2**	**1**					**76.00**		**$ 40.00**		**$ 32.50**	**$ 72.50**					**$ 2.40**	**$ 9.12**
$0.12/kWh, 4000 hrs, $20/LED	**F28T8/841/ECO FL**																		
	One K12 Troffer - lamps	2	1	F28T8/841/ECO	36000	26	4000	204.00	$6.50	$ 13.00		$8.13	$ 21.13	0.22		$ 1.44	$ 2.22	$ 3.67	$ 24.48
	One K12 Troffer - ballast	0	1	IOPA2P32N	60000		4000				$ 17.00	$8.13	$ 25.13		0.07	$ 1.13	$ 0.67	$ 1.80	
	TOTALS	**2**	**1**					**204.00**		**$ 13.00**	**$ 17.00**	**$ 16.25**	**$ 46.25**					**$ 5.47**	**$ 24.48**
	Average T8 LED lamp																		
	One K12 Troffer - lamps	2	1	Mean LED lamp	50000	19	4000	152.00	$20.00	$ 40.00		$ 32.50	$ 72.50	0.16		$ 3.20	$ 1.60	$ 4.80	$ 18.24
	TOTALS	**2**	**1**					**152.00**		**$ 40.00**		**$ 32.50**	**$ 72.50**					**$ 4.80**	**$ 18.24**

Figure 2. Cost and energy use data of a benchmark 28 W T8 fluorescent lamp and linear LED system, estimated to have an installation time of 30 minutes, used in the LCC analysis. The cost of any electronics associated with the initial installation of the LED system is assumed to be included in the lamp cost.

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