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SSL Pricing and Efficacy Trend Analysis for Utility Program Planning

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DISCLAIMER

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COMMENTS

PNNL and the U.S. Department of Energy are interested in receiving feedback on the material presented in this report. Please direct any questions or comments to jason.tuenge@pnnl.gov.

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Acronyms and Abbreviations

$/klm	dollars per kilolumen
$/klm-h	dollars per kilolumen-hour
1x4	one foot by four feet in dimension (nominal)
2x2	two feet by two feet in dimension (nominal)
2x4	two feet by four feet in dimension (nominal)
avg	average
BBA	Better Buildings Alliance
CBCP	center-beam candlepower
CFL	compact fluorescent lamp
CFR	Code of Federal Regulations
CMH	ceramic metal halide
CSA	Canadian Standards Association
DLC	DesignLights Consortium
DOE	U.S. Department of Energy
eCMH	electronically-ballasted ceramic metal halide
EISA	Energy Independence and Security Act
ES	ENERGY STAR
FEMP	Federal Energy Management Program
HID	high-intensity discharge
HIR	halogen infrared
HPS	high-pressure sodium
IES	Illuminating Engineering Society of North America
klm	kilolumen (i.e., thousand lumens)
LED	light emitting diode
LF	LED Lighting Facts
lm	lumen(s)
lm/W	lumens per watt
LMT	Lighting Market Transformation
max	maximum
min	minimum
MSSLC	Municipal Solid-State Street Lighting Consortium
MYPP	DOE SSL R&D Multi-Year Program Plan
PNNL	Pacific Northwest National Laboratory
R^2	coefficient of determination
SCL	Seattle City Light
SSL	solid-state lighting
TWh	terawatt-hour(s)
W	watt(s)

1.0 Executive summary

This report represents a first step toward addressing needs identified during the April 2012 U.S. Department of Energy (DOE) Technical Information Network for Solid-State Lighting (TINSSL) Utility Planning Roundtable. The roundtable participants agreed that a roadmap was needed to forecast the order in which important SSL product applications will become cost-effective, and estimate when each "tipping point" will be reached, looking two to three years forward. It was thought this roadmap might include performance trend analysis from the LED Lighting Facts and CALiPER programs, plus cost analysis from various sources. Application-specific projections could provide time for planning, enable prioritization by application or product category, inform delivery and education approaches, and allow estimation of energy savings potential and appropriate incentive levels to overcome price barriers.

An LED lamp or luminaire can generally be found that matches or exceeds the efficacy of benchmark technologies in a given product category, and LED products continue to expand into ever-higher lumen output niches. However, the price premium for LED continues to pose a barrier to adoption in many applications, in spite of expected savings from reduced energy use and maintenance. Other factors—such as dimmability and quality of light—can also present challenges.

The appropriate type, timing, and magnitude of energy efficiency activities will vary from organization to organization based on local variables and the method of evaluation. A number of factors merit consideration when prioritizing activities for development. Category-specific projections for pricing and efficacy are provided herein to assist in efficiency program planning efforts. Following is a summary of key findings from the analysis:

- Average efficacy for LED lamps and LED luminaires is projected to remain well below L Prize and DOE SSL R&D Multi-Year Program Plan (MYPP) thresholds through 2017, but given the high variability among products and the performance potential of new color mixing technologies, these goals might soon be met by leading products;
- In several key LED product categories (omnidirectional lamps, decorative lamps, downlight luminaires, and troffer luminaires) projected efficacies based on LED Lighting Facts listings are substantially higher than projections based on the corresponding ENERGY STAR or DesignLights Consortium (DLC) listings;
- Comparison of historical data compiled by CALiPER and Seattle City Light indicates two distinct normalized curves—one for LED lamps, and one for LED luminaires—can be used to make projections from current $/klm pricing for a given product category;
- LED lamp $/klm pricing is expected to decrease roughly 55% by 2017, relative to current pricing—a more modest decrease of 30% is projected for LED luminaires over this same period.

This report is intended to serve as a starting point—to be updated, detailed, and expanded in subsequent reports as appropriate based on input from utilities and energy efficiency organizations. For example, additional CALiPER data for LED troffer upgrade products—ranging from lamps to kits and luminaires—will soon be published and may enable additional trend analysis.

2.0 Introduction

This report represents a first step toward addressing needs identified during the April 2012 U.S. Department of Energy (DOE) Technical Information Network for Solid-State Lighting (TINSSL) Utility Planning Roundtable. Meeting participants included representatives from American Electric Power, British Columbia (BC) Hydro, ComEd Energy Efficiency Services, DTE Energy, Duke Energy, Efficiency Vermont, Energy Futures Group, Energy Trust of Oregon, Franklin Energy Services, Hydro Quebec, Long Island Power Authority, MidAmerican Energy, Midwest Energy Efficiency Alliance, New York State Energy Research and Development Authority (NYSERDA), Northeast Energy Efficiency Partnerships (NEEP), Northwest Energy Efficiency Alliance (NEEA), Pacific Gas & Electric (PG&E), Sacramento Municipal Utility District (SMUD), San Diego Gas & Electric, Southern California Edison (SCE), Tennessee Valley Authority, The United Illuminating Company, Wisconsin Public Service, and Xcel Energy.

The roundtable participants agreed that a roadmap was needed to forecast the order in which important SSL product applications will become cost-effective, and estimate when each "tipping point" will be reached, looking two to three years forward. It was thought this roadmap might include cost analysis, supplemented by performance trend analysis based on data from programs such as the following:

- LED Lighting Facts (LF, www.lightingfacts.com). The DOE's LF program maintains a searchable database of LED product performance data. Participating manufacturers must submit industry-standard test data supporting performance claims, but products are not held to specific thresholds.
- ENERGY STAR (ES, www.energystar.gov). ES-certified LED products must satisfy criteria in specifications developed by the program, and corresponding product performance data are published in a searchable database. ES covers many types of LED replacement lamps, as well as some categories of LED luminaires, primarily residential and decorative types. Notably, there is some overlap between the LF and ES datasets.
- DesignLights Consortium (DLC, www.designlights.org). DLC-qualified LED products must satisfy criteria developed by the program, and corresponding product performance data are published in a searchable database. The DLC covers a number of commercial lighting product categories not presently addressed by ES, although both programs include track lighting. In addition, there is substantial overlap between the LF and DLC datasets—see the DLC website for details.
- CALiPER (www.ssl.energy.gov/caliper.html). Since 2006, the DOE's CALiPER program has generated and reported independent test data for a wide variety of anonymously-acquired LED products for general illumination, including some from the LF, ES, and DLC datasets. CALiPER also conducts limited benchmark testing.

Participants indicated that DOE was viewed as a credible source of such data for regulatory review, and suggested that DOE might model the approach after recent collaborative work by the Lighting Market Transformation program, a group of California utilities focusing on key applications for maximum impact and minimal duplication of effort.[1,2] Application-specific projections could provide time for planning, enable prioritization by application or category, inform delivery and education approaches, and allow estimation of energy savings potential and appropriate incentive levels to overcome price barriers.[3]

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3.0 Energy savings potential in specific applications

DOE has published four reports over the past decade characterizing LED performance and potential in specific applications where the technology is having the greatest energy savings impact, as detailed in Table 3.1.[4,5,6,7] In the latest of these reports, *Adoption of Light-Emitting Diodes in Common Lighting Applications* (2013 Adoption), these applications were first broken down into three product types: indoor lamps, indoor luminaires, and outdoor luminaires. These types were then subdivided to enable differentiation between distinct product categories.

Table 3.1 DOE targeted applications for white-light LEDs

Type	Category	Year of DOE publication			
		2003	2008	2011	2013
Indoor lamps	**A lamps**			•	•
	Directional (PAR, R, BR) lamps			•	•
	MR16 lamps			•	•
	Decorative lamps				•
Indoor luminaires	*Refrigerated display case lighting*	•	•		
	Retail display lighting		•		
	Portable task lights		•		
	Undershelf/undercabinet luminaires		•		
	Downlight luminaires		•		•
	Troffers et al. (includes other linear fluor.)			•	•
	High-bay luminaires (includes fluorescent)				•
Outdoor luminaires	*Step, path, and porch lighting (residential)*		•	•	
	Area/parking/flood lighting		•	•	•
	Street/roadway lighting		•	•	•

Of these categories only refrigerated display case lighting was addressed in the 2003 report, and this category was among a handful of others (retail display, task, undershelf/undercabinet) that were not specifically addressed after 2008. LED market penetration in refrigerated display case applications was estimated at 3.6% in the 2007 report, versus 0.0% for the other white-light applications evaluated in the 2008 report, and this category (including the existing fluorescent installations) was estimated to account for 13.4 TWh of U.S. annual site energy use. Residential step, path, and porch lighting were not addressed in the 2013 Adoption report.

Table 3.2 summarizes some key findings from the 2013 Adoption report. Generally speaking, the greater the energy savings potential of a given product category, the lower its 2012 market penetration. Taken together, these applications were estimated to consume 637 TWh in 2012, thus representing roughly 90% of all U.S. lighting energy use. The calculations of potential energy savings did not account for efficiency improvements required by the Energy Independence and Security Act of 2007 (EISA 2007) and other federal or state legislation, which effectively reduce the efficacy gap between LED and benchmark (i.e.,

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baseline) products in some cases.[1] However, these effects were offset to some degree by only considering the efficacy of available products—no adjustments were made in anticipation of future improvements to LED technology.

Table 3.2 LED market penetration and savings potential in key product categories [7]

LED product category	Savings potential in 2012 (TWh)	Penetration in 2012 (%)	Installed base in 2012 (million units)
Troffers et al.	110.4	< 0.1	0.7
A lamps	79.1	< 1	19.9
High-bay luminaires	46.5	< 1	0.3
Decorative lamps	28.7	< 1	4.7
Downlights	26.8	< 1	5.5
Parking lot luminaires	20.4	1	0.2
Parking garage luminaires	15.3	1	0.4
Streetlight luminaires	22.9	2	1.0
Directional lamps (PAR, BR, R)	16.7	4.6	11.4
MR16 lamps	6.2	10	4.8

It is important to note that the "troffers et al." category covered a wide variety of products, including striplights and wraps. Consequently, the savings potential of troffer luminaires is less than the value indicated in the table for this category. The apparent rank-order of the troffers et al. category merits special consideration since its subcategories have different performance attributes.

The troffers et al. category might exhibit different market penetration if subdivided into specific categories for troffers, striplights, etc. In addition, within a given product category or subcategory, lower-output models might exhibit greater market penetration than higher-output models due to lower initial cost and availability of suitable products (e.g., 40 W incandescent A lamp replacements versus 100 W equivalents). Penetration for a given category may also differ between markets (e.g., residential versus commercial).

[1] Information regarding current and future federal energy conservation standards for lighting products is provided at http://www1.eere.energy.gov/buildings/appliance_standards/standards_test_procedures.html

4.0 Current performance for key product categories

The following subsections provide more complete descriptions for the key product categories identified in section 3.0, and summarize current LED product performance levels and criteria relevant to section 5.0, primarily based on data and specifications published by LF, ES, DLC and CALiPER. Benchmark testing conducted by CALiPER is particularly limited in scope—these data are shown for reference only, and are not intended to illustrate the breadth of available products.

4.1 LED omnidirectional and decorative lamps

The ES omnidirectional lamp category covers A, BT, P, PS, S and T bulb shapes (see Figure 4.1) with specific exclusions.[8] Effective September 30, 2014, ES-labeled omnidirectional lamps rated for less than 15 W of input power will have at least 55 lm/W initial efficacy, and higher wattage lamps will achieve 60 lm/W; the current ES specification has somewhat lower efficacy thresholds of 50 lm/W for LED omnidirectional lamps drawing less than 10 W input power, and 55 lm/W for higher wattage lamps.[9] By comparison, the L Prize (www.lightingprize.org) 21st Century Lamp competition will require a minimum efficacy of 150 lm/W.

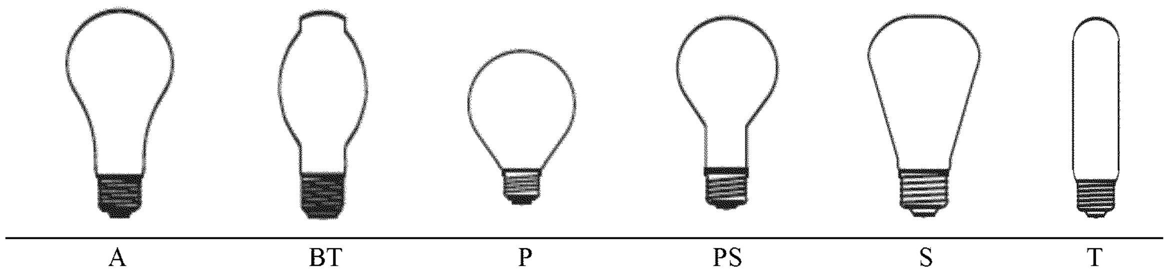

Figure 4.1 ES omnidirectional lamp shape examples

The ES decorative lamp category covers B, BA, C, CA, DC, F and G bulb shapes (see Figure 4.2). The new ES lamp specification will require that labeled decorative lamps rated for less than 15 W of input power achieve 45 lm/W initial efficacy, and that those with input power of 25 W or more be at least 60 lm/W; a minimum of 50 lm/W will be required for intermediate wattage lamps. The current ES specification has a lower threshold of 40 lm/W for all LED decorative lamps.

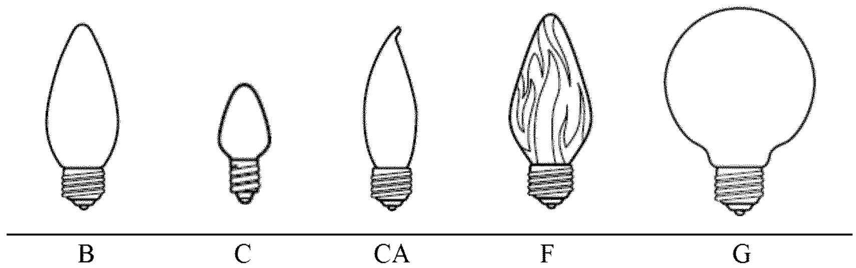

Figure 4.2 ES decorative lamp shape examples

Lumen output requirements for both ES product categories depend on the wattage of the incandescent lamp targeted for replacement. Figure 4.3 illustrates the range of currently available LED A lamps. CALiPER benchmarks, the L Prize winner, and ES target performance for a 100 W incandescent lamp replacement are also shown for comparison. In addition to their comparatively high efficacy, a few LF-listed and ES-qualified LED A lamps now offer output comparable to a 100W incandescent lamp. Halogen lamps offer improved efficacy over standard incandescent and some comply with EISA 2007, but these do not approach levels currently achieved by LED products. Some LED A lamps now match or exceed the initial lumen output and efficacy of the L Prize winning product from Philips, which was submitted for the 60 W replacement competition in late 2009. Figure 4.4 illustrates the range of currently available LED decorative lamps. In addition to their comparatively high efficacy, a few LF-listed and ES-qualified LED decorative lamps now offer output comparable to a decorative 60W incandescent lamp. Halogen lamps offer improved efficacy over standard incandescent and some covered products comply with EISA 2007, but these do not approach levels currently achieved by LED products.

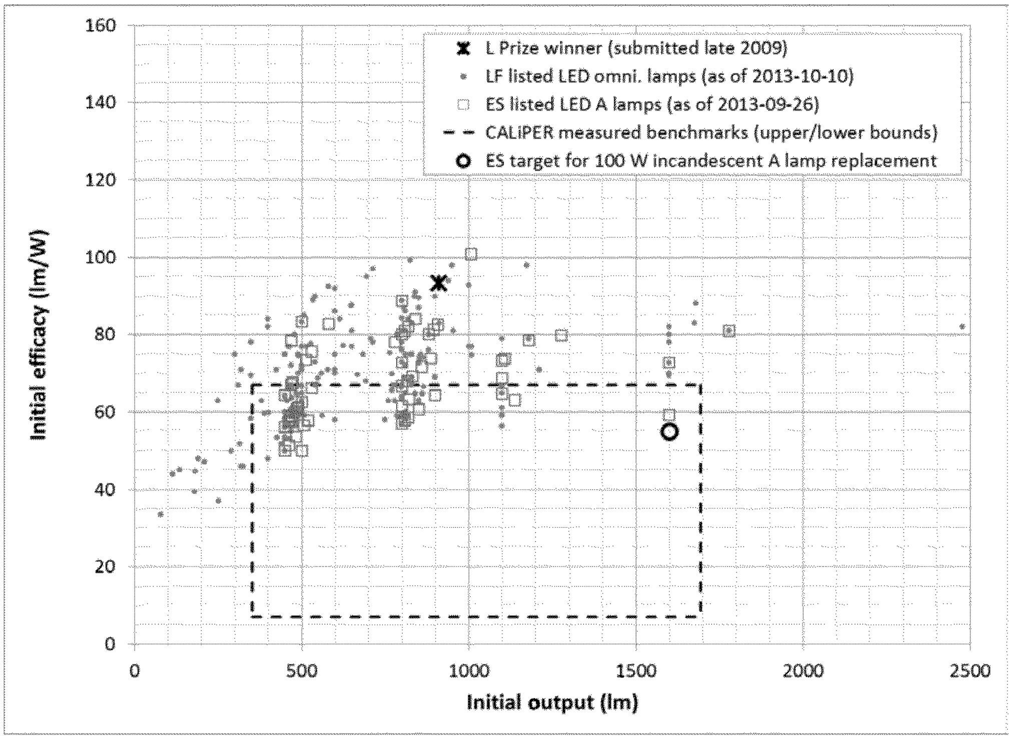

Figure 4.3 Initial output and efficacy for omnidirectionallamps. Shown are 328 LF products and 191 ES products. CALiPER benchmarks include incandescent, halogen, and CFL.

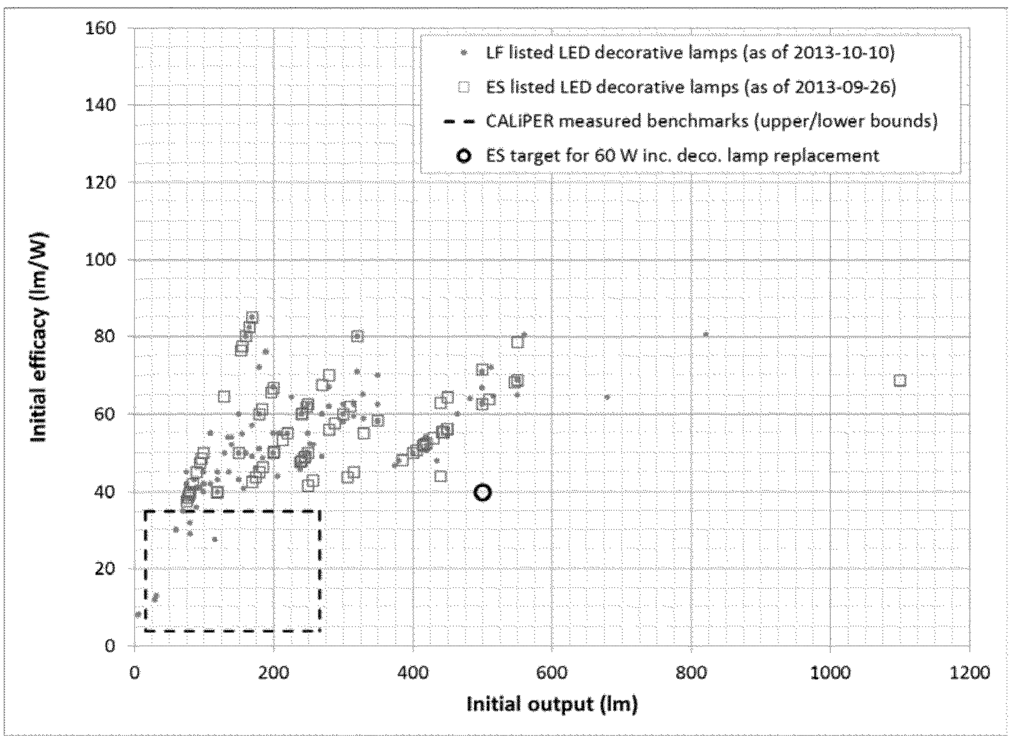

Figure 4.4 Initial output and efficacy for decorative lamps. Shown are 230 LF products and 212 ES products. Three LF products over 3,000 lm are not shown. CALiPER benchmarks include incandescent, halogen, and CFL.

4.2 LED directional lamps

The ES directional lamp category covers R, BR, ER, MR and PAR lamps (see Figure 4.5). The new ES criteria are determined on the basis of input power—lamps below 20 W will need to produce at least 40 lm/W, whereas the threshold for higher wattage lamps will be 50 lm/W. Efficacy criteria in the current ES specification for LED lamps is defined based on lamp size—lamps greater than 20 eighths of an inch in diameter (e.g., PAR30) are required to have at least 45 lm/W, whereas smaller lamps (e.g., PAR20) must to attain 40 lm/W. MR and PAR lamps must meet ES center-beam intensity thresholds to receive the label. Other directional lamps are evaluated in terms of lumen output, with the minimum depending on the wattage of the incandescent lamp targeted for replacement. The LF Residential Performance Scale indicates the lumen output of all LED directional lamps should be at least ten times the wattage of the incandescent lamps they replace.[10]

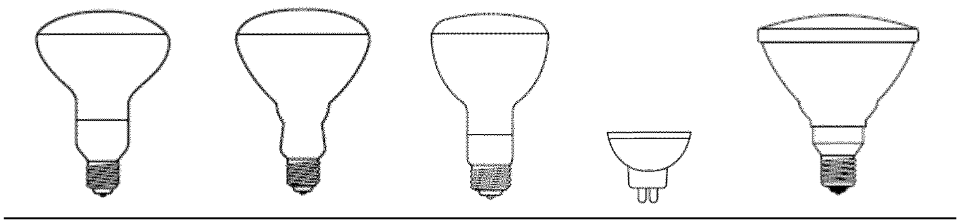

Figure 4.5 ES directional lamp shape examples

Figure 4.6 illustrates the range of currently available LED PAR, BR, and R lamps—including products measuring 20, 30, or 38 eighths of an inch in diameter. CALiPER benchmarks, the L Prize PAR38 criteria (www.lightingprize.org), and rated performance for a ceramic metal halide (CMH) lamp with integral ballast are also shown for comparison. Although integrated CMH lamps can offer higher initial efficacy than CFL, this technology has limited dimming capability and requires special consideration due to delays associated with warm-up and restrike. Integrated CMH lamps can also suffer from poor lumen maintenance, e.g., just 69% of initial output at 40% of rated life.[11] In addition to their comparatively high efficacy, a few LF-listed and ES-qualified LED downlight luminaires now exceed the rated initial output of the example CMH lamp. Halogen infrared (HIR) lamps offer improved efficacy over standard incandescent, but do not approach levels currently achieved by LED products. However, the L Prize efficacy criterion of 123 lm/W remains a challenge.

Figure 4.7 illustrates the range of currently available LED MR lamps. CALiPER benchmarks and target performance for 50 W halogen replacement are also shown for comparison. LED MR16 efficacy is superior to that of halogen MR16 lamps, and a number of LF-listed and ES-qualified LED products can now provide lumen output comparable to that of a 50 W halogen MR16. However, as the smallest of the ES lamps, and the only ES lamp that might require an external transformer for low-voltage operation, LED MR lamps face a number of challenges in terms of compatibility and miniaturization. These challenges have generally precluded the application of CFL or electronically-ballasted ceramic metal halide (eCMH) technology to this product category, and presently all ES-labeled MR lamps are LED; this may help explain why market penetration for this product category has led the other LED lamp and luminaire product categories. Metal halide MR lamps are available but these have a GX10 base and require an external ballast.

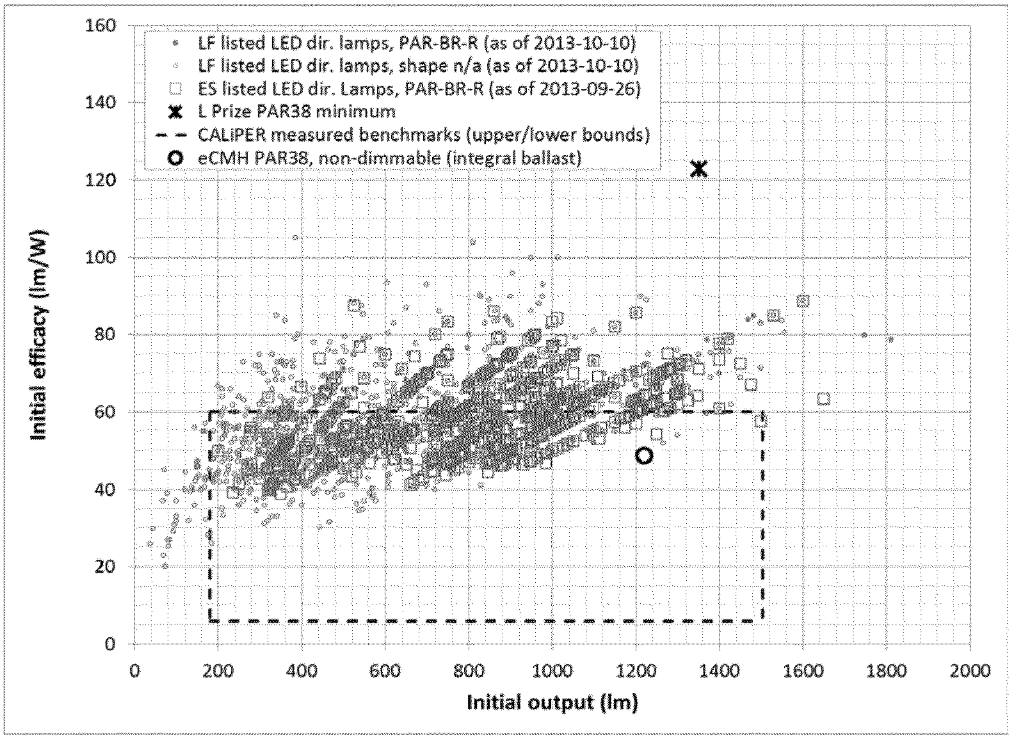

Figure 4.6 Initial output and efficacy for PAR, BR, and R lamps. Shown are 1,803 LF products and 1650 ES products. Eight LF products over 2,900 lm are not shown. CALiPER benchmarks include incandescent, halogen, CFL, and metal halide.

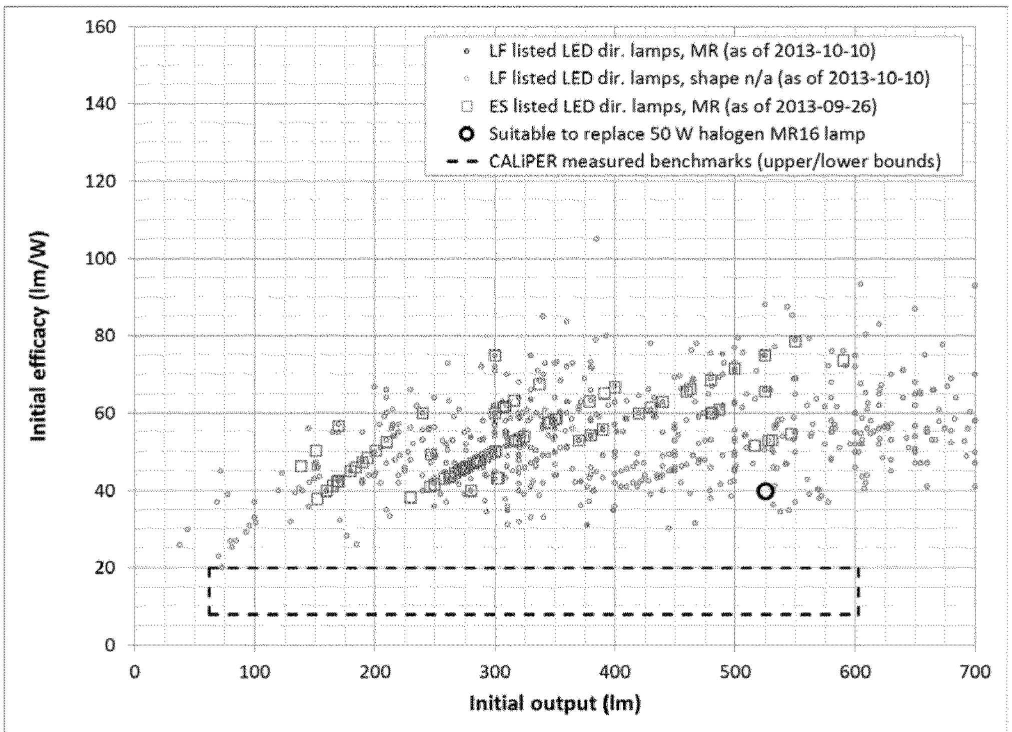

Figure 4.7 Initial output and efficacy for MR lamps. Shown are 15 LF products indicated "MR" and 220 ES products. CALiPER benchmarks are halogen and CFL.

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4.3 LED downlights

Non-LED recessed downlights are typically specified and purchased as three separate parts: housing, reflector trim (sometimes including a lens), and lamp. Since the 2007 introduction of the LR6 by LED Lighting Fixtures, Inc. (subsequently acquired by Cree), LED downlight retrofit units that combine light source and reflector trim have gained in popularity and appear to have few—if any—direct CFL counterparts. Figure 4.8 shows examples of downlight luminaires and downlight retrofit units; the latter subcategory was the focus of CALiPER Summary Report 14, which also evaluated the thermal effects of in situ operation.[12]

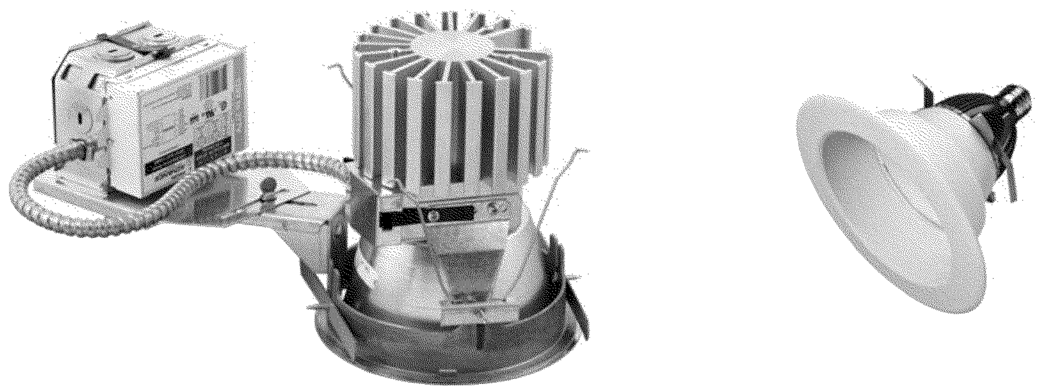

Figure 4.8. Example LED downlight luminaire (left) and LED downlight retrofit unit (right)

Downlights are typically less than 12 inches in diameter—but can also be square in shape—and may be recessed, surface-mounted, or suspended as pendants. Related product categories include wall-wash luminaires, aimable accent luminaires, and track heads. ES-qualified downlights must have a minimum initial efficacy of 42 lm/W, and must emit at least 575 lm if more than 4.5 inches in diameter (otherwise 345 lm).[13]

Figure 4.9 illustrates the range of currently available LED downlights (including luminaires and retrofit units) relative to CALiPER benchmarks, the DOE SSL R&D Multi-Year Program Plan (MYPP) target for luminaires in 2017,[21] and an example luminaire utilizing an eCMH lamp-ballast system. Although eCMH can offer higher luminaire efficacy than with CFLs, this technology has limited dimming capability and requires special consideration due to delays associated with warm-up and restrike. In addition to their comparatively high efficacy, a number of LF-listed and ES-qualified LED downlight luminaires now exceed the rated output of the example eCMH luminaire.

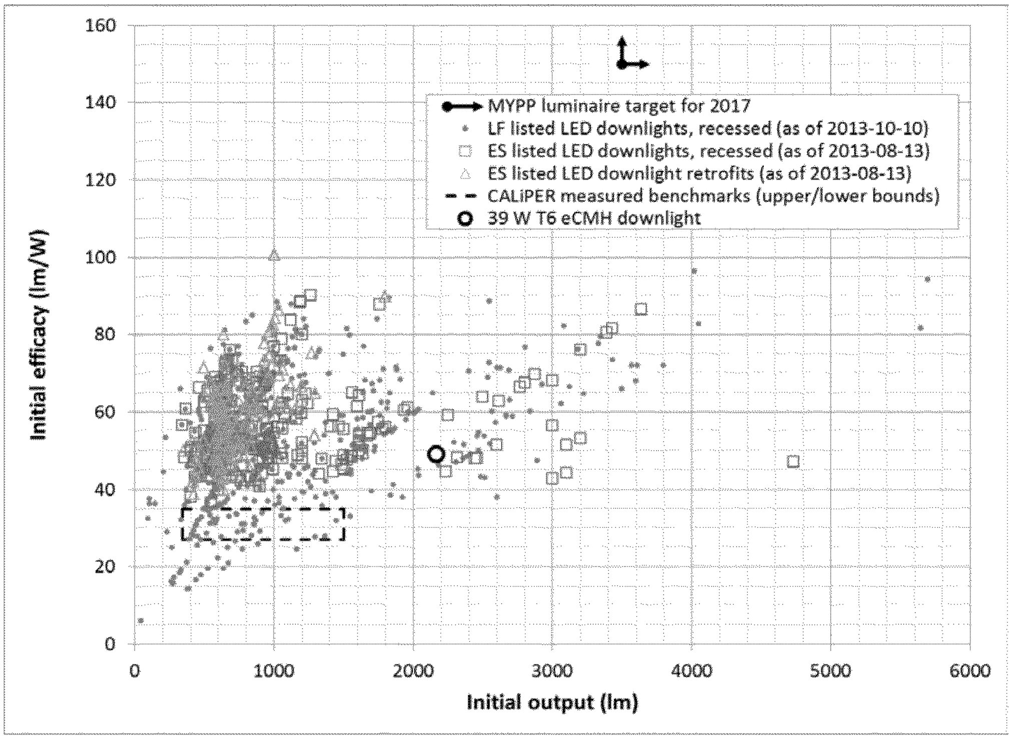

Figure 4.9 Initial output and efficacy for recessed downlight luminaires and downlight retrofit units. Shown are 882 LF products and 1,204 ES products. Two LF products and six ES products over 7,000 lm are not shown. CALiPER benchmarks are CFL.

4.4 LED troffer luminaires

As previously noted, the DOE "troffers et al." category included striplights, wraps, and other indoor luminaire types that utilize linear fluorescent lamps. Figure 4.10 shows examples of products included in the troffers et al. category. Suspended linear pendants (e.g., direct/indirect), another product type, are a popular alternative to troffers in office lighting applications. The following analysis focuses on troffers, which are also sometimes referred to as linear panels. Troffers are typically recessed into the ceiling but may also be surface-mounted.

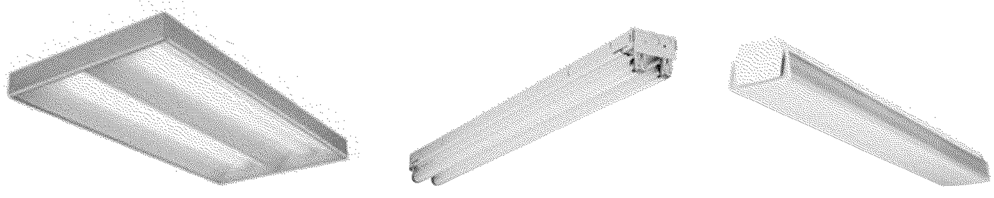

Figure 4.10 Products covered in the "troffers et al." category included troffers (left), striplights (middle), and wraps (right), among other indoor product types that utilize linear fluorescent lamps; high-bay luminaires were excluded.[7]

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The example shown in Figure 4.10 is herein simply termed an architectural troffer to distinguish this popular type from the more traditional parabolic-louvered and prismatic-lensed designs. Troffers measuring roughly two feet in width and four feet in length (i.e., 2x4 troffers) are most common. Troffers remain a significant product category even when the other product types are excluded—in fact, it was estimated that 2x2 troffers alone accounted for 12.0 TWh of U.S. site energy use in 2010.[6]

Efficacy for fluorescent 2x2 troffers is often lower than for fluorescent 1x4 or 2x4 troffers due to space restrictions and the different lamps used.[14] However, the Better Buildings Alliance (BBA) model specification simply calls for 85 lm/W minimum initial luminaire efficacy for all troffers.[15] The DLC uses this same criterion since LED troffer efficacy does not depend on troffer dimensions. The DLC allows troffers to be suspended but requires a minimum troffer width of eight inches, thereby differentiating these products from recessed slotlights and similarly narrow linear pendants (where benchmark efficacy is generally lower).

Figure 4.11 illustrates the range of currently available LED troffers relative to CALiPER benchmarks, the MYPP target for luminaires in 2017, and a fluorescent troffer recognized in the 2012 IES Progress Report.[16] In addition to their comparatively high efficacy, a number of LF-listed and DLC-qualified LED troffers meet the 3,000 lm minimum initial output specified by the BBA for 2x4 LED luminaires. In fact, the handful of luminaires above 120 lm/W are centered around this lumen output threshold—approaching or exceeding the MYPP targets of over 150 lm/W and 3,500 lm, respectively. Many of these LED troffers already rival or outperform best-in-class fluorescent troffers.

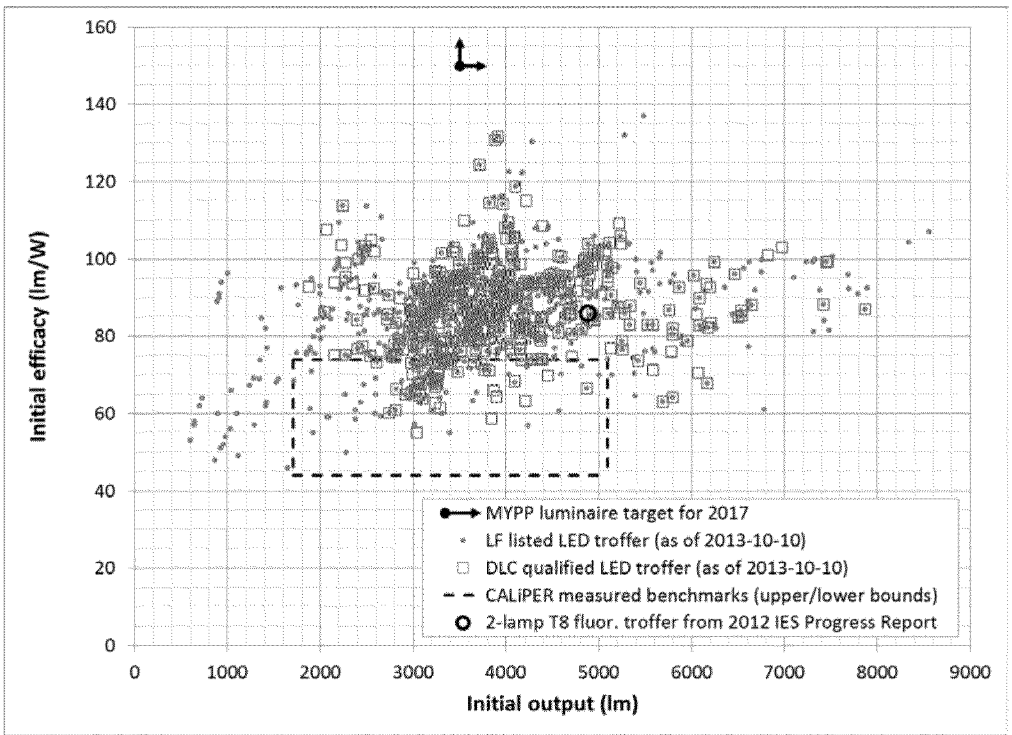

Figure 4.11 Initial output and efficacy for troffer luminaires. Shown are 923 LF products and 526 DLC products. One LF product and one DLC product over 10,000 lm are not shown. CALiPER benchmark troffers are linear fluorescent.

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4.5 LED high-bay and low-bay luminaires

Linear fluorescent high-bay and low-bay luminaires can resemble troffers in profile, but are generally pendant-mounted rather than recessed or surface-mounted, and are often installed at greater mounting heights. High-intensity discharge (HID) luminaires are also used in these applications but generally do not offer the same degree of controllability. LED high-bay and low-bay luminaires are grouped into a single category by LF. The DLC has established separate categories for low-bays, high-bays, and high-bays specifically intended for aisle lighting. DLC-qualified high-bays must have an initial output of at least 10,000 lm, versus 5,000 lm for low-bays; a minimum initial efficacy of 80 lm/W is required for both categories.

Figure 4.12 illustrates the range of currently available LED high-bays and low-bays relative to CALiPER benchmarks, the MYPP target for luminaires in 2017, and an example fluorescent high-bay luminaire. In addition to their comparatively high efficacy, a number of LF-listed and DLC-qualified LED high-bay and low-bay luminaires exceed the rated output of the selected 8-lamp T5HO high-bay luminaire.

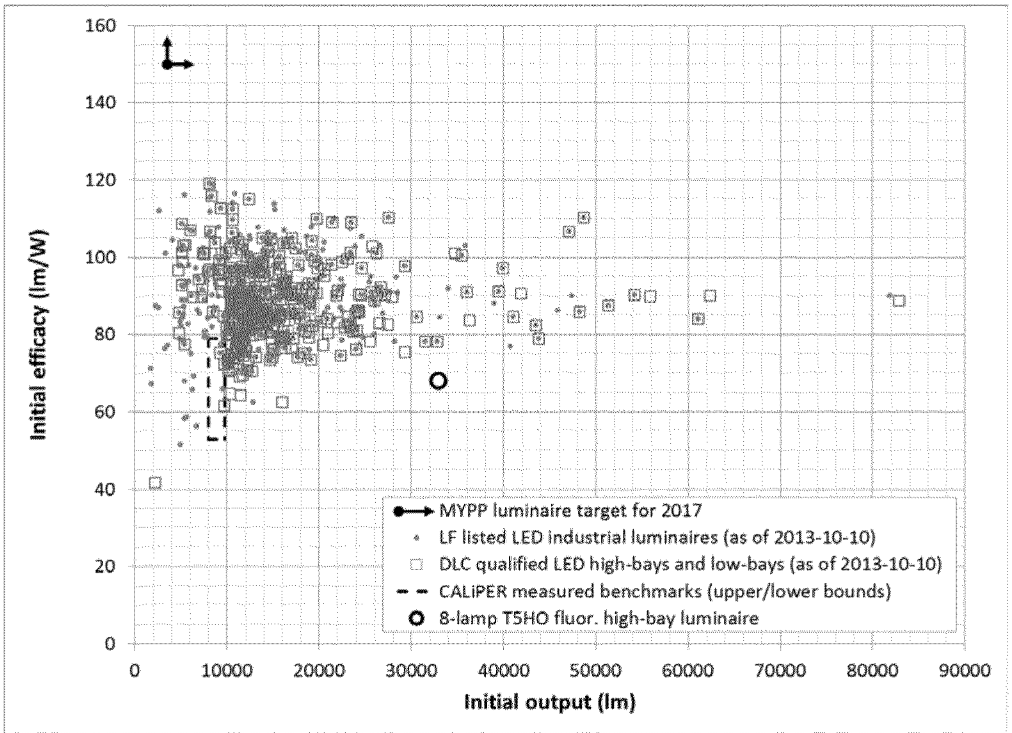

Figure 4.12 Output and efficacy for high-bay and low-bay luminaires. Shown are 526 LF products and 408 DLC products. CALiPER benchmarks include linear fluorescent and metal halide.

4.6 LED parking structure luminaires

There is some overlap between the low-bay, parking structure (i.e., garage or deck), and street/area lighting product categories. Some manufacturers describe a single model as suitable for both low-bay and garage lighting applications. However, some parking structures are periodically hosed-down to maintain surface reflectances—products used in these environments may need to be suitably enclosed akin to polemounted street/area luminaires to prevent water ingress. There is also some overlap with canopy luminaires such as those used in gas stations, although many of these are recessed or semi-recessed rather than surface or pendant-mounted.

The BBA parking structure lighting specification requires a minimum initial efficacy of 60 lm/W for LED, fluorescent, or induction luminaires. By comparison, DLC-qualified products (all LED) must be at least 75 lm/W and emit no less than 2,000 lm. Figure 4.13 illustrates the range of currently available LED garage luminaires relative to CALiPER benchmarks, the MYPP target for luminaires in 2017, and an example garage luminaire utilizing an eCMH lamp. Although eCMH lamp-ballast systems can offer high efficacy and enable good optical control via the small light source, this technology has a shorter rated lifetime than induction and some fluorescent and is not as flexible in terms of dimmability or frequent switching. In addition to their comparatively high efficacy, a number of LF-listed and DLC-qualified LED garage luminaires exceed the rated output of the example eCMH luminaire and many fluorescent or induction luminaires.

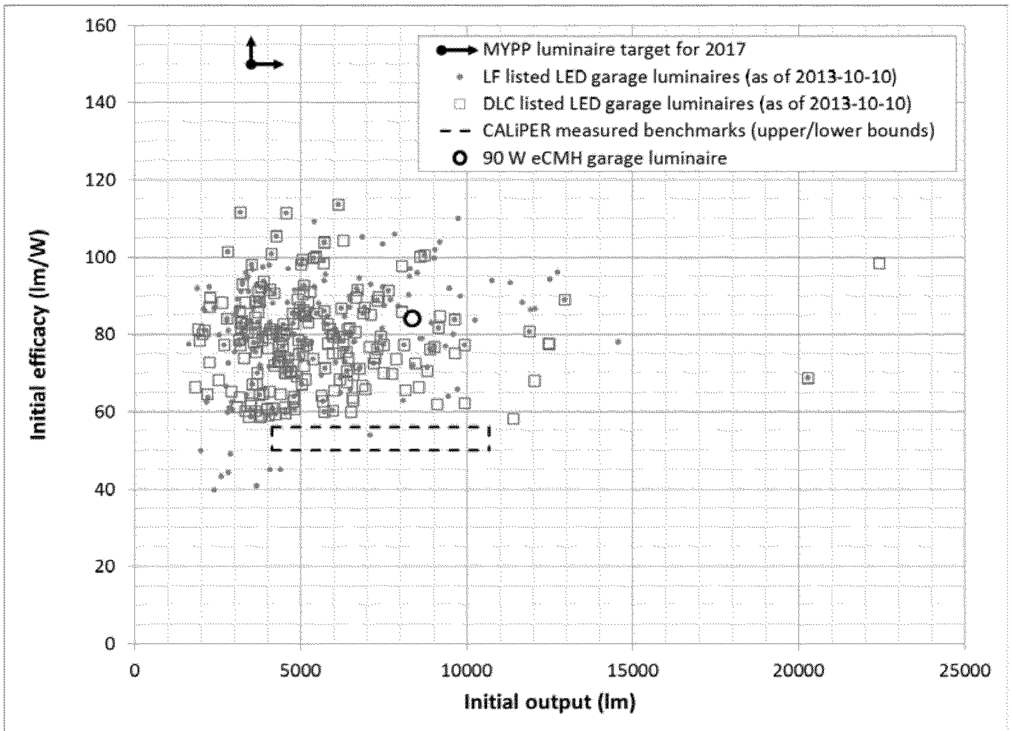

Figure 4.13 Initial output and efficacy for parking structure/garage luminaires. Shown are 291 LF products and 265 DLC products. CALiPER benchmarks include linear fluorescent, metal halide, and induction.

4.7 LED area/roadway luminaires

A variety of luminaire types are used for area (i.e., site or parking lot) and street or roadway lighting applications. The following analysis focuses on cobrahead and shoebox-style luminaires; high-mast, post-top decorative, tunnel, floodlight, and barn light (i.e., NEMA head) luminaires are not specifically addressed.

DLC-qualified area/roadway luminaires must exhibit 70 lm/W minimum initial efficacy. By contrast, the BBA site (i.e., area or parking lot) lighting specification does not establish a minimum threshold for initial luminaire efficacy—input power is instead restricted on the basis of lighting power density (input power per unit area). This specification more directly characterizes site-specific performance, including qualitative considerations such as uniformity of illumination, while also capturing energy savings associated with improved uniformity in parking lots (fewer lumens are needed if "hot spots" of excessive illuminance are mitigated). Although improved uniformity is not necessarily of benefit in roadway and many other applications, where the design criterion is typically average illuminance rather than minimum illuminance, such site-specific evaluation has also been incorporated into Canadian Standards Association (CSA) roadway lighting standards and the Municipal Solid-State Street Lighting Consortium (MSSLC) model specification for LED roadway luminaires.[17,18] However, simple luminaire efficacy is evaluated herein for the purposes of this report.

Figure 4.14 illustrates the range of currently available LED area/roadway luminaires relative to CALiPER benchmarks, the MYPP target for luminaires in 2017, and an example area/roadway luminaire utilizing an eCMH lamp-ballast system. Although eCMH can offer high efficacy and enable better optical control via the small light source, this technology has a shorter rated lifetime than induction; however, at least one major city has standardized on this technology.[19] Induction can also compete in these applications, and has proven to be particularly effective in post-top decorative luminaires.[20] In addition to their comparatively high efficacy, many LF-listed and DLC-qualified LED area/roadway luminaires exceed the rated output of induction luminaires, and a few now exceed the rated output of the example eCMH luminaire.

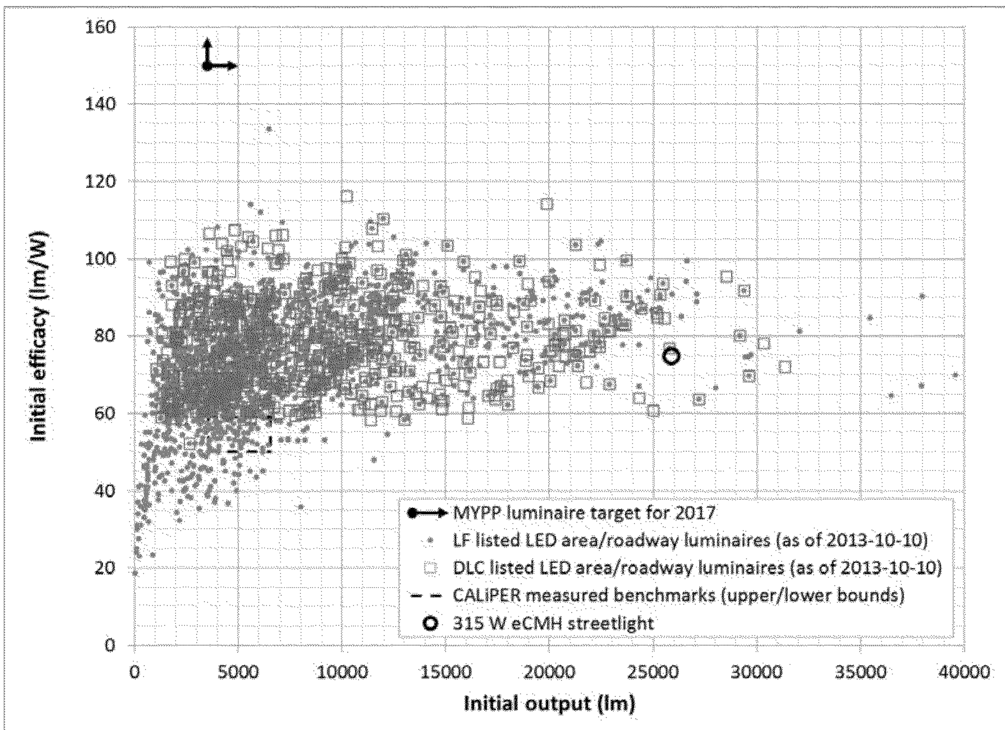

Figure 4.14 Initial output and efficacy for area/roadway luminaires. Shown are 1,847 LF products and 786 DLC products. One LF product and one DLC product above 50,000 lm are not shown. CALiPER benchmarks include high-pressure sodium, metal halide, and induction.

5.0 Efficacy trends for LED lamps and luminaires

This section provides efficacy projections using least-squares regression fits to logarithmic mathematical models based on historical product data from LF, ES, and the DLC. Additional curves based on CALiPER data are given for product categories where sufficient data are available (e.g., no curve is shown if only one round of testing has been conducted for a given product category). The coefficient of determination (R^2) values are fairly low for all fitted efficacy curves shown, reflecting the diversity of products in each dataset and in the market at large. However, a number of the ES and DLC curves have particularly low R^2 values, due at least in part to the relatively low slope of the curves.

Whereas trends for LED omnidirectional (Figure 5.1) and LED decorative lamps (Figure 5.2) differ between LF and ES, the trends for LED directional lamps (Figure 5.3 and Figure 5.4) appear to be quite similar between the two programs. Similarly, Figure 5.5 indicates trends for LED downlight luminaires are similar between LF and ES, but trends for LED downlight retrofit units appear to differ between the two programs. Such differences are also seen between LF and DLC datasets—trends for LED troffers (Figure 5.6) differ between programs, but are similar for high-bay and low-bay luminaires (Figure 5.7), garage luminaires (Figure 5.8), and area/roadway luminaires (Figure 5.9). A consolidated set of projected average efficacy values is provided in Table 5.1.

Following are some possible explanations for the differences observed between the LF and ES or DLC datasets for a given category:

- Whereas products qualified by ES or DLC must meet minimum performance requirements, LF-labeled products must only make accurate performance claims. The LF dataset partially overlaps the ES and DLC datasets, and the LF dataset may include products higher or lower in efficacy than those found in the in the ES or DLC datasets for a given product category.
  - Notably, some LF-labeled A lamps meet ES efficacy criteria but do not meet the corresponding criteria for luminous intensity distribution, and are categorized as non-standard lamps as a result.
- Manufacturers must balance the competing goals of increased efficacy and reduced initial cost. Motivation to significantly exceed the required efficacy for ES or DLC qualification may be compromised by competition from benchmark technologies—this pressure can vary by product category depending on relative product price, efficacy, longevity, quality of light, and other factors.
  - Periodic upward ratcheting of efficacy requirements can help to maintain an emphasis on improved efficacy, better reflecting ongoing improvements in LED package efficacy. Recent changes to ES and DLC specifications will likely result in such an increase in slope; however, such corrections may be temporary.
  - No equation is given for DLC troffers. The slope of the modeled curve is negative in value, perhaps due to very high efficacy among those products first qualifying. The substantially more stringent Version 2.0 criteria are expected to have a dramatic positive effect on the efficacy trend for this product category.

Differences between the CALiPER and LF curves could be attributed to the more limited variety of products evaluated by CALiPER (i.e., sampling error).

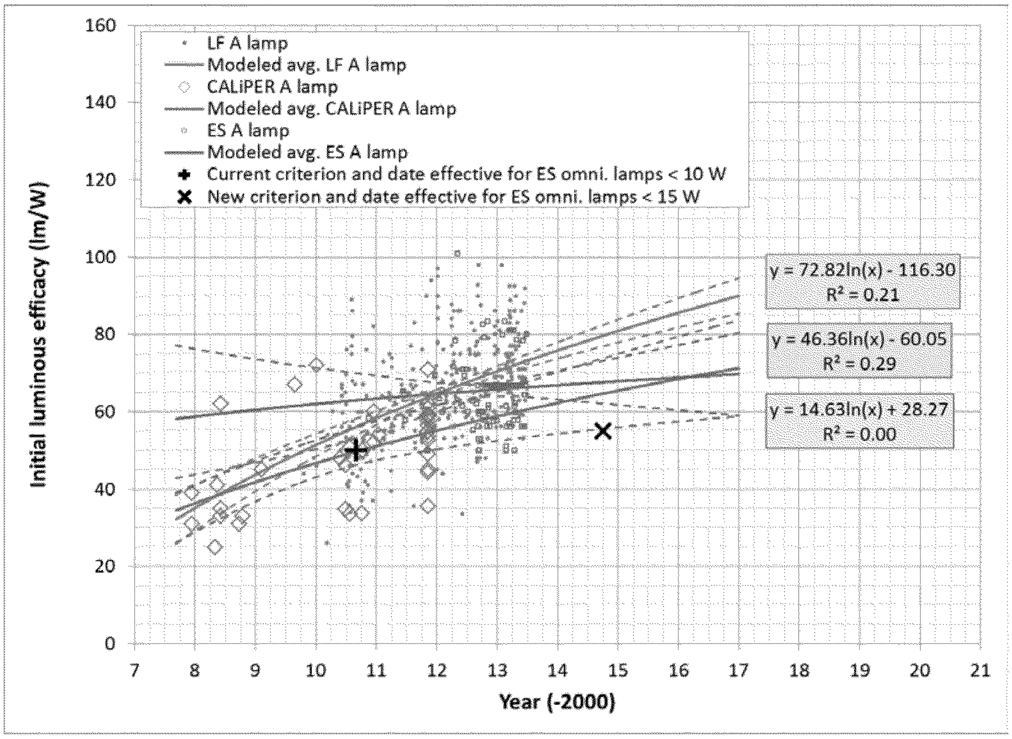

Figure 5.1 Luminous efficacy for LED omnidirectional lamps. Dashed lines indicate 95% confidence bands for modeled average. ES criteria are shown for reference.

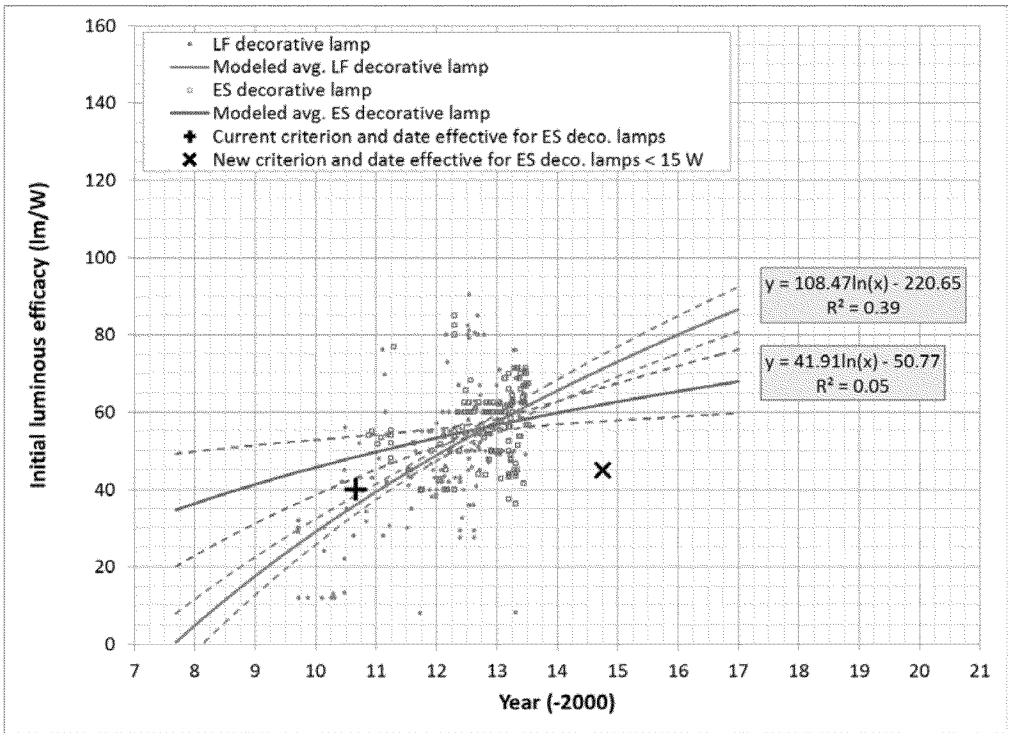

Figure 5.2 Luminous efficacy for LED decorative lamps. Dashed lines indicate 95% confidence bands for modeled average. ES criteria are shown for reference. Two ES products appear slightly below the current 40 lm/W criterion due to rounding error.

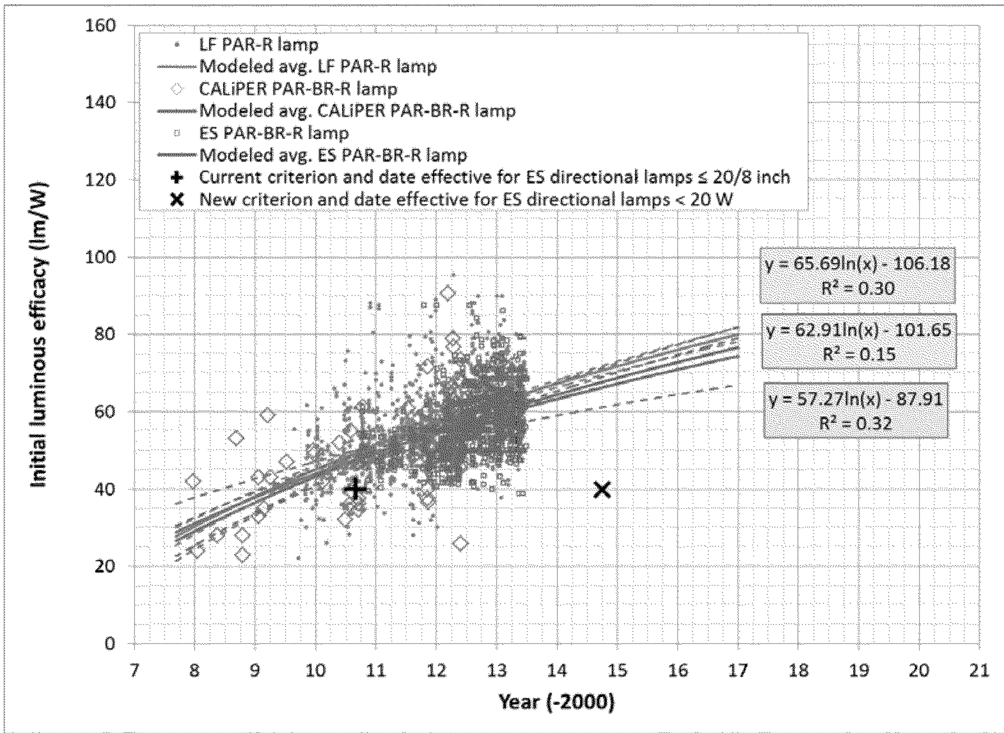

Figure 5.3 Luminous efficacy for LED PAR, BR, and R lamps. Dashed lines indicate 95% confidence bands for modeled average. ES criteria are shown for reference.

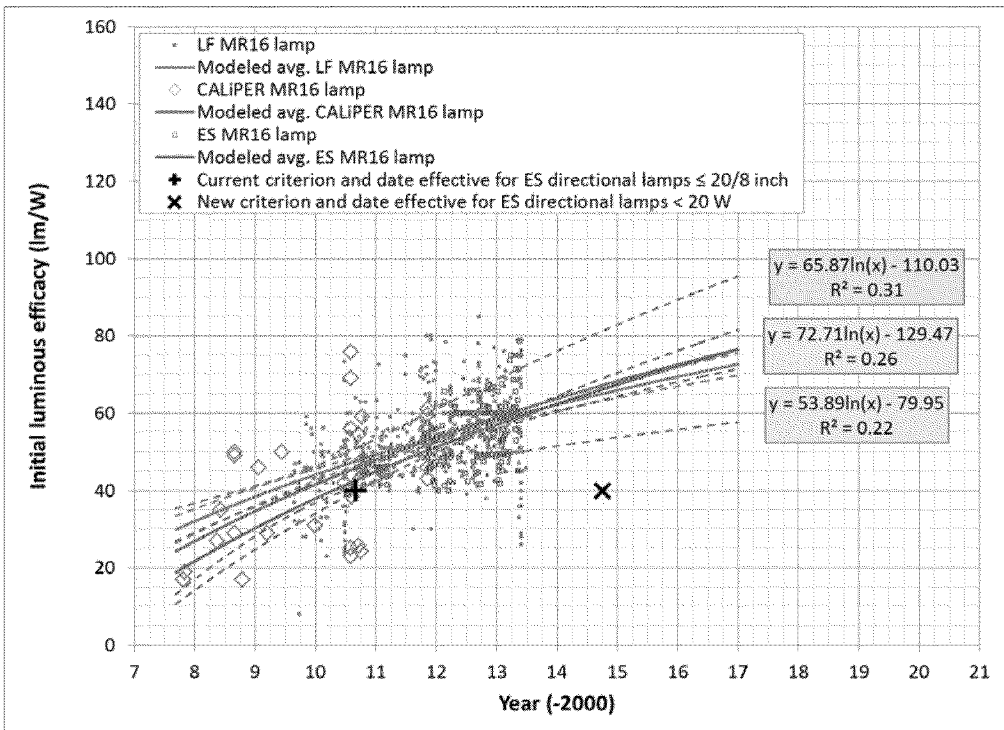

Figure 5.4 Luminous efficacy for LED MR lamps. Dashed lines indicate 95% confidence bands for modeled average. ES criteria are shown for reference.

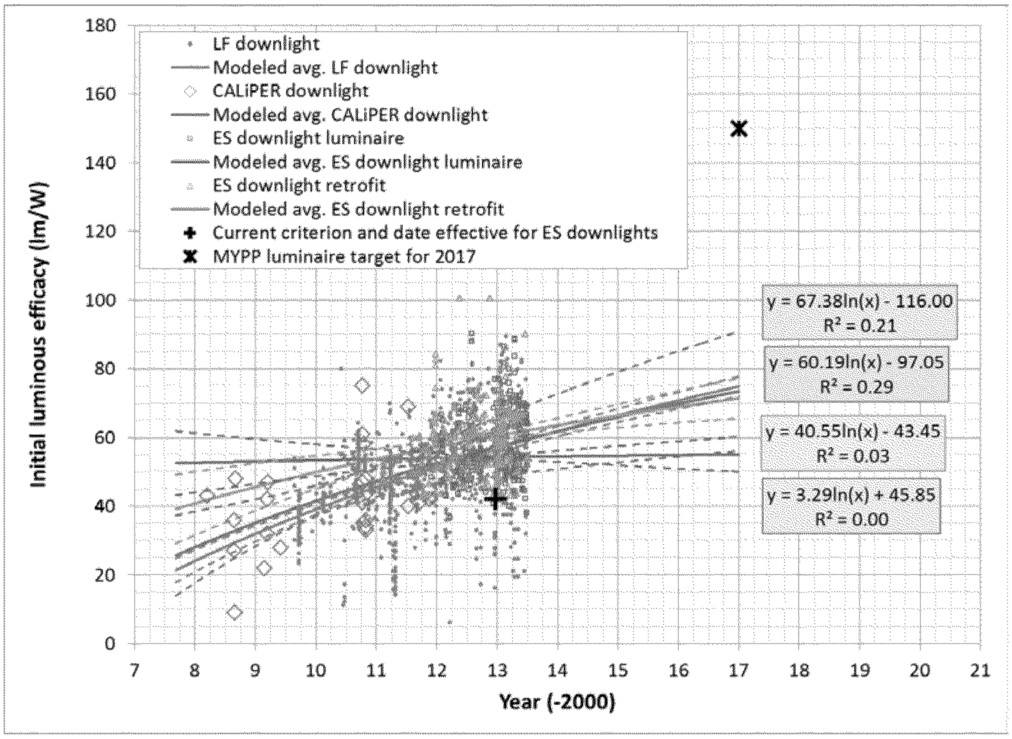

Figure 5.5 Luminous efficacy for LED downlight luminaires and LED downlight retrofit units. Dashed lines indicate 95% confidence bands for modeled average. ES criteria are shown for reference.

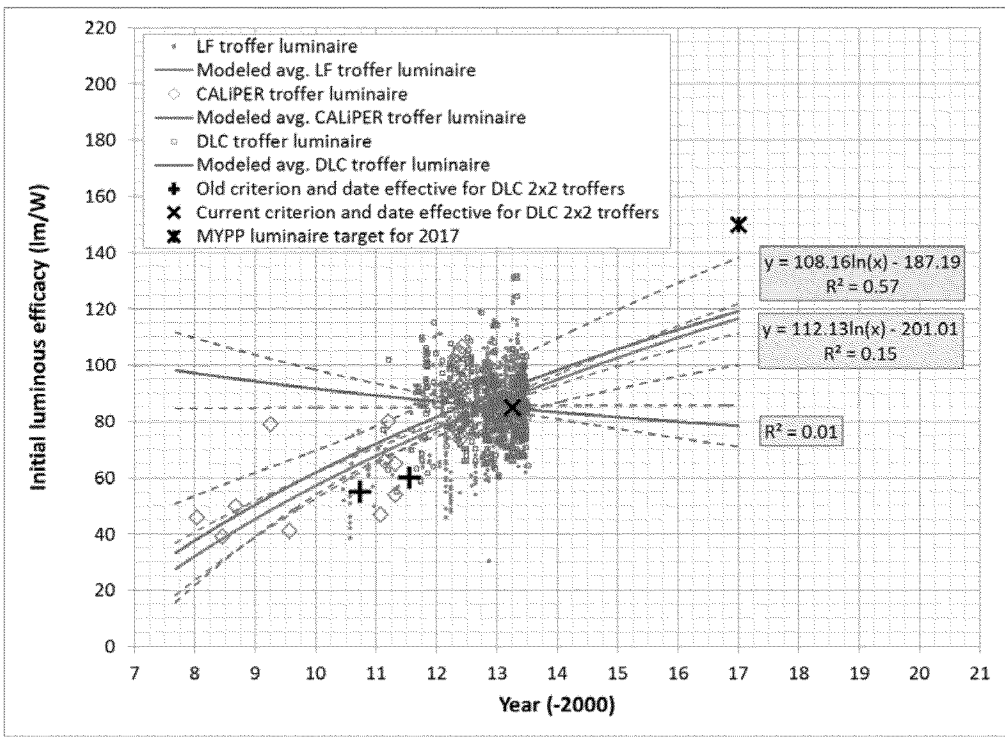

Figure 5.6 Luminous efficacy for LED troffer luminaires. Dashed lines indicate 95% confidence bands for modeled average. DLC criteria are shown for reference.

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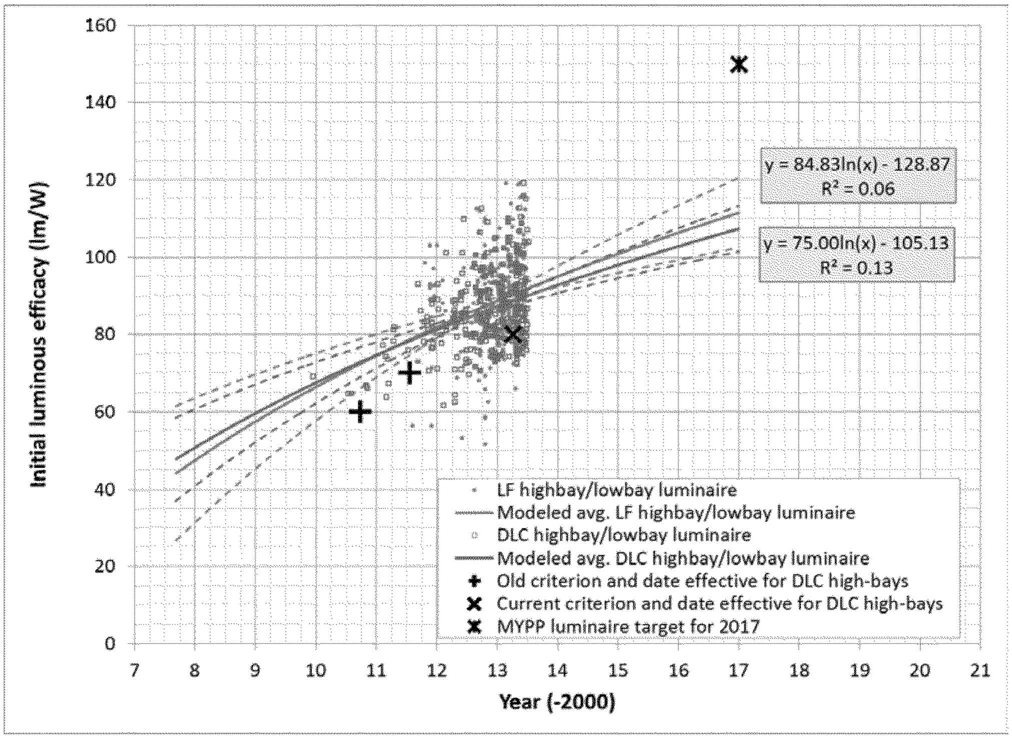

Figure 5.7 Luminous efficacy for LED high-bay and low-bay luminaires. Dashed lines indicate 95% confidence bands for modeled average. DLC criteria are shown for reference.

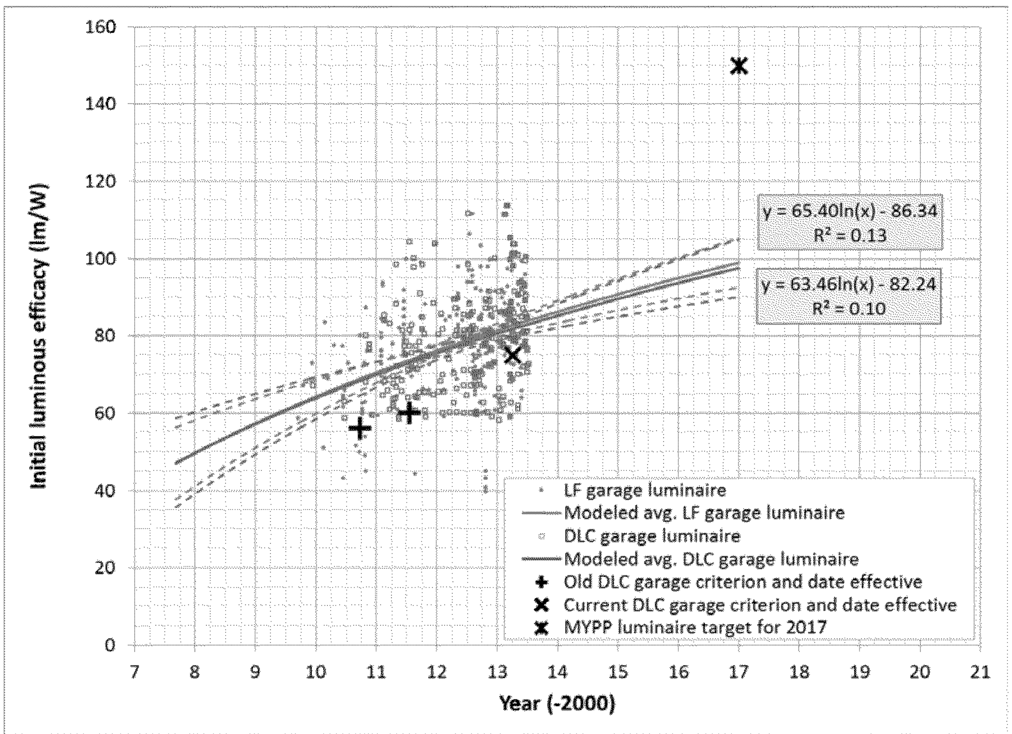

Figure 5.8 Luminous efficacy for LED parking structure/garage luminaires. Dashed lines indicate 95% confidence bands for modeled average. DLC criteria are shown for reference.

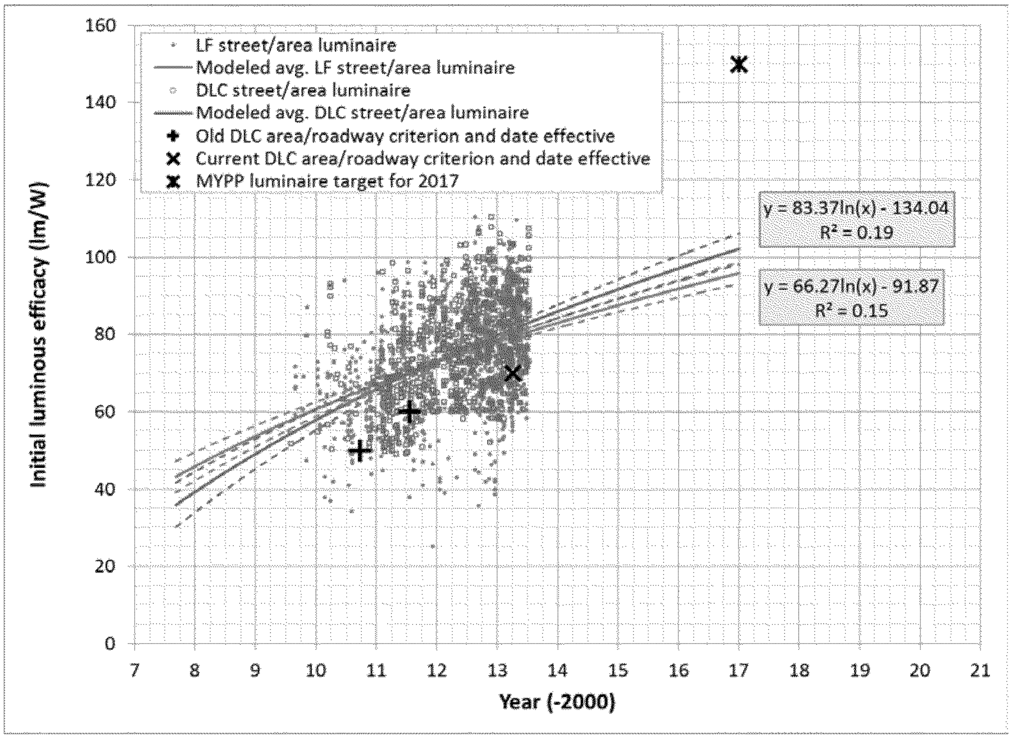

Figure 5.9 Luminous efficacy for LED area/roadway luminaires. Dashed lines indicate 95% confidence bands for modeled average. DLC criteria are shown for reference.

Table 5.1 Projected efficacy for key LED lamp categories

Product category	Dataset	Curve	Projected efficacy at start of year (lm/W)			
			2014	2015	2016	2017
LED omnidirectional lamps	LF	Upper 95% confidence band	78	84	89	95
		Modeled average	76	81	86	90
		Lower 95% confidence band	74	78	82	85
	ES	Upper 95% confidence band	71	74	77	80
		Modeled average	67	68	69	70
		Lower 95% confidence band	63	62	60	59
LED decorative lamps	LF	Upper 95% confidence band	68	77	85	92
		Modeled average	66	73	80	87
		Lower 95% confidence band	63	69	75	81
	ES	Upper 95% confidence band	63	68	72	76
		Modeled average	60	63	65	68
		Lower 95% confidence band	57	58	59	60
LED PAR-BR-R lamps	LF	Upper 95% confidence band	68	73	78	82
		Modeled average	67	72	76	80
		Lower 95% confidence band	66	70	74	78
	ES	Upper 95% confidence band	65	70	75	79
		Modeled average	64	69	73	77
		Lower 95% confidence band	63	67	71	74
LED MR lamps	LF	Upper 95% confidence band	64	68	72	76
		Modeled average	62	66	69	73
		Lower 95% confidence band	61	64	67	70
	ES	Upper 95% confidence band	64	71	76	82
		Modeled average	62	67	72	77
		Lower 95% confidence band	60	64	68	72

Table 5.2 Projected efficacy for key LED luminaire and retrofit categories

Product category	Dataset	Curve	Projected efficacy at start of year (lm/W)			
			2014	2015	2016	2017
LED downlight luminaires	LF	Upper 95% confidence band	63	68	73	78
		Modeled average	62	66	71	75
		Lower 95% confidence band	60	65	68	72
	ES	Upper 95% confidence band	56	58	59	60
		Modeled average	55	55	55	55
		Lower 95% confidence band	53	52	51	50
LED downlight retrofit units	ES	Upper 95% confidence band	66	70	74	77
		Modeled average	64	66	69	71
		Lower 95% confidence band	61	63	64	66
LED troffer luminaires	LF	Upper 95% confidence band	97	106	114	122
		Modeled average	95	103	110	117
		Lower 95% confidence band	93	100	106	111
	DLC	Upper 95% confidence band	*	*	*	*
		Modeled average	*	*	*	*
		Lower 95% confidence band	*	*	*	*
LED highbay & lowbay luminaires	LF	Upper 95% confidence band	98	106	113	121
		Modeled average	95	101	106	111
		Lower 95% confidence band	92	96	99	102
	DLC	Upper 95% confidence band	95	101	108	113
		Modeled average	93	98	103	107
		Lower 95% confidence band	91	95	98	101
LED parking garage luminaires	LF	Upper 95% confidence band	89	95	100	105
		Modeled average	86	91	95	99
		Lower 95% confidence band	83	87	90	93
	DLC	Upper 95% confidence band	88	94	100	105
		Modeled average	85	90	94	98
		Lower 95% confidence band	82	85	88	90
LED area/roadway luminaires	LF	Upper 95% confidence band	84	89	94	99
		Modeled average	83	88	92	96
		Lower 95% confidence band	82	86	90	93
	DLC	Upper 95% confidence band	88	94	100	106
		Modeled average	86	92	97	102
		Lower 95% confidence band	84	89	94	98

* No projections given for this dataset.

6.0 Pricing trends for LED lamps and luminaires

The MYPP included a general target for LED luminaire pricing in 2017, and provided price projections for an LED A lamp.[21] The 2013 Adoption report provided a similar projection for an LED downlight retrofit unit.[7] These values updated and expanded upon projections provided for an average LED lamp and an average LED luminaire in the 2012 Energy Savings Potential (ESP) report published by DOE.[22] Historical price data are available for ES-labeled lamps, but this can only provide rough estimates of dollars per kilolumen ($/klm) pricing since lumen values are not indicated.[23] Similarly, product longevity would ideally be considered (e.g., by evaluating $/klm-h), but such information is not consistently available, reliable, or suitable for apples-to-apples comparison.

The CALiPER program has acquired and tested a wide variety of LED lamps and luminaires over the past several years. The CALiPER database was examined to determine which LED product categories had adequate data for the purpose of pricing trend analysis, based on the following criteria:

- Substantial number of models for which purchase date, purchase price, and measured lumens could be determined— thereby enabling calculation of $/klm pricing;
- Purchases were dispersed fairly well over time, i.e., without excessive clustering at one or two dates;
- Substantial span between purchase dates for oldest and most recent models tested.

CALiPER data for the following key LED product categories were found to satisfy the above criteria: omnidirectional lamps, decorative lamps, directional lamps, and troffer luminaires. Figure 6.3, Figure 6.4, Figure 6.1, and Figure 6.2 illustrate apparent price trends for integrated LED lamps acquired and tested through the CALiPER program. Solid lines indicate least-squares regression fits to power mathematical models; dashed lines indicate the corresponding 95% confidence bands on the predicted average. Taxes, shipping, and contractor markup were not included in $/klm calculations. Whereas a single unit of each luminaire was usually acquired for testing, three units of each lamp were obtained simultaneously and averaged.

To supplement the single CALiPER luminaire product category (troffers) satisfying the above criteria, LED streetlight data provided by Seattle City Light (SCL) was also evaluated. Figure 6.5 and Figure 6.6 illustrate apparent $/klm price trends for LED troffer luminaires and cobrahead-style LED streetlight luminaires. Note that whereas CALiPER typically obtained one luminaire of a given model, SCL obtained hundreds or thousands (nearly one thousand on average) of units of a given model in each order. In addition, whereas CALiPER product selection was not specification-driven, luminaires selected by SCL met stringent criteria for performance and cost, thereby reducing variability. Lacking measurement data, SCL luminaires were assumed to emit exactly the minimum required light output (3,900 lm).

It should be noted that although the CALiPER dataset represents a diverse sample of commercially-available products, it is of limited size and is not a strictly random sample; consequently, it may not be truly representative for one or more of these product categories. Furthermore, since the fitted curves and projections indicate the estimated average and associated confidence intervals for each product category, no particular product should be expected to coincide with the fitted curve for its category.

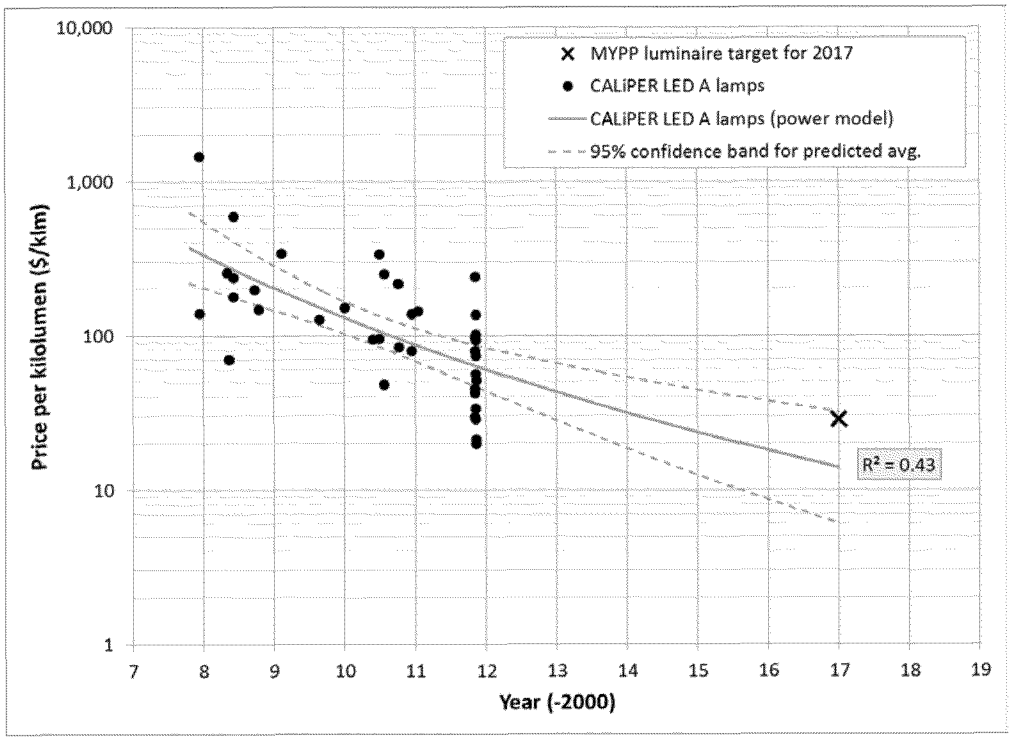

Figure 6.1 Apparent pricing trend for CALiPER LED A lamps.

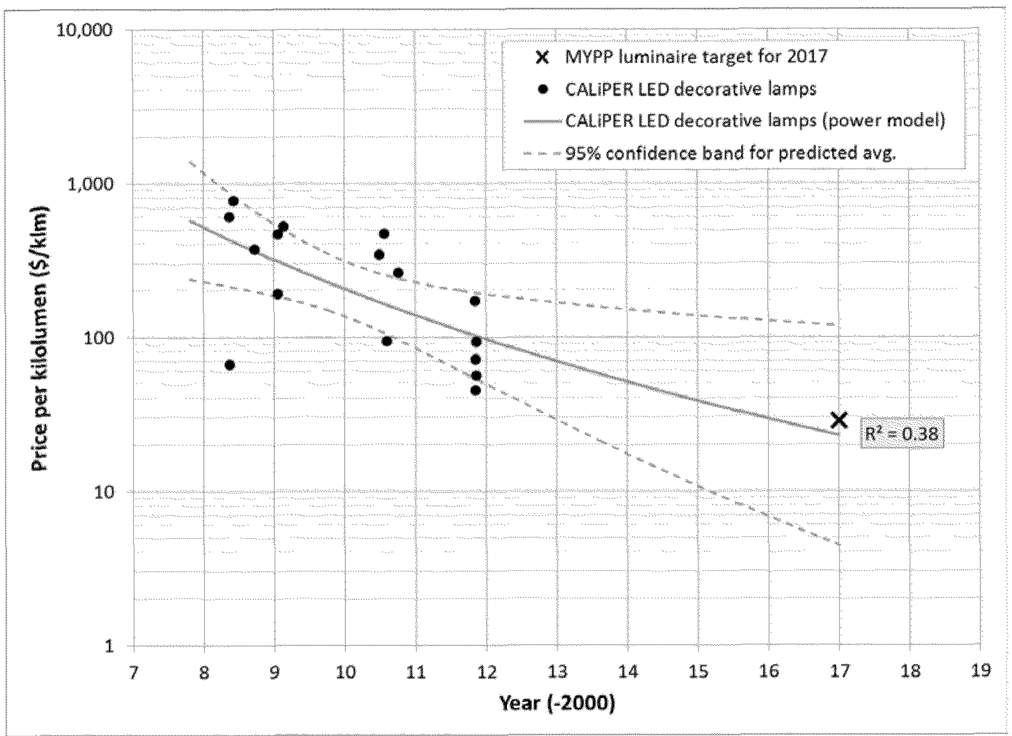

Figure 6.2 Apparent pricing trend for CALiPER LED decorative lamps.

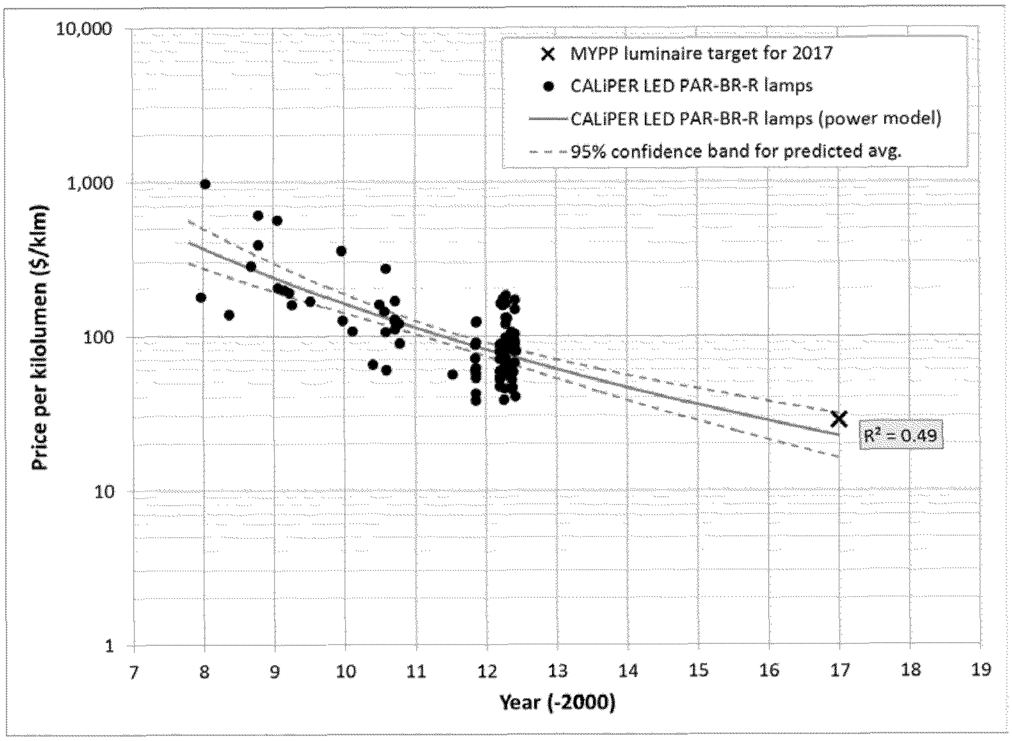

Figure 6.3 Apparent pricing trend for CALiPER LED PAR, BR, and R lamps.

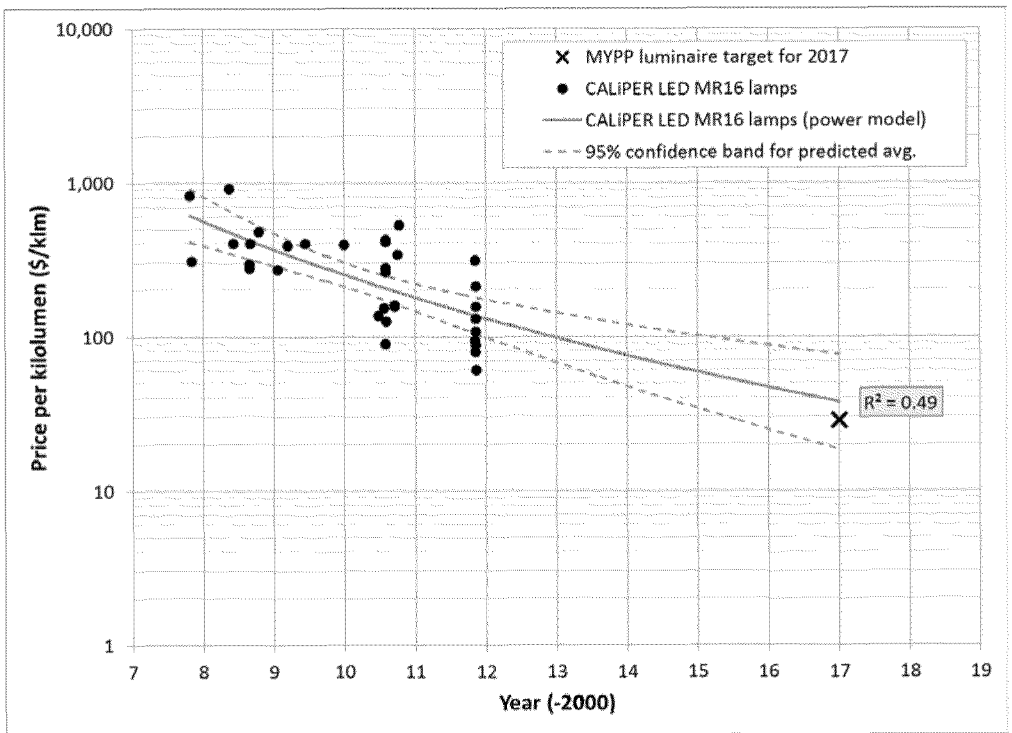

Figure 6.4 Apparent pricing trend for CALiPER LED MR16 lamps

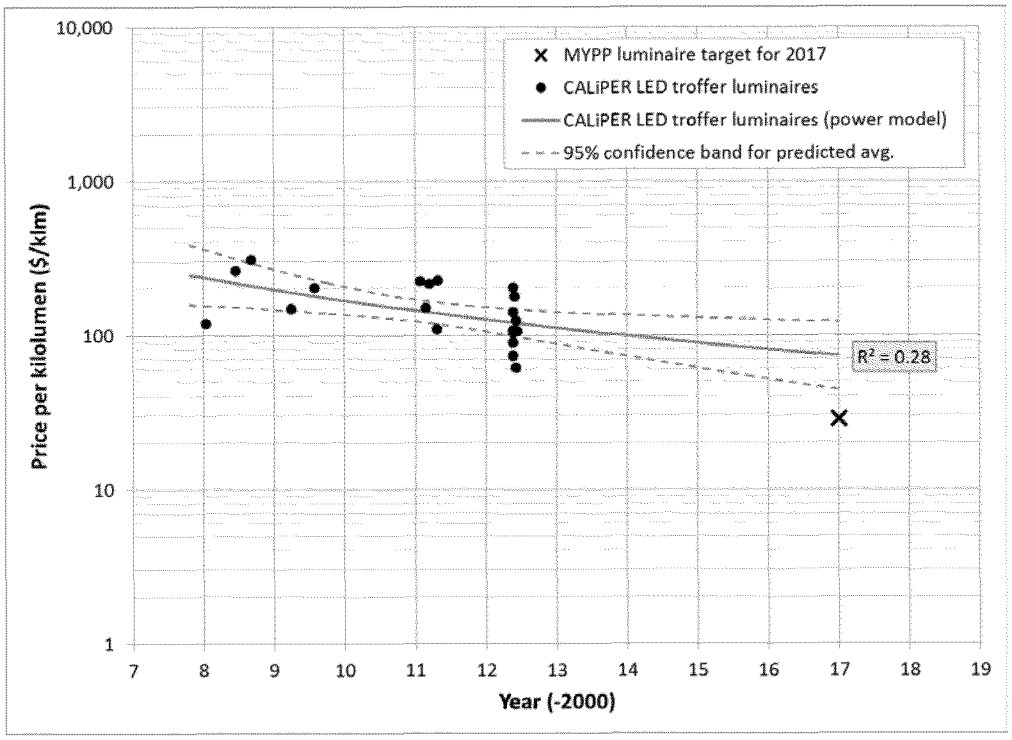

Figure 6.5 Apparent pricing trend for CALiPER LED troffer luminaires.

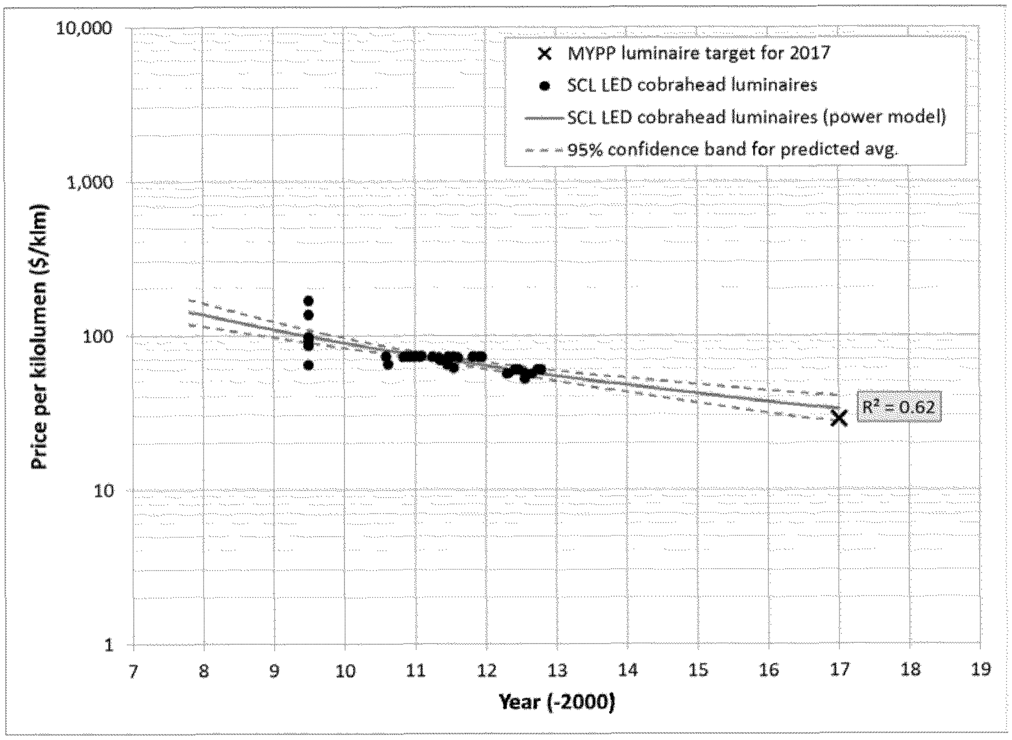

Figure 6.6 Apparent pricing trend for SCL LED streetlight luminaires.

These datasets were then normalized for equal pricing at the start of 2008 to evaluate the relative rates of change, as shown in Figure 6.7. This comparison reveals that although $/klm pricing has differed from category to category, some of these categories appear to be diminishing in price at very similar rates. In fact, when the corresponding confidence intervals are taken into consideration, the available CALiPER and SCL data does not support differentiating among lamp categories or among luminaire categories on this basis. Instead, lamps and luminaires appear to represent two distinct groups of product categories. This interpretation is supported by prior DOE price trend analysis and projections for LED downlight retrofit units (a product category intermediate to lamps and luminaires as discussed in subsection 4.3) and LED A lamps.[7, 21] However, the 2012 ESP report indicated an equal rate of change for LED lamps and LED luminaires.

Price pressure from incumbent technologies is one of a number of factors that might contribute to the apparently differing behavior between lamps and luminaires. Another possible explanation is the portion of the overall product price represented by the LED light source(s). Whereas pricing for LED light sources has been rapidly decreasing over the last several years, prices for many other product components (e.g., the housing/chassis and optical media) have been stable or have even been increasing in cost. If LED light sources typically represent a greater portion of overall product price for lamps than for luminaires, then lamps would be expected to decrease in $/klm pricing more rapidly than luminaires—most notably in the early stages of market introduction—and LED downlight retrofit units would be expected to diminish at an intermediate rate.

Figure 6.8 shows consolidated curves for LED lamps (from Figure 6.3, Figure 6.4, Figure 6.1, and Figure 6.2) and LED luminaires (from Figure 6.5 and Figure 6.6), normalized for equal value at the start of 2013-Q4. This facilitates extrapolation from current pricing for a given product category, as illustrated by the example provided in section 6.1 for LED directional lamps. The relatively wide confidence bands are at least partly attributable to the lack of CALiPER data for these product categories in 2013 (dates are based on product purchase date rather than report publication date). Additional data may be incorporated as it becomes available, enabling ongoing refinement of these curves.

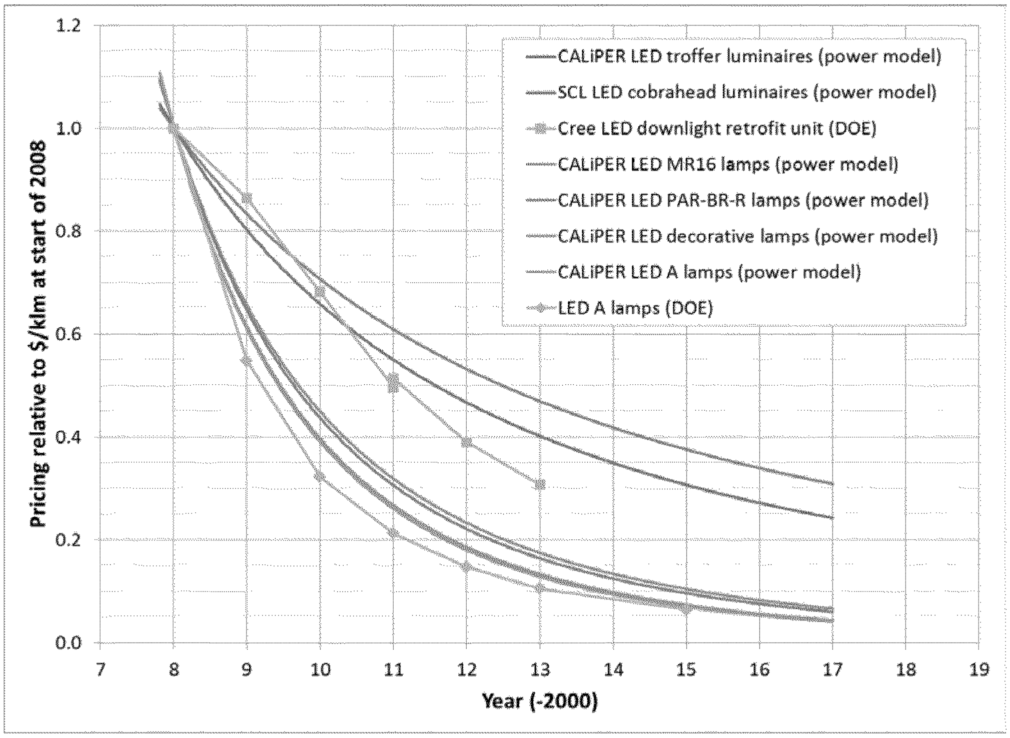

Figure 6.7 Pricing trends normalized for equal value at start of 2008. Trends from prior DOE reports for LED A lamps and downlight retrofit units are shown for comparison.

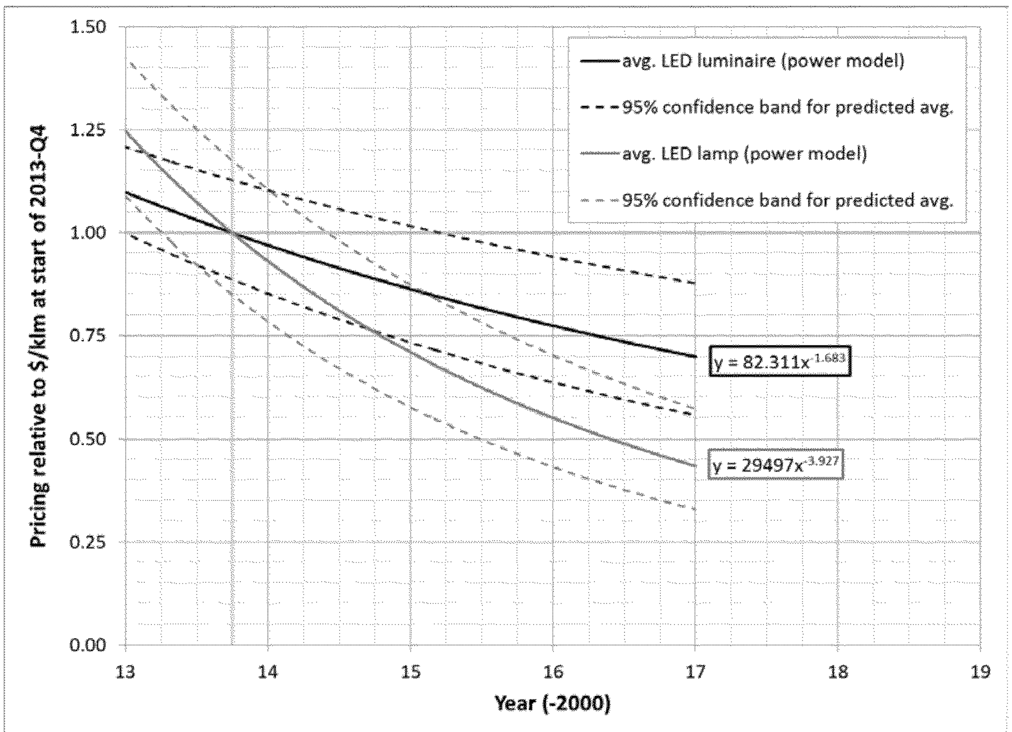

Figure 6.8 LED lamp (CALiPER) and LED luminaire (CALiPER and SCL) pricing trends merged and normalized for equal value at start of 2013-Q4.

6.1 Example projection: LED directional lamps

Pricing data for LED directional lamps was collected by PNNL in late September 2013 from the websites of the following major retailers: Ace Hardware, Best Buy, The Home Depot, Lowe's, Sears, and True Value. Products included in the analysis were packaged individually for sale as single units and had a rated CCT of 2700-3000 K; if CCT was not indicated, products designated "cool white" or "daylight" were excluded. Although CRI and ENERGY STAR certification may affect pricing, these parameters were not consistently reported on the websites and thus were not used as criteria for product selection.

A total of 192 unique model-price combinations were generated for the analysis, with some overlap among retailers (i.e., some models were sold by more than one retailer). Product brands included Array, Cree, EcoSmart, Feit, GE, Insignia, LSGC, Philips, Samsung, Sylvania, Utilitech, and TCP. Nearly all of the available models were rated below the 20 W threshold in the new ES lamp specification. Lamps emitting less light and lamps of smaller diameter were generally found to have higher $/klm pricing, as shown in Figure 6.9, which shows data from the two largest retailers. This apparent relationship may be partly attributable to the cost of non-LED components, and partly a reflection of the difficulties encountered when maximizing output from a small LED lamp. Preliminary analysis by PNNL indicates a similar relationship between pricing and lumen output exists for LED omnidirectional and decorative lamps.

Estimation of current "average" pricing for a given product category is confounded by a number of issues, including but not limited to:

- Unknown relative sales volume—sales data for each specific model at each retailer would be needed to apply accurate weighting;
- Differing number of models offered by each brand—a simple average would introduce artificial weighting that does not necessarily reflect relative sales volume;
- Differing proportion of older and newer models offered by each retailer—retailers with a greater proportion of older (and more expensive) models were found to have a significantly higher average;
- Substantial variability between brands due to real or perceived differences in quality;
- Substantial variability for some product subcategories, e.g., smaller directional lamps.

Similar challenges are encountered when using percentiles or quartiles in lieu of the average. The following alternative approach was used to avoid these problems:

1. Restrict product search to approximately 5-10 major retailers;
2. Obtain pricing for all models meeting criteria from approximately 10 leading brands;
3. For each brand, find the lowest $/klm model across included retailers;
4. Average pricing for lowest $/klm models across included brands.

Table 6.1 illustrates the outcome of this approach, indicating current pricing of approximately $30/klm for price-leading LED directional lamps greater than three inches in diameter, and $50/klm (67% more) for smaller models. Larger models appear to have already surpassed the approximate $64/klm price point for self-ballasted eCMH lamps. No attempt was made to adjust for effects of possible upstream utility incentives.

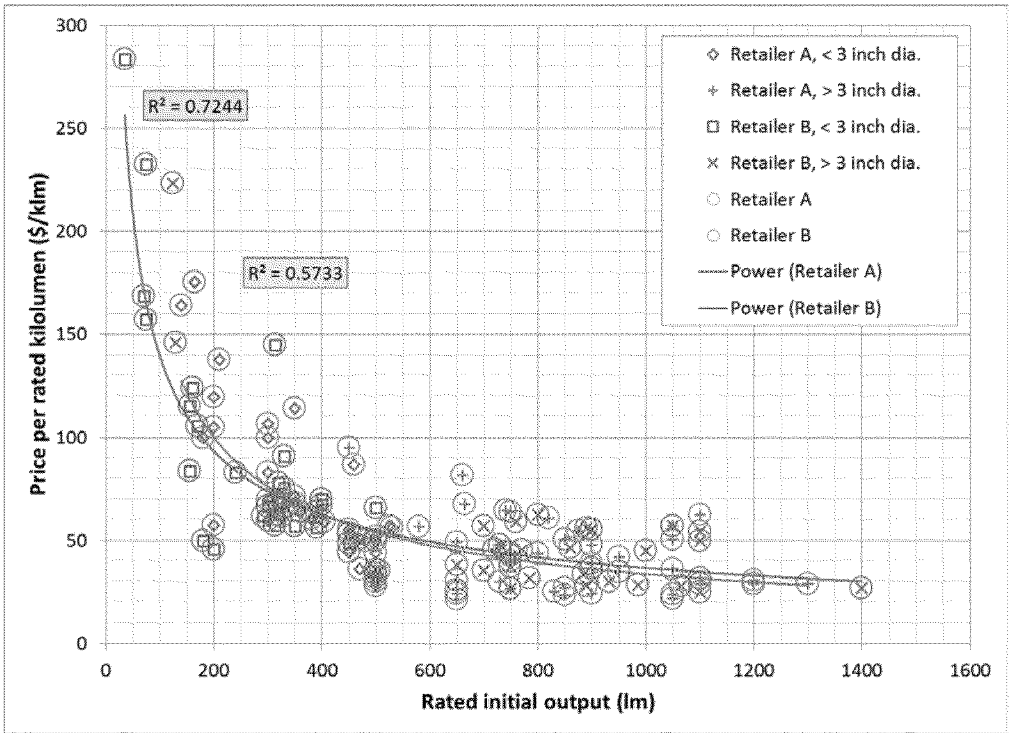

Figure 6.9 Rated output and pricing for selected LED directional lamps from two retailers

Table 6.1 Lowest pricing for LED directional lamps from each brand among the selected retailers at start of Q4 in 2013

Brand	< 3" diameter		> 3" diameter	
	Lowest pricing ($/klm)	Efficacy (lm/W)	Lowest pricing ($/klm)	Efficacy (lm/W)
A	28	56	22	62
B	44	56	24	72
C	69	57	25	61
D	30	50	25	64
E	49	56	27	61
F	57	67	27	58
G	*	*	27	61
H	50	55	28	55
I	*	*	31	68
J	46	50	36	70
K	67	66	42	54
L	56	49	45	51
Mean	50	56	30	61

* No model available for this brand at these retailers.

Table 6.2 applies the mean values from Table 6.1 to the lamp curve in Figure 6.8, yielding separate projections for larger and smaller lamps. Larger models are expected to approach $12/klm in 2017, roughly at parity with R30 CFLs. Smaller models are projected to approach $19/klm in 2017, roughly at parity with a GU10-based 35 W halogen MR16 lamp.

Table 6.2 Projected typical retail pricing for price-leading LED directional lamps with CCT of 2700-3000 K and sold individually

Lamp diameter	$/klm pricing at beginning of year			
	2014	2015	2016	2017
< 3 inch	47	36	28	22
> 3 inch	28	21	17	13

7.0 Discussion

The example provided in section 6.1 illustrates how a normalized pricing curve for LED lamps can be applied to current pricing for a specific product category—LED directional lamps—to generate future pricing estimates for that category. This generalized LED lamps curve can be applied to other lamp categories (e.g., omnidirectional and decorative), and the generalized LED luminaires curve can be applied to luminaire categories (e.g., troffers and streetlights) in a similar manner. Pricing projections for intermediate product categories (e.g., LED downlight retrofit units) might be performed by merging the generalized lamp and luminaire curves, perhaps giving more weight to the lamp curve if products in the intermediate category are considered more like lamps than luminaires, or vice-versa.

Whereas a pair of generalized curves for LED lamps and LED luminaires appears adequate for pricing projections, rates of change in efficacy appear to differ widely between product categories; consequently, no such normalization was performed for efficacy. Furthermore, it appears that in many cases the rate of improvement is reduced among products qualified by the voluntary ES or DLC programs (which specify minimum performance), relative to the broader set of products submitted to LF (which does not specify minimum performance). This discrepancy is presumably attributable to manufacturers focusing on cost reduction or other performance considerations once the relevant efficacy criterion is satisfied. In addition to the pair of efficacy curves (LF and ES or DLC) provided for each product category, efficacy curves generated from CALiPER data are also provided for some categories (depending on the adequacy of available data).

The following subsections provide additional discussion of the findings in this report.

7.1 Product variability

A given product model can fall above or below a corresponding efficacy or pricing curve for the product category. For example, a product that emits relatively little light but features a premium "fit and finish" desired by designers may fall well above typical $/klm price points for price-leaders in the category. Additional factors possibly influencing efficacy and pricing include:

- LED light source—the higher performance of newer model LED packages or LED modules/arrays may be accompanied by higher prices;
- LED drive current and thermal management—for a given model LED light source, fewer are needed (and at less cost) if driven at higher current, but this can compromise efficacy and longevity if thermal management is not improved commensurately;
- Dimmability—nominally dimmable products are often priced higher than non-dimmable products, and the associated premium can depend on the required performance and technologies involved;
- Quality of light—products with improved color and optical control may be more highly priced;
- Quality of construction—products with improved "fit and finish" and serviceability may be more highly priced;
- Benchmark price pressure—LED products may be priced higher in categories where the incumbent technology is priced highly and/or performs poorly (e.g., is marked by poor quality or high cost of ownership);
- Benchmark efficacy pressure—LED products may have lower efficacy in categories where the incumbent technology has relatively low efficacy;
- Buying power—large volume "bulk" purchases (or the promise of such purchases in the near future) can mitigate distribution costs and enable negotiated pricing.

The relatively low R^2 values and wide confidence bands associated with many of the efficacy and pricing curves are a reflection of the substantial variation among products on the market.

7.2 Mathematical model selection

Only power models are reported herein for pricing; however, exponential models were also evaluated by PNNL and determined to be equally applicable to the available data for all six product categories. Neither type of mathematical model yields a high R^2 value (i.e., good fit) for all product categories considered, but this is not surprising given the high variability in the market and the diversity of models tested by CALiPER within a given product category. The power mathematical models consistently yielded higher projected values in 2017 than the exponential models, but both types of mathematical model suggest the SCL (bulk purchase) luminaire pricing is on pace for the 2017 MYPP target. Power models were selected for use in this report based on the prior DOE projections for LED lamps and luminaires.

Although efficacy trends are assumed to be sigmoid in form,[21] a logarithmic mathematical model was used herein due to a lack of early data approaching the lower asymptotes.

7.3 Historical basis

These projections are based on historical data and do not anticipate future changes to criteria for efficacy and other parameters established by ES and the DLC. Similarly, these projections have not been adjusted to anticipate future changes in technology that could cause faster or slower-than expected growth or decay, such as a shift from phosphor-conversion (PC) technology to color-mixing technologies that offer greater efficacy potential. For example, projected average efficacy for LED troffers and downlights evaluated by CALiPER appears to be tracking closely with MYPP forecasts for LED luminaires utilizing

PC technology, as shown in Figure 7.1. If a substantial portion of LED lamp or luminaire manufacturers begin utilizing color-mixing technology in lieu of PC technology, new projected efficacy values offered in this report may prove to be somewhat understated.

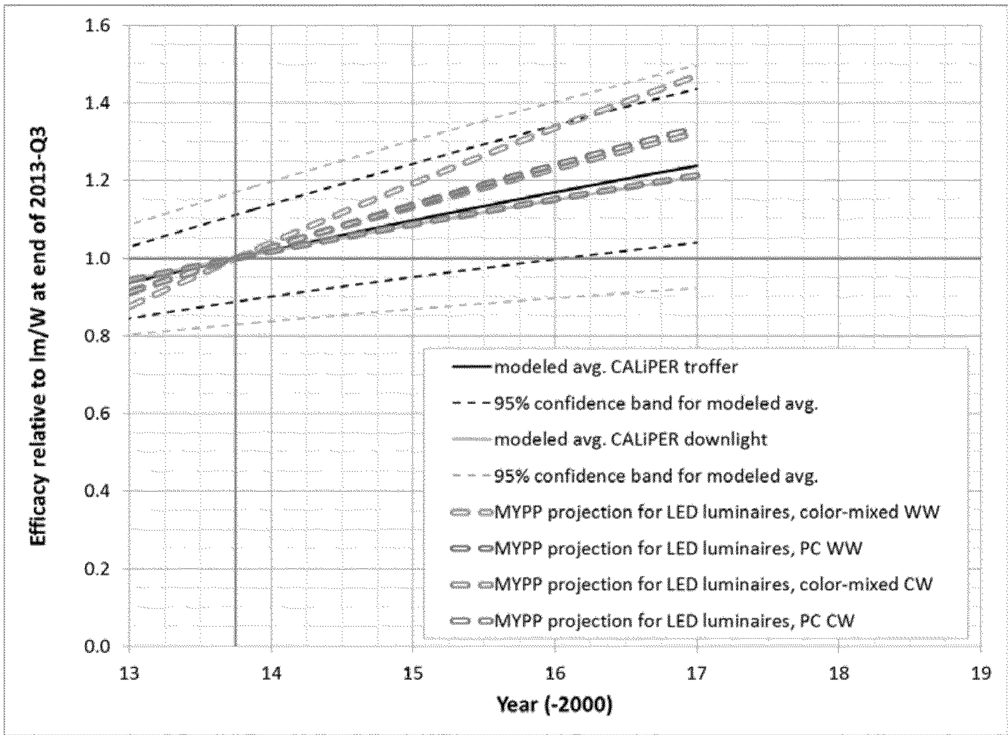

Figure 7.1 Efficacy projections for LED luminaires from CALiPER and the MYPP. The modeled average CALiPER downlight curve roughly overlaps the MYPP projection for PC CW LED luminaires.

7.4 Lumen output vs. pricing and efficacy

As illustrated in Figure 7.2, lamp efficacy for some benchmark technologies generally improves with increasing lamp wattage. For example, median 400 W high-pressure sodium (HPS) lamp efficacy is roughly 30% higher than at 100 W.[24] By contrast, efficacy for LED products is generally not highly dependent on lumen output. Exceptions include models offered with a choice of LED drive current; all other things being equal, such products generally offer higher efficacy at the lower drive current setting(s).

Compounding the issue of increased efficacy at higher wattages for some benchmark technologies, $/klm pricing for some of these products can decrease substantially as wattage (and lumen output) are increased, as illustrated in Table 7.1. By contrast, $/klm for LED products is generally not highly dependent on lumen output (i.e., LED product price can be nearly proportional to lumen output). Exceptions include lower-output LED lamps, as discussed in section 6.1.

If $/klm pricing for LED is comparable to a given benchmark at lower lumen values this may not hold true at higher lumen values. To mitigate this effect, LED and benchmark products should be selected for comparable lumen output.

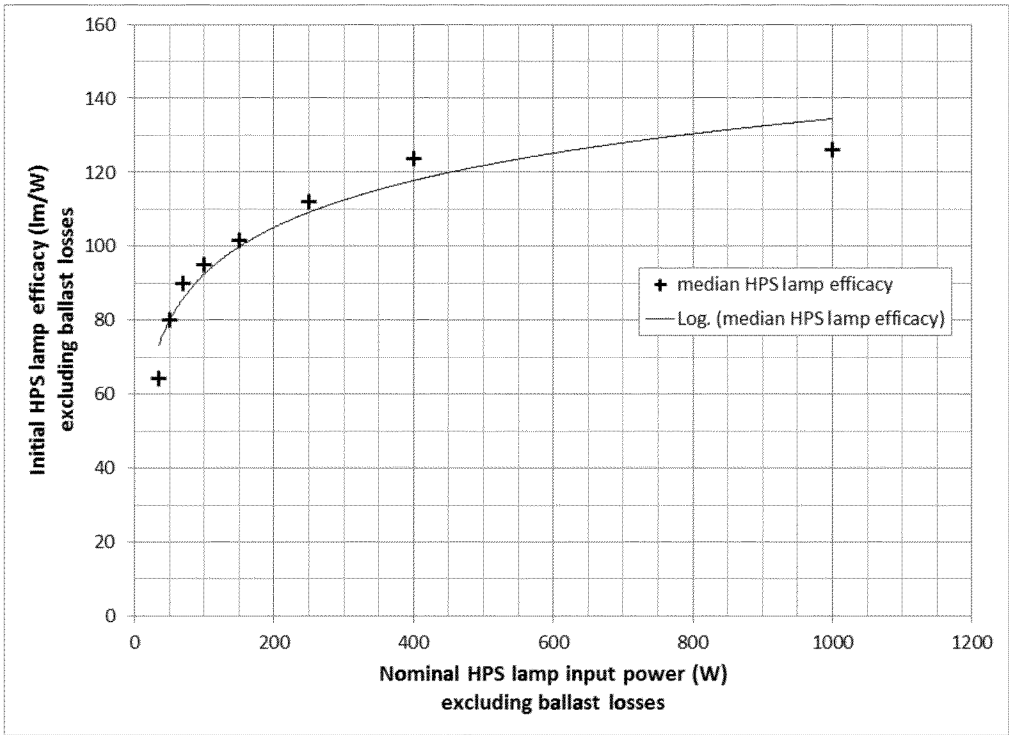

Figure 7.2 HPS lamp efficacy as a function of lamp input power [24]

Table 7.1 HPS lumens and pricing as a function of lamp input power [25]

HPS luminaire	150 W nominal		250 W nominal	
	Lumen output vs. 100 W	Luminaire price vs. 100 W	Lumen output vs. 150 W	Luminaire price vs. 150 W
Indoor	161%	102%	179%	104%
Outdoor	161%	102%	179%	103%

7.5 Equivalent illumination

The analysis performed for this report assumes LED products must match the lumen output of benchmark products; this requirement is built into ES and DLC criteria for several LED lamp and luminaire categories, and is necessary in such situations where site-specific parameters (e.g., spacing and mounting height) cannot be directly addressed in product specifications. However, it may be appropriate in some situations to use LED lamps or luminaires that do not match illumination levels produced by the benchmark technology—this practice can help to reduce waste while also minimizing LED product price.[26] Following are a number of scenarios that can enable reduced lumen output using LED products:

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- Existing illumination is deemed excessive by owner, occupants, etc.;
- The LED product offers higher utilization factor (i.e., application efficiency), delivering a greater percentage of its lumen output to the target;
- The LED product enables reduced average illumination via improved uniformity (e.g., in parking lots where minimum—rather than average—illuminance is often the criterion);
- The LED product offers improved lumen maintenance—for example, the L Prize winner has exhibited no lumen depreciation after more 25,000 hours of operation;[27]
- The LED product offers enhanced color—thereby improving photopic visual acuity,[28] mesopic vision,[29] or color contrast.[30]

The analysis in this report effectively assumes equivalent lumen maintenance for LED and benchmark technologies. Lumen maintenance can vary widely between different LED products, ranging from very poor to excellent,[27, 34] but the ES and DLC specifications mitigate the uncertainty by including criteria restricting lumen depreciation. It is best to obtain lumen depreciation curves specific to the products being considered—whether LED or a benchmark technology—to help ensure comparisons are equitable and indicative of long term operation. However, lumen depreciation is just one of a number of possible failure mechanisms for lighting products,[31] and LED product lifetime should not be estimated on the simple basis of estimated lumen maintenance—especially if available test data does not support the extent of extrapolation.[32]

7.6 Benchmark performance

Electrodeless fluorescent (i.e., induction) luminaire manufacturers considered for benchmark performance comparisons in this study were often found to publish rated lumens on product cutsheets without clarifying whether these values represented luminaire output or lamp output. Analysis of photometric reports and IES-format data files published by these manufacturers revealed luminaire output was as much as 31% lower than the lumen values indicated on product cutsheets (i.e., efficiencies were as low as 69%). Similarly, CALiPER testing has found efficiencies of 57% to 66% for induction streetlights and 66% for an induction garage luminaire.[33, 34] To ensure losses are accounted for, luminaire light output should be evaluated in lieu of lamp output for LED and induction luminaires. The IES has published an approved method for photometric testing of LED luminaires; no such test method exists for induction luminaires.[35]

Projections of efficacy or pricing for benchmark technologies are beyond the scope of this report.

8.0 Conclusions

An LED lamp or luminaire can generally be found that matches or exceeds the efficacy of benchmark technologies in a given product category, and LED products continue to expand into ever-higher lumen output niches.[36] However, the price premium for LED continues to pose a barrier to adoption in many applications, in spite of expected savings from reduced energy use and maintenance. Other factors—such as dimmability and quality of light—can also present challenges.

The appropriate type, timing, and magnitude of energy efficiency activities will vary from organization to organization based on local variables and the method of evaluation.[37] A number of factors merit consideration when prioritizing activities for development. Category-specific projections for pricing and efficacy are provided herein to assist in efficiency program planning efforts. Following is a summary of key findings from the analysis:

- Average efficacy for LED lamps and LED luminaires is projected to remain well below L Prize and MYPP thresholds through 2017, but given the high variability among products and the performance potential of new color mixing technologies, these goals might soon be met by leading products;
- In several key LED product categories (omnidirectional lamps, decorative lamps, downlight luminaires, and troffer luminaires) projected efficacies based on LED Lighting Facts listings are substantially higher than projections based on the corresponding ENERGY STAR or DesignLights Consortium (DLC) listings;
- Comparison of historical data compiled by CALiPER and Seattle City Light indicates two distinct normalized curves—one for LED lamps, and one for LED luminaires—can be used to make projections from current $/klm pricing for a given product category;
- LED lamp $/klm pricing is expected to decrease roughly 55% by 2017, relative to current pricing—a more modest decrease of 30% is projected for LED luminaires over this same period.

This report is intended to serve as a starting point—to be updated, detailed, and expanded in subsequent reports as appropriate based on input from utilities and energy efficiency organizations. Forexample, additional CALiPER data for LED troffer upgrade products—ranging from lamps to kits and luminaires—will soon be published and may enable additional trend analysis.

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