Best-in-Class List for LED Directional Lamps

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LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

blm	Beam lumens
CALiPER	Commercially Available LED Product Evaluation and Reporting Program (DOE)
CCT	Correlated color temperature
CRI	Color rendering index
DOE	Department of Energy
Duv	Distance from blackbody locus
IEE	Institute for Energy Efficiency
IESNA	Illuminating Engineering Society of North America
LED	Light emitting diode
lm	Lumen
LRC	Lighting Research Center, Troy, NY
NEEA	Northwest Energy Efficiency Alliance
PAR	Parabolic aluminized reflector
PF	Power factor
PNNL	Pacific Northwest National Laboratories
SCE	Southern California Edison
SPD	Spectral power distribution
W	Watt

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EXECUTIVE SUMMARY

The goal of this project was to develop a list of best-in-class LED reflector lamps that not only save energy, but also are likely to meet or exceed residential consumer expectations in their overall performance. In the case of lighting, this means excelling in visual parameters, compatibility with common controls, and cost-effectiveness. In the near term this will have the effect of pushing the market toward increased energy efficiency.

We began with ENERGY STAR's Qualified Bulbs list for PAR38 LED reflector lamps and PAR30 LED reflector lamps and developed multiple screening and testing methodologies to narrow down the list to a subset of top performers.

The overall evaluation consisted of five phases:

- Phase 1: Lamp selection
- Phase 2: Laboratory evaluations
- Phase 3: Human factors testing
- Phase 4: Scoring and ranking lamps
- Phase 5: Generating two lists of the ten Best-in-Class LED PAR30s and PAR38s

Results of this research will be publicly available on the IEE and TopTenUSA websites by December 2012. In addition to the two lamp lists, a key innovation of this research project is the pioneering and robust methodology developed by the research team, with considerable input from PG&E, other funding organizations, and lighting efficiency stakeholders. This methodology enables relatively straightforward updates to the initial best-in-class lists of PAR30s and PAR38s LED reflector lamps. It also lays the groundwork to expand into a multitude of other lamp shapes, sizes and technologies.

PG&E and other utilities can utilize these findings to provide a greater degree of promotion, education, and potentially larger incentives than they would normally provide to other LED lamps that bear the ENERGY STAR label. The selected lamps exceed ENERGY STAR's efficiency specifications, operate well on common LED-specific dimmers, produce beams of light preferred by participants in a human factors evaluation, and provide fast paybacks relative to other LED reflector lamps. While the ultimate goal of lighting efficiency programs is to save energy, the path to those savings is to highlight high quality, efficient products that everyday consumers will enjoy using and readily adopt. This study, which identified best-in-class LED reflector lamps through a rigorous series of laboratory and human evaluations, is an important advancement in the market transformation to high quality, highly efficient residential lighting.

INTRODUCTION

Reflector lamps are used to produce directional light. There are 840 million reflector lamps in use in the United States, found in a wide variety of downlight, track and accent applications (DOE, 2012). Of those, nearly 90% (737 million) are used in the residential sector. Incandescent and halogen models account for more than 80% (603 million) of the current residential installed base and just under 40% (38.9 million) of the commercial installed base. Over the past several years CFL reflector lamps have begun to make inroads into these markets, yielding significant energy savings. LED reflector lamps have become available much more recently, are particularly promising for this application because they are inherently directional and naturally suited to focusing their light into narrow and moderately wide beam angles. The focus of this study is LED reflector lamps that are marketed to residential customers and readily available in common retail channels such as big box stores and easily accessible online vendors.

ENERGY STAR has already labeled more than 900 new LED reflector lamp models, primarily on the basis of their energy efficiency and color performance, but those products can vary in purchase price, light quality, ability to be dimmed and other attributes of importance to consumers. Some utilities have simply decided to offer a fixed rebate and uniform promotional support to all ENERGY STAR models. Others offer supplemental incentives and promotion to the very best models, provided that they can develop a principled basis for selecting those products most likely to meet consumer expectations in a cost effective manner.

This research was co-funded by PG&E, Progress Energy, Southern California Edison (SCE), DTE Energy, MidAmerican and the Northwest Energy Efficiency Alliance (NEEA) with the intent of establishing just such a data-driven research and scoring process for selecting optimal LED reflector lamps. IEE (formerly known as the Institute for Electric Efficiency) coordinated funding from these utility and regional efficiency group sponsors and oversaw the technical research, which was conducted by Ecova in its Durango, Colorado research laboratory. TopTenUSA managed the project advisory group and is publishing the resulting findings in the form of two lists of the top ten models – one for PAR38 LED reflector lamps, and one for PAR30 LED reflector lamps.

BACKGROUND

As compared to general purpose light bulbs, or *lamps*, which produce omni-directional light, a reflector lamp is a cone-shaped bulb that creates a directional beam of light. Reflector lamps are typically used in recessed can, track and outdoor lighting fixtures, and are designed to either provide ambient lighting or illuminate a task, a floor, workspace or wall. Reflector lamps are an ideal choice when the light source must be a significant distance away from the illuminated area or light must be delivered unobtrusively and controlled within a very specific beam angle. They are designed for applications where the user wants to shine light in a particular direction, and provide a range of illumination options from a narrow column of concentrated light (spot lighting) to a broader cone of more diffuse light (flood lighting).

Incandescent reflector lamps come in a variety of types, shapes and sizes. The focus of this study is on LED replacement options for halogen parabolic aluminized reflector (PAR) lamps which constitute about one quarter of the reflector lamps in use in homes today in the United States.[1]

[1] Sources used in Ecova analysis:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf and
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

Today, most residential reflector lamps utilize conventional incandescent lighting technology. Early federal standards encouraged the broader use of halogen fill gas in many reflector lamps, which gave the resulting light a slightly whiter, cooler color while also increasing lamp lifetime and—to some extent—efficiency. In response to the most recent federal energy efficiency standards[2] that took effect in 2012, some halogen incandescent reflector lamps adopted infrared reflective coatings on their filament capsules to further improve efficiency; however, exemptions, exceptions and allowances in the law continue to permit the sale of many inefficient products.

In recent years, many CFL reflector lamps have come to market, offering energy savings and the promise of longer lifetimes over typical halogen reflector lamps. However, many CFL reflector lamps are not dimmable or do not dim in the same way that halogen reflector lamps do. Similarly, although a CFL reflector lamp can provide a broad swath of diffuse light much like an incandescent flood lamp, they are not able to focus their light in a more concentrated way like halogen lamps can, making them appear dimmer to many users. For these reasons, many consumers were not satisfied with CFL reflector lamps and reverted back to less-efficient incandescent and halogen lamps.

Early LED reflector lamp designs came with numerous performance limitations. They often consisted of multiple concentric rings of individual LEDs, each with relatively low light output, all aimed in the same direction, but with no optical lenses or diffusers to help blend the resulting beam into a smooth distribution. Very cool color temperatures (CCTs), sometimes appearing bluish-green or having color variations within the light patterns were also the norm in the early models. These lacked dimming capability and were often no more energy efficient, but still were far more expensive than the CFL reflectors with which they were intended to compete.

Over time, LED reflector lamps have improved considerably, now utilizing far fewer LEDs per lamp because the intensity of individual LED "chips" has dramatically increased. In conjunction, precision optics blend and control the chip array's light output better, generally producing smoother and more predictable beams. Advanced phosphor formulations now make possible warmer color temperatures (CCT) and higher color rendering indices (CRI), which combine to yield an overall appearance more comparable to the incandescent and halogen lamps with which people are familiar. Behind that appearance, they offer customers much longer lifetimes than halogen (30,000 hours or more), far better energy efficiency and a range of color palettes from which to choose. Dimmability is now commonplace, and is a prime focus of continuing development.

Though essentially identical in overall dimensions, today's LED reflector lamp models still differ in obvious cosmetic ways from the more familiar halogen reflector lamps. For example, most require thermal management elements in the form of metal heat sinks that contribute significantly to their size, weight and cost.

However, even with all the obvious benefits over our existing incandescent technology, a central question remains: Do they offer a compelling value proposition—are they sufficiently appealing for large numbers of consumers to pay $30-$100 apiece?

[2] See: http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/74fr34080.pdf

EMERGING TECHNOLOGY/PRODUCT

LED reflector lamps have been available for several years now, and today they are not typically considered an emerging technology. However, a mechanism by which to periodically identify the highest performing, best-in-class LED lamps is an emerging concept, or tool, that can help PG&E and other utilities spur market transformation. PG&E will be able to utilize this methodology and the resulting lists to support the burgeoning LED replacement lamp market as well as to increase customer satisfaction by continually assessing the top performing LED lamps.

ENERGY STAR's Qualified Bulbs list[3] has grown rapidly since the first LED lamp specification became effective in 2010 (see Figure 1). Therefore, a central goal of this research project was to help customers and utilities identify promising lamps by narrowing the list to 20 best-in-class ENERGY STAR LED reflector lamps (ten PAR38s and ten PAR30s). However, new, ENERGY STAR-qualified LED reflector lamps continue to become available at such a rapid pace that any list will become outdated quickly. The key innovation of this research project is the pioneering and robust methodology developed by the research team with considerable input from PG&E, other funding organizations, and lighting efficiency stakeholders. This methodology enables relatively straightforward updates to the initial best-in-class lists of PAR30s and PAR38s. It also lays the groundwork to expand into a multitude of other lamp shapes, sizes and technologies.

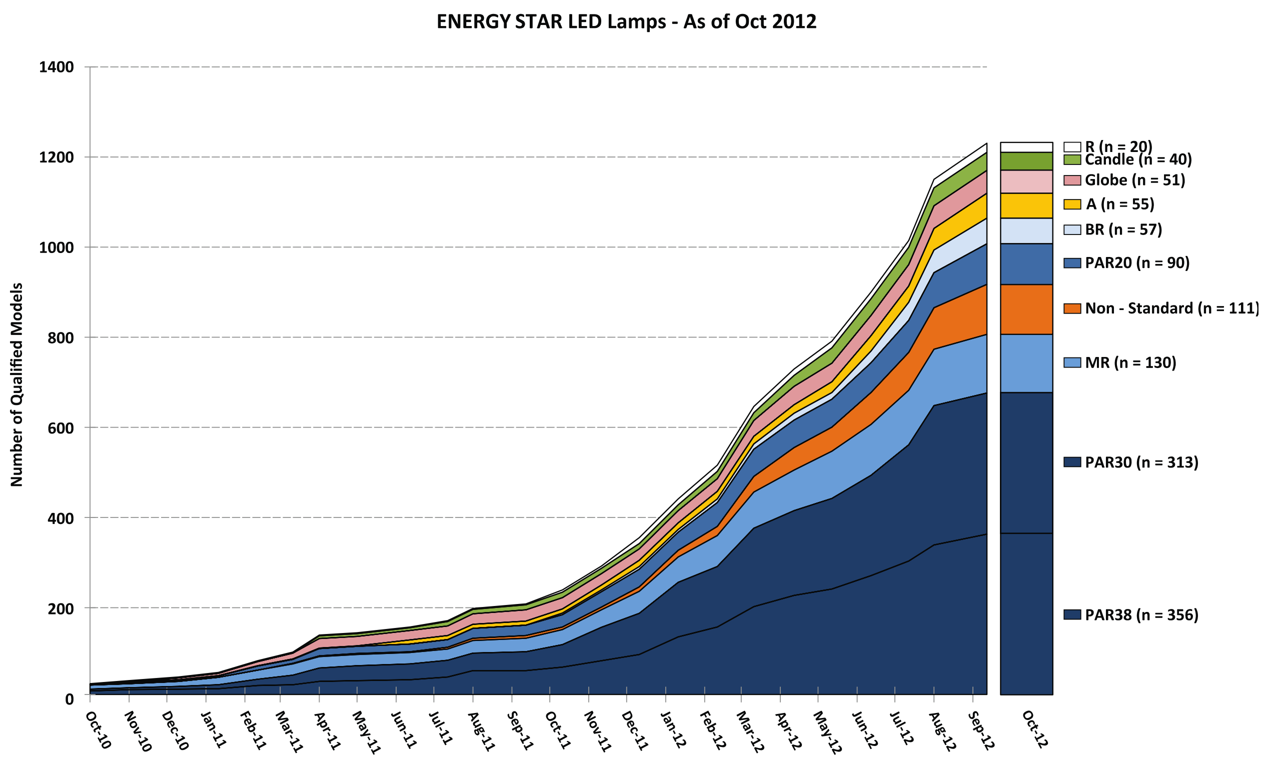

FIGURE 1. ENERGY STAR-QUALIFIED INTEGRAL LED LAMPS ARE INCREASING OVER TIME

[3] Lamps on the list meet the requirements of ENERGY STAR Integral LED Lamps specification Version 1.4 (effective August 2010)
Available from: https://www.energystar.gov/index.cfm?fuseaction=products_for_partners.showLightbulbs

ASSESSMENT OBJECTIVES

In this project, we sought to select 20 best-in-class LED reflector lamps—ten PAR38s and ten PAR30s—from ENERGY STAR's Qualified Bulbs list of more than 400 of these lamp types that were available at the outset of this project in July 2012. To do so, we screened that list for the lamps that met a more narrow set of requirements, and then we developed additional test methodologies and scoring metrics to help PG&E and the other research sponsors identify the best LED reflector lamps. First, we included *human factors research*, which systematically tallies preferences of a diverse group of users regarding beam pattern and color uniformity within that beam pattern for each lamp relative to all other lamps. For consumers to justify the additional cost of these lamps and use them in their homes, it is vitally important to understand which lamps typical users prefer.

Second, we included explicit consideration of cost effectiveness. Given the very wide range of energy savings and retail prices observed among the available ENERGY STAR LED reflector lamps, it is natural that PG&E and its customers would prefer those models that deliver the most energy savings for the least cost, all other things being equal. This aligns very closely with the notion of delivering value to consumers—being able to cogently summarize the benefits they receive for the additional cost they are being asked to pay when buying an LED reflector lamp.

Third, we directly measured or obtained third party data for other aspects of lamp performance that affect the user experience in a meaningful way, including dimming attributes, lighting color, energy efficiency, and ability to deliver the majority of their light output within a defined beam. We address each of these attributes in more detail below.

The goal of this project is to develop a list of best-in-class LED reflector lamps that not only save energy, but also are likely to meet or exceed consumer expectations in their overall performance. In the case of lighting, this means excelling in visual parameters, compatibility with common controls, and cost-effectiveness.

There are numerous benefits associated with conducting this additional degree of product testing and evaluation. Customers are more likely to purchase best-in-class models, especially if the screening and updating of those lists is done rigorously and frequently. PG&E customers who purchase best-in-class LED reflector lamps are more likely to be satisfied with their purchases and keep them installed in their frequently-used sockets rather than returning them to the store and replacing them with inefficient incandescent lamps. Perhaps most importantly, fully satisfied customers are more likely to speak positively to other customers about their experiences participating in this PG&E efficiency program, which ultimately contributes to the success of the utility's broader efforts to transform the residential lighting market to high quality, highly efficient lamps that consumers will enjoy using for years to come.

TECHNICAL APPROACH/TEST METHODOLOGY

OVERVIEW

The overall evaluation consisted of five phases:

- Phase 1: Lamp selection
- Phase 2: Laboratory evaluations
- Phase 3: Human factors testing
- Phase 4: Scoring criteria
- Phase 5: Generating two lists of the ten Best-in-Class PAR38s and PAR30s

PHASE 1: LAMP SELECTION

As part of Phase 1, Ecova used a screening process to choose PAR38 and PAR30 LED reflector lamps from the ENERGY STAR Qualified Bulbs list[4] on or before July 5, 2012 and met the following criteria:

- Are marketed as dimmable
- Have a CCT range between 2700 and 3000K
- Have an efficiency (lm/W) at least 15% better than ENERGY STAR's minimum requirement of 45 lm/W (which translates to 52 lm/W)
- Report a beam angle within a range of 20° to 40°, the most commonly available LED beam angles for PAR30 and PAR38 lamps.

This screening process reduced the initial 243 PAR38s and 229 PAR30s down to 110 and 113, respectively. The remaining lamps contained some identical or similar models, so the final steps were to choose one model within each of the following product families:

- One unique model per manufacturer — if otherwise identical lamps were available with slightly different sets of features (e.g. exterior finishes, base types)
- One unique manufacturer — if otherwise identical lamps were obviously sold under more than one private label, we based our brand purchase first on the lamp's availability through a common retail channel, followed by price.
- One beam angle — within a make and model of similar products

Applying the above criteria for evaluation reduced the possible candidates to the following quantities. See FIGURE 2.

- PAR38 lamps — 243 ENERGY STAR → 31 final candidates
- PAR30 lamps — 229 ENERGY STAR → 32 final candidates

[4] https://www.energystar.gov/index.cfm?fuseaction=products_for_partners.showLightbulbs

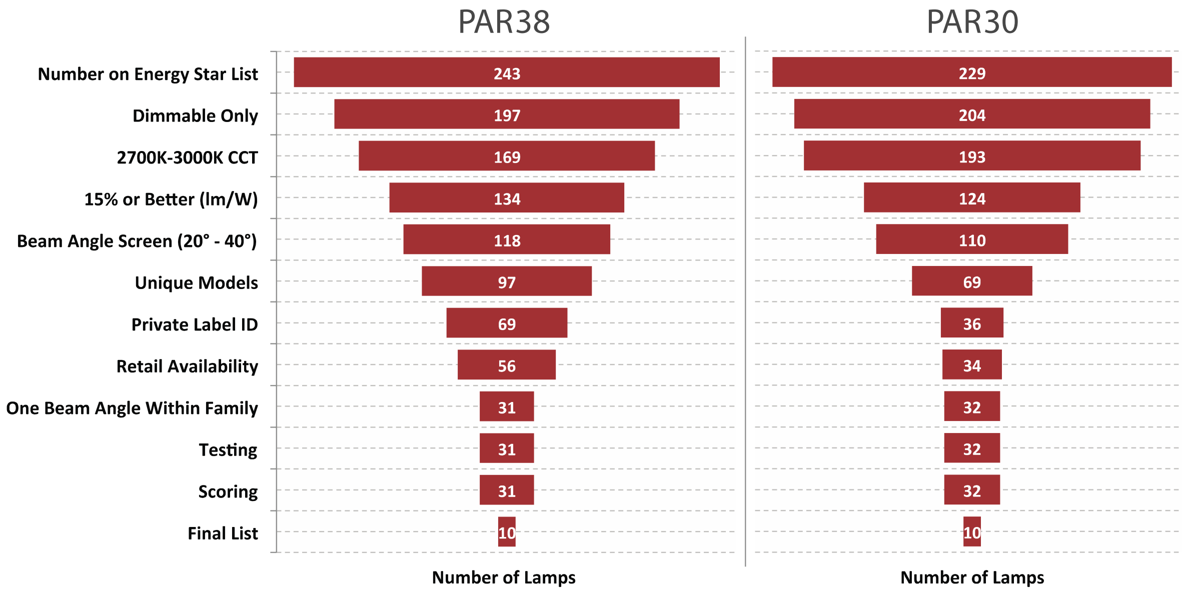

Figure 2. Funnel diagram illustrating product selection criteria

PHASE 2: LABORATORY EVALUATION

OVERVIEW

The next phase of the ranking assessment included a laboratory evaluation of product performance. For photometric parameters such as electrical power, efficiency, chromaticity and total luminous flux we followed the Illuminating Engineering Society of North America (IESNA) LM-79-08: IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products (IESNA, 2008) with one minor deviation.[5] All tests were performed using an integrating sphere with reference power sources and calibrated power analyzers.

DIMMING METHODOLOGY

Dimming is a critical factor to mass-market adoption of LEDs (Cooper, 2011); however, an accredited dimming test methodology has not yet been adopted. As of this writing, many institutions are currently researching the topic, including The Department of Energy's (DOE) Commercially Available LED Product Evaluation and Reporting (CALiPER) Program, Pacific Northwest National Laboratories (PNNL), the Lighting Research Center (LRC) and others. For this research, we designed a methodology to predict whether a typical residential consumer will experience acceptable dimming performance with the LED lamps we evaluated. By developing our own procedure, the intention was not to replace the work of the above

[5] To measure a number of products of the same model, LM-79 permits the pre-burning of lamps before testing if it has been demonstrated that the method produces the same stabilized condition as when using the standard method. To save time, Ecova pre-burned lamps and achieved similar results, but the lamps were not all the same model.

organizations, but rather to identify a reproducible methodology appropriate for this research.

While the dimming evaluation is not an accredited test, we followed all relevant accredited test procedures as set forth in IESNA LM-79. For example, before collecting quantitative data, we stabilized lamps as needed to achieve less than ±0.5% variation in light output over three consecutive measurements taken 15 minutes apart. Due to the wide variety of dimmer types installed in homes and available in stores, we chose to test each LED lamp on two types of dimmers:

- A "traditional" incandescent dimmer — Leviton, model 6681, Push On/Off rotary dimmer
- A dimmer designed to be compatible with LED light sources — Lutron C·L, model TGCL-153PH-IV

FIGURE 3. TRADITIONAL INCANDESCENT (LEFT), AND LED-SPECIFIC DIMMERS (RIGHT)

The "traditional" unit is the typical rotary type dimmer, originally introduced in 1959 as a device that could fit into a household wall box. These dimmers are relatively unchanged in their basic design and function, and represent the worst-case (but very probable) scenario where a consumer purchases an LED lamp without referencing the manufacturer-provided list of compatible dimmers, or simply may not know what type of dimmer already controls the circuit on which the LED will be installed. In contrast to the traditional dimmer, "LED specific" dimmers employ specific strategies to deal with low wattage lighting loads, such as solid state lighting and CFLs.[6]

Much as any consumer would make a purchase, we chose the ubiquitous push-on/push-off rotary-type dimmer based on its availability and lowest cost at a walk-in national home center. The LED-specific dimmer was chosen during a store visit because it was the only model on the shelf that explicitly branded itself for use with "dimmable CFL and LED bulbs."[7]

The Lutron LED-specific dimmer (pictured on the right, above) has a mechanism to adjust for the low end of the dimming range that is concealed behind the wall plate. Before collecting photometric data points, we connected each lamp to the dimmer and adjusted the dial to produce the least amount of light possible without flicker or audible noise. The level of dial adjustment was recorded in the testing notes for that sample. We then collected photometric, energy and performance data points at the following four conditions of light output:

- 100% full light output
- 20% of full light output
- Lowest flicker-free light output setting (while dimming down from full power)

[6] Although LED-specific dimmers also operate other low wattage light sources, such as CFLS, our evaluation focused specifically on dimmer behavior when operating LEDs.

[7] This dimmer also claimed to be compatible with incandescent halogen sources up to 150W.

- Lowest flicker-free light output setting (while dimming up from the off-state)

Photometric and energy data collected:

- Photometric Data (measured with SphereOptics 20-inch integrating sphere)

  Light output – lumens (lm)
  Correlated color temperature (CCT) – °K
  Color rendering index (CRI)
  Chromaticity coordinates – *X*, *Y*, *Z*, *u'*, *v'*, Duv
  Spectral power distribution (SPD)

- Energy Data (measured with Voltech PM300)

  Power – Watts
  Current – Amps
  Power Factor (PF)

- Performance (assessed by human observation)

  Audible noise
  Perceptible flicker

Performance parameters had to be confirmed by two Ecova researchers standing 3 feet in front of the open integrating sphere. To fail the test, the two researchers had to agree that the lamp in question was flickering or making noise.

We collected photometric, energy, and performance data at each light output level, and then analyzed the data to determine which lamps pass or fail the minimum performance criteria.

The minimum passing requirements were, for each dimmer:

1. Must be able to dim down to 20% of the full rated light output.
2. Restrike ratio, which is derived from the difference between cut-out and pop-on levels, must not exceed 25% of full rated light output.[8] (see Equation 1)

   Restrike example – A 1000 lm lamp that cuts out at 100 lm and pops on at 350 lm

$$350lm - 100lm = 250lm \rightarrow \frac{250lm}{1000lm} = 25\% = PASS, BORDERLINE$$

EQUATION 1. RESTRIKE RATIO

3. CCT must not increase more than 100K (cooler) throughout full dimming range.
4. Must not exhibit any perceivable flicker in 100-20% rated light output dimming range.
5. Must not exhibit any perceivable audible noise in 100-20% rated light output dimming range.

If a lamp did not meet all of the minimum-passing requirements outlined above on the LED-compatible dimmer, we removed it from consideration for the TopTen list. Lamps that did

[8] Cut-out = the light level where the lamp turns off when ramping down. Pop-on = light level where the lamp turns on when ramping up from the state of fully-off.

not meet the requirements on the traditional incandescent dimmer remained in the broader evaluation; however, performance on the incandescent dimmer affected each lamp's total score in the scoring portion (Phase 4) of this research.

PHASE 3: HUMAN FACTORS TESTING

In the human factors portion of the research, we measured people's preference for the beam patterns of LED reflector lamps. The uniformity of beam patterns, their smoothness and predictability is not captured in traditional lighting metrics. This human factors study determined whether those differences mattered.

Here, each of 15 subjects was asked to evaluate the appearances of the 31 PAR38 and 32 PAR30 lamps selected during Phase 1. The participants were a diverse group of 8 females and 7 males with a variety of professions and backgrounds, representing a rough cross section of the general population. To suppress subject bias, we chose not to include people who specialized in the lighting or energy fields, nor who were artists, photographers, or anyone who would bring a heightened visual sensitivity to the light they saw. Only one subject at a time was present in the test area so that any one individual's impressions did not influence the other subjects. Using a commonly employed comparative method (Houser, 2010), subjects were presented with pairs of lamp beams projected simultaneously on a wall surface. We asked subjects to select the light they preferred in each pair. All of the 112 comparisons were randomized to eliminate both position and order effects, but every lamp was compared to every other lamp. Subjects marked a datasheet indicating whether they preferred the beam on the left or right. The votes were tallied after all subjects had participated, and lamps receiving the most votes scored highest in the human factors portion of the study. For both PAR38s and PAR30s, each lamp had the possibility of earning up to 105 votes. In total, we collected 1,680 decision points during the experiment for each lamp type. See Figure 4.

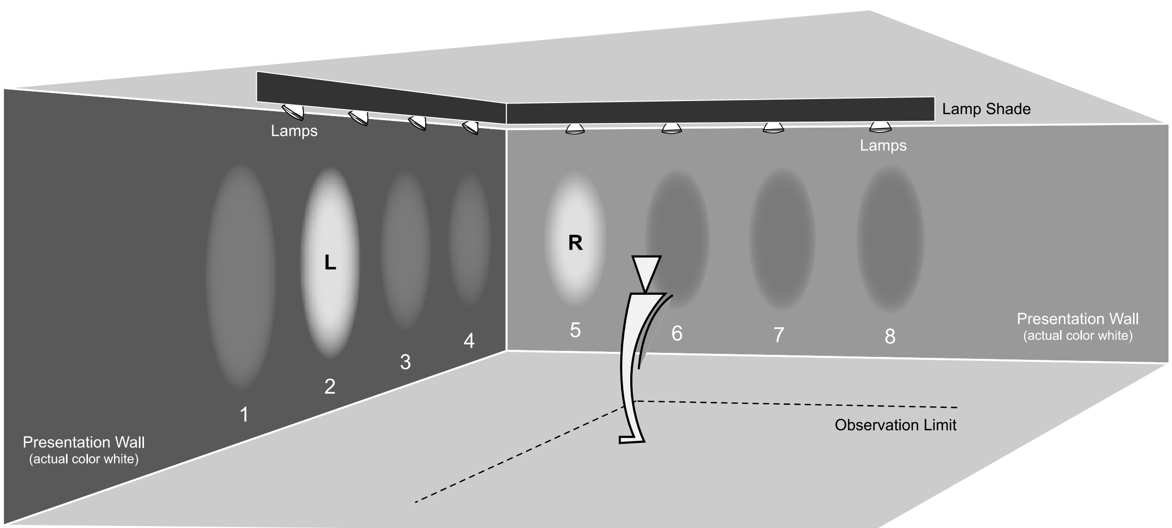

FIGURE 4. HUMAN FACTORS PAIRED LAMP STUDY SETUP

To produce a reasonably common residential example of light beams upon a wall, we suspended two 16-foot tracks in an "L" shape at a fixed distance of 24 inches from a vertical wall. Each track carried four lamp sockets spaced at 4-foot intervals. We used seamless cyclorama paper to create a matte-white, diffusely reflective continuous wall surface. When lamps were placed in the sockets, they were 86 inches off the floor and 22 inches from the wall surface. The lamp-to-wall distance accommodated lamps of varying beam widths and had no affect on a subject's perception of patterning (van Kemenade, 1988). The beams were at a 35° angle from nadir, typical of what might be found in residential applications. Each beam was visually centered at an eye-level elevation of 53 inches and we shielded the lamps with dark cloth to block possible backspill and prevent subjects from identifying any by their shape. Subjects maintained a minimum distance of 7 feet (84 inches) from the wall to keep views consistent and avoid casting shadows on the beam patterns. A table lamp in the back of the room maintained a low ambient light level between sessions so subjects' eyes did not have to readjust. All sockets were measured at 123.2 V. See Figure 5.

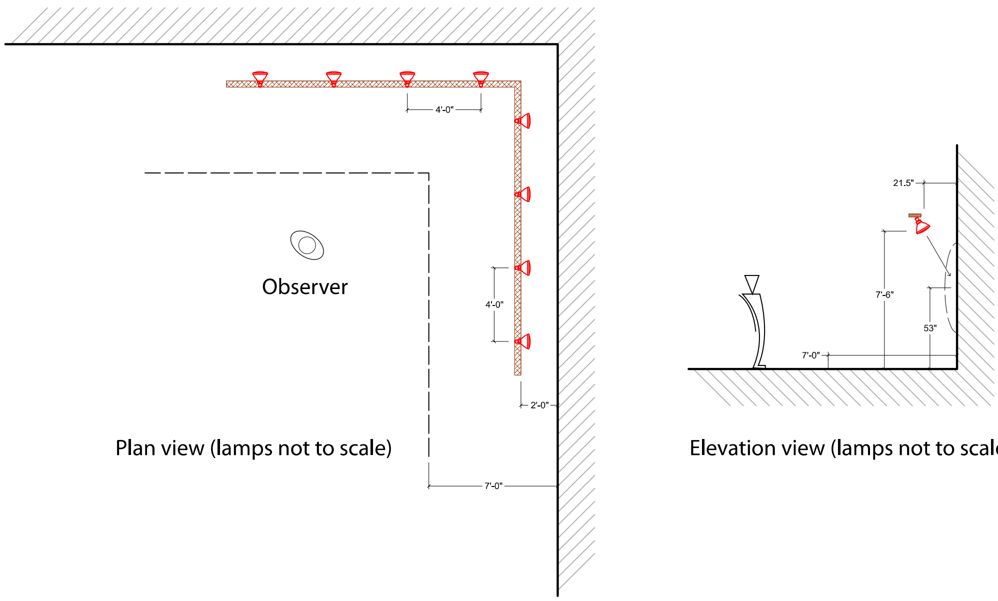

FIGURE 5. HUMAN FACTORS PAIRED LAMP STUDY SETUP, PLAN AND ELEVATION

PHASE 4: SCORING METHODOLOGY

With input from the research sponsors and stakeholders, we designed a scoring system to address the needs of utility efficiency programs that is similar in concept to other well-known ranking systems like LEED or Consumer Reports. These kinds of scoring systems are finding increasing use in comparing products with a wide variety of advantages and disadvantages, because they can be tailored to speak to the type of product being evaluated. When faced with a mix of product features and tradeoffs, a scoring system can be used in lieu of a set of mandatory criteria, which treat all qualifying products equally.

We developed five overarching categories—energy, economics, laboratory measured performance, human factors, and physical—then assigned a maximum available score for each category. Most categories have sub-categories so that we could address each metric in a variety of ways. Lamps could earn from 0 to 100 points on this scale; however, because our intent is to use this same scoring methodology for future updates as products improve, we made it rigorous enough so that no lamp in this round would approach 100 points. This leaves open the possibility for new lamps to out-rank existing lamps in future evaluations.

Below we explain each ranking criteria in turn. See Table 1 for a summary. We awarded points for all categories on a sliding scale between zero and the maximum shown for each category.

Scoring Categories	Weighting (Points)
Energy	**24**
Efficiency exceeds ENERGY STAR requirements (15% or better)	11
Beam efficiency	10
Power factor	3
Economics	**20**
Simple payback	10
Cost of light	10
Laboratory measured performance	**31**
Lumen output (measured vs. rated)	10
CRI variance (color rendering index)	6
Duv (distance from blackbody locus)	5
Dimming behavior (on incandescent dimmer)	10
Human factors	**22**
Paired comparison evaluation	22
Physical	**3**
Weight	3
Highest Possible Score	**100**

TABLE 1. RELATIVE WEIGHTING OF LAMP PERFORMANCE CRITERIA

Energy

We focused on three energy efficiency metrics to rank overall lamp energy efficiency. Lamps could earn up to 24 points in this category.

Efficiency exceeds ENERGY STAR requirements (15% or better). Products earn points in this category based on the percentage that they *exceed* ENERGY STAR requirements. All lamps considered for this project had to exceed ENERGY STAR by at least 15%. If a lamp exceeded ENERGY STAR's minimum requirements by 80% we awarded it the full 11 points.

Beam efficiency. A measure of the useful light within a reflector lamp's stated beam angle, divided by the total lamp power, or *beam lumens per watt* (blm/W). This category rewards directional lamps for placing the light where you want it and minimizing the electrical power needed to do so. The brighter the beam, the more light is contained within the beam angle. We awarded up to 10 points to lamps that effectively produce and direct light while using minimal power. Lamps begin to earn points at 15 blm/W, up to a maximum of 45 blm/W.

Power factor. Products with a power factor nearest to 1.0 cause fewer distribution losses in building wiring[9]. ENERGY STAR lamps that draw 5 or more watts are required to have a minimum PF ≥ 0.7. Products are awarded points for the extent to which they exceed ENERGY STAR power factor requirements, and can earn up to 3 points for a PF = 1.0. Currently, no LED PAR replacement lamp on the ENERGY STAR list achieves a PF = 1.0.

Economics. We included two economic criteria—simple payback and cost of light—into our overall lamp assessment. Lamps that pay back the fastest and provide light least expensively can earn up to 20 points in this category.

Simple payback. Using average purchase price[10] and kWh saved[11], we calculated simple payback, measured in years. Simple payback is the amount of time it will take to recover the initial investment in energy savings. See Equation 2. We awarded 10 points to lamps with payback periods of 8 years or less, with fewer points awarded for longer paybacks and no points for paybacks of longer than 8 years.

$$simple\ payback = \frac{cost}{savings} = \frac{cost\ of\ lamp\ (\$)}{\left(\frac{\Delta \mathrm{W}}{1000}\right)\left(\frac{\$}{\mathrm{kWh}}\right)\left(\frac{\mathrm{h}}{\mathrm{day}}\right)\left(\frac{\#\mathrm{days}}{\mathrm{year}}\right)} = years\ to\ repay$$

where,
ΔW = wattage difference between the LED lamp and the halogen lamp it replaces[12]
kWh = kilowatt hours
h = hours of use
# days = 365

EQUATION 2. SIMPLE PAYBACK EQUATION

Cost of light. The cost of light incorporates the purchase price of the product, the amount of light it produces and the cost of the energy drawn by the lamp over a lifetime of 25,000 hours. We awarded 10 points to lamps with the lowest cost of light. Cost of light is measured in dollars per million-beam-lumen-hours ($/mblh). Lamps begin earning at $16/mblh, earning a maximum number of points at $2/mblh or less.

Laboratory measured performance. In this section, we evaluated reported laboratory performance values on a number of parameters. ENERGY STAR sets an acceptable range for correlated color temperature (CCT) and a minimum for color rendering index (CRI). Hundreds of LED reflector lamps now on the market meet these two specifications. To select the ten best lamps, we employ a narrower set of requirements that quantify subtleties in color and performance that mimic the halogen incandescent bulbs with which consumers are familiar. Lamps with the most halogen-like behavior may achieve the highest overall score of 31 points for this category.

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[9] http://efficientpowersupplies.epri.com/pages/Latest_Protocol/Power_Factor_Report_CEC_500-04-030.pdf

[10] Purchase price was the average taken from all products on Google Shopping.

[11] Energy savings ("kWh saved") were based on the difference between the rated wattage of the LED lamp and the rated wattage of the incandescent or halogen lamp it replaces.

[12] Calculated using the ENERGY STAR Center Beam Candle Power (CBCP) tool: http://energystar.supportportal.com/link/portal/23002/23018/Article/32655/For-the-Center-Beam-Candle-Power-CBCP-tool-should-a-certification-body-use-the-measured-or-reported-value-to-evaluate-the-products

Light output. Laboratory-measured light outputs were compared to the manufacturer-reported values on the lamp packaging. We awarded 10 points to lamps that met or exceeded their reported light output. Lamps still received points when measured down to −15% of their claimed light output value.

Color Rendering Index (CRI) Variance. ENERGY STAR-qualified lamps must have a CRI of 80 or greater, which requires that manufacturers follow the industry standard practice of deriving CRI based on tests of 8 standard color swatches. In our study, LED lamps could earn a maximum of 9 points for having a CRI of 100, which is the same as that of most halogen incandescent light sources.[13]

Duv. Color measurement metrics attempt to reduce color qualities down to a single number. Because of this, two lamps can still have a different color appearance even though they may have the same CCT, due to other subtleties about their color that CCT doesn't measure. Duv is a supplemental metric for capturing the subtleties more specific to LEDs. While incandescent sources tend to deviate from "whiteness" in a yellowish to bluish manner, solid state lamps tend to shift between greenish to pinkish. Duv measures this shift. LEDs are rewarded for having minimal Duv, and appearing most similar to halogens in color. Lamps earned up to 4 points by displaying minimal Duv, and earned 0 points if they exceeded the ENERGY STAR maximum of 0.006.

Dimming behavior. Using the test procedure described above, lamps could earn up to 10 bonus points if they passed the minimum criteria on the incandescent dimmer. They earned 0 points for passing minimum criteria on the LED-specific dimmer; however, if they failed the LED-specific dimmer tests, they were removed from consideration for the final best-in-class lists.

Human factors. Lamps that earned the highest scores in this category received the most votes from our 15 subjects. A lamp could earn up to 22 points in this category.

Physical. Excessively heavy LED PAR lamps could torque track cans, or render fixtures inordinately top heavy, which could lead to negative consumer sentiment. In addition, heavier lamps may have greater overall environmental impacts from the energy associated with manufacturing and shipping. Therefore, we awarded up to 3 points to lamps that were equal to, or lighter than an average halogen PAR lamp.

RESULTS

In total, we reviewed data on 472 PAR38 and PAR30 LED reflector lamps, and purchased 63 (31 PAR38, 32 PAR30) for laboratory testing and human factors evaluations. Even within this sub-set of lamps, we found a wide variety of physical lamp designs, performance characteristics, and prices.[14] Some of our most notable findings were related to measured versus rated light output and power values, dimming performance, human factors testing, and purchase price compared to lamp preference.

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[13] Halogen incandescent light sources have CRIs of 95 to 100. Higher CRI means that a light source should render objects more naturally, and in some cases, more vividly.

[14] See Appendix 1, Table 4 and Table 5 for manufacturers' offerings of alternate beamspreads and color temperatures within the line extensions of best-in-class lamps.

PAR38		mfg	model #	beam angle	CCT	lm	W	lm/ W	lamp
Rank	Score								
1	62.6	TCP	LED17E26P3830 KNFL	25°	3000K	1050	17	61.8	
2	59.3	Philips	18PAR38/END/F 36 2700-900 DIM SM	36°	2700K	900	18	50.0	
3	57.7	Philips	18E26PAR38-4	25°	3000K	1200	18	66.7	
4	56.6	ATG Electronic s	HSL-PT20W-38120D-H1	25°	3000K	1100	20	55.0	
5	53.9	Utilitech	L18PAR38/DM/L ED	38°	3000K	885	18	49.2	
6	52.6	Toshiba	LDRB2030ME6U SD2	25°	3000K	1120	20	55.2	
7	52.5	Philips	18PAR38/END/F 25 3000-950 DIM SM	25°	3000K	950	18	52.8	
8	50.8	Greenlite	20W/LED/PAR3 8/FL/D	40°	3000K	1200	20	60.0	
9	50.5	TCP	LED17E26P3827 KNFL	25°	2700K	950	17	55.9	
10	48.3	NaturaLE D	LED17PAR38/DI M/NFL/30K	25°	3000K	950	17	54.8	

TABLE 2. LED PAR38 BEST-IN-CLASS LIST

PAR30 Rank	PAR30 Score	mfg	model #	beam angle	CCT	lm	W	lm/ W	lamp
1	63.7	ecosmart	ECS R30 WW V2 FL 120	40°	3000K	950	17	55.9	
2	61.8	Lighting Science Group	DFN 30 WW V2 FL 120	40°	3000K	950	18	52.8	
3	56.2	TCP	LED14E26P3030 KNFL	25°	3000K	820	14	58.6	
4	55.8	Philips	13PAR30L/END/ F25 2700-800 DIM	25°	2700K	800	13	61.5	
5	54.0	Philips	12PAR30L/END/ F36 3000 DIM	36°	3000K	700	12	58.3	
6	52.5	Philips	12PAR30L/END/ F36 2700 DIMM	36°	2700K	660	12	55.0	
7	51.9	LightKiwi	LK-PAR30- 6BV40	40°	3000K	620	10	62.0	
8	51.4	TCP	LED14E26P3027 KNFL	25°	2700K	820	14	58.6	
9	50.7	Verbatim	P30ES-LN-L800- C30-B25	25°	3000K	800	14	57.1	
10	50.5	Nu Vue	NV/PAR30/ES/6. 1/D/WW/NFL/2 6/CX	25°	3000K	620	10	62.0	

TABLE 3. LED PAR30 BEST-IN-CLASS LIST

Measured versus rated light output and power

While all lamps of these report their rated light output (lumens) and power (watts) on their packaging as well as to ENERGY STAR, we measured these and other criteria in our lab to determine how well the reported specifications matched the performance of the samples we had purchased.

Energy use observations

For the PAR38 LED reflector lamps, 27 out of 31 lamps tested for lower energy consumption than the manufacturer claimed on the package. 25 out of 31 were within a range of −10% to 0% than that claimed on the package. 2 out of 31 were −15%. 4 out of 31 tested higher than rated, showing a maximum of up to 4% over the reported value.

For the PAR30 LED reflector lamps, 22 out of 32 lamps tested for lower energy consumption than the manufacturer claimed on the package. 19 out of 32 were within a range of −10% to 0% than that claimed on the package. 3 out of 32 were down to a minimum of −13%. 10 out of 32 tested higher than rated, 8 lamps were within 10% over claimed light output, one being 12% over.

Light output observations

For the PAR38 LED reflector lamps, 19 out of 31 tested at, or above their manufacturer-rated value. 11 out of 31 were within a range of 0 to 10% of this. 8 out of 31 lamps produced over 10% more light than claimed, with a maximum output of 20% over. 12 out of 31 lamps tested below their rated value. 9 out of 31 fell to less than 0 to −10% below, while 5 out of 31 fell more than −10% of their rating, with a minimum of −18% below their manufacturer-claimed light output.

For the PAR38 LED reflector lamps, 22 out of 32 tested at, or above their manufacturer-rated value. 16 out of 32 were within a range of 0 to 10% of this. 6 out of 32 lamps produced over 10% more light than claimed, with a maximum output of 30% over. 10 out of 32 lamps tested below their rated value. 9 out of 32 fell to less than 0 to −10% below, while 1 out of 32 fell more than −10% of their rating, with a minimum of −12% below their manufacturer-claimed light output.

Dimming performance

To be considered for the final best-in-class list, a lamp had to pass all of the dimming criteria on the LED-specific dimmer. Six lamps (3 PAR38s and 3 PAR30s) failed to do this, and were dropped from consideration for the Best-in-Class LED list. Of the 57 that remained, only 9 (4 PAR38s and 5 PAR30s) failed our minimum requirements on the traditional incandescent dimmer.

Human factors

Both in their comments and voting patterns, subjects slightly favored lamps of average or above average brightness over lamps of below average brightness. They also expressed a slight preference for 3000K lamps over 2700K lamps. After testing, interviews revealed that our subjects found the following attributes pleasing: no color variation across the beam, symmetrical beam spreads and smooth, tapering beam edges.

Purchase price compared to lamp preference

A simple finding could have been that you get what you pay for with LED reflector lamps. In fact, we found that purchase price is not a clear predictor of efficiency, dimming performance, or human factors preference. One of the least expensive lamps was the most efficient.

In summary, there is a wide variety of LED reflector lamps available to residential consumers, and no one attribute is the sole indicator of which lamps customers will prefer. Our resulting lists of the ten best-in-class PAR30s and PAR38 LED reflector lamps are derived from the criteria and scoring system described earlier in this report. Results are presented in Table 4 and Table 5.

CONCLUSIONS AND RECOMMENDATIONS

At the outset of this research, it was unknown if human subjects could qualitatively evaluate the performance and lighting quality of LED reflector lamps in a way that would be as rigorous and useful as measuring those same lamps in the laboratory. We found that human factors testing results are quite robust and useful if sufficient attention is paid upfront to test setup and methodology. In the end, human subjects were able to express a statistically significant preference for certain lamps over others. They also similarly rated instances of identical, but rebranded versions of the same lamp, even when they and the operators running the test were unaware of the location of those lamps in the sample set. Human factors testing proved to be reproducible, reliable and quantifiable in a way that clearly complements laboratory performance testing. This suggests that human factors fundamentally belong within the set of lamp attributes being assessed by utilities in deciding which LED lamps to promote or rebate.

Similarly, at the outset of this research it was not possible to discern whether the scoring system would be robust enough to select a fairly similar set of Top Ten LED reflector lamps, even if the score weights were to shift modestly from one attribute to another. We found, in fact, that the final list is quite resilient under a wide variety of scoring scenarios. Certain LED reflector lamps consistently rise to the top, for a few very good reasons:

- **They save a significant amount of energy relative to their incremental cost**, so they provide a relatively short payback time to their purchaser *and* a cost effective efficiency resource to the utility that chooses to support them.
- **Their light beam is controlled, uniform, free of shadowing or color aberrations.** In other words, it does not call attention to itself in unexpected ways, but rather, delivers its light cleanly and unobtrusively into the living space, whether operating at full brightness or when dimmed.
- **It is no longer sufficient simply to publish only numbers on specification sheets.** That kind of thorough documentation *helps*, but metrics like efficiency, CRI, Duv and CCT measure only a portion of what the humans who are buying the lamps really care about, and numerical charts do not tell consumers the complete story about what they will see. Ultimately, people purchase light bulbs to provide light, not to save energy, and it is entirely reasonable for them to expect highly aesthetic lighting performance, and to receive good value for the additional investment they are being asked to make.

We were encouraged to see that the TopTen lists consist of a wide array of manufacturers; no single company or product design dominates. Similarly, the winning lamps are not always the brightest lamps assessed, though brighter models were, in general, slightly more cost effective than the dimmest models.

Perhaps most importantly, we learned that creating a Top Ten list of LED reflector lamps is not simply a matter of choosing the ten most energy efficient models in each lamp size. This approach is more commonly used with some other Top Ten lists, though increasingly, additional attributes are considered as well. When reviewing the ENERGY STAR Qualified Bulb list for this project, we found that many of the models listed are simply unavailable for purchase. In some cases, previously-qualified models had already been replaced by successor models, but were not deleted from ENERGY STAR's Qualified Bulb lists. In spite of these hidden challenges, the screening process devised by the research team delivers significant value to utility incentive programs and to final lamp purchasers, because it weeds out those lamps from consideration. Likewise, it can be confusing to consumers if technically identical lamps are sold under a variety of manufacturer names and model numbers. This screening process helps to consolidate those duplicates into product "families," letting buyers know when they might be able to obtain comparable or identical performance and energy savings from another product at lower cost.

Going forward, we recommend that PG&E and other utilities utilize these findings to help steer residential customers to LED reflector lamps that are not only efficient, but also are very desirable products in terms of cost and performance. The models selected here are more likely to be cost effective, and more likely to meet or exceed consumer needs for a high quality light source than other ENERGY STAR-qualified LED reflector lamps. PG&E and other utilities can continue to generate significant energy savings in residential lighting by identifying and highlighting efficient light bulbs that people will truly enjoy using.

APPENDIX 1

Lamp availability

Many manufacturers of best-in-class lamps offer similar products in other beamspreads and color temperatures. While these are extensions of a family of lamps, the individual product alternatives were not tested in this study. See Table 4 and Table 5.

PAR38 Rank	mfg	model #	beam angle	CCT	availability
1	TCP	LED17E26P3830KNFL	25°	3000K	Also available in a 40° beamspread, and a color temperature of 2700K
2	Philips	18PAR38/END/F36 2700-900 DIM SM	36°	2700K	Also available in a 15° and 25° beamspread, and a color temperature of 3000K and 4000K
3	Philips	18E26PAR38-4	25°	3000K	Also available in a 15° beamspread
4	ATG Electronics	HSL-PT20W-38120D-H1	25°	3000K	Single model; no other options available
5	Utilitech	L18PAR38/DM/LED	38°	3000K	Single model; no other options available
6	Toshiba	LDRB2030ME6USD2	25°	3000K	Also available in 35° beamspread, and a color temperature of 2700K, 3500K, 4000K
7	Philips	18PAR38/END/F25 3000-950 DIM SM	25°	3000K	Also available in 15 and 36° beamspreads, and a color temperature of 2700K and 4000K
8	Greenlite	20W/LED/PAR38/FL/D	40°	3000K	Single model; no other options available
9	TCP	LED17E26P3827KNFL	25°	2700K	Also available in a 40° beamspread, and a color temperature of 3000K
10	NaturaLED	LED17PAR38/DIM/NFL /30K	25°	3000K	Also available in a 45° beamspread, and a color temperature of 2700K and 4000K

TABLE 4. PAR38 ALTERNATE PRODUCT AVAILABILITY

PAR30 Rank	mfg	model #	beam angle	CCT	availability
1	ecosmart	ECS R30 WW V2 FL 120	40°	3000K	Single model; no other options available
2	Lighting Science Group	DFN 30 WW V2 FL 120	40°	3000K	Also available in a 15° and 25° beamspread, and a color temperature of 2700K and 4000K
3	TCP	LED14E26P3030KNFL	25°	3000K	Also available in a 40° beamspread, and a color temperature of 2700K and 4100K
4	Philips	13PAR30L/END/F25 2700-800 DIM	25°	2700K	Single model; no other options available
5	Philips	12PAR30L/END/F36 3000 DIM	36°	3000K	Also available in a 15° and 22° beamspread, and a color temperature of 2700K
6	Philips	12PAR30L/END/F36 2700 DIMM	36°	2700K	Also available in a 15° and 22° beamspread, and a color temperature of 3000K
7	LightKiwi	LK-PAR30-6BV40	40°	3000K	Single model; no other options available
8	TCP	LED14E26P3027KNFL	25°	2700K	Also available in a 40° beamspread, and a color temperature of 3000K and 4100K
9	Verbatim	P30ES-LN-L800-C30-B25	25°	3000K	Also available in a color temperature of 2700K
10	Nu Vue	NV/PAR30/ES/6.1/D/WW/NFL/26/CX	25°	3000K	Also available in a 40° beamspread

TABLE 5. PAR30 ALTERNATE PRODUCT AVAILABILITY

APPENDIX 2

Range of observed results

Maximum-minimum observed data values, 31 PAR38 LED PAR lamps, 32 PAR30 LED PAR lamps.

Energy

Efficiency exceeds ENERGY STAR requirements (15% or better)
PAR38: Max – 65% Min – 18%
PAR30: Max – 52% Min – 15%

Beam efficiency (blm/W)
PAR38: Max – 37.1 Min – 20.1
PAR30: Max – 35.8 Min – 18.9

Power factor
PAR38: Max – 0.99 Min – 0.72
PAR30: Max – 0.98 Min – 0.72

Economics

Simple payback (years)
PAR38: Max – 16.3 Min – 3.7
PAR30: Max – 11.7 Min – 3.7

Cost of light ($/mblh)
PAR38: Max – 21.2 Min – 6.0
PAR30: Max – 17.3 Min – 5.2

Laboratory measured performance

Light output (%)
PAR38: Max – +20% Min – -18%
PAR30: Max – +30% Min – -12%

Color rendering index (CRI) variance
PAR38: Max – 93.5 Min – 80.0
PAR30: Max – 93.2 Min – 79.6

Duv
PAR38: Max – 0.006 Min – 0.0001
PAR30: Max – 0.0048 Min – 0.0001

Dimming behavior. Using the test procedure described above, lamps could earn up to 10 bonus points if they passed the minimum criteria on the incandescent dimmer. They earned 0 points for passing minimum criteria on the LED-specific dimmer; however, if they failed the LED-specific dimmer tests, they were removed from consideration for the final best-in-class lists.

Human factors

Paired comparison evaluation (# of votes)
PAR38: Max – 83 Min – 15
PAR30: Max – 82 Min – 26

Physical

Weight (lbs)
PAR38: Max – 1.47 Min – 0.61
PAR30: Max – 0.90 Min – 0.47

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GLOSSARY

Average rated life. A rating that indicates when 50% of a large group of lamps has failed.

Beam angle. The rated beam angle for a PAR lamp is defined by ANSI as the angle where the light output is 50% as intense as the center of its beam (center along the lamp axis). This 2:1 ratio of center-to-edge output is undetectable to the eye, so the beam of the PAR lamp will actually appear much wider than published.

Beam efficiency. The measure of the useful light delivered within a reflector lamp's stated beam angle, divided by the total lamp power.

Beam lumens. The total luminous flux (light) found within the declared beam angle. See "light," "lumen," luminous flux."

Blackbody. An ideal light source that absorbs all radiation falling upon it, and reflecting none. It emits radiation equally across all wavelengths. In concept, a blackbody is black when cold, and begins to emit light when it is heated, such as would a piece of metal. An incandescent filament can be considered a blackbody radiator. See "correlated color temperature."

Blackbody locus. The series of points plotted on a color diagram representing the chromaticities (color coordinates) of blackbodies having various color temperatures. See "correlated color temperature."

Candela (cd). The SI unit of luminous intensity. See "luminous intensity."

Candlepower (cp). Luminous intensity expressed in candelas.

Center beam candlepower (CBCP). The intensity of light at the center of a reflector lamp's beam.

Color rendering index (CRI). A measure of how well a light source renders a set of standard colors relative to the same colors illuminated by a reference source having the same CCT as the light source of interest. For lights with a CCT below 5000°K, the reference is incandescent. Above 5000°K, it is daylight. CRI is a psychological measurement of appearance. See "correlated color temperature," "Kelvin."

Compact fluorescent (CFL). A self-contained fluorescent lamp of small diameter tubing folded into a compact shape, typically containing an integrated ballast and screw base.

Correlated color temperature (CCT). The temperature of a blackbody radiator at the point it matches the color of the light source of interest. This is called the "color temperature" (CT), measured in degrees Kelvin. Exact matches cannot be obtained, so the closest match is called the "correlated color temperature" (CCT). This indicates that the light does not exactly match a color in a defined series of standard colors. CCT is a physically defined measurement.

Dimmer. An electrical control device that modifies the intensity of a light source by modifying the voltage or current available to it. ELV (electronic low voltage) dimmers are solid-state devices for controlling dimmable LED power supplies and electronic low voltage transformers.

Duv. The variation of a light source from greenish to pinkish expressed as a deviation from the blackbody locus. A greenish color has a positive Duv, and a pinkish color has a negative Duv value. See "blackbody locus."

Downlight. A lighting fixture that directs light predominantly downward, usually ceiling-mounted, and can be recessed, surface-mounted or suspended.

Efficiency. Expressed as lumen output per watt of power. The total luminous flux emitted by a lamp, divided by the lamp's total power input.

Incandescent lamp. A lamp in which light is produced by a tungsten filament heated to incandescence by an electric current.

Kelvin (°K). The unit of temperature used to designate the color temperature of a light source. See "correlated color temperature." The Kelvin scale is a temperature scale, where each degree is the same dimension as a Celsius degree (°C), however, 0 °K = 273 °C.

Light. The narrow band of the electromagnetic spectrum to which the human visual system is most sensitive. Luminous flux. See "luminous flux."

Light emitting diode (LED). A solid-state semiconducting device that produces visible light by passing current through a p-n diode junction.

Lumen (lm). The fundamental unit of luminous flux. A lumen is the SI unit of luminous flux. See "luminous flux."

Luminous flux (lm). Radiant flux that has the capacity to produce a visual sensation. Luminous flux quantifies the total lumen output of a light source in all directions. It is the radiant flux of a source multiplied by the relative spectral sensitivity of the human visual system.

Luminous intensity (cd). A unit quantifying the total lumen output of a source in a given direction.

Power factor. Represents the ratio of "real" AC power consumed by an electrical load to the amount of "apparent" power that travels on the grid. An ideal device has a power factor of 1.0, where the device draws the same amount of apparent power as real power.