EVALUATION OF BEST-IN-CLASS LED REFLECTOR LAMPS

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Prepared by

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DISCLAIMER

The authors of the report are solely responsible for the recommended findings and methods contained in this report. The views contained in this report do not necessarily reflect those of the project sponsors or advisors.

EXECUTIVE SUMMARY

This project identifies sets of 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, to be 'best-in-class' the lamp must excel in visual parameters, be compatible with common controls, and deliver energy savings cost-effectively. In the near term, these lists will have the effect of pushing the market toward increased energy efficiency.

We began the evaluation 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, and
- Phase 5: Generating two lists of the ten best-in-class LED PAR30s and PAR38s.

Results of this research include two lamp lists and a pioneering and robust methodology developed by the research team, with considerable input by funding organizations and lighting efficiency stakeholders. This methodology enables relatively straightforward updates to the 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.

We found, under a wide variety of scoring scenarios, that 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 supports them.
- *Their light beam is controlled, uniform, and 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 space, whether operating at full brightness or when dimmed.

Utilities can utilize these findings to provide a greater degree of certainty when promoting, incentivizing, and educating consumers about these bulbs than they would normally have with other LED lamps that bear the ENERGY STAR label because 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. Selecting best-in-class LED reflector lamps is not simply a matter of choosing the most energy efficient models in each lamp size. It is no longer sufficient to publish only numbers on specification sheets. Metrics like efficiency, CRI, and CCT measure only a portion of what people buying light bulbs really care about; numerical charts do not tell consumers the complete story about what they will see.

While the ultimate goal of lighting efficiency programs is to save energy, the best strategy to achieve energy savings is to highlight high quality, efficient products that everyday consumers will enjoy using and readily adopt. This study, which identifies best-in-class LED reflector lamps through a rigorous series of laboratory and human evaluations, is an important step in the transformation of the residential lighting market toward high quality, highly efficient technologies.

INTRODUCTION

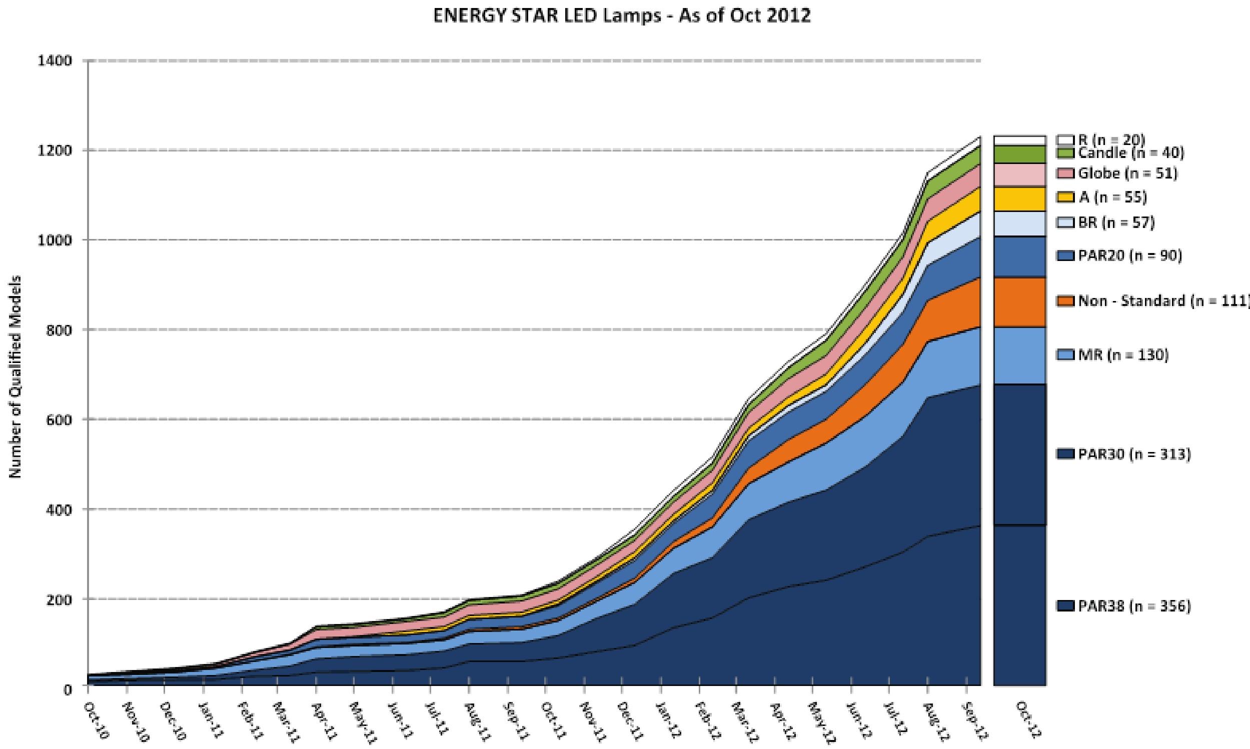
The purpose of this study is to guide both utilities and customers to "best-in-class" LED reflector lamps that are both energy efficient and aesthetically pleasing. Reflector lamps (i.e., bulbs) are used to produce directional light. With the implementation of new national standards for lighting efficiency and product labeling, providing guidance to consumers about which lamps are both energy efficient and aesthetically pleasing is essential.

The focus of this study is LED reflector PAR 38 and PAR30 lamps that are marketed to residential customers and readily available in common retail channels such as big box stores and easily accessible online vendors. There are 840 million reflector lamps in use in the United States, found in a wide variety of applications.[1] Of those, nearly 90 percent (737 million) are in the residential sector. Incandescent and halogen models account for more than 80 percent (603 million) of the current residential installed base and just under 40 percent (38.9 million) of the commercial installed base. Of the 603 million lamps installed within residences, about one-quarter are PAR38 and PAR30 lamps. LED reflector lamps, which have become available much more recently, are particularly promising for this application in PAR38 and PAR30 beam widths because they are inherently directional and naturally suited to focusing their light into narrow to moderately wide beam angles.

Figure 1 shows that as of October 2012, ENERGY STAR has already labeled more than 1,200 models of LED lamp, over 900 of which are reflectors. ENERGY STAR labeling criteria primarily ensure the energy efficiency and color performance of qualifying products, but those products can vary in purchase price, light quality, ability to be dimmed, and other attributes important to consumers.

[1] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

Figure 1. ENERGY STAR Qualified LED Lamps Increasing Over Time



Some utilities have 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. This study develops a principled basis for selecting products most likely to meet or exceed consumer expectations in a cost effective manner.

This research was co-funded by DTE Energy, Duke Energy, MidAmerican Energy, Northwest Energy Efficiency Alliance, Pacific Gas & Electric, and Southern California Edison with the intent of establishing a data-driven research and scoring process for selecting optimal LED reflector lamps for use in their residential lighting programs. IEE managed the project and oversaw the technical research, which was conducted by Ecova in its Durango, Colorado research laboratory. TopTenUSA managed the project advisory group and published the findings at www.toptenusa.org.

LED REFLECTOR LAMPS: OVERVIEW

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. Figure 2 shows that reflector lamps are typically used in recessed can and track lighting fixtures. Incandescent reflector lamps come in a variety of types (e.g. blown or parabolic aluminized reflector), shapes (e.g. PAR, R, BR and MR), and sizes (e.g. PAR38, PAR30, PAR20). *The focus of this study is on LED replacement options for halogen PAR 38 and PAR30 lamps, which constitute about one-quarter of the reflector lamps in use in U.S. homes today.*[2]

Figure 2. Examples of Common Uses for Reflector Lamps

Source: ENERGY STAR

Reflector lamps are intended for applications where you want to shine light in a particular direction and provide either a narrow cone of concentrated light (spot lighting) or a broader cone of more diffuse light (flood lighting). When the light source must be located some distance away from the target, reflector lamps are often the best choice to produce the relatively narrow beams required. Common applications include illuminating surfaces such as walls or countertops, use from high ceilings, and outdoor security lighting.

Today, most residential reflector lamps use conventional incandescent lighting technology. Early federal standards encouraged the broader use of halogen fill gas in many reflector lamps, which gives 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[3] that took effect in 2012, some halogen incandescent reflector lamps have adopted infrared reflective coatings on their filament capsules to further improve efficiency; however, loopholes in the law continue to permit the sale of many inefficient products.

In recent years, CFL reflector lamps have come to market. CFLs offer energy savings and longer lifetimes than typical halogen reflector lamps, however, many CFL reflector lamps are not

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2 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/nichefinalreport_january2011.pdf
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf

3 See: http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/74fr34080.pdf

dimmable or do not dim in the same way as halogen reflector lamps. *Similarly, although CFL reflector lamps can provide a broad cone of diffuse light for flood lighting, they are not able to focus light in a more concentrated cone like halogen lamps, making them appear dimmer to many users.* For these reasons, many consumers have been unsatisfied with CFL reflector lamps and have reverted 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 smooth distribution. Cool color temperatures (CCTs), sometimes appearing bluish-green or having color variations within the light pattern, were common in early models. Early LEDs lacked dimming capability and were often no more energy efficient, but far more expensive, than the CFL reflectors with which they were intended to compete.

Over time, LED reflector lamps have improved considerably. Newer products offer many of the aesthetic and performance advantages of halogen lamps while providing even higher energy efficiency and longer lifetimes than CFL reflector lamps.[4] Some LEDs now last for 30,000 hours or more – about 30 years of typical use. Dimmability is now commonplace.

Because LEDs are inherently directional, yield large energy savings, are durable and readily dimmable, they are a great fit for reflector lamp applications. However, even with the obvious benefits over existing incandescent technology, a central question remains: Do LEDs offer a compelling value proposition? LED reflector lamps are expensive to purchase relative to other options, and can vary widely in their visual performance. Are LEDs sufficiently appealing for large numbers of consumers to pay $30-$100 apiece?

For these reasons, we evaluate currently available LED PAR replacement lamps to assist consumers and utilities in selecting lamps which will deliver energy efficient, aesthetically pleasing light.

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[4] Fewer LEDs per lamp needed 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 consumers are familiar.

HOW WE EVALUATE

OVERVIEW

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, and
- Phase 5: Generating two lists of the ten best-in-class LED PAR30s and PAR38s

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[5]. Selected lamps were on the ENERGY STAR Qualified Bulb list 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), and
- 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 118 and 110 models, 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:

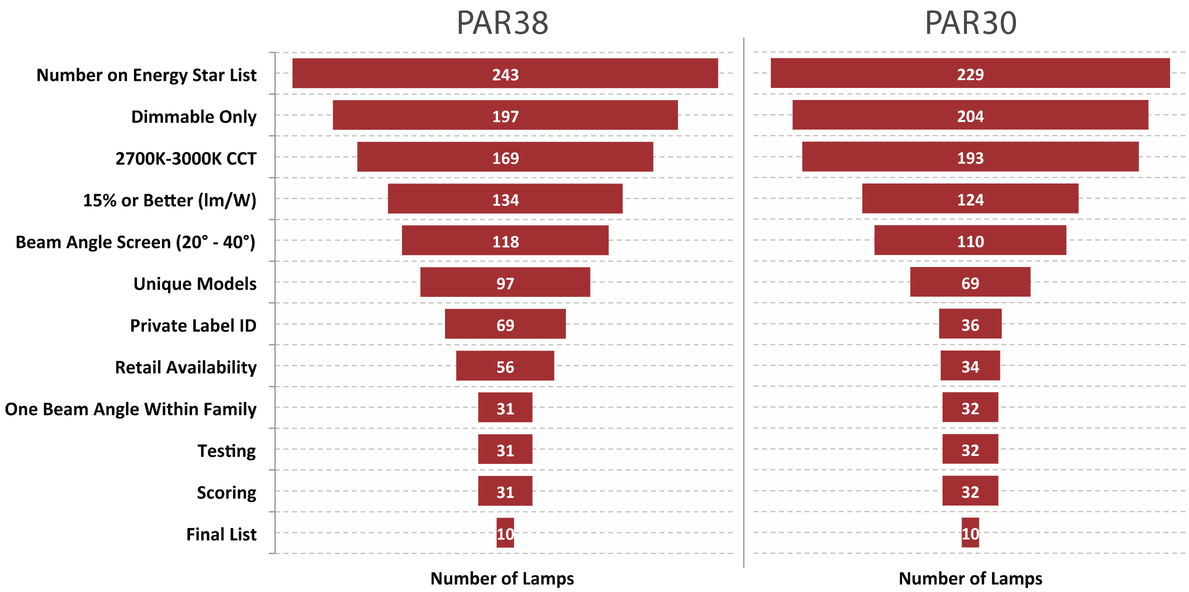
- One unique model per manufacturer — if otherwise identical lamps were available with slightly different sets of features (e.g., exterior finishes, base types);
- One unique manufacturer — if otherwise identical lamps were obviously sold under more than one private label (brand purchase was based first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

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

Figure 3 shows how applying the above criteria for evaluation reduced the possible candidates to the following quantities.

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

Figure 3. 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, 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) was followed, with one minor deviation.[6] All tests were performed using an integrating sphere with reference power sources and calibrated power analyzers.

[6] 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.

Dimming Methodology

Dimming is a critical factor to mass-market adoption of LEDs; however, an accredited dimming test methodology has not yet been adopted.[7] 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 would experience acceptable dimming performance with the LED lamps evaluated.* By developing our own procedure, the intention was not to replace the work of the above organizations, but rather to identify a reproducible methodology appropriate for this research.

While the dimming evaluation is not an accredited test, all relevant accredited test procedures as set forth in IESNA LM-79 were followed. For example, before quantitative data collection, lamps were stabilized 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, each LED lamp was tested on two types of dimmers as shown in Figure 4:

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

Figure 4. Traditional Incandescent (left) and LED-Specific (right) Dimmers

The "traditional" unit is the typical rotary style 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 a worst-case (but very probable) scenario where a consumer

[7] *Dimming LED lighting*, AEG Power Solutions (2011).

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.[8]

The ubiquitous push-on/push-off rotary-style dimmer was chosen 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.”[9]

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 collection, each lamp was connected to the dimmer and the dial adjusted 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. Photometric, energy, and performance data points were then collected 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), and
- Lowest flicker-free light output setting (while dimming up from the off-state).

Photometric data collected, as measured with SphereOptics 20-inch integrating sphere, included:

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

Energy data collected, as measured with Voltech PM300, included:

[8] Although LED-specific dimmers also operate other low wattage light sources, such as CFLS, our evaluation focused specifically on dimmer behavior when operating LEDs.
[9] This dimmer also claimed to be compatible with incandescent halogen sources up to 150W.

- Power – Watts,
- Current – Amps, and
- Power Factor (PF).

Performance, as assessed by human observation, included:

- Audible noise, and
- Perceptible flicker.

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

Photometric, energy, and performance data were collected at each light output level and analyzed to determine which lamps met the minimum performance criteria. The minimum passing requirements for each dimmer were:

1. The lamp must be able to dim down to 20% of the full rated light output.
2. The lamp's restrike ratio, which is derived from the difference between cut-out and pop-on levels, must not exceed 25% of full rated light output.[10]
    i. Restrike example – A 1000 lm lamp that cuts out at 100 lm and pops on at 350 lm:

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

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

Lamps that failed to meet any of the minimum-passing requirements outlined above on the LED-compatible dimmer were removed from consideration for the TopTen list. Lamps that did 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.

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

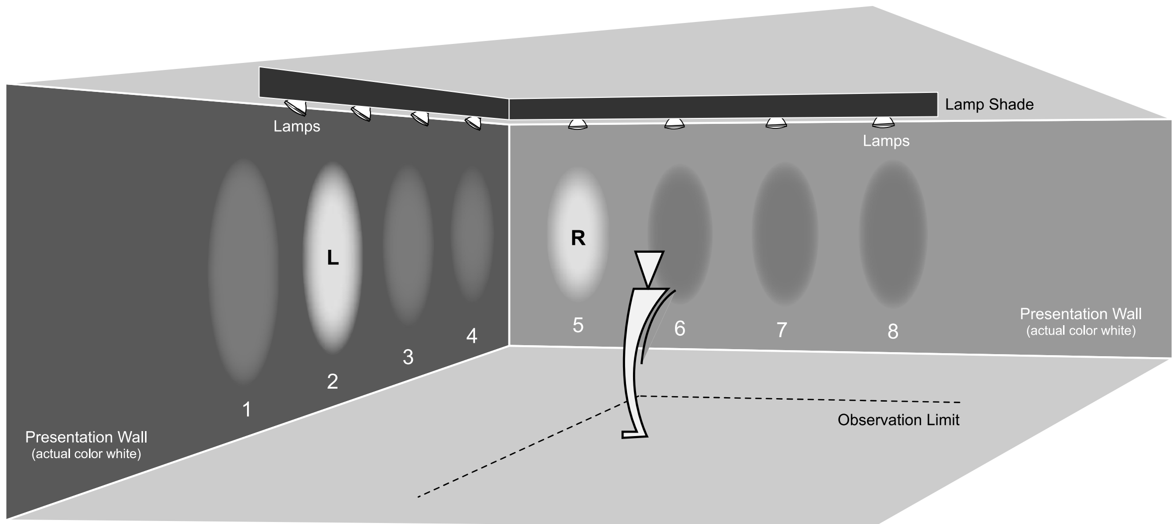
PHASE 3: HUMAN FACTORS TESTING

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. The human factors study determined whether those differences mattered and how these elements influence people's subjective evaluation of the lamp's aesthetic quality and performance.

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, specialists in the lighting and energy fields were not included, nor were artists, photographers, or anyone who would bring a heightened visual sensitivity to the light they saw. Only one subject was present in the test area at a time, so no one individual's impressions could influence other subjects.

Using a commonly employed comparative method (Houser, 2010), subjects were presented with pairs of lamp beams projected simultaneously on a wall surface. *Subjects were asked to select the light they preferred in each pair.* Subjects marked a datasheet indicating whether they preferred the beam on the left or right. Each lamp was compared to every other lamp, with all 112 comparisons randomized to eliminate both position and order effects. After all subjects had participated, the votes were tallied, and lamps receiving the most votes scored highest in the human factors portion of the study. Each lamp had the possibility of earning up to 105 votes. In total, 1,680 decision points during the experiment for each lamp type. Figure 5 shows how the study area was set up.

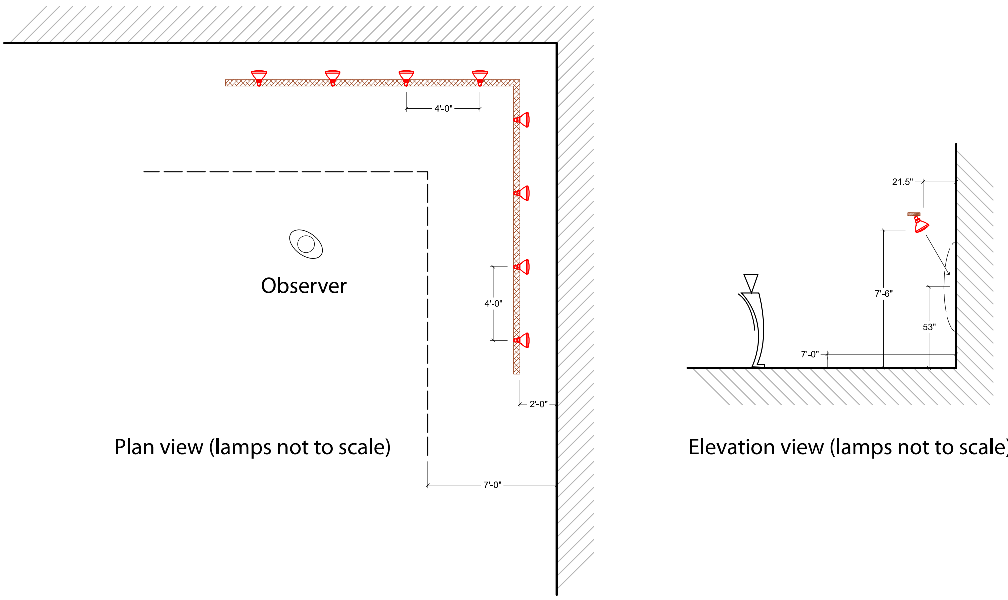
Figure 5. Human Factors Study Setup



To produce a reasonably common residential example of light beams upon a wall, two 16-foot tracks were suspended 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. Seamless cyclorama paper was used 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 placed at a 35° angle from nadir, typical of what might be found in residential applications. Each beam was visually centered at an elevation of 53 inches (eye-level). Lamps were shielded with dark cloth to block possible back spill 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.

Figure 6 shows the human factors setup from overhead and cross-section views.

Figure 6. Human Factors Study Setup, Plan and Elevation



PHASE 4: SCORING METHODOLOGY

With input from the research sponsors and other stakeholders, a scoring scale was designed to score the evaluated lamps based on the needs of utility efficiency programs. The system 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, and have a wide variety of advantages and disadvantages because they can be tailored to any 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. Mandatory criteria sets treat all qualifying products equally, rather than quantifying and ranking their performance.

Our scoring system contains five overarching categories—energy, economics, laboratory performance, human factors, and physical characteristics. Most categories have sub-categories that quantify each characteristic with a variety of metrics. Lamps can earn from 0 to 100 points on this scale; however, no lamp in this round of testing approaches 100 points. This scoring methodology is rigorous enough to use for future updates as products improve, leaving open the possibility for new lamps to out-rank existing lamps in future evaluations.

Table 1 summarizes the relative weighting and maximum score possible for each category and sub-category. Points were awarded for each category on a sliding scale between zero and the maximum shown.

Table 1. Relative Weighting of Lamp Performance Criteria

Scoring Categories	Weighting (Max. 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 Performance	**31**
Lumen Output (Measured vs. Rated)	10
Color Rendering Index Variance (CRI)	9
Duv	4
Dimming Behavior (On Incandescent Dimmer)	10
Human Factors	**22**
Paired Comparison Evaluation	22
Physical Characteristics	**3**
Weight	3
Highest Possible Score	**100**

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 earned points in this category based on the percentage that they *exceeded* ENERGY STAR requirements. All lamps considered for this project exceed ENERGY STAR minimum requirements by at least 15 percent. If a lamp exceeded ENERGY STAR minimum requirements by 80 percent, it was awarded 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 a user wants it and minimizing the electrical power needed to do so. The brighter the beam, the more the 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 started earning points at 15 blm/W, up to a maximum of 10 points at 45 blm/W.

Power Factor. Power factor is a characteristic of alternating current (AC) circuits, and is defined as the ratio of the real power flowing to the load to the apparent power in the circuit. Products with a high power factor (near to 1.0) cause fewer distribution losses in building wiring.[11] ENERGY STAR lamps that draw 5 or more watts are required to have a minimum PF $\geq$ 0.7. Products were awarded points for the extent to which they exceed the ENERGY STAR power factor requirements, and could earn up to 3 points for a PF = 1.0. Currently, no LED PAR replacement lamp on the ENERGY STAR list has a PF = 1.0.

ECONOMICS

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

Simple Payback. Simple payback is the amount of time it will take to recover the initial investment of purchasing an LED lamp through energy cost savings. Using average purchase price[12] and kWh saved[13], we calculated simple payback for each lamp evaluated, measured in years (see Equation 1). 10 points were awarded to lamps with payback periods of 2 years or less, with fewer points awarded for longer paybacks and no points for paybacks of longer than 8 years.

Cost of Light. The cost of light incorporates the purchase price of the lamp, the amount of light it produces, and the cost of the energy drawn by the lamp over a lifetime of 25,000 hours. Cost of light is measured in dollars per million-beam-lumen-hours ($/mblh). Points were awarded to

[11] http://efficientpowersupplies.epri.com/pages/Latest_Protocol/Power_Factor_Report_CEC_500-04-030.pdf
[12] Purchase price was the average taken from all products on Google Shopping, November 2012.
[13] 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.

lamps with the lowest cost of light. Lamps started earning at $16/mblh, and could earn a maximum number of 10 points at $2/mblh or less.

Equation 1. Simple payback equation

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

Where:
ΔW = wattage difference between the LED lamp and the halogen lamp it replaces[14]
kWh = kilowatt hours
h = hours of use
# days = 365

LABORATORY PERFORMANCE

In this section, reported laboratory performance values on a number of parameters were evaluated. 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 employed a narrower set of requirements that quantify subtleties in color and performance and 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 in this category.

Lumen Output (Measured vs. Rated). Laboratory-measured light output was compared to the manufacturer-reported value on the lamp packaging. 10 points were awarded to lamps that met or exceeded their reported light output. Lamps still received points when measured down to 15% of their claimed light output.

Color Rendering Index Variance (CRI). CRI is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or natural light source. CRI is measured on a scale of 0-100, with higher CRI scores indicating more faithful color transmission. Standard industry practice requires deriving CRI based on tests of 8 standard color swatches. ENERGY STAR-qualified lamps must have a CRI of 80 or greater. For

[14] 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.

this 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.[15]

Duv. Color measurement metrics attempt to reduce color qualities to a single number. Because of this, two lamps can have a different color appearance even though they may have the same CCT, due to subtleties about their color that CCT doesn't capture. Duv is a supplemental metric for measuring color subtleties specific to LEDs. While incandescent light sources tend to deviate from "whiteness" in a yellowish to bluish manner, solid state lamps tend to shift along a spectrum of greenish to pinkish. Duv measures this shift. Lamps were rewarded for appearing most similar to halogens in color. Lamps could earn up to 4 points for 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 all criteria on the incandescent dimmer. They earned 0 points for passing minimum criteria on the LED-specific dimmer, and were removed from consideration if they failed the LED-specific dimmer tests.

HUMAN FACTORS

Paired Comparison Evaluation. 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 CHARACTERISTICS

Weight. Excessively heavy LED PAR lamps could torque track cans or render fixtures inordinately top-heavy, which could lead to negative consumer experience. 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.

[15] 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.

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 evaluation. Even within this subset, we found a wide variety of lamp designs, performance characteristics, and prices.[16] Some notable findings were related to measured versus rated light output and energy use values, dimming performance, human factors testing, and purchase price compared to lamp preference.

ENERGY USE OBSERVATIONS: MEASURED VERSUS RATED

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

For the PAR38 LED reflector lamps, 27 out of 31 lamps tested used less energy than the manufacturer claimed on the package. 25 of 31 used 0% to 10% less energy than claimed. 2 of 31 used more than 10% less energy than claimed, down to a minimum of -15%. 4 of 31 lamps tested used more energy than claimed on the package, up to a maximum of 4% over the reported value.

For the PAR30 LED reflector lamps, 22 out of 32 lamps tested used less energy than the manufacturer claimed on the package. 19 of 32 used 0% to 10% less energy than claimed. 3 of 32 used more than 10% less energy than claimed, down to a minimum of -13%. 10 of 32 lamps tested used more energy than claimed on the package. 8 lamps used 0% to 10% more energy than claimed. One lamp used 12% more energy than the reported value.

LIGHT OUTPUT OBSERVATIONS: MEASURED VERSUS RATED

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

[16] See Appendix A, Table 4 and Table 5 for manufacturers' offerings of alternate beam spreads and color temperatures within the line extensions of best-in-class lamps.

For the PAR30 LED reflector lamps, 22 out of 32 lamps tested at or above their manufacturer-rated output. 16 of 32 were within a range of 0 to 10% higher. 6 of 32 produced over 10% more light than claimed, with a maximum output of 30% higher than claimed. 10 out of 32 lamps tested below their rated output. 9 of 32 produced 0 to 10% less light than claimed, while 1 of 32 produced than 12% less light than claimed.

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. 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 to lamps of below average brightness. Subjects also expressed a slight preference for 3000K lamps over 2700K lamps. After testing, interviews revealed that subjects found the following attributes pleasing: no color variation across the beam, symmetrical beam spreads, and smooth, tapered 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 single attribute is the sole indicator of which lamps customers will prefer. To provide guidance to customers and utilities, Tables 2 and 3 list the ten best-in-class PAR30 and PAR38 LED reflector lamps, as derived from the criteria and scoring system described above.

Table 2. LED PAR38 Best-in-Class List

PAR38 Rank	PAR38 Score	mfg	Model #	Beam Angle	CCT	lm	W	lm/W	Lamp
1	62.6	TCP	LED17E26P38 30KNFL	25°	3000K	1050	17	61.8	
2	59.3	Philips	18PAR38/END /F36 2700-900 DIM SM	36°	2700K	900	18	50	
3	57.7	Philips	18E26PAR38-4	25°	3000K	1200	18	66.7	
4	56.6	ATG Electronics	HSL-PT20W-38120D-H1	25°	3000K	1100	20	55	
5	53.9	Utilitech	L18PAR38/DM /LED	38°	3000K	885	18	49.2	
6	52.6	Toshiba	LDRB2030ME 6USD2	25°	3000K	1120	20	55.2	
7	52.5	Philips	18PAR38/END /F25 3000-950 DIM SM	25°	3000K	950	18	52.8	
8	50.8	Greenlite	20W/LED/PAR 38/FL/D	40°	3000K	1200	20	60	
9	50.5	TCP	LED17E26P38 27KNFL	25°	2700K	950	17	55.9	
10	48.3	NaturaLED	LED17PAR38/ DIM/NFL/30K	25°	3000K	950	17	54.8	

Table 3. LED PAR30 Best-in-Class List

PAR30		mfg	model #	Beam Angle	CCT	lm	W	lm/W	Lamp
Rank	**Score**								
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	LED14E26P3 030KNFL	25°	3000K	820	14	58.6	
4	55.8	Philips	13PAR30L/E ND/F25 2700-800 DIM	25°	2700K	800	13	61.5	
5	54	Philips	12PAR30L/E ND/F36 3000 DIM	36°	3000K	700	12	58.3	
6	52.5	Philips	12PAR30L/E ND/F36 2700 DIMM	36°	2700K	660	12	55	
7	51.9	LightKiwi	LK-PAR30-6BV40	40°	3000K	620	10	62	
8	51.4	TCP	LED14E26P3 027KNFL	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/26/CX	25°	3000K	620	10	62	

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.[17] Human factors testing proved to be reproducible, reliable, and quantifiable in a way that complements laboratory performance testing. This suggests that human factors belong within the set of lamp attributes being assessed by utilities when 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 similar set of top LED reflector lamps if the score weights were to shift modestly between attributes. 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 supports them.
- *Their light beam is controlled, uniform, and 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 space, whether operating at full brightness or when dimmed.

The best-in-class lists consist of a wide array of manufacturers; no single company or product design dominates. Similarly, the best 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, selecting best-in-class LED reflector lamps is not simply a matter of choosing the most energy efficient models in each lamp size. *It is no longer sufficient to publish only numbers on specification sheets. Metrics like efficiency, CRI, Duv, and CCT measure only a portion of what people buying light bulbs really care about*; *numerical charts do not tell consumers the complete story about what they will see.*

[17] Subjects 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.

Many of the models listed the ENERGY STAR Qualified Bulb lists are unavailable for purchase. In some cases, previously-qualified models have already been replaced by successor models, but have not been deleted from ENERGY STAR's lists. Another potential source of confusion for consumers is the presence of technically identical lamps sold under a variety of manufacturer names and model numbers. A screening process can deliver significant value to utility incentive programs and to consumers by eliminating unavailable products and consolidating 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 utilities utilize these findings to help steer residential customers to LED reflector lamps that are not only efficient, but also are desirable 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 high quality light than other ENERGY STAR-qualified LED reflector lamps. Utilities can continue to generate significant energy savings in residential lighting by identifying and highlighting efficient light bulbs that people will truly enjoy using.

Ultimately, people purchase light bulbs to provide light, not to save energy. It is entirely reasonable for them to expect aesthetic lighting performance from LED lamps and good value for their additional investment.

APPENDIX A
GLOSSARY OF TERMS

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 efficacy. 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 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 "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 used to modify the intensity of light emitted by a light source by modifying the voltage or current available to it. ELV (electronic low voltage) dimmers are solid-state devices for controlling electronic low voltage transformers and dimmable LED power supplies.

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

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."

Efficacy. The luminous efficiency of a light source expressed as lumen output per watt of power. The total luminous flux emitted by a lamp, divided by the lamp's total power input.

Efficiency. The luminous efficiency of a luminaire expressed as the percentage of lumen output of a luminaire relative to the lumen output of the lamp(s) alone.

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, where the device draws the same amount of apparent power as real power.

APPENDIX B
LAMP AVAILABILITY

Many manufacturers of best-in-class lamps offer similar products in other beam spreads and color temperatures. While these are extensions of a family of lamps, the individual product alternatives were not tested in this study. Table 4 and Table 5 identify the availability of alternate beam spreads and color temperatures by selected product.

Table 4. PAR38 Alternate Product Availability

PAR38 Rank	Mfg	Model #	Beam Angle	CCT	Availability
1	TCP	LED17E26P3830K NFL	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/LE	38°	3000K	Single model; no other options available
6	Toshiba	LDRB2030ME6US D2	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	LED17E26P3827K NFL	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 5. PAR30 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	LED14E26P3030 KNFL	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	LED14E26P3027 KNFL	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

APPENDIX C
RANGE OF OBSERVED RESULTS AND SCALE OF POINTS BY SCORING CRITERIA

The boxed information shows an abbreviated range of possible observed outcomes and points that could be allocated for each scoring criteria.

Maximum and minimum observed data values for 31 PAR38 LED PAR lamps and 32 PAR30 LED PAR lamps are listed by each scoring criteria below.

Energy

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

Efficiency Exceeds ENERGY STAR (lm/W)	
(Points available=11)	
Range	Points
79%	11.00
75%	10.32
65%	8.63
55%	6.94
45%	5.25
35%	3.55
25%	1.86
15%	0.17
0-14%	0.00

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

Beam Efficiency (blm/W)	
(Points available=10)	
Range	Points
45	10.00
40	8.33
35	6.67
30	5.00
25	3.33
20	1.67
15	0.00

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

Power Factor	
(Points available=3)	
Range	Points
1.0	3
0.9	2
0.8	1
0.7	0

Economics

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

Simple Payback (yrs)	
(Points available=10)	
Range	Points
2	10.00
3	8.33
4	6.67
5	5.00
6	3.33
7	1.67
8	0.00

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

Cost of Light ($/mblh)	
(Points available=10)	
Range	Points
2	10.00
4	8.57
6	7.14
8	5.71
10	4.29
12	2.86
14	1.43
16	0.00

Laboratory Performance

Lumen Output: Measured vs. Rated (%)

PAR38: Max – +20% Min – -18%

PAR30: Max – +30% Min – -12%

Lumen Output (Measured vs. Rated)	
(Points available=10)	
Range	Points
≥0%	10
-3%	8
-6%	6
-9%	4
-12%	2
-15%	0

Color Rendering Index Variance (CRI)

PAR38: Max – 93.5 Min – 80.0

PAR30: Max – 93.2 Min – 79.6

Color Rendering Index Variance (CRI)	
(Points available=6)	
Range	Points
100	6.0
95	4.5
90	3.0
85	1.5
80	0.0

Duv

PAR38: Max – 0.006 Min – 0.0001

PAR30: Max – 0.0048 Min – 0.0001

Duv	
(Points available=5)	
Range	Points
0	5.00
0.001	4.17
0.002	3.33
0.003	2.50
0.004	1.67
0.005	0.83
0.006	0.00

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.

Dimming Behavior	
(Points available=10)	
Range	Points
Pass	10
Fail	0

Human Factors

Paired Comparison Evaluation

PAR38: Max – 83 Min – 15

PAR30: Max – 82 Min – 26

Human Factors	
(Points available=22)	
Range	Points
105	22.0
85	17.6
65	13.2
45	8.8
25	4.4
5	0.0

Physical Characteristics

Weight (lbs)

PAR38: Max – 1.47 Min – 0.61

PAR30: Max – 0.90 Min – 0.47

PAR38 Weight (lbs)	
(Points available=3)	
Range	Points
0.6	3.0
0.8	2.4
1.0	1.8
1.2	1.2
1.4	0.6
1.6	0.0

PAR30 Weight (lbs)	
(Points available=3)	
Range	Points
0.4	3.00
0.5	2.23
0.6	1.50
0.7	0.75
0.8	0.00

APPENDIX D
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