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PNNL-29342

Energy Saving Opportunity from Advanced LED Lighting Research

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Abstract

Pacific Northwest National Laboratory (PNNL) estimated the energy saving opportunity enabled by PNNL research leading to advanced LED lighting features. This report describes the results of that effort. To complete this work, PNNL selected a methodology created for and used in the electric utility industry, called Non-Energy Benefits methodology, and a lighting market model created for DOE to estimate future energy savings potential from solid-state lighting. The study found an energy saving opportunity from select planned PNNL lighting research equivalent to annual energy savings of 10% of total lighting energy use in the year 2035, or in absolute terms, 334 tBtu (source energy). Energy savings in earlier years are smaller, primarily due to the early years of low market uptake of the new technologies expected from PNNL lighting research. In 2030, annual energy savings are projected to be 4.5%, or 165 tBtu (source energy).

Summary

Due to rapid changes in the lighting industry, lighting technology, and the lighting market, Pacific Northwest National Laboratory (PNNL) conducted a study to estimate the energy saving opportunity associated with newly emerging lighting research to be conducted by PNNL during FY19–21. This report describes that study and its findings. The planned lighting research in question spans several lighting topics: visual glare, flicker, and color rendering; non-visual effects; and outdoor environmental effects, including the impact of outdoor lighting on dark skies.

With DOE's concurrence, PNNL designed part of this study to depend on methodologies developed for the electric utility industry, known as Non-Energy Benefits (NEB) methodology. PNNL decided to use NEB methodology because it provided well-vetted and extensively used methods for estimating difficult-to-quantify values associated with energy using technologies. PNNL hired a subcontractor well-known for its work in developing and practicing NEB methodology; Skumatz Economic Research Associates (SERA). Using NEB methods, SERA estimated the value perceived by likely buyers of future products containing technologies (or features) likely to result from the planned PNNL research.

SERA's research focused on three lighting product categories, selected by PNNL: commercial 4-foot linear LED luminaires, residential general service LED lamps, and street/roadway luminaires. These products were selected for investigation because time and budget did not allow investigation of all lighting product categories in the general illumination market, and because PNNL believed results from investigating these three product categories could be reliably extrapolated to the entire general service lighting market. These three particular products were selected because they are good representatives of the larger market sectors from which they were drawn (commercial, residential, and outdoor). The results of SERA's research are summarized in Tables S-1, S-2, and S-3.

PNNL hired a second subcontractor, Navigant Consulting, Inc. (Navigant), to conduct the second part of the study. Navigant had developed for the DOE Solid-State Lighting (SSL) program a lighting market model that had been used by DOE over the preceding decade to estimate the energy savings potential of SSL technology. This model offered an opportunity to translate SERA's findings into estimates of energy saving opportunity. And importantly, since the model is the same one that DOE has used for estimating SSL lighting energy savings, its use in this study would make the results of the new analysis consistent with and comparable to other estimates of potential lighting energy savings.

Starting with the value estimates produced by SERA for the three product categories, Navigant subtracted those values from the first cost values (purchase and installation costs) for each of those product categories to estimate the first cost values for the three product categories. Neo-classical micro-economic theory, findings about the shape of demand curves in the Navigant model, and some reasonable assumptions made this a viable means of simulating the effects of an unknown future demand curve for advanced products containing features likely to result from PNNL lighting research.

Modeling runs estimated the energy saving opportunity for advanced LED products in the three categories. In order to extrapolate those results to other lighting products, Navigant developed and applied a set of scaling factors, based on the fraction of total sector lighting energy use in each category of products. When summed, these estimates of energy saving potential by

product category yielded estimates of energy saving opportunity by market sector (commercial, residential, and outdoor) and in total. Tables S-4 and S-5 show the results of this effort.

All energy savings were calculated from the “Current SSL Path” scenario baseline, which assumes the advanced features expected to result from PNNL work will not enter the market. The Current SSL Path scenario is the same baseline now used by DOE for estimating SSL program energy savings.

Table S.1. Values Estimated for Commercial, 4-foot Linear Advanced LED Luminaires

NEAR-TERM TECHNOLOGIES	Method 1- Incremental Value – Purchase Price Effect	Method 1- Incremental Value Annualized	Method 2- Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized
Glare with 15% lower EE	$46	$4.04	$29	$2.49
Flicker with 10% price increase	$20	$1.72	$29	$2.56
Color Rendition with 10% EE increase	$32	$2.83	$26	$2.25
Adjustable/Color with 10% lower EE	$26	$2.31	$20	$1.74
LONG-TERM TECHNOLOGIES – price premium for feature	Method 2- Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized		
Glare – no change in EE	$26	$2.26		
Flicker – no change in EE	$28	$2.47		
Color Rendition – 20% EE increase	$20	$1.78		
Adjustable/Color – 10% EE increase	$22	$1.89		
All Features Combined	$54	$4.69		
EE = energy efficiency				

Table S.2. Values Estimated for Residential, General Service Advanced LED Lamps

NEAR-TERM TECHNOLOGIES	Method 1- Incremental Value – Purchase Price Effect	Method 1 – Incremental Value Annualized	Method 2- Incremental Value – Purchase Price Effect	Method 2- Incremental Value Annualized
Flicker with 10% price increase	$1.71	$0.10	$3.18	$0.19
Color Rendition with 10% EE increase	$1.83	$0.11	$2.88	$0.17
Adjustable/Color with 10% lower EE	$1.59	$0.09	$3.71	$0.22
LONG-TERM TECHNOLOGIES	Method 2- Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized		
Flicker – no change in EE	$2.96	$0.17		
Color Rendition – 20% EE Increase	$4.37	$0.26		
Adjustable/Color with 10% EE increase	$3.42	$0.20		
All Features Combined	$4.58	$0.27		

Table S.3. Values for Street/Roadway Advanced LED Luminaires

	Average Incremental Value – Purchase Price Effect	Average Incremental Value Annualized	Incremental Value – Purchase Price Effect (Most Conservative Estimate)	Incremental Value – Purchase Price Effect (Most Conservative Estimate)
Color Near Term – Warm, Reduce Night Sky Impacts, No Blue, 50% higher LER than baseline	$62.98	$6.15	$39.47	$3.85
Color Long Term – Reflects research on light/wildlife/night sky interactions, improved human visibility, 80% higher LER	$83.36	$8.14	$46.00	$4.49
Color – Long Term – Same as above but energy use for new feature is also 10% less	$92.02	$8.99	$52.27	$5.10
LER = luminous efficacy of radiation				

Table S.4. Advanced LED Technology Source Energy Savings (tBtu)

Sector	2025	2030	2035	Cumulative (2023-2035)
Commercial/Industrial	-5.9	29.0	102.0	380.4
Residential	54.6	105.7	147.5	1,208.5
Outdoor	2.3	30.5	84.7	398.3
Total	51.0	165.2	334.3	1,987.2

Table S.5. Advanced LED Technology Source Energy Savings (% of sector lighting energy use)

Sector	2025	2030	2035	Cumulative (2023-2035)
Commercial/Industrial	-0.2%	1.4%	5.7%	1.4%
Residential	5.1%	11.6%	18.1%	9.7%
Outdoor	0.3%	4.2%	11.7%	4.1%
Total	1.2%	4.5%	10.0%	4.0%

As shown in the tables above, the annual energy savings opportunity from PNNL's lighting energy research is substantial in the final year of the projection, 2035, relative to total lighting energy use in the baseline scenario (10%) and relative to baseline energy use in the sectors in which the savings occur, especially residential (18.1%). Total energy savings increase throughout the projection years, slowly at first, and then substantially by 2035.

Acknowledgments

Numerous staff at PNNL were very helpful in compiling information and suggesting ideas for resolving problems, including Kelly Gordon, Naomi Miller, Michael Royer, Bruce Kinzey, Andrea Wilkerson, and Bob Davis. We would also like to thank a number of economists for reviewing some of the economic methodology used in this study: Doug Elliott, Michael Warwick, and Patrick Balducci of PNNL. Finally, we would like to thank several managers from DOE for their guidance and useful suggestions, including Jim Brodrick (retired), Karma Sawyer, and Brian Walker.

Acronyms and Abbreviations

BTO	Buildings Technologies Office
DOE	U.S. Department of Energy
EE	energy efficiency
LED	light-emitting diode
LER	Luminous Efficacy of Radiation
NAICS	North American Industry Classification System
Navigant	Navigant Consulting, Inc., n/k/a Guidehouse Inc.
NEB	Non-Energy Benefits
NEI	Non-Energy Impacts
PNNL	Pacific Northwest National Laboratory
SERA	Skumatz Economic Research Associates
SSL	solid-state lighting
tBtu	terra British thermal units

Contents

Figures

Tables

1.0 Introduction

Due to rapid changes in the lighting industry, lighting technology, and the lighting market, Pacific Northwest National Laboratory (PNNL) conducted a study to estimate the energy saving opportunity associated with newly emerging lighting research to be conducted by PNNL during FY19–21. This report describes that study and its findings. The planned lighting research in question spans several lighting topics: visual glare, flicker, and color rendering; non-visual effects; and outdoor environmental effects, including the impact of outdoor lighting on dark skies.

Starting in early FY19, PNNL began reviewing literature and speaking to experts about methods that might be used for this kind of study. Importantly, the work had to be completed within 1 year. After much discussion, PNNL rejected the idea of investigating potential energy savings on a case-by-case basis for each expected effect from the planned lighting research because such an approach would be complicated, expensive, and unlikely to conclude within 1 year. Instead, with DOE's concurrence, PNNL began to investigate approaches that might lean on methodologies developed for the electric utility industry's energy efficiency programs. Specifically, PNNL began looking into methods used to investigate what are generally called "Non-Energy Benefits" (NEB) or alternately, "Non-Energy Impacts" (NEI).

NEB methodologies have been used to quantify the benefits from energy efficiency programs other than those that result in reduced energy use. For example, they have been used by some states and utilities to estimate the value of improvements in human comfort resulting from house insulation, and reduced air pollution from less fossil fuel burning (Skumatz et al. 2009; Regional Technical Forum 2018). NEB methodologies were deemed appropriate for this study because they can be used to estimate the value of difficult-to-quantify values, they can address a broad range of effects, and most of the methodologies used for their estimation have been well-vetted for decades by state electric utility regulators.

But using NEB methods for estimating the value of the various effects on future SSL luminaires from PNNL research doesn't directly result in an estimate of future potential energy savings. Those estimates of future value that result from using NEB estimation methods need to be converted into energy savings. For that, PNNL decided it best to use a lighting market model developed by Navigant Consulting, Inc. (Navigant) for DOE's SSL program because the model is well-vetted, and because the results would be directly comparable to other energy savings estimates used in the DOE SSL program.

To summarize, we used a two-step approach to estimate the opportunity for energy savings from planned PNNL lighting research:

- **Step One**: Using NEB methodology, estimate the value (purchase price effect) to potential buyers of advanced light-emitting diode (LED) features/technologies likely to result from PNNL research.
- **Step Two**: Use the values estimated in Step One as inputs to the lighting market model developed by Navigant for DOE to estimate energy savings opportunity from PNNL research.

This report provides some context for that work, which was largely subcontracted to two contractors: Skumatz Economic Research Associates (SERA) and Navigant. It also presents and interprets the results achieved.

2.0 Advanced Luminaire Descriptions

PNNL had to first develop descriptions of the lamps and luminaires expected to result from PNNL lighting research before SERA could begin its investigations. Importantly, we assumed the products to be thus described are not in the market now and would be introduced as new products to the market in 2022, 1 year after PNNL completes its 3-year research effort (the results of which will be released over the years 2019, 2020, and 2021).

In discussing this effort with SERA and Navigant, we learned the descriptions had to have two levels of future performance so that SERA could establish trend lines for its analysis. We also learned that the number of luminaire descriptions needed to be limited to a small number, and selected from the existing set of submarkets (Navigant’s term for the market segment addressed by a particular luminaire/lamp type) used by the model in order to make the effort with the lighting market model a task that could be completed within allowed time and budget.

After much discussion, PNNL decided that three luminaire/lamp types and associated “submarkets” would be used for the analysis. Individual luminaire descriptions would then be written for those submarkets for each category of research planned by PNNL. Table 2.1 indicates which research effects descriptions were developed for each of the submarkets. Complete luminaire descriptions can be found in Appendix A. Further, we decided energy savings in other submarkets would be estimated using scaling factors, extending the results of the modeled submarkets to the other submarkets not directly investigated.

Table 2.1. Advanced Luminaire Description Topics

Research Effects:	Commercial 4-ft Linear Luminaires	Residential General Service Lamps	Outdoor Street and Roadway Luminaires
Glare	X		
Flicker	X	X	
Color Rendering	X	X	
Non-Visual Effects	X	X	
Environmental Effects			X

3.0 Using NEB Methodology to Value Advanced Luminaires

Several methods were used by SERA to estimate these values, but they are collectively dubbed “purchase price effects” because the values estimated are based on methods that can be used to adjust purchase prices of the investigated products in order to estimate the market demand for these products. Much more detail on that work can be found in Appendix B, which contains the complete research report prepared by SERA for PNNL.

SERA started with the luminaire descriptions provided by PNNL, as described in Section 2.0, and contained in Appendix A. From those descriptions, SERA used its expertise in designing surveys that would yield information suitable for analysis using NEB methodologies. Copies of those surveys can be found at the end of the report in Appendix B. Unique surveys were developed for five potential buyers’ groups, as detailed in Table 3.1 (extracted from Figure 2.1 in Appendix B) and used to collect information from potential buyers.

Table 3.1. Detail on Survey Groups and Responses

Sector / Respondent Group	Source / Administration Method	Population Mailed to (adjusted for bounce backs)	Number of Responses	Calculated Response Rate
Commercial – Lighting Designers	Purchased email addresses in relevant North American Industry Classification System (NAICS) business codes; SERA emailed link to web survey	9717	184	1.9%
Commercial – Business Owners	Purchased panel survey responses, statistically representative nationwide	n.a.	400	n.a.
Commercial – Business Owner Follow-up Sample	Purchased panel survey responses, statistically representative nationwide	n.a.	104	n.a.
Residential – Builders	Purchased email addresses in relevant NAICS business codes; SERA emailed link to web survey	8275	104	1.3%
Street/Roadway – Public Works and Utilities (combined)	Purchased email addresses in relevant NAICS business codes; SERA emailed link to web survey	7161	79	1.1%

SERA used two main methods well-established in NEB literature to estimate values communicated by survey respondents:

- **Method 1: Labeled Magnitude Scaling:** This method asked respondents to characterize how valuable certain technology features were relative to a known quantity (in dollars) using qualitative descriptors, such as much less valuable, somewhat less valuable, etc. These qualitative descriptors were then translated into quantitative multipliers, primarily using sample-derived factors, and then when multiplied by the known dollar quantity, used to calculate the dollar value of the technology features.
- **Method 2: Ranking and Valuing:** As stated in Appendix B, “A back-up approach was also used, combining rank ordering of technology choices, with requests for responses about the willingness to pay for ranked options.” This method, like Method 1 above, resulted in estimates of the dollar value of technology features and their combinations.

In addition to the above primary methods, SERA used a “Willingness to Pay” method to collect additional information on the surveys aimed at the Street/Roadway sector. Unlike Method 2 above, this method did not ask respondents to rank the various combinations of features. The Willingness to Pay method asks respondents how much they would be willing to pay for technology features presented in the surveys. The results from the Willingness to Pay method, which were used exclusively on the Street/Roadway sector, were averaged into the results from Method 1 and 2 to produce estimates of “purchase price effects.”

SERA found that the above methods produced consistent estimates of value for LED luminaires and lamps with advanced features, stated both in terms of annual value and in one-time values (purchase price effects). Annual values were translatable into purchase price effects using a present value calculation, with assumed product lifetimes which were the same as the baseline product lifetimes used by Navigant in previous analyses for the DOE SSL program, and with assumed discount rates for the various market sectors from recent DOE regulatory documents; see Table 3.2. Conversely, wherever available information from the surveys first yielded annual values, the same method and assumptions were used to calculate one-time values.

Table 3.2. Discount Rates Used in Converting Annual Values to and from Purchase Price Effects

Submarket	Discount Rate	Source
Commercial - Linear - 4 ft	3.60%	Table 8.2.17 of General Service Fluorescent Lamps Final Rule Technical Support Document (https://www.regulations.gov/document?D=EERE-2011-BT-STD-0006-0066)
Residential - General Service	4.50%	Table 8.1.1 of General Service Lamps Notice of Preliminary Rulemaking Technical Support Document (https://www.regulations.gov/document?D=EERE-2013-BT-STD-0051-0042)
Outdoor - Street/Roadway	3.40%	Table 8.2.13 of Metal Halide Final Rule Technical Support Document (https://www.regulations.gov/document?D=EERE-2009-BT-STD-0018-0069)

Survey respondents were asked to estimate the value of various technology features resulting from PNNL research in the near term (2020-2025) and in the long term (2030-2035). The features presented to the survey respondents were either direct reflections of the features described in the luminaire and lamp descriptions provided by PNNL (Appendix A), or they were derivations of those features, which allowed SERA to collect information in a way that facilitated the analysis they needed to perform on survey responses.

3.1 Valuation Study Results

Table 3.3 through Table 3.5 summarize the results from SERA's application of the two valuation methods. These tables are extracted from Appendix B, Table ES-1.

Note that the last rows of both Table 3.3 and Table 3.4 are labeled "All Features Combined." This reflects questions asking respondents to estimate the value they perceive in products offering a combination of all the advanced features for long-term technologies (2030-2035). The values in these rows are significantly less than the sum of the values for the individual features in the rows above them. Note also that Table 3.5 doesn't have an "All Features Combined" row because the features were not separable for the products in the Street/Roadway Lighting category, and thus already "all features combined." Readers should be aware of three important points about this information contained in Tables 3.3 through Table 3.5:

1. The purpose of the "All Features Combined" questions reflected in Tables 3.3 and 3.4 was to eliminate the possibility of doubling counting. Without these questions, estimating the value of all effects combined may have required summing the individual values, resulting in significant over-estimation of the value. In the case of commercial products, the All Features Combined question revealed a value that was only 56% as large as the sum. In the case of residential products, the All Features Combined question revealed a value that was only 43% as large as the sum. These "All Features Combined" questions were only asked as part of Method 2, so for the Commercial and Residential Sectors, the energy saving opportunity estimation is based solely on Method 2 results, all features combined. (See point 2 below for an explanation of how the Street/Roadway sector results were derived.)

2. Table 3.5 has column headings referring to "average" incremental values. This refers to the simple average calculated from three different measurement methods that were used to estimate values in these columns. The three methods were Method 1, Method 2, and Willingness-to-Pay. As an experiment, SERA chose to add a third estimation methodology, resulting in three different methods for estimating value for Street/Roadway products. Given that no method was superior to others, the results of the three methods were averaged together and reported in Table 3.5. Note that the most conservative estimates from among the three methods is also reported in Table 3.5.

3. Subsequent analysis of SERA's results performed by Navigant focused exclusively on the All Features Combined results (and the average results for Street/Roadway) because these results exclude the possibility of double counting that would have led to an over-estimation of potential energy savings.

Table 3.3. Values Estimated for Commercial, 4-foot Linear Advanced LED Luminaires

NEAR-TERM TECHNOLOGIES	Method 1 - Incremental Value – Purchase Price Effect	Method 1 - Incremental Value Annualized	Method 2 - Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized
Glare with 15% lower EE	$46	$4.04	$29	$2.49
Flicker with 10% price increase	$20	$1.72	$29	$2.56
Color Rendition with 10% EE increase	$32	$2.83	$26	$2.25
Adjustable/Color with 10% lower EE	$26	$2.31	$20	$1.74
LONG-TERM TECHNOLOGIES – price premium for feature	Method 2- Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized		
Glare – no change in EE	$26	$2.26		
Flicker – no change in EE	$28	$2.47		
Color Rendition – 20% EE increase	$20	$1.78		
Adjustable/Color – 10% EE increase	$22	$1.89		
All Features Combined	$54	$4.69		
EE = energy efficiency				

Table 3.4. Values Estimated for Residential, General Service Advanced LED Lamps

NEAR-TERM TECHNOLOGIES	Method 1 - Incremental Value – Purchase Price Effect	Method 1 – Incremental Value Annualized	Method 2 - Incremental Value – Purchase Price Effect	Method 2 - Incremental Value Annualized
Flicker with 10% price increase	$1.71	$0.10	$3.18	$0.19
Color Rendition with 10% EE increase	$1.83	$0.11	$2.88	$0.17
Adjustable/Color with 10% lower EE	$1.59	$0.09	$3.71	$0.22
LONG-TERM TECHNOLOGIES	Method 2 - Incremental Value – Purchase Price Effect	Method 2 – Incremental Value Annualized		
Flicker – no change in EE	$2.96	$0.17		
Color Rendition – 20% EE Increase	$4.37	$0.26		
Adjustable/Color with 10% EE increase	$3.42	$0.20		
All Features Combined	$4.58	$0.27		

Table 3.5. Values for Street/Roadway Advanced LED Luminaires

	Average Incremental Value – Purchase Price Effect	Average Incremental Value Annualized	Incremental Value – Purchase Price Effect (Most Conservative Estimate)	Incremental Value – Purchase Price Effect (Most Conservative Estimate)
Color Near Term – Warm, Reduce Night Sky Impacts, No Blue, 50% higher LER than baseline	$62.98	$6.15	$39.47	$3.85
Color Long Term – Reflects research on light/wildlife/night sky interactions, improved human visibility, 80% higher LER	$83.36	$8.14	$46.00	$4.49
Color – Long Term – Same as above but energy use for new feature is also 10% less	$92.02	$8.99	$52.27	$5.10

LER = luminous efficacy of radiation

4.0 Estimating Energy Savings

The outputs of the SERA investigation described in Section 3.0 were used by Navigant as inputs to their lighting market model to estimate the energy savings opportunity presented by the advanced luminaires and lamps made possible by PNNL's research. Detailed results of this modeling effort are contained in Appendix D. Navigant's lighting market model was developed for DOE's SSL program to help estimate the potential for future energy savings from SSL, (Navigant 2016). A series of these reports can be found on the DOE SSL website at: https://www.energy.gov/eere/ssl/market-studies.

The same model was used to estimate the energy saving opportunity in this study because results from this study would be consistent with and comparable to other energy saving estimates used by the DOE SSL program, and because it presented a ready and suitable tool for making such estimates.

4.1 The Model

The model uses a conditional logit model to allocate available market share to various competing lighting technologies, resulting in a probability-of-purchase estimation. Conditional logit models are a common way of forecasting future market share. Probability-of-purchase is based on the first cost (price) and annual operating costs of each lighting product considered by the model. The lighting market model also uses a Bass diffusion model, another commonly used tool for investigating market adoption of technologies, to simulate the slower market uptake of newer technologies.

For more detail on the model, see the Navigant report in Appendix D to this report, and in particular, see Sections 1.1 and 1.2 in that report.

4.2 Key Model Inputs

Navigant started with a market baseline forecast developed for DOE that is called the "Current SSL Path" scenario. The most recent forecast is available from DOE in the Energy Savings Forecast of Solid-State Lighting series produced by Navigant for DOE (Navigant 2016). This energy use forecast, which extends to the year 2035, is defined as, "the expected future path for LED lamps and luminaires given continuation of current levels of solid-state lighting (SSL) investment and no investment in the advanced LED technologies that are the subject of this study" (see Appendix D, Part V.)

The Current SSL Path scenario was contrasted with an Advanced LED scenario produced for this study. The difference between the scenarios is characterized as the energy savings opportunity associated with the advanced LED lamps and luminaires expected to result from the PNNL lighting research. To generate the Advanced LED scenario, Navigant introduced into their model an additional scenario that was the same as the Current SSL Path scenario, except it included advanced LED lamps and luminaires expected from PNNL lighting research in three submarkets.

The key inputs (assumptions) made about those products are:

- Lamp and luminaire efficacy are as defined in the Advanced Luminaire Descriptions, phased in over time, as shown in Figure 4.1 (taken from Figure II-1 in Appendix D).
- Lamp and luminaire prices are as defined in the Advanced Luminaire Descriptions, converted into $/kilolumen according to the luminous output assumed for baseline products (except for the Outdoor/Streetlight products, whose luminous output was reduced according to the assumed effect of design advances resulting from PNNL research). See Figure 4.2. Importantly, the prices shown in Figure 4.2 do not yet account for the downward price adjustments that were made to account for the advanced LED lamp and luminaire values. See Section 4.3 for an explanation of how those values were used to adjust the prices described here.
- 2022 is assumed to be the first year in which the advanced LED products would be introduced to the market.
- Installation costs, operating hours, lifetime, and lumen output are the same as in the Current SSL Path scenario baseline products, except for the Outdoor/Streetlight luminaire value for lumen output, which was adjusted to reflect 26% lower luminous flux expected to result from PNNL lighting research.

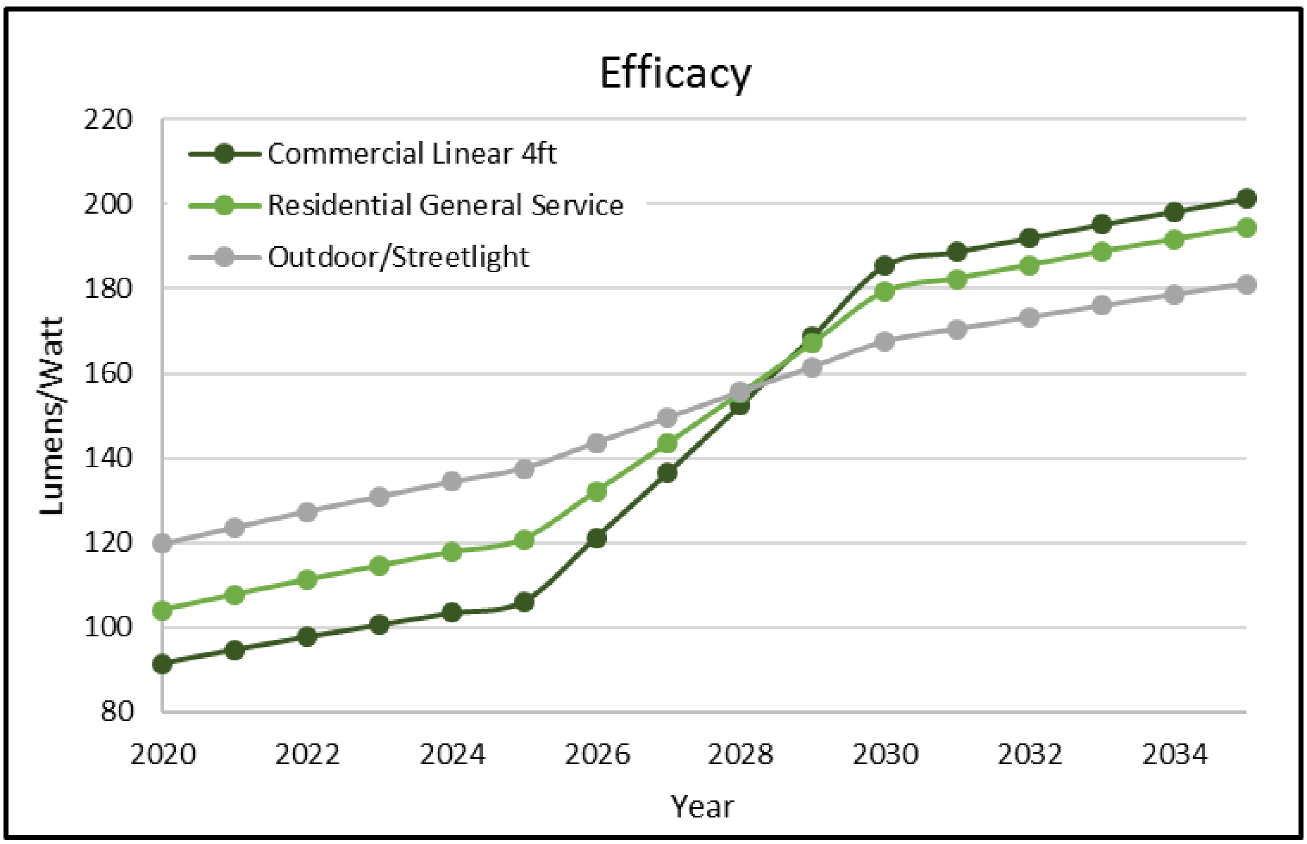

Figure 4.1. Efficacy Phase-In Schedule for Advanced Luminaires and Lamps

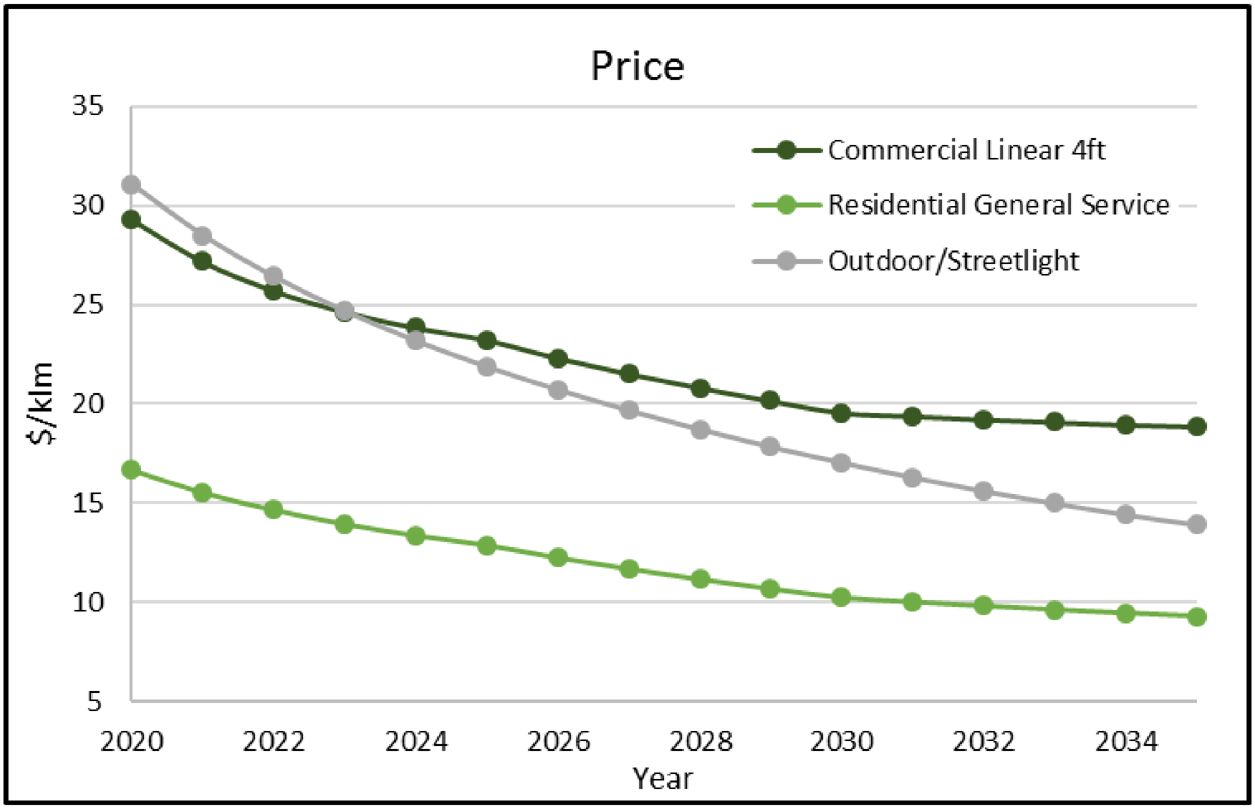

Figure 4.2. Price Phase-In Schedule for Advanced Luminaires and Lamps

4.3 Adjusting Prices for Value of Advanced LED Lamps and Luminaires

In addition to the inputs described in Section 4.2, the output values from the SERA study (purchase price effects) were used as key inputs to the Navigant model for estimating the energy saving opportunity. Put simply, the values for all features combined estimated by SERA for advanced LED lamps and luminaires were subtracted from per unit prices derived from the per kilolumen prices shown in Figure 4.2. We arrived at this method to model how the market would respond to advanced LED products with the following considerations:

- The Advanced LED products are introduced in the Navigant model as a new product category, competing with other lighting technologies, including other LED products that don't have the features in the Advanced category. As such, they do not represent a demand shift of existing products. They represent a wholly new, separate product category, whose key market characteristics must be specified separately from the products they compete against in the model.
- In order to specify those characteristics, we started from the baseline of LED products already specified in the model, and only altered a few of those characteristics, as described in Section 4.2.
- Once specified, we needed to adjust how the advanced LED products were characterized in the Navigant model to reflect the additional value estimated by SERA and reported as purchase price effects.

- We verified that the implicit demand curves in the Navigant model for the advanced LED products are all highly linear, at least over the range of prices we could adjust to reflect the values estimated by SERA. (A demand curve is a function that describes how demand varies according to purchase price, typically depicted as a downward sloping curve or line, indicating demand for the product increases as price for the product drops.) See Figure 4.3 through Figure 4.5 for images of the results of the investigation to verify the demand curves are linear. To derive these demand curves, the Navigant lighting market model was run to estimate market demand at various prices, up to the base price plus the SERA-estimated value, and down to the base price minus the SERA-estimated value. Having verified that the demand curves were linear, and assuming the supply curve was highly elastic (near or completely horizontal) (Neuman 2013; Lipsey and Chrystal 2015), we could subtract the SERA-estimated purchase price effects from the advanced LED product prices in the Navigant model. This was done to simulate the effect that an unknown new demand curve (reflecting the values estimated by SERA) would have on demand for advanced LED products. See Appendix C for more information on this method and its assumptions.

  The method used is consistent with the general body of microeconomic theory referred to as neoclassical (Pindyk and Rubenfeld 2017).

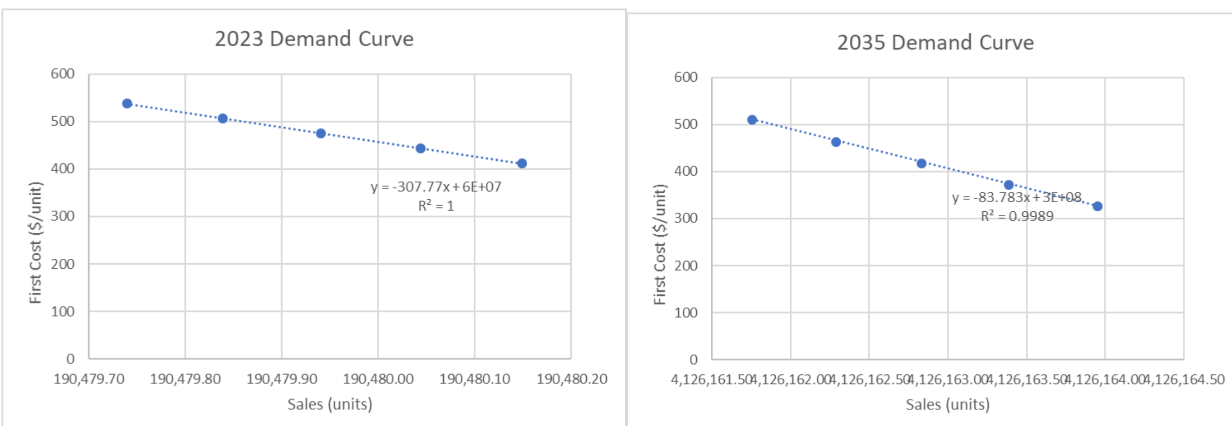

Figure 4.3. Demand Curves for Advanced LED Street/Roadway Luminaires (before SERA value adjustments)

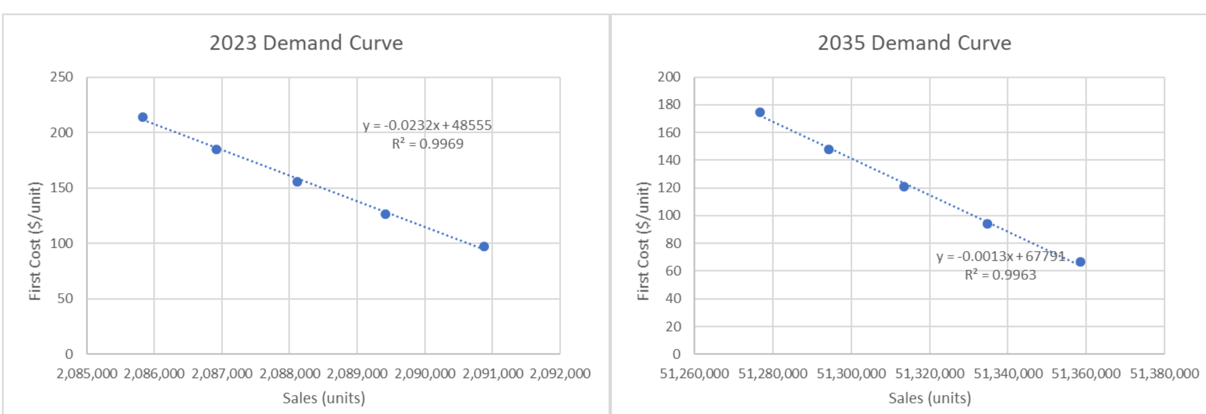

Figure 4.4. Demand Curves for Advanced LED Commercial Linear Luminaires (before SERA value adjustments)

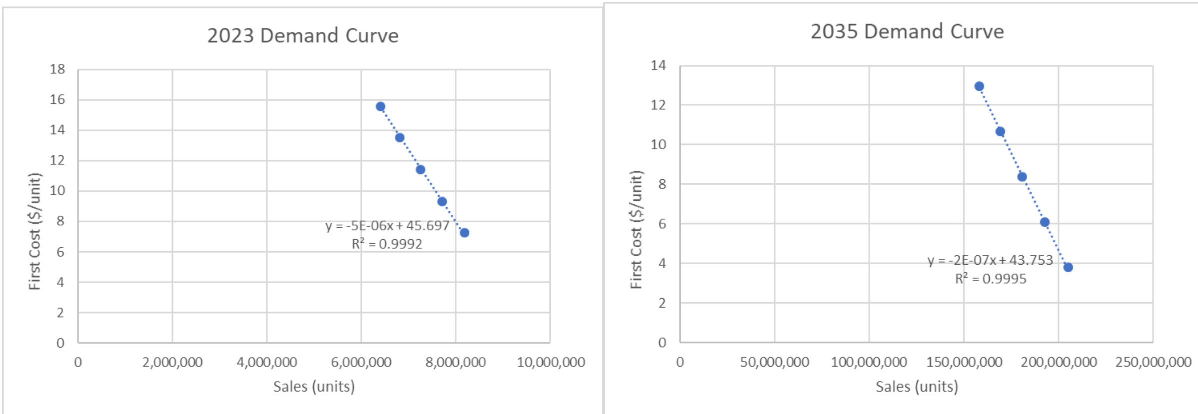

Figure 4.5. Demand Curves for Advanced LED Residential General Service Lamps (before SERA value adjustments)

4.4 Energy Savings Modeling Results

Running the lighting market model produced estimates of potential energy savings for three specific, representative submarkets: commercial linear 4-ft luminaires, residential general service lamps, and street/roadway luminaires. These submarkets were selected for detailed modeling because they are good representatives of their market sectors (commercial, residential, and outdoor). In the case of the commercial and residential sectors, they represent by far the largest submarkets within each of those sectors, and in the case of the outdoor sector, the submarket represents the products most directly affected by planned PNNL research. Modeling results for these three submarkets were then extended to other submarkets to estimate potential savings across all lighting submarkets through use of scaling factors. Specifically, we developed a scaling factor for each submarket for each year of the modeling run using the ratio of projected energy use for each submarket to the total energy use in the sector (for the Current SSL Path scenario). The scaling factors were multiplied by the [modeled submarket energy savings divided by the modeled submarket scaling factor] to estimate energy savings in all other submarkets and years (2023–2035). When totaled, those results gave us estimates of potential energy savings in each year of the model run. For more detail on the scaling methodology, see Section 4 of Appendix D.

All energy savings were calculated from the “Current SSL Path” scenario baseline, which assumes the advanced features expected to result from PNNL work will not enter the market. To estimate the energy savings, it was first necessary to estimate changes in the stock of various luminaires and lamps over time, including the Advanced LED lamps and luminaires that are the subject of this study. Figure 4.6 through Figure 4.8 illustrate those projections. In each of those figures, note that the dotted red line showing the market penetration of Advanced LED luminaires and lamps starts out very slowly, and then gains market share over time, as allowed for new technologies by the Bass Diffusion module in the lighting market model.

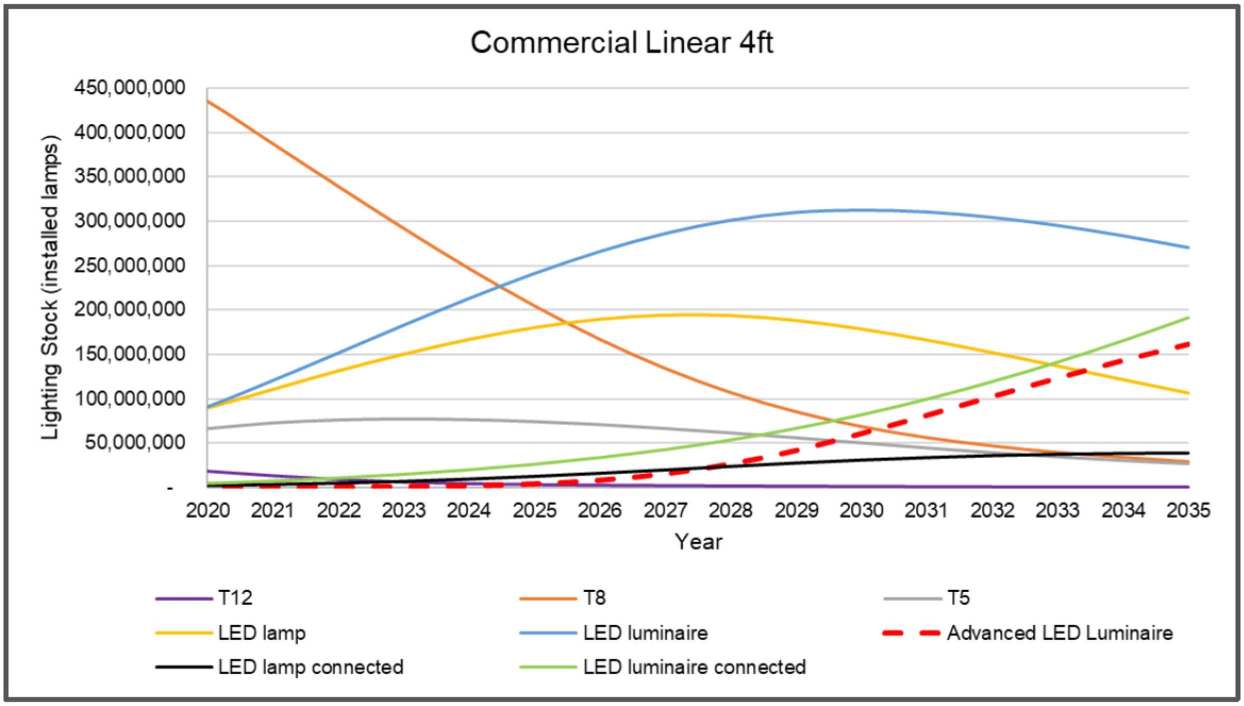

Figure 4.6. Commercial Linear 4-foot Lamp and Luminaire Stock Projections

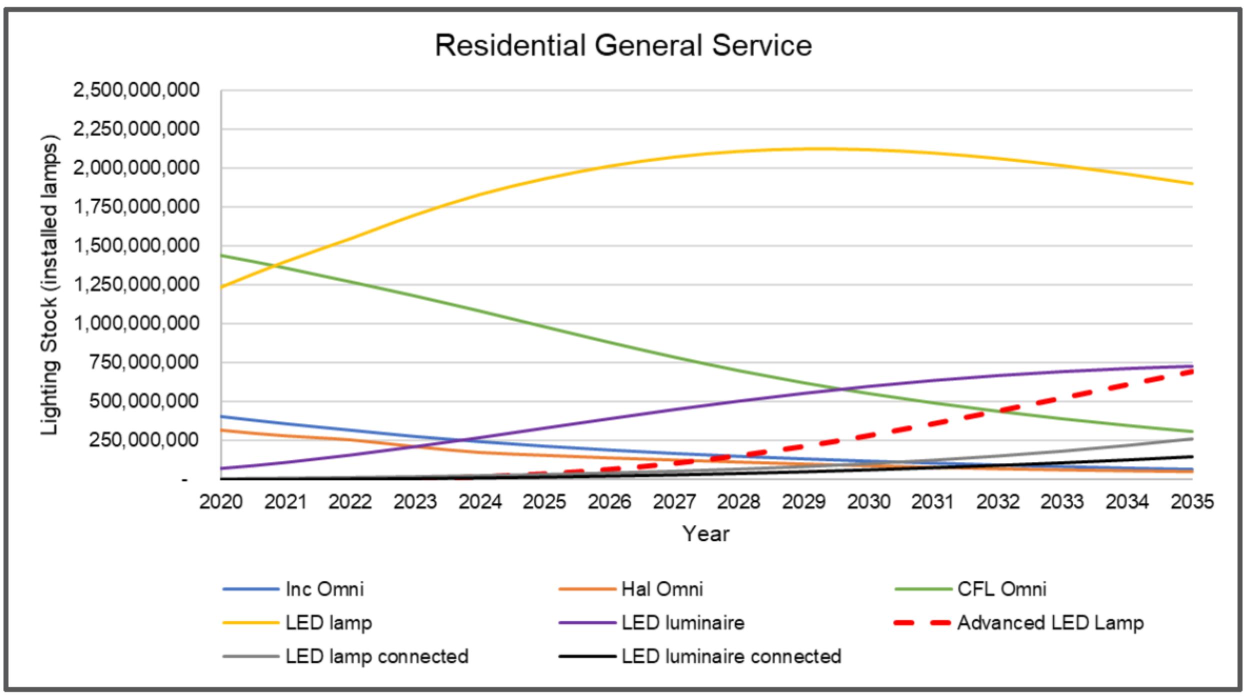

Figure 4.7. Residential General Service Lamp and Luminaire Stock Projections

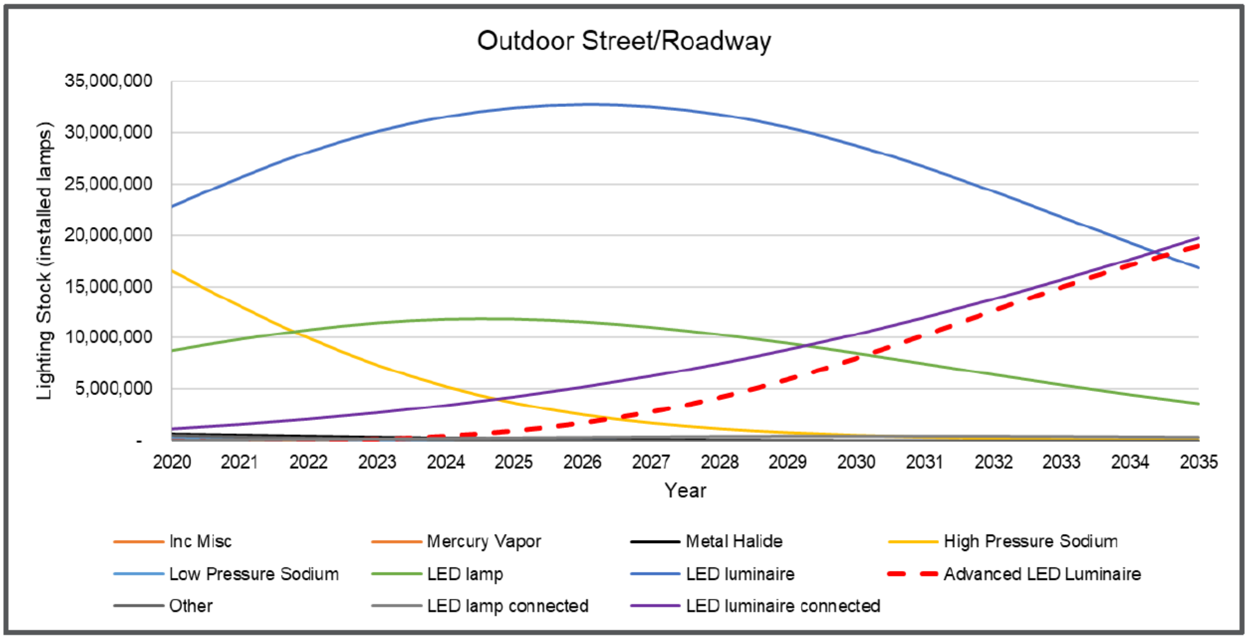

Figure 4.8. Outdoor Street/Roadway Lamp and Luminaire Stock Projections

Based on these stock projections, the assumed performance characteristics of these products, and use of the scaling factors to extend the results to all lighting submarkets, the energy savings opportunity was estimated relative to the Current SSL Path scenario and is summarized in Table 4.1 and Table 4.2.

Table 4.1. Advanced LED Technology Source Energy Savings (tBtu)

Sector	2025	2030	2035	Cumulative (2023-2035)
Commercial/Industrial	-5.9	29.0	102.0	380.4
Residential	54.6	105.7	147.5	1,208.5
Outdoor	2.3	30.5	84.7	398.3
Total	51.0	165.2	334.3	1,987.2

Table 4.2. Advanced LED Technology Source Energy Savings (% of sector lighting energy use)

Sector	2025	2030	2035	Cumulative (2023-2035)
Commercial/Industrial	-0.2%	1.4%	5.7%	1.4%
Residential	5.1%	11.6%	18.1%	9.7%
Outdoor	0.3%	4.2%	11.7%	4.1%
Total	1.2%	4.5%	10.0%	4.0%

As shown in the tables above, the annual energy savings opportunity from PNNL's lighting energy research are substantial in the final year of the projection, 2035, relative to total lighting energy use in the baseline scenario (10%) and relative to the sectors in which the savings occur, especially residential (18.1%). Total energy savings increase throughout the projection years, slowly at first, and then substantially by 2035. This is largely driven by the projected slow early uptake of the new technologies, as reflected in Figure 4.6 through Figure 4.8. Another result that stands out in these modeling runs is the large savings in the residential sector relative to the other sectors. This is partially a consequence of the higher efficacy of advanced LED lamps relative to the baseline over the modeled years, especially in the years 2023 (year after market introduction) to 2030. The lamps installed during this period contribute to the energy savings achieved in 2035. In addition, in the baseline scenario the residential sector generally has higher quantities of the installed stock made up of less efficient lighting technologies (i.e., incandescent, halogen, and compact fluorescents) which are being replaced by advanced LEDs in the Advanced LED scenario.

One other notable result is the short-term dip in commercial sector energy savings in the early years into negative territory (-0.2% in 2025), which in turn limits the level of savings achieved in the commercial sector in later years (5.7% in 2035). The reason commercial sector savings turn negative in the early years is primarily due to the decrease in efficiency of luminaires using early glare control technology. As noted in Appendix A, the Advanced Luminaire Description for Commercial Luminaire Glare Research assumed that near-term technology would reduce efficacy below the baseline by 15%, but that in the long-term, there would be no efficiency penalty. By comparison, the residential sector saw no early negative dip in energy savings because that simulation was based on bare lamps, not whole luminaires, a product category for which glare control was not a good fit, so it was not considered.

5.0 References

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Appendix A – Advanced Luminaire/Lamp Descriptions

GLARE RESEARCH – Commercial

Note: There is no residential counterpart for this research effect because the residential analysis focuses on replacement lamps (bulbs), not luminaires. Since glare is largely a consequence of luminaire design, it doesn't make sense to investigate the value of glare control for residential lamps.

	COLLOQUIAL DESCRIPTION	***TECH DESCRIPTION***
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new and replacements for 4 ft fluorescent type fixtures. No design emphasis on glare control. Glare creates visual discomfort for a significant number of observers.*	*Visible matrix of high-intensity LEDs sometimes visible. Current glare metrics are inadequate for characterizing glare performance. Glare creates visual discomfort for at least 20% of observers.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points.	*Near-term performance* *2020 & 2025: New glare metrics have led to new luminaire designs and application guidelines that eliminate visual discomfort, with modest reduction in energy efficiency.* *Long-term performance* *2030 & 2035: Updated glare metrics combined with new technologies eliminate visual discomfort with no loss of energy efficiency.*	*Near-term Performance: New glare metrics have led to new luminaire designs and new application guidelines that eliminate visual discomfort, with a 15% reduction in energy efficiency compared to the baseline.* *Long-term Performance: Updated glare metrics combined with new findings on optical materials and optical control eliminate visual discomfort with no trade-off in energy efficiency.*

FLICKER RESEARCH -- Commercial

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new and replacements for 4 ft fluorescent type fixtures. Light flickering is noticed by people sensitive to flickering.*	*Current metrics for flicker do not adequately address specific conditions related to SSL lighting; flicker is noticeable to at least 20% of people.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced light source description for 2 performance points	<u>*Near-term performance*</u> *2020 & 2025: new flicker metrics and guidelines lead to new technologies that reduce flicker, so that very few people notice. Causes 10% increase in price relative to baseline.* <u>*Long-term performance*</u> *2030 & 2035: Updated flicker metrics and application guidelines cause new technology development. Noticeable flicker is eliminated for all people. No increase in price relative to baseline.*	<u>*Near-term performance*</u>*: New flicker metrics and guidelines have led to new driver, dimming and control technologies that reduce flicker so that it is noticeable to no more than 5% of the people in typical applications, at a 10% price increase over the baseline product.* <u>*Long-term performance*</u>*: Updated flicker metrics and application guidelines combined with new developments in driver, dimming and control technologies eliminate noticeable flicker with no increase in price.*

NON-VISUAL EFFECTS LIGHTING RESEARCH -- Commercial

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new & replacements for 4 ft fluorescent type fixtures. Light color & intensity not adjustable.*	*Static color temperature, spectrum, and intensity.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points	*<u>Near-term Performance</u>* *2020 & 2025: Lighting is adjustable down to very low levels. Color temperature also adjustable. It addresses the desire to have high color temperatures during the day with higher light levels, and lower color temperatures at night, with lower light levels. Price is same as baseline, with a 10% reduction in efficiency.* *<u>Long-term Performance</u>* *2030 & 2035: wide range of adjustment possible for both light levels and various light colors. (Possible to have more or less blue and red light while keeping light color appearance constant.) Addresses the desire to have bluer light during portions of the day, with higher light levels, and redder light at night, with lower light levels. Price is same as baseline, with a 10% increase in efficiency.*	*<u>Near-term performance:</u> Dims smoothly down to 1% and adjusts in color temperature linearly between 2500 to 5000 K (using 2-channel controls for change in CCT). Allows higher CCTs and light intensity during the day, and lower CCTs and light intensity at night, aligning with best practice based on research.* *<u>Long-term performance</u>: Dims smoothly down to 0%. Using multi-channel color control, the amount of short and long wavelengths can vary while maintaining the same CCT, or allowing CCT to vary between 2000 to 6500 K. Allows more short wavelength content and intensity during portions of the day, and more long wavelength content and less intensity at night, aligning with best practice based on research.*

COLOR RENDERING RESEARCH – Commercial

	COLLOQUIAL DESCRIPTION	TECH DESCRIPTION
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Color rendering similar to that provided by good quality fluorescent luminaires. The lighting makes colors look somewhat dull and unnatural and whites may have a slight yellowish tint; the light itself may have a slight greenish tint.*	*CIE R_a 80-84 and CIE R_9 0-20. LER 330.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: The lighting makes colors look natural, but some colors are a little bit dull. Whites are untinted.* *Energy efficiency increases by approximately 10% versus baseline. No change in price.*	*Near-term Performance* *IES TM-30-18 $R_f \geq 75$, $R_g \geq 95$, $R_{cs,h1} \geq -7\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 365*
	Long-term Performance *2030 & 2035: The light makes colors look vibrant and pleasing. Whites are crisp and clean. The light is an untinted neutral white.* *Energy efficiency increases by approximately 20% versus baseline. No change in cost.*	*Long-term Performance* *IES TM-30-18 $R_f \geq 78$, $R_g \geq 95$, $R_{cs,h1} \geq -1\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 400*

DARK SKY AND ENVIRONMENTAL EFFECTS RESEARCH -- Outdoor

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Streetlights*	*Outdoor -- All street/roadway*
Baseline product description	*Typical LED streetlight fixtures, optimized for first cost minimization. Range of fixed color temperatures available, from warm to cool.*	*Same as colloquial.*
Baseline price	*2020: $324 per unit avg* *2025: $252 per unit avg* *2030: $216 per unit avg* *2035: $195 per unit avg*	*Same as Colloquial*
Baseline efficacy	*2020: almost 10% better than current avg* *2025: about 25% better than current avg* *2030: almost 40% better than current avg* *2035: about 50% better than current avg*	*2020: 120 lm/W avg* *2025: 138 lm/W avg* *2030: 153 lm/W avg* *2035: 165 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: A warm colored light, designed to reduce impact on night sky and wildlife, containing no blue light. Price and energy performance the same as baseline.* *Long-term Performance* *2030 & 2035: Advanced understanding of interactions between light, wildlife and dark skies lead to better metrics and user guidance, allowing light that minimizes impact on dark skies and wildlife, while allowing improved human visibility. Price is the same as baseline. Energy performance is improved by 10%.*	*Near-term Performance: A low CCT LED containing no blue wavelength content with a 50% higher LER than baseline.* *Long-term performance: A more efficacious spectral content that achieves an 80% higher LER than baseline. Only the precise amount of light needed is provided at the precise times it is needed.*

COLOR RENDERING RESEARCH – Residential

	COLLOQUIAL DESCRIPTION	TECH DESCRIPTION
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Color rendering similar to that provided by good quality fluorescent lamps. The lighting makes colors look somewhat dull and unnatural and whites may have a slight yellowish tint; the light itself may have a slight greenish tint.*	*CIE R_a 80-84 and CIE R_9 0-20. LER 330.*
Baseline price	*2020: \$15 avg for 100 W incandescent equiv* *2025: \$12 avg for 100 W incandescent equiv* *2030: \$10 avg for 100 W incandescent equiv* *2035: \$9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg* *2025: about 25% better than current avg* *2030: about 40% better than current avg* *2035: almost 50% better than current avg*	*2020: 105 lm/W avg* *2025: 132 lm/W avg* *2030: 136 lm/W avg* *2035: 147 lm/W avg*
Advanced luminaire description for 2 performance points	<u>*Near-term Performance*</u> *2020 & 2025: The lighting makes colors look natural, but some colors are a little bit dull. Whites are untinted.* *Energy efficiency increases by approximately 10% versus baseline. No change in price.*	<u>*Near-term Performance*</u> *IES TM-30-18 $R_f \geq 75$, $R_g \geq 95$, $R_{cs,h1} \geq -7\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 365*
	<u>*Long-term Performance*</u> *2030 & 2035: The light makes colors look vibrant and pleasing. Whites are crisp and clean. The light is an untinted neutral white.* *Energy efficiency increases by approximately 20% versus baseline. No change in cost.*	<u>*Long-term Performance*</u> *IES TM-30-18 $R_f \geq 78$, $R_g \geq 95$, $R_{cs,h1} \geq -1\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 400*

FLICKER RESEARCH -- Residential

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Typical residential replacement bulbs. 100W incandescent replacement equivalent. Light flickering is noticed by people sensitive to flickering.*	*Current metrics for flicker do not adequately address specific conditions related to SSL lighting; flicker is noticeable to at least 20% of people.*
Baseline price	*2020: $15 avg for 100 W incandescent equiv* *2025: $12 avg for 100 W incandescent equiv* *2030: $10 avg for 100 W incandescent equiv* *2035: $9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg* *2025: about 25% better than current avg* *2030: about 40% better than current avg* *2035: almost 50% better than current avg*	*2020: 105 lm/W avg* *2025: 132 lm/W avg* *2030: 136 lm/W avg* *2035: 147 lm/W avg*
Advanced light source description for 2 performance points	*Near-term performance* *2020 & 2025: new flicker metrics and guidelines lead to new technologies that reduce flicker, so that very few people notice. Causes 10% increase in price relative to baseline.* *Long-term performance* *2030 & 2035: Updated flicker metrics and application guidelines cause new technology development. Noticeable flicker is eliminated for all people. No increase in price relative to baseline.*	*Near-term performance: New flicker metrics and guidelines have led to new driver, dimming and control technologies that reduce flicker so that it is noticeable to no more than 5% of the people in typical applications, at a 10% price increase over the baseline product.* *Long-term performance: Updated flicker metrics and application guidelines combined with new developments in driver, dimming and control technologies eliminate noticeable flicker with no increase in price.*

NON-VISUAL EFFECTS LIGHTING RESEARCH -- Residential

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Typical residential replacement bulbs. 100W incandescent replacement equivalent. Light color & intensity not adjustable.*	*Static color temperature, spectrum, and intensity.*
Baseline price	*2020: $15 avg for 100 W incandescent equiv* *2025: $12 avg for 100 W incandescent equiv* *2030: $10 avg for 100 W incandescent equiv* *2035: $9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg* *2025: about 25% better than current avg* *2030: about 40% better than current avg* *2035: almost 50% better than current avg*	*2020: 105 lm/W avg* *2025: 132 lm/W avg* *2030: 136 lm/W avg* *2035: 147 lm/W avg*
Advanced luminaire description for 2 performance points	*<u>Near-term Performance</u>* *2020 & 2025: Lighting is adjustable down to very low levels. Color temperature also adjustable. It addresses the desire to have high color temperatures during the day with higher light levels, and lower color temperatures at night, with lower light levels. Price is same as baseline, with a 10% reduction in efficiency.* *<u>Long-term Performance</u>* *2030 & 2035: wide range of adjustment possible for both light levels and various light colors. (Possible to have more or less blue and red light while keeping light color appearance constant.) Addresses the desire to have bluer light during portions of the day, with higher light levels, and redder light at night, with lower light levels. Price is same as baseline, with a 10% increase in efficiency.*	*<u>Near-term performance:</u> Dims smoothly down to 1% and adjusts in color temperature linearly between 2500 to 5000 K (using 2-channel controls for change in CCT). Allows higher CCTs and light intensity during the day, and lower CCTs and light intensity at night, aligning with best practice based on research.* *<u>Long-term performance</u>: Dims smoothly down to 0%. Using multi-channel color control, the amount of short and long wavelengths can vary while maintaining the same CCT, or allowing CCT to vary between 2000 to 6500 K. Allows more short wavelength content and intensity during portions of the day, and more long wavelength content and less intensity at night, aligning with best practice based on research.*

Appendix B – SERA Report to PNNL: Study of the Value of Advanced LED Lighting Features

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SERA

SKUMATZ ECONOMIC
RESEARCH ASSOCIATES

STUDY OF THE VALUE OF ADVANCED LED LIGHTING FEATURES: MONETIZING HUMAN PHYSIOLOGICAL AND ENVIRONMENTAL EFFECTS OF LIGHTING

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FINAL REPORT

September 10, 2019

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Contents

0. Executive Summary

0.1 Introduction and Abstract

Pacific Northwest National Laboratory (PNNL) is conducting work for the Department of Energy (DOE) on the development of advanced Light Emitting Diode (LED) features, including market and technology issues. One part of this research is to determine the degree to which the market may find value in the certain features that lend human physiological and environmentally advantages. Skumatz Economic Research Associates (SERA) was selected to conduct this research, because of its background in monetizing hard-to-measure auxiliary effects (called non-energy effects or non-energy benefits – NEBs) associated with energy efficiency programs. Examples include attributable changes in comfort, changes in noise levels, and other effects on the program's participating households or businesses.

Project Goal: This goal of this project was to estimate the value that lighting users associate with certain advanced lighting technologies. "Value" is typically expressed in dollar terms, and if estimates of dollar values could be identified, the values could be incorporated by PNNL and its contractors into models to explore the market potential of such technologies. The value of advances in three main types of lighting, commonly used in three different sectors, were researched: commercial 4-foot overhead luminaires; residential bulbs, and street/roadway lighting fixture technologies.

Approach: Two main approaches were used in this study.

- Method 1: Labeled Magnitude Scaling (LMS): The main approach used in the study was Labeled Magnitude Scaling (LMS), a method adapted from evaluation of energy efficiency program effects. This method was adapted from academic literature on the development of relative hedonic factors, which have been applied to taste (saltier, less salty).[1] In its most basic form, respondents were asked to provide a response on how valuable the technology was relative to something with a known dollar value (much less valuable, somewhat less valuable, etc.). Using factors from academics and within-sample estimates, these labels can be translated to quantitative multipliers, and used to calculate a dollar value for the advanced luminaire feature.

- Method 2: Ranking and Valuing: A back-up approach was also used, combining rank ordering of technology choices, with requests for responses about the willingness to pay for ranked options.

- Additional research on factor combinations: The study added one additional analysis on a smaller sample of respondents, asking about the valuations of pairs of the features and all features combined. This allowed an analysis of whether the values for individual features were additive in the new technology options.

[1] See Green 1993; Bartoshuk, et.al., 2000; Bartoshuk, et.al., 2002; Lin, et. al., 2009, and others.

Results:

The study found promise in both these options, with suggestions about potential improvements for their application in future studies. Generally, the study found the following.

- The two approaches were able to provide estimates for either one-time price (value) impact, or value in terms of an on-going stream of benefits, and both of these estimates could be translated into the other using assumptions about discount rates and lifetimes. The rankings of the four features were not always the same between the two methods, but the orders of magnitude estimates were within ranges that would seem to imply there is value, it can be measured consistently even with two different methods, that the order of magnitude of value can be discerned from the research, and that there is potential from the approaches used. Refinements in the study's methods and applications are suggested at the end of the study.

- There is evidence that using the sum of the values for individual features as the value for a luminaire with multiple features would overstate that LED's value to its potential customers. The estimate found that the sum of individual values would overstate the value by 75% to 150% for the longer-term features. Results on small samples for the near-term technologies imply this factor could be larger, but more study is needed on this effect.

- Commercial: Strong additional value is assigned to the four advanced features of reduced glare, reduced flicker, improved color rendition, and adjustability in spectrum and intensity. Depending on the method used, the one-time value ranged for near-term technologies varied from $20-$46 (or 12% - 29% of the $160 purchase price of the base luminaire). These values are presented in Figure ES.1. The general rankings of value for near-term options from highest to lowest were Glare, Color Rendition, Flicker, and Adjustability, with variations between the methods. Ranking results are summarized in Figure ES.2. The longer-term technologies, which were valued using Method 2 only, were ranked with elimination of Flicker as highest value, followed by elimination of glare, Adjustability, and Color rendition. These results are presented in Figure ES.2. Figure ES.1 shows the values for longer-term features ranged between $20 and $28 in up-front value (13% - 17% additional value beyond the baseline $160 purchase price). Research on the value of aggregated features finds that the sum of the value of all the long-term features is $96, but the estimated value from the ranking approach of all features combined is $54, so the research would indicate that combinations of the features should be discounted to about 56% of the estimated value when combined in a single luminaire.[2] This is presented for the longer term technologies (Figure ES.1).[3] Values and confidence intervals are presented later in the paper.

- Residential: Strong value is assigned to the three advanced residential LED technologies of reduced flicker, improved color rendition, and adjustability in spectrum and intensity. Depending on the method used, the one-time value ranged for near-term technologies varied from $1.59-$3.71 (or 11% - 26% of the $14 purchase price of the base luminaire). These values

[2] The research in NEBs in energy efficiency finds households and businesses assign more value when asked to individually value non-energy benefit than they do to the total of all effects. The differences in the NEBs work are not uncommonly between 2 and 3 or 4 times.

[3] Small-sample results may indicate the discounting factor for near term factors may be even lower.

are presented in Figure ES.1. The general rankings of value changed based on valuation method: color, flicker, adjustability for Method 1, and adjustability, flicker, and color for Method 2. The average of the values for each technology using Method 1 and Method 2 were fairly similar value for the residential technologies (between 17% and 19% of the base price), and the results for Method 2 were always substantially higher value than Method 1 (between 44% and 110% higher).[4] Ranking results are summarized in Figure ES.2. The longer-term technologies (Figure ES.1), which were valued using Method 2 only, were ranked with Color rendition as highest value, followed by adjustability (likely ranking dimming high), and lowest value for flicker. Figure ES.1 shows the values for longer-term single features ranged from about $3-$4.40 in up-front value (21%-33% more value), a substantial increase in value over the $14 base price. The valuation of the combination of all three longer-term features was about $4.58, but the sum of the individual valuations was about $10.75, so in combination, the valuations may need to be discounted to about 43% of the estimated single-feature value. More detailed information on values and confidence intervals is provided in later chapters.

- Street/Roadway: Again, strong additional value was found for the combined advanced features of reduced night impacts, lower blue light, improved human visibility and other features associated with improved LED street/roadway lighting technologies. The same features were included for both the near and longer-term technologies, so separate sets of questions were not asked in the survey instruments. In each case, the respondents ranked the technologies in the most logical way: highest value to the future, most advanced technology with energy efficiency savings; second to the same technology without energy savings; and third to the somewhat less sophisticated near-term technology. The valuations are presented in Figure ES-1, and more detailed results are presented in the body of the report. The one-time value for the technologies ranged from $39-$92 (12% to 28% of the $324 price of the base luminaire). These values are presented in Figure ES-1. Values and confidence intervals are presented later in the paper.

[4] This was not the case for the commercial sector, when sometimes Method 1 was higher value, and sometimes Method 2.

Figure ES-1: Valuation Results across Technologies

COMMERCIAL				
NEAR TERM TECHNOLOGIES	Method 1 - Incremental Value - Purchase Price Effect	Method 1 - Incremental Value - Annualized	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized
Glare with 15% lower EE	$46	$4.04	$29	$2.49
Flicker with 10% price increase	$20	$1.72	$29	$2.56
Color Rendition 10% INCREASE EE	$32	$2.83	$26	$2.25
Adjustable / Color with 10% lower EE	$26	$2.31	$20	$1.74
LONGER TERM TECHNOLOGIES - price premium for feature	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized		
Glare - no change in EE	$26	$2.26		
Flicker - no change in EE	$28	$2.47		
Color Rendition - 20% INCREASE EE	$20	$1.78		
Adjustable / Color with 10% INCREASE EE	$22	$1.89		
All Features Combined	$54	$4.69		

RESIDENTIAL				
NEAR TERM TECHNOLOGIES	Method 1 - Incremental Value - Purchase Price Effect	Method 1 - Incremental Value - Annualized	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized
Flicker with 10% price increase (wtd)	$1.71	$0.10	$3.18	$0.19
Color Rendition 10% INCREASE EE	$1.83	$0.11	$2.88	$0.17
Adjustable / Color with 10% lower EE (wtd)	$1.59	$0.09	$3.71	$0.22
LONGER TERM TECHNOLOGIES	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized		
Flicker - no change in EE	$2.96	$0.17		
Color Rendition - 20% INCREASE EE	$4.37	$0.26		
Adjustable / Color with 10% INCREASE EE	$3.42	$0.20		
All Features Combined	$4.58	$0.27		

STREET / ROADWAY LIGHTING TECHNOLOGIES				
STREET / ROADWAY LIGHTING TECHNOLOGIES	Average Incremental Value - Purchase Price Effect	Average Incremental Value - Annualized	Incremental Value - Purchase Price Effect (most conservative estimate)	Incremental Value - Annualized (most conservative estimate)
Color Near Term - Warm, Reduce Night Sky Impacts, No blue, 50% higher LER than baseline	$62.98	$6.15	$39.47	$3.85
Color Longer Term - Reflects research on light / wildlife / night sky interactions, improved human visibility, 80% higher LER	$83.36	$8.14	$46.00	$4.49
Color - Longer Term - Same as above but energy use for new feature is also 10% less.	$92.02	$8.99	$52.27	$5.10

Figure ES-2: Ranking Results and Patterns

	A. Commercial-Near Term	B. Commer-cial-Long Term	C. Residential – Near Term Rankings vary between method	D. Residential – Long Term	E. Street/Roadway – Near Term
	Values vary between methods; Value of flicker increases greatly with Method 2, otherwise rankings are Glare, Color R, Adj.	The order of options for the longer term differs from the near-term options, but Method 2 for the near term also identifies flicker as the first-ranked option (glare is second).	Rankings and values vary per method; average values for the two methods for all three features are close (17-19% of value of base). All have substantial value. Method 1 valued Color R highest and adjustability the lowest. Method 2 reversed those rankings.	It makes sense that the ranking for longer term options would be similar to Method 2 for Near Term, as the data collection and analysis methods are the same.	All methods valued the features in the same order, but this is expected; the options were near term improved technology compared against long term technology with no EE improvements and with EE improvements.
Top Valued	Less Glare	No Flicker	Near Tie - Adjustable	Color Rendit	Long term night and visibility improvements with 10% better energy efficiency
Less Valued	Color Rendit.	Less Glare	Near tie - Flicker	Adjustable	Long term night and visibility improvements
Less Valued	Less Flicker	Adjustable	Near tie - Color Rendit.	Flicker	Near term night and visibility improvement
Less Valued	Adjustability	Color Rendit.			Long term night and visibility improvements with 10% better energy efficiency

Additional detail on these results is presented in the remainder of the report.

1. Introduction and Summary of Approach

1.1 Introduction

Pacific Northwest National Laboratory (PNNL) is conducting work for the Department of Energy (DOE) on the development of advanced Light Emitting Diode (LED) features, including market and technology issues. This study is designed to provide information on the value of certain lighting features that lend human physiological and environmental advantages, including:

- Whether potential users associate "(positive) value" with specific advanced lighting features, and
- whether estimates could be developed of the size of the value.

"Value" is to be expressed in dollar terms, so the estimates can be incorporated into detailed models to estimate the potential energy savings of such technologies. The value of advances in three main types of lighting, commonly used in three different sectors, were researched:

- commercial 4-foot overhead luminaires;
- residential bulbs, and
- street/roadway lighting fixture technologies.

1.2 Detail on Sectors and Technologies Examined

For this research, it was necessary to limit the technologies to a manageable number, but a number that addressed significant markets. In order to examine the impact of technology changes, PNNL selected three market sectors, and specified a "baseline product" that would serve as the likely new / replacement technology for each market. For each sector, near-term and longer-term technology / feature enhancements were examined, with changes specified relative to that "baseline product".

The three market sub-sectors that were examined as part of this research (in bold), and the associated "baseline technologies" are listed below.

- **Commercial 4-ft linear**: A mix of typical commercial overhead office lighting, specifically four-foot linear LED luminaires. The baseline technology is assumed to include no design emphasis on the specific advanced features examined in this study.
- **Residential general service**: A mix of residential LED light bulbs (general service),
- **Street/Roadway**: A mix of outdoor LED street/roadway fixtures, optimized for first cost minimization.

1.2.1 Commercial Luminaire Options Studied

For the commercial sector, the four features studied included the following.[5] For each, two levels of technology improvement are studied, with the first, denoted with 1 (one), reflecting near-term (2020-

[5] Note that only colloquial descriptions of the technologies were used in the valuation research, but the tables in Appendix B (developed by PNNL) include technical feature descriptions for reference. For each market sector, the baseline technology, prices are expected to decrease over time, and the baseline efficacy (expressed relative to energy efficiency and lumens per

2025) projected technology change, and the second, denoted with 2 (two), reflecting long-term (2030-2035) projected technology change. [6]

- **Reduced glare**. Glare levels associated with "baseline" lighting products can create visual discomfort for a significant number (perhaps 20%) of observers.
  - Glare 1: Research results in new glare metrics, which support product changes that eliminate visual discomfort to observers through luminaire designs and new application guidelines, and are accompanied by a 15% reduction in energy efficiency compared to the baseline (with no change in purchase price).
  - Glare 2: In the longer term, research results in updated glare metrics, combined with new technologies that eliminate visual discomfort with no trade-off in energy efficiency and no change in purchase price.

- **Reduced flicker**. Current flicker metrics do not adequately address specific conditions related to LED lighting. Flicker levels associated with "baseline" lighting products are noticeable to at least 20% of observers.
  - Flicker 1: The nearer-term technology performance improvements that were studied result from new flicker metrics and guidelines, that in turn result in use of new driver, dimming, and control technologies so that flicker is noticeable to no more than 5% of observers in typical applications, and is accompanied by a 10% increase in purchase price compared to the baseline (with no change in energy efficiency).
  - Flicker 2: The longer-term technology studied result from updated flicker metrics and application guidelines, combined with new developments in driver, dimming and control technologies that eliminate noticeable flicker with no increase in price over the baseline product (with no change in energy efficiency).

- **Improved Color Rendering**. Color rendering from the "baseline" product is similar to that provided by good quality fluorescent luminaries. This lighting makes colors look somewhat dull and unnatural, whites may have a yellow-ish tint, and the light itself may have a greenish tint.
  - Color 1: The nearer-term technology performance improvements that were studied make colors look natural, and whites are un-tinted, but some colors are a bit dull. These performance improvements are accompanied by a 10% <u>increase or improvement</u> in energy efficiency of the equipment compared to the baseline (with no change in cost).
  - Color 2: The longer-term technology makes colors look vibrant and pleasing, with crisp, clean whites. The light is perceived as an un-tinted neutral white. These performance improvements are accompanied by a 20% <u>increase or improvement</u> in energy efficiency of the equipment compared to the baseline (with no change in cost).

- **Improved Lighting Adjustability (Color and Light Intensity)**. Baseline lighting is assumed to have a static color temperature, spectrum, and intensity.
  - Adjustable 1: The nearer-term technology performance improvements that were studied provides lighting that is adjustable down to very low levels (dimming) and provides adjustable color temperatures. Color temperature adjustability addresses the desire to have high color temperatures during the day (with higher light levels) and

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watt) are expected to increase over time. These tables also summarize the baseline price and efficacy level assumptions used in the research.

[6] Note that the time horizons for the two sets of technologies were not specifically mentioned in the questionnaires.

lower color temperatures at night (with lower light levels), better mimicking natural light patterns, and improving observer comfort and productivity, aligning with best practice research. The performance improvements are associated with a 10% reduction in energy efficiency relative to baseline (with no change in cost).

    - Adjustable 2: The longer-term technology uses multi-channel color control to provide a wide range of adjustments in both light levels and various light colors, adjusting blue and red components while keeping light color appearance constant. This adjustability addresses the desire to have bluer light during some portions of the day (with higher light levels) and redder light at night (with lower light levels), aligning with best practice research. Full dimmability capabilities (to 0%) are also provided. The performance improvements are associated with a 10% <u>increase or improvement</u> in energy efficiency relative to baseline (with no change in cost).

1.2.2 Residential Luminaire Options Studied

For the residential sector, the three features studied, each quite parallel to the commercial improvements (omitting "glare"), included the following.

- **Reduced flicker**. Current flicker metrics do not adequately address specific conditions related to LED lighting. Flicker levels associated with "baseline" lighting products are noticeable to at least 20% of observers.
    - Flicker 1: The nearer-term technology performance improvements that were studied result from new flicker metrics and guidelines, that in turn result in use of new driver, dimming, and control technologies so that flicker is noticeable to no more than 5% of observers in typical applications, and is accompanied by a 10% increase in purchase price compared to the baseline (with no change in energy efficiency).
    - Flicker 2: The longer-term technology studied result from updated flicker metrics and application guidelines, combined with new developments in driver, dimming and control technologies that eliminate noticeable flicker with no increase in price over the baseline product (with no change in energy efficiency).

- **Improved Color Rendering**. Color rendering from the "baseline" product is similar to that provided by good quality fluorescent luminaries. This lighting makes colors look somewhat dull and unnatural, whites may have a yellow-ish tint, and the light itself may have a greenish tint.
    - Color 1: The nearer-term technology performance improvements that were studied make colors look natural, and whites are un-tinted, but some colors are a bit dull. These performance improvements are accompanied by a 10% <u>increase or improvement</u> in energy efficiency of the equipment compared to the baseline (with no change in cost).
    - Color 2: The longer-term technology makes colors look vibrant and pleasing, with crisp, clean whites. The light is perceived as an un-tinted neutral white. These performance improvements are accompanied by a 20% <u>increase or improvement</u> in energy efficiency of the equipment compared to the baseline (with no change in cost).

- **Improved Lighting Adjustability (Color and Light Intensity)**. Baseline lighting is assumed to have a static color temperature, spectrum, and intensity.
    - Adjustable 1: The nearer-term technology performance improvements that were studied provides lighting that is adjustable down to very low levels (dimming) and provides adjustable color temperatures. Color temperature adjustability addresses the

desire to have high color temperatures during the day (with higher light levels) and lower color temperatures at night (with lower light levels), better mimicking natural light patterns, and improving observer comfort, aligning with best practice research. The performance improvements are associated with a 10% reduction in energy efficiency relative to baseline (with no change in cost).
    - Adjustable 2: The longer-term technology uses multi-channel color control to provide a wide range of adjustments in both light levels and various light colors, adjusting blue and red components while keeping light color appearance constant. This adjustability addresses the desire to have bluer light during some portions of the day (with higher light levels) and redder light at night (with lower light levels), aligning with best practice research. Full dimmability capabilities (to 0%) are also provided. The performance improvements are associated with a 10% <u>increase or improvement</u> in energy efficiency relative to baseline (with no change in cost).

1.2.3 Street/Roadway Luminaire Options Studied

For the street/roadway sector, gradations of one main feature were studied.

- **Environmental and Dark Skies Impacts**. "Baseline" LED street/roadway fixtures are optimized for first cost minimization and there is a range of fixed color temperatures available, from warm to cool.
    - Color 1: The nearer-term technology performance improvement provides a warm-colored light containing no blue wavelengths to reduce impact on night sky and wildlife. The price and energy efficiency performance are the same as the baseline.
    - Color 2: The longer-term technology provides that improvements to metrics and guidelines leads to improved spectral content of light output and other technology changes to allow lighting that minimizes impact on dark skies and wildlife, and allows improved human visibility. Only the precise amount of light needed is provided at the precise times needed. This performance improvement is associated with a 10% improvement in energy efficiency compared to baseline (and no change in price).

1.2.4 Summary of Options Studied

A summary table of the options studied follows in Figure 1.1, including the effect on price or energy efficiency (EE). If a potential change is omitted from the table, there is no associated change in price or EE.

Figure 1.1: Summary of Key Features of Lighting Technologies Studied (EE is Energy Efficiency)

Sector	Feature	Near term, vs. baseline	Longer Term, vs. baseline
Commercial linear	Glare 1 & 2	15% lower EE, no price change	No EE or price changes
Commercial linear	Flicker 1 & 2	10% price increase, no EE change	No change in price or EE
Commercial linear	Color 1 & 2	10% <u>better</u> EE, no price change	20% <u>better</u> EE, no price change
Commercial linear	Adjustable 1 & 2	10% lower EE, no price change	10% <u>better</u> EE, no price change
Residential	Flicker 1 & 2	10% price increase, no EE change	No change in price or EE
Residential	Color 1 & 2	10% <u>better</u> EE, no price change	20% <u>better</u> EE, no price change
Residential	Adjustable 1 & 2	10% lower EE, no price change	10% <u>better</u> EE, no price change
Street/Roadway	Color 1 & 2	No change in EE or price	10% <u>better</u> EE, no price change

1.3 Analysis and Data Collection Method Overview

Quantifying "hard to measure" (HTM) effects can be complicated. Conceptually, consider the problem of how to monetize improved comfort from an energy efficiency program delivered by a utility. The traditional option is to ask the question in terms of willingness to pay (WTP) or willingness to accept (WTA).[7] A household would be asked to state how much they would be willing to pay (in dollar terms) for that amenity, or how much they would be willing to accept to have that amenity taken away. This turns out to be a relatively difficult question for many households to answer, and the more difficult the question, the longer it takes for the household to answer, and the more varied and potentially unreliable the answers become.[8] And as answers are slower, surveys become more costly, and sample sizes for a given budget are smaller, and statistical properties associated with the study are harmed.

Another option is to ask about relative value – particularly "value" relative to a factor that can be monetized. One can ask what percent more or less valuable the comfort is relative to the value of a candy bar or some other factor that can be readily monetized. If twice as valuable, and the candy bar costs $0.50, the estimate of the value of the perceived comfort to the householder is $1. Two issues arise with this method. Households have particular difficulty with percentages and quantitative statements of value. Again, speed, sample sizes and properties are compromised. Second, the factor should be something meaningful to all respondents.

The third option, first applied to energy efficiency and non-energy benefits (like comfort) by the authors,[9] is to adapt academic research on labeled magnitude scaling (LMS). This approach asks respondents to express their relative value from among a set of verbal labels, or word terms (e.g. "much more valuable", "somewhat more valuable", etc.). This question can be readily and quickly answered by respondents. Then, this verbal scale can be translated into quantitative factors in two ways. The survey can ask one or several quantitative (percentage) questions from within the sample to provide a translation from "much more valuable" to a number from the sample. The second approach is to adapt or apply estimated factors from the literature to translate the labeled scale to quantitative multipliers.[10] This LMS approach is a common method now used for estimating NEBs associated with residential and low-income weatherization programs and a host of other energy efficiency program types.[11]

In the NEB and energy efficiency arena, this approach has most commonly used "program energy savings" as the comparison factor, *a la* 'would you say the comfort you experienced due to the program: much more valuable, somewhat more valuable, same value, somewhat less valuable, or much less valuable than the energy savings from the program'.[12]

We were uncertain whether this approach would be successful for measuring these effects. We were also uncertain how to best apply the LMS approach when there were no savings or no price change upon which to directly and internally leverage the valuations. Finally, there was later interest expressed in identifying the value of pairs and combination of features, and the LMS approach would be clunky and

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[7] For example, Breidert, et. al., 2006.

[8] Skumatz and Gardner, 2002; Skumatz and Gardner, 2006

[9] Skumatz and Gardner, 2002

[10] This LMS approach is developed from the "taste" literature (saltier, less salty). See, for example, Green, 1993; Bartoshuk, et. al., 2000; Bartoshuk, et. al., 2002; Lin et. al., 2009.

[11] Skumatz, et. al., 2009, Skumatz 2014.

[12] For example, see studies by Skumatz et. al. 2005; Summit Blue et. al., 2005; NMR 2016.

lengthy to use for the application. Therefore, we developed a second approach. We used a combination of an ordered ranking approach with a willingness to pay approach. We presented a list of near or longer-term options, and asked the respondents to rank from most valuable to least valuable. Most questions included five or six options to rank. Then we followed up the question with questions asking about the willingness to pay for the highest ranked / highest valued option, and for the lowest ranked option that wasn't a traditional bulb. For some, especially those with six options, we also asked for the value of their second ranked option. This minimized the number of (difficult) quantitative questions we had to ask respondents. The assumption was that respondents would value and rank these differently, and therefore, we would get WTP amounts across all the options from various subsets of the respondents. Ranking questions provide a great deal of information quickly. Not only does it provide rankings, but with values at the high and lower ends, you also get information about the values of ranked items between; their values are in-between the high and low as well.

These were the two options used in the study: Labeled magnitude scaling, and ranking with willingness to pay follow-ups. Copies of the web-based questionnaires are included under separate cover in Appendix E. To gather information on the relevant sectors, we used web-based surveys. In order to try to provide robust results, and to hedge in case some groups were not well able to answer the types of questions we were asking, we issued surveys to two groups for each sector, assigned as follows:

- Commercial technologies: Responses were sought from lighting designers who are involved in commercial lighting decisions (new and remodel), and from commercial businesses.
- Residential technologies: Responses were sought from households, and from builders / remodelers, all assumed to be purchasers of substantial amounts of household lighting equipment.
- Street/roadway technologies: Responses were sought from municipal public works departments, street/roadway lighting contractors, and to a lesser degree from electric utilities, partly because sample sizes were small, , and because they can also play a role in ownership and promotion of street/roadway lighting technologies.

1.4 Organization of the Report

The report includes:

- More detailed discussion of the data collection approach, analysis, and results in Chapter 2.
- Results, conclusions, and next steps included in Chapter 3.

A number of appendices are attached, including:

- Technology alternatives studied are described in Appendix A;
- Survey sampling and outreach procedures are presented in Appendix B;
- Data cleaning procedures are discussed in Appendix C;
- Confidence intervals for the responses are provided in Appendix D, and;
- Survey instruments by sector are presented in a separate document, as Appendix E.

2. Data Collection and Analysis

2.1 Data Collection

As mentioned, data were sought from at least two groups of respondents for each sector. Figure 2.1 outlines the survey groups, how the population was gathered, and the responses we received from each group. In each case, the goal was a minimum of 68 surveys, and no more than 400 are needed for strong representativeness.[13] Incentives were offered to each group to encourage response; higher incentives were needed for the scarcer public works group to improve response rates. At least two email mailings were used to improve statistical properties, as a strategy to include responses from first-round non-respondents.[14]

Figure 2.1: Detail on Survey Respondents

Sector / Respondent Group	Source / Administration Method[15]	Population Mailed to (adjusted for bouncebacks)	Number of Responses	Calculated Response Rate
Commercial – Lighting Designers	Purchased email addresses in relevant NAICS business codes; SERA emailed link to web survey	9717	184	1.9%
Commercial – Business Owners	Purchased panel survey responses, statistically representative nationwide	n.a.	400	n.a.
Commercial – Business Owner Follow-up sample[16]	Purchased panel survey responses, statistically representative nationwide	n.a.	104	n.a.
Residential – Builders	Purchased email addresses in relevant NAICS business codes; SERA emailed link to web survey	8275	104	1.3%
Residential – Households	Purchased panel survey responses, statistically representative nationwide	n.a.	400	n.a.
Street/roadway – Public Works and Utilities (combined)	Purchased email addresses in relevant NAICS business codes; SERA emailed link to web survey	7161	79	1.1%

[13] The standard metric for surveys is, for large populations, 68 responses provides +/-10% at 90% confidence, 97 provides +/-10% at 95% confidence, 270 provides +/-5% at 90% confidence, and 380 provides +/-5% at 95% confidence. Note that this assessment depends on random responses, large samples, and officially (often forgotten), represents the performance for questions that have two options, that would each be answered in a roughly 50/50 answer (male / female, etc.). It does not strictly provide the performance for numeric answers, or multiple options, or 2-choice responses that vary from 50/50. However, this is the standard metric used to compare / assess survey confidence.

[14] They were asked to self-report on a question asking first or second round (identified in the email solicitation). We did not weigh specially for these cohorts.

[15] Emails were purchased from InfoUSA and emailed by SERA; panels were purchased from SSI / Dynata.

[16] Late in the study we found we mis-specified one question related to longer term options in the commercial survey, and also used the opportunity to add new questions gathering information on the 'sum vs. total value' question for near term as well as longer term technology list (since the questionnaire was shorter for the follow-up group).

2.2 Analysis / Estimation Method

Two main methods were used to develop estimates of the value of enhanced LED features:

- Method 1: Labeled Magnitude Scaling (LMS)
- Method 2: Ranking and Valuing.

Each approach is described in more detail below.

Method 1: Labeled Magnitude Scaling (LMS):

The main approach used in the study used verbal Labeled Magnitude Scaling (LMS), a method adapted from evaluation of energy efficiency program effects. This method was adapted from academic literature on the development of relative hedonic factors, which have been applied to taste (saltier, less salty).[17] The rationale is that, willingness to pay requires quantitative responses that are hard for respondents to answer – at least not very quickly, consistently, or reliably.[18] However, they may be able to answer a question that asks if the factor under study is more valuable or less valuable than something for which there is a known dollar value. In that way, a value may be produced without asking respondents something they have a great deal of difficulty answering directly. The last step in the process is translating the labeled relative scale to a number that can be multiplied times the known dollar value. In the approach used here, we bring in two sources for those figures: values from the academic literature and values from within-the-sample.

Additional advantages are provided using this method. Statistical properties improve with more response and more reliable responses; with a fixed budget for a survey, there are improved properties if respondents can answer more quickly and more reliably. Respondents can answer relative questions more quickly than they can provide quantitative responses.

In its most basic form, respondents were asked to provide a response on how valuable the technology was relative to something with a known dollar value (much less valuable, somewhat less valuable, etc.). The following response categories were offered:

- Much more valuable than the comparison factor provided for the question (varied with technology and feature), abbreviated below as MMV.
- Somewhat more valuable (SMV)
- About the same value (SV)
- Somewhat less valuable (SLV)
- Much less valuable (MLV).

The literature provides figures for translating these values to multipliers. The values from the literature are relative to scales for salty / less salty, or other features. They are not used in quite the way used here, but previous research has shown that these factors have transferred successfully to NEBs work reasonably well, and that the values estimated from the NEB studies are similar magnitudes to those

[17] See Bartoshuk et. al. 2002; Lin, et. al., 2009, and others.

[18] See Skumatz and Gardner 2002 and Skumatz and Gardner 2006 in application to energy efficiency, for example.

identified in the literature.[19] Typical values from a quantitative study in labeled magnitude or hedonic scaling are reproduced in Figure 2.2.

Figure 2.2: Semantic Phrases, and scale values developed from geometric mean ratings for 5 positive and 5 negative descriptors
(Source: Lim, Wood, and Green, Chemical Senses, 2009)

Positive Phrases - Descriptors	Scale value	Negative Phrases - Descriptors	Scale values
Most liked sensation imaginable	100	Most disliked sensation imaginable	-100
Like extremely	65.72	Dislike extremely	-62.89
Like very much	44.43	Dislike very much	-41.58
Like moderately	17.82	Dislike moderately	-17.59
Like slightly	6.25	Dislike slightly	-5.92

The surveys used in this study asked a series of questions that allowed us to develop "within-sample" values for these semantic phrase scales, or labeled magnitude scales. The surveys asked each respondent to assign a semantic phrase to a variety of different LED scenarios. Then, for a subset of those answers, the survey instrument also asked the respondent to assign a numeric multiplier to the same LED scenario. In the analysis step, the responses that contained both a labeled response (MMV, etc.) and a numeric response were assembled for all of the respondents from each group separately (lighting designers vs. public works staff, etc.). These data sets then allowed calculation of the average quantitative multiplier associated with each semantic phrase or labeled magnitude from within each sample group. The values developed from the within-samples for the descriptors used in this study are remarkably similar to the values translated from these estimates. These values – and the translated values for the academic values – are provided in the shaded areas in the Labeled Magnitude Scaling figures provided later - next to the academic values.

The Labeled Magnitude Scaling figures also provide the multiplier values for each of the five survey groups – lighting designers and business owners for commercial – are provided below in Figures 2.4 and 2.5; builders and households for residential (Figures 2.8 and 2.9); and combined public works, contractors, and utilities for street and roadway lighting (Figure 2.13). The multiplier values are generated using the survey responses for percent selecting MMV, SMV, SV, SLV, and MLV times the following:

- Academic value for the multipliers
- A more aggressive value for the academic multipliers
- In-sample sample-wide / all-inclusive multiplier (point estimate) and
- In-sample 90% confidence interval values for the in-sample multiplier.

One additional value is provided for the commercial sample. It is an in-sample point estimate for just the 38 surveys that were completed in the follow-up.

The in-sample values are used for the computations because this is an empirical project, and using values representative of the perception-based multipliers from the respondents themselves is consistent, and the in-sample estimates were based on the same verbal terminology used in the study; the academic values are provided for comparison. When these multipliers are applied to the appropriate known valuation factor for the feature (e.g. 5% less energy efficiency), each of which has an

[19] Skumatz, et. al., 2009, NMR 2016, for example.

associated dollar value, the results are the dollar value of the LMS estimate for the value of the new enhanced LED feature. These results are provided in the Figures containing valuation results below.

Method 2: Ranking and Valuing

A back-up approach was also used, combining rank ordering of technology choices, with requests for responses about the willingness to pay for ranked options. Respondents were provided with a list of 4-6 technology options (with associated impacts on price or energy efficiency relative to the baseline). They were asked to rank the options from best to worst. Then they were asked to identify what price they would be willing to pay for the enhanced technology. They were also asked to state the price for the lowest ranked technology, and for longer lists, they were also asked about the second-highest ranked option. Across respondents, each technology was ranked top or worst by some of the respondents, so willingness to pay values were reported for each technology scenario.

Using regression analysis, these ordered rankings were used to develop ranked order/willingness to pay values for each of the technologies, and these are the values presented as Method 2 in the near-term and longer-term technology sections. Associated confidence intervals for the prices (coefficients) are presented in Appendix D.

Additional Research:

Additional limited research was conducted on factor combinations. This work was identified later in the study and was conducted using exploratory analysis on a smaller sample of respondents, asking about the valuations of pairs of the features and all features combined. This allowed an analysis of whether the values for individual features were additive in the new technology options.

2.3 Study Results

The study found promise in both these methods of valuing advanced features in LEDs.

- The two approaches were able to provide estimates for either one-time price (value) impact, or value in terms of an on-going stream of benefits, and both of these estimates could be translated into the other using assumptions about discount rates and lifetimes. The rankings of the four features were not always the same between the two methods, but the orders of magnitude estimates were within ranges that would seem to imply there is value, it can be measured consistently and to similar value levels even with two different methods, that value estimates can be developed that have reasonable confidence levels, and that there is potential from the approaches used. Refinements in the study's methods and applications are suggested at the end of the study.

- There is evidence that using the sum of the values for individual features as the value for a luminaire with multiple features would overstate that LED's value to its potential customers. The estimate found that the sum of individual values would overstate the value by 75% to 150% for the longer-term features. Results on small samples for the near-term technologies imply this factor could be larger, but more study is needed on this effect.

The following sections describe the multiplier results, the ranking results, and the near- and longer-term valuation results for each sector. *All figures from Figure 2.3 (ranking results across all sectors) through Figure 2.13 (longer-term results for the street/roadway lights) are provided as a group after the discussion of street/roadway t results in Section 2.3.3. Finally, these are estimates, and it may be appropriate to use the ranges of the confidence intervals or use rounded values.*

Contents of the figures follows:

Rankings: Figure 2.3 summarizes the rankings of the features across all sectors.
Interpreting the LMS figures (two each for commercial and residential sectors, one for street/roadway): In the shaded area in the left of the figure, are presented a simple score associated for each Labeled Magnitude (MMV, SMV, etc.). Simple scores vary from 5 (MMV) to 1 (MLV). Also presented are the values for the academic multiplier (including a more conservative value), and the results for the in-sample sample wide multiplier. The feature names across the top vary in feature and energy savings or price variations. The percentages (in the white area) are the share of respondents that answered MMV, SMV, and so on for each of the advanced feature scenarios presented to the respondents. The count for the responses is also provided, followed by a simple scoring average (LMS percentages weighted by simple 1-5 scores), and its translation back into LMS terms.

In the bottom half of the table, the multiplier results for each technology scenario is presented. These figures represent the product of the share of respondents selecting each LMS (MMV, SMV, etc.) multiplier times the valuation factor – in turn, the results using the academic multiplier, more conservative interpretation of the academic multiplier, the in-sample derived multiplier, and the low and high confidence ranges for the in-sample multiplier.

In this table, weighted average simple scores that are in the top half (above average) are shaded red and the single highest score is boxed. The bottom two values are shaded grey.

Interpreting the Near-Term Results figures (Figures 2.6 and 2.10, one for each sector, commercial and residential): The near-term results include the results from Method 1 and Method 2, and provide the results for all respondent groups in one Figure. Using Method 1, the value multipliers relative to EE or price change are presented, and they are valued somewhat differently depending on whether they are annual effects (energy efficiency, from annual energy savings) or price change (which is a one-time multiplier), with the path traced using the arrows at the top of the Figure (again, Figures 2.6 and 2.10). Results from Method 2 area presented under the green heading, providing the point estimate of one-time values, plus the values associated with the 90% confidence intervals. Finally, annual results are translated to up-front purchase price effects, and vice versa, using assumptions about measure life and discount rates (assumptions included at the top of the figure). Results are presented under the yellow heading, and the inputs from the contributing survey sources (respondent types) are weighted based on the relative respondent counts for the surveys. The street/roadway figure has only one respondent source, and is not weighted in this way.

Interpreting the Longer-Term Results figures (Figures 2.7 and 2.11, one for each sector, commercial and residential): The longer-term results are presented, with the point estimates and confidence intervals for each respondent type for each feature in the grey areas of the table. The combined valuations for the features are developed using an average of the values from each survey, weighted by the number of survey responses from each group. The street/roadway figure has only one respondent source, and is not weighted in this way.

2.3.1 Detailed Results – Commercial

The results for the derivation of the labeled magnitude scaling multiplier factors for each feature studied are presented in Figures 2.4 and 2.5. Figures 2.6 and 2.7 present the results of valuations from the estimate methods for, respectively, near-term and longer-term technologies.

LMS multiplier Derivation Commercial (Figure 2.4 and Figure 2.5).

There are two sets of surveys that provide LMS results for commercial technologies: lighting designers are presented in Figure 2.4 and commercial business owner results are presented in Figure 2.5.

- Lighting Designers: The results for lighting designers show that the highest valued feature is no flicker at a 5% higher price. This translates to the highest values using the in-sample multipliers as well. Second highest is vibrant color and a low-flicker option. The lowest ranked options are better color rendition and less glare options with 10% and 15% worse energy efficiency respectively. Within each feature, generally sensible multipliers arise. As the options become less energy efficient, value decreases (with the exception of the 10% better color rendition option). In addition, note that the in-sample multiplier is higher than the academic values on the high end, but generally lower on the low end. Percentages are higher at the high value end of the choices (MMV and SMV are more common than SV, SLV, and MLV). Therefore, the In-sample multipliers are generally higher than the academic sources. The 90% ranges for the confidence intervals at the bottom of the figure provide some indication of which resulting multipliers are and are not significantly different.[20] The highest ranked option, E, is significantly higher than all options except C, D, and I. The lowest ranked option, A (and G) is significantly lower than all options except F and G.

- Commercial Business Owners / Managers: The highest ranked option is the better color rendition with 10% better energy efficiency than base. This was true for both the full sample and the follow-up sample. The in-sample valuations for the multipliers were higher in the follow-up sample, leading to a higher-resulting multipliers from these options. The next highest option was the vibrant color rendition with 20% better energy efficiency (EE) savings, asked only of the smaller follow-up sample. The worst-scoring options were adjustable feature associated with 10% lower energy efficiency, and the better color rendition (not vibrant) with 5% lower energy efficiency. Glare and flicker were both ranked fairly highly, given that these options had 15% worse energy efficiency, and a 10% price increase, respectively. The 90% confidence intervals indicate that the highest ranked option, F, is higher than all options except G and D. The lowest is significantly lower than all options except B and C.

Ranking and Valuation Results, Commercial (Figure 2.3, Figure 2.6 and Figure 2.7)

- Strong additional value is assigned to the four advanced features of reduced glare, reduced flicker, improved color rendition, and adjustability in spectrum and intensity. Depending on the

[20] The test lacks the sample size adjustment, but the sample sizes we are comparing are similar.

method used, the one-time value ranged for near-term technologies varied from $20-$46 (or 12% - 29% of the $160 purchase price of the base luminaire). These values are presented in Figure 2.6.

- The general rankings of value for near-term options from highest to lowest were Glare, Color Rendition, Flicker, and Adjustability, with variations between the methods. Ranking results are summarized in Figure 2.3 and Figure 2.4. The longer-term technologies, which were valued using Method 2 only, were ranked with elimination of Flicker as highest value, followed by elimination of glare, Adjustability, and Color rendition. These results are presented in Figure 2.3 and Figure 2.5
- Figure 2.7 shows the values for longer-term features ranged between $20 and $26 in up-front value (13% - 17% additional value beyond the baseline $160 purchase price).
- Research on the value of aggregated features finds that the sum of the value of all the long-term features is $96, but the estimated value from the ranking approach of all features combined is $54, so the research would indicate that combinations of the features should be discounted to about 56% of the estimated value when combined in a single luminaire.[21] This is presented for the longer term technologies (bottom of Figure 2.7).[22]

2.3.2 Detailed Results – Residential

LMS Multiplier Derivation, Residential (Figure 2.8 and Figure 2.9).

There are two sets of surveys that provide LMS results for residential technologies: builder results are presented in Figure 2.8 and household results are presented in Figure 2.9.

Builders: The results for builders show that the highest valued feature is better color with 10% *better* energy efficiency. Again, this also translates to the highest values using the in-sample multipliers as well[23]. Next highest rank is adjustability with 10% lower energy efficiency, followed by flicker and better color rendition with 5% *lower* energy efficiency ranked lower. These are logical directions for the two better color options: as the options become less energy efficient, value decreases. The in-sample multiplier for the builder case is a bit higher than the conservative academic values on the high end, but very close the values for SV, SLV and MLV. Because more respondents view the features as MMV or SMV than other rankings, the in-sample multiplier results are generally higher than the academic sources. Finally, the confidence intervals at the bottom of the figure indicate that the highest ranked option is significantly higher than the two lowest options.

Households: The results for households show that the highest valued feature matches that for the builders – better color with 10% *better* energy efficiency. Here, the second highest ranking is less flicker, followed a bit distantly by adjustability (ranked second by builders) and the better color option (5% less EE). Again, there are sensible directions for the two better color options when the energy efficiency is

[21] The research in NEBs in energy efficiency finds households and businesses assign more value when asked to individually value non-energy benefit than they do to the total of all effects. The differences in the NEBs work are not uncommonly between 2 and 3 or 4 times.

[22] Small-sample results may indicate the discounting factor for near term factors may be even lower.

[23] Recall the in-sample multipliers were selected because this is an empirical project, and using values representative of the perception-based multipliers from the respondents themselves is consistent, and the in-sample estimates are based on the same terminology for the verbal scalings, and they differ somewhat from the academic values. The academic values were interpolated to provide estimates for the verbal scalars that were used in this study.

taken into account. The sample wide multipliers again are a bit higher for the MMV and SMV options, which are the most common responses, so the resulting multipliers for in-sample are higher than those using the academic multipliers. Finally, the confidence intervals at the bottom of the Figure indicate that the multiplier for the lowest option is significantly lower than the other options, and that the highest is significantly higher than adjustability.

Ranking and Valuation Results, Residential (Figure 2.3, Figure 2.10 and Figure 2.11)

- Strong value is assigned to the three advanced residential LED technologies of reduced flicker, improved color rendition, and adjustability in spectrum and intensity. Depending on the method used, the one-time value ranged for near-term technologies from $1.59-$3.71 (or 11% - 26% of the $14 purchase price of the base luminaire). These values are presented in Figure 2.10.
- The general rankings of value changed based on valuation method: color, flicker, adjustability for Method 1, and adjustability, flicker, and color for Method 2.
- The average of the values for each technology using Method 1 and Method 2 were fairly similar for the residential technologies (between 17% and 19% of the base price). In addition, the results for Method 2 were always substantially higher value than Method 1 (between 44% and 110% higher).[24] Ranking results are summarized in Figure 2.3.
- The longer-term technologies (Figure 2.11), which were valued using Method 2 only, were ranked with Color rendition as highest value, followed by adjustability (likely ranking dimming high), and lowest value for flicker. Figure 2.11 shows the values for longer-term single features ranged from about $3-$4.40 in up-front value (21%-33% more value), a substantial increase in value over the $14 base price.

- This portion of the research also allowed exploration of one more question; does the full value hold when a new LED incorporates multiple of these features? The research findings imply that when more than one feature is included, the value assigned to each individual feature is discounted. The valuation of the combination of all three longer-term features was about $4.58, but the sum of the individual valuations was about $10.75, so in combination, the valuations may need to be discounted to about 43% of the estimated single-feature value.

2.3.3 Detailed Results – Street/Roadway

LMS Multiplier Derivation, Street/Roadway (Figure 2.12).

One survey was issued to all respondents for the street/roadway valuations; sample sizes for individual decision-maker groups were too small to provide information separately. Three options were presented: reduced night impact with no blue light, and 50% LER; the same with additional human visibility and 80% LER, and an option with the same features but 10% better energy efficiency. The results are presented in Figure 2.12.

The results for street/roadway show that the highest valued option is the most advanced lighting option with 10% improved energy efficiency, followed by that same lighting quality without a change in energy efficiency from baseload. The lowest ranked option is the one with fewer embedded lighting quality

[24] This was not the case for the commercial sector, when sometimes Method 1 was higher value, and sometimes Method 2.

improvements, the nearer-term technology. The highest option is significantly more valued than the lowest ranked option, based on the confidence intervals. The in-sample multipliers differ from the academic values particularly in the values for both MMV and SMV.

Ranking and Valuation Results, Street/roadway lighting (Figure 2.3, Figure 2.13)

- Strong additional value was found for the combined advanced features of reduced night impacts, lower blue light, improved human visibility and other features associated with improved LED street/roadway technologies. The fact that the technologies in the street/roadway case were a combination of desirable features, with some gradations, meant the comparison questions included both near and longer-term variations. In each case, the respondents ranked the technologies in the most logical way: highest value to the future, most advanced technology with energy efficiency savings; second to the same technology without energy savings; and third to the somewhat less sophisticated near-term technology. The valuations are presented in Figure 2.13.
- This ranking is represented in the point estimates from Method 1 (first yellow column) and the confidence intervals in grey to the left indicate that the lowest and highest options are significantly different in value. The ranking from a willingness to pay question mimics the same order, as does the ranking developed in Method 2.
- The one-time value for the technologies ranged from $39-$92 (12% to 28% of the $324 price of the base luminaire). These values are presented in Figure 2.13.
- The confidence intervals associated with Method 1 were discussed above (the highest ranked option had a significantly higher multiplier than the lowest ranked). The confidence intervals for Method 2 do not indicate significant differences between the estimates for the three options.

Figure 2.3: All Sector – Ranking Results, Near and Longer-Term Technology Options

	A. Commercial-Near Term	B.Commercial-Long Term	C.Residential – Near Term Rankings vary between method	D.Residential – Long Term	E.Street/Roadway – Near Term
	Values vary between methods; Value of flicker increases greatly with Method 2, otherwise rankings are Glare, Color R, Adj.	The order of options for the longer term differs from the near-term options, but Method 2 for the near term also identifies flicker as the first-ranked option (glare is second).	Rankings and values vary per method; average values for the two methods for all three features are close (17-19% of value of base). All have substantial value. Method 1 valued Color R highest and adjustability the lowest. Method 2 reversed those rankings.	It makes sense that the ranking for longer term options would be similar to Method 2 for Near Term, as the data collection and analysis methods are the same.	All methods valued the features in the same order, but this is expected; the options were near term improved technology compared against long term technology with no EE improvements and with EE improvements.
Top Valued	Less Glare	No Flicker	Near Tie - Adjustable	Color Rendit	Long term night and visibility improvements with 10% better energy efficiency
Less Valued	Better Color Rendit.	Less Glare	Near tie - Flicker	Adjustable	Long term night and visibility improvements
Less Valued	Less Flicker	Adjustable	Near tie - Color Rendit.	Flicker	Near term night and visibility improvement
Less Valued	Adjustability	Color Rendit.			

Figure 2.4: Labeled Magnitude Scaling Multiplier Results - Commercial Lighting Designers[25,26,27]

RESULTS - LIGHTING DESIGNERS			Target Near Term Scenarios=>		NT		NT							NT	
	Simple Score	Academic Multiplier	Academic - conservative	Sample- Wide Multiplier	A.Less Glare, 15% Less EE	B.Less Glare, 5% Less EE	C.Less Flicker, 10% Higher P	D.No Flicker, 15% Higher P	E.No Flicker, 5% Higher P	F.Untinted Color R, 15% Less EE	G.Untinted Color R, 10% Less EE	H.Untinted Color R, 5% Less EE	I.Vibrant Color R, 5% Less EE	J.Adjustability, 10% Less EE	K.Enhanced Adjustability, 10% Less EE
MMV	5	1.55	1.44	1.79	23%	47%	62%	50%	72%	18%	21%	35%	52%	40%	38%
SMV	4	1.18	1.18	1.47	33%	28%	15%	30%	13%	43%	31%	34%	29%	29%	33%
SV	3	1	1	0.85	19%	16%	11%	14%	11%	21%	27%	19%	13%	18%	20%
SLV	2	0.82	0.82	0.55	16%	4%	9%	4%	2%	13%	12%	9%	4%	9%	6%
MLV	1	0.475	0.58	0.43	10%	5%	3%	2%	1%	6%	9%	3%	2%	4%	4%
Sum					100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Count					141	141	139	140	141	141	86	141	141	141	141
Weighted Average for "Simple Score"					3.43	4.09	4.24	4.21	4.53	3.55	3.43	3.89	4.26	3.91	3.96
Translation of Average Simple Score					**SV**	**SMV**	**SMV**	**SMV**	**MMV**	**SMV**	**SV**	**SMV**	**SMV**	**SMV**	**SMV**
Relative Value Multiplier using Academic mult.					1.10	1.28	1.34	1.31	1.41	1.12	1.10	1.22	1.32	1.23	1.24
Relative Value Multiplier using Academic conservative					1.09	1.23	1.27	1.26	1.33	1.11	1.09	1.19	1.27	1.19	1.20
Relative Value using In-sample multipliers					1.18	1.44	1.49	1.49	1.60	1.22	1.17	1.35	1.51	1.36	1.38
Value - In-sample 90% conf int (low)					*1.11*	*1.37*	*1.42*	*1.42*	*1.53*	*1.16*	*1.10*	*1.28*	*1.44*	*1.29*	*1.31*
Value - In-sample 90% conf int (high)					*1.25*	*1.51*	*1.56*	*1.56*	*1.68*	*1.29*	*1.24*	*1.42*	*1.58*	*1.43*	*1.45*
Notes:	*Red shading is above average; outline is highest, grey shading is 2 lowest*													*SERA 7/19/19*	
	Value abbreviations: Much More Valuable, Somewhat More Valuable, Same Value, Somewhat Less Valuable, Much Less Valuable														
	Academic multiplier adapted from Lin, Wood, and Green, Chemical Senses 2009.														

[25] Note, NT at top indicates specific Near Term scenario required as part of the research, matching in both technology features and in price or energy savings aspects. The other options were included to confirm the values made sense in a progression of improved and worsening cases.
[26] Weighted average scores are computed as percent of respondents selecting the LMS value times the simple score (1-5) to derive an average "labeled magnitude score or verbal ranking, which is then translated in the next row. The remainder of the scores following are the quantitative value multipliers that are most important in the table. The bold for "weighted average score" was used to delineate the data from the surveys versus the computations using those values that follow.
[27] Note that this figure includes a few scenarios that provide information on longer-term technologies, but not longer-term price or savings benefits. Therefore, they do not represent the pure longer-term scenarios, but they provide information on whether the longer-term technological feature (an enhancement on the nearer-term interim technology) would be preferred at a similar price / savings point as the near-term option (they generally are). In this table, the long term features incorporated into the list are "no flicker" and "vibrant color".

Figure 2.5: Labeled Magnitude Scaling Multiplier Results - Commercial Businesses

RESULTS - COMMERCIAL	Simple Score	Academic Multiplier	Academic - conservative	Sample- Wide Multiplier	A.Less Glare, 15% Less EE	B.Less Flicker, 10% Higher P	C.Untinted Color R, 5% Less EE	D.Untinted Color R, 10% Better EE	E.Adjustable, 10% Less EE	F.Untinted Color R, 10% Better EE	G.Vibrant Color R, 20% Better EE
Target Near/Longer Term Scenarios=>					NT	NT		NT	NT	*Follow-up NT*	*Follow-up LT*
MMV	5	1.55	1.44	1.44	34%	37%	30%	36%	28%	31%	39%
SMV	4	1.18	1.18	1.36	32%	24%	31%	35%	27%	50%	36%
SV	3	1	1	0.84	23%	29%	30%	25%	31%	14%	11%
SLV	2	0.82	0.82	0.39	8%	8%	7%	3%	10%	3%	8%
MLV	1	0.475	0.58	0.33	3%	2%	2%	1%	4%	3%	6%
Sum					100%	100%	100%	100%	100%	100%	100%
Count					405	405	387	391	400	36	36
Weighted Average for "Simple Score"					3.84	3.85	3.81	4.01	3.64	4.03	3.94
Translation of Average Simple Score					SMV	SMV	SMV	SMV	SMV	SMV	SMV
Multiplier Value - Academic weights					1.21	1.22	1.20	1.25	1.16	1.24	1.23
Relative Value Multiplier using Academic conservative					1.18	1.18	1.17	1.21	1.14	1.21	1.20
Multiplier Value - In-sample weights					1.15	1.14	1.14	1.22	1.08	1.26	1.20
Multiplier - In Sample 90% Conf Int (low)					*1.12*	*1.10*	*1.11*	*1.18*	*1.05*	*1.22*	*1.16*
Multiplier - In Sample 90% Conf Int (high)					*1.19*	*1.17*	*1.17*	*1.25*	*1.11*	*1.29*	*1.23*
Multiplier Value - In-sample weights for follow-up Com'l survey (applied to follow-up questions only)										1.38	1.38

Notes: *Red shading is above average; outline is highest, grey shading is 2 lowest* *SERA 7/19/19*

Value abbreviations: Much More Valuable, Somewhat More Valuable, Same Value, Somewhat Less Valuable, Much Less Valuable

Academic multiplier adapted from Lin, Wood, and Green, Chemical Senses 2009.

Figure 2.6: Commercial Valuation Results – Near Term Technology Results

RESULTS FOR COMMERCIAL LUMINAIRES SERA 7/19/2019

Based on Surveys from Commercial Businesses (400) and Lighting Designers (183 responses)

Assumptions for Estimates

Annual Energy Cost	$23.19
Price	$160
Lifetime	15
Discount Rate	3.6%

Commercial Office Luminaires *(note: Com'l responses are for 25% lease, 75% own; Lighting designers are 60% lease, 40% own)*	Results from Method 1: NEB Questions Using Labeled Magnitude Scaling (LMS) Approach (Relative Value)										*Results from Method 2 - Ranking Style Questions: Near-Term Technologies*			*Incremental Value of Advanced LED Features*			
Commercial LED Features Estimates	NEB Multiplier Relative to EE		NEB Multiplier Relative to Price Change		ANNUAL Extra Dollar Value of Feature if Annual Energy Cost for baseline fixture=$23.19			ONE TIME Dollar Value of Feature (in 2020) if Price is			ONE TIME Dollar Value of Feature (valued now) from RANKING Questions - Near Term Features	90% Confidence Interval for estimate		Method 1 - Relative Values: First Cost	Method 1 - Relative Values: Annualized stream	Method 2 - Ranking - Purchase Price Effect	Method 2 - Ranking - Annual Stream
NEAR TERM TECHNOLOGIES	Low	High	Low	High	$ 20.00	High	Point Est	Low	High	Point Est	wner occ & Leased Space Combine	Low	High				
Glare with 15% lower EE (wtd avg.)	1.12	1.21			$3.89	$4.19	$4.04				$29			$46	$4.04	$29	$2.49
Commercial Business Respondents	1.12	1.19			$3.90	$4.14					*$27*	*$22*	*$33*				
Lighting Designer Respondents	1.11	1.25			$3.86	$4.35					*$33*	*$20*	*$45*				
Flicker with 10% price increase (wtd avg)			1.18	1.27				$19	$20	$20	$29			$20	$1.72	$29	$2.56
Commercial Business Respondents			1.10	1.17				$18	$19		*$30*	*$23*	*$37*				
Lighting Designer Respondents			1.42	1.56				$23	$25		*$28*	*$19*	*$37*				
Color Rendition 10% INCREASE EE (wtd avg)	1.18	1.25			$2.74	$2.91	$2.83				$26			$32	$2.83	$26	$2.25
Commercial Business Respondents	1.18	1.25			$2.74	$2.90					*$26*	*$19*	*$34*				
Small Follow-up sample of Commercial Businesses	1.22	1.29			$2.83	$2.99					*$19*	*$8*	*$31*				
Adjustable / Color with 10% lower EE (wtd)	1.12	1.20			$2.23	$2.40	$2.31				$20			$26	$2.31	$20	$1.74
Commercial Business Respondents	1.05	1.11			$2.10	$2.22					*$22*	*$17*	*$27*				
Lighting Designer Respondents	1.31	1.45			$2.62	$2.90					*$14*	*$6*	*$23*				

Table Note: Low vs. high values based on 90% confidence interval for multiplicative factors. Values should be rounded.

Small Sample sum compared to total: 450%

Table note: weighted averages for technology scenarios are weighted from Commercial and designer respondents based on number of responses from the survey sources used for the estimates.

Figure 2.7: Commercial Valuation Results – Longer Term Technology Results

Commercial Office Luminaires		ONE TIME (purchase price) Dollar Value of Feature (valued now) from Ranking questions - Long Run Options	90% Confidence Interval for estimate		INCREMENTAL VALUE OF ADVANCED LED FEATURES	
LONGER TERM TECHNOLOGIES - price premium for feature			Low	High	Method 2 - Ranking - Purchase Price Effect	Method 2 - Ranking - Annual Stream
Glare - no change in EE	At right	*$26*			$26	$2.26
Commercial Business Respondents		*$26*	*$21*	*$31*		
Lighting Designer Respondents		*$26*	*$16*	*$35*		
Flicker - no change in EE	At right	*$28*			$28	$2.47
Commercial Business Respondents		*$26*	*$21*	*$32*		
Lighting Designer Respondents		*$34*	*$24*	*$44*		
Color Rendition - 20% INCREASE EE	At right	*$20*			$20	$1.78
Commercial Business Respondents		*$21*	*$14*	*$24*		
Small Follow-up sample of Commercial Businesses		*$17*	*$10*	*$24*		
Adjustable / Color with 10% INCREASE EE	At right	*$22*			$22	$1.89
Commercial Business Respondents		*$22*	*$19*	*$26*		
Lighting Designer Respondents		*$19*	*$14*	*$23*		
All Features Combined	*small sample, indicative only*	*$54*			$54	$4.69
Commercial Business Respondents	*small sample, indicative only*	*$55*	*$10*	*$100*		
Lighting Designer Respondents	*small sample, indicative only*	*$51*	*$28*	*$74*		
BACKGROUND INFORMATION FROM PNNL SCENARIO DESCRIPTIONS				*Sum Vs. Tota*	*$96*	*179%*

Price and Energy Efficiency Data provided by PNNL for scenarios -- YEAR	Baseline Price	Baseline Lm/W
2020	$160	109
2025	$127	126
2030	$117	140

Figure 2.8: Labeled Magnitude Scaling Multiplier Results – Residential Builders

RESULTS - BUILDERS				Target Near/Longer Term Scenarios=>	NT		NT	NT
	Simple Score	Academic Multiplier	Academic - conservative	Sample- Wide Multiplier	A.Less Flicker, 10% Higher Price	B.Better Color R, 5% Less EE	C.Better Color R, 10% Better EE	D.Ajustability, 10% Less EE
MMV	5	1.55	1.44	1.67	26%	30%	54%	44%
SMV	4	1.18	1.18	1.34	42%	35%	41%	34%
SV	3	1	1	0.94	21%	20%	5%	14%
SLV	2	0.82	0.82	0.87	8%	14%	0%	5%
MLV	1	0.475	0.58	0.54	2%	2%	0%	3%
Sum					100%	100%	100%	100%
Count					85	81	81	79
Weighted Average Simple Score					3.81	3.75	4.49	4.13
Translation of Average Simple Score					SMV	SMV	SMV	SMV
Relative Value Multiplier using Academic mult.					1.19	1.19	1.37	1.28
Relative Value Multiplier using Academic conservative					1.17	1.16	1.31	1.24
Relative Value using In-sample multipliers					1.28	1.27	1.50	1.39
Value - In Sample 90% Conf Int (low)					*1.19*	*1.18*	*1.41*	*1.29*
Value - In Sample 90% Conf Int (high)					*1.37*	*1.37*	*1.59*	*1.48*

Notes:	*Red shading is above average; outline is highest, grey shading is 2 lowest*
	Value abbreviations: Much More Valuable, Somewhat More Valuable, Same Value, Somewhat Less Valuable, Much Less Valuable
	Academic multiplier adapted from Lin, Wood, and Green, Chemical Senses 2009.

Figure 2.9: Labeled Magnitude Scaling Multiplier Results – Residential Households

RESULTS - HOUSEHOLDS	Simple Score	Academic Multiplier	Academic - conservative	Target Near/Longer Term Scenarios=> Sample- Wide Multiplier	NT A.Less Flicker, 10% Higher P	B.Better Color R, 5% Less EE	NT C.Better Color R, 10% More EE	NT D.Adjustability, 10% Less EE
MMV	5	1.55	1.44	1.56	31%	19%	38%	22%
SMV	4	1.18	1.18	1.40	32%	27%	34%	30%
SV	3	1	1	0.88	25%	30%	23%	26%
SLV	2	0.82	0.82	0.52	10%	21%	4%	15%
MLV	1	0.475	0.58	0.36	3%	5%	2%	7%
Sum					100%	100%	100%	100%
Count					429	429	432	425
Weighted Average Simple Score					3.79	3.34	4.03	3.47
Translation of Average Simple Score					SMV	SV	SMV	SV
Multiplier Value - Academic weights					1.20	1.09	1.25	1.12
Relative Value Multiplier using Academic conservative					1.17	1.07	1.21	1.10
Multiplier Value - In-sample weights					1.21	1.05	1.29	1.10
Multiplier - In Sample 90% Conf Int (low)					*1.15*	*0.99*	*1.23*	*1.05*
Multiplier - In Sample 90% Conf Int (high)					*1.27*	*1.10*	*1.35*	*1.16*

Notes:	*Red shading is above average; outline is highest, grey shading is 2 lowest*
	Value abbreviations: Much More Valuable, Somewhat More Valuable, Same Value, Somewhat Less Valuable, Much Less Valuable
	Academic multiplier adapted from Lin, Wood, and Green, Chemical Senses 2009.

Figure 2.10: Residential Valuation Results – Near Term Technology Results

RESULTS FOR RESIDENTIAL BULBS SERA 7/19/2019

Based on Surveys from Households (400) and Residential Builder / Remodelers (104 respondents)

Assumptions for Estimates

Baseline Price	$14.00
Energy Savings	$0.81
Lifetime	33
Discount Rate	4.5%

Residential Light Bulbs	Results from Method 1 - NEB Questions using Labeled Magnitude Scaling (LMS) Approach (Relative Value)										Calculations Using Method 2 - Ranking Style Questions for Near-Term Technologies			Incremental Value of Advanced LED Features			
Commercial LED Features Estimates	NEB Multiplier Relative to EE (Low/High 90% Conf.Int.)		NEB Multiplier Relative to Price Change (Low/High 90% Conf.Int.)		ANNUAL Extra Dollar Value of Feature if full EE savings/yr (Low/High 90% Conf.Int)			ONE TIME Dollar Value of Feature (in 2020) if Price is (Low/High 90% Conf.Int.)			ONE TIME Dollar Value of Feature (valued now) from RANKING Questions - Near Term Features	90% Confidence Interval for estimate		Method 1 - Relative Values: First Cost	Method 1 - Relative Values: Annualized stream	Method 2 - Ranking - Purchase Price Effect	Method 2 - Ranking - Annual Stream
NEAR TERM TECHNOLOGIES	Low	High	Low	High	Low	High	Point Est.	Low	High	Point Est	Owner occ & Leased Space Combined	Low	High				
Flicker with 10% price increase (wtd avg)			1.16	1.29				$1.62	$1.80	$1.71	$3.18			$1.71	$0.10	$3.18	$0.19
Household Respondents			1.15	1.27				$1.61	$1.78		*$3.41*	*$2.91*	*$3.90*				
Builder Respondents			1.19	1.37				$1.67	$1.92		*$2.06*	*$1.18*	*$2.93*				
Color Rendition 10% INCREASE EE (wtd avg)	1.26	1.39			$0.10	$0.11	$0.11				$2.88			$1.83	$0.11	$2.88	$0.17
Household Respondents	1.23	1.35			$0.10	$0.11					*$3.12*	*$2.61*	*$3.64*				
Builder Respondents	1.41	1.59			$0.11	$0.13					*$1.69*	*$0.18*	*$3.19*				
Adjustable / Color with 10% lower EE (wtd)	1.09	1.21			$0.09	$0.10	$0.09				$3.71			$1.59	$0.09	$3.71	$0.22
Household Respondents	1.05	1.16			$0.09	$0.09					*$3.74*	*$3.19*	*$4.30*				
Builder Respondents	1.29	1.48			$0.10	$0.12					*$3.57*	*$2.46*	*$4.67*				

Table Note: Low vs. high is based on 90% confidence interval for multiplicative factors. Values should be rounded.

Table note: weighted averages for technology scenarios are weighted from HH and builder respondents based on number of responses from the survey sources used for the estimates.

Figure 2.11: Residential Valuation Results – Longer Term Technology Results

Residential Light Bulbs			One Time (purchase price) Dollar Value of Feature (valued now) from Method 2 Ranking Questions - Long Term Features	90% Confidence Interval for estimate		Incremental Value of Advanced LED Features - Long Term Estimates	
LONGER TERM TECHNOLOGIES			Owner occ & Leased Space Combined	Low	High	Method 2 - Ranking - Purchase Price Effect	Method 2 - Ranking - Annual Stream
Flicker - no change in EE (wtd avg)	At right		*$2.96*			$2.96	$0.17
Household Respondents			*$3.26*	*$2.54*	*$3.99*		
Builder Respondents			*$2.31*	*$1.17*	*$3.45*		
Color Rendition - 20% INCREASE EE (wtd avg)	At right		*$4.37*			$4.37	$0.26
Household Respondents		*(note: color rendition with 10% increase EE valued at $3.29 by HHs)*	*$4.79*	*$3.91*	*$5.68*		
Builder Respondents		*(note: color rendition with 10% increase EE valued at $1.13 by HHs)*	*$3.48*	*$1.91*	*$5.05*		
Adjustable / Color with 10% INCREASE EE (wtd	At right		*$3.42*			$3.42	$0.20
Household Respondents			*$3.87*	*$2.63*	*$5.11*		
Builder Respondents			*$2.47*	*$1.73*	*$3.21*		
All Features Combined (wtd avg)	At right		*$4.58*			$4.58	$0.27
Household Respondents		*Small sample, indicative*	*$4.96*	*$3.41*	*$6.51*		
Builder Respondents		*Small sample, indicative*	*$3.77*	*$2.84*	*$4.71*		
			Sum of feature costs (compared to impacts):			*$10.75*	*235%*

BACKGROUND INFORMATION FROM PNNL SCENARIO DESCRIPTIONS

Price and Energy Efficiency Data provided by PNNL for scenarios -- YEAR	Baseline Price	Baseline Efficacy	Baseline Lm/W
2020	$14	10%	105
2025	$11	25%	132
2030	$9	40%	136
2035	$8	50%	147
Multiplier / correction factor for price	0.9		

Figure 2.12: Labeled Magnitude Scaling Multiplier Results – Street/Roadway Respondents

RESULTS - STREET/ROADWAY	Target Near/Longer Term Scenarios=>				NT		LT
	Simple Score	Academic Multiplier	Academic - conservative	Sample- Wide Multiplier	A.Reduced Impact, No Blue, 50% higher LER, No change EE or P	B.Improved Human Visibility, 80% higher LER, No change EE or P	C.Improved Human Visibility, 80% higher LER, 10% Better EE
MMV	5	1.55	1.44	1.71	26%	38%	52%
SMV	4	1.18	1.18	1.46	38%	40%	28%
SV	3	1	1	0.84	21%	17%	16%
SLV	2	0.82	0.82	0.51	11%	2%	3%
MLV	1	0.475	0.58	0.93	5%	3%	2%
Sum					100%	100%	100%
Count					66	65	64
Weighted Average Simple Score					3.70	4.09	4.25
Translation of Average Simple Score					SMV	SMV	SMV
Multiplier Value - Academic weights					1.17	1.26	1.32
Relative Value Multiplier using Academic conservative					1.14	1.23	1.27
Multiplier Value - In-sample weights					1.27	1.42	1.45
Multiplier - In Sample 90% Conf Int (low)					*1.18*	*1.34*	*1.37*
Multiplier - In Sample 90% Conf Int (high)					*1.35*	*1.50*	*1.54*

Notes:	*Red shading is above average; outline is highest, grey shading is 2 lowest*
	Value abbreviations: Much More Valuable, Somewhat More Valuable, Same Value, Somewhat Less Valuable, Much Less Va
	Academic multiplier adapted from Lin, Wood, and Green, Chemical Senses 2009.

Figure 2.13: Public Works Valuation Results – Near and Longer-Term Technology Results

RESULTS FOR STREET LIGHTING

Based on Surveys from Public Works and Utility Staff - (79 obs)

SERA 7/19/19

Assumptions for Estimates	
Annual Energy Cost	$44.57
Price	$324
Lifetime	12.8
Discount Rate	3.4%

Street/Roadway Light LED Features Estimates	From Method 1: NEBs Labeled Magnitude Scaling (LMS) responses - Multiple of value relative to Baseline Fixture				Willingness-to-Pay (WTP) Approach	From Method 2: Specialized Ranking / Ordered Valuations & Regressions			Results: One Time and Annual Value for Advanced Lighting Features			
STREET/ROADWAY LIGHTING TECHNOLOGIES	90% confidence Interval (low range)	90% confidence Interval (high range)	Point Estimate	Estimated Price - Method 1: Multiplier for extra value (multiplied times Luminaire price)	Reported WTP after LMS Questions: Dollars worth paying for Advanced Feature	Point Estimate	90% Conf. Int. (low)	90% Conf. Int. (high)	Estimated Price Increment for Advanced Feature - Average of Three Methods	Annual Discounted value for Feature	Estimated Price Difference for Feature - Most Conservative Value	Annual Discounted Value for Feature
Color Near Term - Warm, Reduce Night Sky Impacts, No blue, 50% higher LER than baseline	1.18	1.35	1.27	$87	$62	*$39*	*$17.79*	*$61.16*	$63	$6.15	$39	$3.85
Color Longer Term - Reflects research on light / wildlife / night sky interactions, improved human visibility, 80% higher LER	1.34	1.42	1.42	$136	$68	$46	*$16.11*	*$75.89*	$83	$8.14	$46	$4.49
Color - Longer Term - Same as above but energy use for new feature is also 10% less.	1.37	1.54	1.45	$146	$78	$52	*$32.12*	*$72.42*	$92	$8.99	$52	$5.10

Table Note: Low vs. high values based on 90% confidence interval for multiplicative factors. Values should be rounded.

BACKGROUND INFORMATION FROM PNNL SCENARIO DESCRIPTIONS

Price and Energy Efficiency Data provided by PNNL for scenarios -- YEAR	Baseline Price	Baseline Lm/W
2020	$324	120
2025	$252	138
2030	$216	153
2035	$195	165

3. Summary of Results, Conclusions, and Next Steps

3.1. Results and Conclusions

Figure 3.1 provides the summary of quantitative results from the research conducted under this study. The results show that potential purchasers attribute substantial value to the individual enhanced features that LED research is developing – including features related to glare, flicker, color rendition, and adjustability of color and intensity. In the outdoor lighting sphere, improvements in dark skies features, color spectrum, human visibility, and output / LER performance are also valued. The values are presented for the array of near- and longer-term technologies under study in Figure 3.1. Rounded values of these results provide order-of-magnitude results for use in modeling future market scenarios. Note that if multiple technologies are included in one scenario, discounted values for these dollar figures may be needed to adjust the valuations based on results for smaller-scale work on multi-attribute prices.

This work reached several conclusions.

- **Useful Approach** - The analytical approaches showed promise for further application in this field.
    - Both the LMS and the ranking / valuation approach provided relatively – but not perfectly – logical and consistent results for valuations between the various feature options, and the values were within ranges that were credible, and could be compared with future research.

- **Positive Value** - The advanced LED features appear to have positive value to the relevant sectors / purchasers. This is true for all features studied.

- **Monetary Estimates** – Responses to questions that were not directly monetary were used to develop monetary estimates of the valuations of these features. The monetary results can be used for research or scenario purposes, in market projection models.
    - The research indicates that both Method 1 and Method 2 can be applied to near or longer-term options in the future. There do not seem to be barriers in applying these methods within the context of research questions similar to the ones analyzed in this project.[28]

- **Hierarchy of Value** - These monetized estimates indicated a tentative hierarchy of value for various features.
    - However, note that the hierarchy was not always consistent between methods. More research is likely needed to further explore this phenomenon. It may relate to sample sizes, or the methods may require further exploration.

- **Value from Multiple Features are not Fully Additive** - The sum of the values from each of the individual features exceeds the value respondents assign to a luminaire with all of the features combined.
    - This result has also been identified in research on non-energy benefits in energy efficiency.[29] The results imply that values should be discounted when multiple features are included in a luminaire. However larger sample sizes are needed to explore this issue, and to apply the question to near-term options.

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[28] Greater use of drop-down menus for responding on relative valuation percentages for Method 1 would clarify responses and reduce data cleaning time. This was used for the limited commercial follow-up survey to good results.

[29] Skumatz et. al., 2004, Summit Blue et. al. 2005, Skumatz, et. al., 2009, , Skumatz et. al. 2010, NMR 2016, for example.

3.2 Next Steps and Suggestions

This project was conducted on an accelerated schedule, on the topic of valuing hypothetical, near and longer-term technologies for LED lighting in three sectors: commercial, residential, and street/roadway. The research is imperfect; lessons were learned that should be applied to next phases of the research and similar research in related areas.

- It is suggested that the researchers test different terminology forthe labeled magnitude scaling, and if budget allows, consider using 7 points of labels rather than the five used in this study, to allow even greater adherence to the LMS literature multiplier values and exploration of the relationship to literature values.
- It is suggested that future research test additional comparison factors, especially for the features that don't have trade-offs. The comparison factors used in this study adhered to the energy sphere, and related to the measures themselves. There is nothing that theoretically bars using candy bars or other commonly-known commodities or services that could be used. An internal test of two options should be tested and compared.
- Consider splitting the surveys that have long lists of options between two samples. This would increase the number of options that could be asked about, but keep surveys shorter and reduce respondent fatigue, and potentially increase response rates.

Figure 3.1: Summary of Key Valuation Results

COMMERCIAL				
NEAR TERM TECHNOLOGIES	Method 1 - Incremental Value - Purchase Price Effect	Method 1 - Incremental Value - Annualized	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized
Glare with 15% lower EE	$46	$4.04	$29	$2.49
Flicker with 10% price increase	$20	$1.72	$29	$2.56
Color Rendition 10% INCREASE EE	$32	$2.83	$26	$2.25
Adjustable / Color with 10% lower EE	$26	$2.31	$20	$1.74
LONGER TERM TECHNOLOGIES - price premium for feature	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized		
Glare - no change in EE	$26	$2.26		
Flicker - no change in EE	$28	$2.47		
Color Rendition - 20% INCREASE EE	$20	$1.78		
Adjustable / Color with 10% INCREASE EE	$22	$1.89		
All Features Combined	$54	$4.69		

RESIDENTIAL				
NEAR TERM TECHNOLOGIES	Method 1 - Incremental Value - Purchase Price Effect	Method 1 - Incremental Value - Annualized	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized
Flicker with 10% price increase (wtd)	$1.71	$0.10	$3.18	$0.19
Color Rendition 10% INCREASE EE	$1.83	$0.11	$2.88	$0.17
Adjustable / Color with 10% lower EE (wtd)	$1.59	$0.09	$3.71	$0.22
LONGER TERM TECHNOLOGIES	Method 2- Incremental Value - Purchase Price Effect	Method 2 - Incremental Value - Annualized		
Flicker - no change in EE	$2.96	$0.17		
Color Rendition - 20% INCREASE EE	$4.37	$0.26		
Adjustable / Color with 10% INCREASE EE	$3.42	$0.20		
All Features Combined	$4.58	$0.27		

STREET / ROADWAY LIGHTING TECHNOLOGIES				
STREET / ROADWAY LIGHTING TECHNOLOGIES	Average Incremental Value - Purchase Price Effect	Average Incremental Value - Annualized	Incremental Value - Purchase Price Effect (most conserative estimate)	Incremental Value - Annualized (most conserative estimate)
Color Near Term - Warm, Reduce Night Sky Impacts, No blue, 50% higher LER than baseline	$62.98	$6.15	$39.47	$3.85
Color Longer Term - Reflects research on light / wildlife / night sky interactions, improved human visibility, 80% higher LER	$83.36	$8.14	$46.00	$4.49
Color - Longer Term - Same as above but energy use for new feature is also 10% less.	$92.02	$8.99	$52.27	$5.10

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APPENDIX A – TECHNOLOGY DESCRIPTION DETAILS

A.1 Commercial Technologies

DRAFT ADVANCED LUMINAIRE DESCRIPTIONS
FEB 20, 2019
NOTE: All prices expressed in 2010 US Dollars

GLARE RESEARCH – Commercial
Note: There is no residential counterpart for this research effect because the residential analysis focuses on replacement lamps (bulbs), not luminaires. Since glare is largely a consequence of luminaire design, it doesn't make sense to investigate the value of glare control for residential lamps.

	COLLOQUIAL DESCRIPTION	***TECH DESCRIPTION***
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new and replacements for 4 ft fluorescent type fixtures. No design emphasis on glare control. Glare creates visual discomfort for a significant number of observers.*	*Visible matrix of high-intensity LEDs sometimes visible. Current glare metrics are inadequate for characterizing glare performance. Glare creates visual discomfort for at least 20% of observers.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points.	*<u>Near-term performance</u>* *2020 & 2025: New glare metrics have led to new luminaire designs and application guidelines that eliminate visual discomfort, with modest reduction in energy efficiency.* *<u>Long-term performance</u>* *2030 & 2035: Updated glare metrics combined with new technologies eliminate visual discomfort with no loss of energy efficiency.*	*<u>Near-term Performance</u>: New glare metrics have led to new luminaire designs and new application guidelines that eliminate visual discomfort, with a 15% reduction in energy efficiency compared to the baseline.* *<u>Long-term Performance</u>: Updated glare metrics combined with new findings on optical materials and optical control eliminate visual discomfort with no trade-off in energy efficiency.*

FLICKER RESEARCH -- Commercial

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new and replacements for 4 ft fluorescent type fixtures. Light flickering is noticed by people sensitive to flickering.*	*Current metrics for flicker do not adequately address specific conditions related to SSL lighting; flicker is noticeable to at least 20% of people.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced light source description for 2 performance points	*<u>Near-term performance</u>* *2020 & 2025: new flicker metrics and guidelines lead to new technologies that reduce flicker, so that very few people notice. Causes 10% increase in price relative to baseline.* *<u>Long-term performance</u>* *2030 & 2035: Updated flicker metrics and application guidelines cause new technology development. Noticeable flicker is eliminated for all people. No increase in price relative to baseline.*	*<u>Near-term performance</u>: New flicker metrics and guidelines have led to new driver, dimming and control technologies that reduce flicker so that it is noticeable to no more than 5% of the people in typical applications, at a 10% price increase over the baseline product.* *<u>Long-term performance</u>: Updated flicker metrics and application guidelines combined with new developments in driver, dimming and control technologies eliminate noticeable flicker with no increase in price.*

NON-VISUAL EFFECTS LIGHTING RESEARCH -- Commercial

	COLLOQUIAL DESCRIPTION	TECH DESCRIPTION
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Typical office lighting; new & replacements for 4 ft fluorescent type fixtures. Light color & intensity not adjustable.*	*Static color temperature, spectrum, and intensity.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points	<u>*Near-term Performance*</u> *2020 & 2025: Lighting is adjustable down to very low levels. Color temperature also adjustable. It addresses the desire to have high color temperatures during the day with higher light levels, and lower color temperatures at night, with lower light levels. Price is same as baseline, with a 10% reduction in efficiency.* <u>*Long-term Performance*</u> *2030 & 2035: wide range of adjustment possible for both light levels and various light colors. (Possible to have more or less blue and red light while keeping light color appearance constant.) Addresses the desire to have bluer light during portions of the day, with higher light levels, and redder light at night, with lower light levels. Price is same as baseline, with a 10% increase in efficiency.*	<u>*Near-term performance:*</u> *Dims smoothly down to 1% and adjusts in color temperature linearly between 2500 to 5000 K (using 2-channel controls for change in CCT). Allows higher CCTs and light intensity during the day, and lower CCTs and light intensity at night, aligning with best practice based on research.* <u>*Long-term performance*</u>*: Dims smoothly down to 0%. Using multi-channel color control, the amount of short and long wavelengths can vary while maintaining the same CCT, or allowing CCT to vary between 2000 to 6500 K. Allows more short wavelength content and intensity during portions of the day, and more long wavelength content and less intensity at night, aligning with best practice based on research.*

COLOR RENDERING RESEARCH – Commercial

	COLLOQUIAL DESCRIPTION	TECH DESCRIPTION
Submarkets addressed	*Typical commercial overhead office lighting*	*Commercial – All Linear – 4 ft LED Luminaires*
Baseline product description	*Color rendering similar to that provided by good quality fluorescent luminaires. The lighting makes colors look somewhat dull and unnatural and whites may have a slight yellowish tint; the light itself may have a slight greenish tint.*	*CIE R_a 80-84 and CIE R_9 0-20.* *LER 330.*
Baseline price	*2020: $160 each avg* *2025: $127 each avg* *2030: $117 each avg* *2035: $113 each avg*	*Same as Colloquial*
Baseline efficacy	*2020: About 10% better than current avg* *2025: About 25% better than current avg* *2030: About 40% better than current avg* *2035: About 50% better than current avg*	*2020: 109 lm/W avg* *2025: 126 lm/W avg* *2030: 140 lm/W avg* *2035:152 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: The lighting makes colors look natural, but some colors are a little bit dull. Whites are untinted.* *Energy efficiency increases by approximately 10% versus baseline. No change in price.*	*Near-term Performance* *IES TM-30-18 $R_f \geq 75$, $R_g \geq 95$, $R_{cs,h1} \geq -7\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 365*
	Long-term Performance *2030 & 2035: The light makes colors look vibrant and pleasing. Whites are crisp and clean. The light is an untinted neutral white.* *Energy efficiency increases by approximately 20% versus baseline. No change in cost.*	*Long-term Performance* *IES TM-30-18 $R_f \geq 78$, $R_g \geq 95$, $R_{cs,h1} \geq -1\%$, $R_{cs,h1} \leq 15\%$* *Future whiteness index.* *Future updates to chromaticity.* *LER 400*

A.2 Street/Roadway lighting Technologies

DARK SKY AND ENVIRONMENTAL EFFECTS RESEARCH -- Outdoor

	COLLOQUIAL DESCRIPTION	***TECH DESCRIPTION***
Submarkets addressed	*Streetlights*	*Outdoor -- All street/roadway*
Baseline product description	*Typical LED streetlight fixtures, optimized for first cost minimization. Range of fixed color temperatures available, from warm to cool.*	*Same as colloquial.*
Baseline price	*2020: $324 per unit avg* *2025: $252 per unit avg* *2030: $216 per unit avg* *2035: $195 per unit avg*	*Same as Colloquial*
Baseline efficacy	*2020: almost 10% better than current avg* *2025: about 25% better than current avg* *2030: almost 40% better than current avg* *2035: about 50% better than current avg*	*2020: 120 lm/W avg* *2025: 138 lm/W avg* *2030: 153 lm/W avg* *2035: 165 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: A warm colored light, designed to reduce impact on night sky and wildlife, containing no blue light. Price and energy performance the same as baseline.* *Long-term Performance* *2030 & 2035: Advanced understanding of interactions between light, wildlife and dark skies lead to better metrics and user guidance, allowing light that minimizes impact on dark skies and wildlife, while allowing improved human visibility. Price is the same as baseline. Energy performance is improved by 10%.*	*Near-term Performance: A low CCT LED containing no blue wavelength content with a 50% higher LER than baseline.* *Long-term performance: A more efficacious spectral content that achieves an 80% higher LER than baseline. Only the precise amount of light needed is provided at the precise times it is needed.*

A.3 Residential Technologies

COLOR RENDERING RESEARCH – Residential

	COLLOQUIAL DESCRIPTION	**TECH DESCRIPTION**
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Color rendering similar to that provided by good quality fluorescent lamps. The lighting makes colors look somewhat dull and unnatural and whites may have a slight yellowish tint; the light itself may have a slight greenish tint.*	*CIE R_a 80-84 and CIE R_9 0-20. LER 330.*
Baseline price	*2020: $15 avg for 100 W incandescent equiv 2025: $12 avg for 100 W incandescent equiv 2030: $10 avg for 100 W incandescent equiv 2035: $9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg 2025: about 25% better than current avg 2030: about 40% better than current avg 2035: almost 50% better than current avg*	*2020: 105 lm/W avg 2025: 132 lm/W avg 2030: 136 lm/W avg 2035: 147 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: The lighting makes colors look natural, but some colors are a little bit dull. Whites are un-tinted.* *Energy efficiency increases by approximately 10% versus baseline. No change in price.*	*Near-term Performance* *IES TM-30-18 $R_f \geq 75$, $R_g \geq 95$, $R_{cs,h1} \geq -7\%$, $R_{cs,h1} \leq 15\%$ Future whiteness index. Future updates to chromaticity. LER 365*
	Long-term Performance *2030 & 2035: The light makes colors look vibrant and pleasing. Whites are crisp and clean. The light is an un-tinted neutral white.* *Energy efficiency increases by approximately 20% versus baseline. No change in cost.*	*Long-term Performance* *IES TM-30-18 $R_f \geq 78$, $R_g \geq 95$, $R_{cs,h1} \geq -1\%$, $R_{cs,h1} \leq 15\%$ Future whiteness index. Future updates to chromaticity. LER 400*

FLICKER RESEARCH -- Residential

	COLLOQUIAL DESCRIPTION	*TECH DESCRIPTION*
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Typical residential replacement bulbs. 100W incandescent replacement equivalent. Light flickering is noticed by people sensitive to flickering.*	*Current metrics for flicker do not adequately address specific conditions related to SSL lighting; flicker is noticeable to at least 20% of people.*
Baseline price	*2020: $15 avg for 100 W incandescent equiv* *2025: $12 avg for 100 W incandescent equiv* *2030: $10 avg for 100 W incandescent equiv* *2035: $9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg* *2025: about 25% better than current avg* *2030: about 40% better than current avg* *2035: almost 50% better than current avg*	*2020: 105 lm/W avg* *2025: 132 lm/W avg* *2030: 136 lm/W avg* *2035: 147 lm/W avg*
Advanced light source description for 2 performance points	*<u>Near-term performance</u>* *2020 & 2025: new flicker metrics and guidelines lead to new technologies that reduce flicker, so that very few people notice. Causes 10% increase in price relative to baseline.* *<u>Long-term performance</u>* *2030 & 2035: Updated flicker metrics and application guidelines cause new technology development. Noticeable flicker is eliminated for all people. No increase in price relative to baseline.*	*<u>Near-term performance</u>: New flicker metrics and guidelines have led to new driver, dimming and control technologies that reduce flicker so that it is noticeable to no more than 5% of the people in typical applications, at a 10% price increase over the baseline product.* *<u>Long-term performance</u>: Updated flicker metrics and application guidelines combined with new developments in driver, dimming and control technologies eliminate noticeable flicker with no increase in price.*

NON-VISUAL EFFECTS LIGHTING RESEARCH -- Residential

	COLLOQUIAL DESCRIPTION	TECH DESCRIPTION
Submarkets addressed	*Residential LED Light Bulbs*	*Residential - All - General Service LED Lamps*
Baseline product description	*Typical residential replacement bulbs. 100W incandescent replacement equivalent. Light color & intensity not adjustable.*	*Static color temperature, spectrum, and intensity.*
Baseline price	*2020: $15 avg for 100 W incandescent equiv* *2025: $12 avg for 100 W incandescent equiv* *2030: $10 avg for 100 W incandescent equiv* *2035: $9 avg for 100 W incandescent equiv*	*Same as colloquial*
Baseline efficacy	*2020: about 10% better than current avg* *2025: about 25% better than current avg* *2030: about 40% better than current avg* *2035: almost 50% better than current avg*	*2020: 105 lm/W avg* *2025: 132 lm/W avg* *2030: 136 lm/W avg* *2035: 147 lm/W avg*
Advanced luminaire description for 2 performance points	*Near-term Performance* *2020 & 2025: Lighting is adjustable down to very low levels. Color temperature also adjustable. It addresses the desire to have high color temperatures during the day with higher light levels, and lower color temperatures at night, with lower light levels. Price is same as baseline, with a 10% reduction in efficiency.* *Long-term Performance* *2030 & 2035: wide range of adjustment possible for both light levels and various light colors. (Possible to have more or less blue and red light while keeping light color appearance constant.) Addresses the desire to have bluer light during portions of the day, with higher light levels, and redder light at night, with lower light levels. Price is same as baseline, with a 10% increase in efficiency.*	*Near-term performance: Dims smoothly down to 1% and adjusts in color temperature linearly between 2500 to 5000 K (using 2-channel controls for change in CCT). Allows higher CCTs and light intensity during the day, and lower CCTs and light intensity at night, aligning with best practice based on research.* *Long-term performance: Dims smoothly down to 0%. Using multi-channel color control, the amount of short and long wavelengths can vary while maintaining the same CCT, or allowing CCT to vary between 2000 to 6500 K. Allows more short wavelength content and intensity during portions of the day, and more long wavelength content and less intensity at night, aligning with best practice based on research.*

APPENDIX B. SURVEY SAMPLING AND OUTREACH PROCEDURES

B.1 Survey Instruments

Five (finally six) survey instruments were designed to understand the values of various effects of LED lighting from different perspectives and market segments. The survey questions were created based on information from the literature review and responses from subject expert interviews. To increase the breadth of the responses, surveys were administered through a web survey platform. Two surveys, The Advanced LED Lighting Technologies-Household Survey (Residential) and The Advanced LED Lighting Technologies- Commercial Business Survey (Commercial), were developed for distribution to a broader range of respondents from the residential and commercial segments. The surveys were collected by a third-party market research firm. The Residential Survey was completed by 440 respondents and the Commercial survey received 442 completed surveys.

The remaining three surveys, The Advanced LED Lighting Technologies-Street/Roadway / Public Works Survey, The Advanced LED Lighting Technologies-Home Building & Design Survey, and The Advanced LED Lighting Technologies-Lighting Designers, focused on smaller and more specialized market segments. Surveys were developed with specific questions geared towards each of these groups. The following sections relate to these three surveys.

B.2 Survey Sampling and Invitation

Contact information including emails was purchased from a sampling firm. Sample included information from the following sectors:

- Electric Companies
- Home Improvement
- Home Builders
- Kitchen and Bathroom Remodeling
- Residential Designers
- Government Offices, City and County
- Public Works Departments
- Electrical Designers
- Street Lighting Contractors
- Lighting Engineers, Contractors, and Consultants
- Lighting maintenance and supply
- Architects
- Developers
- Business and Building Owners
- Homeowners

Research participants were recruited through emails which were tailored to establish legitimacy of the project, urgency for timely response, and sufficient incentive to compel taking action. Since participants were asked to consider limited, but intricate scenarios, the incentive was set at $50 to encourage full participation to the end of the survey. As an added incentive, respondents completing the survey were entered into a drawing for a $200 gift card. Thousands of emails were sent out in batches based on their intended survey designation. A second invitation was sent out approximately a week after the first email invitation. Figure B.1 is an example of a first-round email for the Public Works Street Lighting Survey.

Figure B.1: Example First-round Email Invitation

> Please HELP Us Out on Future Street Lighting Designs (and get a gift card)
>
> We are working on a research project about future LED streetlighting designs for a US Department of Energy (DOE) National Laboratory, and need your input! We value your expertise.
>
> We are a research-only firm and are NOT selling anything!
>
> Our project needs feedback on the value of a set of next generation streetlighting features. If you know something about streetlights or are involved in selection / purchasing, please complete our survey by ***TUESDAY June 4*** and we will send you a $50 Amazon gift certificate and enter your name into a drawing for a $200 gift certificate. To complete the survey, click here
>
> https://www.surveymonkey.com/r/StreetlightLED
>
> If you have questions, please feel free to contact us at skumatz@serainc.com.
>
> Lisa A. Skumatz, Ph.D., Survey Task Manager
> Skumatz Economic Research Associates (SERA)

B.3 Survey Instruments

At the beginning of each survey, participants were given a brief background on the project, survey description, and incentives. Basic background information was gathered and a qualifying question regarding level of involvement in lighting purchase decisions. Those “not at all” involved were disqualified. Participants were asked a set of scenario questions on lighting attributes; glare, flicker, and dimming / color rendering. They were then asked to rank the previous scenario questions. The Public Works Survey followed the same format but the attributes included impacts on dark skies and wildlife, and improvements for human visibility. Figure B.2 below is an example of the instructions in the beginning of the survey. The full survey instruments are provided in Appendix C.

Figure B.2: Example Background and Survey Directions

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of *different features of advanced LED lighting* that are being developed.

As a person knowledgeable about *residential home building and / or design and remodeling* your input is extremely important to us.

As a thank you for your for the quick turnaround and your thoughtful input (received by TUESDAY 6/11/19) , *we are providing $50 gift certificates* to Amazon.com for your completed survey (one per respondent).
In addition, your name will be entered into a drawing for a $200 gift certificate.

The questions are a bit complicated; the survey takes about 10-13 min. Please read carefully and answer to the best of your ability.
Thank you,
If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

B.4 Survey Responses

After the first and second round of emails were sent out the survey targets and results were compared. Surveys were also reviewed for completeness and validity of answers to eliminate those providing nonsensical answers. The Public

Works Survey and the Home Builder Survey were still below the target range. Another round of emails was sent with the incentive increased to $75 and providing the survey was completed within a short deadline in order to meet the project timeline. Participants completing the survey in this short time frame were also entered into an additional $200 drawing per survey just for this group.

At the end of these efforts the completed response counts for the email (not panel) surveys were:

- Home Builders and Designers – 104
- Lighting Designers – 184
- Utility, Street/Roadway Lighting, and Public Works – 79

B.5 Gift Card and Prize Drawing Process

After each round of emails, responses were reviewed for completeness and validity of answers. Those participants were then sent Amazon Gift Cards electronically to the email address they provided. Email notices were sent to respondents letting them know they had gift cards on the way so they wouldn't be considered junk mail and deleted. Amazon.com tracks gift cards and whether or not they have been opened by the recipient. Participants that provided notification that they had not received their gift card were resent the e-card. The original validation code would be deactivated and replaced with a new code.

The email addresses of all the participants that qualified for gift card were tracked in excel spreadsheets by survey. In each group, they were assigned random numbers. Those numbers were then sorted. The participants whose number appeared at the top of the list was selected as the $200 gift card winner. This was conducted for all three surveys. Additionally, two more drawings were held only for those participants the completed surveys during the quick turnaround time frame.

The $200 gift card winners and all eligible participants were notified through bcc emails that the drawing had taken place and winners had been selected.

APPENDIX C – DATA CLEANING PROCEDURES

D.1 Basic Data Cleaning for Labeled Magnitude Scaling (LMS) Questions

Cleaning these data was much more complicated than expected. The respondents included a substantial amount of verbiage in some cases, and only numbers, that required some interpretation in other cases. This was partly due to the lack of clarity in the phrasing of some of the labeled magnitude scaling (LMS) questions. In general, percentage answers are difficult for respondents to answer. In an attempt to be clearer and provide examples for the respondents, we provided too much detail (beyond what we have provided in previous NEB studies), and phrased the examples in ways that could be confusing to some respondents. Therefore, systematic cleaning rules were developed, and they are specified below. The cleaning procedures assured that values for MMV and SMV provided values of 1 or larger relative to the comparison factor, and those in the sections for SLV and MLV were between 0 and 1.

Assume data are in column AP of an Excel spreadsheet.

MMV and SMV: = if(ap3<1,1+ap3,ap3)

MLV and SLV: =if(ap3>1,ap3-1,ap3)

SV: =if(ap3 >=.5,ap3,1-ap3) for logical and conservative(?)

Note, that in a follow-up survey conducted under this study, we used drop-down menus to make responses unambiguous. These drop-down menus required answers that were consistent with the category (much more valuable must be greater than 1, so all the responses were percentages greater than 1). If the respondent decided these values were not what they meant, they were also provided with an option for “other”, that would allow them to insert their intended response. This provided improved clarity and also greatly simplified the data cleaning procedures. This is a highly recommended procedures in future studies using this method.

C.2 Basic Data Cleaning for Ranking Questions

1. Respondents were asked to rank a list of various lighting scenarios in order to determine which of those scenarios were preferred.
2. Each ranking question was followed by open-response question asking respondents to enter a value for the maximum dollar amount extra (or less) they would be willing to pay per luminaire (or per bulb) for the first and last ranked options.
3. In order to ensure reliable results the data from these dollar amount questions were cleaned prior to the analysis.
4. Observations that reported a greater dollar value for the last ranked option than the best ranked option were removed. It was assumed that such respondents either didn’t fully understand the questions or were typing in numbers at random.
5. Observations that reported the baseline option as their best choice, but did not report a negative dollar value for their last ranked scenario were removed.

6. Then the upper and lower extremes of the data were removed (above the 90th percentile & below the 10th percentile).
7. After cleaning the dollar value data, indicator variables were created for the lighting scenario ranking data.
8. Two sets of indicator variables were created:
    a) The first set indicated which scenario was chosen as the best option for each respondent, and;
    b) The second set indicated which scenario was chosen as the worst option for each respondent.

C.3 Analysis Approach for Ranking Questions

1) Regressions were run with a well-vetted statistical analysis software using the cleaned dollar value data and the indicator variable set for the best and wort options separately as well as a combined together.
2) Separate regressions were performed for each respondent group in addition to several sub groups like commercial owners vs non-owners.
3) Depending on the specific questions asked to each respondent group, results were produced for near-term and long-term technologies as well as for a combination of lighting scenarios.
4) The results provided statistically significant dollar values for each lighting scenario when it was chosen as the best and worst option separately as well as combined in order to see its total value.

Example of Regression Output:

The survey asked respondents to rank the LED technology options from most valuable to least, and then to assign a dollar value for the extra they would be willing to pay (WTP) for the top ranked and for the bottom-ranked (that was not the base technology with no features). Averages for the WTP values for each ranked technology were then calculated using regressions to estimate the coefficients or averages, the most convenient way to compute the WTP values for each technology. In this survey question, the ordering was only used to 1) provide variety in which of the technologies was assigned a WTP value by each respondent, and 2) as a data validity check to confirm higher WTP values were assigned to higher ranked options. Those providing lower WTP values for higher-ranked options were omitted from the estimation.

Residential Respondents (Q1)	
Lighting Scenario	**Willingness to Pay ($/bulb)**
Flicker Reduction: *From noticed by 20% to noticed by 5% of residents; Price Increase: 10% over Base Case LED bulb*	**$3.41**
Color Rendering Improvement: *Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10% less than Base Case LED bulb*	**$3.12**
Adjustability/Dimmability: *to 1%; Color Temperature: Adjustable throughout the day , aligning with best research and alertness and physiological effects ; Energy Efficiency: 10% less*	**$3.74**

APPENDIX D – RANKING QUESTIONS: REGRESSION RESULTS AND CONFIDENCE INTERVALS

Confidence intervals for the LMS questions were estimated using a straightforward approach. The survey provided the percent of respondents that valued the advanced feature as one of five categories – much more valuable, somewhat more valuable, about the same value, somewhat less valuable, and much less valuable (abbreviated as MMV, SMV, SV, SLV, and MLV). No confidence intervals were computed around these factors.

The respondents were also asked to identify the percent more valuable or less valuable for a subset of the times they were asked about the verbal labeled responses (much more, much less, etc.). We used the responses from all of these percentages of valuation factors to craft the "in-sample" valuation multipliers associated with each verbally-labeled response category. Each respondent group was used to estimate its own in-sample valuation multipliers. Using all the multiplicative answers within the group provided a relatively large sample of values that were associated with the term MMV for each group. We then calculated the standard error and confidence bands around each of the labeled terms, and used these to provide confidence intervals for LMS (Method 1) responses for the study. Note that the values were reasonably close to the two multipliers from the literature.

The remainder of this appendix presents the derivation of the confidence intervals for the ranking questions.

D.1: Lighting Designers: Ranking Questions – Regression Results

The Lighting Designers Survey contained three questions asking respondents to rank various sets of lighting options including a base model. They were then asked to provide a dollar amount for how much more or less they would pay for their first ranked option and their worst option (not including the base or "typical" model). The first choice of each option was then assigned to the highest dollar amount. The second to last choice (or last choice above the base model) was assigned the lower dollar amount. The list of highest-ranking options with associated dollar amount and the lowest ranking option (excluding base model) and corresponding dollar amount were included in the regression model. The highest and lowest dollar amounts are in the dependent variable titled "CombinedDollar". The number following this label refers to the first, second, and third ranking questions as they appear in the survey. The resulting Coefficients represent the dollar value associated with the ranked lighting options. For further details on the specific question phrasing and response options, see each survey instrument in Appendix E.

Lighting Designer (Q1) Combined Dollar

Question 1: Variable Scenario Descriptions:
A: Glare Reduction
B: Flicker Reduction
C: Color Rendering Improvement and Energy Efficiency 10%
D: Color Rendering Improvement and Energy Efficiency 20%
F: Adjustability and Dimmability
G: Typical or base case LED

Lighting Designer (Q2) Combined Dollar

Question 2: Variable Scenario Descriptions:
A: No Glare
B: No Flicker
C: Color Rendering Improvement and Energy Efficiency 10%
D: Adjustability and Dimmability
E: Typical or base case LED

Lighting Designer (Q3) Combined Dollar

Question 3: Variable Scenario Descriptions:
G: No Glare, No Flicker, Excellent Color, Wide Range Adjustability (4 features)
H: Typical or base case
I: No Glare, No Flicker, Adjustability
J: No Glare, Color Rendering, Adjustability
K: No Flicker, Color Rendering, Adjustability
L: No Glare, No Flicker, Color Rendering

Dependent Variable: COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 21:35
Sample: 1 48 IF BAD_OBS=1
Included observations: 31
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
G_ALL_FOUR_FEATURESC	50.88889	13.51397	3.765649	0.0009
IGLARE_FLICKER_ADJUSTABILITYGLAREC	29.41667	12.57327	2.339620	0.0273
JGLARE_COLORR_ADJUSTABILITYGLAREC	22.05000	19.12471	1.152958	0.2594
KFLICKER_COLORR_ADJUSTABILITYFLICKERC	37.50000	9.936699	3.773889	0.0008
LGLARE_FLICKER_COLORRGLAREC	43.64286	15.75988	2.769239	0.0102

R-squared	0.085860	Mean dependent var	38.71774
Adjusted R-squared	-0.054777	S.D. dependent var	36.42279
S.E. of regression	37.40707	Akaike info criterion	10.22829
Sum squared resid	36381.50	Schwarz criterion	10.45957
Log likelihood	-153.5384	Hannan-Quinn criter.	10.30368
Durbin-Watson stat	1.954346		

D.2: Lighting Designers: Ranking Questions - Confidence Intervals

Lighting Designer Confidence Intervals - Ranking Questions 1, 2, and 3.

The following figure provides the 90%, 95%, and 80% confidence intervals for the ranking questions. The variable abbreviations are the same as the ones used for the regressions with the descriptions relating to the same lighting scenario choices.

Lighting Designer Q1 Combined										
Date: 06/27/19 Time: 15:05										
Sample: 1 266 IF _1BAD_OBS=1										
Included observations: 105										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
AGLARE15_EEC	32.74		20.27	45.21		17.83	47.64		23.05	42.43
BFLICKER10_PPC	28.31		19.24	37.38		17.47	39.15		21.26	35.36
CCOLORR10_EEC	7.82		3.61	12.03		2.79	12.85		4.55	11.09
DCOLORR20_EEC	21.10		9.99	32.20		7.83	34.36		12.47	29.72
FADJ10_EEC	14.38		6.25	22.51		4.66	24.10		8.06	20.70

Lighting Designer Q2 Combined										
Date: 06/27/19 Time: 15:08										
Sample: 1 266 IF _2BAD_OBS=1										
Included observations: 114										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_2AGLARE_NODIFFC	25.69		16.47	34.92		14.67	36.71		18.52	32.86
_2BFLICKER_NODIFFC	34.03		24.06	44.00		22.12	45.95		26.29	41.78
_2CCOLOR_EE10__C	13.18		6.97	19.40		5.75	20.61		8.35	18.01
_2DADJUST_EE10__C	19.39		13.51	25.28		12.37	26.42		14.82	23.97

Lighting Designer Q3 Combined										
Date: 06/27/19 Time: 15:09										
Sample: 1 48 IF BAD_OBS=1										
Included observations: 31										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
G_ALL_FOUR_FEATURESC	50.89		27.84	73.94		23.11	78.67		33.12	68.66
IGLARE_FLICKER_ADJUSTABILITYGLAREC	29.42		7.97	50.86		3.57	55.26		12.88	45.95
JGLARE_COLORR_ADJUSTABILITYGLAREC	22.05		-10.57	54.67		-17.26	61.36		-3.10	47.20
KFLICKER_COLORR_ADJUSTABILITYFLICKERC	37.50		20.55	54.45		17.07	57.93		24.43	50.57
LGLARE_FLICKER_COLORRGLAREC	43.64		16.76	70.52		11.25	76.04		22.92	64.37

D.3 Commercial / Businesses: Ranking Questions – Regression Results

For this survey, respondents were asked four ranking questions. There was a first round of questions asked in the original survey and a second round of updated questions were asked for this survey group. The original set of ranking question results are provided below the follow-up survey results.

Commercial- Follow-up (Q1) Combined Dollar

Question 1: Short Run Variable Scenario Descriptions:
A: Glare Reduction
B: Flicker Reduction
C: Color Rendering Improvement and Energy Efficiency 10%
F: Adjustability and Dimmability
G: Typical or base case LED

Dependent Variable: _1DOLLAR_C
Method: Least Squares
Date: 07/16/19 Time: 15:04

Sample: 1 95 IF _1_OBS_GOOD_C=1
Included observations: 48
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_1ASR_GLARE	22.75000	9.330809	2.438159	0.0190
_1BSR_FLICKER	25.33333	10.82569	2.340113	0.0240
_1CSR_COLOR	19.42083	6.826236	2.845028	0.0068
_1FSR_ADJ	18.57692	6.907638	2.689331	0.0101
_1GSR_BASE	16.66667	5.183955	3.215049	0.0025

R-squared	0.011484	Mean dependent var	20.89167
Adjusted R-squared	-0.080471	S.D. dependent var	25.99417
S.E. of regression	27.01982	Akaike info criterion	9.529351
Sum squared resid	31393.04	Schwarz criterion	9.724268
Log likelihood	-223.7044	Hannan-Quinn criter.	9.603010
Durbin-Watson stat	1.914763		

Commercial- Follow-up (Q2) Combined Dollar

Question 2: Long Range Variable Scenario Descriptions:
A: No Glare
B: No Flicker
C: Color Rendering
D: Adjustability and Dimmability
E: Typical or base case LED

Dependent Variable: _2DOLLAR_C
Method: Least Squares
Date: 07/16/19 Time: 15:06
Sample: 1 95 IF _2_OBS_GOOD_C=1
Included observations: 51
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_2ALR_GLARE_C	30.33333	10.52532	2.881940	0.0060
_2BLR_FLICKER_C	12.50000	3.619968	3.453069	0.0012
_2CLR_COLOR_C	16.90250	3.950377	4.278705	0.0001
_2DLR_ADJ_C	29.00000	8.984044	3.227945	0.0023
_2ELR_BASE_C	7.937500	2.355264	3.370111	0.0015

R-squared	0.129389	Mean dependent var	19.32451
Adjusted R-squared	0.053683	S.D. dependent var	22.77766
S.E. of regression	22.15783	Akaike info criterion	9.127153
Sum squared resid	22584.60	Schwarz criterion	9.316548
Log likelihood	-227.7424	Hannan-Quinn criter.	9.199527
Durbin-Watson stat	2.104639		

Commercial- Follow-up (Q3) Combined Dollar

Question 3: Short Range Variable Scenario Descriptions:
E: Typical or base case LED
G: Glare, Flicker, Color Rendering, Adjustability / Dimming
I: Glare, Flicker, Adjustability / Dimming
J: Glare, Color Rendering, Adjustability / Dimming
K: Flicker, Color Rendering, Adjustability / Dimming
L: Glare, Flicker, Color Rendering

Dependent Variable: _3DOLLAR_C
Method: Least Squares
Date: 07/16/19 Time: 15:08
Sample: 1 95 IF _3_OBS_GOOD_C=1
Included observations: 62
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic
_3ESR_BASE_C	21.25000	7.526923	2.823199
_3GSR_GLAREFLICKCOLORADJ_C	19.23077	7.759317	2.478410
_3ISR_GLAREFLICKADJ_C	25.30769	7.219828	3.505304
_3JSR_GLARECOLORADJ_C	16.44444	6.482268	2.536835
_3KSR_FLICKCOLORADJ_C	19.80000	5.436569	3.642003
_3LSR_GLAREFLICKCOLOR_C	13.61538	4.038105	3.371726

R-squared	0.036021	Mean dependent var	
Adjusted R-squared	-0.050049	S.D. dependent var	
S.E. of regression	21.62948	Akaike info criterion	
Sum squared resid	26198.73	Schwarz criterion	
Log likelihood	-275.4105	Hannan-Quinn criter.	
Durbin-Watson stat	1.104412		

Commercial- Follow-up (Q4) Combined Dollar

Question 4: Longer Run Variable Scenario Descriptions:
E: Typical or base case LED
G: Glare, Flicker, Color Rendering, Adjustability / Dimming
I: Glare, Flicker, Adjustability / Dimming
J: Glare, Color Rendering, Adjustability / Dimming
K: Flicker, Color Rendering, Adjustability / Dimming
L: Glare, Flicker, Color Rendering

Dependent Variable: _4DOLLAR_C
Method: Least Squares
Date: 07/16/19 Time: 15:09
Sample: 1 95 IF _4_OBS_GOOD_C=1
Included observations: 45
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.

_4ELR_BASE_C	20.17647	9.458047	2.133260	0.0393
_4GLR_GLAREFLICKCOLORADJ_C	48.00000	18.77498	2.556593	0.0146
_4ILR_GLAREFLICKADJ_C	31.58333	7.754711	4.072793	0.0002
_4JLR_GLARECOLORADJ_C	19.88889	6.553406	3.034893	0.0043
_4KLR_FLICKCOLORADJ_C	18.47059	5.427009	3.403456	0.0016
_4LLR_GLAREFLICKCOLOR_C	19.00000	7.975323	2.382349	0.0222

R-squared	0.188973	Mean dependent var	25.46667
Adjusted R-squared	0.084995	S.D. dependent var	24.60192
S.E. of regression	23.53319	Akaike info criterion	9.278266
Sum squared resid	21598.63	Schwarz criterion	9.519155
Log likelihood	-202.7610	Hannan-Quinn criter.	9.368067
Durbin-Watson stat	1.837707		

D.4: Commercial / Businesses Follow-up: Ranking Questions - Confidence Intervals

Commercial- Follow-up (Q1)

Coefficient Confidence Intervals
Date: 07/16/19 Time: 17:14
Sample: 1 95 IF _1_OBS_GOOD_C=1
Included observations: 48

		90% CI		95% CI		80% CI	
Variable	Coefficient	Low	High	Low	High	Low	High
_1ASR_GLARE	22.75000	7.064250	38.43575	3.932630	41.56737	10.60547	34.89453
_1BSR_FLICKER	25.33333	7.134586	43.53208	3.501253	47.16541	11.24314	39.42352
_1CSR_COLOR	19.42083	7.945448	30.89622	5.654416	33.18725	10.53613	28.30553
_1FSR_ADJ	18.57692	6.964695	30.18915	4.646343	32.50750	9.586275	27.56757
_1GSR_BASE	16.66667	7.952073	25.38126	6.212226	27.12111	9.919482	23.41385

Commercial- Follow-up (Q2)

Coefficient Confidence Intervals
Date: 07/16/19 Time: 17:13
Sample: 1 95 IF _2_OBS_GOOD_C=1
Included observations: 51

		90% CI		95% CI		80% CI	
Variable	Coefficient	Low	High	Low	High	Low	High
_2ALR_GLARE_C	30.33333	12.66490	48.00177	9.146968	51.51970	16.64802	44.01865
_2BLR_FLICKER_C	12.50000	6.423303	18.57670	5.213383	19.78662	7.793216	17.20678
_2CLR_COLOR_C	16.90250	10.27116	23.53384	8.950803	24.85420	11.76611	22.03889
_2DLR_ADJ_C	29.00000	13.91884	44.08116	10.91606	47.08394	17.31869	40.68131
_2ELR_BASE_C	7.937500	3.983812	11.89119	3.196600	12.67840	4.875120	10.99988

Commercial- Follow-up (Q3)

Coefficient Confidence Intervals
Date: 07/16/19 Time: 17:11
Sample: 1 95 IF _3_OBS_GOOD_C=1
Included observations: 62

		90% CI		95% CI		80% CI	

Variable	Coefficient	Low	High	Low	High	Low	High
_3ESR_BASE_C	21.25000	8.661053	33.83895	6.171761	36.32824	11.48869	31.01131
_3GSR_GLAREFLICKCOLORADJ_C	19.23077	6.253138	32.20840	3.686989	34.77455	9.168078	29.29346
_3ISR_GLAREFLICKADJ_C	25.30769	13.23237	37.38302	10.84464	39.77075	15.94464	34.67075
_3JSR_GLARECOLORADJ_C	16.44444	5.602707	27.28618	3.458902	29.42999	8.037898	24.85099
_3KSR_FLICKCOLORADJ_C	19.80000	10.70722	28.89278	8.909243	30.69076	12.74957	26.85043
_3LSR_GLAREFLICKCOLOR_C	13.61538	6.861563	20.36921	5.526088	21.70468	8.378557	18.85221

Commercial- Follow-up (Q4)

Coefficient Confidence Intervals
Date: 07/16/19 Time: 17:10
Sample: 1 95 IF _4_OBS_GOOD_C=1
Included observations: 45

		90% CI		95% CI		80% CI	
Variable	Coefficient	Low	High	Low	High	Low	High
_4ELR_BASE_C	20.17647	4.240843	36.11210	1.045765	39.30718	7.846596	32.50635
_4GLR_GLAREFLICKCOLORADJ_C	48.00000	16.36650	79.63350	10.02401	85.97599	23.52421	72.47579
_4ILR_GLAREFLICKADJ_C	31.58333	18.51761	44.64905	15.89795	47.26872	21.47399	41.69267
_4JLR_GLARECOLORADJ_C	19.88889	8.847218	30.93056	6.633373	33.14440	11.34562	28.43216
_4KLR_FLICKCOLORADJ_C	18.47059	9.326756	27.61442	7.493426	29.44775	11.39573	25.54545
_4LLR_GLAREFLICKCOLOR_C	19.00000	5.562578	32.43742	2.868388	35.13161	8.603062	29.39694

D.5: Commercial / Business: Original Ranking Questions – Regression Results

The Original Commercial Survey had three ranking questions.

Commercial (Q1) Combined Dollar

Question 1: Variable Scenario Descriptions:
A: Glare Reduction
B: Flicker Reduction
C: Color Rendering Improvement and Energy Efficiency 10%
D: Color Rendering Improvement and Energy Efficiency 20%
F: Adjustability and Dimmability
G: Typical or base case LED

Dependent Variable: _1COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 14:43
Sample: 1 884 IF _1BAD_OBS=1
Included observations: 395
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_1AGLAREREDUCTION_15_EEC	27.04348	3.316992	8.153013	0.0000
_1BFLICKERREDUCTION_10_PC	29.78571	4.196108	7.098414	0.0000

_1CCOLORRENDERINGIMPROVEMENT_10_EEC	26.37719	4.498916	5.863011	0.0000
_1DCOLORRENDERINGIMPROVEMENT_20_EEC	24.25758	3.947010	6.145811	0.0000
_1FADJUSTABILITY_DIMMABILITY_10_EEC	21.75691	2.982666	7.294449	0.0000

R-squared	0.007626	Mean dependent var	25.49559
Adjusted R-squared	-0.002552	S.D. dependent var	32.59250
S.E. of regression	32.63406	Akaike info criterion	9.821168
Sum squared resid	415343.0	Schwarz criterion	9.871533
Log likelihood	-1934.681	Hannan-Quinn criter.	9.841123
Durbin-Watson stat	2.155569		

Commercial (Q2) Combined Dollar

Question 2: Variable Scenario Descriptions:

A: No Glare

B: No Flicker

C: Color Rendering

D: Adjustability and Dimmability

E: Typical or base case LED

Dependent Variable: _2COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 14:47
Sample: 1 884 IF _2BAD_OBS=1
Included observations: 374
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_2AGLARENODIFFC	25.90291	2.995697	8.646707	0.0000
_2BNOFLICKERNODIFFC	26.42857	3.346581	7.897185	0.0000
_2CCOLORRENDERING_10_EEC	21.38141	3.113911	6.866416	0.0000
_2DADJUSTABILITY_DIMMING_10_EEC	22.31707	2.287886	9.754450	0.0000

R-squared	0.005799	Mean dependent var	23.87901
Adjusted R-squared	-0.002262	S.D. dependent var	27.73151
S.E. of regression	27.76285	Akaike info criterion	9.495912
Sum squared resid	285187.0	Schwarz criterion	9.537883
Log likelihood	-1771.736	Hannan-Quinn criter.	9.512576
Durbin-Watson stat	1.814680		

Commercial (Q3) Combined Dollar

Question 3: Variable Scenario Descriptions:

E: Typical or base case LED

G: Glare, Flicker, Color Rendering

I: Glare, Flicker, Adjustability / Dimming

J: Glare, Color Rendering, Adjustability / Dimming

K: Flicker, Color Rendering, Adjustability / Dimming

L: Glare, Flicker, Color Rendering

Dependent Variable: COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 14:59
Sample: 1 90 IF _3BAD_OBS=1
Included observations: 21
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GGLARE_FLICKER_COLORR_ADJUSTABILITYC	55.00000	25.77699	2.133686	0.0487
IGLARE_FLICKER_ADJUSTABILITYC	36.50000	21.63683	1.686939	0.1110
JGLARE_COLORR_ADJUSTABILITYGLAREC	38.33333	20.46126	1.873459	0.0794
KFLICKER_COLORR_ADJUSTABILITYFLICKERC	66.66667	31.18048	2.138090	0.0483
LGLARE_FLICKER_COLORRGLAREC	46.25000	24.24998	1.907218	0.0746

R-squared	0.055716	Mean dependent var	46.71429
Adjusted R-squared	-0.180356	S.D. dependent var	45.51609
S.E. of regression	49.45058	Akaike info criterion	10.84408
Sum squared resid	39125.75	Schwarz criterion	11.09278
Log likelihood	-108.8629	Hannan-Quinn criter.	10.89805
Durbin-Watson stat	1.028942		

D.6: Commercial / Businesses: Original Ranking Questions - Confidence Intervals

Commercial Q1 Combined										
Date: 06/27/19 Time: 15:11										
Sample: 1 884 IF _1BAD_OBS=1										
Included observations: 395										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_1AGLAREREDUCTION_15_EEC	27.04		21.57	32.51		20.52	33.56		22.79	31.30
_1BFLICKERREDUCTION_10_PC	29.79		22.87	36.70		21.54	38.04		24.40	35.17
_1CCOLORRENDERINGIMPROVEMENT_10_EEC	26.38		18.96	33.79		17.53	35.22		20.60	32.15
_1DCOLORRENDERINGIMPROVEMENT_20_EEC	24.26		17.75	30.77		16.50	32.02		19.19	29.32
_1FADJUSTABILITY_DIMMABILITY_10_EEC	21.76		16.84	26.67		15.89	27.62		17.93	25.59

Commercial Q2 Combined										
Date: 06/27/19 Time: 15:14										
Sample: 1 884 IF _2BAD_OBS=1										
Included observations: 374										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_2AGLARENODIFFC	25.90		20.96	30.84		20.01	31.79		22.06	29.75
_2BNOFLICKERNODIFFC	26.43		20.91	31.95		19.85	33.01		22.13	30.73
_2CCOLORRENDERING_10_EEC	21.38		16.25	26.52		15.26	27.50		17.38	25.38
_2DADJUSTABILITY_DIMMING_10_EEC	22.32		18.54	26.09		17.82	26.82		19.38	25.25

Commercial Q3 Combined										
Date: 06/27/19 Time: 15:15										
Sample: 1 90 IF _3BAD_OBS=1										
Included observations: 21										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
GGLARE_FLICKER_COLORR_ADJUSTABILITYC	55.00		10.00	100.00		0.36	109.64		20.54	89.46
IGLARE_FLICKER_ADJUSTABILITYC	36.50		-1.28	74.28		-9.37	82.37		7.58	65.42
JGLARE_COLORR_ADJUSTABILITYGLAREC	38.33		2.61	74.06		-5.04	81.71		10.98	65.69
KFLICKER_COLORR_ADJUSTABILITYFLICKERC	66.67		12.23	121.10		0.57	132.77		24.99	108.35
LGLARE_FLICKER_COLORRGLAREC	46.25		3.91	88.59		-5.16	97.66		13.83	78.67

D.7: Home Building and Design: Ranking Questions – Regression Results

Builder / Designer (Q1) Combined Dollar

Question 1: Variable Scenario Descriptions:
A: Flicker Reduction
B: Color Rendering Improvement and Energy Efficiency 10%
C: Adjustability and Dimmability
D: Typical or base case LED

Dependent Variable: _1COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 13:02
Sample: 1 177 IF _1BAD_OBS=1
Included observations: 51
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_1A_FLICKERREDUCTION_10_PC	2.057500	0.521425	3.945917	0.0003
_1B_COLORRENDERING_10_EEC	1.687500	0.897027	1.881215	0.0660
_1C_ADJUSTABILITY_DIMMING_10_EEC	3.565217	0.660418	5.398428	0.0000

R-squared	0.083792	Mean dependent var	2.679412
Adjusted R-squared	0.045617	S.D. dependent var	2.834187
S.E. of regression	2.768789	Akaike info criterion	4.931720
Sum squared resid	367.9773	Schwarz criterion	5.045357
Log likelihood	-122.7589	Hannan-Quinn criter.	4.975144
Durbin-Watson stat	2.069465		

Builder / Designer (Q2) Combined Dollar

Question 2: Variable Scenario Descriptions:
A: No Flicker
B: Color Rendering Excellent and Energy Efficiency 10%
E: Color Rendering Excellent and Energy Efficiency 20%
C: Adjustability and Dimmability
D: Typical or base case LED

Dependent Variable: _2COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 13:07
Sample: 1 177 IF _2BAD_OBS=1
Included observations: 76
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_2A_FLICKERNODIFFC	2.310000	0.685714	3.368752	0.0012
_2B_COLORRENDERING_10_EEC	1.133333	0.275964	4.106809	0.0001

_2C_ADJUSTABILITY_DIMMING_10_EEC	2.467391	0.443982	5.557419	0.0000
_2E_COLORRENDERING_20_EEC	3.480769	0.941954	3.695266	0.0004

R-squared	0.068111	Mean dependent var	2.325658
Adjusted R-squared	0.029282	S.D. dependent var	2.767978
S.E. of regression	2.727150	Akaike info criterion	4.895587
Sum squared resid	535.4891	Schwarz criterion	5.018258
Log likelihood	-182.0323	Hannan-Quinn criter.	4.944612
Durbin-Watson stat	1.337335		

Builder Designer (Q3) Combined Dollar

Question 3: Variable Scenario Descriptions:

A: No Flicker

B: Color Rendering Excellent, Adjustability / Dimming, and Energy Efficiency 10%

E: No Flicker, Adjustability / Dimming

C: Flicker, Adjustability / Dimmability

D: Typical or base case LED

Builder (Q3) Combined Dollar

Dependent Variable: _3COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 13:32
Sample: 1 177 IF _3BAD_OBS=1
Included observations: 85
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_3A_FLICKER_COLORR_20_EEC	3.225000	0.652649	4.941399	0.0000
_3B_COLOR_ADJUSTABILITY_20_EEC	2.500000	0.518560	4.821044	0.0000
_3C_FLICKER_ADJUSTABILITY_10_EEC	3.113636	0.450164	6.916669	0.0000
_3E_FLICKER_COLOR_ADJUSTABILITY_10_EEC	3.773913	0.561904	6.716297	0.0000

R-squared	0.032702	Mean dependent var	3.174118
Adjusted R-squared	-0.003124	S.D. dependent var	2.523669
S.E. of regression	2.527607	Akaike info criterion	4.738339
Sum squared resid	517.4928	Schwarz criterion	4.853287
Log likelihood	-197.3794	Hannan-Quinn criter.	4.784574
Durbin-Watson stat	1.874164		

D.8: Home Building and Design: Ranking Questions - Confidence Intervals

Builder (Q1) Combined										
Date: 06/28/19 Time: 10:15										
Sample: 1 177 IF _1BAD_OBS=1										
Included observations: 51										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_1A_FLICKERREDUCTION_10_PC	2.06		1.18	2.93		1.01	3.11		1.38	2.74
_1B_COLORRENDERING_10_EEC	1.69		0.18	3.19		-0.12	3.49		0.52	2.85
_1C_ADJUSTABILITY_DIMMING_10_EEC	3.57		2.46	4.67		2.24	4.89		2.71	4.42

Builder (Q2) Combined										
Date: 06/28/19 Time: 10:18										
Sample: 1 177 IF _2BAD_OBS=1										
Included observations: 76										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_2A_FLICKERNODIFFC	2.31		1.17	3.45		0.94	3.68		1.42	3.20
_2B_COLORRENDERING_10_EEC	1.13		0.67	1.59		0.58	1.68		0.78	1.49
_2C_ADJUSTABILITY_DIMMING_10_EEC	2.47		1.73	3.21		1.58	3.35		1.89	3.04
_2E_COLORRENDERING_20_EEC	3.48		1.91	5.05		1.60	5.36		2.26	4.70

Builder (Q3) Combined										
Date: 06/28/19 Time: 10:11										
Sample: 1 177 IF _3BAD_OBS=1										
Included observations: 85										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_3A_FLICKER_COLORR_20_EEC	3.23		2.14	4.31		1.93	4.52		2.38	4.07
_3B_COLOR_ADJUSTABILITY_20_EEC	2.50		1.64	3.36		1.47	3.53		1.83	3.17
_3C_FLICKER_ADJUSTABILITY_10_EEC	3.11		2.36	3.86		2.22	4.01		2.53	3.70
_3E_FLICKER_COLOR_ADJUSTABILITY_10_EEC	3.77		2.84	4.71		2.66	4.89		3.05	4.50

D.9: Household: Ranking Questions – Regression Results

Household (Q1) Combined Dollar

Question 1: Variable Scenario Descriptions:

A: Flicker Reduction

B: Color Rendering Improvement and Energy Efficiency 10%

C: Adjustability and Dimmability, Color Rendering

D: Typical or base case LED

Dependent Variable: _1COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 11:47
Sample: 1 880 IF BAD_OBS_TYPICALB_POS_OR_NO_WORST_DOLLAR=
1
Included observations: 351
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_1AFLICKERREDUCTION_10_PC	3.409231	0.301339	11.31360	0.0000
_1BCOLORRENDERINGIMPROVEMENT_10_EEC	3.123118	0.313644	9.957523	0.0000
_1CADJUSTABILITY_DIMMABILITY_COLOR_TEMPERATURE_10_EEC	3.741797	0.335733	11.14515	0.0000

R-squared	0.004990	Mean dependent var	3.454701
Adjusted R-squared	-0.000728	S.D. dependent var	3.471130
S.E. of regression	3.472393	Akaike info criterion	5.336076
Sum squared resid	4196.016	Schwarz criterion	5.369074
Log likelihood	-933.4813	Hannan-Quinn criter.	5.349209
Durbin-Watson stat	2.257731		

Household (Q2) Combined Dollar

Question 2: Variable Scenario Descriptions:

A: No Flicker

B: Color Rendering and Energy Efficiency 10%

C: Adjustability and Dimmability

D: Typical or base case LED

E: Color Rendering and Energy Efficiency 20%

Dependent Variable: _2COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 12:23
Sample: 1 266 IF BAD_OBS_TYPICALB_POS_OR_NO_WORST_DOLLAR=
1
Included observations: 162
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
_2AFLICKERNODIFFC	3.263704	0.436078	7.484213	0.0000
_2BCOLOR_RENDERING_10_EEC	3.288462	0.526967	6.240350	0.0000
_2CADJUSTABILITY_DIMMING_10_EEC	3.869048	0.748897	5.166330	0.0000
_2ECOLORRENDERING_20_EEC	4.794872	0.534849	8.964910	0.0000

R-squared	0.034477	Mean dependent var	3.773086
Adjusted R-squared	0.016145	S.D. dependent var	3.687006
S.E. of regression	3.657122	Akaike info criterion	5.455612
Sum squared resid	2113.178	Schwarz criterion	5.531849
Log likelihood	-437.9045	Hannan-Quinn criter.	5.486565
Durbin-Watson stat	1.803568		

Household (Q3) Combined Dollar

Question 3: Variable Scenario Descriptions:

A: Flicker, Color Rendering

B: Color Rendering, Adjustability / Dimming

C: Flicker, Adjustability and Dimmability

D: Typical or base case LED

E: Flicker, Color Rendering, Adjustability / Dimming

Dependent Variable: COMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 14:27
Sample: 1 396 IF SERIES01=1
Included observations: 81
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
A_FLICKER_COLORC	4.823529	0.989465	4.874884	0.0000
B_COLOR_ADJUSTABILITYC	4.437500	1.219534	3.638685	0.0005
C_FLICKER_ADJUSTABILITYC	3.102174	0.929245	3.338380	0.0013
E_FLICKER_COLOR_ADJUSTABILITYC	4.961538	0.930939	5.329604	0.0000

R-squared	-0.137963	Mean dependent var	4.217901
Adjusted R-squared	-0.182299	S.D. dependent var	4.139167
S.E. of regression	4.500666	Akaike info criterion	5.894449
Sum squared resid	1559.711	Schwarz criterion	6.012694
Log likelihood	-234.7252	Hannan-Quinn criter.	5.941891
Durbin-Watson stat	1.260437		

D.10: Households: Ranking Questions - Confidence Intervals

Household (Q1) Combined
Date: 06/28/19 Time: 10:23
Sample: 1 880 IF BAD_OBS_TYPICALB_POS_OR_NO_WORST_DOLLAR=1
Included observations: 351

			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_1AFLICKERREDUCTION_10_PC	3.41		2.91	3.91		2.82	4.00		3.02	3.80
_1BCOLORRENDERINGIMPROVEMENT_10_EEC	3.12		2.61	3.64		2.51	3.74		2.72	3.53
_1CADJUSTABILITY_DIMMABILITY_COLOR_TEMPERATURE_10_EEC	3.74		3.19	4.30		3.08	4.40		3.31	4.17

Household (Q2) Combined
Date: 06/28/19 Time: 10:28
Sample: 1 266 IF BAD_OBS_TYPICALB_POS_OR_NO_WORST_DOLLAR=1
Included observations: 162

			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
_2AFLICKERNODIFFC	3.26		2.54	3.99		2.40	4.12		2.70	3.82
_2BCOLOR_RENDERING_10_EEC	3.29		2.42	4.16		2.25	4.33		2.61	3.97
_2CADJUSTABILITY_DIMMING_10_EEC	3.87		2.63	5.11		2.39	5.35		2.91	4.83
_2ECOLORRENDERING_20_EEC	4.79		3.91	5.68		3.74	5.85		4.11	5.48

Household (Q3) Combined
Date: 06/28/19 Time: 10:34
Sample: 1 396 IF SERIES01=1
Included observations: 81

			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
A_FLICKER_COLORC	4.82		3.18	6.47		2.85	6.79		3.54	6.10
B_COLOR_ADJUSTABILITYC	4.44		2.41	6.47		2.01	6.87		2.86	6.01
C_FLICKER_ADJUSTABILITYC	3.10		1.56	4.65		1.25	4.95		1.90	4.30
E_FLICKER_COLOR_ADJUSTABILITYC	4.96		3.41	6.51		3.11	6.82		3.76	6.16

D.11: Street/Roadway: Public Works / Utilities: Ranking Questions – Regression Results

The variables for Street/roadway lighting vary from the other surveys due to the type of lighting and questions regarding impacts on wildlife. There is only one ranking question in the Street/roadway survey.

Public Works (Q1) Combined Dollar

Question 1: Variable Scenario Descriptions:
A: Warm Light, Reduced Wildlife Impact, No Blue Light, Price / EE same as baseline
B: Minimum Wildlife Impact, Improved Human Visibility, Price / EE same as baseline
C: Minimum Wildlife Impact, Improved Human Visibility, EE 10%
D: Typical or Baseline LED

Dependent Variable: PWCOMBINED_DOLLAR
Method: Least Squares
Date: 06/26/19 Time: 12:05
Sample: 1 100 IF BAD_OBS_TYPICALB_POS_OR_NO_WORST_DOLLAR=
1
Included observations: 51
Huber-White-Hinkley (HC1) heteroskedasticity consistent standard errors
and covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
A_WARMERLIGHT_IMPACT_NOBLUE_BASELINEC01	39.47368	10.86312	3.633734	0.0007
BIMPACT_HUMANVIS_BASELINEC01	46.00000	25.29921	1.818239	0.0753

CIMPACT_HUMANVIS__10_BASELINEEC01	52.27273	11.99452	4.358050	0.0001

pR-squared	0.009974	Mean dependent var	46.27451
Adjusted R-squared	-0.031277	S.D. dependent var	57.88647
S.E. of regression	58.78476	Akaike info criterion	11.04266
Sum squared resid	165871.1	Schwarz criterion	11.15630
Log likelihood	-278.5880	Hannan-Quinn criter.	11.08609
Durbin-Watson stat	0.969983		

D.12: Street/roadway: Public Works / Utilities: Ranking Questions - Confidence Intervals

Public Works Combined										
Date: 06/27/19 Time: 15:25										
Sample: 1 100										
Included observations: 59										
			90% CI			95% CI			80% CI	
Variable	Coefficient		Low	High		Low	High		Low	High
A_WARMERLIGHT_IMPACT_NOBLUE_BASELINEC01	39.47		17.79	61.16		13.50	65.45		25.358	53.590
BIMPACT_HUMANVIS_BASELINEC01	46.00		16.11	75.89		10.20	81.80		13.125	78.875
CIMPACT_HUMANVIS__10_BASELINEEC01	52.27		32.12	72.42		28.13	76.41		36.687	67.859

Appendix E: Survey Instruments - Advanced LED Lighting Technologies

E.1: Household Survey

Advanced LED Lighting Technologies Household Survey

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of different features of advanced LED lighting that are being developed. Your responses are extremely important to us.

The questions are a bit complicated - Please read carefully and answer to the best of your ability. Thank you.

If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

* 1. What is your involvement in decisions about lighting?

- Significant involvement
- Somewhat involved
- Not at all involved

Advanced LED Lighting Technologies Household Survey

* 2. Please characterize your primary home.

- Single family detached
- Single family attached (row house, condo, etc.)
- Small apartment building (6 or fewer units)
- Medium apartment building (7-20 units)
- Large apartment building (more than 20 units)
- Manufactured home / mobile home
- Other (please specify)

* 3. Do you own or rent your home?

- Own
- Rent
- Other (please specify)

Design Options and Values

Consider the following situation:

- Think about the light bulbs inside your home (not in common areas of apartments, and not outside your home). Assume you need to replace some of the light bulbs. Normally you might consider replacement with a LED bulb (the “Base Case”).
- Assume it has no special performance relative to flicker, color, or dimmability in the “Base Case” lighting.

We are going to ask you about a series of trade-offs in lighting features inside your home.

* 4. FLICKER - Next 2 questions:
Assume the “Base Case” LED bulb creates flicker that is noticeable to at least 20% of the population (residents in your home), but a more advanced LED bulb reduces flicker. Both are more energy efficient than the fluorescents they are replacing.

Flicker 1: Assume the energy costs for the two LEDs are the same, but the advanced LED bulb reduces flicker so fewer than 5% notice it and costs 10% more than the base case LED luminaire.
Would you say the *reduction in visual discomfort* from flicker is:

- ◯ Much more valuable than the 10% higher purchase price
- ◯ Somewhat more valuable than the 10% higher purchase price
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 10% higher purchase price
- ◯ Much less valuable than the 10% higher purchase price
- ◯ Of no value at all beyond the basic bulb

* 5. Flicker 2: Approximately what percent more or less valuable do you consider the reduction of flicker is relative to this 10% change in purchase price?____percent.

(e.g. use word terms or percentage terms. For same value put 100%; for “twice” as valuable, put 200% of value, for “half” as valuable, put 50%, or other value)

Example: The reduction in flicker is *half (50%) as valuable* as the 10% change in purchase price. OR The reduction in flicker is *twice (200%)* as valuable as the 10% change in purchase price.

* 6. COLOR RENDERING- Next 3 questions:
Assume the "Base Case" LED bulbs provide color rendering similar to good quality fluorescents *(colors somewhat dull and unnatural, yellowish tinge to whites, and light has a slight greenish tint - assume about two-thirds of residents find this color rendering acceptable).*

Assume the more advanced bulbs make colors look natural, whites are untinted, but some colors remain a bit dull (*assume 80% of residents find this color rendering acceptable*). Both are more energy efficient than the fluorescents they are replacing.

COLOR 1: Assume the up-front cost for the two LEDs are the same, AND the advanced LED bulb is 10% MORE energy efficient (and thus costs LESS to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering AND efficiency savings are:

- Much more valuable than the traditional bulb
- Somewhat more valuable than the traditional bulb
- About the same value / about even / no difference in value
- Somewhat less valuable than the traditional bulb
- Much less valuable than the traditional bulb
- Of no value at all beyond the basicbulb

* 7. COLOR RENDERING 2:

COLOR 1: Assume the up-front cost for the two LED bulbs are the same, but the advanced LED bulb is 5% less energy efficient (and thus costs more to operate) than the base case LED bulb. Would you say these *moderate improvements* in color rendering are:

- Much more valuable than the 5% loss of energy efficiency
- Somewhat more valuable than the 5% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 5% loss of energy efficiency
- Much less valuable than the 5% loss of energy efficiency
- Of no value at all beyond the basic bulb

* 8. COLOR 3: Approximately what percent more or less valuable do you consider the strong color rendition improvements are relative to this 5% change in energy efficiency?_____percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The color rendition improvements are half (50%) as valuable as the 20% change in energy efficiency. OR The color rendition improvements are twice (200%) as valuable as the 20% change in energy efficiency.

* 9. ADJUSTABLE LIGHTING COLOR & INTENSITY / DIMMING - Last New Feature. Next 2 questions: Assume the "Base Case" LED bulb does not dim and is not color adjustable. Assume the more advanced LED bulb dims smoothly down to 1% and is color-adjustable - allowing you to make colors warmer or cooler as you choose, which can address physiological issues and improve alertness and have other positive effects on your household.

ADJUSTABLE 1: Assume the up-front costs for the two bulbs are the same, but the advanced LED bulb is 10% less energy efficient (and thus costs more to operate) than the base case LED bulb. Would you say the ability to dim and adjust lighting color is:

- Much more valuable than the 10% loss of energy efficiency
- Somewhat more valuable than the 10% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% loss of energy efficiency
- Much less valuable than the 10% loss of energy efficiency
- Of no value at all beyond the basic luminaire

Other (please specify)

* 10. ADJUSTABLE 2: Approximately what percent more or less valuable do you consider the dimmability and control improvements are relative to this 10% change in energy efficiency?____percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The dimmability and control improvements are half (50%) as valuable as the 10% change in energy efficiency. OR
The dimmability and control improvements are twice (200%) as valuable as the 10% change in energy efficiency.

* 11. Please provide your best guess if answer not known; On what planet does the United States currently reside?

- The planet Earth
- The planet Mars
- The planet Venus
- Other (please specify)

Advanced LED Lighting Technologies Household Survey

Ranking Options

Think about replacing bulbs in your home.
Normally you might consider replacement with a typical LED (or fluorescent) bulb (the "Base Case"). Assume no special functionality on glare, flicker, color, or adjustability in the "Base Case" lighting.

We are going to ask you about a series of trade-offs in lighting features in your home.

12. <MOST IMPORTANT> Please rank the following scenarios from most (1) to least (4) preferred.

A – Flicker Reduction: From noticed by 20% to noticed by 5% of residents; Price Increase: 10% over Base Cas LED bulb

B – Color Rendering Improvement: Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10% less than Base Case LED bulb

C – Adjustability/Dimmability: to 1%; Color Temperature: Adjustable throughout the day , aligning with best research and alertness and physiological effects; Energy Efficiency: 10% less

D – Purchase of typical LED bulb to replace existing bulbs in sockets.

13. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case? $_______per bulb.

14. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $_______Specify MORE or LESS per bulb.

15. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case?___% more per bulb.

16. About how much in annual energy savings do you expect from the replacement of a traditional bulb with an LED fixture?
$______per year

17. About how much is the cost of new, basic LED bulb? $______per LED bulb

18. A FEW LAST QUESTIONS - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A – Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED

B – Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

E – Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

C – Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

D – Purchase of typical LED bulb to replace existing bulbs in the home.

19. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $________per bulb.

20. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case bulb? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per bulb.

21. THE LAST RANKING QUESTION- VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A-Flicker & Color –

Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color

Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

B- Color & Adjustability –
Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

D – Purchase of typical LED bulb to replace existing bulbs in the home.

C – Flicker & Adjustability -
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

E - Flicker & Color & Adjustability -
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

22. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $________per bulb.

23. What is the maximum dollar amount extra you think it would be worth paying for your SECOND BEST ranked option relative to the Base Case LED $_____per bulb.

24. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case bulb? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per bulb.

25. What kind of lighting do you currently have in place inside your home?

- Mostly traditional incandescent light bulbs
- Mostly compact fluorescent bulbs (CFL - often spiral tube)
- Mostly LED (newer type)
- Other (please specify)

26. THANK YOU for your time and expertise. Your answers are very important to our research. Please feel free to include any other comments you may have about this topic in the box below. If you have questions, contact Dr. Lisa Skumatz (skumatz@serainc.com or 303/494-1178).

THANK YOU again for your help.

E.2: Follow-up Business Survey

Advanced LED Lighting Technologies Commercial Business Survey Follow Up

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of different features of advanced LED lighting that are being developed. Your responses, as businesses in owned or leased space, are extremely important to us. Your answers will be used in aggregate and your responses are anonymous.

NOTE we are most interested in responses from business OWNERS or those involved in DECISIONS ABOUT LIGHTING. Please answer to the best of your ability.
Thank you.

If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

1. Please characterize your business (check all that apply).

- ☐ Small / medium retail
- ☐ Large / big-box retail
- ☐ Small/medium office
- ☐ Large office
- ☐ Mixed use
- ☐ Other (please specify)
- ☐ Manufacturing, small / medium
- ☐ Manufacturing, large
- ☐ Hospitality or food, small / medium
- ☐ Hospitality or food, large

Do you or the company you work for....

- ◯ Own the company work space
- ◯ Lease the work space - not involved in lighting decisions Lease your space, but am involved in lighting decisions

Directions: Please read carefully the following questions- they have multiple components and require thoughtful answers about the value of lighting attributes.

Flicker-Rapid on / off not always noticeable but can cause discomfort
Glare creates visual discomfort, but a more advanced LED luminaire (and application guidelines) dramatically reduces visual discomfort without affecting visual interest.
Dimmable refers to a light that dims smoothly brighter or softer. warmer or cooler as you choose and change reds etc.

These can address physiological issues and improve alertness and have other positive effects on work spaces.

3. Consider the following situation:

Think about the office space in your business with office workers performing a mix of computer and paper work.

The Existing Situation is a traditional overhead linear 4-foot fluorescent-type light fixture, and assume the normal BASE CASE replacement situation would be to replace the lights with a typical LED luminaire with no special color rendition, flicker, glare, or other capabilities.

COLOR RENDERING: Assume the "Base Case" LED luminaire provides color rendering similar to good quality fluorescents - colors somewhat dull and unnatural, yellow-ish tinge to whites, and light has a somewhat greenish tint. Assume 65% of workers find this color rendering acceptable.

ADVANCED COLOR 1: Assume more advanced luminaires make colors look natural, whites are untinted, but some colors remain a bit dull (80% of workers find this acceptable).

Assume the up-front cost for the two LEDs are the same AND the advanced LED luminaire is10% MORE energy efficient than baseline (no difference in price.)
Would you say these moderate improvements in color rendering AND energy efficiency makes the luminaries:

- Much more valuable than the traditional LED luminaire
- Somewhat more valuable than the traditional LED luminaire
- About the same value as the traditional LED luminaire without these features
- Somewhat less valuable than the traditional LED luminaire
- Much less valuable than the traditional LED luminaire
- Of no value at all

Advanced LED Lighting Technologies Commercial Business Survey Follow Up

Advanced Color 2

9. Now consider a more advanced luminaire.

ADVANCED COLOR 2: Assume more advanced luminaires make colors look vibrant and pleasing with crisp, clean, and untinted whites.

Assume the up-front cost for the two LEDs are the same AND the advanced LED luminaire is20% MORE energy efficient than baseline (no difference in price.)
Would you say these strong improvements in color rendering AND energy efficiency makes the luminaries?

Much more valuable than the traditional LEDluminaire
Somewhat more valuable than the traditional LED luminaire
About the same value as the traditional LED luminaire without these features
Somewhat less valuable than the traditionalLED luminaire
Much less valuable than the traditional LED luminaire
Of no value at all

Advanced LED Lighting Technologies Commercial Business Survey Follow Up

RankingQ

15. Across Features 1: Please rank the following scenarios from most (1) to least (5) preferred.

A –Glare Reduction: From noticed by 20% to noticed by 0% of workers (eliminated); Energy Efficiency: 15% less than Base Case LED

B – Flicker Reduction: From noticed by 20% to noticed by 5% of workers; Price Increase: 10% over Base Case LED

C – Color Rendering Improvement: Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10% BETTER than Base Case LED

F – Adjustability/Dimmability: to 1%; Color Temperature: Adjustable (reds, blues) throughout the day, aligning with best research and alertness / productivity effects; Energy Efficiency: 10% less than Base Case LED

G – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

16. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option compared to the Base Case LED luminaire? $________per luminaire.

17. What is the maximum dollar amount extra you think it would be worth paying for your 2nd ranked option compared to the Base Case luminaire? $__per luminaire.

18. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $__Specify MORE or LESS per luminaire.

19. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option compared to the price of the Base Case luminaire?_% more per luminaire.

Advanced LED Lighting Technologies Commercial Business Survey Follow Up

RankingQ

20. Across Features 2: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A –Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED

B – Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED

C – Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

D – Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

21. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

22. What is the maximum dollar amount extra you think it would be worth paying for your 2nd ranked option relative to the Base Case LED $_per luminaire.

23. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $__Specify MORE or LESS per luminaire.

24. What is the maximum percentage extra you think it would be worth paying for your FIRST ranked option compared to the cost of the Base Case luminaire? _______% more per luminaire.

Advanced LED Lighting Technologies Commercial Business Survey Follow Up

RankingQ

25. ALMOST THERE: The following represent near term technologies. Please rank the following scenarios from most (1) to least (6) preferred.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

G - Glare & Flicker & Color R & Adjustability -
Glare: Delivers NO glare, 15% less energy efficient AND Flicker: Only 5% notice flicker and 10% higher price AND Color Rendering: Natural color rendering (but dull), 10% IMPROVEMENT in energy efficiency AND Adjustability/Dimming: Flexible color temperatures and dimming, 10% less energy efficient compared to base case LE

I - Glare & Flicker & Adjustability -
Glare: Delivers NO glare, 15% less energy efficient AND Flicker: Only 5% notice flicker and 10% higher price AND Adjustability/Dimming: Flexible color temperatures and dimming, 10% less energy efficient compared to base case LE

J-Glare & Color R & Adjustability

Glare: Delivers NO glare, 15% less energy efficient AND Color Rendering: Natural color rendering (but dull),
10% IMPROVEMENT in energy efficiency AND Adjustability/Dimming: Flexible color temperatures and dimming, 10% less energy efficient compared to base case LE

K- Flicker & Color R & Adjustability

Flicker: Only 5% notice flicker and 10% higher price AND Color Rendering: Natural color rendering (but dull),
10% IMPROVEMENT in energy efficiency AND Adjustability/Dimming: Flexible color temperatures and dimming, 10% less energy efficient compared to base case LED

L-Glare & Flicker & Color
Glare: Delivers NO glare, 15% less energy efficient AND Flicker: Only 5% notice flicker and 10% higher price AND Color Rendering: Natural color rendering (but dull), 10% IMPROVEMENT in energy efficiency

26. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

27. What is the maximum dollar amount extra you think it would be worth paying for your SECOND BEST ranked option relative to the Base Case LED $__per luminaire.

28. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

29. What is the maximum percentage extra you think it would be worth paying for your FIRST ranked option compared to the cost of the Base Case luminaire? ________% more per luminaire.

Advanced LED Lighting Technologies Commercial Business Survey Follow UP

Last Page

30. LAST QUESTIONS: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (6) preferred.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

G - Glare & Flicker & Color R & Adjustability -
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND
Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

I - Glare & Flicker & Adjustability -
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 20% IMPROVEMENT in energy efficiency compared to base case LED

J-Glare & Color R & Adjustability
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Color Rendering Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED
AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

K- Flicker & Color R & Adjustability
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

L-Glare & Flicker & Color R; Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

31. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

32. What is the maximum dollar amount extra you think it would be worth paying for your SECOND BEST ranked option relative to the Base Case LED $___per luminaire.

33. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

34. What is the maximum percentage extra you think it would be worth paying for your FIRST ranked option compared to the cost of the Base Case luminaire? ________% more per luminaire.

35. About how much in annual dollar energy savings do you expect from the replacement of a traditional bulb with an LED fixture? $______per year

36. About how much is the cost of a new, basic LED luminaire for a commercial building? $____per LED bulb

37. How much extra would you be willing to pay for a bulb that had these four features, than for a base case LED? $_____per luminaire

Glare: Delivers NO glare, 15% less energy efficient AND Flicker: Only 5% notice flicker and 10% higher price AND Color Rendering: Natural color rendering (but dull), 10% IMPROVEMENT in energy efficiency AND Adjustability/Dimming: Flexible color temperatures and dimming, 10% less energy efficient compared to base case LED

38. How much extra would you be willing to pay for a bulb that had these four features, than for a base case LED? $_____per luminaire

Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

39. Do you have any other comments you would like to make about lighting in commercial buildings?

- Yes
- No

Yes (please specify)

End - Advanced LED Lighting Technologies-Commercial Business Survey - Follow-Up

E.3: Business Survey (Original)

Advanced LED Lighting Technologies Commercial Business Survey (Original)

40. What is your involvement in decisions about lighting?

- ◯ Significant involvement
- ◯ Somewhat involved
- ◯ Not at all involved

41. Please provide the following background information:

Role or Title

About how many employees are at this location?

42. Please characterize your business (check all that apply).

- ☐ **Small / medium retail**
- ☐ **Large / big-box retail**
- ☐ **Small/medium office**
- ☐ **Large office**
- ☐ **Mixed use**
- ☐ **Other (Please specify)**
- ☐ **Manufacturing, small / medium**
- ☐ **Manufacturing, large**
- ☐ **Hospitality or food, small / medium**
- ☐ **Hospitality or food, la**

43. Is your business located in a leased office location, or is the space owned by your business?

- ◯ Owner occupied offices or other business
- ◯ Leased, non-owner occupied offices, short to medium lease
- ◯ Other (please specify)

Advanced LED Lighting Technologies Commercial Business Survey (Original)

Design Options and Values

Consider the following situation:

- Think about the office space in your business.
- The office workers perform a mix of computer and paper work.
- Existing Situation: Traditional commercial overhead linear 4-foot fluorescent-type fixtures.
- Assume you need to replace the lights. Normally you might consider replacement with a typical LED luminaire (the “Base Case”).
- Assume no special functionality on glare, flicker, color, or color rendition in the “Base Case” lighting.

We are going to ask you about a series of trade-offs in lighting features in office space.

44. GLARE - Next 2 questions:

Assume the “Base Case” LED luminaire creates visual discomfort from glare for at least 20% of the workers, but a more advanced LED luminaire (and application guidelines) dramatically reduces visual discomfort without affecting visual interest. Both are more energy efficient than the fluorescents they are replacing.

Glare 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is15% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the *reduction in visual discomfort* from glareis:

- ◯ Much more valuable than the 15% loss of energy efficiency
- ◯ Somewhat more valuable than the 15% loss of energy efficiency
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 15% loss of energy efficiency
- ◯ Much less valuable than the 15% loss of energy efficiency
- ◯ Of no value at all beyond the basic luminaire

45. Glare 2: Approximately what percent more or less valuable do you consider the reduction of glare is relative to a 15% reduction in energy efficiency?___percent.

(e.g. use word terms or percentage terms. For same value put 100%; for “twice” as valuable, put 200% of value, for “half” as valuable, put 50%, or other value)

Example: The reduction in glare is *half (50%) as valuable* as the 10% change in energy efficiency. OR The reduction in glare is *twice (200%)* as valuable as the 15% change in energy efficiency.

46. FLICKER - Next 2 questions:
Assume the “Base Case” LED luminaire creates flicker that is noticeable to at least 20% of the workers, but a more advanced LED luminaire (and application guidelines) reduces flicker. Both are more energy efficient than the fluorescents they are replacing.

Flicker 1: Assume the energy costs for the two LEDs are the same, but the advanced LED luminaire reduces flicker so fewer than 5% notice it and costs 10% more than the base case LED luminaire.
Would you say the *reduction in visual discomfort* from flicker is:

- Much more valuable than the 10% higher purchase price
- Somewhat more valuable than the 10% higher purchase price
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% higher purchase price
- Much less valuable than the 10% higher purchase price
- Of no value at all beyond the basic luminaire

47. Flicker 2: Approximately what percent more or less valuable do you consider the reduction of flicker is relative to this 10% change in purchase price?_______percent.

(e.g. use word terms or percentage terms. For same value put 100%; for “twice” as valuable, put 200% of value, for “half” as valuable, put 50%, or other value)

Example: The reduction in flicker is *half (50%) as valuable* as the 10% change in purchase price. OR The reduction in flicker is *twice (200%)* as valuable as the 10% change in purchase price.

48. COLOR RENDERING- Next 3 questions:
Assume the “Base Case” LED luminaires provide color rendering similar to good quality fluorescents *(colors somewhat dull and unnatural, yellowish tinge to whites, and light has a slight greenish tint - assume 65% of workers find this color rendering acceptable).*

Assume the more advanced luminaires make colors look natural, whites are untinted, but some colors remain a bit dull (*assume 80% of workers find this color rendering acceptable*). Both are more energy efficient than the fluorescents they are replacing.

COLOR 1: Assume the up-front cost for the two LEDs are the same, AND the advanced LED luminaire is 10% MORE energy efficient (and thus costs LESS to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering AND efficiency savings are:

- Much more valuable than the traditional luminaire
- Somewhat more valuable than the traditional luminaire
- About the same value / about even / no difference in value
- Somewhat less valuable than the traditional luminaire
- Much less valuable than the traditional luminaire
- Of no value at all beyond the basic luminaire

49. COLOR RENDERING 2:

COLOR 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 5% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering are:

- ◯ Much more valuable than the 5% loss of energy efficiency
- ◯ Somewhat more valuable than the 5% loss of energy efficiency
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 5% loss of energy efficiency
- ◯ Much less valuable than the 5% loss of energy efficiency
- ◯ Of no value at all beyond the basic luminaire

50. COLOR 3: Approximately what percent more or less valuable do you consider the strong color rendition improvements are relative to this 5% change in energy efficiency?_____percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The color rendition improvements are half (50%) as valuable as the 20% change in energy efficiency. OR The color rendition improvements are twice (200%) as valuable as the 20% change in energy efficiency.

51. ADJUSTABLE LIGHTING COLOR & INTENSITY / DIMMING - Last New Feature. Next 2 questions:
Assume the "Base Case" LED luminaire does not dim and has a static color temperature and spectrum. Assume the more advanced LED luminaire dims smoothly down to 1% and is color-adjustable.

This capability allows varying light profiles during the workday, aligning with best practices research. This color flexibility addresses physiological issues related to lighting wave lengths, and can improve alertness, productivity, and other workplace effects.

ADJUSTABLE 1: Assume the up-front costs for the two luminaires are the same, but the advanced LED luminaire is 10% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the ability to adjust lighting color and intensity/dimming is:

- ◯ Much more valuable than the 10% loss of energy efficiency
- ◯ Somewhat more valuable than the 10% loss of energy efficiency
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 10% loss of energy efficiency
- ◯ Much less valuable than the 10% loss of energy efficiency
- ◯ Of no value at all beyond the basic luminaire
- ◯ Other (please specify)

52. ADJUSTABLE 2: Approximately what percent more or less valuable do you consider the dimmability and control improvements are relative to this 10% change in energy efficiency?__percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The dimmability and control improvements are half (50%) as valuable as the 10% change in energy efficiency. OR
The dimmability and control improvements are twice (200%) as valuable as the 10% change in energy efficiency.

53. Please provide your best guess if not known; on what planet is the United States currently located?

- The planet Earth
- The planet Venus
- The planet Mars
- Other (please specify)

Advanced LED Lighting Technologies Commercial Business Survey (Original)

Ranking Options

Consider the following situation:

Think about the office space in your business.
The office workers perform a mix of computer and paper work.
Existing Situation: Traditional commercial overhead linear 4-foot fluorescent-type fixtures.
Assume you need to replace the lights. Normally you might consider replacement with a typical LED luminaire (the "Base Case").
Assume no special functionality on glare, flicker, color, or color rendition in the "Base Case" lighting.

We are going to ask you about a series of trade-offs in lighting features in office space.

54. <MOST IMPORTANT> Please rank the following scenarios from most (1) to least (6) preferred.

A –Glare Reduction: From noticed by 20% to noticed by 0% of workers (eliminated); Energy Efficiency: 15% less than Base Case LED

B – Flicker Reduction: From noticed by 20% to noticed by 5% of workers; Price Increase: 10% over Base Case LED

C – Color Rendering Improvement: Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10 less than Base Case LED

D – Color Rendering Improvement: Strong (colors vibrant and pleasing, crisp / clean whites, light is untinted, neutral white); Energy Efficiency: 20% less than Base Case LED

F – Adjustability/Dimmability: to 1%; Color Temperature: Adjustable (reds, blues) throughout the day, aligning with best research and alertness / productivity effects; Energy Efficiency: 10% less

G – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

55. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case? $_per luminaire.

56. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $__Specify MORE or LESS per luminaire.

57. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case?___% more per luminaire.

58. Describe how your rankings above would change if the office space:

Had no outside windows – was fully internal?

Included a significant night shift / was 24 hours?

59. About how much in annual energy savings do you expect from the replacement of a 4 foot linear fluorescent fixture with an LED fixture? $______per year

60. About how much is the cost of new, basic, 4-foot linear LED luminaire? $______per LED luminaire

61. NEARLY THERE - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A –Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED

B – Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED

C – Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

D – Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

62. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

63. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

64. What is the maximum percentage extra you think it would be worth paying for your FIRST ranked option compared to the cost of the Base Case luminaire? _______% more per luminaire.

65. LAST QUESTIONS - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (6) preferred.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

G - Glare & Flicker & Color R & Adjustability -
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND
Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

I - Glare & Flicker & Adjustability -
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

J-Glare & Color R & Adjustability
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

K- Flicker & Color R & Adjustability
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / productivity effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED

L-Glare & Flicker & Color R
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

66. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

67. What is the maximum dollar amount extra you think it would be worth paying for your SECOND BEST ranked option relative to the Base Case LED $__per luminaire.

68. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

69. What kind of lighting do you currently have in place in your office space?

- Mostly 4 foot linear fluorescent luminares
- Mostly 4 foot linear LED luminaires
- Other (please specify)

70. THANK YOU for your time and expertise. Your answers are very important to our research. If you have questions, contact Dr. Lisa Skumatz (skumatz@serainc.com or 303/494-1178).

Please make any additional comments you may have in the space below. THANK YOU again for your help.

End - Advanced LED Lighting Technologies-Commercial Business Survey-(Original)

E.4: Home Building and Design Survey

Advanced LED Lighting Technologies -Home Building & Design Survey

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of *different features of advanced LED lighting* that are being developed.

As a person knowledgeable about *residential home building and / or design and remodeling*, your input is extremely important to us.

As a thank you for your for the quick turnaround and your thoughtful input (received by TUESDAY 6/11/19) , *we are providing $50 gift certificates* to Amazon.com for your completed survey (one per respondent).
In addition, your name will be entered into a drawing for a $200 gift certificate.

The questions are a bit complicated; the survey takes about 10-13 min. Please read carefully and answer to the best of your ability.
Thank you,
If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

1. What is your involvement in decisions about lighting?

○ Significant involvement ○ Somewhat involved ○ Not at all involved

Do you mostly work with...

○ New Construction
○ Remodeling

3. Please characterize the TYPE of housing you mostly work with.

○ Single family detached
○ Single family attached (row house, condo, etc.)
○ Medium apartment building (7-20 units)
○ Large apartment building (more than 20 units)
○ Manufactured home / mobile home
○ Other (please specify)

Design Options and Values

Consider the following situation:

- Think about the light bulbs inside a standard home (not in common areas of apartments, and not outside the home). Assume you need to install, design, upgrade the lighting. Normally you might consider using a LED bulb (the "Base Case").
- Assume it has no special performance relative to flicker, color, or dimmability in the "Base Case" lighting.

We are going to ask you about a series of trade-offs in lighting features inside the home.

4. FLICKER - Next 2 questions:
Assume the “Base Case” LED bulb creates flicker that is noticeable to at least 20% of the population (in a typical home), but a more advanced LED bulb reduces flicker. Both are more energy efficient than the fluorescents they are replacing.

Flicker 1: Assume the energy costs for the two LEDs are the same, but the advanced LED bulb reduces flicker so fewer than 5% notice it and costs 10% more than the base case LED luminaire.
Would you say the *reduction in visual discomfort* from flicker is:

- Much more valuable than the 10% higher purchase price
- Somewhat more valuable than the 10% higher purchase price
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% higher purchase price
- Much less valuable than the 10% higher purchase price
- Of no value at all beyond the basic bulb

5. Flicker 2: Approximately what percent more or less valuable do you consider the reduction of flicker is relative to this 10% change in purchase price?_______percent.

(e.g. use word terms or percentage terms. For same value put 100%; for “twice” as valuable, put 200% of value, for “half” as valuable, put 50%, or other value)

Example: The reduction in flicker is *half (50%) as valuable* as the 10% change in purchase price. OR The reduction in flicker is *twice (200%)* as valuable as the 10% change in purchase price.

6. COLOR RENDERING- Next 3 questions:
Assume the “Base Case” LED bulbs provide color rendering similar to good quality fluorescents *(colors somewhat dull and unnatural, yellowish tinge to whites, and light has a slight greenish tint - assume about two-thirds of residents find this color rendering acceptable).*

Assume the more advanced bulbs make colors look natural, whites are untinted, but some colors remain a bit dull (*assume 80% of residents find this color rendering acceptable*). Both are more energy efficient than the fluorescents they are replacing.

COLOR 1: Assume the up-front cost for the two LEDs are the same, AND the advanced LED bulb is 10% MORE energy efficient (and thus costs LESS to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering AND efficiency savings are:

- Much more valuable than the traditional bulb
- Somewhat more valuable than the traditional bulb
- About the same value / about even / no difference in value
- Somewhat less valuable than the traditional bulb
- Much less valuable than the traditional bulb
- Of no value at all beyond the basic bulb

7. COLOR RENDERING 2:

COLOR 1: Assume the up-front cost for the two LED bulbs are the same, but the advanced LED bulb is 5% less energy efficient (and thus costs more to operate) than the base case LED bulb. Would you say these *moderate improvements* in color rendering are:

- Much more valuable than the 5% loss of energy efficiency
- Somewhat more valuable than the 5% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 5% loss of energy efficiency
- Much less valuable than the 5% loss of energy efficiency
- Of no value at all beyond the basic bulb

8. COLOR 3: Approximately what percent more or less valuable do you consider the strong color rendition improvements are relative to this 5% change in energy efficiency?_____percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The color rendition improvements are half (50%) as valuable as the 20% change in energy efficiency. OR The color rendition improvements are twice (200%) as valuable as the 20% change in energy efficiency.

9. ADJUSTABLE LIGHTING COLOR & INTENSITY / DIMMING - Last New Feature. Next 2 questions: Assume the "Base Case" LED bulb does not dim and is not color adjustable. Assume the more advanced LED bulb dims smoothly down to 1% and is color-adjustable - allowing you to make colors warmer or cooler as you choose, which can address physiological issues and improve alertness and have other positive effects on your household.

ADJUSTABLE 1: Assume the up-front costs for the two bulbs are the same, but the advanced LED bulb is 10% less energy efficient (and thus costs more to operate) than the base case LED bulb. Would you say the ability to dim and adjust lighting color is:

- Much more valuable than the 10% loss of energy efficiency
- Somewhat more valuable than the 10% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% loss of energy efficiency
- Much less valuable than the 10% loss of energy efficiency
- Of no value at all beyond the basic luminaire

Other (please specify)

10. ADJUSTABLE 2: Approximately what percent more or less valuable do you consider the dimmability and control improvements are relative to this 10% change in energy efficiency?__percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:

The dimmability and control improvements are half (50%) as valuable as the 10% change in energy efficiency. OR
The dimmability and control improvements are twice (200%) as valuable as the 10% change in energy efficiency.

11. Please provide your best guess if answer not known; On what planet does the United States currently reside?

- The planet Earth
- The planet Mars
- The planet Venus
- Other (please specify)

Ranking Options

Think about installing or replacing bulbs in a home.

Normally you might consider replacement with a typical LED (or fluorescent) bulb (the "Base Case"). Assume no special functionality on glare, flicker, color, or adjustability in the "Base Case" lighting.

We are going to ask you about a series of trade-offs in lighting features in a typical home of your clients.

12. <MOST IMPORTANT> Please rank the following scenarios from most (1) to least (4) preferred.

A – Flicker Reduction: From noticed by 20% to noticed by 5% of residents; Price Increase: 10% over Base Case LED bulb

B – Color Rendering Improvement: Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10% less than Base Case LED bulb

C – Adjustability/Dimmability: to 1%; Color Temperature: Adjustable throughout the day , aligning with best research and alertness and physiological effects ; Energy Efficiency: 10% less

D – Purchase of typical LED bulb to replace existing bulbs in sockets.

13. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case? $_per bulb.

14. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $__Specify MORE or LESS per bulb.

15. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case?___% more per bulb.

16. About how much in annual energy savings do you expect from the replacement of a traditional bulb with an LED fixture? $______per year

17. About how much is the cost of new, basic LED bulb? $______per LED bulb

18. A FEW LAST QUESTIONS - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A – Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED

B – Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

E – Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

C – Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

D – Purchase of typical LED bulb to replace existing bulbs in the home.

19. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per bulb.

20. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case bulb? Use the last ranked that is NOT the base case. $_______Specify MORE or LESS per bulb.

21. THE LAST RANKING QUESTION- VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A-Flicker & Color –
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED

B- Color & Adjustability –
Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

D – Purchase of typical LED bulb to replace existing bulbs in the home.

C – Flicker & Adjustability -
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

E - Flicker & Color & Adjustability -
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 20% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day according to best research providing alertness / positive household effects and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

22. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per bulb.

23. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case bulb? Use the last ranked that is NOT the base case. $_______Specify MORE or LESS per bulb.

24. What kind of lighting do you typically install / design for a home?

- Mostly traditional incandescent light bulbs
- Mostly compact fluorescent bulbs (CFL - often spiral tube)
- Mostly LED (newer type)
- Other (please specify)

25. THANK YOU for your time and expertise. Your answers are very important to our research. Please feel free to include any other comments you may have about this topic in the box below. If you have questions, contact Dr. Lisa Skumatz (skumatz@serainc.com or303/494-1178).

THANK YOU again for your help.

Please enter the name for the Gift-card

Please provide the email that we should use for the Gift-Card

Please provide any other comments you have regarding this survey subject.

End - Advanced LED Lighting Technologies -Home Building & Design Survey

E.5: Lighting Designer Survey

Advanced LED Lighting Technologies Lighting Designers Survey

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of different features of advanced LED lighting that are being developed. Your responses, as informed *lighting designers,* are extremely important to us. However, note your answers will be used only in aggregate and will be kept anonymous.

As a thank you for your carefully-considered response (received by *FRIDAY 6/7/19*) we are providing $50 gift certificates to Amazon.com for your completed survey (one per respondent). In addition, your name will be entered into a drawing for a $200 gift certificate.

Please answer to the best of your ability. Thank you,

If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

1. Please provide the following background information:

Name (for gift certificate)

Email (needed for gift certificate)

Phone (in case problem with gift certificate)

Years in Industry

Role or Title

2. Please provide the following background information on your projects (numbers only please):

For YOU: Number of projects per year involving lighting (or architectural lighting)?

For the COMPANY: Number of projects per year involving lighting (or architectural lighting)?

What is the average / most common square footage of your projects?

About how many staff are involved in lighting design at your company?

3. Please characterize your typical clients.

- [ ] Small / medium retail
- [ ] Large / big-box retail
- [ ] Small/medium office
- [ ] Large office
- [ ] Mixed use
- [ ] Multifamily
- [ ] Single family
- [ ] Parking lots

Other (please specify)

4. Which letter does your last name begin with...?

- ◯ Letter A - K ==>If so, please answer questions for the perspective of "owner occupied offices"
- ◯ Letter L-Z ==> If so, please answer questions for the perspective of "leased, non-owner occupied offices, short to medium lease".

Advanced LED Lighting Technologies Lighting Designers Survey

Design Options and Values

<MOST IMPORTANT> Consider the following situation:

- Medium-sized office configuration, mix of windowed and internal space
- Owner occupied (your last name A-K) or Leased / non-owner occupied, short to medium lease (your last name L-Z). Office workers with a mix of computer and paper work.
- Existing Situation: Traditional commercial overhead linear 4-foot luminaires, fluorescent-type fixtures.
- You are hired to consider options for new luminaires. Normally you might consider replacement with a typical LED luminaire (the “Base Case”).
- Assume no special functionality on glare, flicker, color, or color rendition in the “Base Case” lighting.

We are going to ask you about a series of trade-offs in lighting features.

5. GLARE - Next 2 questions:

Assume the “Base Case” LED luminaire creates visual discomfort from glare for at least 20% of the workers, but a more advanced LED luminaire (and application guidelines) dramatically reduces visual discomfort without affecting visual interest. Both are more energy efficient than the fluorescents they are replacing.

Glare 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 5% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the *reduction in visual discomfort* from glare is:

- ◯ Much more valuable than the 5% loss of energy efficiency
- ◯ Somewhat more valuable than the 5% loss of energy efficiency
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 5% loss of energy efficiency
- ◯ Much less valuable than the 5% loss of energy efficiency
- ◯ Of no value at all beyond the basic luminaire

6. Glare 2: Assume the same situation but the advanced LED is now 15% less energy efficient than base luminaire. (same up front cost, glare dramatically reduced). Would you say the *reduction in visual discomfort* from glare is:

- ◯ Much more valuable than the 15% loss of energy efficiency
- ◯ Somewhat more valuable than the 15% loss of energy efficiency
- ◯ About the same value / about even / no difference in value
- ◯ Somewhat less valuable than the 15% loss of energy efficiency
- ◯ Much less valuable than the 15% loss of energy efficiency
- ◯ Of no value at all beyond the basic luminaire

7. Glare 3: Approximately what percent more or less valuable do you consider the reduction of glare is relative to a 15% reduction in energy efficiency?___percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Example: The reduction in glare is *half (50%) as valuable* as the 10% change in energy efficiency. OR The reduction in glare is *twice (200%)* as valuable as the 15% change in energy efficiency.

8. FLICKER - Next 4 questions:
Assume the "Base Case" LED luminaire creates flicker that is noticeable to at least 20% of the workers, but a more advanced LED luminaire (and application guidelines) reduces flicker. Both are more energy efficient than the fluorescents they are replacing.

Flicker 1: Assume the energy costs for the two LEDs are the same, but the advanced LED luminaire reduces flicker so fewer than 5% notice it and costs 10% more than the base case LED luminaire.
Would you say the *reduction in visual discomfort* from flicker is:

- Much more valuable than the 10% higher purchase price
- Somewhat more valuable than the 10% higher purchase price
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% higher purchase price
- Much less valuable than the 10% higher purchase price
- Of no value at all beyond the basic luminaire

9. Flicker 2: Approximately what percent more or less valuable do you consider the reduction of flicker is relative to this 10% change in purchase price?_______percent.
(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Example: The reduction in flicker is *half (50%) as valuable* as the 10% change in purchase price. OR The reduction in flicker is *twice (200%)* as valuable as the 10% change in purchase price.

10. Flicker 3: Assume the energy costs for the two LEDs are the same, but the advanced LED luminaire eliminates ALL flicker and costs 15% more than the base case LED luminaire. Would you say the *reduction in visual discomfort* from flicker is:

- Much more valuable than the 15% higher purchase price
- Somewhat more valuable than the 15% higher purchase price
- About the same value / about even / no difference in value
- Somewhat less valuable than the 15% higher purchase price
- Much less valuable than the 15% higher purchase price
- Of no value at all beyond the basic luminaire

11. Flicker 4: Assume the energy costs for the two LEDs are the same, but the advanced LED luminaire eliminates ALL flicker and costs 5% more than the base case LED luminaire. Would you say the *reduction in visual discomfort* from flicker is:

- Much more valuable than the 5% higher purchase price
- Somewhat more valuable than the 5% higher purchase price
- About the same value / about even / no difference in value
- Somewhat less valuable than the 5% higher purchase price
- Much less valuable than the 5% higher purchase price
- Of no value at all beyond the basic luminaire

12. COLOR RENDERING- Next 3 questions:
Assume the "Base Case" LED luminaires provide color rendering similar to good quality fluorescents *(colors somewhat dull and unnatural, yellowish tinge to whites, and light has a slight greenish tint - assume 65% of workers find this color rendering acceptable).*

Assume the more advanced luminaires make colors look natural, whites are untinted, but some colors remain a bit dull (*assume 80% of workers find this color rendering acceptable*). Both are more energy efficient than the fluorescents they are replacing.

COLOR 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 15% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering are:

- Much more valuable than the 15% loss of energy efficiency
- Somewhat more valuable than the 15% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 15% loss of energy efficiency
- Much less valuable than the 15% loss of energy efficiency
- Of no value at all beyond the basic luminaire

13. COLOR RENDERING 2:

COLOR 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 5% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering are:

- Much more valuable than the 5% loss of energy efficiency
- Somewhat more valuable than the 5% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 5% loss of energy efficiency
- Much less valuable than the 5% loss of energy efficiency
- Of no value at all beyond the basic luminaire

14. COLOR RENDERING 2:

COLOR 1: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 10% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say these *moderate improvements* in color rendering are:

- Much more valuable than the 10% loss of energy efficiency
- Somewhat more valuable than the 10% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% loss of energy efficiency
- Much less valuable than the 10% loss of energy efficiency
- Of no value at all beyond the basic luminaire

15. COLOR 3: Approximately what percent more or less valuable do you consider the strong color rendition improvements are relative to this 10% change in energy efficiency?___percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The color rendition improvements are half (50%) as valuable as the 20% change in energy efficiency. OR The color rendition improvements are twice (200%) as valuable as the 20% change in energy efficiency.

16. COLOR RENDERING- This question:
Assume instead that the more advanced luminaires make colors look vibrant and pleasing, whites are crisp and clean, and the light is untinted neutral white *(assume 90% find this color rendering acceptable)*. Both base case and the advanced luminaries more energy efficient than the fluorescents they are replacing.

COLOR 2: Assume the up-front cost for the two LEDs are the same, but the advanced LED luminaire is 5% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the *strong improvements* in color rendering are:

- Much more valuable than the 5% loss of energy efficiency
- Somewhat more valuable than the 5% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 5% loss of energy efficiency
- Much less valuable than the 5% loss of energy efficiency
- Of no value at all beyond the basic luminaire

17. ADJUSTABLE LIGHTING COLOR & INTENSITY / DIMMING - Last New Feature. Next 2 questions:
Assume the "Base Case" LED luminaire does not dim and has a static color temperature and spectrum. Assume the more advanced LED luminaire dims smoothly down to 1% and is color-adjustable.

This capability allows varying light profiles during the workday (CCT and intensity, 2500-5000 K), aligning with best practices research. This color flexibility addresses physiological issues related to lighting wave lengths, and can improve alertness, productivity, and other workplace effects.

ADJUSTABLE 1: Assume the up-front costs for the two luminaires are the same, but the advanced LED luminaire is 10% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the ability to adjust lighting color and intensity/dimming is:

- Much more valuable than the 10% loss of energy efficiency

- Somewhat more valuable than the 10% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% loss of energy efficiency
- Much less valuable than the 10% loss of energy efficiency
- Of no value at all beyond the basic luminaire

18. ADJUSTABLE 2: Approximately what percent more or less valuable do you consider the dimmability and control improvements are relative to this 10% change in energy efficiency?__percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Examples:
The dimmability and control improvements are half (50%) as valuable as the 10% change in energy efficiency. OR
The dimmability and control improvements are twice (200%) as valuable as the 10% change in energy efficiency.

19. Assume the advanced luminaire dims smoothly to0% and using multi-channel color control, adjusts color temperature smoothly between *2000K and 6500K*. This capability allows varying blue and red content during morning / mid-day / evenings, aligning with best practices research.
Again, both the Base Case and advanced luminaires are more energy efficient than the fluorescents they are replacing.

ADJUSTABLE 3: Assume the up-front cost for the two LEDs are the same, but the Advanced LED luminaire is 10% less energy efficient (and thus costs more to operate) than the base case LED luminaire. Would you say the ability to *dim lights AND adjust color temperature in abroader range* is:

- Much more valuable than the 10% loss of energy efficiency
- Somewhat more valuable than the 10% loss of energy efficiency
- About the same value / about even / no difference in value
- Somewhat less valuable than the 10% loss of energy efficiency
- Much less valuable than the 10% loss of energy efficiency
- Of no value at all beyond the basic luminaire

Advanced LED Lighting Technologies Lighting Designers Survey

Ranking Options

<MOST IMPORTANT>For Questions in this section, consider the following situation:

- Medium-sized office configuration, mix of windowed and internal space.
- Ownership (<u>owner-occupied</u> if your last name group is <u>A-K</u>, <u>leased</u>, not owner-occupied if your last name group is <u>L-Z</u>)
- Office workers with a mix of computer and paper work.
- Existing situation: Traditional commercial overhead linear 4-foot luminaires, fluorescent-type fixtures.
- You are hired to consider options for new luminaires. Normally you might consider replacement with a typical LED luminaire (the "BaseCase").
- Assume no special functionality on glare, flicker, color, or color rendition in the "Base Case" lighting.

20. <MOST IMPORTANT> Please rank the following scenarios from most (1) to least (6) preferred.

A –Glare Reduction: From noticed by 20% to noticed by 0% of workers (eliminated); Energy Efficiency: 15% les than Base Case LED

B – Flicker Reduction: From noticed by 20% to noticed by 5% of workers; Price Increase: 10% over Base Case LED

C – Color Rendering Improvement: Modest (colors natural but a bit dull, whites untinted): Energy Efficiency: 10% less than Base Case LED

D – Color Rendering Improvement: Strong (colors vibrant and pleasing, crisp / clean whites, light is untinted, neutral white); Energy Efficiency: 20% less than Base Case LED

F – Adjustability/Dimmability: to 1%; Color Temperature: Adjustable (reds, blues) throughout the day , aligning with best research; Energy Efficiency: 10% less

G – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

21. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case? $_per luminaire.

22. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked that is NOT the base case. $__Specify MORE or LESS per luminaire.

23. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option if the energy efficiency was exactly the same as the Base Case?___% more per luminaire.

24. Describe how your rankings above would change if the office space:

Had no outside windows – was fully internal?

Included a significant night shift / was 24 hours?

25. About how much in annual energy savings do you expect from the replacement of a 4 foot linear fluorescent fixture with an LED fixture? $______per year

26. About how much is the cost of new, basic, 4-foot linear LED luminaire? $______per LED luminaire

27. NEARLY LAST QUESTIONS - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (5) preferred.

A –Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED

B – Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED

C – Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

D – Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day (2000-6500 K) and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

E – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

28. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

29. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

30. VERY LAST RANKING QUESTION - VERY IMPORTANT: The following represent longer run technologies. Please rank the following scenarios from most (1) to least (6) preferred.

G - All four features - Glare, Flicker, Color, Adjustability -
<u>Glare</u>: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND <u>Flicker</u>: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND <u>Color Rendering</u>: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND
<u>Adjustability/Dimming</u>: Wide range of flexibility allowing color changes during portions of day (2000-6500 K) and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

H – Purchase of typical LED luminaire to replace existing 4-foot linear fluorescent overhead office lighting.

L - Glare & Flicker & Color R
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED

I - Glare & Flicker & Adjustability
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day (2000-6500 K) and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

J - Glare & Color R & Adjustability
Glare: Delivers NO glare, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day (2000-6500 K and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

K - Flicker & Color R & Adjustability
Flicker: Delivers NO flicker, no difference in price or energy efficiency from Base Case LED AND Color Rendering: Excellent color rendering (vibrant, pleasing), 10% IMPROVEMENT in energy efficiency from base case LED AND Adjustability/Dimming: Wide range of flexibility allowing color changes during portions of day (2000-6500 K) and dims to 0, 10% IMPROVEMENT in energy efficiency compared to base case LED.

31. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case LED $_____per luminaire.

32. What is the maximum dollar amount extra you think it would be worth paying for your SECOND BEST ranked option relative to the Base Case LED $__per luminaire.

33. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the cost of the Base Case luminaire? Use the last ranked that is NOT the base case. $_____Specify MORE or LESS per luminaire.

34. If the email you responded to said it was a second time we reached out, please let us know (it does not affect your gift card or chances in the drawing; however, recall only one completed response per person receives a gift card.)

◯ The email mentioned 'Second chance, we reached out before...' ◯ The email did not mention second email

35. THANK YOU for your time and expertise. Your answers are very important to our research. If you have questions, contact Dr. Lisa Skumatz (skumatz@serainc.com or 303/494-1178).

IF you did not supply your email above, and now want to receive a gift card, please enter your email below. THANK YOU again for your help.

End - Advanced LED Lighting Technologies-Lighting Designers Survey

E.6: Street & Road Lighting / Public Works Survey

Advanced LED Lighting Technologies Street Lighting / Public Works Survey

Background

We are conducting work with the US Department of Energy's Pacific Northwest National Laboratory (PNNL) to understand the market attractiveness of different features of advanced LED lighting that are being developed. Your responses, as a person knowledgeable about street lighting, are extremely important to us.

As a thank you for your carefully-considered response (received by *FRIDAY 6/7/19*), we are providing *$75* gift certificates to Amazon.com for your completed survey (one per respondent). In addition, your name will be entered into a drawing for a $200 gift certificate.

NOTE we are most interested in responses from public works staff or others with some knowledge about STREET LIGHTING. Please answer to the best of your ability.
Thank you,

If you have any questions, please feel free to contact Lisa Skumatz at SERA at 303/494-1178 or by email at skumatz@serainc.com

1. Please provide the following background information:

Name

Email (needed for gift certificate)

Phone

Role or Title

What is the population of your jurisdiction?

2.What is your involvement in decisions about street lighting?

○ Significant involvement ○ Somewhat involved ○ Not at all involved

Design Options and Values

Consider the following situation:

- The "base case" streetlighting replacement fixtures for streets / roadways would be optimized for first cost minimization. There is a range of fixed color temperatures available, from warm to cool.
- Assume you need to replace the lights.
- Also assume that baseline energy use by these replacement fixtures is generally improving. By 2020-2025, assume the efficacy is 10%-25% better than current average (about 120-138 lm/W average).
- Also, assume the prices of the fixtures are falling over the period, from about $324 per unit average in 2020 to about$ 252 per unit average in 2025.

3. STREETLIGHT COLOR NEAR-TERM - Next 3 questions:

Assume an advanced LED fixture is available that delivers a warm-colored light, designed to reduce impacts on the night sky and wildlife, and contains no blue wavelength/light. The LER is 50% higher than baseline.

Option 1: Assume the up-front COST for the two LEDs are the same, and the ENERGY USE is also the same as baseline. Would you say the reduction in night sky and wildlife impact is:

- ○ Much more valuable than the baseline fixture
- ○ Somewhat more valuable than the baseline fixture
- ○ About the same value / about even / no difference in value compared to the baseline fixture
- ○ Somewhat less valuable than the baseline fixture - the baseline fixture and color/performance is preferred
- ○ Much less valuable than the baseline fixture - the baseline fixture and color/performance is preferred

4. Option 1 Detail: Approximately what percent more or less valuable do you consider the color and night sky / wildlife effects are relative to a standard fixture?___percent.
(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Example: The performance improvements associated with the advanced fixture makes it *twice (200%)* as valuable as the baseline fixture.

5. What is the maximum dollar amount extra (or less) you think it would be worth paying for the advanced fixture if the energy efficiency was exactly the same as the Base Case? Be sure to state MORE or LESS.
$______per fixture.

6. STREETLIGHT COLOR - LONGER TERM:
Assume the advanced fixture has additional features. Assume research on interactions between light, wildlife, and dark skies produces an advanced fixture that minimizes impact on dark skies and wildlife, AND allows improved human visibility.

The light achieves 80% higher LER than baseline, and only the precise amount of light needed is produces at the precise time it is needed.

Also assume baseline lighting efficacy improves to 40%-50% better than baseline (153-165 lm/W average), and baseline prices keep decreasing (to about $205 per unit average).

Option 2: Assume the up-front COST for the two LEDs are the same, and the ENERGY USE is also the same as baseline. Would you say the reduction in night sky and wildlife impact and improved human visibility is:

- Much more valuable than the baseline fixture
- Somewhat more valuable than the baseline fixture
- About the same value / about even / no difference in value compared to the baseline fixture
- Somewhat less valuable than the baseline fixture - the baseline fixture and color/performance is preferred
- Much less valuable than the baseline fixture - the baseline fixture and color/performance is preferred

7. Option 2 Detail: Approximately what percent more or less valuable do you consider the color and night sky / wildlife and human visibility effects are relative to a baseline fixture? _percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Example: The performance improvements associated with the advanced fixture makes it *twice (200%)* as valuable as the baseline fixture.

8. What is the maximum dollar amount extra (or less) you think it would be worth paying for the advanced fixture if the energy efficiency was exactly the same as the Base Case? Be sure to state MORE or LESS.
$______ per fixture.

9. STREETLIGHT COLOR - LONGER TERM:

Option 3 - LAST OPTION: Assume the up-front COST for the two LEDs are the same, but the ENERGY USE is 10% LESS than the baseline. Would you say the reduction in night sky and wildlife impact, improved human visibility, and energy savings is:

- Much more valuable than the baseline fixture
- Somewhat more valuable than the baseline fixture
- About the same value / about even / no difference in value compared to the baseline fixture
- Somewhat less valuable than the baseline fixture - the baseline fixture and color/performance is preferred
- Much less valuable than the baseline fixture - the baseline fixture and color/performance is preferred

10. Option 3 Detail: Approximately what percent more or less valuable do you consider the color and night sky / wildlife and human visibility effects - and energy savings - are relative to a baseline fixture?
_______percent.

(e.g. use word terms or percentage terms. For same value put 100%; for "twice" as valuable, put 200% of value, for "half" as valuable, put 50%, or other value)

Example: The performance improvements associated with the advanced fixture makes it *twice (200%)* as valuable as the baseline fixture.

11. If the prices weren't the same, what is the maximum dollar amount extra (or less) you think it would be worth paying for the advanced fixture with 10% LESS energy cost as the Base Case? Be sure to state MORE or LESS. $_per fixture.

Advanced LED Lighting Technologies Street Lighting / Public Works Survey

Ranking Options

Consider the same situation as above.

12. Please rank the following scenarios from most (1) to least (4) preferred.

A –Option 1: Warmer light, reducing impact on night sky and wildlife, with no blue light. Price and energy performance same as baseline LED

B – Option 2: Minimizes impact on dark skies and wildlife, and improves human visibility. Price and energy performance same as baseline LED

C – Option 3: Minimizes impact on dark skies and wildlife, and improves human visibility. Energy use is 10% less than baseline LED

D – Purchase of baseline LED fixture to replace current street / roadway streetlight fixtures

13. What is the maximum dollar amount extra you think it would be worth paying for your 1st (BEST) ranked option compared to the base case? State in terms of $_____per luminaire.

14. What is the maximum dollar amount extra (or less) you think it would be worth paying for your LAST ranked option compared to the price of the Base Case luminaire? Use the last ranked option that is NOT the base case. $______specify MORE or LESS per luminaire.

15. What is the maximum percentage amount extra you think it would be worth paying for your 1st (BEST) ranked option relative to the Base Case?__% more per luminaire.

16. What conditions (urban / rural or other factors) might change your rankings?

17. About how much in annual energy savings do you expect from an existing streetlight with an LED fixture?
$______per year

18. What kind of lighting do you currently have in place in your streetlights?

19. If the email you responded to said it was a second time we reached out, please let us know (it does not affect your gift card or chances in the drawing; however, recall only one completed response per person receives a gift card.)

○ The email mentioned 'Second chance, we reached out before...' ○ The email did not mention second email

20. THANK YOU for your time and expertise. Your answers are very important to our research. If you have questions, contact Dr. Lisa Skumatz (skumatz@serainc.com or 303/494-1178).
IF you did not supply your email above, and now want to receive a gift card, please enter your email below. THANK YOU again for your help.

End - Advanced LED Lighting Technologies-Street Lighting / Public Works Survey

Appendix C – Rationale for Subtracting SERA Estimates of Price Effects from Advanced LED Product Prices to Capture Value of Advanced LED Features

In order to subtract the Skumatz Economic Research Associates (SERA)-estimated values from the prices assumed for the advanced Light-Emitting Diode (LED) products as a means of modeling the effect of their increased value to buyers, we need to assume that the demand curves for the advanced LED products (before adjusting for the SERA-estimated values) are linear, along with the following simplifying assumptions:

- The demand curves for the advanced LED products after adjusting for the SERA-estimated values are linear.
- The two above demand curves are parallel.
- The supply curve is perfectly or near perfectly elastic (horizontal).
- The values estimated by SERA are translatable into price effects.

First, we verified that the demand curves for the advanced LED products were indeed linear. (See Figure 4.3 to Figure 4.5 in Section 4.3.) Second, we assumed that the new demand curve reflecting the SERA-estimated values is also linear because we have no information or indication they are otherwise. Third, we assumed the new demand curves are parallel to the unadjusted demand curves because we have no information or indication they are otherwise. Fourth, we assumed the supply curve is highly elastic as is typical for the electronics industry (Neuman 2013). And last, given that SERA used a number of methods to estimate the value of the advanced LED features, but primarily relied on price related questions, we assumed the value they uncovered was translatable into price adjustments. The figure below illustrates these considerations and assumptions.

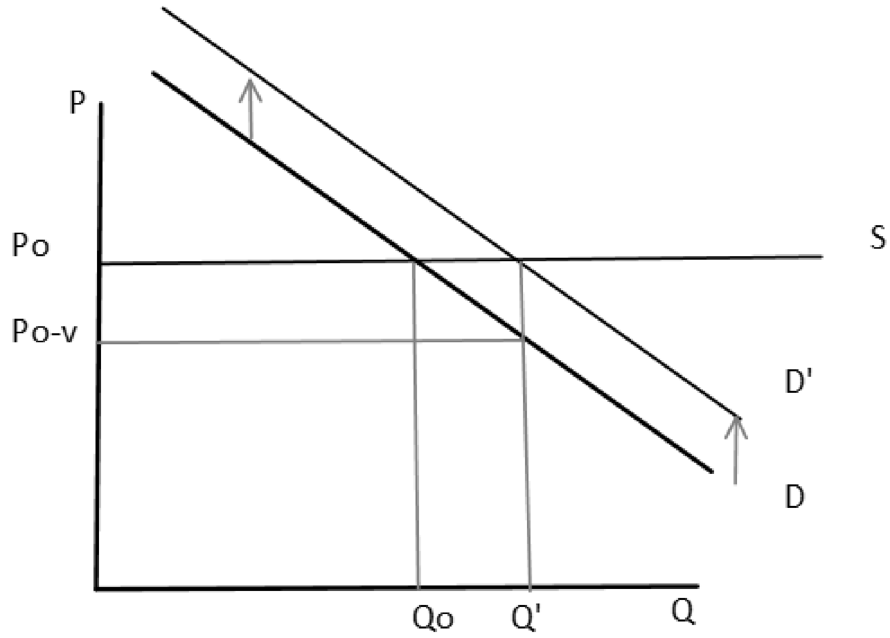

Figure C.1. Modeling an Unknown Demand Curve (D’) with a Price Reduction on a Known Demand Curve

In Figure C.1, demand curve D’ (for advanced LED products after adjusting for the extra values estimated by SERA) is unknown, but is assumed to be linear and parallel to the demand curve for advanced LED products derived from the Navigant lighting market model (D). If it lies a distance above the known demand curve equal to the value estimated by SERA, then the SERA estimates (v) can be subtracted from the advanced LED prices used in D to model the results one would achieve if D’ were known. In this case, the increase in demand from Qo to Q’ is the same if unadjusted prices (Po) were used with D’, as if adjusted prices (Po-v) were used with D.

Appendix D – Navigant Report to PNNL: Study of the Value of Research on the Human Physiological and Environmental Effects of Lighting

NAVIGANT

Study of the Value of Research on the Human Physiological and Environmental Effects of Lighting

Prepared for:

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September 19, 2019

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DISCLAIMER

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LIST OF ACRONYMS AND ABBREVIATIONS

LED	light emitting diode
BTO	Building Technologies Office
CFL	compact fluorescent
DOE	Department of Energy
HPS	high-pressure sodium
klm	kilolumen
LER	luminous efficacy of radiation
NEB	non-energy benefit
NEI	non-energy impacts
O&M	operation and maintenance
PNNL	Pacific Northwest National Laboratory
SERA	Skumatz Economic Research Associates
SSL	solid state lighting
TBtu	tera British thermal units

EXECUTIVE SUMMARY

PNNL is performing research that will investigate the impacts that various lighting technology features have on human physiology, such as its impact on the human circadian system, perceptions of lighting quality, and various environmental effects of lighting. The lighting research will focus on color rendition, glare, temporal light modulation (flicker), intensity/spectrum adjustments, and night visibility. SERA estimated the value of advanced features (technologies) likely to result from PNNL research using methodologies developed to help quantify “non-energy benefits (NEB)” of energy efficiency programs for electric utilities. Then, Navigant used these results as inputs to DOE’s lighting market model to quantify future energy savings that might arise from these advanced LED lighting features and PNNL’s future research.

The lighting market model uses a conditional logit model to award available market to multiple competing lighting technologies. For this study, advanced LED lamps and luminaires were added to the lighting market model as new technologies that can compete for market share. PNNL provided values for the required inputs to the lighting market model including price, efficacy, introduction year, labor costs, operating hours, lifetime, and lumen output. In addition to these inputs, the estimated values of advanced LED technologies (provided by SERA) were used to adjust the first cost of the advanced LED technologies. The reduced first cost is used to simulate the increased favorability of the technology in the model based on the additional advanced features that are provided. The lighting market model also uses a Bass diffusion model to simulate a lag effect for newer technologies being adopted in the market, which requires technology diffusion coefficients. Because the advanced LED products investigated in this study are not commercially available today, the technology diffusion coefficients cannot be easily estimated, and the default coefficient values were used.

For simplification purposes and to reduce the number of model runs, advanced LED technologies were only modeled for three large submarkets, focusing on the most common type of lighting products sold in those submarkets. The energy savings from these three submarkets were then scaled to all other submarkets using the ratio of energy use between each submarket and the larger sectors (residential, commercial/industrial, and outdoor). Results showed that adoption of advanced LED technologies is expected to increase substantially from 2026 to 2035 in all submarkets. By 2035, advanced LED technologies are projected to comprise a substantial portion of each modeled submarket: 17% in residential general service, 20% in commercial linear 4ft, and 32% in outdoor street/roadway. The increased penetration of these technologies is projected to lead to substantial energy savings. Results showed the greatest cumulative energy savings in the residential sector, then outdoor, and finally the commercial/industrial sector. Over the entire modeled period (2023-2035), cumulative source energy savings are projected to be 1,987 TBtu, or approximately 4% of all lighting energy use, relative to Current SSL Path scenario (i.e., no advanced LED technologies).

1. BACKGROUND

Pacific Northwest National Laboratory (PNNL) provides lead technical support to the U.S. Department of Energy's (DOE) Solid-State Lighting (SSL) Program within the Building Technologies Office (BTO). PNNL is performing research that will investigate the impacts that lighting of various intensities, spectra, duration, waveform, and timing have on human physiology, such as its impact on the human circadian system, perceptions of lighting quality, and various environmental effects of lighting. Navigant is assisting PNNL in providing research to help PNNL better understand and quantify energy savings that might arise from these lighting technologies.

The human physiology effects research performed by PNNL focuses on lighting-related human visual phenomena including color rendition, glare, temporal light modulation (flicker), intensity/spectrum adjustments, and night visibility. This topic also includes collaborative research on lighting-related human non-visual phenomena related to circadian and other behavioral and cognitive effects. The environmental effects-related research performed by PNNL focuses on the effects of light on non-human organisms in domains where lighting energy efficiency and energy use will be affected, such as wildlife and the outdoor night environment.

First, PNNL subcontracted with Skumatz Economic Research Associates (SERA) to develop data necessary to complete this work. SERA estimated the value of advanced luminaires and lamps expected to result from PNNL research (denominated in current dollars per luminaire or lamp), using methodologies developed to help quantify "non-energy benefits (NEB)" of energy efficiency programs for electric utilities, alternately known as the "non-energy impacts (NEI)." The per-luminaire/lamp values estimated by SERA served as inputs to DOE's lighting market model. The model, which is held and maintained by Navigant, produces estimates of future potential energy savings, relative to a baseline level (Current SSL Path) of future energy use by lighting. That is, the estimates of value produced by SERA were used by Navigant to estimate future lighting energy savings that are expected to result from the research conducted by PNNL.

1.1 Econometric Logit Model

The lighting market model uses a conditional logit model to award available market to multiple competing lighting technologies, similar to the model used in the National Residential Sector Demand Module of the National Energy Modeling System 2018[1] for the lighting technology choice component.

The conditional logit model is a widely recognized method of forecasting a product's market penetration based on several quantitative or categorical explanatory variables. The result of the conditional logit is a probability of purchase, which represents an aggregation of a large number of individual consumer purchasing decisions. The logit model is predicated on the assumption that these individual decisions are governed by consumer utility (i.e., the relative value) that consumers place on the various technology attributes of an alternative. For example, consumers may be strongly influenced by a product's first cost but may also place some lesser value on a product's efficacy. In the lighting market model, it is assumed that lighting purchasing decisions are primarily governed by two economic parameters, both of which are expressed in dollars per lamp system, for comparison among technologies:

- *First Cost* includes the lamp price, ballast price (if applicable), and, in the case of the new and retrofit market segments, the fixture price. For LED luminaires, first cost indicates the price of the complete luminaire. This also includes a labor charge for installation, where applicable.

[1] U.S. Energy Information Administration. Residential Demand Module of the National Energy Modeling System: Model Documention 2018. s.l. : U.S. Department of Energy, 2018 https://www.eia.gov/outlooks/aeo/nems/documentation/residential/pdf/m067(2018).pdf

- *Annual Operation and Maintenance (O&M)* Cost includes annual energy cost and annual replacement cost. It is a function of the mean lamp or ballast life, annual operating hours, lamp price, ballast price (if applicable), and a labor charge (if applicable).

These parameters, which collectively determine the life-cycle cost of a lighting product, were chosen to help characterize two types of lighting consumers:

- Those who prefer low retail price. These consumers place less importance on annual cost savings, which is derived from the efficacy and lifetime performance of a lighting product.

- Those who make purchasing decisions based primarily on the life-cycle or annual cost of a lighting product. These consumers place less importance on the upfront product cost.

The lighting market model bases market share calculations in each lighting application on one of these two characteristic consumers. To estimate how purchasing decisions are made for each application (i.e., to determine the characteristic relationship between the two cost variables), logistic regressions of historical price and performance data were performed for several lighting applications.

The econometric model used to forecast market share relies entirely on economic metrics and is therefore a simplification of consumer rationale. In reality, consumers consider other factors, such as color quality, dimmability, or aesthetics in their lighting decisions, in addition to economic factors. To account for these qualities, the lighting market model applies acceptance factors to particular technologies (non-advanced LED technologies only) to moderate that technology's value to a consumer. For example, the lighting market model assumes acceptance factors less than one in some cases for compact fluorescent (CFL) and high-pressure sodium (HPS) technologies in indoor applications, which, despite competitive price and performance with other technologies, have low market share largely due to their color quality and dimmability.

1.2 Conditional Logit Model

Logistic regression is a statistical method of predicting the probability of the occurrence of an event by fitting data to a logistic curve, which takes the form:

$$p_j(z) = \frac{e^{z_j}}{\sum_{j=1}^{n} e^{z_j}}$$

Where:

$p_j(z)$ is the probability of an individual choosing product j, and

z is a linear relationship between the independent variables called the logit.

The logit, which represents the natural logarithm of the odds of an event occurrence, is defined as such:

$$z = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

Where:

x_i represent the independent variables, and

β_i represent the regression coefficients.

The conditional logistic regression model is a form of logistic regression that is commonly used in marketing to model consumer choices. It predicts the probability of multiple discrete, categorical (i.e., unable to be ordered in any meaningful way) outcomes, such as occurs in a marketplace with several competitive products. By defining a relationship between a response variable and several independent, explanatory variables, which can be ordinal (ordered) or categorical, the conditional logit model is able to predict the expected market shares of various products.

2. LIGHTING MARKET MODEL INPUTS

For this study, advanced LED technologies were added to the lighting market model as a new technology that can compete for market share. The lighting market model requires a set of inputs for any lighting technology that is available to compete. As such, PNNL provided values for the required inputs to the lighting market model. PNNL defaulted to using baseline product values for labor costs, operating hours, and lifetime, and used expert judgement for estimates of price, efficacy, introduction year, and lumen output.

2.1 Advanced LED Descriptions

PNNL is conducting advanced LED lighting research focused on glare reduction, flicker reduction, non-visual effects (lighting intensity and color temperature adjustment), color rendering, and dark sky and environmental impacts. Table 2-1 below summarizes the advanced features (technologies) likely to result, in PNNL's estimation, from such research. Advanced features are shown for the applicable submarket(s) affected, the baseline condition, and the expected technological advances in the near term (2020-2025) and the long term (2030-2035).

Table 2-1. Summary of Advanced Technologies Likely to Result from LED Lighting Research

Research Features	Submarket	Baseline Description	Advanced Technology Description	
			Near Term (2020 2025)	Long Term (2030 2035)
Glare Reduction	Commercial Linear 4ft	No design emphasis on glare control. Glare creates visual discomfort for at least 20% of observers.	New glare metrics have led to new luminaire designs and new application guidelines that eliminate visual discomfort.	Updated glare metrics combined with new findings on optical materials and optical control eliminate visual discomfort.
Flicker Reduction	Commercial Linear 4ft Residential General Service	Light flickering is noticed by people sensitive to flickering (at least 20%).	New flicker metrics and guidelines have led to new driver, dimming, and control technologies that reduce flicker so that it is noticeable to no more than 5% of the people in typical applications.	Updated flicker metrics and application guidelines combined with new developments in driver, dimming, and control technologies eliminate noticeable flicker.
Non-Visual Effects	Commercial Linear 4ft Residential General Service	Light color and intensity not adjustable.	Lighting is adjustable down to very low levels. Color temperature also adjustable. It addresses the desire to have high color temperatures during the day with higher light levels, and lower color temperatures at night, with lower light levels.	Wide range of adjustment possible for both light levels and various light colors. Addresses the desire to have bluer light during portions of the day, with higher light levels, and redder light at night, with lower light levels.

Color Rendering	Commercial Linear 4ft Residential General Service	Color rendering similar to that provided by good quality fluorescent luminaires. The lighting makes colors look somewhat dull and unnatural and whites may have a slight yellowish/green tint.	The lighting makes colors look natural, but some colors are slightly dull. Whites are untinted.	The light makes colors look vibrant and pleasing. Whites are crisp and clean. The light is an untinted neutral white.
Dark Sky/ Environ-mental Effects	Outdoor Street/ Roadway	Range of fixed color temperatures available, from warm to cool.	A warm colored light, designed to reduce impact on night sky and wildlife, containing no blue light, with a 50% higher luminous efficacy of radiance (LER) than baseline.	Advanced understanding of interactions between light, wildlife, and dark skies lead to better metrics and user guidance, allowing light that minimizes impact on dark skies and wildlife, while allowing improved human visibility; 80% higher LER than baseline.

2.2 Price and Efficacy

PNNL provided estimates of the price and efficacy effects in the near term and the long term that are expected from their research conducted on each lighting feature. These serve as inputs to the lighting market model. These inputs are summarized in Table 2-2. The efficacy values were combined using a multiplicative method according to the following formula:

$$x = [(1+g)*(1+f)*(1+n)*(1+c)] - 1$$

Where:

x is percent efficacy difference of all features combined,

g is the percent efficacy difference from glare reduction,

f is the percent efficacy difference from flicker reduction,

n is the percent efficacy difference from non-visual effects, and

c is the percent efficacy difference from color rendering.

Table 2-2. Advanced LED Price and Efficacy Effects

Results for all features combined are shown in bold.

Technology		Price Difference from Baseline		Efficacy Difference from Baseline	
Submarket	Feature(s)	Near Term (2020 2025)	Long Term (2030 2035)	Near Term (2020 2025)	Long Term (2030 2035)
Commercial Linear 4ft	Glare Reduction	0%	0%	-15%	0%
	Flicker Reduction	+10%	0%	0%	0%
	Non-Visual Effects	0%	0%	-10%	+10%
	Color Rendering	0%	0%	+10%	+20%
	All Features	**+10%**	**0%**	**-16%**	**+32%**
Outdoor Street/ Roadway	**Dark Sky/ Environmental Effects**	**0%**	**0%**	**0%**	**+10%**
Residential General Service	Color Rendering	0%	0%	+10%	+20%
	Flicker Reduction	+10%	0%	0%	0%
	Non-Visual Effects	0%	0%	-10%	+10%
	All Features	**+10%**	**0%**	**-1%**	**+32%**

2.2.1 Estimation of Mid-Term Data 2025-2030

As data were given for only near-term years (2020-2025) and long-term years (2030-2035), calculations were needed to estimate the price and efficacy values in the mid-term years (2026-2029) for all submarkets (commercial linear 4ft, outdoor street/roadway, residential general service). To estimate these values for efficacy and price, a linear regression between the 2025 and the 2030 data points was used as the interpolation method. The results are shown in below. As shown in Table 2-2, there are substantial differences in efficacy between the near-term years and the long-term years for commercial linear 4ft (-16% to +32%) and residential general service (-1% to +32%), while the price differences are relatively minor for commercial linear 4ft (+10% to 0%) and residential general service (+10% to 0%). Because of this, the slope of the linear regression lines for efficacy in the mid-term years is steeper than the linear regression lines for price in the mid-term years.

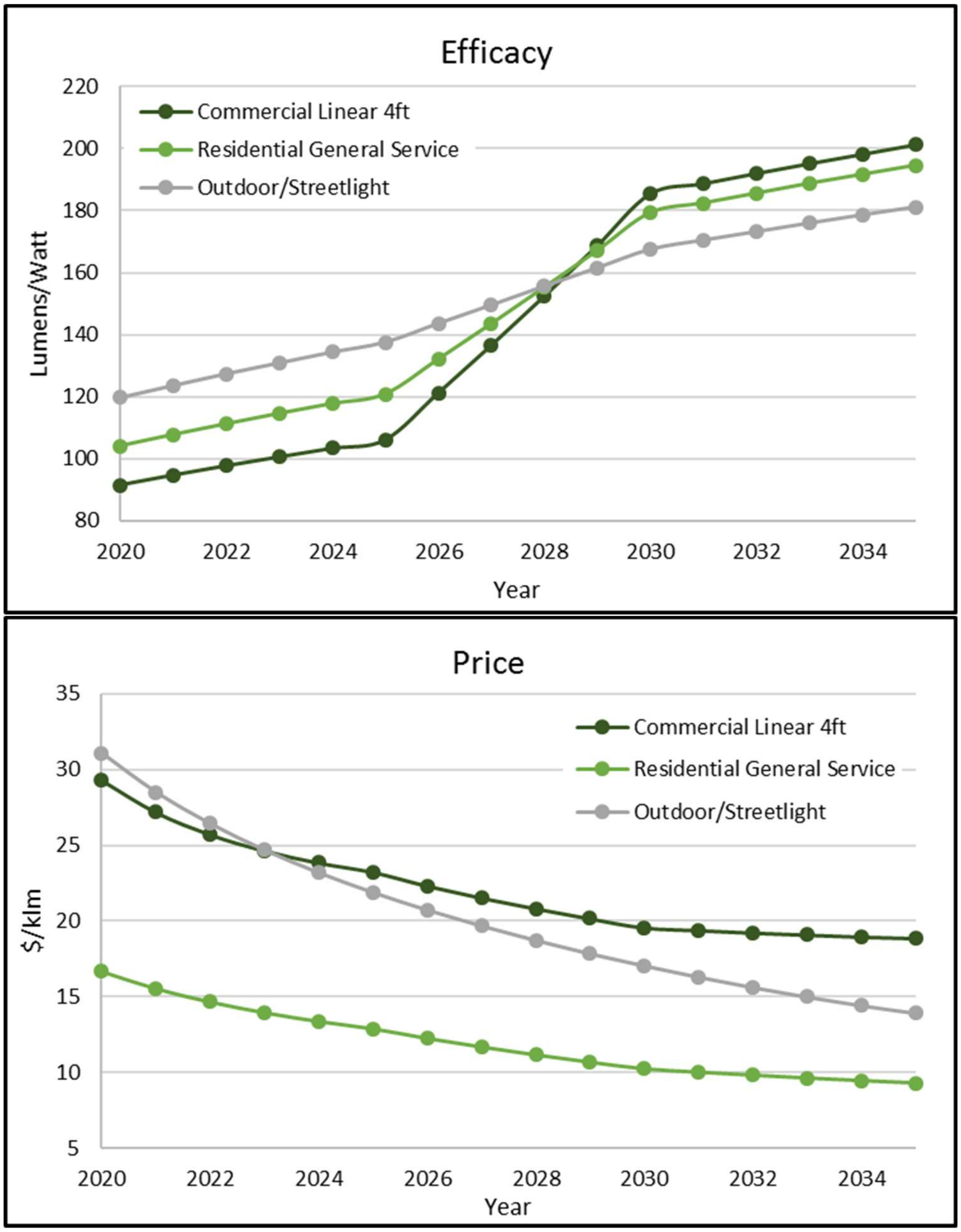

Figure 2-1. Estimation of Mid-Term Price and Efficacy Data

2.3 Other Advanced LED Model Inputs

In addition to the price and efficacy values for advanced LED technologies outlined in the previous section, PNNL provided inputs for introduction year, labor costs, operating hours, lifetime, and lumen output. These inputs are summarized in Table 2-3. The introduction year for the advanced LED technologies is assumed to be 2022. The labor costs, operating hours, and lifetime projections are assumed to be the same as the non-advanced LEDs in the same submarkets. The lumen outputs are the same for residential and commercial advanced technologies, but outdoor street/roadway lumen output is decreased by 26% relative to the baseline LED values due to scheduled maintenance dimming and late-night dimming.

Table 2-3. Other Advanced LED Model Inputs

Submarket	Introduction Year*	Labor Cost ($/unit)**	Operating Hours (hrs./day)**	Lifetime (hrs.)**	Lumen Output (lumens)*
Commercial Linear 4ft	2022	7.73	9.7	53,100	6,000
Outdoor Street/ Roadway	2022	272.75	11.8	55,100	8,505[2]
Residential General Service	2022	0	1.8	21,700	900

* PNNL used expert judgement to develop these estimates.
** PNNL used the same values as were used for the baseline products for these estimates.

2.4 Value of Advanced Technolgy Adjustment

In addition to the inputs required for any technology that competes in the lighting market model, an additional input was needed to account for the value of advanced technology associated with advanced LED technologies, as estimated by SERA. This was done by adjusting the first cost of the advanced LED technologies based on the estimates provided by SERA. The first cost adjustment values provided by SERA are shown in Table 2-4.

Table 2-4. SERA Estimated First Cost Adjustments

Technology		First Cost Adjustment ($/unit)	
Submarket	**Feature(s)**	**Near Term (2020 2025)**	**Long Term (2030 2035)**
Commercial Linear 4ft	Glare Reduction	-$29	-$26
	Flicker Reduction	-$29	-$28
	Non-Visual Effects	-$20	-$22
	Color Rendering	-$26	-$20
	All Features	Not Provided	-$54
Outdoor Street/ Roadway	**Dark Sky/ Environmental Effects**	-$62.98	-$92.02
Residential General Service	Color Rendering	-$2.88	-$4.37
	Flicker Reduction	-$3.18	-$2.96
	Non-Visual Effects	-$3.71	-$3.42
	All Features	Not Provided	-$4.58

[2] Note: this value is for the year 2025 as the lumen output projections vary by year.

2.4.1 Estimation of All Features Combined

The lighting market model only used one advanced LED product (combining all advanced features into individual products) for each submarket to simplify the number of model runs required and to eliminate the possibility of double counting; this required inputs that included all advanced features combined. SERA provided estimates of values for commercial and residential near-term (2020-2025) for each individual feature but not for all features combined. However, SERA provided the estimates of value for the long term (2030-2035) for both each individual feature and all features combined. In order to approximate the adjustment values for the near term, the ratio of the sum of the individual feature values to the value of all features combined was calculated for the long term. Then, this ratio was applied to the sum of the individual feature values in the near term. This calculation is summarized in Table 2-5 below.

Table 2-5. Calculation of All Features Combined

Technology		First Cost Adjustment ($/unit)	
Submarket	**Feature(s)**	**Near Term (2020 2025)**	**Long Term (2030 2035)**
Commercial Linear 4ft	Glare Reduction	-$29	-$26
	Flicker Reduction	-$29	-$28
	Non-Visual Effects	-$20	-$22
	Color Rendering	-$26	-$20
	Features Subtotal	-$104	-$96
	All Features Ratio	0.56 (long term value)	0.56
	All Features	-$58.5 (calculated)	-$54
Residential General Service	Color Rendering	-$2.88	-$4.37
	Non-Visual Effects	-$3.71	-$3.42
	Flicker Reduction	-$3.18	-$2.96
	Features Subtotal	-$9.77	-$10.75
	All Features Ratio	0.43 (long term value)	0.43
	All Features	-$4.16 (calculated)	-$4.58

2.4.2 First Cost Adjustments

The first cost adjustments, outlined in Table 2-4, were applied in the lighting market model as deductions from the first cost of the technology. As an example, the advanced LED costs, adjustment values, and adjusted prices for the three advanced LED submarkets are shown in below. The reduced first cost or capital cost (technology cost plus installation costs) is used to simulate the increased favorability of the technology based on the additional advanced features that are provided.

Table 2-6. 2025 First Cost Adjustments

First costs includes the lamp/luminaire costs and labor costs for installation.

Submarket	2025 Advanced LED First Cost	2025 First Cost Adjustments	2025 First Cost Adjusted Advanced LED Cost
Commercial Linear 4ft	$147.12/luminaire	-$58.5/luminaire	$88.62/luminaire
Outdoor Street/Roadway	$459.01/luminaire	-$62.98/luminaire	$396.03/luminaire
Residential General Service	$11.59/lamp	-$4.16/lamp	$7.43/lamp

3. TECHNOLOGY DIFFUSION AND CALIBRATION

While the conditional logit model provides a probability of purchase for each technology under perfect competition, the lighting market model also recognizes that newer technologies are at a relative disadvantage compared with well-established incumbent technologies. The rate of market penetration is subject to certain market barriers, including, but not limited to, initial acceptance and availability of the technology. Typically, these barriers only apply to newer market entrants, such as LED/advanced LED technologies, as technologies may initially be unknown to consumers or may not be readily available to purchase. However, as a product establishes itself on the market, benefits are communicated by word-of-mouth to the consumer base, manufacturers are able to ramp up production capacity, and stocking distribution channels emerge. To simulate this lag effect on newer technologies, the lighting market model applies a Bass technology diffusion model to the logit model market share predictions. The Bass diffusion model is a widely recognized marketing tool used in technology forecasting that effectively slows the rate of technology adoption based on the time necessary for consumers to become aware of and adopt a new lighting technology.

During the calibration process, technology diffusion coefficients are adjusted to set the technology adoption rate. There are three primary coefficient factors that affect bass diffusion curve:

- Word of mouth factor: represents the fraction of unaware consumers that become aware each year by word-of-mouth from adopters; the word-of-mouth factor is the combination of a contact rate and an awareness rate.

- Marketing factor: represents the fraction of unaware turned to aware per number of unaware per time period

- Initial acceptance factors: generic term that encompasses numerous non-economic barriers to adoption (impacts beginning of bass diffusion curve)

Because the advanced LEDs investigated in this study are not commercially available today, the technology diffusion coefficients cannot be easily estimated. Therefore, the default coefficient values were used, which assume moderate word of mouth, marketing, and initial acceptance factor values. Further, because advanced LED technologies represent improvements on existing LED technologies as opposed to entirely novel technologies, Navigant believes the use of moderate diffusion coefficients is justified.

4. SCALING METHODOLOGY

For simplification purposes and to reduce the number of model runs, advanced LED technologies were only modeled for three large submarkets (residential general service, commercial linear 4ft, and outdoor street/roadway) as representative submarkets in the larger lighting market sectors (residential, commercial/industrial, and outdoor, respectively). The energy savings results from these three submarkets were then scaled to the other submarkets within the sectors using the ratio of energy use for each submarket to the total energy use in the sector. Energy use was found to be the most suitable scaling factor for energy savings relative to other potential options as it represents both the market characteristics (i.e., installations, sales) and technology characteristics (i.e., efficacy, operating hours, etc.). Though this scaling method may not be ideal for every submarket, a single scaling methodology was used for consistency purposes. These scaling factors were calculated for each relevant energy savings year (2023-2035). Energy use is taken from the lighting market model Current SSL Path scenario, which assumes no advanced LEDs. The scaling factors and energy use for 2025 are shown in Table 4-1. The complete energy saving results are outlined in Section 5.

Table 4-1. 2025 Submarket Scaling Factors
Modeled submarkets are shown in bold.

Submarket	2025 Scaling Factor	2025 Source Energy Use (TBtu)
Commercial - All - General Service	1.6%	38.0
Commercial - All - Decorative - Low Lumen	1.9%	45.4
Commercial - All - Decorative - High Lumen	0.2%	4.0
Commercial - All - Downlight - Large - screw	0.9%	21.7
Commercial - All - Downlight - Large - pin	1.9%	46.4
Commercial - All - Downlight - Small	0.1%	2.1
Commercial - All - Track - Large	0.3%	6.8
Commercial - All - Track - Small	0.1%	3.1
Commercial - All - Linear - <4ft	2.4%	57.7
Commercial - All - Linear - 4ft	**48.5%**	**1161.9**
Commercial - All - Linear - >4ft	5.6%	134.1
Commercial - All - Low/Hi Bay	18.2%	436.8
Commercial - All - Other	2.4%	56.5
Industrial - All - General Service	<0.0%	0.1
Industrial - All - Directional	<0.0%	0.2
Industrial - All - Linear - <4ft	0.1%	1.6
Industrial - All - Linear - 4ft	5.9%	140.3
Industrial - All - Linear - >4ft	0.3%	7.8
Industrial - All - Low/Hi Bay	8.5%	203.0
Industrial - All - Other	1.1%	27.0
Residential - All - General Service	**38.0%**	**409.0**
Residential - All - Decorative - Low Lumen	14.9%	159.9
Residential - All - Decorative - High Lumen	5.9%	63.3
Residential - All - Downlight - Large	12.0%	128.7
Residential - All - Downlight - Small	0.2%	2.3
Residential - All - Track - Large	11.3%	121.3
Residential - All - Track - Small	0.3%	2.8
Residential - All - Linear - <4ft	0.1%	0.5
Residential - All - Linear - 4ft	11.0%	118.7
Residential - All - Linear - >4ft	1.0%	11.0
Residential - All - Other	5.4%	58.1
Outdoor - All - Street/Roadway	**26.5%**	**202.2**
Outdoor - All - Parking Lot	27.9%	212.7
Outdoor - All - Garage	20.4%	155.3
Outdoor - All - Building Exterior - Low Output	1.1%	8.3
Outdoor - All - Building Exterior - High Output	23.0%	175.5
Outdoor - All - Other	1.1%	8.0

5. RESULTS

For the three modeled submarkets (residential general service, commercial linear 4ft, and outdoor street/roadway), energy savings attributed to the penetration of advanced LED technologies were estimated relative to a 'Current SSL Path' scenario, which assumes no advanced LED technologies enter the market. The Current SSL Path is defined as the expected future path for LED lamps and luminaires given continuation of current levels of solid-state lighting (SSL) investment and no investment in the advanced LED technologies that are the focus of this study. Figure 5-1, Figure 5-2, and Figure 5-3 below show the penetration of Advanced LED technologies as projected in the lighting market model for each of the three modeled submarkets. Adoption of advanced LED technologies is expected to increase substantially from 2026 to 2035 in all submarkets. In 2035, advanced LED technologies are projected to represent the second most installed lighting technology in the outdoor street/roadway submarket and the third most installed lighting technology in the residential general service and commercial linear 4ft submarkets. This represents 17% of the market in residential general service, 20% in the commercial linear 4ft market, and 32% in the outdoor street/roadway market in 2035.

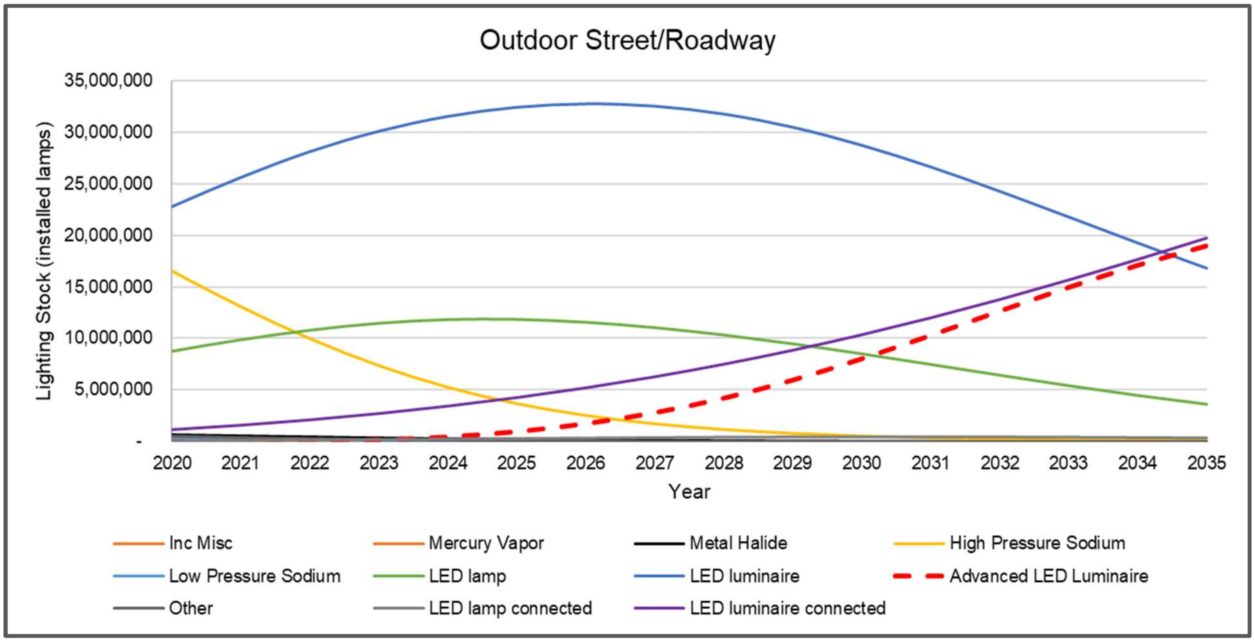

Figure 5-1. Outdoor Street/Roadway Submarket Stock Projections

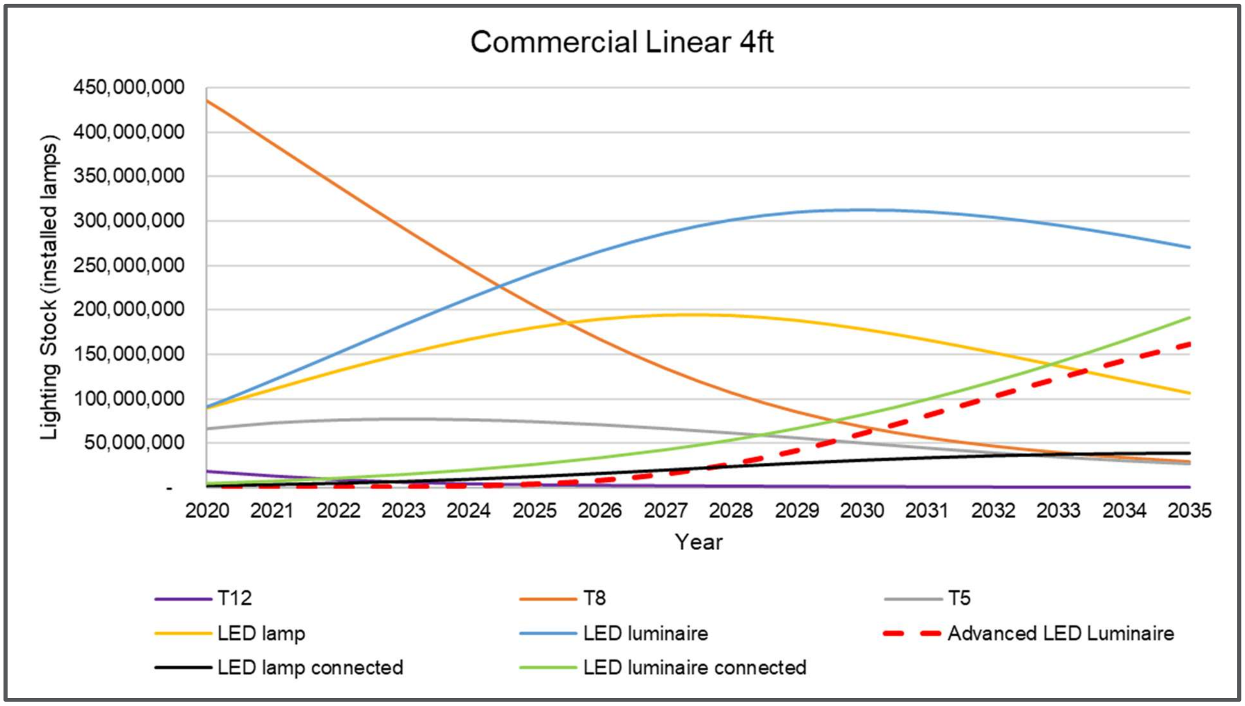

Figure 5-2. Commercial Linear 4ft Stock Projections

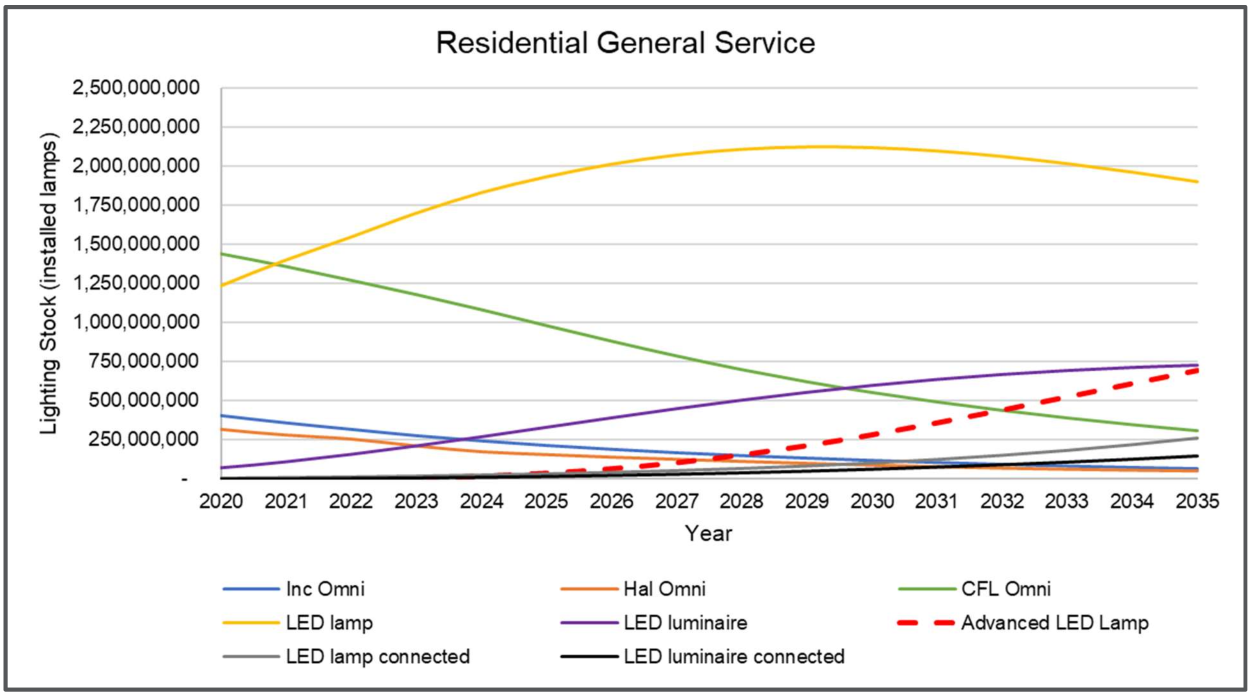

Figure 5-3. Residential General Service Stock Projections

After applying the scaling factors to attribute the advanced LED technology savings in the modeled submarkets to all other submarkets (as discussed in the previous section), the estimated total source[3] energy savings for each sector were calculated relative to the Current SSL Path scenario. The energy savings as a fraction of total sector lighting energy use are presented in Table 5-1, and the absolute energy savings in TBtu are presented in Table 5-2.

Table 5-1. Advanced LED Technology Source Savings (% of Sector Total)

Sector	Advanced LED Technology Source Energy Savings (% of Sector Lighting Energy Use)			
	2025	2030	2035	Cumulative (2023 2035)
Commercial/ Industrial	-0.2%	1.4%	5.7%	1.4%
Residential	5.1%	11.6%	18.1%	9.7%
Outdoor	0.3%	4.2%	11.7%	4.1%
Total	1.2%	4.5%	10.0%	4.0%

Table 5-2. Advanced LED Source Energy Savings in TBtu

Sector	Advanced LED Technology Source Energy Savings (TBtu)			
	2025	2030	2035	Cumulative (2023 2035)
Commercial/ Industrial	-5.9	29.0	102.0	380.4
Residential	54.6	105.7	147.5	1,208.5
Outdoor	2.3	30.5	84.7	398.3
Total	51.0	165.2	334.3	1,987.2

[3] Source energy consumption is calculated by multiplying electricity consumption by using a source-to-site conversion factor of 3.14.

The results showed the greatest cumulative energy savings in the residential sector, then outdoor, and finally the commercial/industrial sector. In the residential sector, advanced LED projected energy savings increase steadily over time (see Figure 5-4). In the commercial/industrial sector, advanced LED projections show a slight decrease in energy savings from 2023-2028, which reflects the lower efficacy levels in advanced LED in the near term relative to baseline LED technologies (see Table 2-2); this is followed by a sharp increase in energy savings for the remaining years (see Figure 5-4). In the outdoor sector, advanced LED projected energy savings are expected to remain low from 2023-2026, followed by a sharper increase in savings from 2028-2035 (see Figure 5-4). This delayed upswing in energy savings owes partly to the delayed but substantial increase in product efficacy expected in the long term.

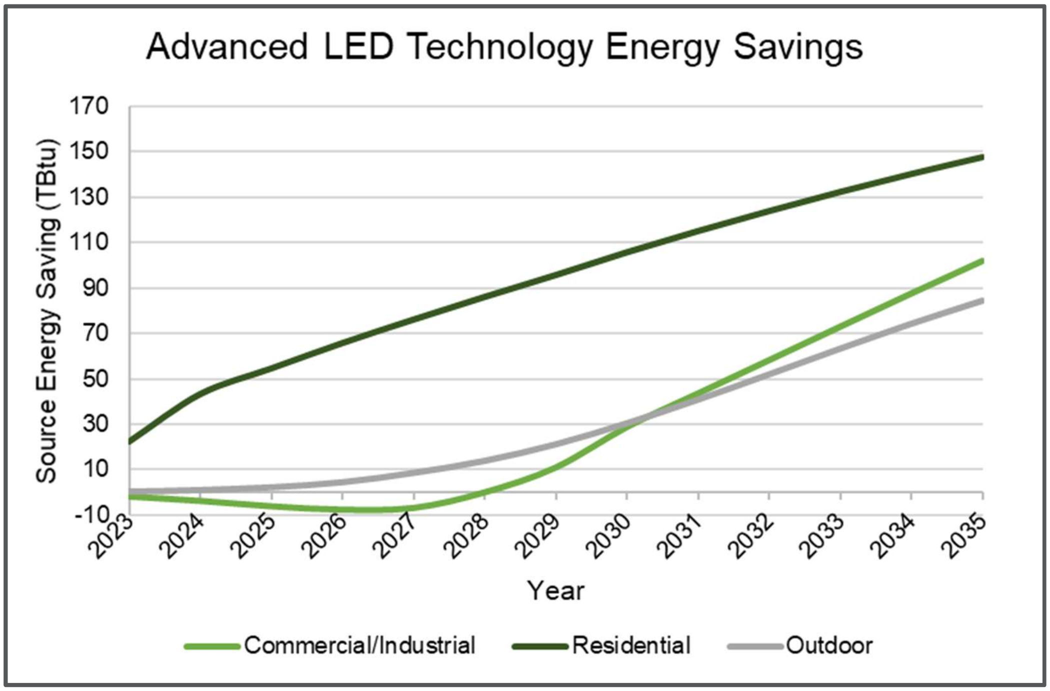

Figure 5-4. Advanced LED Source Energy Savings in TBtu

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