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California Statewide Non-Residential LED Quality and Market Characterization Study

Part 1 – Preliminary Non-Residential LED Quality Criteria

Final Report

Prepared for:

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EXECUTIVE SUMMARY

Navigant Consulting, Inc. (Navigant) was contracted by Pacific Gas and Electric Company (PG&E), on behalf of California's electric investor-owned utilities (IOUs), to conduct market research, including a market share study, in an effort to determine the size of the non-residential LED market and the relative market share of products on the DesignLights Consortium (DLC) Qualified Products List (QPL). This research also included the development of a proposed definition of "quality" for non-residential LED lighting. This Study was designed to include the following research objectives:

1. Within a set of DLC QPL priority product categories agreed upon by the California Investor-Owned Utilities (CA IOUs), how can the market for non-residential LED lighting be characterized?
    a. How will the non-residential LED lighting market evolve over the next 3-5 years?
    b. Which LED products require greater program assistance now and in the future?
    c. How will U.S. Department of Energy (DOE) energy efficiency lighting standards impact California's non-residential lighting baseline and energy efficiency code?
2. What is the market share of the DLC QPL and DLC "premium" for LED priority products?
3. What are the criteria and specification requirements that define non-residential LED products that exhibit top-half of lighting quality?
4. What proportion of the non-residential LED lighting market conforms to the lighting quality definition proposed in this study?

This report describes Part One of the California Statewide Non-Residential LED Quality and Market Characterization Study, and includes discussion of the methodologies, results and recommendations for the Preliminary Non-Residential LED Lighting Quality Criteria (hereafter referred to as the "Criteria"). The final proposed Criteria are dependent on the results of Part Two of the Study.

ES 1. Methodology

Lighting product quality is dependent on multiple factors – including visibility, comfort, function, color, and health. The struggle is in the development and application of numeric metrics to provide an indication of top level lighting quality. Therefore, Navigant used a decision framework model to help guide the definition and criteria development process and ensured key stakeholders were engaged and given opportunity to provide feedback and comment. The framework illustrated in Figure ES - 1 was used to develop criteria for defining the "top-half of lighting quality" for commercially available non-residential LED lighting products. Part One, which is the focus of this report, is shown within the dotted boxed line and culminates in the development of the Preliminary Criteria. Part Two, shown outside of the dotted boxed line is ongoing and the results of the market characterization will be used to modify and finalize the Criteria as needed.

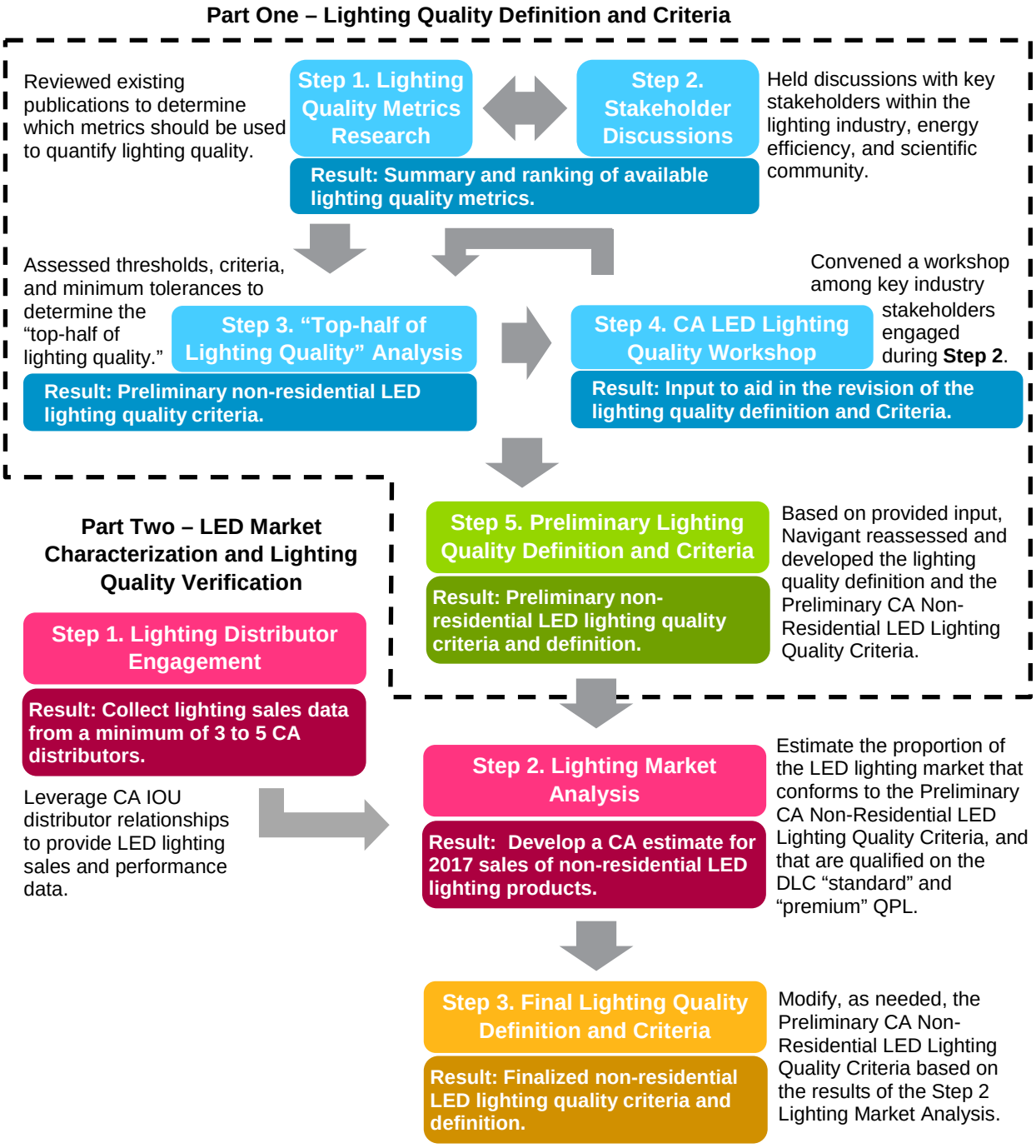


Figure ES - 1 Part One and Two of the Lighting Quality Definition and Criteria Framework Process

ES 2. LED Lighting Quality

While lighting quality is dynamic, and its definition is ever-changing, the goal of Part One of this Study is to develop a procedure to evaluate an LED product's lighting quality relative to those available within California's non-residential lighting market. Therefore, Part One aimed to develop a lighting quality definition based on parameters and metrics that can be controlled at the product level, rather than at the application level or during installation. Based on this premise, and the input from the CA IOUs, California Energy Commission (CEC), and industry stakeholders, Navigant proposes that non-residential LED lighting quality be defined based on its performance in the following parameter categories: Power Quality,

Optical Performance, Reliability & Safety, Efficiency, Spectrum and Controllability. At this time, these six parameters best describe the categories of LED product performance which can be used to evaluate a product's lighting quality. It should be noted, however, that as the non-residential LED market continues to develop, these parameters could change or be enhanced based on R&D progress and the introduction of new product attributes.

Each of these parameters is described in the summary below.

Power Quality – Electricity-consuming products contribute to overall power quality in buildings and power grids. Building owners, utilities, and end users are affected by power quality, as electric power loads, transmission and distribution networks, circuitry in buildings, and visible flicker can be adversely impacted by poor management of power quality in lighting products.

Optical Performance – Lighting products are designed to meet a vast array of applications and task areas. In order to properly deliver light, in terms of light intensity and direction, manufacturers and lighting designers specify optical attributes that enable lighting products to meet customer and end-use application needs.

Reliability & Safety – A basis quality parameter for any lighting product is that it meets performance claims and operates safety for the duration of its use. In particular, LED products have very long anticipated lifetimes relative to much of the electrical equipment installed in non-residential buildings and outdoor spaces. Therefore, ensuring that products are reliable in meeting their rated light levels and spectral parameters for the duration of their rated lifetimes, while operating under safe conditions, is an important quality factor for LED products.

Efficiency – The ratio of the useful work performed by a product to the total energy expended is an important parameter throughout all electric appliance industries for rating quality. High efficiency products reduce electric load-burden and improve building performance. In the lighting industry, one of the most commonly analyzed product attributes is the ratio of light emitted over the power input required to produce it. Higher quality products are designed to optimize this ratio, while not overproducing light and causing unnecessary glare.

Spectrum – Human color perception is a vital aspect of lighting quality, as the spectral emission of the installed lighting products change the appearance of objects in a space. Lighting designers and specifiers use light spectrum parameters to select products for their intended applications. Quantifying and describing the product's light spectrum, in the most comprehensive manner, allows lighting designers and specifiers to appropriately design indoor and outdoor environments in which end users operate and perform tasks.

Controllability – A relatively new lighting parameter, controllability is a product's ability to be controlled during its useful life. Controls better enable a lighting product to provide the right amount and type of light where and when it is needed. The number and capabilities of controllable LED products continue to expand, as these products often lead to reduced consumption (i.e., dimmed light levels results in lower operating wattages), as well as increased human comfort and added services (e.g., health-centric lighting, asset tracking in retail settings, etc.). However, standardizing communication protocols and ensuring these systems offer interoperability between manufacturers, is key to customer and end user acceptance.

Within each of these six quality parameters, Navigant categorized metrics that quantitatively describe the performance of product components or features. Table ES - 1 below illustrates how the available lighting metrics map to the lighting quality parameters identified for the Criteria. Furthermore, Navigant completed

a feasibility exercise to identify the lighting metrics that best relate to and quantify lighting quality, while reducing burden and complexity for the CA IOUs, industry, lighting designers, specifiers, and end users. As such, only metrics that best represented lighting quality, at minimal burden, were considered viable to include in the Criteria. The following five ranking criteria were used in the feasibility exercise:

- **Available Test Methods**: Availability of test procedures to ensure metric is quantifiable and measurable.
- **Industry Acceptance**: Prevalence of metric's use within industry, including associated tolerances/thresholds in industry standards or specifications, and general stakeholder familiarity with the metric.
- **Complexity**: Level of complexity associated with including metric in criteria, such as database management logistics and certification procedures required.
- **Expected Burden**: Burden expected to be placed on various stakeholders (manufacturers, customers, lighting designers, State of California) if metric is included.
- **Lighting Quality Definition**: How well the metric contributes to the identification of the "top-half of lighting quality" in LED products.

Metrics listed in bold font in Table ES - 1 were determined feasible to include in the Criteria.

Table ES - 1 Lighting Quality Parameters and Metric Categorization

Power Quality	– **Total Harmonic Distortion (THD)** – Electrical Power Consumption – **Operating Frequency**	– **Power Factor** – Flicker Index – Percent Flicker	– Flicker (IEC P_{st}) – Stroboscopic Effect (SVM) – NEMA-77-2017
Optical Performance	– **Lumen Output** – **Zonal Lumen Density** – Perceived Luminance	– **Beam Angle Classification** – Upward Light Ratio – BUG Rating	– Visual Comfort Probability (VCP) – Unified Glare Rating (UGR)
Reliability & Safety	– **Lumen Maintenance** – **Color Maintenance** – **Driver ISTMT**	– **Warranty** – **IP Rating** – **Safety Certification**	
Efficiency	– **Luminous Efficacy** – Application Efficacy – Lighting Power Density	– Light Utilization – Power Supply Efficiency	
Spectrum	– **Color Rendering Index (CRI)** – **Correlated Color Temperature (CCT)** – Red Rendering (**R_9**)	– **Color Fidelity (Rf)** – **Color Gamut (Rg)** – Color Consistency	– **Color Angular Uniformity**
Controllability	– **Dimmability** – Networked Lighting Control Features – Communication Protocols (e.g., Bluetooth, Wi-Fi, Zigbee, etc.)	– Luminaire-Level Control Features	

Following the metric feasibility analysis, Navigant identified that the "top-half of lighting quality" can best be measured with a combination of prescriptive, performance, and reporting requirements. The prescriptive requirements raise the base level of quality to a minimum of, and in certain instances exceeding, the DLC or ENERGY STAR requirements, depending on the product category and lighting quality parameter. The performance requirements extend beyond those outlined in the prescriptive requirements and incentivize manufacturers to improve the design of products based on tiered levels of

lighting quality performance. Products that receive a performance score of greater than or equal to 50 meet the performance requirements. Lastly, Navigant recommended enhanced reporting requirements for metrics that are new to industry – yet vital to ensuring greater industry-wide transparency and accessibility to product information and data enabling consumers to make more informed decisions. Products that meet the requirements for each component – prescriptive, performance, and reporting – meet the California Non-Residential LED Lighting Quality Criteria. This blended approach best serves to comprehensively ensure that the Criteria successfully influences the quality of LED lighting products entering the California market.

ES 3. Limitations and Challenges

Navigant identified several challenges that arose when developing the Criteria. These limitations and challenges are focused on the following areas: data availability; lighting quality definition and available metrics and test methods; and product-level vs. application-level metrics.

- **Data Gaps**: Resources such as the DLC's QPL and DOE's LED Lighting Facts database were essential during the "top-half of lighting quality" analysis effort to understand the statistical distribution and variations in product performance for various metrics. However, these datasets have significant data gaps. For well-established metrics, such as L70 lumen maintenance, dimmability, and R9, lack of reported LED product data limits the ability of Part One of this Study to determine the representative distribution of performance. In addition, metrics such as IP Rating, operating frequency, color fidelity (Rf), and color gamut (Rg) are often not reported. Without knowing the distribution of performance for these important lighting quality metrics, the ability of this analysis to determine the "top-half of lighting quality" is limited.
- **Lack of Quantifiable Metrics**: Lighting quality is dependent on multiple factors – including visibility, comfort, function, color, and health. Many of these factors are still debated within the academic and research community, while others have no quantifiable metrics to enable quality assessment. The struggle is in the development and application of numeric metrics to provide an indication of top level lighting quality. For example, metrics for flicker, glare, color consistency, and communication protocols were all identified by industry stakeholders as important to lighting quality; however, none of the available metrics are currently feasible to include based on the lack of industry accepted test methods or precedent through existing specifications. Part One of this Study aimed to define lighting quality for inclusion within the Criteria, though it is important to acknowledge that this Study is limited to the best available metrics.
- **Application-Based Quality**: One of the main challenges associated with defining lighting quality is that it is highly dependent on the end-use application. For example, a high bay LED luminaire that is installed in a warehouse will need to be optimized for drastically different operating conditions and lighting quality parameters compared to one installed in a gymnasium. Because the Criteria is limited to those metrics that can be controlled at the product-level, or point-of-sale, there are several metrics that are important to lighting quality that cannot feasibly be included. Metrics such as application efficacy, lighting power density, light utilization, and perceived luminance are not feasible to include because they must be measured when the LED is "in-installation." While the Criteria does enable the identification of the "top-half of lighting quality" for non-residential LED products on the market, it does not replace codes and standards, such as

California's Title 24, which are still critical for ensuring the right quality product is installed for a given application.

ES 4. Recommendations

Navigant has identified the following recommendations for consideration by the CA IOUs and other stakeholders:

DLC and ENERGY STAR Requirements

Align with DLC Technical Requirements and ENERGY STAR Program Requirements. Stakeholder engagement and research showed that DLC and ENERGY STAR are the most established organizations for developing specification tolerances and thresholds that influence product design and lighting quality. As such, CA IOUs should continue to reference the most current versions of the DLC Technical Requirements (currently V4.3) and the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria (currently V2.1) as first levels of qualification for the Criteria.

Maintain ongoing coordination with DLC and ENERGY STAR. CA IOUs should monitor and examine changes made within each new version of the DLC Technical Requirements and ENERGY STAR Program Requirements. Contact should be maintained between the CA IOUs, DLC, and ENERGY STAR representatives as new versions of each organization's specifications or criteria are being developed to align interests with industry and minimize conflicts with the California Non-Residential LED Lighting Quality Criteria.

Criteria Implementation

Move forward with the blended prescriptive, reporting, and performance approach to the Criteria. The research and analysis showed that the "top-half of lighting quality" is best identified by a combination of prescriptive, reporting, and performance criteria. In particular, the performance criteria, which is implemented through the Lighting Quality Rating described in Section 3.3.3, rewards higher performance using a tiered point structure. In addition, several industry stakeholders were in favor of the performance approach since it incentivizes increased lighting quality performance while allowing for tradeoffs between the metrics included.

The Criteria has been vetted with key industry stakeholders to ensure LED products meeting the Criteria are of higher lighting quality compared to those qualified by the DLC and ENERGY STAR. Additionally, existing data from the DOE's LED Lighting Facts database and DLC's QPL were used to optimize the Lighting Quality Rating approach. The results of this optimization are discussed in Appendix B, which indicate that more stringent lighting quality tolerances and metrics are needed beyond DLC and ENERGY STAR to identify LED products that meet the "top-half of lighting quality."

Utilize the LED Product Quality Evaluation Tool to analyze LED products meeting or not meeting the Criteria. The LED Product Quality Evaluation Tool should be updated annually to evaluate future versions of each database, as well as additional metrics and revised performance tolerances as needed. This update process will help to ensure that LED products available on the market are able to meet any future revised Criteria, and 2) that any future revised Criteria continues to represent the "top-half of lighting quality."

Test and Verification Considerations

Work with the CPUC and CEC to determine the most suitable route forward for ensuring product compliance. Stakeholders suggested that fully developing the structure of a testing and verification system parallel to finalizing the Criteria is vital to ensuring high quality products are adopted by customers as a result of the Criteria's implementation. Therefore, as the process unfolds to present the Criteria to the CPUC, the CA IOUs should work with the CPUC and CEC to determine the most viable route to ensure product compliance.

Consider three potential testing and verification pathways identified as a starting point for the CA IOUs, CPUC, and CEC. These pathways are as follows: 1) allow manufacturers to self-report certification data, 2) CA implement its own testing and verification system, or 3) CA could leverage the DLC reporting infrastructure (with the exclusion of downlight products).

Future Revisions

Utilize the outlined Criteria Future Revisions Plan for updating the Criteria. Several key industry stakeholders emphasized the need for the CA IOUs to remain vigilant as new metrics and test methods become available for defining and quantifying lighting quality for LED products. In addition, stakeholders commented that revisions should be continued for the Criteria, preferably on an annual basis. The LED industry is evolving rapidly, and industry standards and metrics are continually developed to assess the performance of products coming to market.

In order to maintain the relevancy of the Criteria, the CA IOUs should refer to Section 3.5 which described the recommended process for updating the Criteria. This Criteria Future Revisions Plan indicates the CA IOUs should 1) review new and updated metrics, test methods and industry-accepted tolerances, 2) continually engage with key stakeholders, 3) regularly update the LED Product Quality Evaluation Tool with new products, and lastly 4) propose new metrics and tolerances for consideration with the CPUC.

1. INTRODUCTION

Lighting has been a major and important part of California's electric Investor-Owned Utilities ("IOUs") Energy Efficiency portfolio for more than a decade, and the lighting market is changing. There are changes in available technology, with an increasing number and variety of products, manufacturers and sales channels. The evolution of the lighting market, and particularly the emergence of light emitting-diode (LED) technology, has led to greater uncertainty and presents challenges to the CA IOUs' Statewide Program team and their goals to better serve their customers and improve energy savings reporting to the California Public Utilities Commission ("CPUC"). It is important that the CA IOUs only offer incentives for quality lighting products that meet customer expectations and result in a favorable lighting experience.

This research includes a market share study, which is an effort to determine the size of the non-residential LED market in California and the relative market share of products on the DesignLights Consortium (DLC) Qualified Products List (QPL). This research also includes the development of a proposed definition of "quality" for non-residential LED lighting.

1.1 Research Objectives and Scope

This Study includes the following research objectives:

1. Within a set of DLC QPL priority product categories agreed upon by the CA IOUs, how can the market for non-residential LED lighting be characterized?
    a. How will the non-residential LED lighting market evolve over the next 3-5 years?
    b. Which LED products require greater program assistance now and in the future?
    c. How will U.S. Department of Energy (DOE) energy efficiency lighting standards impact California non-residential lighting baseline and energy efficiency code?
2. What is the market share of the DLC QPL and DLC "premium" for LED priority products?
3. What are the criteria and specification requirements that define non-residential LED products that exhibit top-half of lighting quality?
4. What proportion of the non-residential LED lighting market conforms to the lighting quality definition proposed in this study?

From the research objectives, Navigant has divided the Study into two major tasks, the first being the LED lighting quality definition and criteria development, and the second is a market characterization. This report describes Part One of the California Statewide Non-Residential LED Quality and Market Characterization Study, and includes discussion of the methodologies, results and recommendations for the Preliminary California Non-Residential LED Lighting Quality Criteria (hereafter referred to as the "Criteria").[1] The remainder of this report is organized as follows:

- **Section 2: Methodology** presents a discussion of the approach used to address research objectives for the non-residential LED lighting quality definition and criteria development.
- **Section 3: LED Lighting Quality** describes the various metrics and criteria used to define non-residential LED lighting quality.
- **Section 4: Recommendations** provides Navigant's recommendations to the CA IOUs based on the results and outcomes of Part One – Preliminary California Non-Residential LED Lighting Quality Criteria for the Study.

[1] The results of Part One are preliminary, as the results of Part Two of the Study (i.e., the Market Characterization portion) can impact metrics and subsequent thresholds chosen for the Criteria if the California market dictates such changes.

2. METHODOLOGY

This section details the selected approach for each research objective and discusses the LED product categories considered for Part One of the Study – Preliminary California Non-Residential LED Lighting Quality Criteria (hereafter referred to as "Part One").

2.1 Approach Overview

Navigant considered several potential approaches to address the set of key research objectives relevant to Part One. Given the resources available and the nature of the research objectives at hand, Navigant proposed the following high-level approach for this, Part One of, the California Statewide Non-Residential LED Quality and Market Characterization Study:

Part One – Preliminary California Non-Residential LED Lighting Quality Criteria

1. Lighting quality metrics research – Reviewed existing publications to determine which metrics, specifications, and test methods should be used to quantify lighting quality.
2. Stakeholder discussions – Explored lighting quality metrics, specification and test methods through in-depth discussions with key CEC and CA IOU staff, as well as industry stakeholders.
3. Top-half of lighting quality analysis – Utilized the DOE LED Lighting Facts® Database and the DLC QPL to assess thresholds, or minimum tolerances, that can be applied to determine LED products that represent the top-half of lighting quality.
4. CA LED Lighting Quality Workshop – Convened a workshop among the key stakeholders engaged during the in-depth discussions to gather feedback on the preliminary Criteria.
5. Preliminary Lighting quality definition and Criteria – Develop the lighting quality definition and Preliminary California Non-Residential LED Lighting Quality Criteria based on the input received during the stakeholder discussions, CA LED Lighting Quality Workshop, as well as feedback from the CA IOUs and CPUC.

The approaches for each major component of Part One are discussed in greater detail in the following Section 2.2.

2.2 Defining Lighting Quality

Lighting quality is dependent on multiple factors – including visibility, comfort, function, color, and health. The struggle is in the development and application of numeric metrics to provide an indication of top level lighting quality. Therefore, Navigant used a decision framework model to help guide the definition and criteria development process and ensured key CEC, CA IOU, and industry stakeholders were engaged and given opportunity to provide feedback and comment. The framework illustrated in Figure 2-1 was used to develop the Criteria for defining the "top-half of lighting quality" for commercially available non-residential LED lighting products.

Part One, which is the focus of this report, is shown within the dotted boxed line and culminates in the development of the Preliminary Criteria. Part Two, shown outside of the dotted boxed line, is ongoing, and the results of the market characterization will be used to modify and finalize the Criteria as needed.

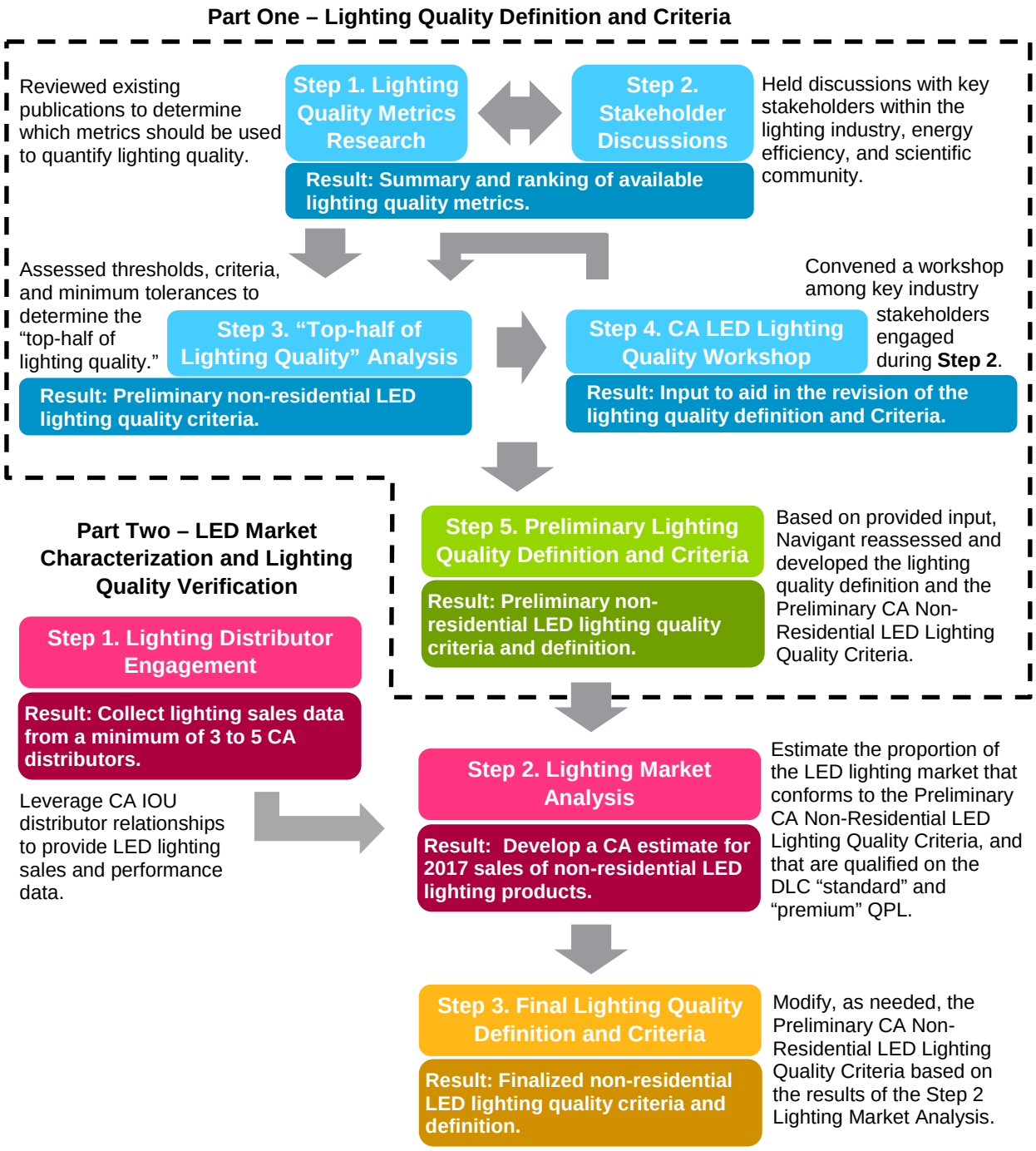


Figure 2-1. Part One and Two of the Lighting Quality Definition and Criteria Framework Process

2.2.1 Lighting Quality Metrics Research

Navigant reviewed publications authored by the CEC, California Lighting Technology Center (CLTC), DLC, Illuminating Engineering Society (IES), National Institute of Standards and Technology (NIST), DOE, ENERGY STAR, and national laboratory and academic documents. These documents provided lighting measurement, testing, calculation, technical, and design guidance that are used as indicators to help quantify lighting product performance and quality. Navigant reviewed the following list of publications, shown in Table 2-1, which aided with the identification of available lighting metrics for defining lighting quality.

Table 2-1. Publications Reviewed for Lighting Quality Research

#	Publication Title	Organization	Lighting Metrics Discussed
1	Voluntary California Quality LED Lamp Specification – 2012	CEC	Correlated color temperature (CCT), color rendering index (CRI), color maintenance, rated life, power factor, dimming, warranty
2	2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings, Title 24, Part 6	CEC	Lighting power density, input power, CRI, CCT, Backlight Uplight Glare (BUG) Rating, efficacy, safety certification
3	DesignLights Consortium Technical Requirements V4.3	DLC	Efficacy, CCT, CRI, lumen maintenance, lumen output, TM-30, warranty, light distribution, power factor, total harmonic distortion (THD), driver in-situ temperature measurement testing (ISTMT), safety certification
4	ENERGY STAR Program Requirements: Product Specification for Luminaires (Light Fixtures)	ENERGY STAR	Efficacy, lumen output, light distribution, CCT, CRI, flicker, lifetime, color angular uniformity, color maintenance
5	TM-30-15 Evaluating Light Source Color Rendition	IES	CRI, color fidelity (Rf), color gamut (Rg), color vector graphic (CVG)
6	QPL Impact Study	Navigant, DLC	Efficacy, CRI, glare
7	ENERGY STAR Lighting Webinar: CPUC LED Lab Test Study Update	Itron, Erik Page & Associates, CPUC	Lumen output, input power, efficacy, CCT, CRI
8	Voluntary California Quality LED Lamp Specification – 2014	CEC	CCT, CRI, color maintenance, rated life, power factor, dimming, warranty
9	Development of the IES method for evaluating the color rendition of light sources	Various	CRI (Ra), Rf, and Rg
10	CA Energy Efficiency Strategic Plan: Stakeholder Meeting, October 2015	CPUC	Efficacy, flicker, glare, light distribution, lumen output, color maintenance
11	Decision Approving 2013-2014 Energy Efficiency Programs and Budgets	CPUC	CRI, lumen output
12	LM-79-08 Electrical and Photometric Measurements of Solid-State Lighting Products	IES	Lumen output, efficacy, CCT, CRI, power factor, chromaticity coordinates
13	LM-84-14 Measuring Luminous Flux and Color Maintenance of LED Lamps, Light Engines, and Luminaires	IES	Lumen output, lumen maintenance, chromaticity coordinates
14	TM-28-14 Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaires	IES	Lumen maintenance projection
15	Human Perceptions of Color Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape	PNNL, DOE SSL Program	CRI, Rf, CVG, light intensity, spectral power distribution, efficacy
16	Nonresidential Lighting and Electrical Power Distribution	CLTC	NA
17	CA Energy Efficiency Strategic Plan: January 2011 Update	CPUC	NA
18	CA Energy Efficiency Strategic Plan: Codes and Standards Action Plan 2012-2015	CPUC; CEC	Efficacy
19	Color Quality Metrics - Recent Progress and Future Perspective	NIST	CRI (Ra), Rf, and Rg
20	DOE 81 FR 76877 Energy Conservation Program: Test Procedures for Integrated LED Lamps	DOE	Provides test procedures for LED lamps - primarily references IES industry standards

21	Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification 3.0 – 2016	CEC	CCT, CRI, color maintenance, rated life, power factor, dimming, warranty
22	National Electric Code (NEC) – 2017	NFPA	NA
23	NEMA 77 – 2017 Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria	NEMA	Flicker
24	ANSI C136.2 – 2015 American National Standard for Roadway and Area Lighting Equipment – Dielectric Withstand and Electrical Transient Immunity Requirements	NEMA	Minimum requirements for dielectric withstand and electrical transient immunity for outdoor luminaires
25	ANSI C137.3 American National Standard for Lighting Systems— Minimum Requirements for installation of Energy Efficient Power over Ethernet (PoE) Lighting Systems	NEMA	Provides minimum installation requirements for PoE systems
26	LM-80-15 Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules	IES	Lumen maintenance, color maintenance
27	TM-21-11 Projecting Long-Term Lumen Maintenance of LED Light Sources	IES	Lumen maintenance
28	Lighting Technology Overview - 2015	CLTC	Efficacy, dimmability, light distribution
29	DOE CALiPER Snapshot: Downlights	DOE	Efficacy, CCT, CRI
30	DOE CALiPER Snapshot: Troffers	DOE	Efficacy, CCT, CRI
31	DOE CALiPER Snapshot: Industrial Luminaires	DOE	Efficacy, CCT, CRI
32	DOE CALiPER Snapshot: Outdoor Area Lighting	DOE	Efficacy, CCT, CRI
33	Solid-State Lighting: Early Lessons Learned on Way to Market	PNNL	Flicker, glare, color maintenance
34	DLC Market Impacts Report	Meister Consultants Group	Lumen output, efficacy, CCT, CRI, light distribution, power quality, safety/warranty
35	ENERGY STAR Lighting Webinar: CPUC LED Lab Test Study Update	Itron, Erik Page & Associates	Lumen output, power quality, efficacy, CCT, CRI
36	Workpaper Disposition for PGECOLTG179 LED Ambient Commercial Fixtures and Retrofit Kits	CPUC	Lumen output, input power, electricity consumption, lighting power density

From this literature review, Navigant developed an extensive list of available lighting metrics for defining lighting quality. See Section 3.2 for the full analysis of these metrics as they pertain to the Criteria.

2.2.2 Stakeholder Discussions

In conjunction with Step 1, Navigant leveraged relationships garnered through work with the DOE, energy efficiency organizations, national laboratories, lighting manufacturers, and the CA IOUs to informally interview key stakeholders with the goal of identifying key metrics, thresholds, test procedures and implementation methods that could be used to define and specify the "top-half of lighting quality." Navigant conducted discussions with 36 staff from the CA IOUs, CLTC, DLC, IES (including the members of the newly formed Energy Efficiency Program Committee), the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute, Pacific Northwest National Laboratory (PNNL), the International Association of Lighting Designers (IALD), as well as several non-residential LED lighting manufacturers (e.g., Acuity, Philips, GE Lighting, etc.). A list of the stakeholder organizations Navigant engaged with is provided below in Table 2-2.

Table 2-2. Stakeholder Organizations Engaged for Lighting Quality Discussions

Organization	Participants	Organization Type	Interview Participant	Workshop Participant
Telelumen	1	Manufacturer	Yes	Yes
Acuity	2	Manufacturer	Yes	Yes
Signify	2	Manufacturer	Yes	Yes
Lumileds	2	Manufacturer	Yes	Yes
GE Lighting	2	Manufacturer	Yes	Yes
Osram	1	Manufacturer	No	Yes
Enlighted	1	Manufacturer	Yes	No
RAB Lighting	1	Manufacturer	No	Yes
DLC	3	Lighting Organization	Yes	Yes
IES	1	Lighting Organization	Yes	Yes
LRC/RPI	1	University	Yes	Yes
CLTC/UC Davis	1	University	Yes	No
PNNL	1	National Laboratory	Yes	No
DOE SSL Program	2	Government	No	Yes
CEC	2	Government	Yes	No
IALD	2	Lighting Designer	No	Yes
PG&E	4	Utility	Yes	No
SCE	3	Utility	Yes	No
SDG&E	4	Utility	Yes	No

Based on the research (Step 1) and stakeholder input (Step 2), Navigant developed a qualitative summary of each lighting quality metric's applicability, industry acceptance, and development stage (e.g., categorized in terms of well-established versus on-going R&D) which was used as an initial metric ranking system (see Section 3.1). In addition, these steps enabled the identification of three potential methods for implementing the Criteria that are currently used within industry to enforce quality. These distinct methods are detailed below in Table 2-3.

Table 2-3. Potential Methods for Implementing Lighting Quality Criteria

Criteria Method	Description
Performance	The performance method incorporates a lighting quality scoring mechanism for LED products based on their performance in various quality metrics. Increased levels of product performance with each metric evaluated would result in more points accrued. This method gives manufacturers the flexibility to design products that emphasize different aspects of quality based on the intended application of the product. With this method, products would receive a maximum possible score of 100 and a minimum possible score of 0 – where products that receive a score of greater than or equal to 50 represents the "top-half of lighting quality." This method is similar to the certification and score process used by the Leadership in Energy and Environmental Design (LEED) rating system.
Prescriptive	The prescriptive criteria method institutes minimum/maximum allowable tolerances for a set number of performance metrics such that only the "top-half of lighting quality" of LED products meet these thresholds. This method is similar to other specifications such as the DLC, ENERGY STAR®, as well as the California Energy Commission's Quality Specification for LED lamps.
Reporting	The reporting method requires manufacturers to report the performance of their products in a centralized database. This method would require reporting of metrics such as R_9, lumen maintenance, power factor, THD, dimming, color fidelity (Rf), and color gamut (Rg) with the goal of greater transparency in product performance.

Ultimately, Navigant, in conjunction with feedback from the CA IOUs, incorporated a blended approach for the Criteria. The blended approach uses components of each method – performance, prescriptive and reporting – to identify non-residential LED lighting products in the California market that represent the "top-half of lighting quality." As discussed in the following Section 2.2.4, Navigant proposed the preliminary Criteria during the California LED Lighting Quality Workshop. Further discussion of the methods implemented for the Criteria can be found in Section 3.

A complete summary of the primary takeaways and comments from the stakeholder interviews, are provided in Appendix A.

2.2.3 "Top-half of Lighting Quality" Analysis

Using the metric rankings and potential methods determined in Steps 1 and 2, Navigant utilized DOE's LED Lighting Facts database and the DLC's QPL to assess thresholds, or minimum tolerances, data fields, and implementation methods that could be applied to determine the "top-half of lighting quality" for non-residential LED products. As an example, using the databases, acceptable ranges for various spectral metrics, such as CCT, CRI, and R_9 were used to determine the tolerances that constitute the "top-half of lighting quality." While for other spectral metrics, such as color fidelity (Rf) and color gamut (Rg), it was determined greater transparency in product performance leads to higher quality, and also aids customers in LED product selection.

For the analysis, both the DLC's QPL and DOE's LED Lighting Facts database were used to maximize quantifiable metric data available, thus helping accommodate for the data gaps within each. To demonstrate the extent of the data gaps, Table 2-4 summarizes the percent of products for which the data field entries were completed for efficacy, CRI, R_9, lumen maintenance, power factor, THD, and dimming for LED recessed troffers products. This is further divided into the percentage of products that provide manufacturer reported values versus test data. While both the DLC's QPL and DOE's LED

Lighting Facts database require tested and manufacturer reported performance be submitted, not all of those data are provided in the publicly available databases.

Table 2-4. % of LED Recessed Troffers with Publicly Completed Data Field by Metric[1]

Lighting Quality Metrics	% of Products with Publicly Completed Data Field by Metric			
	DesignLights Consortium		DOE LED Lighting Facts	
	Manufacturer Reported	Tested	Manufacturer Reported	Tested
Lumen Maintenance (L70)	7%	0%	4%	0%
Efficacy	100%	12%	100%	78%
CRI	99%	12%	100%	80%
Power Factor	98%	12%	36%	0%
R_9[2]	0%	0%	19%	0%
THD	98%	12%	22%	0.1%
Dimming	100%	0%	100%	0%

1. The data in the above table is representative of the DLC QPL and DOE LED Lighting Facts® Database as of November 8, 2017 and October 30, 2017, respectively.
2. The DCL QPL does not collect or report R_9 performance data.

In order to ensure that the California Non-Residential LED Lighting Quality Criteria best represents the "top-half of lighting quality," Navigant developed an optimization algorithm to determine the prescriptive minimum/maximum tolerances, and performance tiers and point values such that products meeting the Criteria roughly represented the top-half of available lighting products. While the Criteria also includes a metric reporting approach (see Section 2.2.2), due to the lack of available data, these were not considered in the analysis.

Using DOE's LED Lighting Facts database and DLC's QPL, Navigant developed an objective function which was calibrated to determine the best-possible solution that meets the initial condition – that 50% of LED products meet the prescriptive and performance Criteria. The decision variables within this optimization were defined as the prescriptive minimum/maximum tolerances, and the performance points for each point tier. For each metric used within the performance portion of the Criteria, the tiers were developed such that the minimum represented the DLC and ENERGY STAR minimum requirements and the highest tier represented roughly the 90th percentile value in the dataset. Each tier was then calibrated using an iterative process to ensure that the performance thresholds and point allocations scored the top-half of these datasets to meet the Criteria.

The results of this analysis were presented in two spreadsheets (one for the Indoor product categories and one for the Outdoor product categories) in the form of a LED Product Quality Evaluation Tool (hereafter referred to as the "Tool"). The Tool aids in determining the appropriate metrics and thresholds that define the "top-half of lighting quality" for LED non-residential products, and it can be updated to evaluate future versions of each database, as well as additional metrics and revised performance tolerances as needed.

This iterative and calibration analysis for optimizing the appropriate prescriptive and performance thresholds was used to develop the preliminary Criteria presented at the California LED Lighting Quality Workshop discussed below in Section 2.2.4 and the preliminary proposed Criteria discussed in Section 2.2.5.

2.2.4 California LED Lighting Quality Workshop

Navigant convened a workshop among key industry stakeholders engaged during the interview process in Step 2. The goal of this effort was to gather input and feedback on the preliminary Criteria, including the identified metrics and parameters, as well as the implementation methods for determining the "top-half of lighting quality," for non-residential LED lighting products.

In order to attract attendance from key industry stakeholders, Navigant identified several potential lighting conference venues which could be leveraged for the California LED Lighting Quality Workshop. To help assess which would be the most valuable location to target, Navigant developed a criteria matrix. Table 2-5 indicates the expected attendance, location, timing, ease of coordination, and meeting credibility criteria that were used to rank the viability and preference for each conference venue.

Table 2-5. Ranking Criteria for Determining the Lighting Conference Venue for Hosting the "California LED Lighting Quality Workshop"

Ranking Criteria	Score 1	Score 2	Score 3	Definition
Expected Attendance	Poor	Okay	Best	The expected attendance for each stakeholder group based on past conference attendance levels or feasibility in attracting attendance.
Location	Poor	Okay	Best	The proximity to San Francisco (either PG&E or Navigant offices).
Timing	Poor	Okay	Best	The feasibility both in terms of having enough time to coordinate the meeting and whether the date may cause delays in the project schedule.
Ease of Coordination	Poor	Okay	Best	The level of effort required for planning and organizing a meeting at the described event.
Meeting Credibility	Poor	Okay	Best	How the meeting credibility is/would be viewed within the lighting industry.

Using the above ranking criteria, Navigant and the CA IOUs determined the February 2018 Strategies in Light conference, which received the top-ranking score, would be the ideal venue to host the California LED Lighting Quality Workshop.

The meeting took place on February 13, 2018 in Long Beach, CA, coinciding with the first day of the Strategies in Light conference. Navigant collected feedback on the lighting metrics best-suited for defining lighting product quality, as well as the preliminary Criteria and implementation methods. In total, 14 industry stakeholders – including manufacturers, SSL experts, DOE, lighting designers and DLC representatives – attended the California LED Lighting Quality Workshop (see Table 2-2) and contributed to a lively discussion, signifying the importance and impact of this Study. The discussions at the California LED Lighting Quality Workshop, as well as the stakeholder interviews described in Section 2.2.2, were leveraged to develop the preliminary proposed Criteria discussed in Section 3.3.

A complete summary of the primary takeaways and comments from the discussions at the California LED Lighting Quality Workshop and stakeholder interviews, is provided in Appendix A.

2.2.5 Lighting Quality Definition and Criteria

Based on the input received during the California LED Lighting Quality Workshop described above in Section 2.2.4, Navigant reassessed and finalized the Criteria and lighting quality definition. In addition, the iterative and calibration analysis for optimizing the appropriate prescriptive and performance thresholds,

described in Section 2.2.3, was used a second time to incorporate the feedback received during the California LED Lighting Quality Workshop to develop the preliminary proposed Criteria discussed in Section 3.3. Navigant worked closely with CA IOU staff who are involved with LED lighting customer experience studies to cross-reference and cross-check Step 5 results and adjusted as needed based on that review.

Navigant identified that the "top-half of lighting quality" can best be measured with a combination of prescriptive, performance, and reporting requirements. The prescriptive requirements raise the base level of quality to a minimum of, and in certain instances exceeding, the DLC or ENERGY STAR requirements, depending on the product category and lighting quality parameter. The performance requirements extend beyond those outlined in the prescriptive requirements and incentivize manufacturers to improve the design of products based on tiered levels of lighting quality performance. Products that receive a performance score of greater than or equal to 50 meet the performance requirements. Lastly, Navigant has recommended enhanced reporting requirements for metrics that are new to industry – yet vital to ensuring greater industry-wide transparency and consumer accessibility to product information and data that enables more informed decision-making – such as the color rendition test methods incorporated by IES TM-30-15.

Products that meet the requirements for each component – prescriptive, performance, and reporting – meet the California Non-Residential LED Lighting Quality Criteria. This blended approach best serves to comprehensively ensure that the Criteria successfully influences the quality of LED lighting products entering the California market. Discussion of each of these requirements in the Criteria can be found in Section 3.3, and a detailed analysis of the LED products that qualify for the Criteria can be found in Appendix B.

2.3 Limitations and Challenges

Navigant has identified several challenges that arose when developing the preliminary proposed Criteria. These limitations and challenges are focused on the following areas: data availability; lighting quality definition and available metrics and test methods; and product-level vs. application-level metrics.

2.3.1 Data Availability

Resources such as the DLC's QPL and DOE's LED Lighting Facts database were essential during the "top-half of lighting quality" analysis effort to understand the statistical distribution and variations in product performance for various metrics. However, these datasets have significant data gaps, as discussed in Section 2.2.3 and Appendix B. For well-established metrics, such as L70 lumen maintenance, dimmability, and R_9, lack of reported LED product data limits the ability of Part One of this Study to determine the representative distribution of performance. In addition, metrics such as IP Rating, operating frequency, Rf, and Rg are not reported at all in some cases. Without knowing the distribution of performance for these important lighting quality metrics, the ability of this analysis to determine the "top-half of lighting quality" is limited.

2.3.2 Lighting Quality Definition, and Available Metrics and Test Methods

As stated in Section 2.2, lighting quality is dependent on multiple factors – including visibility, comfort, function, color, and health. Many of these factors are still debated within the academic and research community, while others have no quantifiable metrics to enable quality assessment. The struggle is in the development and application of numeric metrics to provide an indication of top level lighting quality. For example, metrics that are available for measuring flicker, glare, and color consistency, as well as

reporting for communication protocols were all identified by industry stakeholders as important to lighting quality; however, none of these are currently feasible to include based on the lack of industry-accepted test methods or precedent through existing specifications. Part One of this Study aimed to define lighting quality for inclusion within the Criteria, though it is important to acknowledge that this Study is limited to the best *available* metrics.

2.3.3 Product-Level vs. Application-Level

One of the main challenges associated with defining lighting quality is that it is highly dependent on the end-use application. For example, a high bay LED luminaire that is installed in a warehouse will need to be optimized for drastically different operating conditions and lighting quality parameters compared to one installed in a gymnasium. Because the Criteria is limited to those metrics that can be controlled at the product-level, or point-of-sale, there are several metrics that are important to lighting quality that cannot feasibly be included. Metrics such as application efficacy, lighting power density, light utilization, and perceived luminance are not feasible to include because they must be measured when the LED is "in-installation." While the Criteria does enable the identification of the "top-half of lighting quality" for non-residential LED products on the market, it does not replace codes and standards, such as California's Title 24, or the expertise that can be offered by a certified lighting designer which are both critical for ensuring the right quality product is installed for a given application.

3. LED LIGHTING QUALITY

This section discusses the preliminary proposed Criteria, including the metrics considered for inclusion in the Criteria, the detailed technical requirements of the Criteria, the proposed plan for updating the Criteria in future revisions, and a basic framework for implementing the Criteria through testing and verification.

As previously indicated, this report documents the findings of Part One for the California Statewide Non-Residential LED Quality and Market Characterization Study. Part Two is ongoing and the results of this second phase of the study will be used to modify and finalize the proposed Criteria as needed.

3.1 Lighting Quality Definition

While lighting quality is dynamic, and its definition is ever-changing, the goal of Part One of this Study is to develop a procedure to evaluate an LED product's lighting quality relative to those available within California's non-residential lighting market. Therefore, Part One aimed to develop a lighting quality definition based on parameters and metrics that can be controlled at the product-level, rather than at the application-level or during installation. Based on this premise, and the input from the CA IOUs, CEC, and industry stakeholders, Navigant proposes that non-residential LED lighting quality be defined based on its performance in the following parameter categories: Power Quality, Optical Performance, Reliability & Safety, Efficiency, Spectrum and Controllability. At this time, these six parameters best describe the categories of LED product performance which can be used to evaluate a product's lighting quality. It should be noted, however, that as the non-residential LED market continues to develop, these parameters could change or be enhanced based on R&D progress and the introduction of new product attributes.

Each of these parameters is described in the summary below and in detail in Sections 3.2.1 to 3.2.6.

Power Quality – Electricity-consuming products contribute to overall power quality in buildings and power grids. Building owners, utilities, and end users are affected by power quality, as electric power loads, transmission and distribution networks, circuitry in buildings, and visible flicker can be adversely impacted by poor management of power quality in lighting products.

Optical Performance – Lighting products are designed to meet a vast array of applications and task areas. In order to properly deliver light, in terms of light intensity and direction, manufacturers and lighting designers specify optical attributes that enable lighting products to meet customer and end-use application needs.

Reliability & Safety – A basis quality parameter for any lighting product is that it meets performance claims and operates safety for the duration of its use. In particular, LED products have very long anticipated lifetimes relative to much of the electrical equipment installed in non-residential buildings and outdoor spaces. Therefore, ensuring that products are reliable in meeting their rated light levels and spectral parameters for the duration of their rated lifetimes, while operating under safe conditions, is an important quality factor for LED products.

Efficiency – The ratio of the useful work performed by a product to the total energy expended is an important parameter throughout all electric appliance industries for rating quality. High efficiency products reduce electric load-burden and improve building performance. In the lighting industry, one of the most commonly analyzed product attributes is the ratio of light emitted over the power input required to produce it. Higher quality products are designed to optimize this ratio, while not overproducing light and causing unnecessary glare.

Spectrum – Human color perception is a vital aspect of lighting quality, as the spectral emission of the installed lighting products change the appearance of objects in a space. Lighting designers and specifiers use light spectrum parameters to select products for their intended applications. Quantifying and describing the product's light spectrum, in the most comprehensive manner, allows lighting designers and specifiers to appropriately design indoor and outdoor environments in which end users operate and perform tasks.

Controllability – A relatively new lighting parameter, controllability is a product's ability to be controlled during its useful life. Controls better enable a lighting product to provide the right amount and type of light where and when it is needed. The number and capabilities of controllable LED products continues to expand, as these products often lead to reduced consumption (i.e., dimmed light levels results in lower operating wattages), as well as increased human comfort and added services (e.g., health-centric lighting, asset tracking in retail settings, etc.). However, standardizing communication protocols and ensuring these systems offer interoperability between manufacturers is key to customer and end user acceptance.

3.2 Lighting Metrics Summary

Throughout the stakeholder engagement process (including both the interviews and California LED Lighting Quality Workshop), Navigant received feedback that lighting quality is best identified by various metrics that quantitatively describe the performance of product components or features.[2] Therefore, Navigant categorized these metrics into the six lighting quality parameters used by the Criteria to describe and quantify the lighting quality of non-residential LED products. Table **3**-**1** below illustrates how each of the evaluated lighting metrics maps to the lighting quality parameters identified for the Criteria.

[2] Section 2.2.1 discusses the primary research conducted to identify available metrics for use in the Criteria.

Table 3-1. Lighting Quality Parameters and Metric Categorization

Power Quality	− **Total Harmonic Distortion (THD)**	− **Power Factor**	− Flicker (IEC P_{st})
	− Electrical Power Consumption	− Flicker Index	− Stroboscopic Effect (SVM)
	− **Operating Frequency**	− Percent Flicker	− NEMA-77-2017
Optical Performance	− **Lumen Output**	− **Beam Angle Classification**	− Visual Comfort Probability (VCP)
	− **Zonal Lumen Density**	− Upward Light Ratio	− Unified Glare Rating (UGR)
	− Perceived Luminance	− BUG Rating	
Reliability & Safety	− **Lumen Maintenance**	− **Warranty**	
	− **Color Maintenance**	− **IP Rating**	
	− **Driver ISTMT**	− **Safety Certification**	
Efficiency	− **Luminous Efficacy**	− Light Utilization	
	− Application Efficacy	− Power Supply Efficiency	
	− Lighting Power Density		
Spectrum	− **Color Rendering Index (CRI)**	− **Color Fidelity (Rf)**	− **Color Angular Uniformity**
	− **Correlated Color Temperature (CCT)**	− **Color Gamut (Rg)**	
	− Red Rendering (**R_9**)	− Color Consistency	
Controllability	− **Dimmability**	− Luminaire-Level Control Features	
	− Networked Lighting Control Features		
	− Communication Protocols (e.g., Bluetooth, Wi-Fi, Zigbee, etc.)		

In addition, to establish a neutral framework for analyzing the feasibility of each metric, Navigant also developed the metric ranking system displayed in Table 3-2. The dimensions used to rank each metric include: available test methods, industry acceptance, complexity, expected burden, and lighting quality definition. Based on research findings and stakeholder feedback, Navigant completed feasibility rankings for each metric, which are described in the following sections. The goal of this feasibility exercise was to identify the lighting metrics that best relate to and quantify lighting quality, while reducing burden and complexity for the CA IOUs, industry, lighting designers, specifiers, and end users. As such, only metrics that received a score of 13 or higher (15 is the maximum) were considered viable to include in the Criteria.

Table 3-2. Lighting Metric Ranking Criteria and Definitions

Ranking Criteria	Definition	1	2	3
Available Test Methods	Availability of test procedures to ensure metric is quantifiable and measurable.	**No**	**In Development**	**Yes**
Industry Acceptance	Prevalence of metric's use within industry, including associated tolerances/thresholds in industry standards or specifications and general stakeholder familiarity with the metric.	**Low**	**Medium**	**High**
Complexity	Level of complexity associated with including metric in criteria, such as database management logistics and certification procedures required.	**High**	**Medium**	**Low**
Expected Burden	Burden expected to be placed on various stakeholders (manufacturers, customers, lighting designers, State of California) if metric is included.	**High**	**Medium**	**Low**
Lighting Quality Definition	How well the metric contributes to the identification of the "top-half of lighting quality" in LED products.	**Poor**	**Okay**	**Well**

The following Sections 3.2.1 to 3.2.6 describe each of the metrics considered within the six lighting quality parameters, as well as the results of the feasibility ranking.

3.2.1 Power Quality

Power quality is a significant parameter within the Criteria that affects multiple stakeholder groups - primarily utilities, building owners, customers, and general human health. The metrics considered within this quality parameter are power factor, total harmonic distortion (THD), electrical power consumption, operating frequency, percent flicker, flicker index, short term flicker (as defined by the IEC P_{st} metric), and the stroboscopic visibility measure (SVM), with each metric affecting stakeholders to varying degrees. A brief explanation of these metrics and their relative importance to lighting quality is provided below.

Power factor is the ratio between active (or "real," or "consumed") power (measured in watts) and apparent power (measured in volt-amps), while **THD** is a measure of waveform distortion created from the equipment's current draw. Power factor and THD have impacts on electric networks and loads, directly affecting the interests of utilities and building owners. Degradation in power factor and THD can lead to disturbances in distribution networks and subsequent electrical service interruptions, increased transmission and distribution losses, higher electricity costs, and in rare cases safety-related issues. Power factor and THD are quantifiable and currently incorporated by organizations in industry specifications, such as ENERGY STAR and DLC. As such, Navigant has identified these as key metrics for evaluating power quality and recommends their inclusion in the Criteria.

Navigant also received some recommendations from stakeholders to set limits on **electrical power consumption**. Although this is effective for other equipment types, Navigant believes that it could potentially stifle innovation and product offerings within the LED industry. Instead Navigant recommended that efficacy and lumen output requirements be considered, since controlling for these metrics ensures that high efficiency and appropriate light levels are achieved, without limiting the functionality and lighting applications.

The final set of metrics considered within the power quality parameter entail preventing visible flicker, including the use of operating frequency, flicker index, percent flicker, short term flicker, SVM, and NEMA-77-2017.

Photometric flicker has been a concern within the lighting industry for decades (for several lighting technologies) due to the potential human impacts, which can range in severity from a distraction or mild annoyance to neurological problems (i.e., seizures). Although the overwhelming consensus in the industry is that preventing flicker is vital to lighting quality, standardized flicker measurement procedures that account for the affects to human populations have just been recently introduced to industry with NEMA 77-2017.[3]

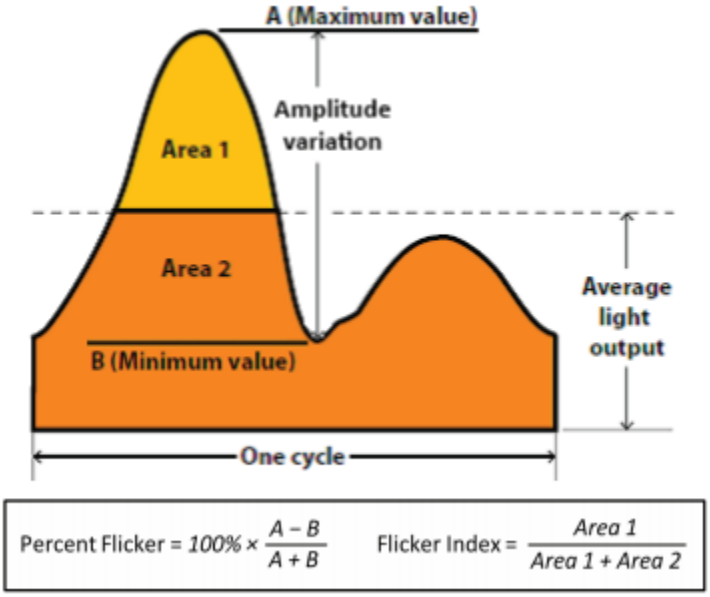
Flicker index is a measure of the cyclic variation in output of a light source, taking into account the waveform of the light output. It is the ratio of the area under the light output curve that is above the average light output level to the total area under the light output curve for a single cycle.[4] **Percent flicker** is a relative measure of the cyclic variation in output of a light source (percent modulation). It is given by

[3] National Electrical Manufacturers Association, "NEMA 77-2017, Temporal Light Artifacts: Test Methods and Guidance for Acceptance Criteria," April 2017. https://www.nema.org/Standards/Pages/Temporal-Light-Artifacts-Test-Methods-and-Guidance-for-Acceptance-Criteria.aspx

[4] Illuminating Engineering Society, "Definitions and Nomenclature: flicker index." https://www.ies.org/definitions/flicker-index/

the expression *(A-B)/(A+B)*, where *A* is the maximum and *B* is the minimum output during a single cycle, and is expressed as a percentage.[5] As an example, Figure 3-1 shows a curve of the light output variation from a fluorescent lamp during each cycle, with the method of calculating the flicker index and percent flicker. One of the main concerns regarding flicker index and percent flicker are that they do not enable the identification of problematic flicker for specific applications or populations. Therefore, these metrics are viewed as incomplete and not ideal metrics for measuring the impacts of flicker on lighting quality. Based on this assessment, Navigant has not recommended these metrics be used in the Criteria.

Figure 3-1. Flicker Index and Percent Flicker Calculation[6]



Another metric that can be used to quantify flicker is **operating frequency**. Operating frequency is used by the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1 to minimize flicker impacts. Navigant has recommended the CA IOUs to use this industry-accepted metric as an initial step to prevent flicker in downlight products by limiting the output frequency to greater than or equal to 120 Hz. This performance characteristic applies to steady-state and dimmed operation (at all light output levels).

Additionally, in the recent publication of the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1 (March 2018), ENERGY STAR referenced NEMA 77-2017 to address problems with visible flicker. In particular, ENERGY STAR will now require the reporting of the **short-term flicker** indicator and **SVM** (effective September 1, 2018) and provides the option of meeting the temporal light modulation limits for those metrics as specified in **NEMA 77-2017** (which suggests tolerances for indoor and outdoor applications). Navigant recognizes this as a significant step forward for addressing flicker and improving the power quality of lighting products, but due to the early stages of industry adoption of NEMA 77-2017, it is recommended for the CA IOUs to omit these metrics from the initial version of the Criteria. However, California should monitor the outcomes and industry feedback on the ENERGY STAR flicker requirements to consider short-term flicker indicator and SVM as metrics to include in future revisions of the Criteria.

[5] Illuminating Engineering Society, "Definitions and Nomenclature: percent flicker." https://www.ies.org/definitions/percent-flicker/

[6] U.S. Department of Energy, "Solid-State Lighting Technology Fact Sheet: Flicker," March 2013. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/flicker_fact-sheet.pdf

The final power quality rankings and metrics decisions are detailed in Table 3-3.

Table 3-3. Power Quality Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
Total Harmonic Distortion (THD)	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Power Factor	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Operating Frequency[1]	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Percent Flicker	2	2	2	2	3	10	No
Flicker Index	2	2	2	2	3	10	No
Flicker (IEC P_{st})	3	2	2	2	3	12	No
Stroboscopic Effect (SVM)	3	2	2	2	3	12	No
NEMA-77-2017	3	2	2	2	3	12	No
Electrical Power Consumption	3	2	3	2	1	12	No

[1]Only applicable to LED downlight fixture products.

3.2.2 Optical Performance

Although LED products continue to offer additional features, the primary reason for their production and installation in non-residential settings remains to produce light and deliver the necessary light levels to a specific area. Metrics to quantify the optical performance of light output have been developed to ensure products can be designed of high quality, while meeting consumer needs. Navigant identified the following optical performance metrics as they relate to lighting quality: lumen output, zonal lumen density, beam angle classification, upward light ratio, backlight, uplight, and glare (BUG) rating, visual comfort probability (VCP), unified glare rating (UGR), and perceived luminance.

Simply put, **lumen output** is the measure of the total amount of visible light (to the human eye) from a light source. Lumen output is one of the most basic metrics used to describe the performance of a lighting product, and is used during the design process, by lighting designers and specifiers to predict the final illuminance in a space. Lumen output is a long-standing metric that has been leveraged by various product specifications to ensure that light products are providing adequate lighting service. As such, Navigant recommends that lumen output be included in the Criteria.

In addition to lumen output, which represents the total light output, light distribution is important information regarding the way light is distributed from the fixture and how that light falls upon a surface. Light distribution can be displayed visually in a distribution plot or summarized quantitatively by its **zonal lumen density**. Zonal lumen density represents the quantity of light emitted in annular zones (measured in candlepower) at various defined vertical angles and can be used as an indirect method for limiting the

impacts of glare.[7] Similar to lumen output, zonal lumen density is a commonly used metric within the lighting industry to predict the lighting quality of a product, therefore, due to the readily available industry test procedure and importance to product quality, Navigant recommends the use of this metric in the Criteria.

Beam angle classification can be a key factor used to evaluate light quality of directional lighting products. This metric is used to help categorize ranges for typical light distributions based on how wide or narrow the light is projected outward. For directional lighting products, such as flood and spot light luminaires, this metric is essential for describing the usefulness of a product for a given application. Beam angle classifications have been designated by the National Electrical Manufactures Association (NEMA) and are largely recognized through the lighting industry in various test procedures and specifications. Navigant recommends that beam angle classifications be included in the Criteria for relevant product types (e.g., LED architectural and landscape/accent flood and spot luminaires).

In addition to defining the intensity and distribution of a light source, it is crucial to understand how these characteristics impact the end user. **Glare** is a term that is often used to describe the instinctive desire to look away from a bright light source or difficulty in seeing a task, and it represents an important consideration for lighting quality. However, work to develop metrics for quantifying glare is ongoing. Currently, the **upward light ratio** (ULR) and **BUG rating** can be used for outdoor LED products to not only control glare, but also address light trespass and unwanted light for non-residential outdoor lighting. Of these available metrics for outdoor, the BUG rating is most commonly referenced for reducing the impacts of glare; however, product specifications have yet to adopt this metric and it is not widely utilized through the lighting industry. Navigant also considered **VCP** which is a metric that is expressed as the percentage of people who, when viewing from a specified location and in a specified direction, will be expected to find it acceptable in terms of discomfort glare. The challenge with adopting criteria for **VCP** is that it is determined at the installation. In addition, this metric relies on human perception, which is challenging to control for at the point-of-sale, or product level. The **UGR** is another glare metric considered for the Criteria and is represented by an equation which considers a number of factors, such as the angle of the luminaire, the likelihood of glare and the luminance value. However, similar to VCP, in order to calculate the UGR for a lighting system, information about the application and installation parameters are necessary. Lastly, Navigant considered **perceived luminance** which can be used to identify glare for both indoor and outdoor non-residential areas. While luminance represents the intensity of a light source directed toward the observer's eye, the *perceived* luminance also relates to apparent brightness of objects and surfaces within an area. For example, a car's headlights will not appear as bright during the day as they will at night, even though their luminance remains the same.[8] The challenge with adopting criteria for perceived luminance is that it is determined at the installation. In addition, this metric relies on human perception, which is challenging to control for at the point-of-sale, or product level. While perceived luminance, and glare overall, is an important issue for improving visual comfort, existing test methods and quantitative metrics still need to be refined. Therefore, Navigant recommends that ULR, BUG rating, and perceived luminance not be included in the Criteria, and that the CA IOUs monitor the progress of glare metrics, specifications, and test procedures within the lighting industry.

The final optical performance rankings and metrics decisions are detailed in Table 3-4.

[7] U.S. DOE Solid-State Lighting Program, "Understanding LM-79 Reports." https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/understanding_lm79_reports.pdf

[8] U.S. DOE Solid-State Lighting Program, "Street Lighting and Blue Light – Frequently Asked Questions." https://www.energy.gov/sites/prod/files/2017/02/f34/Street%20Lighting%20and%20Blue%20Light%20FAQs_1.pdf

Table 3-4. Optical Performance Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
Lumen Output	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Zonal Lumen Density	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Beam Angle Classification[1]	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Upward Light Ratio[2]	2	2	1	1	2	8	No
BUG Rating[2]	3	3	1	2	2	11	No
VCP	1	1	1	1	3	7	No
UGR	1	1	1	1	3	7	No
Perceived Luminance	1	1	1	1	3	7	No

[1]Only applicable to LED architectural and landscape/accent flood and spot luminaires products.
[2]Only applicable to LED pole/arm mounted, wall mounted, and canopy luminaires products.

3.2.3 Reliability and Safety

LED products offer a significant advantage over legacy lighting technologies by being inherently more durable and having long lifetimes. However, to ensure that products are reliable and operate at expected performances, various reliability and safety traits can be tested and specified, encompassed by the following metrics: lumen maintenance, driver in-situ temperature measurement testing (ISTMT), ingress protection rating, safety certification, and color maintenance.

Lumen maintenance, driver ISTMT, safety certification, and color maintenance are existing metrics used by DLC and/or ENERGY STAR. Due to long product lifetimes, **lumen maintenance** serves as a metric to ensure LED products maintain a minimum percentage of the initial lumen output, and it is often used to quantify the rated lifetime of an LED product. When doing so, manufacturers will rate product lifetimes with L70 or L90 values, which are the lifetimes at which the LED product will be producing 70 or 90 percent, respectively, of its initial rated lumen output. Additionally, shortened lumen maintenance test durations combined with projection methods as described by IES LM-84-14/TM-28-14 or LM-80-08/TM-21-11 can be used by manufacturers rather than testing to the point of reaching L70/L90 or failure. IES LM-84-14/TM-28-14 describes test methods for full product testing, while LM-80-08/TM-21-11 details test methods for the LED light source, or package component. Manufacturers are given the option of testing using either method, with the latter option (LM-80-08/TM-21-11) being the predominant method used within the industry. While lumen maintenance is incomplete for describing the lifetime of an LED product, it is currently the best available metric. As such, due to the availability of industry test procedures and importance to product quality, Navigant recommends the use of lumen maintenance in the Criteria.

In conjunction with the lumen maintenance testing, ENERGY STAR also requires products to test for **color maintenance** at the same measurement intervals (which reduces test burden). Color maintenance requirements are important for lighting quality to prevent color shift in LED packages throughout product life cycles. Currently, no IES test methods exist for projecting color maintenance beyond the test duration

interval which has limited the adoption of this metric. However, discussion with industry stakeholders indicates that work to develop an accelerated color maintenance test procedure is underway. Because no precedent exists for requiring color maintenance for non-residential LED products, outside of those products regulated by ENERGY STAR, Navigant recommends to only require color maintenance limits for downlight products.

Stakeholder feedback suggested that replicating testing environments that products normally operate in is also critical to ensuring high quality lighting product design. **Driver ISTMT** is the measurement of the LED case temperature while it is operating at the designed temperature or environment as suggested by the manufacturer, instead of ideal testing conditions that could render inflated test results. Since driver ISTMT measures product performance in use-case conditions, it represents a good indication of expected reliability and has been recommended for inclusion in the Criteria. In addition, existing product specifications already include reporting requirements for driver ISTMT, and therefore inclusion of this metric represents minimal burden to the CA IOUs and industry stakeholders.

For outdoor products, rating products for how well they are insulated from outside elements (e.g., dirt, water, and foreign objects) is critical for quality lighting product design. One way to ensure this is testing for **ingress protection** (IP), which rates the product's resistance to water, dust, and foreign objects. Lack of IP testing can lead to a greater risk of equipment failure. As such, due to the readily available industry test procedure and importance tied to outdoor product quality, Navigant recommends the use of the IP rating for outdoor products in the Criteria. While IP rating is not currently a requirement of existing product specifications, many manufacturers do report the IP rating of their LED products within specification sheets. As such, the inclusion of this metric in the Criteria represents minimal burden to the CA IOUs stakeholders, while providing significant value for identifying products of good lighting quality.

Although stakeholders commented that product warranties do not typically guarantee better lighting quality, **warranty requirements** are incorporated by existing product specifications, and do provide customers with quality assurance, expected reliability, and protection towards their investment. At a minimum, warranties serve as a first line of defense against lower quality products, as manufacturers would be required to cover the repair or replacement of defective lamp/retrofit/luminaire or component parts. As such, Navigant has recommended that warranty requirements be included in the Criteria.

Safety certification requirements, specified by organizations such as Underwriters Laboratories (UL) and Occupational Safety & Health Administration (OSHA), are frequently referenced to ensure lighting products operate safety for their intended use. Due to their effectiveness, the importance of human health effects and safety to lighting quality, and their prolific use within existing product specifications, Navigant also recommended the CA IOUs implement this requirement in the Criteria.

The final reliability and safety quality rankings and metrics decisions are detailed in Table 3-5.

Table 3-5. Reliability and Safety Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
Lumen Maintenance	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Driver ISTMT	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Warranty	**3**	**3**	**3**	**3**	**2**	**14**	**Yes**

IP Rating[1]	**3**	**3**	**2**	**2**	**3**	**13**	**Yes**
Safety Certification	**3**	**3**	**3**	**3**	**3**	**15**	**Yes**
Color Maintenance[2]	**3**	**3**	**3**	**2**	**3**	**14**	**Yes**

[1]Only applicable to LED outdoor products.
[2]Only applicable to LED downlight fixtures.

3.2.4 Efficiency

Stakeholders frequently commented during interviews and the California LED Lighting Quality Workshop that luminous efficacy is currently a very important metric for defining lighting quality – however, this may change in the future.

Although **luminous efficacy** is commonly used within the industry (incorporated by product specifications such as DLC and ENERGY STAR), and easily calculated from tested input power and lumen output, Navigant considered additional efficiency metrics that describe other aspects of efficiency for the Criteria. LED luminous efficacy is an incomplete metric for describing the efficiency of light delivery, and currently new approaches are being explored through ongoing research and development within the DOE, national laboratories, and universities. Therefore, Navigant researched the potential for additional efficiency metrics to be included within the Criteria.

Navigant identified these additional efficiency metrics – light utilization, application efficacy, and light power density – as integral to lighting quality. **Light utilization** represents the fraction of light emitted by a light source that reaches the intended work area or end-use appliance space, which varies by application. **Application efficacy**, is a similar metric to light utilization, and is typically defined as the luminous flux applied to a specific area (or within a specific angle) per unit of power, and it determines (after product installation) how well the lighting system delivers light to the desired application or task area.[9] However, both light utilization and application efficacy are application-specific, meaning they vary by the application or intended space-type, and cannot feasibly be implemented for the product-level Criteria. In addition, **lighting power density** is another commonly used metric to describe efficiency and is the power load of lighting equipment in a specified area of a building, measured in watts per square foot. While this metric is often used in building codes, lighting power density is not feasible to include as a metric in the Criteria because the intended building or space area cannot be controlled prior to installation (at the product-level). None of these metrics – light utilization, application efficacy, and light power density – are recommended for inclusion in the Criteria.

Lastly, **power supply efficiency** was also analyzed as an applicable efficiency metric for the Criteria. This metric measures the amount of power provided to the driver (and other internal components) as a portion of the actual power supplied by the source (i.e., wall-plug or other building feature that supplies power to the product). While existing test methods for power supply efficiency are available and it can be measured at the product-level, no precedent exists for setting power supply efficiency limits. In addition, metrics such as power factor, THD, and efficacy all account for power supply losses, and it is unclear whether power supply efficiency limits would increase quality beyond these well-established metrics. Therefore, power supply efficiency is not recommended for inclusion in the Criteria.

The final efficiency metrics and ranking decisions are detailed in Table 3-6.

[9] Narendran, Nadarahja, et al, "Application Efficacy for Comparing Energy Demand in Lighting Applications," September 2010. https://pdfs.semanticscholar.org/499f/59381449b705077e6a7e89adfa0a41a72b95.pdf

Table 3-6. Efficiency Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
Luminous Efficacy	**3**	**3**	**3**	**3**	**2**	**14**	**Yes**
Application Efficacy	1	2	1	2	3	9	No
Lighting Power Density	3	2	1	2	2	10	No
Light Utilization	1	2	1	2	3	9	No
Power Supply Efficiency	3	2	2	2	2	11	No

3.2.5 Spectrum

Spectral quality is primarily dictated by consumer color perception, or how the illumination of objects or light sources interacts with end users to create differently designed experiences, and it can be measured by various metrics, including color rendering index (CRI), correlated color temperature (CCT), red rendering (R_9), color fidelity (Rf) and gamut (Rg), and color consistency.

CRI is a measure of the degree of color shift objects undergo when illuminated by the source, as compared with the color of those same objects when illuminated by a reference source of comparable color temperature.[10] The CRI metric, as currently used by existing specification (such as DLC and ENERGY STAR), is calculated based on eight test color samples, R_1-R_8, that are of the pastel family. The rendering scores for each of these reference samples are averaged to get the overall CRI value. During the stakeholder engagement activities for Part One of this Study, feedback was received that CRI has shortcomings that limit its ability to *fully* represent how humans perceive color. Stakeholders suggested that because CRI is an average metric, products can receive sufficient CRI ratings to meet specifications while still rendering some colors poorly.[11] Although Navigant acknowledges there are limitations to the CRI metric, Navigant recommends the CA IOUs include it in the Criteria based on its wide adoption, recognition, and remaining value as a contributing factor – i.e., a piece of a larger puzzle – in identifying lighting quality. Navigant believes that CRI can serve to limit the risk of allowing lower quality products, with extremely poor CRI values, to meet the Criteria.

The **R_9** value is a supplementary red color sample that can be tested for during the CRI test, but it is not used in the overall CRI average. Properly rendering red colors is important for many indoor applications that require the saturation of red content in the appearance of an object to be high, such as medical applications (e.g., to ensure accurate diagnoses that use skin tone as a diagnostic tool), photography, textiles, restaurants, retail, etc. While existing test methods are available for measuring R_9, because it is not included in the calculation of the average CRI metric, it is often over-looked by manufacturers. For example, an LED product with a CRI score of 80 can still manage to achieve that score with a poor R_9

[10] Illuminating Engineering Society, "Definitions and Nomenclature: color rendering index (CRI) (of a light source)." https://www.ies.org/definitions/color-rendering-index-cri-of-a-light-source/

[11] Illuminating Engineering Society, "Policy and Initiatives: Color Rendering Index (PS-08-15)," August 2015. https://www.ies.org/policy/position-statements/color-rendering-index-ps-08-15/

rating. The additional test burden associated with testing for R_9 is minimal, as it is likely already tested for or would be a simple to add. As such, Navigant recommends the CA IOUs to include R_9 as a metric within the Criteria, due to its importance for indoor non-residential lighting applications.

In efforts to move away from CRI and towards a more comprehensive color rendering metric, stakeholders suggested Navigant consider including **Rf** and **Rg** in the Criteria. Rf and Rg, which are color fidelity and gamut metrics, respectively, are tested according to IES TM-30-15 (hereafter referred to as "TM-30"). This standard was recently developed and provides a more accurate rendition of color such that colors appear as they would under additional reference illuminants (100 versus 8 in the average CRI metric). Also, the gamut index was developed to describe the average level of color *saturation* relative to familiar (reference) illuminants. TM-30 does not, however, provide suggestions for specification limits or thresholds, so at this time, Navigant recommends to include Rf and Rg as a reporting requirement in the Criteria to 1) generate more data within the industry, and 2) allow the industry to organically understand the best path forward for incorporating TM-30 in future Criteria.

CCT is the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source.[12] CCT has long been accepted as a spectral metric within industry specifications, including those published by DLC and ENERGY STAR. Lighting designers use the CCT of their products' light sources to achieve certain settings or conditions in their designed spaces. Similar to CRI, some stakeholders were also critical of CCT for its failure to accurately communicate the light quality of an LED product. However, based on its wide adoption, recognition, and remaining value to identify the acceptable range of chromaticity, Navigant recommends to include CCT as a metric within the Criteria.

Color consistency refers to the average amount of variation in chromaticity among identical lamp samples.[13] This is important to lighting quality in its relation to consumer satisfaction; having LED products installed in one application or location that are rated with the same chromaticity (out of the same product family) should have the same color appearance with no visible differences. Unfortunately, testing each luminaire for color consistency would result in extensive burden, to both manufacturers to test and California to verify, and currently no industry-approved accelerated test methods for measuring and projecting color consistency are available. However, stakeholder feedback indicated that industry organizations are investigating possible methods to streamline color consistency testing. Based on the lack of industry precedent and available test methods, Navigant does not recommend the CA IOUs include color consistency for the Criteria, though it should be revisited in the future as industry test methods become available.

Color angular uniformity can be a key factor used to evaluate light quality of directional lighting products. However, it is largely specific to LED technology. This is because variations of light color can be significant based on the light path, or angle, through the yellow phosphor (i.e., the majority of LED product rely on phosphor conversion to product white-light). Therefore, the metric of color angular uniformity is used within the lighting industry to minimize the variation in chromaticity throughout the beam angle of an LED product. While color angular uniformity has been a staple requirement within the ENERGY STAR luminaire specification for several years, it has not gained wide spread adoption and reporting. Though Navigant believes this is an important metric for defining light quality, the feasibility to implement it for all directional non-residential LED lighting products would be highly burdensome. Therefore, Navigant recommends that color angular uniformity be included only for downlight fixtures, and that the CA IOUs continue to monitor progress and adoption within the industry for all directional luminaires.

[12] Illuminating Engineering Society, "Definitions and Nomenclature: correlated color temperature (CCT) of a light source." https://www.ies.org/definitions/correlated-color-temperature-cct-of-a-light-source/

[13] Lighting Research Center, "What is color consistency?" October 2004. http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/whatisColorConsistency.asp

The final spectral quality rankings and metrics decisions are detailed in Table 3-7.

Table 3-7. Spectrum Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
CRI	**3**	**3**	**3**	**3**	**1**	**13**	**Yes**
CCT	**3**	**3**	**3**	**3**	**1**	**13**	**Yes**
R_9	**3**	**2**	**3**	**2**	**3**	**13**	**Yes**
Rf and Rg[1]	**3**	**2**	**2**	**3**	**3**	**13**	**Yes**
Color Angular Uniformity[2]	**3**	**2**	**3**	**2**	**3**	**13**	**Yes**
Color Consistency	2	2	2	1	3	9	No

[1]Only applicable to LED indoor products.
[2]Only applicable to LED downlight fixture products.

3.2.6 Controllability

LED products can offer controllability advantages over legacy technologies, leading to additional energy savings and other non-energy benefits (e.g., health-centric lighting, asset tracking in retail settings, etc.). Navigant identified four metrics to describe LED controllability: dimmability, communication protocols, luminaire-level lighting controls, and networked lighting controls features.

In addition to the energy savings achieved by operating at lower light outputs (thus lower operating wattages), **dimmable products** offer greater flexibility for lighting designers and end users. For example, dimmable products enable the light output to be varied at certain times of the day, which can be essential for some applications (e.g., in museums, art galleries, etc.), where light exposure can have a damaging effect over time. However, in all building spaces and applications, the ability to optimize the right amount of light output and the right spectrum throughout the day and night enhances the end user experience and improves light quality. An auxiliary benefit of dimmability, especially to levels of less than one percent initial light output, is that it requires a more sophisticated power supply which in turn can increase the durability and overall quality of the LED product. Given these benefits, Navigant recommends that dimmability be included in the Criteria.

To potentially offer further controllability aspects to non-residential product offerings, Navigant also investigated the feasibility to include the **communication protocols** of networked lighting systems in the Criteria. Communication protocols are the medium through which lighting communication data are transferred, such as Wi-Fi, Bluetooth, Zigbee, etc. Networked lighting systems have the potential to enable data exchange among lighting systems and the cloud to improve not only the lighting quality, but also impact human comfort and productivity. However, one of the greatest challenges thus far has been agreement between manufacturers on common platforms and protocols. Enabling the right level of interoperability is crucial for devices, applications, networks, and systems to work together reliably and to securely exchange data.

Traditionally, there has been little-to-no interoperability between competing lighting control devices and

systems, and the use of proprietary hardware and software essentially forces the users to source all products from a single vendor. Because user needs are likely to change over time, heavy reliance on a single supplier increases user risk when considering new installations by creating dependency.[14] Therefore, metrics that require manufacturers to report the communication protocols that their networked lighting systems leverage increases transparency and may help to move industry closer to interoperability. While specifications currently require reporting of communication protocols at the control system level, this is not required at the lighting product-level. In addition, stakeholders indicated that proprietary technologies currently limit the potential for universal communication protocols. Therefore, based on the complexity to include this reporting metric, Navigant recommends to not include communication protocols in the Criteria. The CA IOUs should continue to monitor the feasibility of its inclusion in future revisions.

Lastly, Navigant explored including the reporting of **networked lighting control features** such as scheduling, energy monitoring, load shedding, external systems integration, and plug load control. Each of these features improves lighting quality by increasing the controllability of the LED product, which in turn, can directly relate to improved power quality and visual comfort. Similarly, **luminaire-level lighting control features** were also investigated for the Criteria, as they do not have some of the limitations of networked lighting control features. The controls are at the product level, which offers flexibility and customization to the end user for how each luminaire's lighting load is controlled and managed. Unfortunately, while precedent does exist for requiring networked lighting control features to be reported at the control system level, this is not required at the lighting product level. Therefore, as this Criteria applies to individual products (and not the network), Navigant does not recommend the Criteria include either of these metrics. Control features are constantly evolving for LED products, so Navigant recommends that the CA IOUs continue to monitor industry progress and improved standardization of reporting requirements.

Table 3-8 displays the final controllability metrics rankings and decisions.

Table 3-8. Controllability Metrics Ranking Results

Metric	Ranking Criteria					Total Score	Include in Criteria?
	Available Test Methods	Industry Acceptance	Complexity	Expected Burden	Lighting Quality Definition		
Dimmability[1]	**3**	**3**	**3**	**3**	**2**	**14**	**Yes**
Communication Protocols	2	1	1	1	3	8	No
Networked Lighting Control Features	2	1	1	1	3	8	No
Luminaire-Level Lighting Control Features	1	1	2	1	3	8	No

[1]Only applicable to LED indoor products.

[14] U.S. DOE Solid-State Lighting Program, "2017 Suggested Research Topics Supplement: Technology and Market Context," September 2017. https://www.energy.gov/sites/prod/files/2017/09/f37/ssl_supplement_suggested-topics_sep2017_0.pdf

3.3 Preliminary Non-Residential LED Lighting Quality Criteria

The analyses discussed in the Methodology Section 2, of this report indicate Navigant has identified that the "top-half of lighting quality" can best be measured with a combination of prescriptive, performance, and reporting requirements. As such, the preliminary proposed Criteria detailed in this section includes a technical description and pathway to qualification based on the combination of these three implementation methods. Based on this Criteria, non-residential LED products that fail any one, or combination of, the three implemented approaches are not eligible, and fail the overall Criteria. Products must comply with each Criteria category in order to be eligible. These pathways are detailed further in Table 3-9.

Table 3-9. Product Pathway for Criteria Eligibility

Criteria Categories	Description
Prescriptive	Product must meet the minimum/maximum metric thresholds detailed in the prescriptive portion of the Criteria as described in Section 3.3.2.
Reporting	Product must meet the reporting requirements detailed in the prescriptive portion of the Criteria as described in Section 3.3.2.
Performance	Product must receive a quality rating score of greater than or equal to 50 points as detailed in the performance portion of the Criteria as described in Section 3.3.3.

The following Sections 3.3.1, 3.3.2, and 3.3.3 detail the specific requirements within the Criteria, and Appendix B discusses the distribution of Criteria performance for products found in the DLC QPL and DOE LED Lighting Facts Database.

3.3.1 Covered Products Categories

Products covered in the Criteria are the LED product categories (i.e., luminaires, retrofit kits, and lamps) as defined by DLC, excluding Mogul (E39) Screw-Base Replacement Lamps, Four Pin-Base Replacement Lamps, Bollard Luminaires, Decorative Luminaires, and Case Lighting Luminaires.

In addition to the DLC's LED product categories, commercial downlights, as defined in the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1, are covered in the Criteria. The following Table 3-10 summarizes the LED product categories subject to the California Non-Residential LED Lighting Quality Criteria.

Table 3-10. LED Products Covered by the CA Non-Residential LED Lighting Quality Criteria

#	Covered Luminaire, Retrofit and Lamp Products	Indoor/Outdoor	Type
1	Outdoor Pole/Arm-Mounted Area and Roadway Luminaires	Outdoor	Luminaire
2	Retrofit Kits for Outdoor Pole/Arm-Mounted Area and Roadway Luminaires	Outdoor	Retrofit
3	Retrofit Kits for Large Outdoor Pole/Arm-Mounted Area and Roadway Luminaires	Outdoor	Luminaire
4	Outdoor Full-Cutoff Wall-Mounted Area Luminaires	Outdoor	Luminaire
5	Outdoor Non-Cutoff and Semi-cutoff Wall-Mounted Area Luminaires	Outdoor	Luminaire
6	Retrofit Kits for Outdoor Full-Cutoff Wall-Mounted Luminaires	Outdoor	Retrofit
7	Parking Garage Luminaires	Outdoor	Luminaire
8	Retrofit Kits for Parking Garage Luminaires	Outdoor	Retrofit
9	Fuel Pump Canopy Luminaires	Outdoor	Luminaire
10	Retrofit Kits for Fuel Pump Canopy Luminaires	Outdoor	Retrofit
14	Landscape/Accent Flood, Spot Luminaires and Wall-Wash Luminaires	Outdoor	Luminaire
15	Architectural Flood and Spot Luminaires	Outdoor	Luminaire
16	1x4, 2x2, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Indoor	Luminaire
17	Linear Ambient Luminaires with Indirect Component	Indoor	Luminaire
18	Integrated-Style Retrofit Kits for 2x2, 1x4, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Indoor	Retrofit
19	Direct Linear Ambient Luminaires	Indoor	Luminaire
20	Linear-Style Retrofit Kits for 2x2, 1x4, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Indoor	Retrofit
21	Retrofit Kits for Direct Linear Ambient Luminaires	Indoor	Retrofit
22	High-Bay Luminaires for Commercial and Industrial Buildings	Indoor	Luminaire
23	Low-Bay Luminaires for Commercial and Industrial Buildings	Indoor	Luminaire
24	High-Bay Aisle Luminaires for Commercial and Industrial Buildings	Indoor	Luminaire
25	Retrofit Kits for High-Bay Luminaires for Commercial and Industrial Buildings	Indoor	Retrofit
26	Retrofit Kits for Low-Bay Luminaires for Commercial and Industrial Buildings	Indoor	Retrofit
27	Downlight Luminaires	Indoor	Luminaire
28	Downlight Retrofits	Indoor	Retrofit
29	T8/T5/T5HO Four-Foot Replacement Lamps	Indoor	Lamp
30	Linear Replacement Lamps ("plug and play") (UL Type A)	Indoor	Lamp
31	Internal-driver/Line Voltage Linear Lamp-Style Retrofit Kits (UL Type B)	Indoor	Lamp
32	External-driver Linear Lamp-Style Retrofit Kits (UL Type C)	Indoor	Lamp
33	Dual Mode Internal Driver Linear Replacement Lamps (UL Type A and Type B)	Indoor	Lamp
34	Stairwell/Passageway Luminaires	Indoor	Luminaire
35	Track or Mono-Point Directional Luminaires	Indoor	Luminaire

3.3.2 Prescriptive and Reporting Criteria

To be eligible for the Criteria, LED products must be listed as “qualified” on the DLC QPL as either “Standard” or “Premium,” or for commercial downlights, these must be listed as ENERGY STAR certified.[15] This is an initial prescriptive requirement for the Criteria, however, DLC or ENERGY STAR certification does not guarantee that a product will meet the prescriptive and reporting requirements described in Section 3.3.3.1.

[15] This general requirement has been set based on research indicating that LED products that meet these specifications represent over 50% of non-residential lighting sales in the State of California.

Sections 3.3.2.1 through 3.3.2.6 describe the Criteria's prescriptive and reporting requirements for each of the six lighting quality parameters. These requirements include those described in the DLC Technical Requirements V4.3 (Final March 26, 2018),[16] or the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1 (Final March 15, 2018),[17] in addition to new requirements not currently adopted by either existing specification.

3.3.2.1 Power Quality

Power Factor

Downlights must comply with the power factor test methods in the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Instead of following the ENERGY STAR requirements – which stipulate that downlights with rated input power less than or equal to 5 watts must have a power factor of greater than or equal to 0.5 and for downlights with rated input power greater than 5 watts, the power factor must be greater than or equal to 0.7 – downlight products must have a minimum power factor of 0.9. The same measurement and reporting tolerances as specified by ENERGY STAR apply to this adjusted requirement. Refer to Appendix D for additional details regarding the ENERGY STAR testing requirements for power factor.

For all other LED products covered by the Criteria (see Table 3-10), products must comply with the DLC Technical Requirements V4.3, which require all DLC-eligible products to have a minimum power factor of 0.9.

Total Harmonic Distortion

LED products covered by the Criteria (see Table 3-10), with the exclusion of downlights, must comply with the THD requirements in the DLC Technical Requirements V4.3, which stipulates a maximum THD of 20%. Refer to Appendix D for additional details regarding the DLC requirements for THD.

Operating Frequency (Downlight Products Only)

All downlight products, as specified in Table 3-10, must comply with the operating frequency requirements detailed in Section 11.6 of the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Products must maintain an operating frequency of greater than or equal to 120 Hz, and this requirement is to be met at all light output levels for dimmable products. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for operating frequency.

[16] DLC, "Technical Requirements Version 4.3," Released March 26, 2018.
https://www.designlights.org/default/assets/File/SSL/DLC_Technical-Requirements-V-4-3.pdf

[17] ENERGY STAR, "ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1," Released March 15, 2018.
https://www.energystar.gov/sites/default/files/Luminaires%20V2.1%20Spec%20Final%20with%20Partner%20Commitments.pdf

3.3.2.2 Optical Performance

Lumen Output, Zonal Lumen Density, and Beam Classification

Downlights must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1, which stipulates lumen output and zonal lumen density requirements for downlight products. Section 9.2 specifies a 345 lumen output minimum for downlight apertures less than or equal to 4.5 inches, and a 575 lumen output minimum for downlight apertures great than 4.5 inches. Zonal lumen density requirements are also provided and states that downlights shall deliver a minimum of 75% of total lumens within the 0-60° zone (axially symmetric about the nadir). Refer to Appendix D for additional details regarding the ENERGY STAR requirements for lumen output and zonal lumen density.

For all other LED products covered by the Criteria (see Table 3-10), products must comply with the lumen output, zonal lumen density, and beam classification requirements in DLC Technical Requirements V4.3. Refer to Appendix D for details regarding the DLC requirements for lumen output, zonal lumen density, and beam classification.

Color Angular Uniformity (Downlight Products Only)

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 9.5 specifies that throughout the beam angle, the variation of chromaticity shall be within a total linear distance of 0.006 from the weighted average point on the CIE 1976 (u',v') diagram. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for color angular uniformity.

3.3.2.3 Reliability and Safety

Lumen Maintenance

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 10.1 specifies the lumen maintenance requirements for indoor, outdoor and inseparable luminaires. However, it is proposed that all downlight products (luminaire or retrofit kit), shall comply with the minimum L70 lumen maintenance requirements for inseparable luminaires, of greater than or equal to 50,000 hours. Products can be tested according to Option 1 or Option 2. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for lumen maintenance.

All other LED products covered by the Criteria (see Table 3-10), must comply with the lumen maintenance requirements in the DLC Technical Requirements V4.3. Refer to Appendix D for details regarding the DLC requirements for lumen output, zonal lumen density, and beam classification. Products can be tested according to Option 1 or Option 2.

For all product categories, product families must certify the "worst case" product with the lowest rated lifetime to qualify all products in that family.

Warranty

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 17 specifies that downlight luminaires incorporating replaceable drivers, a written warranty shall be included with luminaire packaging

at the time of shipment which covers repair or replacement of defective parts of the luminaire housing, mounting hardware, optics, driver and trim for a minimum of 3 years from the date of purchase. Downlight retrofit kits shipped with the luminaire shall carry a minimum 3 year warranty. For downlight luminaires incorporating non-replaceable drivers, the warranty requirement is extended to 5 years. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for warranty.

All other LED products covered by the Criteria (see Table 3-10) must comply with the warranty requirements in the DLC Technical Requirements V4.3. The minimum warranty for all DLC-eligible products is 5 years. Refer to Appendix D for additional details regarding the DLC requirements for warranty.

Drive ISTMT

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 13 describes thermal performance requirements, indicating that downlight luminaires and retrofits must have a measured driver case temperature at thermal equilibrium that does not exceed the driver manufacturer's maximum recommended temperature during in situ (installed in the luminaire) operation. This measurement shall be made at point for the hottest location on the driver case (TMP_C as detailed by the driver manufacturer). Refer to Appendix D for additional details regarding the ENERGY STAR requirements for thermal performance.

All other LED products covered by the Criteria (see Table 3-10), must comply with the driver in-situ temperature measurement testing requirements in the DLC Technical Requirements V4.3. Refer to Appendix D for details regarding the DLC requirements for driver ISTMT.

Color Maintenance (Downlight Products Only)

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 10.3 states that change in chromaticity coordinates from 0-hour measurement, at any measurement point during operation, shall be less than or equal to a total linear distance of 0.007 on the CIE 1976 u'v' diagram. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for color maintenance.

Safety Certification

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 14 indicates that downlight luminaires must comply with ANSI/UL 1574-2004, ANSI/UL 1598-2008, ANSI/UL 1598C-2014, ANSI/UL 2108-2004 or 2015, and ANSI/UL 8750-2009 or 2015, as applicable. While downlight retrofit kits must comply with ANSI/UL 8750-2009 or 2015 – LED Component and ANSI/UL 1598C-2014 – LED Retrofit. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for safety certification.

All other LED products covered by the Criteria (see Table 3-10), must comply with the safety certification requirements in the DLC Technical Requirements V4.3. Refer to Appendix D for details regarding the DLC requirements for safety certification.

3.3.2.4 Efficiency

Efficacy

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 9.2 specifies that downlight luminaires must have initial rated efficacies of 55 lm/W or higher, while downlight retrofit kits must have initial rated efficacies of 60 lm/W or higher. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for efficacy.

All other LED products covered by the Criteria (see Table 3-10), must comply with the efficacy requirements displayed in Table 1, Table 2, and Table 3 within the DLC Technical Requirements V4.3. Refer to Appendix D for details regarding the DLC requirements for efficacy.

3.3.2.5 Spectrum

Color Rendering Index

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 9.4 states that all downlight products shall be capable of meeting or exceeding a CRI of 80. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for CRI.

All other LED products covered by the Criteria (see Table 3-10), must comply with the CRI requirements displayed in Table 1, Table 2, and Table 3 within the DLC Technical Requirements V4.3. Refer to Appendix D for additional details regarding the DLC requirements for CRI.

R_9 (Indoor Products Only)

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 9.4 states that all downlight products shall be capable of exceeding a R_9 of 0. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for R_9.

All indoor LED products, as specified in Table 3-10, must conduct R_9 testing as specified in Section 9.4 of the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1, and report R_9 tested results.

Correlated Color Temperature

Downlight products must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 9.3 states that downlight products shall be capable of providing at least one of the following nominal correlated color temperatures: 2700 K, 3000 K, 3500 K, 4000 K, or 5000 K. In addition, products shall also have a chromaticity that falls within the corresponding 7- step chromaticity quadrangles as defined in ANSI C78.377-2015 or C78.377-2017. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for correlated color temperature.

All other LED products covered by the Criteria (see Table 3-10), must comply with the correlated color temperature requirements displayed in Table 1, Table 2, and Table 3 within the DLC Technical

Requirements V4.3. Refer to Appendix D for additional details regarding the DLC requirements for correlated color temperature.

Color Gamut and Fidelity

All LED products covered by the Criteria, including downlights (see Table 3-10), must comply with the optional color fidelity (Rf) and color gamut (Rg) reporting procedures provided in the DLC Technical Requirements V4.3. Refer to Appendix D for additional details regarding the DLC requirements for reporting color fidelity (Rf) and color gamut (Rg).

3.3.2.6 Controllability

Dimming

Downlight products listed as dimmable must comply with the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1. Section 15.1 states downlight products shall provide continuous dimming from 100% to 20% of light output, and that at the minimum light output, the product shall not emit noise above 24 dBA when measured within one meter of the luminaire. Refer to Appendix D for additional details regarding the ENERGY STAR requirements for dimming.

All other products listed as dimmable and covered by the Criteria (see Table 3-10) must comply with the reporting requirements outlined in the DLC Technical Requirements V4.3. Refer to Appendix D for additional details regarding the DLC requirements for dimming.

3.3.3 Performance Criteria

In addition to the prescriptive criteria detailed in Section 3.3.2, Navigant recommends the Criteria evaluate lighting quality based on a performance approach for the most relevant lighting quality parameters. Points are allocated to an LED product based on the level of performance within the tiered metric tables detailed in the following sections. Separate scoring parameters, metrics, and tiering values are provided for indoor and outdoor LED products (see Table 3-10 for complete listing of indoor and outdoor products covered by the Criteria). For both indoor and outdoor classifications, products that receive a total score of less than 50 points do not qualify and subsequently fail the Criteria. As stated in Section 3.3.2, products that do not meet the DLC Technical Requirements or ENERGY STAR Specification requirements also do not qualify and fail the Criteria. Where applicable, the prescriptive minimum requirements are listed in the quality rating tables throughout this section for reference.

As discussed in Section 2.2, the DLC QPL and DOE's LED Lighting Facts database were used to calibrate and optimize the Lighting Quality Rating, including the number of point tiers and point values for each lighting quality parameters included (i.e., Power Quality, Optical Performance, Reliability and Safety, Efficiency, Spectrum, and Controllability).

Section 3.3.3.1 describes the performance, or Lighting Quality Rating, for *indoor* non-residential LED products, while Section 3.3.3.6 describes the Lighting Quality Rating for *outdoor* non-residential LED products prescriptive requirements for each of the six lighting quality parameters.

3.3.3.1 Lighting Quality Rating: Indoor

Table 3-11 illustrates the quality parameters and associated metrics to be included in the indoor Lighting Quality Rating portion of the Criteria. For indoor, four of the six lighting quality parameters are included.

Table 3-11. Indoor Quality Rating Criteria Structure

Quality Parameter	Metrics Included	Total Points Possible
Reliability and Safety	Lumen Maintenance	25
Efficiency	Efficacy	40
Spectrum	CRI and R9	35
Controllability	Dimming	10
	Total Points Possible =	**110**

Optical Performance and Power Quality have been omitted due to feedback from stakeholders, as well as Navigant analysis, which indicated that there is not significant product variation at the higher performance values beyond the prescriptive thresholds. Therefore, given the available metrics, it is currently not feasible to develop a performance approach for the above stated two lighting quality parameters.

3.3.3.2 Reliability and Safety

provides the Indoor Quality Rating tiers for the Reliability and Safety parameter, which rates products based on their lumen maintenance performance. In Section 3.3.2, Navigant proposed a prescriptive minimum lumen maintenance requirement for products to have an L70 rating of at least 50,000 hours for all eligible LED products. Tier 1 corresponds to the L70 and L90 requirements associated with the Premium level of performance in the DLC Technical Requirements V4.3. The performance structure contains two additional lumen maintenance tiers that incentivize increasingly higher lumen maintenance projections and incorporates thresholds for L70 and L90 ratings.

Table 3-12. Indoor Lumen Maintenance Criteria

Tiers	Qualification Thresholds (hours)	Points Accrued
Minimum	L70 ≥ 50,000	0
Tier 1	L90 ≥ 36,000 and L70 ≥ 50,000	15
Tier 2	L90 ≥ 50,000 and L70 ≥ 75,000	20
Tier 3	L90 ≥ 75,000 and L70 ≥ 100,000	25

3.3.3.3 Efficiency

The indoor Lighting Quality Rating tiers for the Efficiency parameter rates products based on their efficacy performance. Due to the varying nature of product category efficacies, different efficacy requirements are set for five indoor product groupings. Each product category has a prescriptive minimum efficacy (as discussed in Section 3.3.2) and five additional tiers of increasing efficacy ranges. Products included within each grouping are summarized below in Table 3-13.

Table 3-13. LED Products Covered by the CA Non-Residential LED Lighting Quality Criteria

Covered Luminaire, Retrofit and Lamp Products	Indoor Product Grouping
1x4, 2x2, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Ambient Commercial Lighting and Linear Replacement Lamps
Linear Ambient Luminaires with Indirect Component	Linear Ambient
Integrated-Style Retrofit Kits for 2x2, 1x4, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Ambient Commercial Lighting and Linear Replacement Lamps
Direct Linear Ambient Luminaires	Linear Ambient
Linear-Style Retrofit Kits for 2x2, 1x4, and 2x4 Luminaires for Ambient Lighting of Interior Commercial Spaces	Ambient Commercial Lighting and Linear Replacement Lamps
Retrofit Kits for Direct Linear Ambient Luminaires	Linear Ambient
High-Bay Luminaires for Commercial and Industrial Buildings	Low-High Bay
Low-Bay Luminaires for Commercial and Industrial Buildings	Low-High Bay
High-Bay Aisle Luminaires for Commercial and Industrial Buildings	Low-High Bay
Retrofit Kits for High-Bay Luminaires for Commercial and Industrial Buildings	Low-High Bay
Retrofit Kits for Low-Bay Luminaires for Commercial and Industrial Buildings	Low-High Bay
Downlight Luminaires	Downlight
Downlight Retrofits	Downlight
T8/T5/T5HO Four-Foot Replacement Lamps	Ambient Commercial Lighting and Linear Replacement Lamps
Linear Replacement Lamps ("plug and play") (UL Type A)	Ambient Commercial Lighting and Linear Replacement Lamps
Internal-driver/Line Voltage Linear Lamp-Style Retrofit Kits (UL Type B)	Ambient Commercial Lighting and Linear Replacement Lamps
External-driver Linear Lamp-Style Retrofit Kits (UL Type C)	Ambient Commercial Lighting and Linear Replacement Lamps
Dual Mode Internal Driver Linear Replacement Lamps (UL Type A and Type B)	Ambient Commercial Lighting and Linear Replacement Lamps
Track or Mono-Point Directional Luminaires	Interior Directional

Table 3-14 provides efficacy performance tiers for interior directional products; Table 3-15 provides the efficacy performance tiers for downlight products; Table 3-16 provides the efficacy performance tiers for low-high bay products; Table 3-17 provides the efficacy performance tiers for linear ambient products; and Table 3-18 provides the efficacy performance tiers for ambient commercial lighting (troffers) and linear replacement lamp products.

Table 3-14. Efficacy Criteria for Interior Directional Products

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	65 ≤ Efficacy < 85	0
Tier 1	85 ≤ Efficacy < 95	18
Tier 2	95 ≤ Efficacy < 105	22
Tier 3	105 ≤ Efficacy < 110	29
Tier 4	110 ≤ Efficacy < 125	34
Tier 5	Efficacy ≥ 125	40

Table 3-15. Efficacy Criteria for Downlight Products

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	60 ≤ Efficacy < 65	0
Tier 1	65 ≤ Efficacy < 70	18
Tier 2	70 ≤ Efficacy < 75	22
Tier 3	75 ≤ Efficacy < 80	29
Tier 4	80 ≤ Efficacy < 90	34
Tier 5	Efficacy ≥ 90	40

Table 3-16. Efficacy Criteria for Low-High Bay Products

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	105 ≤ Efficacy < 125	0
Tier 1	125 ≤ Efficacy < 130	18
Tier 2	130 ≤ Efficacy < 135	22
Tier 3	135 ≤ Efficacy < 140	29
Tier 4	140 ≤ Efficacy < 145	34
Tier 5	Efficacy ≥ 145	40

Table 3-17. Efficacy Criteria for Linear Ambient Products

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	105 ≤ Efficacy < 115	0
Tier 1	115 ≤ Efficacy < 120	18
Tier 2	120 ≤ Efficacy < 125	22
Tier 3	125 ≤ Efficacy < 130	29
Tier 4	130 ≤ Efficacy < 140	34
Tier 5	Efficacy ≥ 140	40

Table 3-18. Efficacy Criteria for Ambient Commercial Lighting and Linear Replacement Lamp* Products

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	100 ≤ Efficacy < 115	0
Tier 1	110 ≤ Efficacy < 115	18
Tier 2	115 ≤ Efficacy < 125	22
Tier 3	125 ≤ Efficacy < 130	29
Tier 4	130 ≤ Efficacy < 135	34
Tier 5	Efficacy ≥ 135	40

*Requirements for linear replacement lamps are to be based on "in-luminaire" measurements.

3.3.3.4 Spectrum

The indoor Lighting Quality Rating tiers for the Spectrum parameter rates products based on their CRI and R9 performance. As discussed in Section 3.2.5, Navigant identified CRI and R9 as the most appropriate metrics to quantify spectral-related lighting quality in the Criteria.

For indoor lighting, stakeholders noted that CRI is not as valuable to industrial lighting products (i.e., the low-high bay product grouping, as shown in Table 3-13). Most industrial products are installed in end-use applications, such as warehouses and manufacturing facilities where spectral quality is less of a concern. Therefore, for the low-high bay product grouping, separate CRI requirement tiers are provided, and no Spectrum requirements are provided for R_9.

Table 3-19 and Table 3-20 provide the CRI requirements for low/high bay products and all other indoor products, respectively.

Table 3-19. CRI Criteria for Low/High Bay Products

Tiers	Qualification Thresholds	Points Accrued
Minimum	70 ≤ CRI < 80	1
Tier 2	80 ≤ CRI < 85	9
Tier 3	CRI ≥ 85	20

Table 3-20. CRI Criteria for All Other Indoor Products

Tiers	Qualification Thresholds	Points Accrued
Minimum	80 ≤ CRI < 85	5
Tier 2	85 ≤ CRI < 90	12
Tier 3	CRI ≥ 90	20

For all indoor product groupings, with the exclusion of low-high bay, an additional metric for the Spectrum parameter is required. As shown in Table 3-21 the Criteria provides three tiers of points awarded based on R_9 values. No minimum requirements for R_9 are specified since the Criteria currently has no prescriptive requirements. Products only fail if they do not report the R_9 performance as indicated in Section 3.3.2.5. The point tiers shown in Table 3-21 represent an effort to encourage manufacturers to

increase R_9, if applicable. If the product is not awarded any points for R_9, it is still eligible to meet the Criteria based on its performance in the other quality parameters.

Table 3-21. R_9 Criteria for All Other Indoor Products

Tiers	Qualification Thresholds	Points Accrued
Tier 1	$0 \leq R_9 < 12.5$	5
Tier 2	$12.5 \leq R_9 < 50$	10
Tier 3	$R_9 \geq 50$	15

3.3.3.5 Controllability

Controllability is an increasingly integral part of quality lighting in the non-residential lighting market, and Navigant identified dimmability as the most suitable metric available for evaluating the quality of product controllability.

Table 3-22 contains the dimming Lighting Quality Rating tiers for indoor products that are marketed as dimmable. Dimmability is an optional design feature, and as such, there is no prescriptive minimum requirement for dimmability; therefore, products without dimmable features are not disqualified based on this metric. Additionally, if a manufacturer markets a product as "dimmable," but it does not meet Tier 1 (or better) in Table 3-22, the product does not fail the Criteria. No minimum requirements for dimmability are specified since the Criteria currently has no prescriptive requirements. Products only fail if they do not comply with the dimmability reporting requirements as indicated in Section 3.3.2.6. The point tiers shown in Table 3-22 represent an effort to encourage manufacturers to increase dimmability performance, if applicable. If the product is not awarded any points for dimmability, it is still eligible to meet the Criteria based on its performance in the other quality parameters.

Table 3-22. Dimming Criteria for Products Marketed as Dimmable

Tiers	Qualification Thresholds (Minimum Dimming %)	Points Accrued
Tier 1	$10\% \geq Dim > 1\%$	3
Tier 2	$1\% \geq Dim > 0.1\%$	6
Tier 3	$Dim \leq 0.1\%$	10

3.3.3.6 Lighting Quality Rating: Outdoor

Table 3-23 illustrates the lighting quality parameters and associated metrics to be included in the outdoor Lighting Quality Rating portion of the Criteria.

Table 3-23. Outdoor Quality Rating Criteria Structure

Quality Parameter	Metrics Included	Total Points Possible
Reliability and Safety	Lumen Maintenance and IP Rating	55
Efficiency	Efficacy	45
	Total Points Possible =	**100**

For outdoor, two of the six lighting quality parameters are included. Power Quality, Optical Performance, Spectrum, and Controllability have been omitted due to feedback from stakeholders, as well as Navigant analysis, which indicated that there is not significant product variation at the higher performance values beyond the prescriptive thresholds. In addition, many of the applicable lighting quality metrics for outdoor products are not fully developed, and therefore, are not viable for inclusion in the Criteria at this time. Given the available metrics, it is currently not feasible to develop a performance approach for the above stated four lighting quality parameters.

3.3.3.7 Reliability and Safety

For outdoor products, two metrics within the Reliability and Safety lighting quality parameter were identified for the Lighting Quality Rating portion of the Criteria: lumen maintenance and IP rating.

The outdoor lumen maintenance tiers, displayed in Table 3-24, are the same as for indoor products. Similar to indoor products, the Lighting Quality Rating has a prescriptive minimum lumen maintenance requirement for products to have an L70 rating of at least 50,000 hours. If products do not meet this minimum they fail the Criteria.

To incentivize increased lumen maintenance performance, Tier 1 corresponds to the L70 and L90 requirements associated with the Premium level of performance in the DLC Technical Requirements V4.3. The performance structure contains two additional lumen maintenance tiers that incentivize increasingly higher lumen maintenance projections and incorporates thresholds for L70 and L90 ratings.

Table 3-24. Outdoor Lumen Maintenance Requirements

Tiers	Qualification Thresholds (hours)	Points Accrued
Minimum	L70 ≥ 50,000	0
Tier 1	L90 ≥ 36,000 and L70 ≥ 50,000	15
Tier 2	L90 ≥ 50,000 and L70 ≥ 75,000	25
Tier 3	L90 ≥ 75,000 and L70 ≥ 100,000	35

Within the Reliability and Safety lighting quality parameter, outdoor products are also scored based on their IP rating. IP Rating is an optional design feature, and as such, there is no prescriptive minimum requirement for IP Rating. Products only fail if they do not comply with the IP Rating reporting requirements as indicated in Section 3.3.2.3. The point tiers shown in Table 3-21 represent an effort to encourage manufacturers to increase IP Rating performance, if applicable. If the product is not awarded any points for IP Rating, it is still eligible to meet the Criteria based on its performance in the other quality parameters.

Table 3-25 provides two performance tiers of IP Ratings, with points being rewarded on the basis of either the first or second digit, corresponding to the level of protection against solids (e.g., dust and other particles) and liquids intrusion, respectively.

Table 3-25. IP Rating Requirements

Tiers	Qualification Thresholds (IP Rating)	Points Accrued
Tier 1	1 ≤ First Digit < 4, OR 1 ≤ Second Digit < 5	10
Tier 2	First Digit ≥ 4, OR Second Digit ≥ 5	20

3.3.3.8 Efficiency

The outdoor Lighting Quality Rating tiers for the Efficiency parameter rate products based on their efficacy performance. Due to the varying nature of product category efficacies as lumen output increases, different efficacy requirements are set for each of the four outdoor product categories covered in the Criteria. The structure of the outdoor product categories is based on rated lumen output of the product, rather than by end-use application, corresponding to the DLC's low output (250-4,999 lumens), mid output (5,000-9,999 lumens), high output (10,000-29,999 lumens), and very high output (greater than 30,000 lumens) outdoor product categories as described in the DLC Technical Requirements V4.3. Each product category has a prescriptive minimum efficacy and five additional tiers of increasing efficacy ranges. If products do not meet these minimums they fail the Criteria.

To incentivize increased efficacy performance, Table 3-26 provides efficacy performance tiers for low output products; Table 3-27 provides the efficacy performance tiers for mid output products; Table 3-28 provides the efficacy performance tiers for high output products; and Table 3-29 provides the efficacy performance tiers for very high output products.

Table 3-26. Efficacy Criteria for Low Output Outdoor Products (250-4,999 Lumens)*

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	90 ≤ Efficacy < 100	0
Tier 1	100 ≤ Efficacy < 105	20
Tier 2	105 ≤ Efficacy < 110	25
Tier 3	110 ≤ Efficacy < 115	33
Tier 4	115 ≤ Efficacy < 125	38
Tier 5	Efficacy ≥ 125	45

*As described by the DLC Product Eligibility: https://www.designlights.org/solid-state-lighting/qualification-requirements/product-eligibility/.

Table 3-27. Efficacy Criteria for Mid Output Outdoor Products (5,000-9,999 Lumens)*

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	95 ≤ Efficacy < 105	0
Tier 1	105 ≤ Efficacy < 110	20
Tier 2	110 ≤ Efficacy < 115	25
Tier 3	115 ≤ Efficacy < 120	33
Tier 4	120 ≤ Efficacy < 130	38
Tier 5	Efficacy ≥ 130	45

*As described by the DLC Product Eligibility: https://www.designlights.org/solid-state-lighting/qualification-requirements/product-eligibility/.

Table 3-28. Efficacy Criteria for High Output Outdoor Products (10,000-29,999 Lumens)*

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	100 ≤ Efficacy < 115	0
Tier 1	115 ≤ Efficacy < 120	20
Tier 2	120 ≤ Efficacy < 125	25
Tier 3	125 ≤ Efficacy < 130	33
Tier 4	130 ≤ Efficacy < 135	38
Tier 5	Efficacy ≥ 135	45

*As described by the DLC Product Eligibility: https://www.designlights.org/solid-state-lighting/qualification-requirements/product-eligibility/.

Table 3-29. Efficacy Criteria for Very High Output Outdoor Products (≥ 30,000 Lumens)*

Tiers	Qualification Thresholds (lm/W)	Points Accrued
Minimum	100 ≤ Efficacy < 115	0
Tier 1	115 ≤ Efficacy < 120	20
Tier 2	120 ≤ Efficacy < 125	25
Tier 3	125 ≤ Efficacy < 130	33
Tier 4	130 ≤ Efficacy < 135	38
Tier 5	Efficacy ≥ 135	45

*As described by the DLC Product Eligibility: https://www.designlights.org/solid-state-lighting/qualification-requirements/product-eligibility/.

3.4 Test and Verification Considerations

Stakeholders indicated at each engagement point that the CA IOUs' considerations for the certification process, manufacturer burden, and testing and verification plans are critical for the implementation of the Criteria.

Navigant identified three initial testing and verification pathways for the CA IOUs to consider with regard to this stage of the Criteria.

1) **Allow Manufacturers to Self-Report Certification Data**. Similar to the early stages of the CEC's Voluntary California Quality LED Lamp Specification, this option would allow

manufacturers to self-report certification data according to the requirements listed in the Criteria. This option would require the development of a standardized test form for manufacturers to fill out and submit to the State of California, as well as a California-managed database or collection process of manufacturer data.

2) **CA Implement Testing and Verification System**. Similar to California's Appliance Efficiency Regulations (Title 20) which includes a publicly available database of certified products entitled the Modernized Appliance Efficiency Database System (MAEDBS),[18] this option would require the CA IOUs to develop a certification system where manufacturers submit test data. This option would require an ongoing enforcement role implemented by the State of California to ensure products are in compliance with the Criteria. Currently, the MAEDBS for California's Appliance Efficiency Regulations is operated by the CEC.

3) **CA Leverage DLC Reporting Infrastructure**. Navigant conducted an informal interview with DLC representatives to determine the feasibility of this option, and DLC expressed a willingness to offer integration of their database and online application programming interface (API) platform with the Criteria. This would involve leveraging DLC infrastructure to add a "CA Criteria Eligible" field to the DLC QPL. The benefit of this approach is that it minimizes the time commitment burden for the State of California for testing and verification. While Navigant has not conducted an analysis to verify the cost effectiveness of this option, it could potentially represent the most economically-efficient option given the reach and complexity of the non-residential LED lighting market.

4) **Considerations for Downlight Luminaires and Retrofits.** Currently, the DLC does not include downlight luminaire and retrofit products as eligible for the DLC QPL. While these products are eligible for ENERGY STAR certification, it is important to note that as of 2018, ENERGY STAR stopped reporting efficacy and wattage performance in their certified products database for all lighting fixture products.[19] This lack of available data prevents the State of California from leveraging the ENERGY STAR dataset to verify compliance with the Criteria. Therefore, if California includes downlight luminaire and retrofit products within the Criteria, only Options 1 and 2 described above are feasible for these product categories.

3.5 Criteria Future Revisions Plan

During the stakeholder engagement activities for Part One of this Study, Navigant received feedback and recommendation that the Criteria undergo annual revisions to keep-up with the rapidly changing LED industry. Within the means of the CA IOUs and CPUC, Navigant recommends the CA IOUs to undergo an annual review that is composed of the following Steps shown below in Figure 3-2.

[18] The MAEDBS database can be accessed through the following link: https://cacertappliances.energy.ca.gov/Login.aspx

[19] ENERGY STAR product datasets can be found at the following link: https://www.energystar.gov/productfinder/advanced

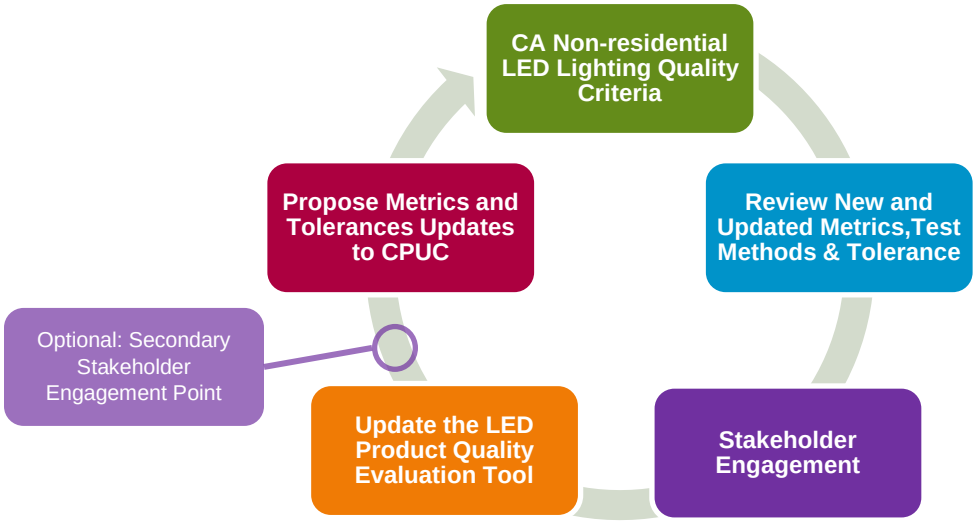


Figure 3-2. Annual Criteria Future Revisions Plan Cycle

1) **Review New and Updated Metrics, Test Methods, and Tolerances**. Navigant proposes that each year the CA IOUs conduct research to investigate new test methods, procedures and specifications that have been published and/or adopted. The goal of this step is to determine whether metrics identified as important to defining lighting quality could now potentially be considered feasible to include in the Criteria (see Section 3.2 for more detail on metrics omitted from this initial version). In addition, updates to existing metrics and tolerances based on LED technology development should also be considered. In particular, Navigant recommends the CA IOUs monitor the status of the following metrics, as they are currently being investigated by industry organizations to improve lighting quality: glare, flicker, color consistency, TM-30, BUG rating, communication protocols, and networked lighting control features.

2) **Stakeholder Engagement**. Following the review process, Navigant recommends that the CA IOUs engage key stakeholders with the goal of garnering consensus and industry perspective on recent trends for LED lighting quality metrics, test methods and performance. Key stakeholder groups to engage include the CEC, CLTC, DLC, IES, DOE, LRC at Rensselaer Polytechnic Institute, PNNL, IALD, as well as non-residential LED lighting manufacturers. Optionally, stakeholders could again be engaged prior to the proposal of metric and tolerance updates for the Criteria. This could serve as a final review prior to providing the CPUC with recommended updates.

3) **Update the LED Product Quality Evaluation Tool**. Part of Navigant's deliverables for Part One of this Study was to provide the CA IOUs with a spreadsheet that analyzes the DLC QPL and DOE's LED Lighting Facts database products which meet the proposed Criteria. This LED Product Quality Evaluation Tool[20] aids in determining the appropriate metrics and thresholds that define the "top-half of lighting quality" for LED non-residential products. This Tool can be updated to evaluate future versions of each database, as well as additional metrics and revised performance tolerances as needed. Navigant recommends this step in the revision plan to ensure 1) that products available are able to meet the revised Criteria, and 2) that the revised Criteria continues to represent the "top-half of lighting quality."

[20] The LED Product Quality Evaluation Tool was provided to the CA IOUs along with this report on May 2, 2018, and the results of its contained analysis are discussed in Appendix B.

4) **Propose Metric and Tolerance Updates to CPUC**. Once Steps 1-3 have been completed, Navigant recommends that the CA IOUs then propose the necessary metric and tolerance updates to the CPUC. These updates can be provided using the technical Criteria outlined and provided in this Part One of the Study (specifically Section 3.3).

4. RECOMMENDATIONS

Navigant has identified the following key findings and recommendations for consideration by the CA IOUs and other stakeholders.

4.1 DLC and ENERGY STAR Requirements

Align with DLC Technical Requirements and ENERGY STAR Program Requirements. Stakeholder engagement and research showed that DLC and ENERGY STAR are the most established organizations for developing specification tolerances and thresholds that influence product design and lighting quality. As such, CA IOUs should continue to reference the most current versions of the DLC Technical Requirements (currently V4.3) and the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria (currently V2.1) as first levels of qualification for the Criteria.

Maintain ongoing coordination with DLC and ENERGY STAR. CA IOUs should monitor and examine changes made within each new version of the DLC Technical Requirements and ENERGY STAR Program Requirements. Contact should be maintained between the CA IOUs, DLC, and ENERGY STAR representatives as new versions of each organization's specifications or criteria are being developed to align interests with industry and minimize conflicts with the California Non-Residential LED Lighting Quality Criteria.

4.2 Criteria Implementation

Move forward with the blended prescriptive, reporting, and performance approach to the Criteria. The research and analysis showed that the "top-half of lighting quality" is best identified by a combination of prescriptive, reporting, and performance criteria. In particular, the performance criteria, which is implemented through the Lighting Quality Rating described in Section 3.3.3, rewards higher performance using a tiered point structure. In addition, several industry stakeholders were in favor of the performance approach since it incentivizes increased lighting quality performance while allowing for tradeoffs between the metrics included.

The Criteria has been vetted with key industry stakeholders to ensure LED products meeting the Criteria are of higher lighting quality compared to those qualified by the DLC and ENERGY STAR. Additionally, existing data from the DOE's LED Lighting Facts database and DLC's QPL were used to optimize the Lighting Quality Rating approach. The results of this optimization are discussed in Appendix B, which indicate that more stringent lighting quality tolerances and metrics are needed beyond DLC and ENERGY STAR to identify LED products that meet the "top-half of lighting quality."

Utilize the LED Product Quality Evaluation Tool to analyze LED products meeting or not meeting the Criteria. The LED Product Quality Evaluation Tool should be updated annually to evaluate future versions of each database, as well as additional metrics and revised performance tolerances as needed. This update process will help to ensure that LED products available are able to meet any future revised Criteria, and 2) that any future revised Criteria continues to represent the "top-half of lighting quality."

4.3 Test and Verification Considerations

Work with the CPUC and CEC to determine the most suitable route forward for ensuring product compliance. Stakeholders suggested that fully developing the structure of a testing and verification system parallel to finalizing the Criteria is vital to ensuring high quality products are adopted by customers

as a result of the Criteria's implementation. Therefore, as the process unfolds to present the Criteria to the CPUC, the CA IOUs should work with the CPUC and CEC to determine the most viable route to ensure product compliance.

Consider three potential testing and verification pathways identified as a starting point for the CA IOUs, CPUC, and CEC. These pathways are as follows: 1) allow manufacturers to self-report certification data, 2) CA implement its own testing and verification system, or 3) CA could leverage the DLC reporting infrastructure (with the exclusion of downlight products).

4.4 Future Revisions

Utilize the outlined Criteria Future Revisions Plan for updating the Criteria. Several key industry stakeholders emphasized the need for the CA IOUs to remain vigilant as new metrics and test methods become available for defining and quantifying lighting quality for LED products. In addition, stakeholders commented that revisions should be continued for the Criteria, preferably on an annual basis. The LED industry is evolving rapidly, and industry standards and metrics are continually developed to assess the performance of products coming to market.

In order to maintain the relevancy of the Criteria, the CA IOUs should refer to Section 3.5 which described the recommended process for updating the Criteria, This Criteria Future Revisions Plan indicates the CA IOUs should 1) review new and updated metrics, test methods and industry-accepted tolerances, 2) continually engage with key stakeholders, 3) regularly update the LED Product Quality Evaluation Tool with new products, and lastly 4) propose new metrics and tolerances for consideration with the CPUC.

Appendix A. SUMMARY OF STAKEHOLDER FEEDBACK

During preparation of the draft Criteria that was presented at the CA LED Lighting Quality Workshop, Navigant conducted interviews with industry stakeholders for initial feedback on the three methods under consideration for the specification – prescriptive, performance and test reporting methods. After collecting feedback from stakeholders and the CA IOUs on the Criteria methodology options, Navigant organized the CA LED Lighting Quality Workshop, which took place on February 13, 2018 in Long Beach, CA, to discuss with industry experts the draft Criteria. The focus of the CA LED Lighting Quality Workshop was to receive feedback on the lighting metrics best-suited for defining lighting product quality, as well as the proposed methodology and approach. In total, 14 industry stakeholders – including manufacturers, SSL experts, and DLC representatives – attended the CA LED Lighting Quality Workshop and contributed to a lively discussion, signifying the importance and impact of this Study.

The following are the primary takeaways from the discussions at the CA LED Lighting Quality Workshop, as well as the stakeholder interviews:

- Requested clarification on the objectives and underlying project drivers. In particular, stakeholders commented on the need for greater definition surrounding "top-half of lighting quality." Asked that CA describe what quality metrics, features, and characteristics are a priority for the State.
- Discussed the need for CA to maintain an annual review cycle after the specification is finalized. This will enable the specification to remain relevant as LED technology continues to evolve and industry test standards are updated.
- Supported the performance approach and the concept of allowing for tradeoffs between metrics. However, there was opposition to the proposal for multiple performance scoring tiers (i.e., bronze, silver, and gold), as there may be unintended outcomes that arise (e.g., utilities may choose to incentivize only products receiving a gold rating).
- Recommended that CA lead ongoing dialogue and collaboration with the DLC. Indicated that strong coordination with the DLC would be necessary for the success of the specification. In addition, this will allow CA to align with upcoming versions of the DLC technical requirements and would eliminate the database management burden if CA were to develop its own certification process.
- Discussed the certification process, manufacturer burden, and testing and verification for the specification. Several stakeholders indicated that these are important considerations for any specification.
- Discussed the importance of including or excluding metrics as they relate to power quality, optical performance, reliability and safety, efficiency, color, and controllability. Stakeholders also noted that designing around glare, flicker, and color maintenance are key aspects of quality, but current industry standards for these metrics do not provide viable test procedures for measurement.

Navigant identified five major comment themes that relate to the specification. These include: General, Scope, Metrics, Quality Rating, and Testing and Verification. The following sections organize and summarize the comments received into these themes.

A.1 General

- Background and motivation for the CA Criteria.
    - Stakeholders requested additional background and transparency from CA on the motivation for the Criteria and the Study.

    - Stakeholders commented on the need for greater definition surrounding “top-half of lighting quality.” Is this a threshold of available LED products on the market, or of performance? What is the meaning of top-half?
    - Stakeholders asked that CA describe what quality metrics, features, and characteristics are a priority for the State.
- Future revisions and annual review process for the CA Criteria.
    - Stakeholders discussed Title 24 at length. It was indicated that one of the main issues of Title 24 is the timing, and that the regulation is unable to keep with the pace of technology innovation. Thus, each Title 24 iteration becomes outdated soon after implementation.
    - Stakeholders recommended the CA IOUs maintain an annual review process to ensure the Criteria remains relevant as LED technology continues to evolve and industry test standards are updated.
- Alignment with the DLC Technical Requirements V4.2 and upcoming V5.0.
    - Some stakeholders recommended that the CA Criteria align with the current DLC Technical Requirements V4.2, and that CA should continuously maintain this alignment as the DLC updates its requirement. However, some manufacturers opposed this suggestion, noting that the DLC update cycle is too rapid, and that the market would not be able to adjust sufficiently.
    - One stakeholder recommended the CA Criteria align with whichever version of DLC is currently active. However, another stakeholder indicated that CA typically references specific version numbers (e.g., V4.2, etc.) in their standards and specifications. Therefore, aligning with the latest version would be an unprecedented approach. This stakeholder noted that, regardless of approach, an annual review of the Criteria is needed to maintain relevance.
    - Stakeholders discussed that the upcoming DLC Technical Requirements V5.0 is investigating the viability of additional lighting quality metrics and criteria, such as color consistency, flicker, and glare.
        - It was recommended that CA work with the DLC to develop Technical Requirements V5.0. In addition, CA could plan to adopt this updated version rather than develop a competing Criteria.
        - Other stakeholders suggested that CA should develop its own quality Criteria. However, CA should require products to be DLC qualified, and then set higher thresholds for quality metrics.
- LED DLC-qualified saturation in CA.
    - One stakeholder estimated that at the national level, the DLC market share is less than half. However, it is more than half in CA because most utility lighting programs require DLC-qualified products in order to be eligible for incentives.

A.2 Scope

- Scope of products covered within the CA Criteria.
    - Some stakeholders were concerned that the Criteria would eliminate certain product types from being eligible for incentive support from the CA IOUs, such as display case luminaires.
        - It was indicated that the energy impact for display case luminaries is minimal, as they represent approximately 2-3% of just the retail market segment.
    - In addition, it was also commented that many products are made-to-order and don’t necessarily fit in the product categories listed.

    - However, other stakeholders argued that the goal of the CA Criteria should not focus on high-end or niche product markets, and that these products could still potentially qualify for incentives through custom programs.
- Proposal to exclude mogul screw base lamps and pin-based CFL replacement lamps.
    - One stakeholder did not agree with the proposal to exclude mogul screw base lamps and pin-based CFL replacement lamps while including LED linear replacement lamps. However, others agreed that the inclusion of LED linear replacement lamps could be justified from a performance standpoint.
- Alternative qualification path for evolving LED products.
    - One stakeholder suggested CA provide an alternate path for qualification outside of the constraints of the proposed Criteria. The stakeholder noted that an alternate path option could embrace evolving LED technologies in smart applications.
        - It was also noted that DLC is considering including this concept for future revisions.

A.3 Metrics

- Metrics not currently included in draft Criteria.
    - Stakeholders commented that many of the metrics not currently included in the draft Criteria are being investigated by DLC to include in the upcoming V5.0 technical requirements, such as color consistency, flicker, and glare.
    - One stakeholder also requested that CA evaluate the quality of product construction (e.g., plastics, metal, silicon, etc.) as a metric to include, as this often influences overall product quality. Other stakeholders agreed that product construction quality is a valuable aspect of quality to consider, but they noted that there are not currently any available metrics for testing construction quality.
    - Several stakeholders commented on the exclusion of a safety certification requirement from the metrics under consideration. However, the stakeholders noted that if meeting the DLC technical requirements is a prerequisite for the CA Criteria, then a safety certification requirement will be inherently included in the CA Criteria as it is already part of the DLC requirements.
- Consideration of flicker and glare as optical performance metrics.
    - Most stakeholders commented that glare is one of the most common issues facing manufacturers and consumers in non-residential lighting.
    - One stakeholder commented that glare should be included in the Criteria, noting that if efficacy is raised, then manufacturers may increase lumen output (superficially raising the efficacy), which would create unnecessary glare.
    - In response to the conversation around glare, one stakeholder noted that luminaire cutoff angles are fundamental to high-quality lighting design and could be part of the solution with regard to measuring and designing against glare. This stakeholder added that luminaire designs incorporating shielding angles could help prevent glare from occurring against a wall.
    - However, most stakeholders agreed that quantifying and measuring glare is an ongoing complex issue in the industry. Currently, there are not any industry-accepted measurement protocols.
        - One stakeholder added that because of the wide-ranging interest surrounding this issue, there is a renewed effort within the industry to quantify and develop glare metrics, so it is likely that a test standard will be developed in the next few years.

        - As such, most stakeholders agreed that it is not feasible to include glare as a metric in this initial Criteria, but CA should acknowledge that it is a common problem and create the flexibility to include it in future revisions should an industry-accepted test standard become available.
    - Most stakeholders also suggested that flicker is an important metric to include due to health and safety concerns.
        - It was noted by some stakeholders that there is an existing standard for measuring flicker (NEMA 77-2017). However, the stakeholders added that because no organizations have incorporated it into an existing Criteria yet, their recommendation was to wait for other organizations, like DLC, to incorporate it (and set thresholds/tolerances) before adding it to the CA Criteria.
        - Several stakeholders noted that requiring an operating frequency of 120 Hz is sufficient as a minimum requirement for now to address some issues with flicker.
            - One stakeholder detailed the main issues with varying operating frequencies. In general, there are four regions of frequency importance: 30 Hz and below (which causes seizures), above 30 Hz (where light strobing can be seen), the high hundreds (stroboscopic frequency), and higher in the thousands (which influences cameras). The stakeholder suggested CA acknowledge that these regions exist, even if standards cannot be set around these frequencies currently and allow for the flexibility to implement stricter flicker requirements in future revisions.
- Replacing ULR metric with BUG rating system.
    - In response to the proposal to include the ULR metric for the outdoor products, some stakeholders suggested to replace ULR with the BUG rating system. The stakeholders added that CALgreen and LEED already require BUG ratings and it is a universally-accepted metric, so it would be easier to incorporate into the CA Criteria than the URL metric.
        - One stakeholder clarified, that the BUG and ULR systems only apply to certain luminaires (e.g., fixed, pole-mounted luminaires), so CA should add language to the Criteria to apply the BUG requirements to only those luminaire types.
- Proposed requirement for lumen maintenance testing to be performed according to LM-84/TM-28 (full product testing) instead of LM-80/TM-21 (LED source testing).
    - All stakeholders at the CA LED Lighting Quality Workshop opposed requiring Option 2 for lumen maintenance testing (LM-84/TM-28 instead of LM-80/TM-21), citing that this would significantly increase manufacturer test burden.
        - One stakeholder noted that if Option 2 was required in the CA Criteria, it would likely result in the consumption of more energy per year to run the lifetime tests than the Criteria would be saving. This stakeholder added that the development of the Option 2 test standard was not intended for this purpose (i.e., to require full product testing instead of source testing).
        - It was also commented that only one product has ever used Option 2 (LM-84/TM-28) for its lumen maintenance compliance with the DLC technical requirements.
- Driver ISTMT and elevated temperature testing.
    - In response to the proposal to require ISTMT for every product attempting to qualify for this Criteria, several stakeholders agreed that this requirement would be fine to include in the Criteria with the caveat that display case lighting would be excluded from the scope of the Criteria.
    - One stakeholder also commented that some manufacturers are making false claims and in extreme cases forging ISTMT data. To prevent this from occurring (typically with retrofit kits), this stakeholder recommended CA implement a labeling requirement that correlates UL elevated temperature testing with the ISTMT datasheets.

        - For similar reasons, this stakeholder also recommended that L70 (lifetime) testing be correlated (on a product label) with the UL elevated temperature test if the product is rated at higher temperatures than ambient.
- Manufacturer warranty is not correlated with product quality.
    - Most stakeholders suggested CA remove the Criteria requirements regarding manufacturer warranties, noting that products tied to warranties have no guarantee of higher product quality.
    - Stakeholders also commented that discussing warranties in the scope of a Criteria is a commercial (anti-trust) issue among manufacturers and is not an engineering or design choice.
- Reporting requirements for metrics associated with spectrum.
    - Multiple stakeholders noted that requiring the reporting of Rf and Rg from TM-30 is reasonable, as long as it is not required retroactively, noting that if there is coordination between CA and the DLC to handle certification/recertification, some burden can be alleviated from manufacturers.
    - One stakeholder recommendation was to require that spectral power distribution (SPD) be reported or, at a minimum, to require the reporting of an accurate SPD graph because tabular SPD test data is difficult to manage in a centralized database and is sometimes sensitive data to publish.
        - The stakeholder argued an SPD requirement would enable lighting designers/end users to fully match the spectrum of multiple light sources in one facility with identical SPDs.
        - Another stakeholder also suggested CA create a tool that uses SPD data to compute other color metrics (CRI, Rf, Rg), which would be very useful for the lighting industry.
    - One stakeholder also recommended that CA require reporting for Rcs,h1 from TM-30, in addition to Rf and Rg, noting that it is equally, or even more important, than the average Rf and Rg values.
    - Most stakeholders noted that TM-30 is more effective as a color quality metric than CRI, and embracing it now (i.e., requiring reporting) is a good step for CA to take in this Criteria.
- Requirements for color maintenance.
    - Several stakeholders commented that the way the color maintenance requirements are structured in the draft will not work, as there are no accelerated test methods for measuring color drift. The stakeholders agreed with the notion that color maintenance is important to consider, but the manufacturer burden would be extensive, and products would be obsolete by the time testing was complete (products are typically designed on a 6- to 12-month life cycle).
        - The stakeholder consensus was for CA to acknowledge that color maintenance is an issue but allow for the Illuminating Engineering Society (IES) to complete an industry standard accelerated test method, which could then be incorporated in a future revision of the CA Criteria.

A.4 Quality Rating

- Suggestions to remove the bronze, silver, and gold scoring tiers associated with the quality ratings for indoor and outdoor products.
    - Multiple stakeholders suggested that CA remove the bronze, silver, and gold scoring tiers.

        - One stakeholder added that an unintended outcome may be similar to what occurred with the DLC program, when utilities and other organizations required only DLC Premium for incentives to be granted. The stakeholder noted that utilities may only allow incentives for LED products that meet the gold tier – which is not the intention or recommendation for how the scoring tiers be applied.
        - The stakeholder added that having a score tied to a rating tier, which ultimately influences a financial incentive, is very risky and difficult to effectively implement without the top (i.e., gold) tier becoming the only option that is chosen by incentive programs.
    - Several stakeholders added that in order to achieve the higher efficacies that result in more points in the quality rating (to reach the gold tier), manufacturers would likely increase lumen output, ultimately increasing product glare.
    - One stakeholder also commented that the bronze, silver, and gold scoring tiers are more difficult from an implementation-level standpoint as well, noting that it may be difficult for utility project managers to vary incentives based on different tiers.
    - Several stakeholders agreed that the best solution is to remove the scoring tiers and create a quality rating that effectively raises the bar set by DLC Premium, while still allowing for the performance tradeoffs.
- Reweighting parameters within the quality rating system.
    - One stakeholder suggested to reweight the points allocated for lumen maintenance and efficacy by placing more importance on lumen maintenance than efficacy, noting that product lifetime is more valuable to the consumer than efficacy.
- Deemphasizing the importance of CRI in the CA Criteria.
    - One stakeholder raised the issue that there are situations where the same product family may be used for drastically different applications – hence influencing the importance of CRI. For example, a high bay product installed in retail applications may require a high CRI, whereas the same product when installed in a heavy industrial application may not.
        - The stakeholder commented that understanding these nuances and ensuring products are not excluded or unable to meet the Criteria is important for CA to consider.
    - One other stakeholder commented as a proponent of proposed CRI tiering (i.e., the tradeoff approach in the quality rating system), even though it is sometimes application-specific. The stakeholder noted that this is the thought process behind the quality rating system, in which products can be designed to focus on other aspects of quality if CRI is not a priority for the application intended.
- Removal of the scoring tiers associated with power factor and THD.
    - Several stakeholders suggested to only have prescriptive requirements (i.e., minimum and maximum thresholds for power factor and THD, respectively) that align with DLC instead of rewarding additional points for higher power factor or lower THD.
        - One stakeholder added that there is minimal value to the consumer with additional tiering above a power factor of 0.90 or below a THD of 20%. This would then potentially lead to products receiving a high score without performing well in the other (more important) metric categories.
- The inclusion of dimming in quality rating system.
    - Several stakeholders commented that rewarding dimming has some value to the consumer, but some noted the points value allocated to this parameter should be adjusted down (with respect to the other parameters). It was suggested that high points for dimming could lead to the neglect of other parameters.
    - Several stakeholders also commented that the dimming tiers proposed in the Criteria do not achieve significant energy savings; however, one stakeholder advocated that there are other aspects of quality important to consumers that those tiers achieve.

        - For example, the stakeholder commented that dimming to 10%, 1%, and 0.1% are functional for lighting designers to deliver products that can meet the needs of various applications, such as museum lighting.
        - One stakeholder added that the dimming tier of below 1% actually serves as an artificial metric for overall product quality and could potentially filter out poor quality products.
- The inclusion of Networked Lighting Control Systems (NLCS) in quality rating system.
    - Multiple stakeholders commented on the proposal to allocate points for products meeting the DLC NLCS requirements, noting that the proposal would need to be modified as currently luminaires do not meet the DLC NLCS requirements. The DLC NLCS requirements relate to the network system, rather than compatible luminaires. Therefore, the stakeholders suggested to remove this parameter as it pertains to luminaire-level controls.
        - One stakeholder also mentioned that TLEDs would be unable to get points for controllability and would thus be automatically limited to less than 100 points.

A.5 Testing and Verification

- Understanding the next steps needed to develop a proper testing and verification system for the Criteria.
    - Several comments were received regarding CA's plan to test and verify product performance. It was emphasized that this is an important step within the Criteria implementation process.
        - Several stakeholders indicated the cost of verification database management is substantial and is something CA should consider in its decision-making process.
        - As such, stakeholders recommended coordination between DLC and CA to implement the verification of products attempting to qualify for the CA Criteria. This would involve the development of a new data sharing system (between DLC and CA) to assign the necessary points for the quality rating aspect of the Criteria and denote which products pass or fail the Criteria.
    - Multiple stakeholders noted that the LED industry is unique from traditional lighting technologies, in that one product family may have thousands of SKUs, which are created by having small variations (i.e., slightly different product characteristics) from a parent product.
        - They noted that this could cause issues with product verification if CA requires every product to be rated in this system, as the size of the database, the cost to manage that database, and the resulting increase in product costs would be significant.
        - Therefore, one stakeholder suggested CA consider implementing a family rating instead of product rating.
    - Lastly, one stakeholder commented that, as with all other industry specifications (including DLC), adding tolerances to test requirements is necessary.
- Additional burden associated with recertification of products.
    - One stakeholder requested CA consider the manufacturer burden that may arise with products that have to be recertified under either the DLC program or the future CA Criteria.
        - For example, there may be recertification burden that occurs by requiring all products in the CA Criteria to undergo ISTMT for products previously not qualified under DLC Premium, because ISTMT is not currently required for DLC

Standard. This comment was made under the assumption that a CA-DLC collaboration would be in place for submitting verification test data to DLC; therefore, in order to qualify for the CA Criteria, an existing product (under DLC Standard) would have to undergo ISTMT and resubmit the associated test data to DLC.

Appendix B. EVALUATION OF NON-RESIDENTIAL LED PRODUCTS THAT MEET THE PROPOSED CALIFORNIA CRITERIA

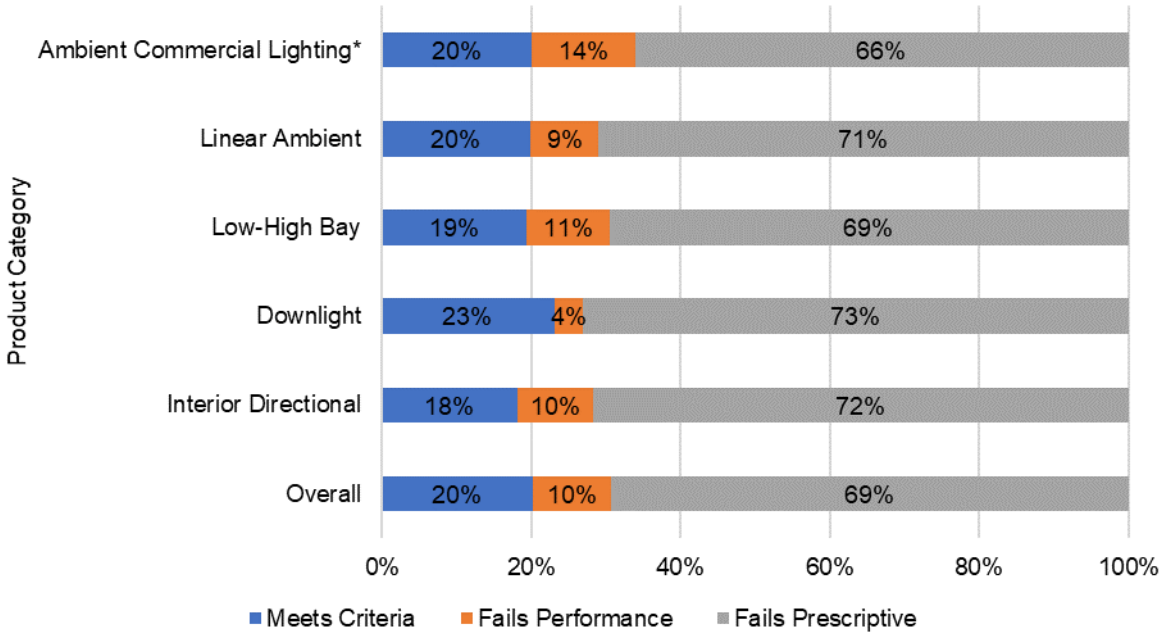
For Part One of the California Statewide Non-Residential LED Quality and Market Characterization Study, Navigant developed an optimization algorithm to determine the prescriptive minimum/maximum tolerances, performance tiers, and point values such that products meeting the preliminary California Non-Residential LED Lighting Quality Criteria roughly represented the top-half of available lighting products in the indoor and outdoor market. While this preliminary Criteria (hereafter referred to as the "Criteria") also includes a metric reporting approach (see Section 2.2.3), due to the lack of available data, these were not considered in the evaluation.

Using DOE's LED Lighting Facts database and DLC's QPL, Navigant developed an objective function which was calibrated to determine the best-possible solution that meets the initial condition – that 50% of LED products meet the prescriptive and performance Criteria outlined in Section 3.3. The decision variables within this optimization were defined as the prescriptive minimum/maximum tolerances, and the performance points for each point tier. For each performance metric, the tiers were developed such that the minimum represented the DLC and ENERGY STAR minimum requirements and the highest tier represented roughly the 90th percentile value in the dataset. Each tier was then calibrated in an iterative process to ensure that the performance thresholds and point allocations scored the top-half of these datasets to meet the Criteria.

Following calibration, the distribution of products meeting the Criteria, failing the performance portion, and failing the prescriptive portion are given separately for indoor and outdoor LED products, and separately for Criteria compliance within DOE's LED Lighting Facts database and the DLC QPL. The results described in this Appendix, can also be found in the LED Product Quality Evaluation Tool.[21] The purpose of the LED Product Quality Evaluation Tool was to provide a concrete dataset upon which the Criteria could be calibrated and demonstrated.

Figure B - 1 shows the distribution of products in DOE's LED Lighting Facts database based on the final calibration of the indoor Criteria. A large proportion of the indoor products in DOE's LED Lighting Facts database failed to meet the prescriptive requirements. As shown in Figure B - 2, the majority of these products' failures were a result of products not meeting the minimum lifetime (L70 lumen maintenance) requirements. In fact, most products in DOE's LED Lighting Facts database did not report lumen maintenance. However, the median score of products *not* failing the prescriptive criteria was 59 points (out of a possible maximum of 110), indicating that if used with a more complete dataset, the Criteria is able to achieve its goal of distinguishing the "top-half of lighting quality" for indoor products. Overall, approximately 20% of indoor products in DOE's LED Lighting Facts database met the prescriptive and performance portion of the Criteria.

[21] The LED Product Quality Evaluation Tool was provided to the CA IOUs along with this report on May 2, 2018.



*Includes linear replacement lamps

Figure B - 1 DOE LED Lighting Facts Database Indoor Criteria Meet/Fail Distribution

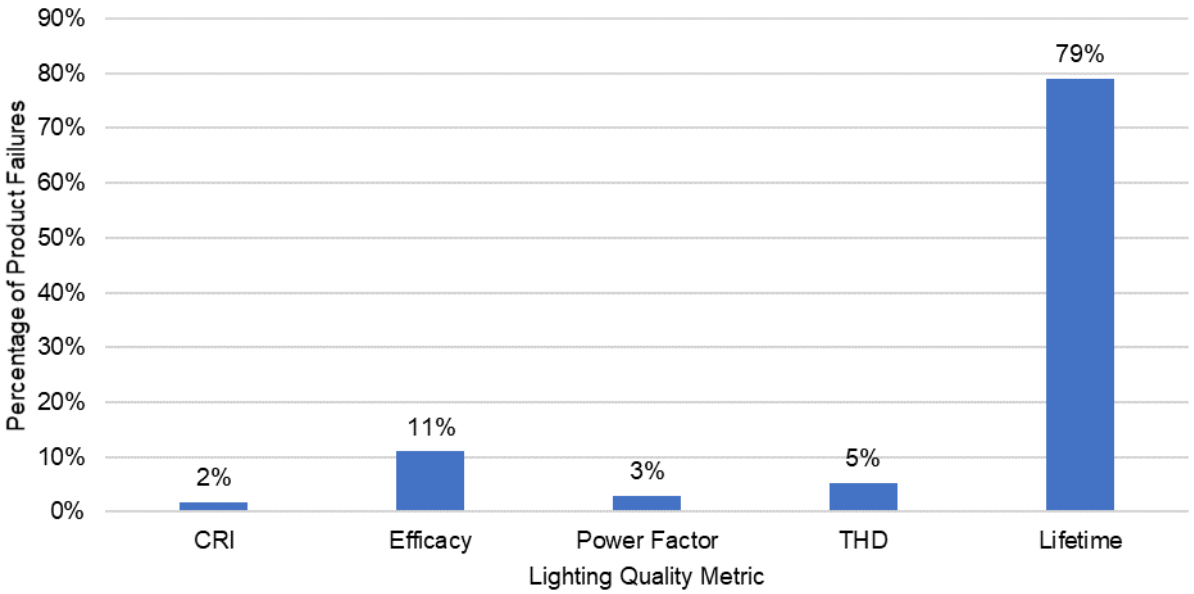
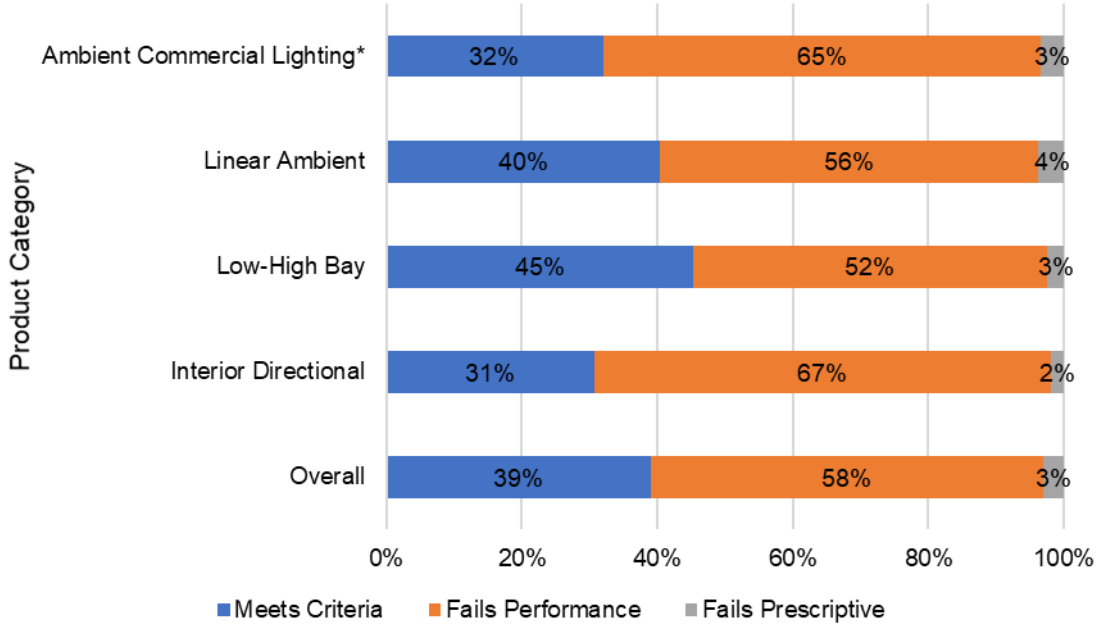


Figure B - 2 DOE LED Lighting Facts Indoor Prescriptive Portion Failure by Lighting Quality Metric

For the indoor products within the DLC QPL, several data limitations were present. The DLC database did not contain data regarding R_9 and reported lumen maintenance was very limited. DLC Standard and DLC Premium designations, which match the minimum requirement and tier 1 respectively,[22] were the only lumen maintenance data available, thereby eliminating the ability to score products above tier 1 for lumen

[22] The minimum and tiered requirements for each metric can be found in Section 3.3.3.

maintenance. Given these data limitations, the Criteria score cut-off was adjusted down. In the Criteria, an indoor product can achieve a maximum score of 110 points, as specified in the performance portion of the Criteria (see Section 3.3.3). However, due to the lack of R_9 data (max 15 points) and lacking granular lumen maintenance, the maximum score that a DLC QPL indoor product could receive was reduced to 85. Therefore, the score required to "meet the Criteria" was adjusted from 50 points to 40 points for this Criteria analysis. Given this scoring adjustment, the distribution of products meeting the Criteria are presented in Figure B - 3. Approximately 39% of the products in the indoor DLC QPL met the Criteria. Only 3% of the indoor products failed to meet the prescriptive portion.



*Includes linear replacement lamps

Figure B - 3 DLC QPL Indoor Criteria Meet/Fail Distribution

When comparing the results of the indoor product Criteria evaluation, there is a drastic difference between the percentage of products that meet the Criteria between DOE's LED Lighting Facts database (20%) and DLC's QPL (39%). While 20% is significantly below half of all indoor products, Navigant believes this is reasonable due to the drastic difference in lumen maintenance performance between the two datasets. As indicated above in Figure B - 2, the majority of indoor products from DOE's LED Lighting Facts database fail the Criteria because of the prescriptive L70 lumen maintenance requirement of 50,000 hours. In addition, based on discussion with key industry stakeholders, DLC eligible products represent the vast majority of non-residential lighting sales in the State of California (see Appendix A for summary of stakeholder feedback). Given the limitations of the available metrics data and 39% of indoor products from the DLC QPL meet the Criteria, Navigant believes the prescriptive minimum/maximum tolerances and the performance points for each point tier adequately represent the "top-half of lighting quality."

For outdoor products, DOE's LED Lighting Facts database contained two data limitations. First, similar to the indoor database, lumen maintenance data were sparse. Secondly, there were no available data for IP Ratings. In the Criteria, an outdoor product can achieve a maximum score of 100 points, as specified in the performance portion of the Criteria (see Section 3.3.3.6). However, due to missing IP Rating (max 20 points), the maximum score that a DOE's LED Lighting Facts database outdoor product could receive was reduced to 80. Therefore, the score required to "meet the Criteria" was adjusted from 50 points to 40 points for this Criteria analysis. Given this scoring adjustment, the distribution of products meeting the

Criteria are given in Figure B - 4. Overall, approximately 41% of the outdoor products in DOE's LED Lighting Facts database met the prescriptive and performance portions of the Criteria. Similar to the indoor database, Figure B - 5 shows that the majority of the prescriptive failures were a result of products not meeting the minimum lifetime (L70 lumen maintenance) requirements and lack reporting on this metric.

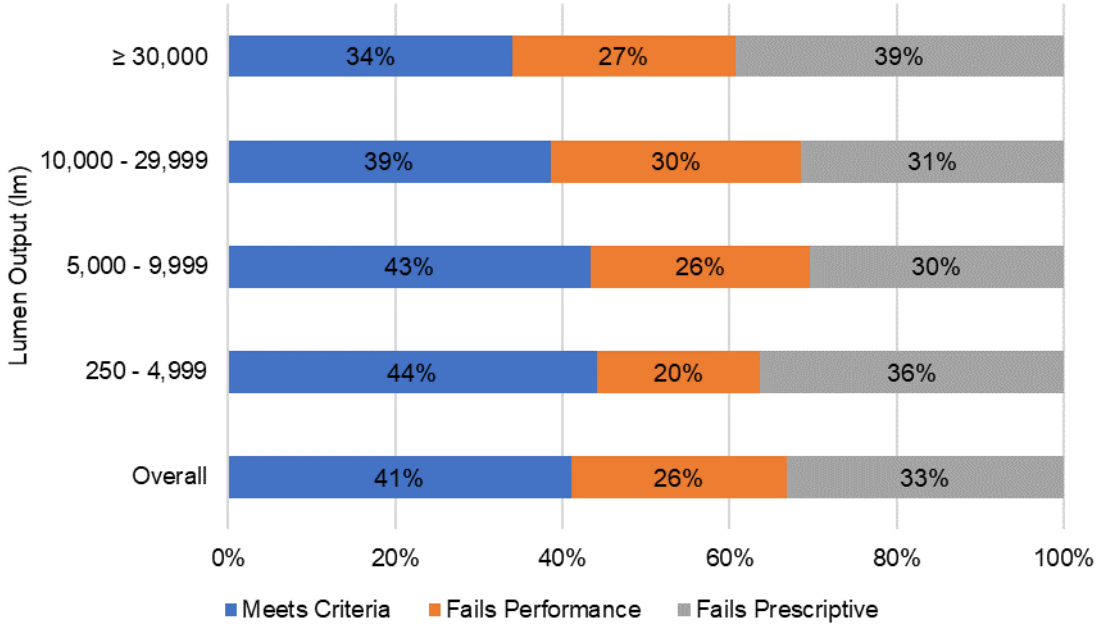


Figure B - 4 DOE LED Lighting Facts Database Outdoor Criteria Meet/Fail Distribution

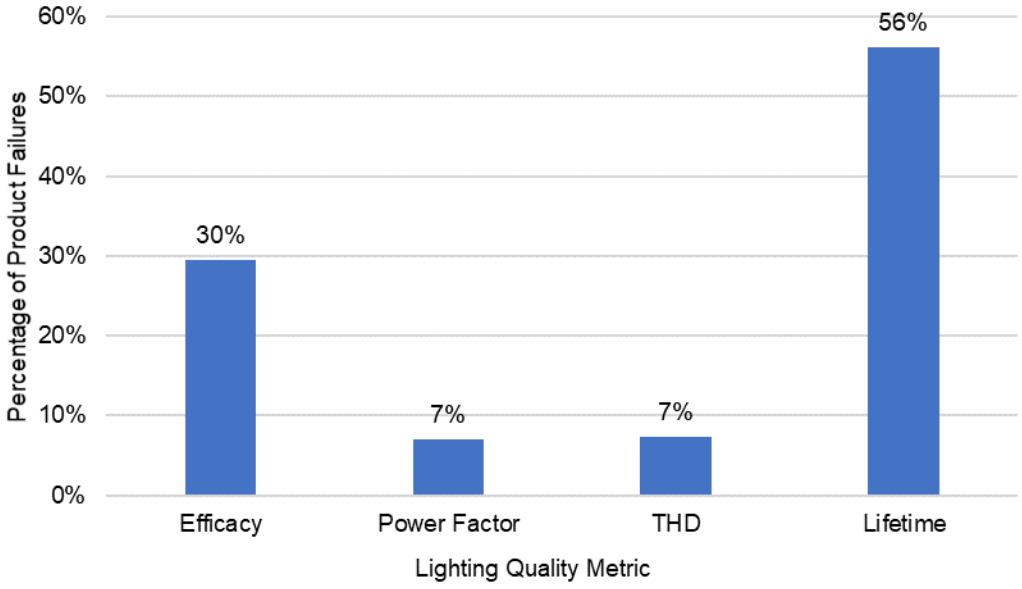


Figure B - 5 DOE LED Lighting Facts Outdoor Prescriptive Portion Failures by Lighting Quality Metric

The outdoor products in the DLC QPL presented similar data limitations to that of indoor. The outdoor DLC data had very limited reporting of lumen maintenance, thereby eliminating the ability to score

products above tier 1 for lumen maintenance. Furthermore, the outdoor DLC database did not contain data for IP Rating. In the Criteria, an outdoor product can achieve a maximum score of 100 points, as specified in the performance portion of the Criteria (see Section 3.3.3.6). However, due to missing IP Rating data (max 20 points) and lack of available lumen maintenance data, the maximum score that a DLC QPL outdoor product could receive was reduced to 60. Therefore, the score required to "meet the Criteria" was adjusted from 50 points to 30 points for this Criteria analysis. Given the scoring adjustment, the distribution of products meeting the Criteria are given in Figure B - 6. Overall, approximately 52% of the outdoor products in the DLC QPL met the prescriptive and performance portions of the Criteria.

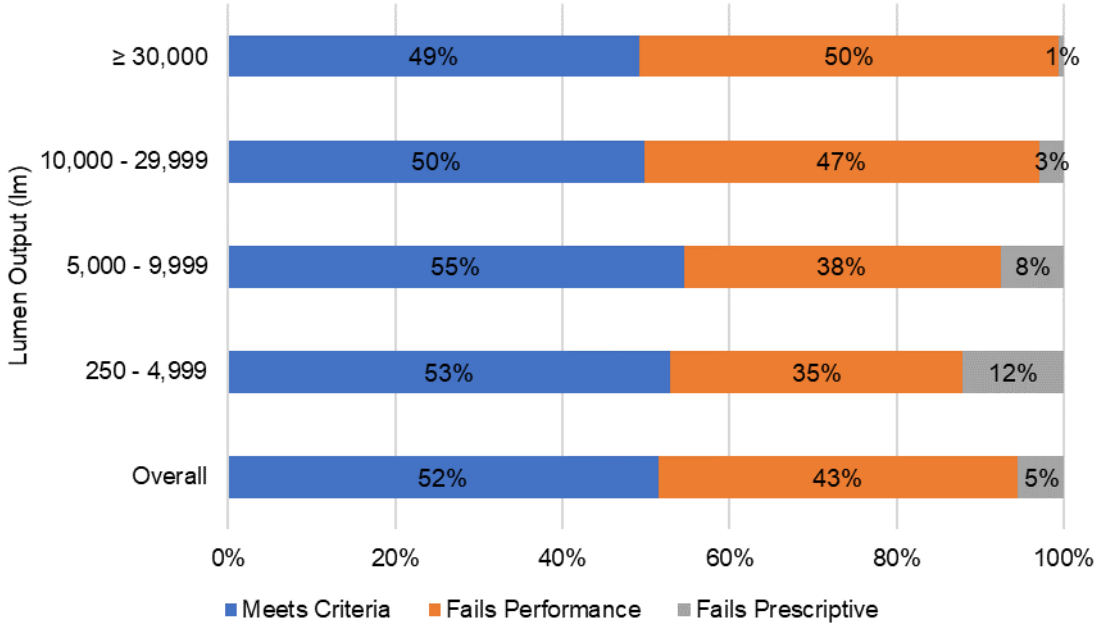


Figure B - 6 DLC QPL Outdoor Criteria Meet/Fail Distribution

When comparing the results of the outdoor product Criteria evaluation, there is some agreement between the percentage of products that meet the Criteria from DOE's LED Lighting Facts database (41%) and DLC's QPL (52%). While 41% is below half of all outdoor products, Navigant believes this is still reasonably within the range of "top-half of lighting quality." In general, Navigant hypothesizes that there is better agreement for the outdoor Criteria evaluation (compared to indoor) due the increasing importance of lumen maintenance for outdoor lighting applications. Because the lumen maintenance performance is more similar among outdoor products within DOE's LED Lighting Facts and the DLC QPL, there is less variation in the percentage of products that meet the Criteria. In addition, since 52% of outdoor products from the DLC QPL meet the Criteria, Navigant believes the prescriptive minimum/maximum tolerances and the performance points for each point tier adequately represent the "top-half of lighting quality."

Overall, despite the data availability limitations of DOE's LED Lighting Facts database and the DLC QPL, adjusting the Criteria threshold requirements allowed for a reasonable evaluation of the "top-half of lighting quality" for indoor and outdoor LED products.

Navigant also examined the scoring distribution of products based on whether they were DLC Standard or DLC Premium qualified. The distribution of products meeting the Criteria, failing based on performance, and failing based on prescriptive requirements is shown in Figure B - 7 and Figure B - 8. Overall, 98% of indoor DLC Premium products and 97% of outdoor DLC Premium products met the Criteria. In comparison, only 15% of indoor DLC Standard products and 38% of outdoor DLC Standard

products met the Criteria. In both indoor and outdoor product groups, the majority of DLC Standard products failed to meet the Criteria based on performance requirements, and not prescriptive requirements.

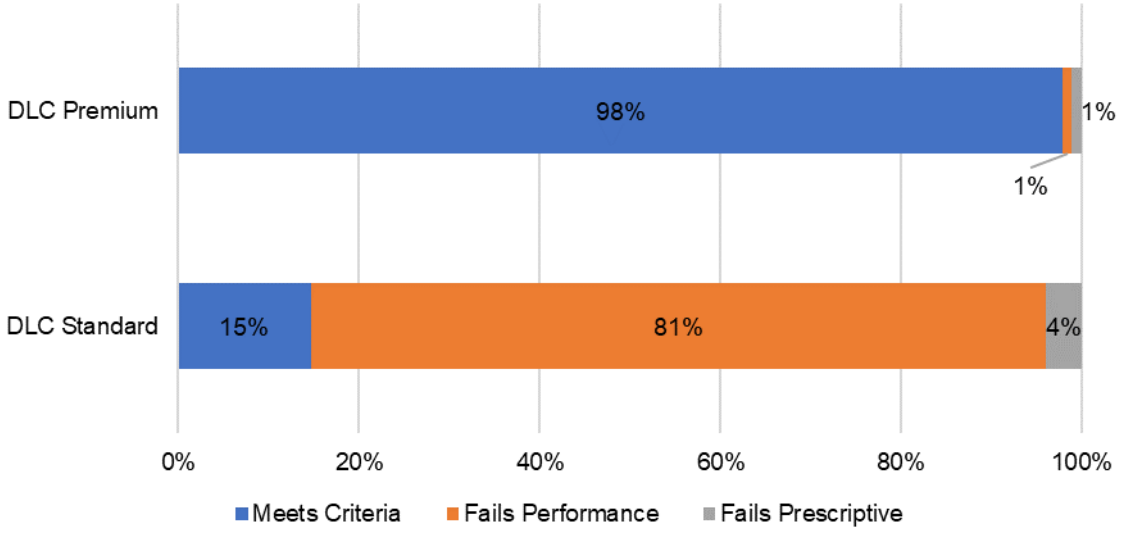


Figure B - 7 DLC QPL Indoor Criteria Meet/Fail Distribution by Standard vs Premium

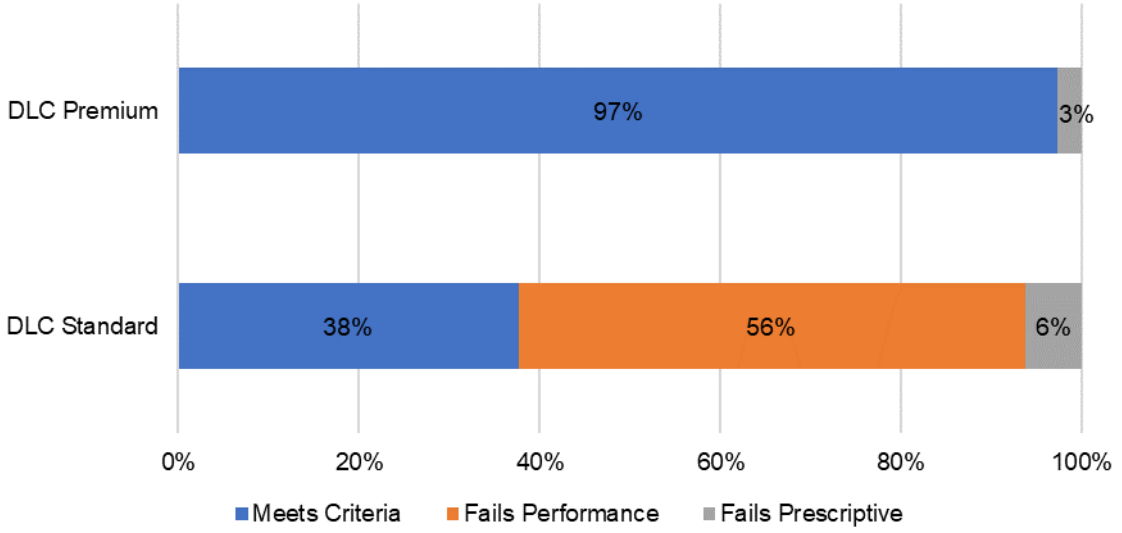


Figure B - 8 DLC QPL Outdoor Criteria Meet/Fail Distribution by Standard vs Premium

While nearly all DLC Premium products met the Criteria, it is critical to note that this is not indicative of DLC Premium being an indicator of whether a product will meet the criteria as it is presented. This is because the DLC QPL data used in this analysis lacks reporting of various additional scored metrics such as R9 for indoor products and IP Rating for outdoor products. Due to the lack of this data, the Criteria score cutoff in this analysis was adjusted down proportionally to these data gaps. In a more complete dataset where R9, IP rating, and more accurate lumen maintenance data is available, DLC Premium and DLC Standard products may score differently based on the Criteria.

Appendix C. SUMMARY OF FINDINGS AND RECOMMENDATIONS

Study ID	Study Type	Study Title	Study Manager		
		California Statewide Non-Residential LED Quality and Market Characterization Study	PG&E		
Recommendation	**Program**	**Summary of Findings**	**Additional Supporting Information**	**Best Practice / Recommendations**	**Recommendation Recipient**
1		Stakeholder engagement and research showed that DLC and ENERGY STAR are the most established organizations for developing specification tolerances and thresholds that influence product design and lighting quality.	Detailed analysis on metrics is given in Section 3.2.	CA IOUs should continue to align with the most current versions of the DLC Technical Requirements (currently V4.3) and the ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria (currently V2.1). CA IOUs should monitor and examine changes made within each new version and maintain contact with DLC and ENERGY STAR representatives as new versions are being developed to align interests and minimize conflicts with the Criteria.	All CA IOUs
2		The research and analysis showed that the "top-half of lighting quality" is best identified by a combination of prescriptive, reporting, and performance criteria. In particular, the performance criteria, which is implemented through the Lighting Quality Rating described in Section 3.3.3, rewards higher performance using a tiered point structure. In addition, several industry stakeholders were in favor of the performance approach since it incentivizes increased lighting quality performance while allowing for tradeoffs between the metrics included.	Detailed Criteria requirements are given in Section 3.3.	CA IOUs should move forward with the blended prescriptive, reporting, and performance approach. The Criteria has been vetted with key industry stakeholders to ensure LED products meeting the Criteria are of higher lighting quality compared to those qualified by the DLC and ENERGY STAR. Additionally, existing data from the DOE's LED Lighting Facts database and DLC's QPL were used to optimize the Lighting Quality Rating approach. The results of this optimization are discussed in Appendix B, which indicate that more stringent lighting quality tolerances and metrics are needed beyond DLC and ENERGY STAR to identify LED products that meet the "top-half of lighting quality." CA IOUs should also utilize the LED Product Quality Evaluation Tool to	All CA IOUs

				analyze LED products meeting or not meeting the Criteria. The LED Product Quality Evaluation Tool should be updated annually to evaluate future versions of each database, as well as additional metrics and revised performance tolerances as needed. This update process will help to ensure that LED products available are able to meet any future revised Criteria, and 2) that any future revised Criteria continues to represent the "top-half of lighting quality."	
3		Stakeholders suggested that fully developing the structure of a testing and verification system parallel to finalizing the Criteria is vital to ensuring high quality products are adopted by customers as a result of the Criteria's implementation	Detailed testing and verification proposals are presented in Section 4.3.	As the process unfolds to present the Criteria to the CPUC, the CA IOUs should work with the CPUC and CEC to determine the most suitable route forward for ensuring product compliance. Navigant identified three potential testing and verification pathways: 1) allow manufacturers to self-report certification data, 2) CA implement its own testing and verification system, or 3) CA could leverage the DLC reporting infrastructure (with the exclusion of downlight products).	All CA IOUs
4		Several key industry stakeholders emphasized the need for the CA IOUs to remain vigilant as new metrics and test methods become available for defining and quantifying lighting quality for LED products. In addition, stakeholders commented that revisions should be continued for the Criteria, preferably on an annual basis. The LED industry is evolving rapidly, and industry standards and metrics are continually developed to assess the performance of products coming to market.	Detailed plan for revising Criteria is presented in Section 3.5.	In order to maintain the relevancy of the Criteria, the CA IOUs should refer to Section 3.5 which described the recommended process for updating the Criteria, This Criteria Future Revisions Plan indicates the CA IOUs should 1) review new and updated metrics, test methods and industry-accepted tolerances, 2) continually engage with key stakeholders, 3) regularly update the LED Product Quality Evaluation Tool with new products, and lastly 4) propose new metrics and tolerances for consideration with the CPUC.	All CA IOUs

Appendix D. DLC AND ENERGY STAR REQUIREMENTS

The DLC Technical Requirements V4.3 can be found at the following link: https://www.designlights.org/default/assets/File/SSL/DLC_Technical-Requirements-V-4-3.pdf.

The ENERGY STAR Program Requirements Product Specification for Luminaires (Light Fixtures) Eligibility Criteria Version 2.1 can be found at the following link: https://www.energystar.gov/sites/default/files/Luminaires%20V2.1%20Spec%20Final%20with%20Partner%20Commitments.pdf.

Note: in the finalized PDF version of this report, this Appendix will include actual PDF versions of the DLC Technical Requirements and ENERGY STAR Program Requirements.