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Solid-State Lighting: Early Lessons Learned on the Way to Market

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Executive Summary

In recent years, solid-state lighting (SSL) has emerged as a promising new lighting technology that could fundamentally alter and improve lighting systems and significantly lower energy use and costs. However, SSL's full performance and energy savings potential is far from realized or assured. The U.S. Department of Energy (DOE) has invested public funds in research and development to support advancements in the performance and energy efficiency of SSL technology, as well as a range of activities intended to increase the likelihood of rapid market uptake of new SSL products.

The purpose of this report is to document early challenges and lessons learned in the SSL market development as part of the DOE's SSL Program efforts to continually evaluate market progress in this area. This report summarizes early actions taken by DOE and others to avoid potential problems anticipated based on lessons learned from the market introduction of compact fluorescent lamps and identifies issues, challenges, and new lessons that have been learned in the early stages of the SSL market introduction.

Actions by DOE, voluntary energy-efficiency programs, and standards organizations have helped the U.S. market to avoid some problems with early SSL products. Standardized testing, minimum performance and reporting requirements, and publication of testing and demonstration results have made it more difficult for poor-performing products to remain on the market, and rewarded manufacturers whose products perform well. As SSL technologies, or more specifically light-emitting diode (LED) technology, continue to develop and reach into most general illumination applications, the steep learning curve that lighting industry and all stakeholders continue to climb will offer many more lessons to learn.

This study identifies and characterizes 12 key lessons that have been distilled from DOE's SSL Program results. These key lessons include the following:

- Lesson 1: Rigorous testing requirements adopted in the early days of SSL industry development were necessary to counter exaggerated claims of performance by some manufacturers, but they eventually led to unreasonably high testing costs
- Lesson 2: Despite the promise of long life, there is no standard way to rate the lifetime and reliability of LED products
- Lesson 3: Specifiers prefer complete families of products, but the rapid evolution of LED technology presents a challenge to manufacturers in creating and maintaining complete product lines
- Lesson 4: The range of color quality available with LED-based products and the limitations of existing color metrics may confuse users
- Lesson 5: The color delivered by some LEDs shifts over time, enough to negatively impact adoption in some applications
- Lesson 6: Some LEDs flicker noticeably, which may negatively impact adoption in some applications
- Lesson 7: LEDs can cause glare, which may negatively impact adoption in some applications
- Lesson 8: Achieving high-quality dimming performance with LED lamps is difficult, but improving

- Lesson 9: Greater interoperability of lighting control components and more sensible specifications of lighting control systems are required to maximize the energy savings delivered by LED-based sources
- Lesson 10: Lack of LED product serviceability and interchangeability has created market adoption barriers in certain sectors
- Lesson 11: Existing lighting infrastructure limits the full potential of SSL; more effort is needed to open the doors to new lighting systems and form factors
- Lesson 12: Programs that provide ways to identify quality LED products have helped support market adoption

Many additional lessons could be listed, but this report focuses on areas where ongoing challenges exist and/or useful information can be applied going forward. Some of the lessons learned from problems that have been addressed or superseded by technology are discussed in Section 2 of this report.

Acronyms and Abbreviations

ANSLG	American National Standard Lighting Group
BUG	backlight, uplight, and glare
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCR	constant current reduction
CCT	correlated color temperature
CFL	compact fluorescent lamp
CIE	International Commission on Illumination
CRI	color rendering index
DLC	Design Lights Consortium
DOE	U.S. Department of Energy
HID	high-intensity discharge
HPS	high-pressure sodium
IALD	International Association of Lighting Designers
IES	Illuminating Engineering Society
LED	light-emitting diode
MSSLC	Municipal Solid-State Street Lighting Consortium
NEEP	Northeast Energy Efficiency Partnerships
NEMA	National Electrical Manufacturer’s Association
NGL	Next Generation Luminaires
NGLIA	Next Generation Lighting Industry Alliance
PWM	pulse-width modulation
QPL	Qualified Products List
R&D	research and development
SPD	spectral power distribution
SSL	solid-state lighting
TINSSL	Technical Information Network for SSL
UGR	Uniform Glare Rating
VCP	Visual Comfort Probability

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1.0 Introduction and Scope

In recent years, solid-state lighting[1] (SSL) has emerged as a promising new lighting technology that could fundamentally alter and improve lighting systems and significantly lower energy use and costs. SSL is controllable and directional, with the potential to change the way we light buildings and outdoor areas by putting light where it is needed, when it is needed, while eliminating wasted light and drawing just a fraction of the power used by traditional light sources. However, SSL's full performance and energy savings potential is far from realized or assured. The technology, market, and infrastructure development needed to capture this potential is significant and likely to take years.

The U.S. Department of Energy (DOE) has invested public funds in research and development to support advancements in the performance and energy efficiency of SSL technology, as well as a range of activities intended to increase the likelihood of rapid market uptake of new SSL products. DOE's strategy in supporting development of SSL was informed significantly by lessons learned during the development and commercialization of another relatively recent lighting technology: compact fluorescent lamps (CFLs). Early CFLs had significant quality and market problems, as acknowledged by the lighting industry and documented by DOE.[2] CFLs ultimately achieved substantial market share, providing huge gains in efficiency and longevity for household lighting, but CFLs never achieved widespread popularity and advances in CFL technology have plateaued. DOE applied lessons learned from the CFL market experience to the nascent light-emitting diode (LED) market, making objective product information available to the market and providing important feedback to the industry to address quality problems early and aggressively. This approach has served the development of LEDs well, as significant progress has been made in the performance of SSL and it is now apparent that LED technology[3] has merely begun to achieve its full market and energy savings potential, and replacement lamps are but one segment of the market for LED lighting. Larger potential market impacts are evident, for example, in outdoor area and roadway lighting, where LED replaces high-intensity discharge (HID) sources, and commercial interior lighting, where LED replaces a number of sources including pin-based CFLs and, increasingly, linear fluorescent sources.

DOE has set aggressive and ambitious goals for SSL research and development (R&D). DOE's price and efficacy projections and goals are listed on Table 1.1. LED performance is improving so rapidly that

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[1] "Solid-state lighting" (SSL) refers to the type of lighting that uses illumination sources that include semiconductor light emitting diodes and encompasses several technologies including inorganic light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs). This report addresses market experience to date with the introduction of lighting products using LEDs. Market issues related to OLED lighting products are outside the scope of this report.

[2] Sandahl LJ, T Gilbride, M Ledbetter, HE Steward, and C Calwell. 2006. *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market*. Prepared by Pacific Northwest National Laboratory for the Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cfl_lessons_learned_web.pdf.

[3] This report addresses market experience to date with the introduction of lighting products using LEDs. To avoid making the report overly complicated, the term "LED" is sometimes used generically to describe LED technologies in general and the terms SSL and LED are sometimes used interchangeably. Specific discussion of LED subassemblies and systems (LED drivers, engines, etc.) are only referenced when the discussion directly relates to these subassemblies.

DOE has revised its projections upward three times in the past 5 years. The current goal is to achieve a 266 lumen/watt efficacy at $0.50 per thousand lumens by 2030 (see Table 1.1).[1]

Table 1.1. Summary of LED Package Price and Performance Projections

	2012	2013	2015	2020	Goal
Cool-White Efficacy (lm/W)	150	164	190	235	266
Cool-White Price ($/klm)	6	4	2	0.7	0.5
Warm-White Efficacy (lm/W)	113	129	162	224	266
Warm-White Price ($/klm)	7.9	5.1	2.3	0.7	0.5

Now that LED lighting is available for most lighting applications and several years of market and installation experience have accumulated, DOE is assessing early lessons and observations from the LED market thus far. This report identifies some of the early actions taken in support of LED market introduction, and focuses on current challenges, lessons learned, and their implications for the future. These lessons are primarily based on insights from DOE's Market Development Support Program, which began in 2006 and serves as an independent third party providing LED technical information, performance data, education materials, and other support for market development and adoption of high-quality, high efficiency LED lighting. DOE SSL Program activities involve coordination with a wide variety of stakeholder groups including manufacturers, utilities and efficiency groups, designers, end users, and distributors.

The scope of this report focuses on LED lighting used for white light, general illumination applications, including interior and exterior lighting of buildings and facilities, and exterior lighting including street, roadway, parking lot, parking garage, and other forms of outdoor lighting. Vehicle, traffic, video display, screen, indicator, and monochromatic lighting applications are outside the scope of this report. Technical performance issues directly related to market development and adoption of LED general illumination products are addressed in the report, as are market barriers, standards, lighting quality, lighting design, and issues related to lighting energy-efficiency programs.

Section 2 discusses key lessons from CFL market introduction that informed early strategies implemented by DOE and others in the LED market. Section 3 identifies and characterizes 12 lessons and observations from the LED market introduction experience to date, focusing on lessons for which ongoing challenges exist and/or useful information can be applied going forward, along with implications for the future. Section 4 provides conclusions.

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[1] DOE. 2013a. *Solid-State Lighting Research and Development: Multi-Year Program Plan*. Prepared for Lighting Research and Development, Building Technologies Office, Office of Energy Efficiency and Renewable Energy, Washington, DC.

2.0 CFL Lessons Applied to Early LED Market

The Energy Policy Act of 2005 established the Next Generation Lighting Initiative, directing DOE to "support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light-emitting diodes" (Section 912, (b)). DOE had laid the groundwork with several technology roadmapping reports developed in cooperation with the SSL industry in the early 2000s. In 2006, looking ahead to imminent market introduction of the first LED-based general illumination products, DOE decided to draw on the collective experience of the lighting industry, energy-efficiency program sponsors, and the federal government in promoting CFLs as an energy-efficient alternative light source. DOE commissioned the report, *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market,*[1] to identify key lessons and assess their potential to inform DOE strategy in support of LED market introduction and development.

The 2006 CFL lessons learned study provides an analysis of the market introduction of CFLs, with an emphasis on identifying lessons that could be applied to the introduction of other new lighting technologies, such as SSL. In particular, the study explored reasons behind the slow acceptance of CFLs even though they last up to ten times longer than standard incandescent bulbs and use at least two-thirds less energy to provide the same amount of light. The study documented lessons that apply directly to LED market development (see text box for summary of CFL lessons learned), and many of the lessons learned from the study have guided DOE's planning and implementation of its SSL Program. The following summarizes the key lessons learned from CFL experience and how they have been applied in the early LED market experience.

Summary of Key Lessons Learned from CFL Experience

Coordination and collaboration is key
- *Coordinate and collaborate at a national level.*

Establish standards and product testing
- *Collaboratively establish minimum performance requirements.*
- *Back up long-life claims with standard-based projections and/or guarantees.*

Introduce new lighting technology first in applications where benefits are clearly established
- *Study market structure to see how best to introduce the technology.*
- *Know and admit technology limitations.*

Respond to the market and resolve problems/issues quickly
- *Determine and address compatibility issues with standard or conventional light fixtures and designs.*
- *Be aggressive about dealing with technology failures and issues that affect user satisfaction and/or the main benefit claims.*
- *Don't launch a product until performance issues are ironed out.*

2.1 Coordination and Collaboration is Key

Coordination across the multiple actors and stakeholders in the lighting market was lacking at the time CFLs were introduced to the market. This slowed the ability to influence and address the quality

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[1] Sandahl, et al., *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market.*

problems that inhibited market adoption. Cognizant of this experience, a number of government, utility, and industry-supported collaborative efforts have been developed to help avoid potential problems and speed the market adoption of LEDs, including the following:

- Next Generation Lighting Industry Alliance (NGLIA) – Manufacturers came together in 2003 to form the NGLIA, an alliance of for-profit lighting manufacturers formed to accelerate SSL development and commercialization through government-industry partnership. DOE signed a Memorandum of Agreement with NGLIA in February 2005 detailing a strategy to enhance the manufacturing and commercialization focus of the DOE portfolio by utilizing the expertise of NGLIA.[1] NGLIA coordinates with DOE in project development, review of technical specifications, development of new standards and test procedures, and cosponsoring of DOE events.

- The Illuminating Engineering Society (IES) and International Association of Lighting Designers (IALD) – The IES signed a Memorandum of Understanding with DOE in July 2006 to strengthen their ongoing partnership and commitment to improve the efficient use of energy and to develop standards with a strong energy-efficiency focus. A Memorandum of Understanding between DOE and the IALD was signed in 2008 to strengthen coordination in support of efficient lighting systems and equipment between DOE and lighting designers.[2] Both IES and IALD are involved with DOE in sponsoring the Next Generation Luminaires design competition, review of technical specifications, development of new standards and test procedures, and cosponsoring of DOE events.

- Technical Information Network for SSL (TINSSL) – To better coordinate and share SSL information with key stakeholder groups, including regional energy-efficiency organizations, utilities, lighting trade groups, and other stakeholders, DOE established TINSSL in 2006. Members share information about the technical progress of LED technologies through monthly teleconferences, national events, and distribution of fact sheets, market studies, and technical reports. DOE also hosts an annual SSL market introduction workshop and other information exchanges that draw together experts from industry, academia, and research organizations.

- ENERGY STAR – ENERGY STAR qualifications became available for LED fixtures starting in 2008 and LED integral lamps in 2010.[3] Working with a wide range of stakeholders, the program develops product qualification criteria that cover primarily residential lighting applications. During 2012, CFL technology continued to account for the majority of lighting product promotions according to the U.S. Environmental Protection Agency's 2012 ENERGY STAR Summary of Lighting Programs,[4] but LED promotions were growing in number.

- Design Lights Consortium (DLC) – The DLC is an initiative of Northeast Energy Efficiency Partnerships (NEEP) started in 1998 to raise awareness of the benefits of efficient lighting in

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[1] DOE. 2008. *Multi-Year Program Plan for FY'09-FY'14, Solid-State Lighting Research and Development*. Prepared for Lighting Research and Development, Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC.

[2] DOE and IALD. 2008. Memorandum of Understanding Between the United States Department of Energy and the International Association of Lighting Designers. U.S. Department of Energy, Washington, DC and International Association of Lighting Designers, Chicago, IL. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/iald-doe_mou-final.pdf.

[3] *ENERGY STAR Program Requirements for Solid State Lighting Luminaires*, version 1.0, took effect September 30, 2008. *ENERGY STAR Program Requirements for Integral LED Lamps*, version 1.0, took effect August 31, 2010.

[4] EPA. 2012. *ENERGY STAR Summary of Lighting Programs: September 2012 Update*. Prepared by ICF International, Washington, DC. September 2012. Available at http://www.energystar.gov/ia/partners/downloads/2012_ENERGY_STAR_Summary_of_Lighting_Programs.pdf.

commercial buildings, in support of energy-efficiency programs implemented by NEEP member utilities in the Northeast. In 2010, utilities around the country joined the DLC to initiate the Qualified Products List (QPL) for SSL products meeting minimum performance criteria for commercial grade LED luminaires. DLC qualification has become a requirement for many utility and energy-efficiency programs across the U.S. and Canada.

- National and regional efforts by utility and energy-efficiency groups – Utility and efficiency programs, many of which coordinate at the national and regional levels, have invested significant resources into better understanding the energy savings potential of LEDs and the most appropriate early markets to address with incentive programs (many have programs well underway), and understanding market barriers and how to best support the market adoption of LEDs in various market sectors. These organizations include NEEP, Northwest Energy Efficiency Alliance, the Midwest Energy Efficiency Alliance, and the Consortium for Energy Efficiency. Individual utilities that are part of these organizations have also made great strides. For example, starting in 2008, three of California's investor-owned utilities (Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric) undertook a series of market transformation activities focused on LEDs. These market transformation activities are included in an annual report on the topic[1] and include both residential and commercial-focused programs targeting (1) the technical advancement of LEDs; (2) lighting education and information; and (3) codes, standards, policies, and program administration.

All of these collaborative efforts internalized lessons from the CFL experience, including attention to the accuracy of product performance claims, a commitment to product testing and performance verification, and attention to lighting quality as well as energy efficiency. National level cooperation was necessary to work effectively with the lighting industry and communicate consistent messages about product quality, performance, and efficiency. In some cases, utilities, regions, or individual states have developed their own requirements above and beyond national requirements, but all are underpinned by nationally coordinated test methods, voluntary labeling programs, technical information, and qualified product lists.

2.2 Establish Standards and Product Testing

To help establish trust in the market for LEDs, lighting organizations and DOE began work on LED standards and test procedures soon after DOE initiated its SSL Program. The unique nature of LEDs meant that existing test procedures to measure and evaluate traditional lighting sources could not all be applied to LED technology. As a result, the lighting industry and existing standards bodies, with support from DOE, developed new standards and test procedures for LEDs, including:

- ANSI C78.377-2011 – *Specifications for Chromaticity of Solid State Lighting Products*; originally published in February 2008, updated in 2011, and available for download from the ANSI website.
- IESNA LM-79-08 – *Method for Electrical and Photometric Measurement of SSL Products*; in revision, current version is 2008.

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[1] CALMT. 2013. *Statewide Lighting Market Transformation Program Report*. June 2013. Annual Report. California Utilities Lighting Market Transformation Stakeholders. Available at http://www.lightingmarkettransformation.com/wp-content/uploads/2013/06/2013-Statewide-Lighting-Marketing-Transformation-Program-Report.pdf.

- IESNA LM-80-08 – *Method for Measuring Lumen Maintenance of LED Light Sources*; in revision, current version is 2008.
- IES TM-21-11 – *Method for Projecting Long Term Lumen Maintenance of LED Light Sources*; published in 2011.

DOE started the Commercially Available LED Product Evaluation and Reporting (CALiPER) program in 2006, driven by the lack of reliable LED product performance information in the market at that time. CALiPER purchased LED products through normal market channels (at retail, through distribution, online), tested them, published reports detailing the products' tested performance compared to manufacturer claims, and compared LED product performance to conventional lighting technologies. At the beginning, the standard test methods for measuring LED product performance were in development but not yet available. DOE worked with independent testing laboratories to test early LED products, based on the draft LM-79 photometric test procedure under development by the IES. This collaboration among DOE, testing laboratories, and the IES test procedures committee provided data and feedback loops that helped accelerate the completion of the LM-79 test procedure.

LM-79 and ANSI C78.377 were critical early standards that helped bring order to the chaotic LED market, providing a common basis for evaluating and comparing the performance of LED products to one another and to conventional lighting technologies. Nearly all national, regional, state, and utility energy-efficiency programs reference these industry standards.

2.3 Introduce New Lighting Technology First in Applications Where Benefits Are Clearly Established

While LED products were marketed for many different lighting applications almost from the beginning, the lighting industry largely focused on applications that were most ripe for market adoption, both in terms of performance and cost. Outdoor street and area lighting, for example, where long operating hours and attractive maintenance savings outweighed the challenges of the relatively high required light outputs, were early successful applications for LED lighting, and continue to advance quickly. Recessed downlights took advantage of LED directional output and the availability of the fixture housing for thermal management.

LED replacements for directional lamps such as MR16s and PARs[1] have also proliferated in the market, but GATEWAY[2] evaluations have identified performance problems in some installations due to overheating and optical control challenges. Similarly, CALiPER testing of early LED T8 replacements revealed low light output, poor light distribution, and minimal energy savings compared to high-performance fluorescent T8 lamps.[3] This category of products has since improved in efficacy and output, but light distribution and ease of installation issues continue.

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[1] Where "MR" refers to a multifaceted reflector and "PAR" refers to a parabolic aluminized reflector.

[2] DOE's GATEWAY demonstrations evaluate and showcase real world applications of high-performance LED products for general illumination in a variety of commercial and residential applications.

[3] DOE. 2009. *CALiPER Summary of Results: Round 9 of Product Testing*. October 2009. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round-9_summary.pdf.

To build on early success in LED streetlighting, DOE established the Municipal Solid-State Street Lighting Consortium (MSSLC) in 2010. The purpose of the Consortium is to share technical information and experiences related to LED street and area lighting demonstrations and to serve as an objective resource for evaluating new products on the market intended for those applications. Cities, power providers, and others who invest in street and area lighting were invited to join the MSSLC and share their experiences with an aim toward building a repository of valuable field experience and data. DOE's goal was to significantly accelerate the learning curve for buying and implementing high-quality, energy-efficient LED lighting. Response to the MSSLC has been rapid and enthusiastic. More than 375 members from 46 states are represented in the MSSLC.

LED products appear poised to capture a majority share of the streetlighting market over the next decade. The economic and energy cases are clear, but many of the nation's streetlighting owners are still in the early stages of understanding this new technology and, for example, how to distinguish appropriately performing products from others that are not. To help members successfully implement LED streetlighting projects, the MSSLC developed model specification documents, which members can use as a template and adapt to their own conditions. The MSSLC developed a similar document for adaptive control and remote monitoring systems for LED streetlighting.[1] Both model specifications will be updated regularly to keep pace with LED and controls technology development.

2.4 Respond to the Market and Resolve Problems/Issues Quickly

Addressing product limitations and factors that can cause user dissatisfaction is critical to avoid a lasting bad impression of the new technology. With this lesson from CFLs in mind, DOE took early action to evaluate and test LED product claims. In the first two rounds of CALiPER testing in 2007, less than 15% of the products had light output claims within 30% of tested values.[2] The publication of these discrepancies had an immediate impact: by the third round of CALiPER testing, the proportion of products with reasonably accurate light output claims (within 10% of tested values) had risen to 30%.[3] Of products CALiPER tested in 2012, about 67% had output claims within 10% of the tested value.[4]

DOE continues to use CALiPER testing, GATEWAY demonstrations, annual workshops, the DOE SSL website (www.ssl.energy.gov), fact sheets, R&D updates, studies, design competitions, and other methods to characterize and report the state of the technology and the market. The early and earnest involvement of industry in standards development and collaborative efforts through NGLIA, independent product testing through CALiPER, product qualifications by ENERGY STAR and DLC, and product

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[1] MSSLC. 2013. *Model Specification for Adaptive Control and Remote Monitoring of LED Roadway Luminaires, V1.0.* Municipal Solid-State Street Lighting Consortium, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://www1.eere.energy.gov/buildings/ssl/control-specification.html.

[2] DOE. 2007a. *CALiPER Summary of Results: Round 1 of Product Testing*. March 2007. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cptp_round_1_testing_results_summary.pdf.

[3] DOE. 2007b. *CALiPER Summary of Results: Round 2 of Product Testing*. August 2007. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/cptp_round_2_summary_final_draft_8-15-2007.pdf.

[4] DOE. 2012a. *CALiPER Year in Review 2012*. December 2012. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_2012-review.pdf.

verification by LED Lighting Facts[1] are all strong motivators to ensure accuracy in performance claims and help keep poor quality products off the shelves.

One example of a technical performance issue that has received early attention and efforts at resolution is compatibility of LED products with existing dimmers. Incompatibilities arise with the use of LED lighting products, which are powered by electronic drivers, on dimmers designed for incandescent loads. To date, there is no standard dimming interface, measurement protocol, or compatibility rating system that will ensure LED dimming performance with existing installed dimmers. (There is a dimming standard—NEMA SSL-7a—that addresses dimming compatibility between new lamps and dimmers that comply with the standard.) Manufacturers have taken different approaches to this problem. Most at least indicate in product packaging and literature whether the product may be used on a dimmer. Others publish lists of compatible dimmers. Advances in LED drivers have improved the chances for successful dimming of LED products, but compatibility and dimming performance problems are expected to continue for some time, as the existing installed stock of dimmers is replaced with dimmers designed for LEDs (see Section 3.8 for more information on this topic).

Another example where product concerns were addressed early relates to the environmental impact of light sources. The mercury content of CFLs became a significant concern in the lighting market, and sensitized users and researchers to possible similar issues with LED lighting products. To help address this concern, DOE commissioned a three-part study to investigate the entire life-cycle of selected LED lamps, from manufacturing and transport to use and disposal.[2,3,4] These reports demonstrated that, due to their energy efficiency, the impact of LED lamps over their entire life-cycle is significantly less than incandescent lamps, currently on par with CFLs, and expected to be less than CFLs with ongoing improvements in the efficiency of LED products. Part 3 of the study found that regulated elements in LED products were below restrictions set by the Federal Government, while all three tested light types (LED, CFL, and incandescent) exceeded at least one restriction imposed by the State of California, typically for copper, zinc, antimony, or nickel. LED products were found to be similar to cell phones and other types of electronic devices and should therefore be included in electronic waste recycling and disposal programs.

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[1] DOE's LED Lighting Facts® program showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The program provides information essential to evaluating SSL products available on its website, http://www1.eere.energy.gov/buildings/ssl/ledlightingfacts.html.

[2] DOE. 2012b. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part I: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps*. February 2012, updated August 2012. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf.

[3] DOE. 2012c. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 2: LED Manufacturing and Performance*. June 2012. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf.

[4] DOE. 2013b. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 3: LED Environmental Testing*. March 2013. Solid-State Lighting Program, Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_led_lca-pt3.pdf.

3.0 Current LED Lessons Learned

Actions by DOE, energy-efficiency programs, standards organizations, the SSL industry, and others—many in response to the CFL lessons learned discussed in the previous section—have helped the U.S. market to avoid some problems with early LED products. Standardized testing, minimum performance and reporting requirements, and publication of testing and demonstration results have made it more difficult for poor-performing products to remain on the market, and rewarded manufacturers who meet quality standards. As LED technology has continued to develop and reach into most general illumination applications, the lighting industry and all stakeholders have had to climb a steep learning curve, and much of the curve remains still ahead. LED products currently represent just over 4% of total installed lighting,[1] but their market share is growing rapidly. Now is a good time to pause and consider what has been learned thus far in LED general illumination market development, and the implications those lessons hold for the future.

The following sections present 12 key lessons learned in the development of LED as a general illumination light source. Many more lessons could potentially be listed, but the focus here is on areas in which ongoing challenges exist and/or useful information can be applied going forward. Lessons about problems that have largely been addressed or superseded by technology are not included. For example, two years ago, this lesson may have been salient: "LED replacements for 60-watt incandescent bulbs often do not provide adequate light output, light distribution, and performance." As of 2013, this problem has largely been addressed through improved LED output and efficacy, and product design improvements.

The 12 lessons that follow have been distilled from DOE SSL Program results, including

- CALiPER testing and exploratory studies
- performance data verification by LED Lighting Facts
- GATEWAY demonstration projects
- the multi-year R&D planning process
- regularly updated market studies and technology roadmapping efforts
- DOE annual workshops and major industry events
- extensive interaction with manufacturers, lighting designers and specifiers, retailers, building owners, municipalities, and utilities and energy-efficiency programs.

DOE recognizes the importance of aligning its R&D portfolio with industry partners, research and academic organizations, national laboratories, utilities and efficiency groups, designers, end users and distributors. The early successes of LED development and deployment are partly the result of these successful collaborative efforts. Likewise, each of these stakeholder groups and partnerships has a part in addressing the early LED market lessons outlined in Sections 3.1 through 3.12 of this report.

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[1] Current market data provided in Dan Chwastyk's (Navigant Consulting) presentation, "DOE's Market Introduction Workshop." November 13, 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/chwastyk_mktevolution_portland2013.pdf.

3.1 Lesson 1: Rigorous Testing Requirements Adopted in the Early Days of SSL Industry Development Were Necessary to Counter Exaggerated Claims of Performance by Some Manufacturers, but They Eventually Led to Unreasonably High Testing Costs

LED products face a higher testing burden than conventional lighting technologies due to a number of factors. Among the key factors that contributed to this high testing burden:

1. Characteristics of LED technology—especially the effect of thermal and electrical design on light output and efficacy—required a new test method (LM-79-08) based on absolute photometry,[1] instead of traditional relative photometry, for measuring LED luminaires. LED product performance could not be assumed to scale predictably with light source output or other product variations as is assumed with relative photometry, so the IES committee that developed LM-79 chose to base the new test procedure on absolute photometry.
2. Early CALiPER testing revealed the light output claims on many products were inaccurate, sometimes by very large margins. Once the LM-79 photometric test procedure became available, DOE encouraged buyers, specifiers, and energy efficiency programs to ask for test results for each product, creating a widespread expectation among LED buyers that all products should have an LM-79 report available.[2]
3. Energy-efficiency programs around the country adopted policies that required LM-79 reports to be available for each and every qualifying product, or adopted restrictive product family grouping policies that sharply limited the extent to which the LM-79 test on a product within a grouping could be used to qualify other products in that grouping.

As the LED industry has matured and many manufacturers have developed methods to accurately calculate product performance within a product family, DOE and efficiency program providers have taken steps to decrease this testing burden for manufacturers.

3.1.1 Significance

High testing burdens boost product prices, and slow down product introductions, which in turn can slow the rate of SSL market adoption and associated energy savings. Achieving a balance between the testing burden and the need for accurate performance data is important to encourage greater manufacturer participation in voluntary energy-efficiency and reporting programs, help level the playing field between LED and conventional lighting products, and bring more products and more innovation to the market quicker, while still providing the lighting market the necessary performance data.

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[1] IES LM-79-08. *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*. Illuminating Engineering Society, New York, New York.

[2] DOE, CALiPER Summary Reports, 2006-2008. http://www1.eere.energy.gov/buildings/ssl/report-archives.html.

3.1.2 Background

Absolute photometry and the resulting metric, luminaire efficacy, is a departure from traditional relative photometry used by the lighting industry. Traditionally, light sources were assumed to be omnidirectional, uniform, and scalable. A manufacturer could conduct one test on a single fixture and simply alter the magnitude based on the light source because the distribution remained the same or was "close enough" for industry needs. With the introduction of SSL, its unique properties, directionality, and thermal considerations, the industry developed LM-79, and for the first time every luminaire variation had to be tested. This dramatically increased the volume and costs of testing. ENERGY STAR, the DLC, and LED Lighting Facts all require LM-79 test results for product listing, and each have various product family grouping policies to allow manufacturers to extend the test results of one product to others in the product family. Most utility incentive programs reference one or more of these qualification programs. Many retailers require vendors to have their LED products listed by LED Lighting Facts. This demand for testing resulted in greater accuracy in product performance claims and greater confidence in LED products, but with the growing number of products being offered in the market, testing costs have skyrocketed.

3.1.3 Challenges

With the exploding number of products and product variations entering the market, rapidly rising testing cost has become an important issue for manufacturers. Manufacturer comments expressing frustration with testing costs and requirements have been submitted during voluntary criteria/program review cycles[1] and shared in industry trade press and events. While per product testing played a critical role in early product quality and buyer confidence in LED technology, it is becoming a hindrance to product line expansion. To meet the needs of the lighting market, testing costs will have to decrease to enable faster and more efficient LED product line development.

A growing number of manufacturers have climbed the LED learning curve and are fully capable of accurately predicting product performance within a product family based on limited testing and internally developed methods for extrapolating those results to other products in a family. However, there is still no standardized means of performing these calculations. Buyers and other users of manufacturer performance claims not based directly on photometric testing are thus left not knowing whether they can trust product performance claims. Third-party listing and qualification programs have to keep up with an ever-increasing number of applications to help users choose high-quality products.

3.1.4 Implications for the Future

1. Family grouping policies have been the primary means used by energy-efficiency programs for addressing the testing burden issue. The DLC allows for families of LED products to be qualified based on a single photometric test, along with documentation relating family members to the tested products. ENERGY STAR has a similar policy, and the LED Lighting Facts program has recently implemented a somewhat different family grouping policy, backed with random verification testing paid by manufacturer participants in that program. The voluntary qualification and listing groups should consider working together to continue to reduce the testing burden on manufacturers, while

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[1] DOE. 2012d. *Solid-State Lighting Manufacturing R&D Workshop Report*. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/sanjose2012_report.pdf.

maintaining the integrity of product data through random verification testing. This can be accomplished by increased coordination, data sharing, and uniform requirements across programs.

2. The lighting community should consider continuing to seek methods and strategies to reduce the overall testing burden on manufacturers, as confidence in LED performance continues to increase via evolving product performance expectations, documented long-term performance studies, and additional standards to address overall system reliability.
3. Product listing and qualification programs should ensure that reduced testing requirements do not re-open the door to inaccurate or exaggerated product performance claims. Inaccurate performance claims discovered through random testing should be corrected promptly by the manufacturer or the product removed from qualified lists.

3.2 Lesson 2: Despite the Promise of Long Life, There Is No Standard Way to Rate the Lifetime and Reliability of LED Products

Understanding and communicating how LED products fail and how long they can last is challenging. Predicting LED product life and reliability is complicated by various technical factors, and a single performance metric typically does not fit all lighting types and applications well.[1]

3.2.1 Significance

While LED-based products hold the potential to achieve lifetimes that meet or exceed traditional lighting technologies, the life and reliability of LED products on the market varies widely, and manufacturer claims can be misconstrued by users who do not fully understand why LED products fail or the difference between lifetime and reliability.[2] This uncertainty about lifetime can impede market adoption of LED products in certain sectors, especially those sectors that are particularly cost-sensitive.

3.2.2 Background

Long life has been billed as a key advantage of LED sources. For conventional lighting systems (incandescent, fluorescent, HID), failure most commonly results when a lamp "burns out." In almost all cases, other system components (e.g., ballast or luminaire housing) last longer than the lamp, and have lifetimes that are not dependent on the lamp. As a result, it has been sufficient to consider only the lifetime of the lamp itself.

Unlike conventional lighting systems, LED systems do not necessarily have "lamps." In contrast, they may include a number of integrated components as in fully integrated luminaires or integral-driver lamps, which means that LED system performance is more affected by interactions among system components. These interdependencies complicate both the testing and the rating of the LED system lifetime, as the failure of any LED system component (the electronics, thermal management, optics, wires, connectors, seals, etc.) can directly or indirectly lead to product failure. In addition, while some LEDs may fail catastrophically (i.e., burn out), others may degrade over time to the point where they stop producing an acceptable quantity or quality of light (i.e., exhibit parametric failure).[3] There is currently no standard or well-accepted method for predicting the useful life or reliability of an LED product.

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[1] Next-Generation Lighting Industry Alliance and DOE. 2011. *LED Luminaire Lifetime: Recommendations for Testing and Reporting, Second Edition*. June 2011. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf.

[2] DOE. 2013c. *Solid-State Lighting Technology Fact Sheet: Lifetime and Reliability*. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/life-reliability_fact-sheet.pdf.

[3] DOE. 2013d. *CALiPER Application Summary Report 20: LED PAR 38 Lamps*. November 2012, Addendum September 2013. Prepared by Pacific Northwest National Laboratory for the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20_summary.pdf.

3.2.3 Challenges

At present, manufacturers are designing and developing LED sources using a wide range of materials and approaches, fueled by the rapid improvement and evolution of multiple core technologies. Lifetime and reliability are often at odds with cost in the battle to achieve greater market deployment. The difficulty in developing a standard method for predicting the useful life or reliability of an LED product and the wide variation seen in the lifetime and reliability of market-available products might not be significant barriers to LED product adoption in and of themselves. However, their simultaneous occurrence is causing significant uncertainty.

Market actors have attempted to reduce user uncertainty about the lifetime and reliability of LED products in various ways, ranging from unsubstantiated marketing claims, to the use of standardized metrics, to a more recent focus on product warranties. All present challenges. Unsubstantiated claims take time and effort to uncover, and initially may be overlooked if presented by a known brand. Standardized metrics, like L_{70} (hours of operation during which light output remains above 70% of initial output) provide some means for apples-to-apples comparisons, and represent an improvement over the early days when unsubstantiated claims were commonplace. However, many users do not understand the limitations of metrics and overestimate their value. For example, the use of L_{70}, as determined using IES LM-80 data[1] and IES TM-21[2] calculations, only addresses lumen maintenance of the LED packages, and says nothing about color shift or the lifetime and reliability of the LED driver and other components.

Recent testing undertaken by the LED Systems Reliability Consortium, in cooperation with DOE, found a high level of reliability of LED luminaires tested under extreme stress conditions, with failures occurring in the drive circuitry rather than the LEDs.[3] These findings underscore the need for a systems-level perspective in evaluating LED reliability, including light sources, drivers, optics, and other components.

While warranty coverage is the most important assurance for many users, manufacturer warranty terms vary significantly—making comparisons difficult if not impossible—and most manufacturers find it impossible to absorb the financial commitment required to provide warranty coverage on par with the expected (long) lifetime of well-designed products.

3.2.4 Implications for the Future

1. Variability in lifetime and reliability of similar products needs to be reduced to improve market adoption of LED products.
2. Uncertainty about the lifetime and reliability of LED products is slowly but steadily being reduced, as efforts are made to standardize methods for predicting lifetime and reliability. Standards developers

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[1] IES LM-80-08. *Approved Method: Measuring Lumen Maintenance of LED Light Sources*. Illuminating Engineering Society, New York, New York.

[2] IES TM-21. *Projecting Long Term Lumen Maintenance of LED Light Sources*. Illuminating Engineering Society, New York, New York.

[3] DOE. 2013e. *Hammer Testing Findings for Solid-State Lighting Luminaires*. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/hammer-testing_Dec2013.pdf.

are working on new tools and metrics, some of which will still be limited in their usefulness. Nevertheless, these tools and metrics represent one of many efforts that will be necessary to address this challenge.

3. Some manufacturers are finding the financial wherewithal to provide longer (often 10-year) warranties for products serving key applications and market sectors. Such efforts represent a key step in overcoming uncertainty, whereby users develop trust, first with specific products or perhaps application-specific offerings from proven manufacturers, and then with the technology as a whole.
4. Innovative LED product designs and the expected increased use of lighting controls may further complicate the measurement and reporting of LED product lifetime and reliability in the near future. LED sources that can adjust their output and color characteristics, either automatically or in response to lighting controls, do not operate under a single set of conditions. Varying conditions can improve or degrade lifetime and reliability. All market actors—especially DOE and the research community, standards developers, and manufacturers—will need to stay diligent and work together to explore the effect of such features on lifetime and reliability performance and product variation, and educate the various user communities.

3.3 Lesson 3: Specifiers Prefer Complete Families of Products, but the Rapid Evolution of LED Technology Presents a Challenge to Manufacturers in Creating and Maintaining Complete Product Lines

Lighting professionals have traditionally used families of lamps and luminaires in buildings. Families of luminaires may include products with different light intensities, aperture size, beam angle, direction of light, or trim colors, for example, while maintaining a similar appearance. This allows luminaires used throughout a space or building to have a consistent look and feel, and can also standardize maintenance and spare parts. Similarly, LED replacement lamps may be interchangeable in a luminaire, but lamps that offer different lumen outputs and beam angles make it easier to provide just the right light level and visual effect in different size spaces, or when illuminating a range of objects. The rapid evolution of products within the LED industry has challenged manufacturers trying to develop full product lines. In some cases, manufacturers lack the time to develop full product ranges, or it is difficult to keep products consistent with one another when LED packages and drivers are changing so rapidly.

3.3.1 Significance

Without the option of product families, specifiers may have trouble using LED products across their project. Using a downlight from one manufacturer, a wallwasher from another, and an adjustable accent light from a third may result in three LED products with mismatched light color in a room, or an inability to match fixture finishes. This may lead some specifiers to conclude that it is safer to use older, familiar technology instead, delaying the use of LED products until better options become available. It may also delay the penetration of LEDs into higher-end projects that use lighting professionals. This issue primarily applies to the commercial market for families of both replacement lamps and complete luminaires, where designers need a variety of luminaires/lamps to achieve the project goals. It may also apply to residential customers as they try to replace existing lamps in their homes. Some energy savings are left on the table when a specifier is forced to use a higher output lamp or luminaire than is needed in a space, because of a lack of lower-output options.

3.3.2 Background

The development of LED replacement lamps exemplifies the issue. LED MR16 lamps were developed early on, with a lumen output comparable to a 20W halogen MR16. Soon, LED package improvements led to a 35W halogen equivalent. However, most manufacturers opted to sell only the higher output lamps, when specifiers would have liked to have both a 20W and a 35W equivalent available for different areas of a hotel, for example.

To cite a commercial example, recessed 2x2 luminaires are often used in areas where a 2x4 luminaire will not fit, or where the 2x4 luminaire emits more light than needed. The specifier needs both sizes of luminaires on the job. Early LED troffers were offered in 2x2 **or** 2x4 sizes, but seldom both by the same manufacturer, delaying the adoption of the technology.

3.3.3 Challenges

The rapid evolution of products within the LED industry has challenged manufacturers trying to develop full product lines. In some cases, manufacturers lack the time to develop full product ranges, or it is difficult to keep products consistent with one another when LED packages and drivers are changing so rapidly. In addition, some manufacturers are either not aware or not significantly incentivized in terms of profit margin to understand that specifiers need a range of products within a given family to meet commercial design needs and standards.

The cost of photometric testing of luminaire families presents additional challenges to providing complete families, as the testing costs can be prohibitive since nationally recognized testing laboratories must separately test luminaires with different drivers, different trim colors and configurations, and different lumen output options.

3.3.4 Implications for the Future

1. Manufacturers should consider providing a range of lamps or luminaires with similar appearance, but with different photometric performance.
2. When a product is superseded by a product with greater lumen output, manufacturers should consider keeping both in the product line.
3. Without the option of product families, some specifiers may delay the use of LED products until these options become available.
4. Manufacturers may find the development of complete product families too costly given the rapidly changing LED market. However, manufacturers who can provide product families may find increased LED product specifications in commercial applications.
5. Developing one or more forms of relative testing standards may help manufacturers manage the cost of testing.

3.4 Lesson 4: The Range of Color Quality Available with LED-Based Products and the Limitations of Existing Color Metrics May Confuse Users

Unlike incandescent or halogen lamps, where color quality is very similar from one product to another, LED lamps can exhibit a wide variety of color appearance and color rendering attributes, which may confuse users. The emergence of LED technology has increased awareness of the limitations of existing color quality metrics and spurred the development of new metrics, further complicating efforts to identify the level of color quality that would be acceptable to most users and ensure widespread adoption of the technology.

3.4.1 Significance

Meeting customer expectations is paramount to widespread adoption of LED technology. While the availability of products with a range of color qualities may be an asset in one sense, the variability also presents an impediment to unknowledgeable users who are seeking to replace familiar products. In some cases, this has led to purchased products not meeting expectations, even though acceptable products may have been available. In different ways, the concern over color quality variation is present for both consumers purchasing lamps for residential applications and professionals specifying lamps for commercial applications. In some specific applications, such as roadway lighting, color quality may be less of a concern, but the accuracy of color metrics is still important.

3.4.2 Background

LED products can be engineered to produce white light across the full range of correlated color temperatures (CCTs), typically from 2700K to 6500K—not to mention varying values of D_{uv} for any given CCT.[1] This is very different from the incandescent or halogen lamps that many LED products are intended to replace—which are almost all between 2700K and 3000K (and have very small D_{uv} values). The range in CCT for LED-based products also exceeds the typical range for high-pressure sodium (HPS) or metal-halide-based streetlights, and is similar to what is available for fluorescent lamps.

Given the efficacy advantage of converting less energy to long-wavelength red emission, higher-CCT LED products tend to be more prevalent than higher-CCT CFLs, and in general were marketed and specified more frequently in the early years of LED adoption compared to CFLs. This was partially because LED products needed to have the highest efficacy possible to compete with other technologies and to provide enough life-cycle cost savings to justify higher purchase prices. Rising efficacy and the more widespread availability of lower-CCT products have provided some relief for this issue. Nonetheless, for some users, LEDs have been stigmatized as providing blue light, despite the availability of products with a full range of color qualities.

Beyond color appearance, LED lamps have more variability in the color rendering capability than most other technologies. All incandescent lamps have a color rendering index (CRI) near 100, and

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[1] DOE. 2012e. *LED Color Characteristics*. Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf.

CFLs—with color quality that disappointed many consumers[1]—almost all have a CRI in the low 80s. This makes for easier decisions for specifiers and purchasers. A similar case is true for HPS, metal halide, and fluorescent lamps, which are all predominantly available in one CRI range. In contrast, it is easy to tune the spectral power distribution (SPD) of an LED to produce a chosen CRI. Over time, the market for interior products has largely settled on CRIs in the low 80s—similar to fluorescent lamps—but there is ongoing debate as to whether this is appropriate, given the relative ease—albeit often with modest efficacy tradeoffs—of achieving a higher CRI. A small percentage of products already have a CRI in the 90s.

Reliance on existing metrics, like CCT and CRI, has posed another challenge for LED technology. CCT[2] and CRI[3] were developed approximately 50 years ago, when the types of available light sources were substantially different. The context and purpose of the development of CRI differs from how CRI is used today, as are the capabilities to repeatedly perform complex calculations and the general state of lighting calculation methodology. LED products can have substantially different SPDs compared with conventional light sources, which can stress the capability of the CRI metric. Additionally, LEDs can easily be engineered to have a wide variety of chromaticities, either near or away from the black body locus.[4]

3.4.3 Challenges

The challenge posed by the variety of color quality attributes for LED products is multifaceted, and includes performance and measurement concerns, as well as communication concerns. In terms of performance and measurement, product variation can mean that the light emitted by two different model lamps having the same nominal CCT does not look the same. Given other concerns with the present state of the LED market—such as the lack of complete product families from some manufacturers—this can make it difficult to specify varying types of LED products for the same space. To address this concern, the American National Standard Lighting Group (ANSLG) and National Electrical Manufacturer's Association (NEMA) established standard C78.377-2008 (subsequently updated in 2011), *American National Standard for Electric Lamps: Specifications for the Chromaticity of Solid State Lighting Products*,[5] which established D_{uv} as a metric to quantify the distance of a source's chromaticity from the black body locus. This metric partially filled the information gap, and also drew awareness to such outlying chromaticities, which were sometimes used to increase efficacy at a given CCT. However, typical consumers do not understand this metric.

The development of LEDs for architectural lighting also led to widespread discussion of the limitations of CRI.[6] When LED products first entered the market, there was widespread concern that CRI would not work for LEDs. While some assertions were unfounded, limitations of the metric—which apply to all sources—became prominent and substantial efforts have been made to update, replace, or

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[1] Sandahl, et al., *Compact Fluorescent Lighting in America: Lessons Learned on the Way to Market.*

[2] CIE 15-2004. *Colorimetry*, 3rd edition. International Commission on Illumination, Vienna, Austria.

[3] CIE 13.3-1995. *Method of Measuring and Specifying Colour Rendering of Light Sources*. International Commission on Illumination, Vienna, Austria.

[4] DOE, 2012e. *LED Color Characteristics.*

[5] ANSI ANSLG C78.377-2011. *Specifications for the Chromaticity of Solid State Lighting Products*. National Electrical Manufacturers Association, Rosslyn, VA.

[6] Houser KW, M Wei, A David, MR Krames, and XS Shen. 2013. "Review of measures for light-source color rendition and considerations for a two-measure system for characterizing color rendition." *Optics Express* 21(8).

augment CRI. More specifically, given the color sample set and methodology used in calculating CRI, it does not always accurately portray the color rendering capability of a source, especially when there are sharp changes in the spectral content of a source over a narrow range of wavelengths. Importantly, CRI is only intended to measure fidelity, comparing a test source to a reference source; it does not indicate preference for a given SPD. This characteristic is misunderstood by many people.

Although several new color rendition metrics have been proposed that address some or all of the identified issues with CRI, to date none has been adopted by any standards or professional organization (e.g., the International Commission on Illumination [CIE] or the IES). Although the reasons for the impasse are varied, some may include the complexity of the issue, including a desire to shift to a metric that accounts for both fidelity and preference, competing opinions of separate research groups, and the potential changes to the performance ratings of existing lamps.

A separate challenge related to color quality and LEDs is effectively communicating product information to unknowledgeable consumers. It is important to include CRI, CCT, and a color scale on products to help the consumer understand the variability of LED products and increase the chance that the consumer will select an acceptable product. Currently, the Federal Trade Commission only requires the listing of CCT; however, market factors and competition may encourage the inclusion of CRI on packaging. While providing CRI, CCT, and a color scale gives consumers additional information, it still may not be enough to completely quantify color quality. Even with complete color quality data on product packaging, successfully purchasing an appropriate product relies on the education of the purchaser.

Written descriptors of color appearance are also prominent (e.g., warm white, soft white, bright white, cool white, daylight white), but their use varies among manufacturers, who sometimes refer to different CCTs with the same descriptors. Further, some terms are ambiguous, which is likely to confuse purchasers more.

A final challenge related to the wide variation of LED product color quality—and in a sense related to the ease of engineering the output of LED products—is determining what level of color quality will be acceptable to most users, resulting in mass adoption of the technology. Due to the typical performance of fluorescent lamps, a minimum CRI of 80 has become the de facto standard for commercial interiors. However, incandescent lamps with a CRI near 100 remain the benchmark for most residences, at least for now. As LEDs transition from a niche, energy-saving product to widely deployed product in a range of applications, it will be important to ensure the widespread availability of products with a desirable CRI. However, there is little research to support choosing a specific value at this time—even if ignoring the limitations of CRI as it relates to color preference. As documented in the LED Lighting Facts database,[1] most LED products intended for interior use have a CRI in the 80s, which meets ENERGY STAR and DLC QPL requirements. However, the California Energy Commission recently published the Voluntary California Quality LED Lamp Specification, which establishes a minimum CRI of 90[2]; the widespread effect of this action remains to be determined.

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[1] Lighting Facts database available online at: http://www.lightingfacts.com/.

[2] CEC. 2012. *Voluntary California Quality Light-Emitting Diode (Led) Lamp Specification: A Voluntary Minimum Specification for "California Quality" LED Lamps*. California Energy Commission, Sacramento, CA. Available at http://www.energy.ca.gov/2012publications/CEC-400-2012-016/CEC-400-2012-016-SF.pdf.

3.4.4 Implications for the Future

1. Retailers should consider continuing their efforts to provide clear information regarding color quality, especially the difference between CCTs.
2. Efforts to improve the consistency of information on product packaging should continue.
3. The industry should consider establishing effective color communication tools to simplify product selection and thus improve purchaser satisfaction.
4. The lighting research community should consider establishing performance criteria for color rendering, perhaps application-dependent, that will ensure acceptability of the technology—based on color quality—to a majority of users.
5. Standards organizations should consider establishing tighter tolerances for chromaticity bins to reduce product-to-product variability at the same CCT, making it easier to specify various LED products in the same space.
6. Revised, new, or additional color rendering metrics are needed to accurately characterize the color rendering capability of all light sources, in the areas of fidelity, preference, and/or discrimination. Ideally, such metrics would include a consumer-oriented aspect that simplifies complex information. This effort will require cooperation throughout the lighting industry, including DOE, researchers, manufacturers, and specifiers. In the meantime, CRI may be used, but its limitations must be better communicated and understood by lighting consumers.
7. The lighting research community should consider investigating thresholds for color quality acceptance, which will enable standards organizations and policymakers to establish meaningful criteria that can balance color quality with energy-efficiency goals.

3.5 Lesson 5: The Color Delivered by Some LEDs Shifts over Time, Enough to Negatively Impact Adoption in Some Applications

LEDs hold the promise of extended lifetimes, but lighting quality must be maintained over that period for the potential to be realized. Some LED-based products have exhibited unacceptable color shift after only a fraction of their rated lifetime,[1] constituting a product failure for applications where color quality is important. A lack of standard procedures for predicting and reporting color stability performance has contributed to user uncertainty—potentially limiting adoption and making it more challenging for manufacturers to provide warranty coverage for color shift.

3.5.1 Significance

Poor color maintenance can be a substantial problem in applications where color quality is important, including

- museum and gallery lighting
- architectural façade lighting
- retail display lighting
- healthcare lighting
- hospitality applications
- cove and wall wash lighting
- downlighting in commercial and residential applications.

If the color of LED products changes too much over time, to the point where it becomes unacceptable to the user or building owner, the products must be replaced. This may result in the product failing to provide the calculated payback, and will always hurt the reputation of LEDs. While many users remain unaware of the potential for color shift due to a lack of data, early installations with growing hours-of-use may soon help to identify the scope of the issue. If the issue is not addressed, LEDs may be limited to applications where color quality is less of a concern, as has occurred with other source types known to shift color over time, such as metal halide.

3.5.2 Background

Typical phosphor-coated white LEDs, the most prominent type on the market today, create white light by mixing the emission from a blue "pump" LED and a broad-emitting phosphor, with peak emission in the yellow region. If the ratio of the two emissions changes, color shift will occur along a blue-yellow axis. As LED technology has developed, the way phosphors are used has changed

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[1] DOE. 2013f. *Color Maintenance of LEDs in Laboratory and Field Applications.* Prepared by Pacific Northwest National Laboratory (PNNL-22759) for DOE SSL Program's Gateway Demonstrations, Buildings Technology Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C. September 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_color-maintenance.pdf.

substantially. This has resulted in variable color maintenance performance—although it is generally improving.[1]

Physical changes—such as delamination, settling, or curling of the phosphor—are the primary cause of color shift at the LED package level. (Non-phosphor-coated and hybrid packages may have additional characteristics to consider.) The changes may occur naturally over time, but they can also be exacerbated by manufacturing defects or poor thermal management in the luminaire. Aside from physical changes to the LED package, color shift may also result from changes to other components of the complete LED product, most notably the optical system. Like lumen maintenance, heat is generally detrimental to color stability.

Early adoption of LEDs mostly took place in applications where color stability is not critical, such as roadway and parking lot lighting. In these early applications, the incumbent systems used HID sources that either offer poor color quality—such as for HPS lamps—or for which variability in color consistency and color stability was a known characteristic—such as with metal halide lamps. As LED manufacturers look to expand market penetration across a wide breadth of applications, including those with high standards for color quality, ensuring or providing warranty coverage for acceptable color stability will help to ease the concerns of purchasers.

The ability of LED products to maintain chromaticity over very long lives has been demonstrated by the L Prize competition winner,[1] but not all available products perform at that level. In fact, performance can vary significantly.

3.5.3 Challenges

While the industry reacted quickly to adopt color consistency metrics for LEDs (i.e., initial lamp-to-lamp color variation) similar to those used for fluorescent sources, test procedures and relevant performance metrics for color stability have not yet been established. IES LM-80-08 details procedures for measuring of chromaticity for LED packages over time, but there is no method analogous to IES TM-21-11—which is for predicting future lumen maintenance from measured data—for predicting color maintenance over time. This has resulted in a dearth of data on color maintenance, especially since color shift may begin after the LM-80-08 measurement period has concluded, leaving specifiers and consumers little option but to overlook the concern or plan for a shorter LED usable life.

The lack of prediction methodology is particularly relevant given the rapid evolution of LEDs. Measuring chromaticity to the end-of-life for LED packages is impractical given the longevity of the products and the rate at which the LED package evolves. In other words, an LED product generation is likely to be discontinued well before data collection can be completed. This challenge may abate in the future as development slows, but that time is likely far into the future.

Another challenge to the widespread availability of color shift data is the dependence of performance on the product into which an LED package is assembled. Thermal management is critical to chromaticity (and lumen) maintenance, and poorly designed lamps or luminaires can compromise the performance of an otherwise acceptable LED package. Given the wide variety of products that use a given LED package, the variation can be large and testing all combinations of products is unrealistic.

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[1] DOE. 2013f.   *Color Maintenance of LEDs in Laboratory and Field Applications.*

The design and manufacturing of LED packages is improving, and some data suggest that newer LED packages have significantly better color stability than older generation packages.[1] This is a step in the right direction, but without standardized and readily available data and instruction on how to use that data, specifiers may still have difficulty identifying which products are likely to perform better.

Warranty coverage could alleviate the concerns of users and specifiers, but color shift is rarely covered for currently available products, in part because of the lack of standards, but also because it is difficult to articulate how color shift should be documented. Most purchasers of LED products do not have the budget or sophisticated equipment to take photometric measurements of the products before and after a problem may occur. Further, there is no established threshold for an acceptable level of shift—although this could happen at the individual product level—and there is no consensus on the baseline for a color shift failure. That is, it must be established whether comparisons should be made to a lamp or luminaire (or its listed performance) in the new state, or to the performance of other lamps/luminaires with the same hours-of-use.

3.5.4 Implications for the Future

1. Color stability measurement and prediction methods are needed to enable performance comparisons between products.
2. There is a need for energy-efficiency programs and product information qualification standards that include color stability metrics.
3. Efforts toward establishing new methods and metrics for color stability assessment with industry and research organizations should continue. With standards and metrics, color shift can rightfully be included in a yet-to-be-developed comprehensive lifetime rating for LED products.
4. LED products need to comply with accepted tolerances for color stability.
5. Manufacturers and related industry committees should continue to share test methods and data for use by standards organizations.
6. Manufacturers should consider including color shift in product warranties.
7. Standards organizations should consider incorporating the new knowledge being generated by research organizations and industry into establishing new standards for color stability. The widespread adoption of the ANSI standards for color consistency provides a good case study for the effectiveness that a standard rating system can have.

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[1] DOE 2013f. *Color Maintenance of LEDs in Laboratory and Field Applications.*

3.6 Lesson 6: Some LEDs Flicker Noticeably, Which May Negatively Impact Adoption in Some Applications

The market adoption of LEDs is exposing the need to measure and report the flicker performance of specific products, especially since there is significant variation and severity in flicker for LED sources. Flicker is primarily a function of the LED driver design. Flicker is present in many products at full output, and dimming can induce or increase flicker, due to either the method used to implement dimming in the LED source or compatibility issues with a specific dimmer. The lighting industry needs to develop, adopt, and apply standards to limit flicker that may lead to health concerns and reduced task performance.

3.6.1 Significance

The effects of flicker range from mild to severe and affect health (headaches, eyestrain, neurological problems—including epileptic seizure[1]), diminish visual performance (reducing performance on visual tasks), cause distraction (phantom array effects seen while driving could draw the eye away from a more important situation), create work hazards (strobe effect stopping or slowing apparent motion of machinery), and provoke disruptive behaviors in individuals with autism. Due to this wide scope, flicker matters greatly for general lighting. The issue of flicker applies to almost all market segments, except outdoor applications where light levels are very low. Example areas where health or task performance are especially critical include general lighting and task lighting in healthcare facilities, classrooms, offices, retail spaces, and industrial spaces. It is less important for applications such as general illumination of roadways and parking lots. [2,3]

3.6.2 Background

Flicker is the repetitive change or modulation in luminous flux and intensity that occurs in all conventional light sources to some degree, whether perceived or not. Visible flicker is luminous modulation that is sensed and *perceived*, as opposed to invisible flicker, which is sensed but not perceived. Photometric flicker, in contrast to electrical flicker, is characteristic of the light source itself rather than being caused by disturbances in electrical input.

Conventional lighting technologies exhibit flicker in a fairly similar manner such that in many cases the issue can be remediated with appropriately designed ballasts. For example, magnetically ballasted fluorescent lamps flicker in a consistent way, and high-frequency electronic ballasts virtually eliminate that flicker. There is significant variation and severity in flicker for LED sources. The LED products most likely to flicker include AC LEDs, DC LEDs with simple/inexpensive drivers, and integral lamp LEDs on some electronic transformers. Dimming an LED source can increase or induce flicker,

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[1] The range of flicker that can affect seizures is 3 to 70 Hz. This is not the normal range of flicker for LED products in the U.S.; however, some past products that used unidirectional strings of LEDs with AC produced 60 Hz flicker, and some holiday lights still use this approach. In addition, the failure mode of some LED systems can produce low frequency flicker.

[2] DOE. 2013g. *Flicker*. Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/flicker_fact-sheet.pdf.

[3] Poplawski M and N Miller. 2011. *Exploring flicker in Solid-State Lighting: What you might find, and how to deal with it*. Prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy, Washington, DC. Available at http://www.e3tnw.org/Documents/2011%20IES%20flicker%20paper%20poplawski-miller-FINAL.pdf.

especially when dimmed with a phase-cut dimmer or when the driver uses a pulse-width modulation (PWM) technique to reduce LED light output.

IES has defined two metrics for flicker: Percent Flicker and Flicker Index. Percent Flicker is on a 0-100% scale, is older and easier to calculate, and thus is more established and used. Flicker Index is on a 0-1.0 scale. Both account for average and peak-to-peak amplitudes, but only Flicker Index accounts for shape and duty cycle. Neither incorporates the critical element of frequency. For conventional sources, the maximum observed Percent Flicker is on the order of 40% and the maximum observed Flicker Index is roughly 0.15. Some LED products may have equal or better performance compared to conventional sources, while others clearly exhibit much more dramatic flicker characteristics. There are no well-defined thresholds that identify problematic flicker for specific applications or populations.[1,2]

3.6.3 Challenges

There are no standardized flicker measurement procedures in the industry, so photometric labs and manufacturers are unable to report flicker waveforms and flicker metrics consistently. Because flicker metrics are not routinely reported, lighting specifiers are forced to discover or detect flicker in other ways. Keeping in mind that the effects of flicker depend on the ambient light conditions, sensitivity of the individuals using the space, and how much eye movement is involved, other methods of discovering or detecting flicker include the following:

- Quantification:
  - ask driver manufacturers to report modulation frequency, based on instrument readings, and
  - ask manufacturers to report the dimming technique used by the LED driver. If PWM is used, and it produces 100% light modulation, then frequencies higher than 500 Hz, and possibly higher than 2000 Hz, are required to completely eliminate neurological detection. A combination of PWM and constant current reduction (CCR) dimming techniques in drivers can reduce flicker detection considerably, even at frequencies as low as 120 Hz.
- Detection:
  - observe the product in person with the same driver/transformer and dimming setting of the final installation and visually evaluate the system with flicker-sensitive clients, or
  - use a flicker wheel/spinning top under the light source; if it flickers, a checkerboard pattern will appear, or
  - rapidly wave fingers or a shiny metal rod in the light produced by the LED. Flicker will produce a stroboscopic effect, making multiple fingers or rods visible, with blank space in between the brighter images.

Developing a predictive and technology-neutral flicker metric (which in turn needs to be calibrated by human factors and medical research) and a risk assessment for difference applications will be challenging. IES and CIE are considering the development of a measurement standard and metric, and an IEEE PAR1789 committee intends to provide recommended practices for applying flicker information.

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[1] DOE, 2013g. *Flicker*.

[2] Poplawski and Miller. *Exploring flicker in Solid-State Lighting*: *What you might find, and how to deal with it*.

LED drivers have to strike a complicated balance between low flicker and many other factors (e.g., cost, size, efficiency, power factor, lifetime). Additional testing may be necessary to identify whether or not the interaction between LED products and some control equipment (phase-cut dimmers, in particular) results in flicker.[1,2]

3.6.4 Implications for the Future

1. Standards organizations should consider developing a measurement procedure for flicker, and a flicker metric that accounts for frequency, so manufacturers can communicate product performance.
2. Manufacturers should consider evaluating and communicating the flicker performance of their products both at full output and when dimmed, accounting for dependencies on the selection of control equipment, if applicable.
3. The lighting research community should consider performing research to establish thresholds for detection of (and perhaps objection to) flicker, risk of neurological impacts, and degradation in task performance for different applications.
4. The lighting research community should consider working together with standards organizations to develop recommended practices for specifying LED product flicker performance for different populations and applications.

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[1] DOE, 2013g. *Flicker*.

[2] Poplawski and Miller. *Exploring flicker in Solid-State Lighting*: *What you might find, and how to deal with it*.

3.7 Lesson 7: LEDs Can Cause Glare, Which May Negatively Impact Adoption in Some Applications

The market adoption of LEDs has grown rapidly in product categories such as streetlighting, parking lot luminaires, and directional lamps including PAR and MR lamps.[1] These lighting applications require high luminous intensities from relatively small sources. Adoption may be slowed in these and other exterior and interior applications if specifiers and users feel that LEDs produce too much glare relative to incumbent light sources that are larger and more diffuse than LEDs.

3.7.1 Significance

Adoption into important applications, many of which represent significant national energy use, may stall if LEDs earn a reputation for producing uncomfortable glare that reduces visibility. Applications where glare could limit market penetration of LEDs include

- pedestrian-scale exterior lighting
- interior high bay
- downlighting
- residential lighting
- commercial and institutional interior lighting where linear fluorescent lamps are the incumbent light source.

3.7.2 Background

The potential for glare from a light source increases both with greater lumens and with smaller source size; thus, the drive for higher light output from inherently small LEDs increases the potential for glare. Market pressure to reduce LED system costs often leads manufacturers to provide a target lumen package in a luminaire by using fewer, higher output LEDs, which also escalates potential glare. Without proper optical management, glare can be uncomfortable and even disabling for a person in a given application.

The IES luminaire classification system for exterior luminaires established a standard method for rating the backlight, uplight, and glare (BUG) from a luminaire based on standard photometric data; this rating system primarily applies to exterior roadway, area, and parking lot applications.[2] For interior applications, longstanding glare rating systems such as Visual Comfort Probability (VCP) and the Uniform Glare Rating (UGR) are generally considered not applicable or unreliable for common luminaires and systems in use today, in part because inherent assumptions in these ratings often are not accurate for contemporary systems. As a result, it is very difficult to compare the rated glare of LED systems to that of incumbent systems for applications listed above. Specifiers and users who select an LED product based only on rated data may therefore be surprised if they find that the LED system

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[1] DOE. 2013h. *Adoption of Light-Emitting Diodes in Common Lighting Applications*. April 2013 (Revised May 2013). Prepared by Navigant Consulting, Inc. for Solid-State Lighting Program, Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-adoption-report_2013.pdf.

[2] IES. 2011. *The Lighting Handbook*, 10th edition. IES-HB-10-11, Illuminating Engineering Society, New York, NY.

produces more glare than indicated. If this becomes a common experience, adoption of LED technology into these applications may be significantly slowed.

In exterior applications, the early adoption of LED solutions was primarily driven by energy and maintenance savings relative to HID light sources. In these applications, the incumbent light source was a high lumen, relatively small source that was mounted high above the normal line of sight. The IES BUG luminaire classification system provides a standard way for assessing glare for luminaires used in these applications. The DOE Next Generation Luminaires (NGL) outdoor competition utilized the glare ratings along with photometric and perceptual measurement from the NGL judges for evaluating LED products.[1]

3.7.3 Challenges

Considering that some of the glare issues have been escalated by the drive to increase lighting output (e.g., using higher output LEDs) or reduce cost (e.g., using fewer LEDs), one challenge to dealing with glare will be finding the balance between potentially competing goals. LED glare issues have been notable in applications where glare is problematic for incumbent technologies; thus, the challenges are not restricted to LEDs. For example, LEDs have also become a popular alternative to directional sources such as the incandescent and halogen PAR and MR lamps commonly used in retail display, museum, and other commercial and residential accent and display lighting applications. For these applications, LEDs offer substantial reductions in input power and increases in operating lifetime. The incumbent light sources produce relatively high intensities from apparent source sizes of 2-inch diameter and greater, and create glare concerns themselves. LED products designed to replace these sources typically attempt to match their intensity, but often from a much smaller apparent area, producing higher luminance and glare potential.

LED penetration into the large commercial applications using linear fluorescent lamps faces high hurdles represented by the efficacy and lifetime of the incumbent technology, and can be further hindered by increasing glare potential. Linear fluorescent lamps are relatively large, diffuse light sources, whose applications are often very sensitive to glare concerns. Even the transition from T8 to T5 fluorescent lamps created glare issues for specifiers and users, since the T5 lamp has a much smaller surface area than the T8 lamp. Even though many fluorescent applications use diffusing media in the luminaires, replacing the linear fluorescent lamps with LEDs in these luminaires can increase the potential for glare. For example, a recent DOE troffer study found that new and retrofitted troffers with odd or distracting patterns, or pronounced bright patches on lenses, were deemed more glaring than those with softer gradients.[2]

LED approaches that use mixing chambers, remote phosphors, and diffusing media in front of emitters can help mitigate the glare potential. However, because there is no widely accepted glare metric for these sources and applications, there is no convenient way for specifiers and users to assess the potential for glare from product ratings. Instead, they typically depend on mockups to evaluate glare.

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[1] NGL provides information on its evaluation criteria and judging process online by year and category. See http://www.ngldc.org/.

[2] DOE. 2013i. *CALiPER Exploratory Study: Recessed Troffer Lighting*. . Prepared by Pacific Northwest National Laboratory (PNNL-22348) for the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. March 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_recessed-troffer_2013.pdf.

These same principles apply for LED downlights, where again the LED solutions attempt to match the output of larger, more diffuse sources, creating greater glare potential. Luminaire manufacturers can use lenses, louvers, and baffles to minimize the glare, but these optical elements also reduce the optical efficiency of the luminaire, which in turn reduces the luminaire efficacy. Because luminaire efficacy is measured as part of a standard photometric test, it is widely reported on manufacturer data sheets and can be a key criterion for product selection. Conversely, the lack of a standard glare metric prevents any assessment of glare from information on a data sheet. A product with good glare control but lower efficacy can be at a competitive disadvantage as a result.

With regard to measuring glare, recent experiences have shown that the BUG ratings may not be relevant for pedestrian-scale exterior lighting systems. For example, a GATEWAY study of walkway lighting on a college campus and street and pathway lighting in a residential arts community suggests that the photometric elevation angles of 80° to 90° from nadir as glare angles in the BUG ratings are not predictive of pedestrian glare response.[1] More study is needed, but LED luminaire manufacturers may need to reexamine product light distributions, as the luminous intensity at angles from 0° to 75° may be more important for pedestrian applications.

3.7.4 Implications for the Future

1. The industry should continue work on developing LED solutions that do not increase glare relative to the incumbent technologies.
2. DOE and research organizations should consider routinely including glare assessments in product and application evaluations and demonstrations. Where a standard glare assessment methodology is not available, these organizations could work toward establishing new methods and metrics for glare assessment.
3. Manufacturers should continue to optimize their use of optical solutions that reduce source luminance, especially for applications where the incumbent light source is much lower in luminance than a typical LED.
4. Energy-efficiency programs should consider the implications of glare control when establishing efficacy standards for products. Since glare control techniques usually involve blocking light at angles most likely to cause discomfort, they almost always reduce the optical efficiency of the luminaire, which in turn reduces luminaire efficacy. A luminaire with no optical techniques for glare control will more easily meet minimum efficacy criteria than a luminaire with glare control.
5. Standards organizations should consider incorporating the new knowledge being generated by research organizations into establishing new metrics for glare assessment. The widespread adoption of the IES BUG ratings in the exterior lighting community provides a good case study for the effectiveness of a standard rating system. Similar systems are needed for the other applications discussed in this lesson.

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[1] DOE. 2013j. *Pedestrian Friendly Outdoor Lighting*. Prepared by Pacific Northwest National Laboratory (PNNL-23085) for DOE SSL Program's Gateway Demonstrations, Buildings Technology Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. December 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_pedestrian.pdf.

3.8 Lesson 8: Achieving High-Quality Dimming Performance with LED Lamps Is Difficult, but Improving

Consumers have high expectations when it comes to dimming LED sources, since the technology is promoted as being inherently controllable. This is particularly true for LED lamps that are intended for applications that have historically been served by incandescent or halogen sources. While some LED sources deliver incandescent-like dimming performance, user experiences have been typically unpredictable and frequently unacceptable. This is especially true when phase-cut dimmers are used; in such instances, performance commonly depends on the specific make and model of dimmer, lamp(s), and low-voltage transformer (if applicable). Identifying combinations that will work well is complicated at best, and often impossible without a full circuit-level mockup. While new products continue to perform better than their predecessors, multiple approaches are likely necessary to fully overcome this challenge to market adoption.

3.8.1 Significance

The ability to dim LED sources holds tremendous potential for delivering even greater energy and cost savings and a wide range of other benefits, including[1]

- increased visual task performance
- enhanced ambience
- enhanced space flexibility
- lighting matched to task and/or personal preference
- demand response/load shedding
- potentially improved light source efficacy and lifetime.

The issue of dimmability is significant for both residential buildings, where phase-cut dimming is dominant, and commercial buildings, where phase-cut dimming is commonly used to control replacement lamps in various applications, such as hotel rooms, conference rooms, and retail display.[1,2]

3.8.2 Background

While there is no standard definition of "dimmable," the ability of all incandescent sources to dim smoothly and continuously down to light levels below 1% when operated by any phase-cut dimmer serves as the unofficial high-quality benchmark. The comparatively poor dimming performance of many of today's LED lamps is limiting their market adoption and damaging the perception of LED sources as inherently controllable. LED dimming performance is typically determined by the design of the LED driver. While all incandescent products are "dimmable," LED products must be designed to dim. At present, the LED lamp market contains products that are "not for use with dimmers" as well as products that make various claims of "dimmability." Such claims vary significantly; while some products advertise

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[1] DOE. 2012f. *LED Dimming: What you need to know*. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/dimming_webcast_12-10-2012.pdf.

[2] MSSLC, *Model Specification for Adaptive Control and Remote Monitoring of LED Roadway Luminaires*.

that they “dim like incandescent” and others specify minimum achievable light levels (e.g., “dims to 10%”), many do not further elaborate on how well they can be expected to perform.

While many LED lamps are not designed to dim as well as incandescent sources, the poor performance seen in the field is frequently not the result of LED source capability, but rather the result of LED source compatibility issues with legacy equipment. Such issues are most commonly seen when trying to dim LED lamps with phase-cut dimmers, which were fundamentally designed to control incandescent sources. LED lamps intended to replace some halogen sources (e.g., MR16) have the additional challenge of needing to be compatible with both a low-voltage transformer and a dimmer. Compatibility issues can result in a host of problems, including erratic dimming behavior, a limited ability to dim to low levels, objectionable flicker, and audible noise.[1,2]

3.8.3 Challenges

LED lamps must be designed to achieve incandescent-like dimming performance to replace those sources in many applications. While this level of performance is technically feasible, there are many barriers limiting its realization:

- Dimmable LED lamps cost more to develop and manufacture; as a result, not all products are dimmable, and those that are deliver varying levels of performance.
- Most existing dimming controls were designed for incandescent sources.
- LED sources have significantly more complex interactions with phase-cut dimmers, the most commonly deployed type of dimming control, which leads to significant technical issues.
- Variation in the installed stock of phase-cut dimmers throughout the commercial and residential markets makes addressing these interactions particularly challenging.
- Dimming approaches other than phase-control have their own challenges and market barriers, which are limiting their adoption as alternatives.

Evidence of these challenges includes the following:

- LED lamp manufacturer claims of dimming performance are often inconsistent with observed performance. [1,2,]
- Market survey results suggest consumers are not satisfied with the observed dimming performance of many of today’s products.[3]
- Laboratory evaluation of various LED lamp and phase-cut dimmer combinations has identified a wide range of technical issues that can lead to undesirable dimming performance.

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[1] DOE. 2012f. *LED Dimming: What you need to know*.

[2] DOE. 2013k. *Dimming LEDs with Phase-Cut Dimmers: The Specifier’s Process for Maximizing Success*. Prepared by Pacific Northwest National Laboratory (PNNL-22945) for DOE SSL Program’s Gateway Demonstrations, Buildings Technology Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. October 2013. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_dimming.pdf.

[3] McGaraghan MD et al. 2013. “LED Lamp Quality: Codes and Standards Enhancement (CASE) Initiative for PY 2013: Title 20 standards Development.” *Analysis of Standards Proposals for LED Replacement Lamp Quality*. Docket #12-AAER-2B. July 29, 2013.

- Industry has steadily acknowledged and made efforts to address the occurrence and reduce the likelihood of technical issues leading to undesirable dimming performance, and their impact on market adoption.[1,2,3]

3.8.4 Implications for the Future

1. Retailers and organizations promoting the purchase of dimmable replacements for LED integral lamps should consider increasing efforts to educate consumers and manage expectations by providing better information to buyers, alerting them to potential dimming problems and providing clear recommendations for how to minimize the likelihood of problems.
2. Industry and organizations promoting the purchase of dimmable integral LED lamps should consider working together to develop better, clearer, and more consistent means for communicating dimming guidance to buyers. The DOE LED Lighting Facts program offers one example of both required content and format for such guidance.
3. The industry should consider working to develop LED lamps capable of high-performance dimming down to levels below 1%, with incandescent-like behavior and maintained high efficacy over the dimming range.
4. The industry should continue efforts to develop greatly improved predictability of dimming performance for specifiers and buyers.
5. Industry should continue the development of advanced dimming circuitry compatible with phase-control, focusing on improving performance with as much of the existing base of installed dimmers as possible.
6. Industry should continue efforts to develop forward-looking standards for phase-cut dimmers and lamps. NEMA SSL-7a is an important step in the right direction, but the follow-up standard (SSL-7b) is still needed.
7. Industry should continue developing and promoting alternative approaches (e.g., wireless, power-line carrier), which have the potential to avoid many of the compatibility issues inherent to phase-control, and may ultimately be necessary to achieve desired performance goals.
8. DOE should continue to study, report, and challenge manufacturers to develop and market new dimming solutions.

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[1] NEMA LSD-49. *Solid State Lighting for Incandescent Replacement—Best Practices for Dimming*. National Electrical Manufacturers Association, Arlington, VA. Available at http://www.nema.org/Standards/Pages/Solid-State-Lighting-for-Incandescent-Replacement-Best-Practices-for-Dimming.aspx.

[2] NEMA SSL 6. *Solid State Lighting for Incandescent Replacement—Dimming*. National Electrical Manufacturers Association, Arlington, VA. Available at http://www.nema.org/Standards/Pages/Solid-State-Lighting-for-Incandescent-Replacement-Dimming.aspx.

[3] NEMA SSL 7a. *Phase Cut Dimming for Solid State Lighting: Basic Compatibility*. National Electrical Manufacturers Association, Arlington, VA. Available at http://www.nema.org/Standards/Pages/Phase-Cut-Dimming-for-Solid-State-Lighting-Basic-Compatibility.aspx.

3.9 Lesson 9: Greater Interoperability of Lighting Control Components and More Sensible Specifications of Lighting Control Systems Are Required to Maximize the Energy Savings Delivered by LED-Based Sources

The inherent controllability of LEDs could deliver unprecedented energy savings and lighting quality, optimized for the lighting application. Appropriate design is critical to maximizing the success of a lighting installation, and even more so when lighting controls are integrated into the installation. However, a well-designed lighting control system may not ultimately meet user needs and expectations if it is improperly installed and not fully commissioned, or is difficult to modify or augment to meet user needs that have changed or become more realized over time. The delivery of energy savings and lighting performance that both maximizes the potential offered by LEDs and meets user needs over time will likely require continuous improvement in the way lighting controls are designed and specified. The ability and willingness of lighting users to learn how to operate and modify sophisticated lighting controls systems varies significantly. Lighting control specifications should focus on delivering solutions that suit both the use and the user. Greater interoperability of lighting control components can increase the chances of proper installation and commissioning, and reduce user risk during specification.

3.9.1 Significance

The controllability of LEDs, including the ability to adjust output level, color temperature or chromaticity, and undergo frequent on/off switching without detriment, significantly enhances the energy savings LEDs are capable of providing. While adjustments that result in lower power levels directly impact energy savings, adjustments that result in improved lighting quality or otherwise increase user satisfaction can also impact energy savings if they increase the adoption of LED technology. The incumbent technology for many applications is not easily dimmed or requires expensive upgrades to enable dimming; in many cases, this has stymied the deployment of controls for those applications. For example, difficulties dimming HPS and HID sources have hindered the use of lighting controls in outdoor applications, and the significant cost difference between standard and dimmable fluorescent ballasts has limited the energy savings achieved from deploying controls in some environments.

No lighting technology has been capable of delivering variable color temperature or chromaticity as effectively and (potentially) efficiently as LED. LED technology is poised to bring high-performance, (potentially) low-cost control of output level, and/or color to many lighting applications for the first time. Integrating lighting controls with a communication network offers additional opportunities to provide value to users and perhaps save money and additional energy. The ability to track real-time energy use and report failures can reduce maintenance costs and save energy in some instances, such as when outdoor lighting dayburners are identified. As the LED lighting market matures, maximizing the energy savings delivered by the installation of LED lighting systems, which if designed well could have unprecedented field life, will become increasingly dependent on maximizing the successful installation of lighting controls that suit the use and the user.

3.9.2 Background

While LEDs are inherently controllable, they are not the only controllable lighting technology. Incandescent sources dim wonderfully and can be controlled by inexpensive equipment (e.g., phase-cut dimmers). However, incandescent sources are inefficient and lose efficacy when dimmed. More efficient HID technologies (e.g., HPS and metal halide) are difficult to dim and can require significant periods following a power shut-off to return to full brightness. Fluorescent sources offer high efficacy and excellent dimming performance when equipped with high-performance (and historically expensive) ballasts, but struggle to deliver the lighting quality required by some applications. Adjusting the color temperature or chromaticity of all these incumbent technologies requires the use of filters, which fundamentally reduce their efficacy.

Lighting controls have been developed and deployed to varying degrees of success for decades. Most control technologies were developed for specific lighting technologies. For example, phase-control was developed for incandescent sources and 0-10V and digital addressable lighting interfaces were developed primarily to control linear fluorescent sources. Multiple strategies exist for using lighting controls to deliver energy savings (e.g., scheduling, daylight harvesting, occupancy sensing, task tuning, and personal tuning) and combining multiple strategies allows for maximum savings. The energy savings and user satisfaction delivered by market-available lighting control solutions has varied significantly; a recent meta-analysis of real-world results in commercial buildings showed a potential variation in energy savings of roughly 40 to 50% for any given strategy, and almost no impact from implementing multiple strategies.[1]

Despite significant research efforts, predicting how much energy savings can be achieved through the implementation of one or more well-established lighting control strategies remains difficult. As summarized by the Lighting Controls Association "…achieving energy savings estimates in practice may require commissioning, including a written controls narrative, verification equipment is installed and aimed in accordance with approved documents, programming and calibration, functional testing, systems manual, end-user training and a plan for periodic recalibration."[2] In addition, factors beyond the choice of strategy and how effectively that strategy is implemented (e.g., how well the selected system works with other [often existing] equipment and how well-suited the solution is for the building and space characteristics, use, and occupants—all of which can change over time) often influence the success of a lighting control installation and the energy savings achieved.

3.9.3 Challenges

Lighting controls cover a broad spectrum of capability and sophistication, ranging from simple wall-box dimmers controlling one lighting circuit to networked building-wide systems that can interface with other (non-lighting) systems and be accessed from anywhere through the internet. Further, the ability and willingness of lighting users to learn how to operate and modify lighting controls varies significantly, which presents a significant matching challenge. Ensuring that a lighting control system well suited to its use (i.e., building, space, occupants) is specified, properly installed, and fully commissioned does not necessarily lead to persistent energy savings. Use characteristics change or sometimes simply become better understood over time, often requiring modification of or augmentation to a lighting controls system. Users are less likely to make changes that prove to be too difficult, time-consuming, or costly,

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[1] Williams AB et al. 2012. "Lighting Controls in Commercial Buildings." *Leukos* 8(3):161-180. Available online at: http://www.ies.org/leukos/samples/1_Jan12.pdf.

[2] Dilouie C. 2013. "Estimating Energy Savings with Lighting Controls." From Lighting Controls Association online publication, available at http://lightingcontrolsassociation.org/estimating-energy-savings-with-lighting-controls.

which leads to reduced user satisfaction and ultimately reduced energy savings over time. In extreme cases, systems may be intentionally defeated or simply turned off.

Lighting control systems have long suffered from the assumption that they are simply "plug and play." This perception poses two major challenges. If insufficient time and attention is given to the design, installation, or commissioning processes, many lighting control systems will not meet user expectations and/or not function optimally. For example, when implementing an occupancy sensing strategy, important design considerations include the placement of the occupancy sensors, the luminaire dimmed level setting when in the "unoccupied" mode, and the occupancy sensor delay setting that determines how long the luminaire stays in the "occupied" mode following a detection. Appropriate time and attention given to the design process can add 30% or more to the energy savings achieved by an LED system installed without such controls. Conversely, failure to adequately address these basic design considerations can essentially render the installed controls and their associated investment useless.[1]

A second set of challenges posed by the "plug and play" misconception include the assumptions that a) lighting control components are compatible with existing infrastructure; b) lighting control components from different manufacturers are interoperable (i.e., work well together); and c) lighting control components that seem to perform the same function and even have similar specifications are, in fact, interchangeable. The frustration caused by these challenges can lead to significant market adoption barriers. For example, the compatibility issues that many LED integral lamps have with the installed base of phase-cut dimmers has led to many early adopters to not trust the dimmability claims of these products. At present, most lighting control systems require the use of proprietary hardware and/or software, thereby requiring the potential user to make a substantial investment in products from a single vendor that then locks them in for future purchases. The user must continue to buy from that same vendor if they want new system components to work well with those purchased previously. This lack of interoperability increases user risk when considering new installations, especially in instances where user needs are not fully understood at the time of specification or are likely to change over time. If the chosen vendor cannot support changing needs, the user may be faced with the decision to start over from scratch or live with an existing, increasingly unsuitable system.

Many lighting controls are marketed as complying with one or more "standards." However, lighting specifiers and users often do not fully understand what some of these standards ensure. For example, the 0-10V standard does not specify when, or even whether, a luminaire should turn off; as a result, when two luminaires are presented with the same control signal, one may turn off, while the other may go to a low lighting level. Similarly, the DALI standard has not historically required compliance testing, leading to different manufacturers developing different "versions" of DALI products, which are often not interoperable.

Interoperability and interchangeability concerns may be less important for relatively small, self-contained lighting systems (e.g., those servicing a conference room or a single parking structure). Conversely, larger-scale building-level or street lighting systems can include thousands of luminaires and other connected equipment spread across numerous locations with different use and geographic

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[1] DOE. 2012g. *Use of Occupancy Sensors in LED Parking Lot and Garage Applications: Early Experiences*. Prepared by Pacific Northwest National Laboratory (PNNL-21923) for DOE SSL Program's Gateway Demonstrations, Buildings Technology Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. October 2012. U.S. Department of Energy, Washington, D.C. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway_sensors.pdf.

characteristics. The higher complexity and variation found in such systems leads to significantly higher risk for users who locks their future to a single vendor. The challenges presented by the lack of interoperability may increase over time as more systems become interconnected in support of net-zero building, smart city, smart grid, and intelligent transportation initiatives.

3.9.4 Implications for the Future

1. The lighting industry should consider continuing its efforts to develop and refine educational and certification programs aimed not only at selecting and designing for control strategies, but at ensuring that the specified lighting control equipment suits both the use and the user, and is correctly installed and fully commissioned. In some cases, simpler is better. Systems with fewer compatibility issues are more likely to be installed correctly and fully commissioned. Similarly, systems that are easier to modify or augment may lead to more persistent energy savings.
2. LED products that deliver on their promise of long lifetime will be in the field, in some cases, for the next 20 years or more. Once installed, the incremental cost required to return to the installation site to add controls may be prohibitive or not in line with payback expectations. The lighting industry should consider exploring all opportunities to maximize the number of LED product installations that incorporate sensibly specified controls. At the same time, the lighting industry should recognize that installations that incorporate controls that are not properly installed; are not fully commissioned; require a degree of user sophistication beyond user capabilities or interest to maintain, modify, or augment; or otherwise do not meet user expectations will only damage the reputation of lighting controls and limit their adoption. In cases where the installation of lighting controls is truly not immediately practical, lighting specifiers and lighting system users should strive to identify and require the installation of “control-ready” LED products that minimize the future hardware, software, and labor costs for installing a control system.
3. The specification of interoperable lighting controls can significantly reduce user risk when first installing a system and maximize the chance that the installed system will continue to meet expectations as user needs change or simply become better understood. Manufacturer consortiums should considering continuing their efforts to develop open-standard specifications and compliance testing programs that allow lighting control products to be brought to market that both offer new features and deliver some level of interoperability. Careful, ongoing attention should be given to balancing the sometimes-conflicting goals of delivering deeper levels of interoperability while allowing for manufacturer competition that encourages innovation and the development of new features. Deeper levels of interoperability should be delivered as the market matures to drive user adoption.
4. Efforts to bring interoperability to the lighting control market are already underway within the ZigBee Alliance, LonMark International, the TALQ Consortium, the Connected Lighting Alliance, and others. Lighting specifiers, lighting control system designers, and lighting system users will likely increasingly demand interoperability (especially if they are installing LED sources) and could help manufacturer consortiums determine what level of interoperability is required at various stages of market maturity. Liaisons with user organizations (e.g., the MSSLC) that can represent the collective voice of specific user communities can aid in both the development of interoperable specifications and the education of what they do and do not deliver. Energy-efficiency organizations that focus their lighting control incentive programs on interoperable equipment may be able to develop cost-effective programs more efficiently and accelerate the development and deployment of such equipment.

3.10 Lesson 10: Lack of LED Product Serviceability and Interchangeability Has Created Market Adoption Barriers in Certain Sectors

Despite the promise of long life, there remains much uncertainty about the lifetime and reliability of LED products. As a result, designers are often uncomfortable specifying products that do not have serviceable components. Furthermore, even in cases where existing LED products offer acceptable performance and cost savings, some users hesitate to buy LED products that cannot be upgraded while the technology is still advancing so rapidly.

3.10.1 Significance

Many lighting clients have strict performance and cost expectations. Designers who fear lifetime and reliability issues and their resultant liability may delay the specification of LED products, thereby forgoing the significant energy savings already available for some applications. Similarly, clients and designers who feel compelled to wait for better performance, lower costs, and/or new features may avoid LED products (and their associated energy savings) until the market is effectively commoditized. Serviceability reduces initial risk, and interchangeability offers protection against obsolescence. This issue applies primarily to the commercial market, especially the architectural and hospitality sectors.

3.10.2 Background

Early experiences with some LED products has shown that, while the LED packages themselves may be long-lived and have acceptable lumen maintenance, driver failure or shifting color can cause what initially looked like a successful installation to fall short of client expectations. The time and cost required to address failures can be a function of luminaire construction. In some cases, the entire luminaire must be removed and replaced, which may be considered wasteful by clients concerned about sustainability, and may be untenable for expensive architectural or decorative luminaires. Alternatively, modular luminaire designs may allow for only the failed component to be removed and replaced. Such serviceable luminaires may not only reduce the risk of unmet lifetime expectations, but may also have lower life-cycle costs.

The continual evolution of LED technology presents challenges of its own for some lighting clients. The reality that tomorrow’s products will perform better and perhaps have more capabilities than today’s products makes it difficult for some designers to decide when is the right time to start specifying LED products, especially for clients who do not consider life-cycle costs. Furthermore, some lighting clients expect to be able to take advantage of evolving LED technology by, for example, upgrading some luminaire component to deliver higher efficacy or the ability to control color temperature in a couple of years. In both cases, luminaires designed with interchangeable components, such as LED modules or light engines, facilitate such upgrades much more than those that do not.

3.10.3 Challenges

Modular luminaire designs have three potentially significant drawbacks. The first is cost; designing any product to have serviceable or interchangeable parts requires the use of plugs, sockets, and perhaps additional wiring and housing materials, all of which increase manufacturing cost. Modularity can also potentially create performance constraints. Any design parameter that is “locked down” to facilitate modularity reduces design freedom, which potentially reduces performance.

Finally, the ability to exchange a failed component for a new one or an old component for a newer, higher performing one also presents the opportunity to install a component that is not well-suited to a given luminaire, potentially leading to reduced performance or safety hazards. While some modular interfaces are very well defined, and their use in products tightly controlled, other (typically more common and familiar) modular interfaces are used in widely varying products, without sufficient consideration for mismatches. Some users may assume that any component that fits into a given receptacle is designed for the system containing the receptacle. In others, a user may not know how to properly install or secure a component into a luminaire. Examples of what can go wrong include

- installing medium screw-based LED lamps into sealed fixtures designed for incandescent lamps, resulting in lamp temperatures that exceed design specifications
- installing double-end powered bi-pin LED T8-replacement tubes or fluorescent T8 tubes (back) into a troffer re-wired for single-end powered LED T8-replacement tubes, resulting in potential safety issues
- installing an LED module that requires a thermal interface material into a socket that requires re-application of such material, or never contained such material.

3.10.4 Implications for the Future

1. The industry should consider adopting standardized modular interfaces. At present, manufacturers are incorporating modularity into their LED luminaire designs to different degrees, and for different purposes. Some manufacturers design modules with a focus on speeding the product development time for traditional or less sophisticated luminaire designers, or see modularity as a means for serviceability (perhaps by trained personnel only), but not interchangeability. Others seek to cater to users familiar with lamp-based luminaires by developing LED modules or light engines that may be exchanged by general users, either to address failures or deliver improved performance or new features. Some manufacturers use proprietary interfaces, while some are working together (e.g., through the Zhaga Consortium) to define standard interfaces. Finally, even when modular design is common for a particular component, as is the case for LED troffers that typically contain a modular LED driver, taking advantage of said modularity may not be straightforward. There is considerable variation in driver design, as well as LED boards and arrays, and there are no industry standard methods for characterizing them.
2. Manufacturers should consider developing products with serviceable or interchangeable components. The challenges presented by the lack of LED product serviceability or interchangeability—or in some cases by the inconsistent implementation of modularity—are likely to persist for the foreseeable future, while LED technology continues to evolve rapidly, driving manufacturers to explore new design approaches and system partitioning.
3. As LED technology matures, market preferences—which may be application- or sector-specific—will likely emerge. In the meantime, applications and market sectors that are most affected by the lack of serviceability and interchangeability should be identified, and manufacturers encouraged to appropriately focus their early efforts at delivering both.

3.11 Lesson 11: Existing Lighting Infrastructure Limits the Full Potential of SSL; More Effort Is Needed to Open the Doors to New Lighting Systems and Form Factors

Almost the entire SSL market remains focused on products that fit into the existing infrastructure of legacy lighting products. This is true for lighting product form factors, customer expectations, and lighting product functionality. While this is a necessary and expected consequence of introducing a radically new technology into a mature market, the current market focus sharply limits the potential for the new technology. The sooner the market begins to transition away from its legacy focus, the sooner SSL can deliver deeper energy savings, and generally better lighting performance possible only with luminaires designed from the ground up to handle LED light sources.

3.11.1 Significance

The unique characteristics of LEDs, including their small size, ease of controllability, directionality of emissions, and durability, among many others, offers unprecedented flexibility for how SSL product designers can deliver lighting and related services to lit spaces. Novel configurations and form factors have high potential for

- deeper energy savings
- better lighting quality
- lower lighting costs
- longer life
- more comfortable and attractively lit spaces
- more light where it is needed or wanted, and less light where it is not
- better controllability with regard to dimming, frequent on/off switching, spectral tuning, beam shape, and other characteristics.

This issue applies across all lighting markets, but especially to those where consumers or non-lighting professionals are purchasing lighting products. It also applies in markets where lighting infrastructure is rarely upgraded or replaced. This means the problem is most prevalent in the residential and small commercial markets, as well as in other commercial markets with high sensitivity to first costs and reluctance to try unfamiliar product designs.[1]

3.11.2 Background

Perhaps nothing better illustrates this issue than the current heavy market focus on integral LED lamps intended as replacements for incandescent light bulbs (A lamps). Because incandescent A lamps were inexpensive, offered good quality lighting, and were quick and easy to replace, they evolved into a standard industry product. They had become the standard light source for a large variety of luminaires,

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[1] These conclusions are based on a series of discussions and input gathered during SSL past workshops and conferences. More information on past conferences is available on the SSL Program website: https://www1.eere.energy.gov/buildings/ssl/past_conferences.html.

from table lamps, to ceiling mounted fixtures, porch lights, downlights, and desk lamps. A huge infrastructure of lighting fixtures, along with customer knowledge and expectations, was built up over the century of incandescent A lamp prevalence. That infrastructure developed around an omnidirectional light source that can withstand high-temperature operation, has a standardized electrical interface (Edison base), has a very low purchase price, functions as a simple resistor on electric circuits, and is nearly identical from product to product except for light output—which varies according to a very easy-to-understand metric (lamp power).

It is therefore only natural that manufacturers developed LED products to fit into this infrastructure and paradigm. But to make LED products function well in that infrastructure, product designers have been forced to sacrifice product life, lumens, controllability, cost, energy efficiency, and lighting quality. As a simple example, consider an integral LED replacement for an incandescent bulb in a table lamp. Side-emitting lumens are wasted because that same lamp might also be installed by a buyer in a ceiling fixture requiring high side emissions. The Edison base largely prevents use of the fixture as a heat sink, causing the lamp to run hotter than it otherwise would. If that bulb is used in a dimmable fixture, sophisticated electronics are needed to make it dim reasonably well on the existing wall dimmer, increasing the cost of the bulb. Energy is wasted because lumens are wasted, and because the LEDs have to be driven relatively hard to produce high light output from the limited bulb size. Finally, the product life is shortened due to high-temperature operation caused by dense packaging of LEDs and electronics within that small form factor.[1]

As with the A lamp example, legacy lighting infrastructure and customer expectations greatly limit product design freedom and functionality across the lighting landscape, from fluorescent troffers to halogen MR16 accent lights.

3.11.3 Challenges

Manufacturers will make only what customers are willing to buy, and customers cannot easily give up their old habits, expectations, and investment in existing hardware. This is true for most mature product markets into which radically new technologies are introduced; for example, early cars had to function (and look) a lot like horse buggies. Upgrading electrical infrastructure in a home or business costs money, requiring the services of qualified electricians, and significant renovation work to walls and ceilings to access wiring. Electrical systems have to comply with the National Electrical Code and local building codes. Even if building owners wanted to renovate and prepare for use of SSL immediately, it is not clear what would be required or advisable, because SSL technology, products, control systems, and market availability all continue to change and evolve rapidly. Over time, newly constructed buildings will incorporate electrical infrastructure that is better suited to full application of digital SSL technology (along with a range of other communications, controls, and grid response features). Decades of infrastructure transition are to be expected.

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[1] Based on input gathered during SSL past workshops and conferences. See SSL Program website for more information on past workshops: https://www1.eere.energy.gov/buildings/ssl/past_conferences.html.

3.11.4 Implications for the Future

1. Government organizations, codes and standards bodies, and specifiers need to be mindful that their lighting requirements may (albeit unintentionally) restrict product form factors, functionality, and system operation. Careful development of these requirements opens the door to innovation and better product designs.
2. Energy-efficiency program operators should consider explicitly allowing for non-conventional form factors and functionality, and to the extent possible, move away from program designs built around the concept of one-for-one product substitutions.
3. Product buyers are more likely to buy products not compromised by the legacy infrastructure if those products offer compelling functionality. For example, lamps controlled wirelessly circumvent the limitations of having to communicate a dimming signal over the wires that conduct power to lamps, but also allow those lamps to be controlled for a wide variety of other characteristics, such as on/off schedules, color point, and light beam shapes.
4. Manufacturers, lighting educators, DOE, and others could induce earlier acceptance by customers of lighting products by frequently raising the issue of what is possible with SSL when unconstrained by existing infrastructure. Manufacturers with innovative product designs at the ready will be in the best position to leverage this new opportunity.

3.12 Lesson 12: Programs that Provide Ways to Identify Quality LED Products Have Helped Support Market Adoption

Individual consumers, utility program managers, retailers, facility managers, and lighting designers all need help sorting through and understanding LED product performance data, but few have the time and expertise to evaluate every product. Several programs have emerged to help: CALiPER, LED Lighting Facts, ENERGY STAR, DLC, and others verify product performance information and make at least some of that information publicly available. These programs have helped support market adoption of LED products by assuring stakeholders that products have been tested and reviewed by an independent entity. These programs have simultaneously discouraged the practice of inflating performance claims, as was rampant in the early days of LED product development.

3.12.1 Significance

The LED lighting market is varied and complicated, with new products and applications appearing continuously. LED lighting cannot be categorized as one single light source type that will replace another discrete light source. LEDs are better characterized as the next phase of lighting, which could potentially replace all other electric light source types, although not yet all lamp wattages or all lighting applications.

Because of this product diversity, LED performance cannot be generalized. It depends on the lighting application, the product category, and individual product design. Qualified product lists and objective third-party LED product information are relevant for all lighting sectors, including residential, commercial, municipal, institutional, and industrial facilities. Program support is essential to help utilities, energy-efficiency programs, retailers, and consumers evaluate LEDs. Verified test data and independent product qualification is needed to

- help utilities determine which products are eligible for incentives and other promotion
- help designers screen products for consideration
- help retailers determine which products to stock
- help facility lighting buyers determine which products to purchase
- inform consumers of basic performance characteristics
- encourage manufacturers to align performance claims with tested, verified results.

3.12.2 Background

When LED products were first introduced in the market, many had unrealistic and unsupported performance claims. Until the IES photometric test procedure, LM-79, was published, there was no standard method for testing LED products, creating much confusion about which metrics should be reported.[1,2,3] Some luminaire manufacturers reported the claimed efficacy or output of the LEDs used in their products, a value based on instantaneous measurements taken during LED package production. Equivalency claims (with respect to the type and output of conventional lamps for which they were claimed to be suitable substitutes) were often highly exaggerated, with products claiming to replace a 40-watt or 60-watt incandescent lamp producing less than one-quarter of the light output of those benchmarks. In the first two rounds of CALiPER testing in 2007, less than 15% of the products had light output claims within 30% of tested values.[2] By the third round of CALiPER testing, however, the proportion of products with reasonably accurate light output claims (within 10% of tested values) had risen to 30%, suggesting that the publication of these discrepancies between output claims and test results had an immediate effect on the market.[3] Of products CALiPER tested in 2012, about 67% had output claims within 10% of the tested value.[4] Once LM-79 testing became available from independent test laboratories, the industry had a standard method to measure LED product performance. This enabled the development of minimum voluntary performance criteria for qualification by ENERGY STAR and the DLC, and the LED Lighting Facts database of verified product performance. As of 2013, more than 2,800 LED integral lamps and 2,100 LED luminaires are ENERGY STAR-qualified, more than 31,000 products are DLC qualified, and more than 10,000 products are listed on LED Lighting Facts.

3.12.3 Challenges

LED product offerings continue to increase very rapidly. Keeping pace with advancements in LED technology and product design is a challenge for qualification programs that have minimum performance requirements. Keeping information current is a challenge for all programs, due to the frequent updating and redesign of products based on new LED component availability, pricing, competitive demands, and other factors. The frequent need to update information presents time and cost burdens to participating manufacturers and to third-party programs themselves.[5,6,7]

3.12.4 Implications for the Future

1. Efficiency program managers should consider prioritizing the development of custom options that help users identify quality LED products. These programs should target energy-efficiency

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[1] DOE, 2007a. *CALiPER Summary of Results: Round 1 of Product Testing*.

[2] DOE, 2007b. *CALiPER Summary of Results: Round 2 of Product Testing*.

[3] DOE. 2007c. *CALiPER Summary of Results: Round 3 of Product Testing*. October 2007. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round_3_summary_fnl.pdf.

[4] DOE. 2012a. *CALiPER Year in Review 2012*.

[5] EPA. 2013. *Energy Star Certified Light Bulbs and Light Fixtures*. U.S. Environmental Protection Agency, Washington, DC. Available at www.energystar.gov.

[6] DLC. 2013. *Design Lights Consortium*. Design Lights Consortium, Northeast Energy Efficiency Partnerships, Inc., Lexington, MA. Available at http://www.designlights.org/.

[7] DOE. 2013l. *LED Lighting Facts*. Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC. Available at http://www.lightingfacts.com/.

performance that will produce significant energy savings if the technology is widely adopted in the market.

2. Efficiency program requirements need to keep pace with LED technology development, balancing energy efficiency, lighting quality, and cost considerations.
3. Testing and documentation requirements should be streamlined as much as possible, while still maintaining confidence in qualified product performance claims.
4. Wherever possible, data should be shared across the various performance verification programs to save time and cost for all participants.
5. It is not clear how long such programs will be necessary, as the LED lighting market continues to evolve and mature. Continued rapid change in the technology, product offerings, and integrated systems indicate objective third-party information will continue to be needed for at least the next 5 years.

4.0 Conclusions

The effective application of the lessons learned from past experiences with technology and product development can significantly improve the outcomes of similar future endeavors when these lessons are effectively applied. DOE and others have clearly applied many of the lessons learned during the development and commercialization of CFLs to the development and market introduction of energy-efficient LED lighting systems for general illumination, as evidenced by proactive, collaborative efforts to establish performance testing, standards, and education programs. Partly as a result of applying these and many other past lessons learned, the development and market introduction of LEDs has gone much more smoothly than CFL market introduction (see Figure 4.1). However, the unique technological characteristics of LED lighting have presented a host of new challenges and lessons.

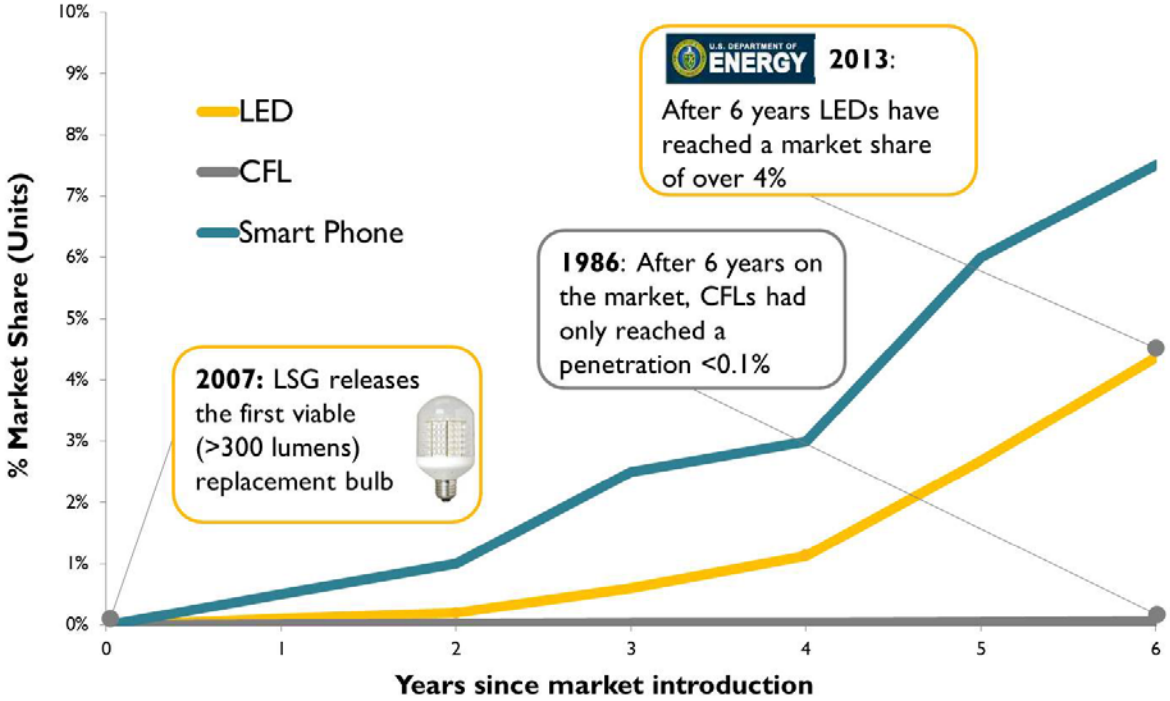

Figure 4.1. Comparison of Market Share Increases after Product Introductions for CFLs, LEDs (Lamps and Luminaires), and Smart Phones. Source: Navigant Consulting, Inc.

This report documents early challenges and lessons learned in the SSL market and summarizes early actions taken by DOE and others to avoid potential problems anticipated based on lessons learned from the market introduction of CFLs. LED technology and product performance cannot be easily generalized. The technology is capable of very high luminous efficacy, color rendering, power quality, beam control, dimming performance, lifetime, and other attributes. The actual performance of any given product depends on the target application, pricing and operating cost structure, form factor, maintenance requirements, and other constraints and tradeoffs. A continuing challenge for the lighting community is the difficult tradeoffs among various performance attributes and price.

Based on early LED market experience, this study identifies and characterizes 12 key lessons distilled from DOE's SSL Program results with a focus on areas for which ongoing challenges exist and/or useful information can be applied going forward. These lessons correspond with technological challenges related to performance and lifetime of LEDs, color quality and measurement, flicker, glare, dimming and control, serviceability; challenges related to developing LED product lines and families; and complications and limitations experienced when trying to fit LEDs into existing lighting infrastructure. Lessons from the many programs that have helped support market adoption are also summarized.

SSL is revolutionizing lighting products, systems, and practices. One can envision a future in which the lights in buildings, homes, and outdoor areas use just a fraction of the electricity now used for lighting; have excellent quality, durability, and ability to adjust the amount and color of light; are integrated with information and communications systems; and are responsive to the needs of the electrical grid. Realization of the full benefits of SSL—in terms of lighting quality, energy efficiency, environmental sustainability, controllability, and value-added technology integration—is a tantalizing possibility, but by no means assured. This early assessment of the LED general illumination market is intended to aid in the continuous course corrections needed to reach that full technology potential.