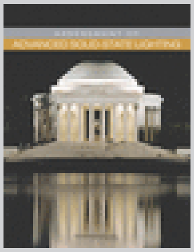

Assessment of Advanced Solid State Lighting

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ASSESSMENT OF
ADVANCED SOLID-STATE LIGHTING

Committee on Assessment of Solid-State Lighting

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

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Cover: The Thomas Jefferson Memorial following a lighting system redesign in 2001 to include installation of metal halide lamps, induction lamps, and light-emitting diodes. The cove lighting application for the memorial utilizes io Lighting LLC's Line .75 fixture, 3KHO, 45 degree beam spread in 18-inch daisy chained segments. Photograph copyright Peter Aaron/OTTO. Reprinted with permission.

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Members and staff at the February 2012 meeting of the Committee on Assessment of Solid-State Lighting. *From left to right, back row:* David Cooke, Steven P. DenBaars, Michael G. Spencer, Stephen Forrest, Michael Ettenberg, Nadarajah Narendran, and Maxine Savitz; *front row:* Inês Azevedo, James Zucchetto, Evelyn L. Hu, Nancy E. Clanton, Gary Marchant, John G. Kassakian, Pekka Hakkarainen, Paul A. DeCotis, Wendy Davis, and Martin Offutt. Photo courtesy of LaNita Jones.

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[1] NAE, National Academy of Engineering.
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[1] NAE, National Academy of Engineering.
[2] NAS, National Academy of Sciences.

Preface

Solid-state lighting (SSL) is a new technology that has evolved from a few key inventions involving light-emitting diodes (LEDs) in the 1960s and spurred more recently by fundamental breakthroughs in LEDs made in the 1990s. As such, SSL lighting is not a refinement of an incumbent lighting technology but has evolved in parallel with, if more rapidly than, the incandescent and fluorescent lamps familiar to consumers. As discussed in this report, SSL lighting not only can offer improvements in efficacy (i.e., the ability to deliver the same amount of light using less electricity) and improved durability and the convenience of less frequent maintenance (e.g., in roadway lighting or in aviation), but also opens up the possibility of new applications owing to the technology's high performance in cold environments, long life, and new form factors.

Whether SSL products are to achieve widespread deployment will depend on factors such as cost and consumer acceptance. Cost will depend on the needs of the basic SSL technology, including the material set of the LED device and the raw materials this implies, and the ease of manufacturing, including the effect of scale economies and learning that can be achieved during ramp-up of production—to name only a few such considerations. Technological breakthroughs—such as innovations in the design of the LED emitter devices or improved materials or manufacturing techniques—will also have a bearing on cost. The report summarizes the current state of technological readiness of the candidate technologies, including organic LEDs (OLEDs), for use in SSL products and evaluates the barriers to their improved cost and performance.

Acceptance by the consumer is more difficult to quantify. As discussed in the report, this will depend on factors related to the technology and also the workings of the marketplace. The former include the quality of light emitted by these devices and the subjective attributes of how this is perceived by the human eye. Also of importance will be the ease of use and the useful lifetime of these devices. The latter set of factors includes the problem of high initial cost, which can be mitigated by economic incentives such as tax credits, utility-sponsored rebates, or breakthroughs in manufacturing technology.

Were widespread deployment of SSL products to be achieved, one benefit would be reduced energy consumption. The Energy Independence and Security Act of 2007 (EISA 2007) mandates higher efficacy in general lighting according to a set of targets and timetables, of which the first has already begun. This report evaluates the likely impacts on energy use of this phase-out and, in addition, considers the benefits that might accrue in scenarios considering market penetration of the SSL products greater than the targets.

This report on advanced solid-state lighting was undertaken at the request of Congress in the EISA 2007. Funding has been provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy via the lighting program directed by James Brodrick, PhD.

John G. Kassakian, *Chair*
Committee on Assessment of Solid-State Lighting

Acknowledgments

This report was made possible through the hard work and dedication of the 13 individuals who served on the Committee on Assessment of Solid-State Lighting, whose biographies are presented in Appendix A.

The data and conclusions presented in the report have benefited from a substantial amount of information provided by federal officials, academic researchers, and industry analysts and technologists who met with the committee during the open sessions of the meetings in Washington, D.C., and Woods Hole, Massachusetts. These individuals are listed in Appendix B.

Special recognition is due the sponsor point-of-contact, James Brodrick, lighting program manager with the U.S. Department of Energy, who on two occasions gave substantive and informative presentations to the committee and made himself available for follow-up discussions—all of which proved invaluable to the committee's understanding of the nature of the problem and the questions being asked.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

William F. Banholzer, NAE,[1] Dow Chemical,
Randy Burkett, Randy Burkett Lighting Design, Inc.,
Makarand Chipalkatti, Osram Sylvania,
Linda Cohen, University of California, Irvine,
P. Daniel Dapkus, NAE, University of Southern California,
Curtis Fincher, DuPont Displays,
Noah Horowitz, Natural Resources Defense Council,
Julia Phillips, NAE, Sandia National Laboratories, and
Sue Tierney, Analysis Group.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen

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[1] National Academy of Engineering.

by Elsa M. Garmire, Dartmouth College. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

Congress, recognizing the potential for energy savings in the use of general lighting for illumination, requested in the Energy Independence and Security Act of 2007 (EISA 2007) that the Department of Energy (DOE) contract with the National Research Council (NRC) to conduct a study to assess the status of solid-state lighting (SSL) as a technology. The contract requested that the National Academies provide an objective and independent assessment of the current state of solid-state lighting and its future potential for accommodating the new minimum efficiency standards for lighting. The NRC established the Committee on Assessment of Solid State Lighting (Appendix A) composed of diverse experts in the fields of solid-state physics, electronics, lighting design, human perception of light, industrial commercialization, and policy. The statement of work directed the committee to review the development and future impacts of SSL, including projections of cost and research and development (R&D) necessary to overcome barriers to widespread adoption and the potential for unintended consequences of deployment.

Solid-state lighting consists of two technologies—the inorganic semiconductor-based light-emitting diode (LED) and the organic polymeric-based light-emitting diode (OLED). Both technologies are the subject of active research worldwide. The LED technology is currently in the early stages of commercial deployment while OLEDs are in the demonstration phase. All LED-based *luminaires*[1] require optics to distribute the unidirectional light emitted by the LED and a large heat sink to maintain the LED temperature within limits. Furthermore, like fluorescent lamps,[2] both LED and OLEDs require they be supplied through an electronic circuit to provide them with the proper form of electric power. Both LEDs and OLEDs and the luminaires based on them are discussed below.

The committee's main findings and its key recommendations for the Department of Energy are listed in Boxes S.1 and S.2, respectively.

LED-BASED SOLID-STATE LIGHTING

Technology and Lighting Products

Because a single LED emits light that is monochromatic, devices that emit white light must do so by combining the emissions of individual red, green, and blue (RGB) LEDs or by using a single blue LED whose emission excites a phosphor, which in turn emits white light. This latter design is the more common. The efficacy[3] of white LEDs has been increasing rapidly and is expected to approach 200 lumens/watt (lm/W) by 2020, greatly exceeding all other general illumination technologies. The committee found that luminaires and lamps based on LEDs will be able to support the lumen output standards Congress required to be promulgated by DOE in Section 321 of EISA 2007.

LED-based lighting products currently are available in two forms. The first consists of lamps that can replace, one-for-one, the incumbent lamp (i.e., the lamp that is currently in use) without modification to the original fixture. The LED, optics, heat sink, and electronic drivers are all packaged in the replacement lamp, typified by the screw-in replacement—now offered by Cree, Philips, OSRAM Sylvania, and others—for the familiar household incandescent bulb (the "A-19"). A 60 W A-19 lamp produce about 850 lumens, for an efficacy of 14 lm/W. The high-quality commercial LED equivalent produces 93 lm/W. For comparison, the equivalent

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[1] A *luminaire* consists of, minimally, a lamp holder, commonly called a socket, and the way to connect the socket to the electrical supply. Most fixtures also contain optical elements that distribute the light as desired, such as a reflector, lens, shade, or globe. When needed, fixtures and luminaires contain a ballast or a driver.

[2] The term *lamp* is equivalent to the term light bulb in every-day usage, i.e., the source of light that attaches to the luminaire by means of a screw-base or pins.

[3] *Efficacy* is a measure of the efficiency with which a lamp or luminaire converts electricity to useful light. It is defined as the ratio of the luminous flux to the total electrical power consumed and has units of lumens per watt.

BOX S.1
Findings

Finding 1: Luminaires and lamps based on LEDs will be able to support the standards for lumen output Congress required to be promulgated by DOE in Section 321 of the Energy Independence and Security Act of 2007.

Finding 2: Cost is the biggest obstacle to the widespread deployment of SSL based on LEDs.

Finding 3: The Bayh-Dole waiver is discouraging some universities and small companies from participating in the DOE program.

Finding 4: On a lifecycle basis, warm and cool white LEDs are already cheaper than incandescent lighting and will likely be comparable to that of fluorescent lighting technologies in the near future.

NOTE: The full text of all findings and recommendations in the report appear in Chapter 7.

BOX S.2
Recommendations to the Department of Energy

Recommendation 1: The Department of Energy should continue to make investments in LED core technology, aimed at increasing yields, and in fundamental emitter research to increase efficacy, including improvements in the controlled growth and performance of the emitter material.

Recommendation 2: The Department of Energy and lamp manufacturers and retailers should work together to ensure that consumers are educated about the characteristics and metrics of these new technology options.

Recommendation 3: The Department of Energy should support research to understand the fundamental nature of efficiency droop at high currents in OLEDs and to seek means to mitigate this effect through materials and device architectural designs.

Recommendation 4: The Department of Energy should focus on efforts that result in significant light outcoupling enhancements for OLED that are low cost to implement and are independent of both wavelength and viewing angle.

Recommendation 5: The Department of Energy SSL program should be maintained and, if possible, increased.

Recommendation 6: The Department of Energy should seek to obtain 50 percent cost sharing for manufacturing R&D projects, as was done with the projects funded by the American Recovery and Reinvestment Act.

Recommendation 7: The committee recommends that the Department of Energy consider ending its waiver of Bayh-Dole for SSL funding.

NOTE: All the findings and recommendations presented in the report are collected in Chapter 7, where the recommendations are double-numbered to indicate the chapter in the main text where they appear in context.

spiral tube compact fluorescent light (CFL) has an efficacy of 63 lm/W. LED lamps have also been developed as drop-in replacements for lamps with other form factors, such as 4-foot linear fluorescents, although the total light output is lower.

The second product form is the retrofit luminaire, which is similar to many existing non-SSL products and requires complete removal and replacement of the incumbent luminaire—recessed troffers, high-bay fixtures, track lighting, and pendant lights, for example. Two further applications in which LED-based luminaires have performed well are downlighting, including recessed cans, where the directional quality of the emitted light is important, and roadway lighting, in which a premium is placed on durability and low maintenance. In 2010 LED luminaires had achieved a 4.3 percent penetration in this latter application. SSL products for downlighting have efficacies of 35 to 85 lm/W compared to 10 to 30 lm/W for fluorescent and halogen luminaires in the same application.

Role of Standards and Testing

Because of the different spectral, electrical, and thermal characteristics of LEDs, OLEDs, and SSL products, existing standards to measure the photometric properties (i.e., measures of perceived light intensity) and colorimetric properties (i.e., measures of perceived color characteristics) of other lighting technologies frequently cannot effectively be employed. A number of standards development organizations are involved in recommending test procedures for the measurement of LEDs, OLEDs, and SSL products.[4] The United States has taken early leadership on several influential standards, such as IES LM-79-08 "Electrical and Photometric Measurements of Solid-State Lighting Products," which specifies the procedures for measuring total luminous flux, electrical power, luminous efficacy, and chromaticity of SSL lamps and luminaires. Despite rapid progress, a number of important test and measurement standards still need to be developed for SSL to be successful. For example, there is currently no way to measure or estimate the lifetime of SSL luminaires.

Cost

The committee found that cost is the biggest obstacle to the widespread deployment of SSL based on LEDs. The high cost relative to conventional light sources is due to a combination of costs associated with the LED device, heat sink, electronics, and packaging, each of which is the subject of substantial R&D activity. All categories of cost will need to be addressed along the value chain to improve the value proposition of higher-quality light, longer product life, and overall lower life-cycle cost compared to current lighting products on the market. Thermal management is particularly challenging because the LED chip must be kept at a temperature below 200°C. The small size of the chip means that even a watt or two of dissipation will raise its temperature well beyond this limit if adequate heat sinking is not provided.

Cost of the LED device is primarily driven by two issues: (1) the mismatch in thermal expansion between the sapphire substrate on which the LED is grown[5] and the nitride LED material, resulting in thermal stresses that decrease device yield; and (2) because of process variability, the variability in the emission characteristics (color) among individual LEDs, which necessitates they be sorted (i.e., "binned") and grouped for consistency. The efficacy of the LED is limited by both physical mechanisms within the semiconductor material and the limited ability to access light trapped in the substrate and emissive layers (i.e., improved outcoupling). Increasing efficacy not only improves energy savings, but also has a strong leveraging effect on the cost of LED lamps and luminaires because, as less heat is generated, smaller and less complicated thermal management and packaging systems are required. **The committee recommends that the Department of Energy continue to make investments in LED core technology, aimed at increasing yields, and in fundamental emitter research to increase efficacy, including improvements in the controlled growth and performance of the emitter material.**

Consumer Acceptance

In addition to cost, consumer acceptance of SSL will depend on an understanding of its unique characteristics and the new vernacular used to specify it. To this end DOE has created the Lighting Facts label for SSL lamps, which provides specifications for luminous output (lumens), power (watts), efficacy (lumens per watt), color temperature, and color rendering index (CRI). The Environmental Protection Agency (EPA) and ENERGY STAR® program are also engaged in developing informative labeling for SSL products. But consumers must be made aware of the significance of label parameters, and to this end EISA 2007 authorized $10 million a year to advance public awareness. This money has yet to be appropriated. **The committee recommends that DOE and lamp manufacturers and retailers work together to ensure that consumers are educated about the characteristics and metrics of these new technology options.**

Poor experience with spiral CFL lamps has made consumers skeptical of new lighting technologies. But unlike spiral CFLs, SSL turns on to full brightness instantly, is unaffected by low temperatures, has good color quality, and is inherently dimmable with properly designed lighting controls. However, a number of SSL performance characteristics may jeopardize consumer acceptance if not addressed. The most significant of these is the incompatibility of SSL lamps with many existing dimming controls, precluding a simple SSL retrofit, particularly in residential applications. Although unlike CFLs LEDs are in principal

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[4] These include, but are not limited to, the following: the Illuminating Engineering Society of North America (IES or IESNA), a professional organization; the International Electrotechnical Commission (IEC), an international consensus standards organization for electrotechnology; the International Commission on Illumination, an international standards body; the National Electrical Manufacturers Association; and the Underwriters Laboratory, which sets safety standards. The American National Standards Institute also provides accreditation and serves as the U.S. national member organization to the IEC.

[5] Some devices are grown on a silicon carbide (SiC) substrate, which some manufacturers believe to be a better, albeit more expensive, alternative.

easily dimmed, their low current and driver electronics require special controls. National Electrical Manufacturers Association (NEMA) is working on a standard to address this issue (NEMA SSL 7-2012; *Phase Cut Dimming for Solid State Lighting: Basic Compatibility*). There is, at present, no standardized method for measuring the lifetime of SSL products, even though lifetime is a critical parameter in economically justifying SSL. Consequently, lifetime is a missing metric on the Lighting Facts label. DOE has instead recently incorporated a lumen maintenance metric, LM-80.[6] This metric gives the number of hours of operation before the lumen output of the LED emitter degrades to 70 percent of its initial value (the so-called L70 point). This metric does not apply to product (luminaire) life, and if the durability of the balance-of-product does not match the expected 25,000-hour life of the LED emitter, the committee expects there will be negative consumer reactions.

Color Quality

The color of illuminated objects is also a key determinant of the perceived quality of lighting products, and in this regard the CRI of LEDs can be very high—comparable to high-CRI fluorescent lamps. There is consensus, however, that improved measures of color quality[7] are needed to guide manufacturers, which, for SSL products, can be more numerous and much smaller in size compared to the incandescent lamp market. This diffuse supplier market compounds the problem of industry standardization.

ORGANIC LED-BASED SOLID-STATE LIGHTING

The OLED offers the possibility of unusual form factors by taking advantage of the inherent slim, flexible character of the device itself, and by leveraging its area-source characteristic to develop possible new applications. Although some OLED-based luminaires are commercially available, their present costs limit widespread adoption. The lifetime of an OLED is very sensitive to its exposure to both air and moisture, making the hermetic sealing of large, flat packages critically important. Both lifetime and efficacy are also negatively impacted by the high currents required to generate light of brightness sufficient for general purpose lighting, leading to the phenomena of current droop and thermal droop (a decrease in lumen output with increasing current or temperature). **The committee recommends that the Department of Energy support research to understand the fundamental nature of efficiency droop at high currents in OLEDs and to seek means to mitigate this effect through materials and device architectural designs.** Color consistency among OLED panels forming a luminaire is also a challenge. While OLEDs are employed extensively for displays, displays do not require the large area packages or high levels of illumination of general purpose lighting. Perhaps the largest efficiency gain that has yet to be achieved is improved outcoupling of light in OLEDs, made particularly difficult compared with LEDs by the large areal dimension and integrated form factor of the former. **The committee recommends that the Department of Energy focus on efforts that result in significant light outcoupling enhancements that are low-cost to implement and are independent of both wavelength and viewing angle.** While there is a manufacturing infrastructure for OLED displays, located almost exclusively in Asia, there is currently none for lighting products.

DOE LIGHTING PROGRAM

Solid-State Lighting has been funded in recent years at roughly $25 million per year, of which roughly $9 million was directed toward R&D in FY2011, emphasizing three interrelated thrusts: (1) core technology research and product development, (2) manufacturing R&D, and (3) commercialization support. The SSL Manufacturing Initiative was added to the SSL R&D portfolio in 2009 with the aim of reducing costs of SSL sources and luminaires, improving product consistency and maintaining high-quality products, and encouraging a significant role for domestic U.S.-based manufacturing.[8] The DOE Lighting program also addresses issues related to commercialization. It supports independent testing of SSL products, supports exploratory studies on market trends and helps to identify critical technology issues, supports workshops to foster collaboration on standards and test procedures, promotes a number of industry alliances and consortia, disseminates information, and supports a number of other initiatives. It also conducts technical, market, economic, and other analyses and provides incentives to the private sector to innovate.

DOE has done a remarkable job of helping to advance SSL R&D and manufacturing and educating the lighting community, and **the committee recommends that the Department of Energy's SSL program be maintained and, if possible, increased.** However, the committee notes that the percentage of matching funds from R&D grant recipients has declined in the past few years. **The committee recommends that the Department of Energy seek to obtain 50 percent cost sharing for manufacturing R&D projects, as was done with the projects funded by the American Recovery and Reinvestment Act.** In addition, the committee found that the Bayh-Dole waiver is discouraging some universities and small companies from participating in the program. **The**

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[6] Illuminating Engineering Society, IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources.

[7] At present, the color rendering index, managed by the International Commission on Illumination (CIE), is the internationally accepted metric for the evaluation of a light source's color rendering abilities and was developed in response to the advent of fluorescent lamps.

[8] U.S. Department of Energy. 2011. *Solid-State Lighting Research and Development: Manufacturing Roadmap.* Washington, D.C.

committee recommends that the Department of Energy consider ending its waiver of Bayh-Dole for SSL funding.

BENEFITS OF DEPLOYMENT OF SSL PRODUCTS

The committee estimated the prospective benefits of reduced energy consumption from the deployment of SSL lighting products. The committee calculated benefits in two scenarios, each measured against a counter-factual baseline in which there were no impacts from EISA 2007. The first scenario calculated the savings that would accrue based on the lamp efficacy standards in EISA 2007 Section 321, and it is estimated that electricity consumption for lighting would be reduced by 514 terawatt hours (TWh[9]) in the residential sector and 60 TWh in the commercial, cumulative from 2012 to 2020. In a scenario with more aggressive assumptions on the improvements in the efficacies of LED luminaires, cumulative savings in the residential sector over the same time period were 939 TWh and in the commercial sector 771 TWh.[10]

The committee prepared a first-order comparison of the consumer life-cycle costs of lighting consumption in a further two scenarios for daily usage of lights: 3 hours per day (h/day) and 10 h/day.[11] These two scenarios are representative of average daily usages in the residential and commercial sectors, and the results are found to be very sensitive to the number of hours of use. **The committee found that on a life-cycle basis, warm and cool white LEDs are already cheaper than incandescent lighting and will likely be comparable to that of fluorescent lighting technologies in the near future.** For applications where the daily usage is larger than 10 h/day, cool, white LEDs now have a similar consumer life-cycle cost to that of CFLs or T12 linear fluorescent tubes.

With continued U.S. government support and funding and DOE leadership, the promise of low-cost and very efficient solid-state lighting could be realized, lowering U.S. energy needs and allowing the United States to be a significant solid-state lighting manufacturer and technology provider.

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[9] The assumed lamp efficacies were as follows: 96 lm/W in 2010; 141 lm/W in 2012; 202 lm/W in 2015; and 253 lm/W in 2020.

[10] A typically sized electric power plant of 500 megawatt capacity, operating 5,000 hours, would generate 2.5 TWh in a year.

[11] The following assumptions were used: a retail electricity price of 0.11 $/kWh and a 10 percent discount rate, reflecting the implicit discount rate of the consumer. It is further assumed that a 60 W incandescent light bulb would be replaced by another lighting technology providing the same energy service (approximately 850 lumens).

1

Introduction

CONTEXT

Illumination is one of a number of modern energy services provided by electricity, a premium energy carrier with the advantage that it can be transmitted over large distances and converted on-demand at the point-of-use. Annual energy consumption in the United States is roughly 100 quadrillion Btu[1] (quads) (Figure 1.1) (NRC, 2010b). Of this, roughly 40 percent is used to generate electricity, the vast majority of which is harnessed and sold to end users (3,750 TWh in 2010) in the residential (38.5 percent), commercial (35.4 percent), industrial (25.9 percent), and transportation (0.2 percent) sectors (EIA, 2011). General lighting for illumination consumes approximately 20 percent of the electricity used in the United States, accounting for between 7 to 19 percent of all residential electricity use and 31 to 36 percent of all commercial electricity use (Azevedo et al., 2009). Reducing energy consumption through conservation (i.e., using less of an energy service), improved thermodynamic efficiency, or greater efficacy (i.e., using less fuel) in delivering energy services (e.g., miles per gallon) has been the focus of a number of federal and state government programs of tax incentives, grants and contracts for research and development, standards (e.g., for appliances and vehicles), and building codes.[2] The extraction of energy resources and their processing, conversion, delivery, and use can have negative impacts on human health and the environment (NRC, 2010a). To the extent such impacts scale with (i.e., are proportional to) the quantity of energy consumed, improving the efficiency of end-use of electricity can mitigate them. This makes improvements in end-use technologies a critical aspect of U.S. energy policies.

The standard incandescent light bulb, in wide use in the residential sector, still works mainly as Thomas Edison invented it, with more than 90 percent of the electricity consumed being converted to heat. The ability to dramatically decrease the energy used for lighting requires new technologies that use less power but are also affordable and capable of producing high-quality light. Given the availability of newer lighting technologies that convert a greater percentage of electricity into useful light, there is a lot of potential to decrease energy used (i.e., the amount of electricity) for lighting. Although technologies such as compact fluorescent lamps (CFLs) have emerged in the past few decades that will help achieve the goal of increased energy efficiency, solid-state lighting (SSL) stands to play a large role in dramatically decreasing our energy consumption for lighting.

Electricity end-use is part of a larger system, and it is instructive to consider the electricity grid and its overall efficiency. The power plants by which electricity is generated in the United States operate such that roughly two-thirds of the primary energy in the fuel is lost in electricity generation.[3] Losses also occur in electricity transmission and distribution (6.5 percent), in which electricity is converted to heat, and finally when converting electricity to energy services such as illumination, space conditioning (i.e., heating, ventilation, and cooling), and cooking services (Figure 1.2).

Since the advent of the incandescent bulb, a number of new lighting technologies, discussed in detail below, have been demonstrated and in some cases entered widespread deployment to provide general and specialized illumination. A recent entrant is SSL. At the epicenter of SSL sits the semiconductor. In addition to using the semiconductor in electronic devices, scientists have been able to make the semiconductor emit light (Holonyak and Bevacqua, 1962). The most common semiconductor-based light source is the light-emitting diode (LED). If organic materials are used to fabricate the LED, it is called an organic LED (OLED). These two technologies are capable of creating "light bulbs"

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[1] Btu stands for British thermal unit and is a measure of energy. For instance, 1 gallon of gasoline would release approximately 124,000 Btu.

[2] A review of such programs can be found in NRC (2010b, pp. 264-269).

[3] The estimated two-thirds loss is based on using a single number for the so-called thermal efficiency of the fleet of power generators (called thermal because it is the amount of heat converted to useful work). There can be large variations among the different plants, however. Natural gas combined cycle plants can, for example, have efficiencies above 50 percent.

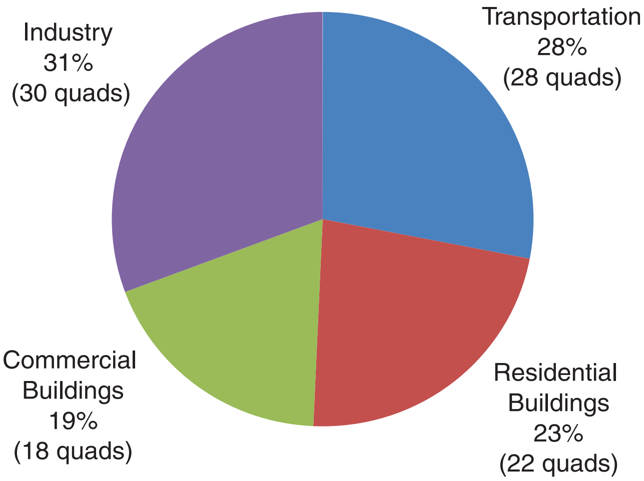

FIGURE 1.1 Total primary energy consumption in the United States, 2010 (in quadrillion Btu, or quads). Total U.S. primary energy use in 2010 was 98.0 quads.

or "lamps" that are much more efficient and have a much longer life span than either incandescent bulbs or compact fluorescent bulbs. LEDs and OLEDs alone cannot be used for illumination applications; additional electrical, thermal, structural, and optical components are necessary to create *SSL products*. Throughout the rest of the report, the term "SSL products" will be used to describe integrated LED or OLED lighting systems. In addition, LEDs and OLEDs are not limited to the current shape of existing lighting technologies and, therefore, have the potential to dramatically alter how we integrate light into our buildings and how our future "light bulbs" and luminaires might look and behave.

STUDY ORIGIN

Congress recognized the potential for energy savings in the lighting sector in the Energy Independence and Security Act of 2007. Congress requested that the Department of Energy (DOE) contract with the National Research Council (NRC) to conduct a study to assess the status of SSL as a technology. The statement of task is separated into three main sections (Box 1.1): a review of the development of SSL technology and products, a discussion of future impacts, and the implications of the study for decision-making. The main tasks for the study were to investigate the following:

- Status of SSL research, development, demonstration, and commercialization in the United States;
- Timeline for commercialization of this technology as a replacement technology for current light sources;
- Past, current, and future cost trajectories for SSL;
- Consumer acceptance of and potential benefits from SSL;
- Potential barriers to success of the industry, both in research and development (R&D) and manufacturing and commercialization;
- International aspects of SSL;
- Applications for the technology, both current and future;
- Unintended consequences of SSL in different applications;
- Application of lessons learned from the commercialization of CFLs to the roll out of SSL; and
- Recommendations to DOE for research, development, and deployment activities.

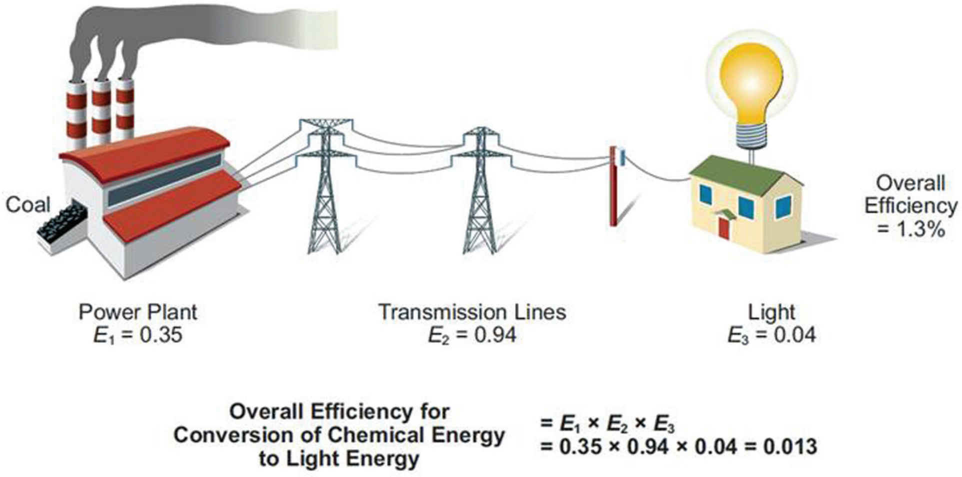

FIGURE 1.2 Example of how end-use efficiency influences overall fuel conversion efficiency. In this example, typical for residential use of electricity for illumination, the efficiency of converting the chemical energy stored in coal to the electricity entering a building is about 33 percent (0.35 × 0.94). But after accounting for the low efficiency of the incandescent light bulb, the efficiency of converting chemical energy to light energy is only 1.3 percent. All values are approximate. SOURCE: Updated and adapted from National Research Council (2010b).

BOX 1.1
Statement of Task

The National Research Council (NRC) will appoint a committee to carry out this study and provide a report on the status of advanced solid-state lighting (SSL), in particular light-emitting diodes and organic light-emitting diodes. The report will provide an assessment of the current status of development of SSL products, a discussion on the future impacts of SSL, and a consideration of the study's implications for the U.S. Department of Energy (DOE) and other agencies. Specifically, the committee will focus on the following three overarching tasks.

(1) Review the Development of SSL Technology and Products

The committee will assess:

- Past and current cost evaluations for SSL in relation to traditional lighting technologies;
- The status of SSL research, development, demonstration and commercialization in the U.S.;
- Potential barriers to development and the prospects for overcoming them;
- The status of SSL activities internationally and their implications for the manufacturing of SSL technologies in the U.S.;
- The cost, lifetime, reliability, and consumer satisfaction associated with SSL for both indoor and outdoor lighting applications and how these factors compare to traditional lighting technologies (incandescent, fluorescent, and high intensity discharge);
- The market-based performance attributes necessary for SSL based on review of on-going activities.

(2) Discussion of SSL Future Impacts

The committee will estimate:

- The time line for the commercialization of SSL (and other possible technologies) that could replace current incandescent and halogen incandescent lamp technology and meet the minimum standards required in Section 321 of the Energy Independence and Security Act of 2007;
- The barriers to widespread adoption of SSL technologies and strategies needed to overcome these barriers;
- The benefits for consumers if SSL development and deployment is successful and the impact if these barriers are not fully overcome, particularly as it relates to the new minimum efficiency standard taking effect;
- Potential unintended consequences of SSL deployment, such as presented by traffic lights using SSL lamps that did not generate enough heat to melt ice that built up on them.

(3) Study Implications

The committee will analyze:

- Lessons from the experience with the commercialization of compact fluorescent lighting and how that may affect potential proactive initiatives by the Department of Energy and other agencies (with legislative direction, such as the Federal Trade Commission [FTC]); and
- Recommendations to the Department of Energy on research, development, and deployment activities, and potential collaborations with market participants, especially manufacturers.

The committee will provide a report to the U.S. Department of Energy, the Committee on Energy and Commerce of the House of Representatives, and the Committee on Energy and Natural Resources of the Senate. As mandated by Energy Independence and Security Act of 2007, the NRC could also provide an updated report by July 31, 2015.

With these tasks in mind, the NRC established the Committee on Assessment of Solid State Lighting (Appendix A) composed of diverse experts in the fields of solid-state lighting, lighting design, human perception of light, industry commercialization, and policy to address the statement of task. In conducting this study, the committee members relied on their own expertise as well as many interactions with experts in the field (Appendix B).

INTRODUCTION TO LIGHTING

Americans are used to purchasing their lamps (i.e., light bulbs) as a function of the rating in watts (and "watt equivalents"), a unit denoting the rate at which energy is produced or consumed. Intuitively, most people understand how much light a 40 W incandescent lamp provides compared to a 60 W or 75 W lamp. As the technological options for lighting shift away from the incandescent lamp to more energy efficient alternatives such as CFLs and solid-state options (LEDs and OLEDs), the basic terms used for lighting discussions also need to change. Instead of thinking in terms of watts, consumers now need to learn a different measurement system, one that tells them how much light a product is going to emit (in absolute terms or per unit of power consumed) instead of the rate at which energy will be consumed. And this is just the beginning of the changes that consumers are likely to see if LED and OLED lighting continue to improve at their current rates. In this section, several key concepts and terms used in the lighting industry are introduced that will be used throughout the rest of the report.

Lighting Equipment

Lighting designers and engineers use different terms for lighting equipment than are used in the vernacular. In this report, the engineering terms will be used. A *luminaire* is the combination of light fixture hardware, a ballast or driver if applicable, and a light source, commonly called a *lamp* (i.e., a light bulb). Thus, the term lamp can refer to an incandescent bulb, a CFL bulb, or an LED replacement "bulb." This report will use the term *lamp*. A *luminaire* consists of, minimally, a lamp holder, commonly called a socket, and the way to connect the socket to the electrical supply. Most fixtures also contain optical elements that distribute the light as desired, such as a reflector, lens, shade, or globe. When needed, fixtures and luminaires contain a ballast or a driver. A *ballast* is an electronic device that converts incoming electricity to the proper voltage and current required to start and maintain the operation of a lamp. The term *driver* refers to the corresponding device used in an SSL luminaire. Luminaire examples include chandeliers, downlights, table lamps, wall sconces, recessed or pendant mounted luminaires, and exterior streetlights. When equipped with lamps, they are called luminaires. The types of lamps typically encountered are discussed below in the section "Annex."

Metrics for Measuring Light Output

The portion of the electromagnetic spectrum that can be perceived by the human visual system is called the *visible spectrum*. The amount of light, weighted by the sensitivity of the visual system, emitted by a source per unit time is its *luminous flux* (Figure 1.3) and is measured in *lumens* (lm). This makes lumens one of the appropriate pieces of information for lamp packaging to help consumers choose the appropriate replacement lamps. Lumens provide a description most closely related to brightness and should be referred to when choosing replacement lamps. A proliferation of fact sheets and labels has accompanied the recent introduction of new lighting technologies, leaving some consumers confused about the relationship between watts and lumens. That relationship is determined by the energy efficiency of the product. Watts describe the amount of electrical power consumed by the product, and lumens describe the rate at which it emits light. For example, most 60 W incandescent lamps emit approximately 850 lumens. Similarly, many 13 W CFLs emit 850 lumens.

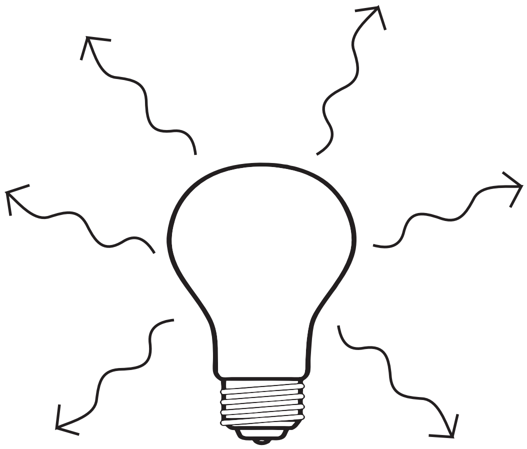

FIGURE 1.3 Luminous flux (lumena).

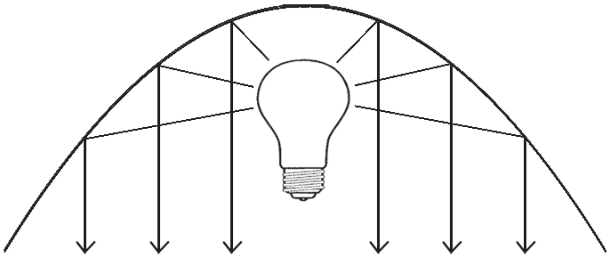

FIGURE 1.4 Luminous intensity (candela).

Luminous intensity (Figure 1.4) is the luminous flux per unit solid angle, evaluated in terms of a standardized visual response and expressed in candela. The magnitude of luminous intensity results from luminous flux being redirected by a reflector or magnified by a lens.[4] This measurement is used primarily to describe the specific light intensity and

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[4] The concept of solid angle has a strict geometric definition but can be thought of as a way to describe the focusing and redirecting of a light source by the lenses and reflectors in the luminaire.

distribution of a luminaire. *Illuminance* is the concentration of luminous flux incident on a surface (Figure 1.5). The unit of illuminance is lux (lx), and it indicates the number of lumens per square meter. Lumens per square foot are called footcandles (ftc). Whereas luminous flux relates to the total output of a lamp or lighting product, illuminance relates to the amount of light striking a surface or point. Illuminance depends on the luminous flux of the light sources and their distances from the illuminated surface.

Luminance is a measure used for self-luminous or reflective surfaces (Figure 1.6). It expresses the amount of light, weighted by the sensitivity of the visual system, per unit area of the surface that is travelling in a given direction and is expressed as candelas per square meter (cd/m^2). When referring to illuminated surfaces, luminance is determined by the incident light (illuminance) and the reflectance characteristics of the surface. For instance, light- and dark-colored walls will have different luminance values when they have the same illuminance. Luminance is a metric used for internally illuminated variable-sized flat light sources forms, such as sheets or tapes, because the total luminous flux will depend on the surface area of the product.

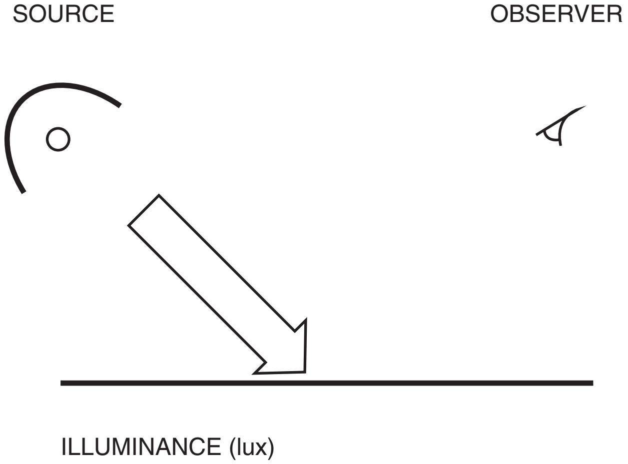

FIGURE 1.5 Illuminance (lux). The amount of light striking a surface or point, measured in lux (lx).

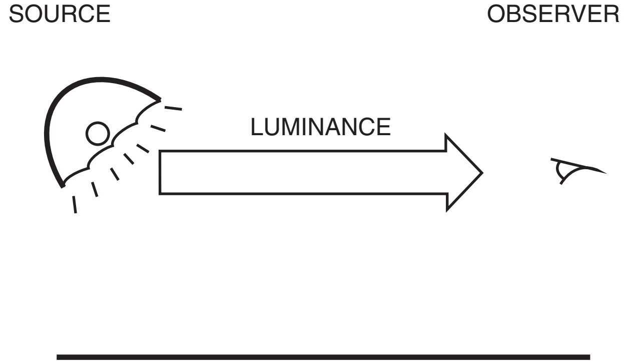

FIGURE 1.6 Luminance of a luminaire.

The *luminous efficacy* of a lighting product is the ratio of the luminous flux to the total electrical power consumed and has units of lumens per watt (lm/W). A perfect light source—that is, one that converts all the electricity into visible light—would have an efficacy of 408 lm/W for an assumed color rendering index (CRI; a measure of color quality, discussed below) of 90 (Phillips et al., 2007).[5] The luminous efficacy of a typical 60 W incandescent lamp (luminous flux of 850 lumens) is such that only 14.2 lumens are emitted per watt of power drawn by the light bulb. As efficacies increase, more of the power is used to generate visible light, and this leads to a more efficient product. High color quality LEDs currently are being manufactured with efficacies in the range of 60 to 188 lm/W. It should be borne in mind that efficacy is different from efficiency. The efficiency of a lighting system is the ratio between the obtained efficacy and the theoretical maximum efficacy of a light source (408 lm/W for a CRI of 90) and is always expressed as a percentage. Thus, it accounts for the ballast efficiency (if there is one), the light source efficacy, and the luminaire efficiency (see Figure 1.7) in one lumped parameter. Thus, incandescent lamps with system efficacies ranging from 4 to 18 lm/W (depending largely on the wattage of the bulb) will have system efficiencies of only about 0.2 to 2.6 percent. Efficiency does not, however, account for the perceived quality of the light. Using the theoretical maximum of 408 lm/W and the ranges of efficacies for different lighting technologies leads to the ranges of system efficiencies shown in Figures 1.7 and 1.8.

VISIBLE SPECTRUM AND QUALITY OF LIGHT

The human eye can generally detect light with wavelengths between 380 nm (corresponding to blue/violet light) and 750 nm (corresponding to red light). The *spectral power distribution* (SPD) determines several important properties of a light source. The SPD describes the relative amount of light per wavelength per unit time emitted by a light source and is often graphically represented, as shown in Figure 1.9. Figure 1.9 shows the SPDs of a halogen lamp, a red, green, blue (RGB) LED (which produces white light by combining red, green, and blue component LEDs), an OLED, and a combination of four colored lasers.

The color of emitted light as perceived by people, called chromaticity, is regulated by the spectral composition. The human visual system does not process light on a wavelength-by-wavelength basis. Instead, the brain receives signals from only three input channels, the different cone photopigments found in the eye. Because of this, countless different SPDs can produce light identical in chromaticity. To illustrate this,

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[5] A different choice of color rendering index = 80 would lead to a maximum efficacy of 423 lm/W, and so forth.

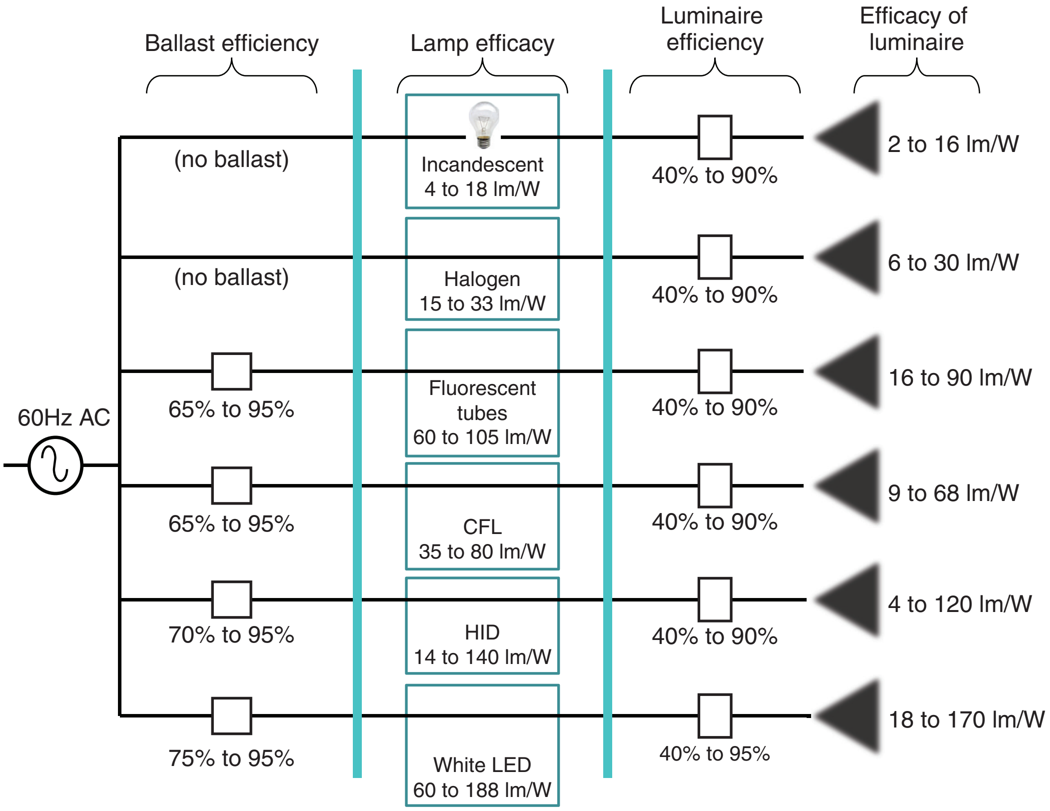

FIGURE 1.7 Efficacy of lamps and luminaires. Values in the left-most column report the range of efficiencies for ballasts and electronic drivers. Values in the central column report efficacies for different lighting devices. The values on the third column report ranges of luminaire efficiencies. The values on the right-most column report the overall system efficacies of the luminaire. SOURCE: Adapted from Azevedo et al. (2009), where the efficacies for white LEDs were updated to reflect currently commercialized warm and cool white LEDs. NOTE: AC = alternating current; HID = high-intensity discharge; Hz = Hertz; LED = light-emitting diode.

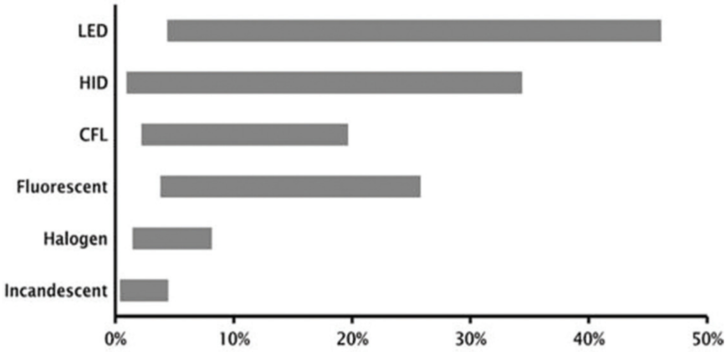

FIGURE 1.8 Overall efficiencies of lighting systems (lower bounds) and devices (upper bounds) when assuming that the theoretical maximum lamp efficacy is 408 lm/W; LED = light-emitting diodes; HID = high-intensity-discharge lamps; CFL = compact fluorescent lamps. Lower and upper bounds correspond to the low- and high-efficacy values shown in Figure 1.7. SOURCE: Azevedo et al. (2009).

the four widely varying SPDs shown in Figure 1.9 would all produce light that would appear indistinguishable.

On the *correlated color temperature* (CCT) scale, all four spectra lights in Figure 1.9 are approximately 3,000 K. Correlated color temperature is used to describe nominally white light sources and refers to the temperature of a blackbody radiator that produces a light perceived to be most similar in chromaticity to the white light source. A typical incandescent lamp has a CCT of 2,500 kelvin (K) to 3,000 K, whereas office and school lighting is often 4,000 K

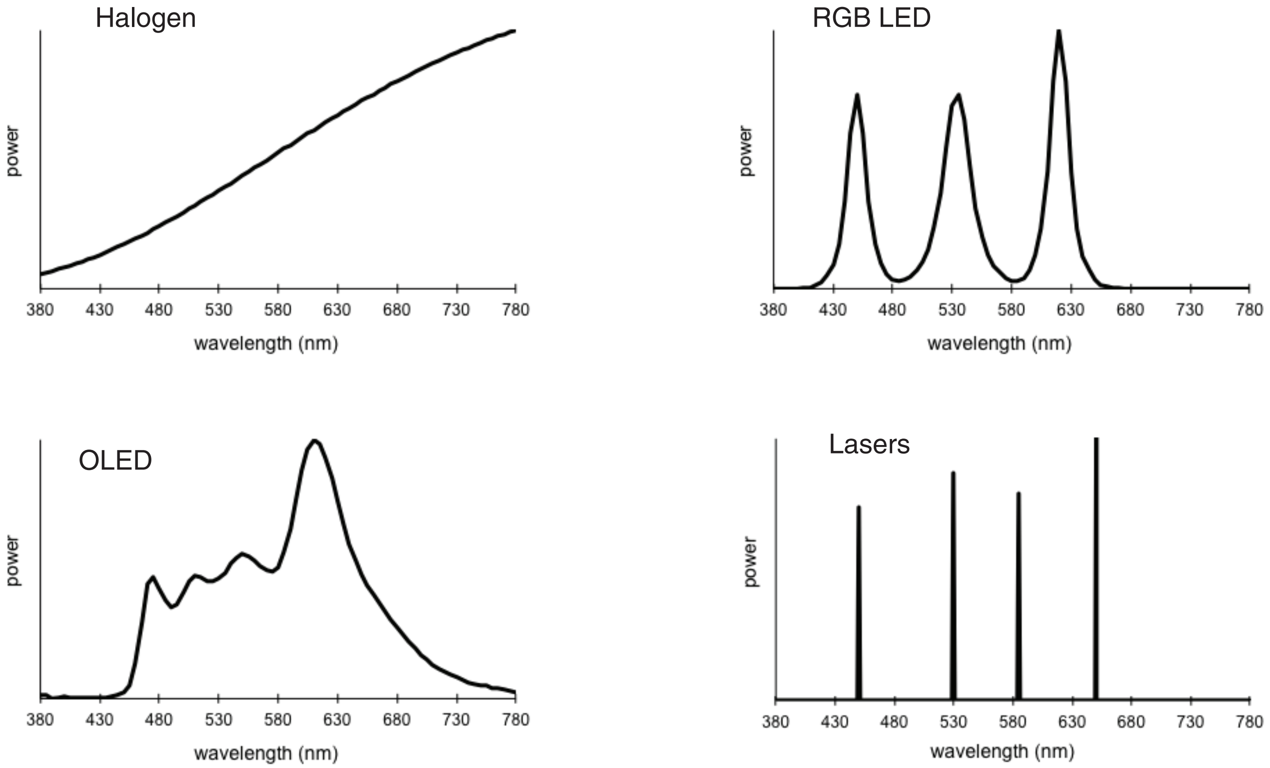

FIGURE 1.9 Spectral power distribution from very different light sources that were chosen to produce identically appearing white light. The red, green, blue (RGB) light-emitting diode (LED) produces white light by combining red, green, and blue component LEDs, as does a combination of four colored lasers.

to 5,000 K. Lower CCTs include more light nearer the red end of the visible spectrum and are perceived to be "warmer," while higher CCTs tend toward the blue end and are perceived to be "cool." In somewhat of a misnomer, the labeling is indicative of the feelings they evoke rather than their actual temperatures. Although the color of daylight changes throughout the day and with location on Earth, it is commonly described as having a CCT of 6,500 K. Although CCT is widely used among lighting manufacturers and designers, it only describes one dimension of light source chromaticity, in the blue-yellow direction. It does not consider pink-green shifts in white light color, although D_{uv} is a measure increasingly used for that information.

The most common system for specifying and communicating the precise chromaticity of light sources uses CIE 1931 (x,y) chromaticity coordinates (CIE, 2004). The CIE 1931 (x,y) chromaticity diagram is shown in Figure 1.10. The curved edge of the outer horseshoe shape on the diagram is the *spectrum locus* and is comprised of the colors of monochromatic (only one wavelength) radiation. The straight edge line is the *purple line*, and the colors are always a combination of red and blue (not monochromatic).

Chromaticity does not provide all of the color information of interest for general illumination applications. The color of the light itself does not predict the appearance of colored objects illuminated by the source, a property referred to as color rendering. Although color rendering is determined by the spectral output of a light source, it cannot be predicted by a cursory inspection of the shape of the spectral power distribution, and subtle differences in SPD can produce marked differences in the chromaticity of illuminated objects (Ohno, 2005).

The SPD also determines the LER (i.e., the luminous efficacy of radiation) of a light source. In technical terms, LER is the ratio of luminous flux to radiant flux.[6] In simple terms, the LER is luminous efficacy that could be achieved if the light source was able to convert electricity to light perfectly with no losses. The final luminous efficacy of a light source is determined from both the LER and the efficiency with which the technology converts electricity to light. The sensitivity of the human visual system differs for the various wavelengths in the visible range. The relationship between wavelength and the relative sensitivity of the human visual system is described by the spectral luminous efficiency function (V_λ) (CIE, 1926) which is shown by the dashed curves in Figure 1.11. This function peaks at 555 nm. Light of this wavelength has a LER of 683 lm/W, setting the upper bound

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[6] Radiant flux is the amount of electromagnetic energy emitted per unit time at all wavelengths including visible light and other spectral bands. As such it will exceed the luminous flux.

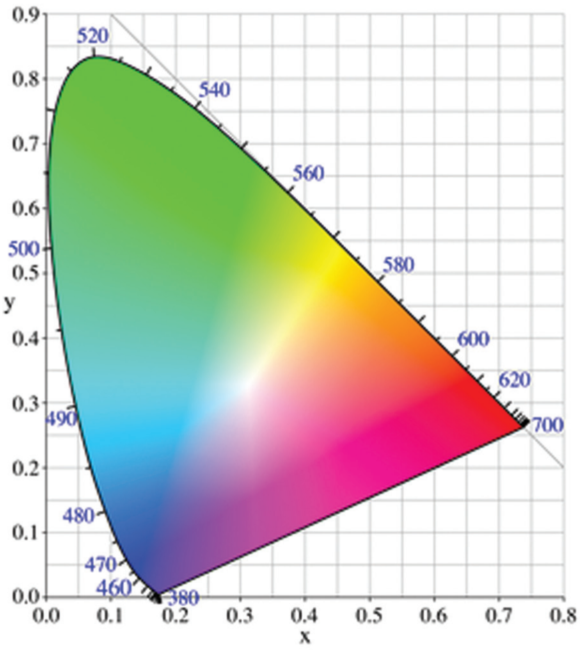

FIGURE 1.10 CIE 1931 (*x*,*y*) chromaticity diagram. Numbers indicate wavelength of light, in nanometers. SOURCE: Wikipedia Commons.

for luminous efficacy, as illustrated by the 555 nm laser in panel a. It is important to note that white light cannot achieve 683 lm/W, only light at 555 nm can. Visual sensitivity is markedly lower for light in the short- and long-wavelength regions of the visible spectrum. The other three panels of Figure 1.11 show different SPDs and their corresponding LER. Panel b shows an RGB white LED, panel c shows a different type of white LED (called a phosphor LED, to be discussed later), and panel d shows the SPD of a typical incandescent lamp. As shown, the effect of spectral power distribution on luminous efficacy can be substantial. The incandescent SPD has a relatively low LER because it has a lot of energy in the very long visible and infrared wavelengths, to which the visual system is either minimally or completely insensitive.

Although the wavelengths of light to which the eye is most sensitive lie in the middle of the spectrum, a light source composed of light only in the middle of the visible spectrum would not be useful for general illumination. To achieve desirable color characteristics, light of other wavelengths must be present. There is generally a trade-off between luminous efficacy and color quality (Ohno, 2005). Depending on the application and goals of a lighting product or lit environment, a luminaire manufacturer or lighting designer may choose to prioritize one trait over the other. For example,

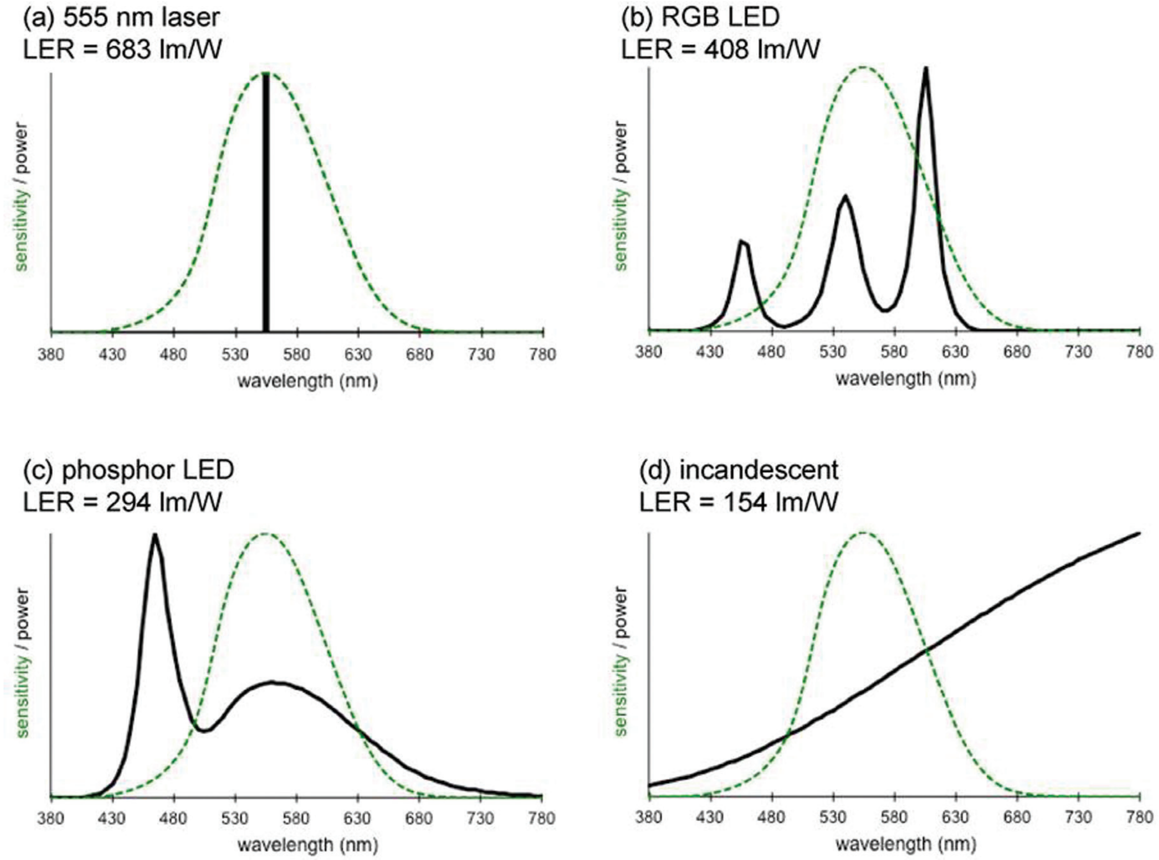

FIGURE 1.11 Spectral power distribution determines luminous efficacy of radiation (LER). The dashed green curves show the Spectral Luminous Efficiency Function and the black curves are light source's spectral power distributions. NOTE: RGB = red, green, blue.

in a parking garage with lights on 24 hours a day, a specifier may require excellent efficacy and accept subpar color quality. On the other hand, a museum may require superior color and be willing to sacrifice efficacy.

Good color rendering can be achieved with such discontinuous light spectra because of the properties of the other two elements in the process of perceiving object colors: the reflectance of the objects and the absorption of the cone photopigments in the human visual system. All objects, natural or artificial, reflect as a function of wavelength in a very broad and continuous manner. The reflectance factors of these objects (the proportion of light reflected as a function of wavelength) do not show sudden spikes or isolated dips in reflectivity across the visible spectrum. Because of this, the general shape of the reflectance factor can be interpolated with fairly coarse wavelength sampling. The three cone photopigments responsible for color vision have absorption functions that are very broad, continuous, and overlapping in wavelength sensitivity. Each cone type responds to many wavelengths, although sensitivity does change depending on the wavelength. The outputs of these photoreceptors do not signal the wavelength composition of the stimulus to the brain. For instance, a certain level of activity from one cone type could result from a small amount of energy at every wavelength it is sensitive to or a lot of energy at only one wavelength it is sensitive to. The visual system makes absolutely no distinction between these two situations (Rushton, 1972). The perception of color arises from combining and comparing the activity among the three cone types. Therefore, countless combinations of input wavelengths can lead to the exact same perception of color. These circumstances, in which objects reflect in a fairly predictable manner and the visual system interprets incoming light in terms of three broadly sensitive channels, allow a great deal of flexibility for the spectral content of light sources. A recent study demonstrated an extreme case of this in which light sources were developed composed of only four lasers (i.e., sources with extremely narrow emission spectra) with high color rendering quality (Neumann et al., 2011).

FINDING: A light source need not emit energy at every visible wavelength in order to achieve high color quality (Figure 1.9). An understanding of the spectral power distribution's effects on luminous efficacy and the color properties of a light source will enable SSL developers to optimize energy efficiency while maintaining good color quality.

CURRENT LIGHTING CONSUMPTION IN THE UNITED STATES

At the beginning of this chapter, we briefly described the U.S. electricity use by sector. Concerning the contribution of lighting to overall electricity consumption, it is generally agreed that nearly 20 percent of U.S electricity generation is used in lighting (Azevedo et al., 2009). However, there are no detailed time-series data, and there is a large uncertainty regarding actual lighting electricity consumption. The recent lighting market characterization for 2010 from DOE (2012) estimates that electricity consumption for lighting in the residential, commercial, industrial, and outdoor stationary sectors is 175 terawatt hours (TWh), 349 TWh, 58 TWh, and 118 TWh, respectively, thus totaling 700 TWh for all sectors. Another recent estimate, from the Energy Information Administration (EIA, 2011), suggests that in 2010 the residential and commercial sectors used about 499 TWh of electricity for lighting, which corresponds to roughly 18 percent of the total electricity consumed by both of those sectors.[7] The most recent (2006) EIA data available for the manufacturing sector show 63 TWh consumed in lighting, which corresponds to 7 percent of all electricity consumed by manufacturing and 2 percent of all electricity used by the United States (EIA, 2009).

DOE (2012) reports a breakdown by technology type for each sector, estimating that in the commercial sector linear fluorescent lamps are responsible for 72 percent of lighting electricity consumption, and that the residential sector is still dominated by incandescent lamps (accounting for 78 percent of residential lighting electricity consumption). In 2010, incandescent lamps accounted for 45 percent of lamps for all sectors in the United States. Linear fluorescent lamps and CFLs together now account for a larger share in terms of number of lamps (48 percent), while LEDs account for 0.8 percent. In terms of shipments, the *Buildings Energy Data Book* (DOE, 2011) estimates that ENERGY STAR® lamps[8] were 15 percent of total shipments of medium screw-based lamps in 2009. Overall, there is a lack of data on annual market characterization, which are crucial to understand the impact of current and future policies.

CONTENT OF THE REPORT

Chapter 2 provides an in-depth look at the suite of instruments—R&D investments, standards, demonstration projects, and so forth—by which governments have stimulated more efficient use of energy for illumination. The chapter also includes a case-study of early-generation CFLs in order to extract lessons applicable to the introduction of SSL products in the market. Chapter 3 discusses the two candidate technologies for manufacture of SSL products—LEDs and OLEDs—and evaluates the barriers remaining to widespread deployment in luminaires, including challenges in research, development, and manufacturing. Included as well is a primer on each technology. Chapter 4 focuses on the luminaires themselves and the challenges to their assembly

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[7] EIA reports that it does not have an estimate for only public street and highway lighting, but these applications are considered part of the commercial sector in the EIA report and are thus included in the 499 TWh.

[8] ENERGY STAR® is a voluntary program created by DOE and the Environmental Protection Agency to encourage energy efficient products and buildings through labeling. Discussed in Chapter 2.

and integration into buildings and electricity systems. Chapter 5 provides a perspective on the design and installation of LED and OLED luminaires. Chapter 6 discusses the market barriers to the adoption of SSL products.

ANNEX

There are many different kinds of lamps. Most of the lamps used in residential applications are *omnidirectional* (emit light in all directions) incandescent lamps, typically with a medium screw base (Figure 1.12) that fits into most residential luminaires. In addition, there are candelabra and intermediate base lamps that are commonly used in residential applications, especially in chandeliers and wall sconces. Incandescent lamps produce light by heating a tungsten filament to a temperature of approximately 2,500 K to 3,000 K where the filament glows or *incandesces*.

Halogen lamps are incandescent lamps in which the tungsten filament has been enclosed in a capsule containing a halogen gas, typically bromine, which allows the filament to operate at a slightly higher temperature without reducing the rated life and resulting in a somewhat higher light output than the standard incandescent lamp. Halogen lamps are available that emit light omnidirectionally, as well as *directional* varieties, often known as reflector lamps. Reflector lamps are designated by the properties of their reflectors, such as PAR (parabolic aluminized reflector (Figure 1.13) or MR (multifaceted mirror reflector), and are most commonly either standard incandescent or halogen. The low-voltage MR-16 lamp (Figure 1.14) commonly used in accent, task, and display lighting uses halogen technology.

Fluorescent lamps are available in a range of shapes and sizes. Linear fluorescent lamps are frequently used in commercial spaces (offices, stores) and are typically long 4-foot tubes. They are often installed in recessed luminaires in the ceiling or are pendant-mounted from the ceiling. All fluorescent lamps require a ballast. CFLs are available with screw bases and an integral ballast (Figure 1.15) for use as replacements for incandescent lamps or with pin bases for use with a separate ballast (Figure 1.16). Both CFLs and linear fluorescent lamps produce light by exciting phosphors, which then *fluoresce*, with ultraviolet energy. A small amount of mercury is added to the lamp to emit ultraviolet light at a suitable wavelength for exciting the phosphor.

High-intensity-discharge (HID) lamps are electric lamps with tubes filled with gas and metal salts. The gas initiates an arc, which evaporates the metal salts, forming a plasma. This results in an efficient and high-intensity light source. These lamps are suitable for both indoor and outdoor applications and are generally used to light large spaces or roadways. All HID lamps require a ballast.

Mercury vapor, metal halide (Figure 1.17), and high-pressure sodium lamps are examples of specific types of HID lamps. HID lamps require a warm-up period to reach stable output as well as a cool-down period before restarting.

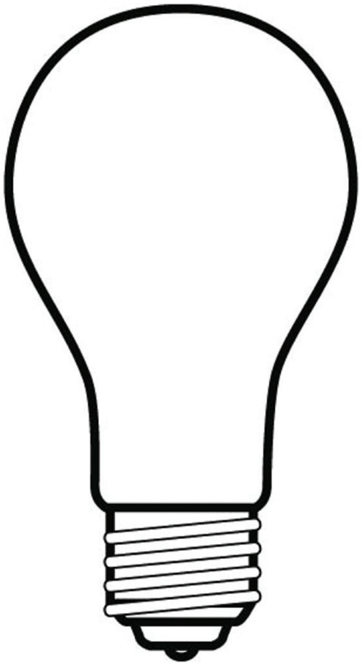

FIGURE 1.12 Incandescent with medium screwbase (A-19).

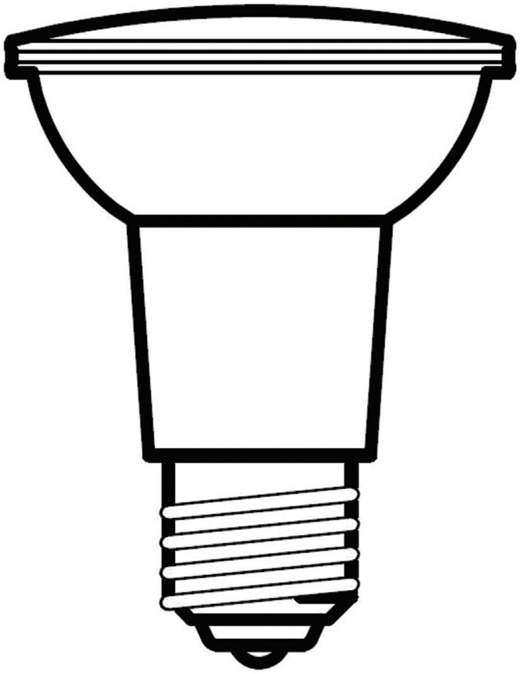

FIGURE 1.13 PAR 20 lamp (tungsten halogen).

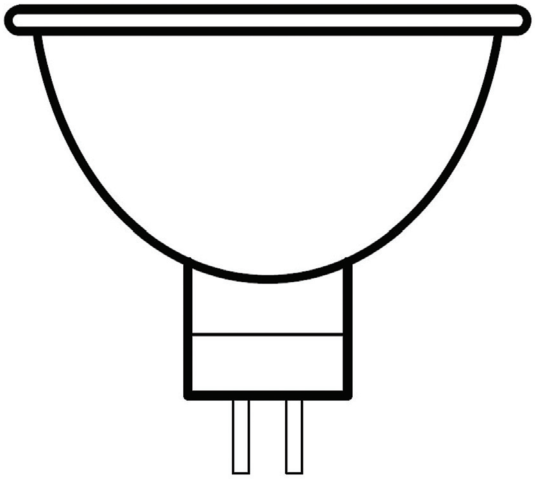

FIGURE 1.14 MR 16 lamp (tungsten halogen).

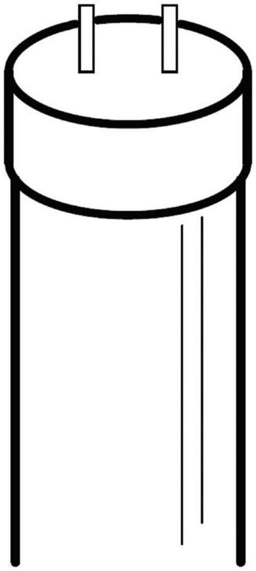

FIGURE 1.16 Fluorescent lamp (T5) without integral ballast.

FIGURE 1.15 Compact fluorescent lamp (screw base with integral ballast).

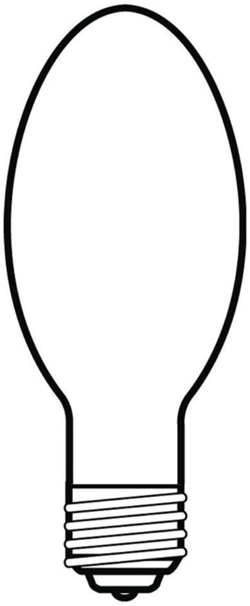

FIGURE 1.17 Metal halide lamp (an example of high-intensity discharge lamp).

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2

History of Public Policy on Lighting

INTRODUCTION

The development of lighting technology, like all technologies, is influenced by the public policy framework in which the relevant innovation and commercialization occurs. This policy framework includes legislation and regulation at the federal, state, and local levels, as well as the equivalent laws in other industrialized countries. Yet, the pertinent policy framework involves more than just laws and also includes governmental research, development, and demonstration (RD&D) funding, consensus and industry standards, voluntary programs, incentive programs, building codes, and industry programs and initiatives, all operating within the context provided by market forces and consumer expectations. All of these factors play a role in the development of solid-state lighting (SSL) and are discussed below.

This chapter begins with a history of federal government policy on lighting, then covers federal legislation addressing lighting efficiency and the Department of Energy (DOE) lighting RD&D program. It then describes current federal and state programs, including federal regulations, federal voluntary programs, and state laws and regulations. Non-regulatory policy instruments affecting lighting efficiency are discussed next, including building codes, state building codes specifications for high-performance building specifications, incentive programs, and testing and measurement consensus standards. The chapter concludes with a brief summary of international regulation of lighting efficiency, followed by a case study on compact fluorescent lamps (CFLs).

History of Federal Government Lighting Policy

Since the early 1970s the federal government has been involved in RD&D and policy related to more energy-efficient lighting. Four months prior to the oil embargo of 1973, President Nixon announced the formation of an Office of Energy Conservation within the Department of the Interior. One of its functions was to coordinate a 7 percent reduction of federal energy consumption (Savitz, 1986). When the oil embargo was imposed, President Nixon ordered government buildings (and requested the private sector) to reduce lighting levels to 50 footcandles (ftc) (approximately 500 lux) for office work; 30 fc (approximately 300 lux) for general lighting/hallways; and 10 ftc (approximately 100 lux) for parking lots—i.e., “50-30-10.”

Following the embargo, RD&D energy efficiency programs were initiated at DOE’s predecessor agencies: the Federal Energy Administration (FEA) and the Energy Research and Development Administration (ERDA). Most of the programs in the buildings sector were applied product research to develop more energy-efficient heating, cooling, and lighting systems. These programs were done in collaboration with industry and some of the national laboratories, predominantly the Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL).

When DOE was formed in 1977, the lighting program covered a wide range of energy-saving opportunities. The overall strategy consisted of three major thrusts: (1) light sources, (2) lighting applications (lighting design, fixtures and controls), and (3) lighting impacts. By 1999, light sources comprised more than half of the lighting program funding, which was $2 million to $4 million per year (NRC, 2001).

In the 1970s and 1980s, the program mainly consisted of contracts to industry, research and development (R&D) companies, and in-house research at LBNL. In spite of the relatively small amount of funding in the 1970s and 1980s, there were major successes from the DOE programs in conjunction with industry and LBNL. Two of these examples—electronic ballasts and CFLs—were case studies in a retrospective study by the National Research Council (NRC, 2001). The market share for electronic ballast increased from about 1 percent in the late 1980s to 47 percent by 2000 and 73 percent by 2005 (NRC, 2010). DOE promulgated minimum efficiency standards in 2000, effective in 2005. The National Research Council (NRC) retrospective study documented at least

$15 billion in net economic benefits for electronic ballasts as of 2000 (NRC, 2001).

The other case study was CFLs. DOE did not have a program targeted for CFLs until 1997, at which point it decided to sponsor R&D on the technology to reduce the cost and size of CFLs and accelerate their deployment. In fiscal year (FY) 1999, Congress provided funds specifically for new R&D projects, which were to be competitive solicitations that were cost-shared with industry. From FY1999 to FY2001 DOE spent $1.8 million on R&D efforts; industry cost-shared $755,000 (NRC, 2001), or roughly 40 percent. Sales increased from about 21 million units in 2000 to almost 400 million units by 2007 (NRC, 2010).

It is generally acknowledged that it is methodologically difficult to estimate the impact of energy efficiency policies on demand reductions. Changes in weather, energy prices, cultural factors, and so on, all contribute to changes in energy consumption, and disentangling those effects from the impact of policies is difficult—but also critical to support the design of effective policies.

Several studies have shown the impact of specific policies on energy consumption reductions. For example, Gillingham et al. (2004) recently reviewed literature on the cost-effectiveness and impacts of a broad range of energy efficiency policies. The authors reviewed several studies that estimated the impact of appliance standards, financial incentives, information and voluntary programs, and government energy use. They concluded that "these programs are likely to have collectively saved up to 4 quadrillion Btu[1] of energy annually, with appliance standards and utility demand-side management likely making up at least half these savings" (abstract, p. i). In their analysis, the authors did not include building and professional codes, and thus these overall savings are likely to be underestimates. The authors also stated that "Energy Star,[2] Climate Challenge, and 1605b voluntary emissions reductions may also contribute significantly to aggregate energy savings, but how much of these savings would have occurred absent these programs is less clear" (abstract, p. i). Another study, focusing on energy efficiency policies in California, citing reductions in per-capita emissions that could not be attributed to other sources finds that, for 2001, totaled "up to about 23 percent of the overall difference between California and the United States could be due to policy measures, the remainder being explained by various structural factors" (Sudarshan and Sweeney, 2008, p. 1). These values were 545 kilowatt-hour (kWh) per capita in the residential sector and 416 kWh and 272 kWh in the commercial and industrial sectors, respectively.

The verification of the impacts of demand-side policies is always complex, given the need to establish a counterfactual of what would have occurred without the policies. However, there is a large amount of literature on the impact of utility demand side management (DSM) and energy efficiency programs, using sophisticated econometric models. A study in 1996 from Parfomak and Lave (1996) suggested that "utilities have a clear economic incentive to overstate the impacts" of these programs. However, when empirically assessing the impact of DSM and energy efficiency programs for several utilities in the northeast and California, the authors found that the reductions claimed by the utilities and the system-level sales after accounting for economic and weather effects they estimated were in agreement.

FINDING: While it is difficult to discern the contribution of public policies on the adoption of energy efficient products, it is likely that a sizable fraction of the decrease in per capita energy consumption may be attributable to such policies, judging from a study of changes in energy consumption in California. However, the actual impact of any specific policy instrument is difficult to disentangle as is the impact on any one type of household energy use.

FINDING: Improvements in energy efficiency of lighting products have been brought about by a combination of legislation, regulation, RD&D funding, consensus standards, industry programs and initiatives, incentive programs, and market forces.

RECOMMENDATION 2-1: The Department of Energy should develop a study to quantify the relative impact of different policy interventions on the benefits of adopting efficient lighting.

Federal Legislation

Over the past quarter century, a series of federal energy statutes have mandated energy efficiency standards and labeling for lighting. These congressional enactments have been contemporaneous with a steady increase in the energy efficiency of lighting technology over this time period.

Congress has given DOE the authority to regulate the energy efficiency of some high-volume lighting products at the federal level. In 1975 the Energy Policy and Conservation Act (EPCA 75), Public Law 94-163, established a program on "energy conservation for consumer products other than automobiles" (Title III), which included major household appliances, but did not include lighting. In 1987, the National Appliance Energy Conservation Act (NAEPA 87), Public Law 100-12, included minimum efficiency standards for fluorescent lamp ballasts and incandescent reflector lamps. In 1992, the Energy Policy Act (EPACT 92), Public Law 102-486, tightened the minimum energy efficiency standards for fluorescent lamps and incandescent reflector lamps. Furthermore, DOE was granted the authority to revise and amend these standards as well as to adopt a standard for additional

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[1] Btu stands for British thermal unit and is a measure of energy. Burning 1 gallon of gasoline would release approximately 124,000 Btu.

[2] ENERGY STAR® is a voluntary program created by DOE and Environmental Protection Agency to encourage energy efficient products and buildings through labeling.

general service fluorescent lamps. In addition, EPACT (92) added standards for some types of fluorescent and incandescent reflector lamps, provided funding for voluntary testing and consumer information programs for luminaries, and created an energy efficient commercial building tax deduction program, which includes lighting. The 1992 statute also set July 1994 as the deadline for states to adopt the lighting standards developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 90.1 standards).

The Energy Policy Act of 2005 (EPACT 05), Public Law, 109-58, included performance standards for additional lighting products (e.g., energy saving fluorescent lamp ballasts) that had not been included in any of the previous legislation. It also provided for the establishment of labeling requirements for these products and preempted state standards for the same products. EPACT (05) also officially recognized and made more transparent the ENERGY STAR® program. Finally EPACT (05) expanded the tax deduction program for commercial building energy efficiency, originally enacted in EPACT (92).

The Energy Independence and Security Act of 2007 (EISA 2007) further amended EPCA (75) to include new provisions for lighting standards. EISA 2007 includes performance-based minimum efficiency standards for general service lamps, which will become progressively more stringent over time. General service lamps are classified as screw-based incandescent and fluorescent lamps and tubes; some specialty lamps were excluded from the standard. EISA also includes minimum efficiency standards for ballasts and lighting requirements for public buildings. Title III, Subtitle B, establishes definitions, standards, and amendments for lighting efficiency, and Section 321 defines energy efficiency standards for general service lamps. Table 2.1 shows the performance standards for lamps set by EISA 2007. The standard sets a maximum number of watts that a specified lamp (e.g., the so-called “A19 shape”) can use whose luminous output falls within a specified range. General service lamps outside this range are exempt from maximum rated wattage limits.

EISA 2007 also sets up standards for federal government buildings that will provide additional incentives for energy efficient lighting. The statute directs that total energy use in federal buildings be reduced 30 percent from a 2005 baseline by 2015. Moreover, the statute directs that every federal facility be subject to a comprehensive energy and water evaluation at least once every 4 years. Finally, new federal buildings and major renovations are required to reduce their energy use, relative to a 2003 baseline, by 55 percent in 2010 and by 100 percent (i.e., zero net energy[3]) by 2030. There were a number of attempts in the 112th Congress to roll back the requirements from EISA 2007 for lamps shown in Table 2.1, which culminated in a FY2012 appropriations rider prohibiting DOE from spending funds to enforce the standards stated in EISA 2007 for 2012. However, manufacturers plan to implement the 2012 standards nevertheless (Howell, 2011).

TABLE 2.1 Rated Lumen Ranges, Maximum Rated Wattages, and Effective Dates for General Service Lamps Goals in EISA 2007, Section 321

Maximum Rated Wattage	Rated Lumen Ranges	Effective Date
72	1490-2600	January 1, 2012
53	1050-1489	January 1, 2013
43	750-1049	January 1, 2014
29	310-749	January 1, 2014

NOTE: Minimum rated lifetime will be 1,000 hours in all cases.

DOE LIGHTING PROGRAM

The SSL Multi-Year Program Plan (DOE, 2011a) notes several efforts within DOE on advancing SSL technology, products, and the underlying science. These efforts occur within the Basic Energy Sciences (BES) program; the Advanced Research Projects Agency-Energy (ARPA-E); and the Building Technologies Program (BTP), which is within the Office of Energy Efficiency and Renewable Energy (EERE). The BES program supports fundamental research to provide the foundations for new energy technologies. Such work at the electronic, atomic, and molecular levels in solid-state physics can lead to multiple applications, including for SSL technologies. One example is the support for the Solid-State Lighting Science Energy Frontier Research Center at Sandia National Laboratories. ARPA-E funds projects that are considered high risk but can potentially lead to high-payoff energy saving results if successful. Some projects funded by ARPA-E are directly related to SSL, such as the development of low-cost, bulk gallium nitride substrates and the development of advanced, energy efficient power supply technologies (DOE, 2011a).

The vast majority of the work on SSL technology at DOE takes place within EERE’s BTP. The BTP oversees the Emerging Technologies subprogram, which focuses on developing cost-effective advanced technologies in such areas as lighting, windows, and space heating and cooling for residential and commercial buildings (DOE, 2010; 2011b). Research across these different areas supports the residential and commercial building goal of reducing total energy use in buildings by up to 70 percent. One budget line under Emerging Technologies is Solid-State Lighting. The funding in recent years for this activity has been about $25 million per year, as delineated in Figure 2.1, of which roughly $9 million was directed toward R&D in FY2011. Most recently, the FY2012 appropriation is $25.83 million for lighting R&D, but specifies that $12 million of that total

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[3] A “zero net energy” building utilizes no net energy from the electrical grid through a combination of reducing overall use of energy (e.g., highly efficient lighting and HVAC technologies) and on-site production of renewable energy (e.g., wind or solar).

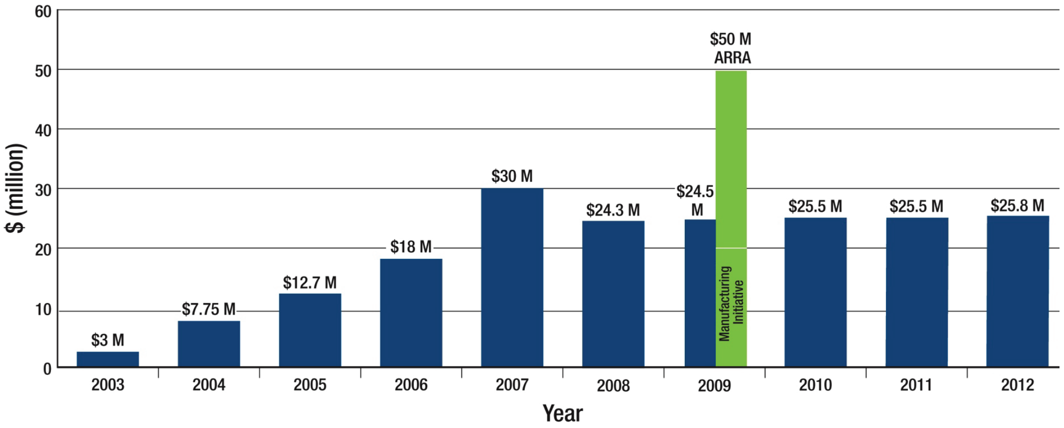

FIGURE 2.1 Budget authority for the Department of Energy's lighting research and development within the Building Technologies Program (millions of dollars). SOURCE: Based on DOE (2010, 2011b) and Brodrick (2012).

must be used for R&D into manufacturing improvements for general illumination SSL. These yearly appropriations received a one-time boost with the American Recovery and Reinvestment Act (ARRA), which in 2009 resulted in about $50 million in additional funding being injected into SSL R&D activities, much of which went to jumpstart the Manufacturing Initiative.

The goal of the SSL R&D program is the following: "By 2025, develop advanced solid-state lighting technologies that, compared to conventional lighting technologies, are much more energy-efficient, longer lasting, and cost-competitive by targeting a product system efficiency of 50 percent with lighting that closely reproduces the visible portions of the sunlight spectrum" (DOE, 2011a, p. 9). Three primary interrelated thrusts are identified in the SSL multi-year program plan for which roadmaps have been developed: (1) core technology research and product development, (2) manufacturing R&D, and (3) commercialization support. The project areas outlined in the Multi-Year Program Plan cover a variety of topics split into core and product development for light-emitting diodes (LEDs) and organic LEDs (OLEDs) (DOE, 2011a).

The LED core technology focus areas are emitter materials research, down-converters (material systems designed to convert shortwavelength emitted radiation to longer wavelengths in the visible spectrum), novel emitter materials and architectures, and optical component materials. The LED product development focus areas are semiconductor materials, phosphors, emitter thermal control, luminaire thermal management techniques, electronic components research, and off-grid lighting. The core technology focus areas for OLEDs are novel device architecture, novel materials, material degradation, and electrode research. OLED product development areas include practical implementation of materials and device architectures, substrate materials, luminaire mechanical design, luminaire thermal management, large area OLED, and OLED light extraction.

The SSL Manufacturing Initiative was added to the SSL R&D portfolio in 2009 and is aimed at reducing costs of SSL sources and luminaires, improving product consistency and maintaining high-quality products, and encouraging a significant role for domestic U.S.-based manufacturing. Most of the one-time $50 million ARRA appropriation in FY2009 went into the manufacturing initiative, a fact reflected in the total obligations listed in Table 2.2. In its funding opportunity announcements, DOE expressed the goal of 50 percent cost-share for manufacturing projects and 20 percent for core technology and technology development projects. To aid in successful market adoption of SSL technology, DOE has also developed a 5-year SSL commercialization support plan to help create the conditions, specifications, standards, opportunities, and incentives that can lead to the accelerated adoption and applications of SSL products that will lead to reduced energy consumption in buildings.

TABLE 2.2 Breakdown of Current Department of Energy (DOE) Solid-State Lighting Research and Development (R&D) Obligations (from both DOE and Matching Funds) as of December 2011

R&D Area	Funding (millions of dollars)	Percentage of Total Funding	Number of Projects
Core Technology			
LEDs	18.2	16	10
OLEDs	8.8	8	7
Product Development			
LEDs	14.6	13	8
OLEDs	5.9	5	4
Manufacturing			
LEDs	46.2	41	6
OLEDs	20.2	18	3
Total	113.9	100	38

SOURCE: Based on DOE (2011b) and Brodrick (2011).

TABLE 2.3 Fiscal Year 2011 Funding for Research and Development for Solid-State Lighting Program

Pathway	Technology	FY2011 DOE Appropriation[a]	Applicant Cost-Share[a]	Cost-Share Percentage
Core	LED	$3.7	$0.9	19.6%
	OLED	$0.7	$0.09	11.4%
Development	LED	$1.5	$0.3	16.7%
	OLED	$1.4	$0.3	17.6%
Manufacturing	LED	$1.3	$0.2	13.3%
	OLED	$0.5	$0.2	28.6%
TOTAL		$9.1	$1.99	17.9%

[a] In millions of dollars.
SOURCE: James Brodrick, DOE.

As of December 2011 (DOE, 2011b) the DOE SSL R&D portfolio (consisting of projects awarded in current and past years that are currently being funded) included 38 projects addressing both LED and OLED technologies, with a total of approximately $114 million in government (including FY2009 ARRA-funded projects that remain ongoing) and industry investment (see Table 2.2). DOE was providing approximately $69 million ($44.6 for LEDs and $23.4 million for OLEDs), and $45.9 million ($34.4 for LEDs and $11.5 million for OLEDs) was provided through cost-shares by project awardees. Twenty-four projects were focused on LED technology and 14 on OLED technology. The BTP, along with ARRA funding, supported 38 projects, to which may be added 9 projects funded by the Small Business Innovation Research (SBIR) program in the Office of Science for an additional total of $4.1 million.

Table 2.3 shows the distribution of FY2011 R&D funding for core technology, product development, and manufacturing, as summarized in Table 2.2. Less than half (48.4 percent) of all R&D funding is devoted to the development of core technologies. Cost-sharing by grantees averages just under 18 percent (17.9 percent) of DOE funding and has declined in the past few years, particularly in the Product Development program, where one might expect more significant industry partnership.

The DOE Lighting R&D program also addresses issues related to commercialization, such as working with industry and other partners (e.g., Pacific Northwest National Laboratory [PNNL][4] and ORNL) to coordinate the development of standards or reduce barriers to market introduction of technologies that emerge from its efforts. It supports independent testing of SSL products, supports exploratory studies on market trends and helps to identify critical technology issues, supports workshops to foster collaboration on standards and test procedures, promotes a number of industry alliances and consortia, disseminates information, and supports a number of other initiatives (Brodrick, 2011). It also conducts technical, market, economic, and other analyses and provides incentives to the private sector to innovate.

FINDING: DOE has done an impressive job in leveraging a relatively small level of funding to play a leading role nationally and internationally in stimulating the development of SSL.

FINDING: In recent years, DOE has expanded its portfolio to include R&D into manufacturing projects, largely at the direction of Congress in the FY2009 ARRA funding and the FY2012 appropriations bill.

FINDING: The percentage of matching funds from R&D grant recipients was 18 percent for FY2011 funds. Ten years ago, for FY1999 to FY2001, it had been roughly 40 percent. It has declined in the past few years, particularly in the Product Development category.

RECOMMENDATION 2-2: The Department of Energy's solid-state lighting program should be maintained and, if possible, increased.

RECOMMENDATION 2-3a: The Department of Energy should seek to obtain 50 percent cost-sharing for manufacturing research and development projects, as was done with the projects funded by the American Recovery and Reinvestment Act.

RECOMMENDATION 2-3b: As part of the next mandated study of the Department of Energy Solid State Lighting program in 2015, an external review should be conducted to provide recommendations on the relative proportions of funding that should be dedicated to core technology, product development, and manufacturing projects, and what the targeted level of matching funding should be in each of these three funding categories.

EPACT (05) directed DOE to establish a Next Generation Lighting Initiative (NGLI) to support the research, development, demonstration, and commercial application of

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[4] In FY2011, $8.5 million was directed toward commercialization work at PNNL (James Brodrick, DOE, personal communication to Martin Offutt, National Research Council, February 22, 2012).

advanced SSL technologies. To that end, DOE was authorized to create an industry alliance (NGLIA) that consists of private, for-profit firms that are competitively selected to represent, as a group, U.S. SSL research, development, infrastructure, and manufacturing expertise. DOE may give preference to participants in the Industry Alliance in issuing competitive grants awards under the NGLI. DOE signed a memorandum of agreement (MOA) with NGLIA in February 2005 in which NGLIA will provide a manufacturing and commercialization emphasis for the NGLI. In order to facilitate this function, NGLIA members are provided a 1-year non-exclusive license to commercialize patented technologies resulting from the Core Technology Program. Most of the participants in the Core Technology Program are small businesses and universities who would retain the intellectual property rights in their federally funded inventions under the Bayh-Dole Act. Accordingly, DOE sought and obtained a determination of an exceptional circumstance that exempts DOE-funded SSL discoveries from the Bayh-Dole Act, as provided by 35 U.S.C. §202(a)(ii) of the statute. This determination will remain valid for 10 years, to 2015. Some of the leading researchers in the field of LED and OLED lighting have stated to the Committee that they have declined to apply for DOE funding because of this Bayh-Dole exemption.

FINDING: DOE's waiver of Bayh-Dole for projects funded by the SSL R&D program is discouraging some universities and small companies from participating in the program.

RECOMMENDATION 2-4: The Department of Energy should consider ending its waiver of Bayh-Dole for SSL funding.

CURRENT FEDERAL AND STATE PROGRAMS

Federal Regulations

EPACT (92) gave DOE the authority to amend energy efficiency standards for covered general service fluorescent lamps and incandescent reflector lamps, and DOE later received a court order to complete the rulemaking by 2009. In July 2009, DOE published a final rule (DOE, 2009a). Its requirements came into effect starting July 14, 2012. In September 2011, DOE initiated another rulemaking on general service fluorescent lamps and incandescent reflector lamps with the aim of increasing the minimum efficacy requirements for these types of lamps by a few percent (DOE, 2011d). The final rule is projected to be published in April 2014 and become effective in April 2017. As a result of National Electrical Manufacturers Association (NEMA) comments to DOE regarding this rulemaking,[5] DOE issued a report in 2011 acknowledging that in the medium term, there are projected to be shortages in the global supply of certain raw materials needed to produce such lamps as would comply with the 2009 rule (DOE, 2011f). Recently, DOE has issued waivers to manufacturers of T8 fluorescent lamps to ease the problem of these shortages, although a solution for the medium and long term is still being developed by industry even as it is developing SSL technology.

Federal Voluntary Programs

Federal voluntary programs have also played a key role in the improvement in lighting energy efficiency over the past two decades. In 1991, Environmental Protection Agency (EPA) created the Green Lights Program, a partnership to promote efficient lighting systems in commercial and industrial buildings (EPA, 2009). In this program, EPA partnered with public and private organizations to promote the use of more energy-efficient lighting. The program involved developing a plan for organizations to follow, required annual reporting of energy savings, and provided a set of free technical and marketing tools for participating organizations to help them transition to more efficient lighting.

In the mid-1990s, EPA merged the Green Lights Program into the ENERGY STAR® program. The latter program was started by EPA in 1992 as a voluntary labeling program designed to promote energy efficient appliances and other end-use products (GAO, 2010). Although ENERGY STAR® did not initially include lighting, luminaires were added in 1997, CFLs in 1999, solid-state luminaires in 2007, and integral LED lamps in 2009 (Baker, 2011). ENERGY STAR® became a collaboration between EPA and DOE in 1996 (GAO, 2010). EPA plays the primary role and has responsibility for setting performance levels, overseeing partnership agreements, product qualification determinations and listing, and monitoring and verification of the ENERGY STAR® performance criteria. DOE is responsible for the development and monitoring of test and measurement procedures, although in the lighting sector, industry has generally been proactive in developing the applicable test procedures.

ENERGY STAR® previously allowed manufacturers to self-certify compliance with ENERGY STAR® requirements, but it is now tightening the standard to require third-party certification of test data prior to ENERGY STAR® qualification and labeling (Baker, 2011). EPA requires that a product be tested by an EPA-recognized laboratory, which then submits the test data to an EPA-recognized, third-party certification body, which certifies that the product meets the ENERGY STAR® specifications. Once the product has been certified and displays the ENERGY STAR® label, the certification body conducts off-the-shelf verification testing (at manufacturers' expense).

The current specifications for lamps receiving an ENERGY STAR® certification provide approximately a 75 percent savings in energy use versus a standard incandescent lamp. While the current ENERGY STAR® approach is

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[5] Personal communication with Clark Silcox, NEMA General Counsel.

to specify different qualification criteria for specific lighting technologies, EPA has stated a goal of moving toward specification integration in which one set of technology-neutral specifications would apply to all lighting technologies. To that end, EPA has recently merged the SSL luminaire and non-SSL residential luminaire specifications into a single specification (EPA, 2011b) and has also proposed to merge the CFL and SSL lamp specifications. However, the lighting industry has expressed concern that recent EPA actions do not fully implement a technology-neutral approach. The current specification has different performance requirements for CFL and LED products with respect to many performance characteristics (life rating, color maintenance requirement, color angular uniformity requirements, lumen maintenance requirements, and power factor requirements, to mention a few) and does not appear to support the inclusion of any other technologies (such as halogen or metal halide), no matter how significant any improvements that were made in them, given that test measurement methods are typically only given for fluorescent and SSL technologies.

FINDING: A technology-neutral specification for lighting would "raise the bar" for energy efficiency without putting the government in the position of picking and choosing which technologies should be included in ENERGY STAR®. Rather, those technologies that meet the specified criteria (e.g., luminous efficacy, color temperature, color rendering) would qualify for ENERGY STAR® labeling.

RECOMMENDATION 2-5: The Environmental Protection Agency should develop technology-neutral specifications for lighting that are based on performance rather than the type of lamp to provide the most objective and even-handed standards for energy efficiency.

While ENERGY STAR® applies to more than 70 product categories, lighting is one of the few product categories in which the ENERGY STAR® qualification is dependent not only on energy efficiency, but also on lighting quality. The ENERGY STAR® lamp specification contains an extensive list of performance requirements (e.g., requirements relating to color consistency, color rendering, turn-on time, run-up time) unrelated to energy efficiency, which are intended to ensure that ENERGY STAR® lighting products have a high level of quality and are acceptable to consumers. EPA recently published a vision document in which it justifies the inclusion of non-energy related requirements in ENERGY STAR® specifications (EPA, 2012). For its part, industry has expressed concerns about the inclusion of non-energy related factors in the ENERGY STAR® lighting criteria, citing the potential for duplicative, inconsistent, or unnecessary requirements, given that other standards and regulations may include similar provisions.

The ENERGY STAR® labeling program for individual lighting products primarily applies to federal procurement and residential applications and generally not to commercial or industrial products. ENERGY STAR® applies to commercial and industrial facilities, but the standards are for overall building energy efficiency (which includes lighting) rather than efficiency of individual components such as lighting (other than those luminaires in commercial buildings subject to federal procurement). The ENERGY STAR® buildings program evolved in the 1990s out of the Green Lights Program to focus not only on technologies but also on the interaction of the various building systems. EPA awarded the first ENERGY STAR® to a building in 1999 (EPA, 2009).

Installation of more energy efficient lighting may help a commercial or industrial facility to meet the ENERGY STAR® criteria, but other energy sources must also be considered. The Design Lights Consortium, a collaboration of utility companies and regional energy efficiency organizations, is attempting to supplement the existing ENERGY STAR® approach by providing awareness of efficient lighting products for commercial buildings.[6]

Additionally, the Consortium for Energy Efficiency provides model incentive programs for utilities to adopt, and commercial lighting products are already included in its programs. Finally, the DOE Municipal SSL Street Light Consortium addresses the energy efficiency of street and roadway lighting and assists cities and municipalities in their energy efficiency needs. However, this program is primarily a listing of products without the certification and labeling requirements of ENERGY STAR® and is not as high-profile as ENERGY STAR®.

FINDING: The ENERGY STAR® program provides useful information to residential consumers on energy efficient lighting products. While the ENERGY STAR® program also has a commercial and industrial segment, that program focuses on overall building efficiency rather than the certification and labeling of individual products (with the exception of luminaires in commercial buildings subject to federal procurement). Many other government and industry organizations address lighting product standards for the commercial sector.

State Laws and Regulations

States have been active in promoting energy conservation and efficiency by adopting a variety of regulatory, policy, and incentive programs, many of which will directly or indirectly encourage more energy efficient lighting (DSIRE, 2011). In addition to these general provisions for energy efficiency, some states have adopted specific regulations for lighting. Although EPCA (75) generally preempts state energy efficiency regulations for lighting that is regulated by the federal government, EISA 2007 provides an exception for California and Nevada to adopt the EISA energy efficiency standards

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[6] See http://www.designlights.org/.

1 year earlier than required by the federal program. Although Nevada has declined to exercise this option, the California Energy Commission adopted regulations implementing the federal standards 1 year earlier, so the standards shown in Table 2.1 above are being implemented 1 year earlier in California, which started in January 2011.

Some states, such as Texas and South Carolina, have adopted or proposed legislation exempting any lamps manufactured entirely within that state from the federal EISA 2007 requirements.[7] However, it is unlikely that any lamps and all their components are or will be manufactured entirely in a single state, and, thus, these state bills (which have also been introduced but not passed in other states) have more symbolic than practical effect.

In California, which has begun to implement the requirements 1 year in advance of the rest of the United States, no significant opposition or problems have been encountered by the initial implementation of the EISA 2007 requirements.

FINDING: The EISA 2007 requirements for phasing out inefficient lighting have sparked significant resistance by some legislators, states, and citizens in advance of the implementations of the requirements.

BUILDING CODES

Model Building Codes

In addition to the regulation of the energy efficiency of individual lighting products by federal and state laws (discussed above), lighting energy use in the United States is also regulated by state-administered building codes that govern the installed power and/or energy use of lighting installations in new construction projects and major renovations that require a building permit. In particular, the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) and the International Code Council (ICC) both publish "model energy codes" for states to adopt. ASHRAE has two minimum codes applicable to new construction: Standard 90.1 for commercial and industrial buildings and Standard 90.2 for residential buildings. The ICC develops the International Energy Conservation Code (IECC) that covers both residential and non-residential requirements. In addition, some states—especially California, Oregon, and Washington—have a history of developing their own codes. At the highest level, all of these codes approach the issue in a similar way—by setting a maximum allowed installed lighting power density (LPD) and prescribing the minimum lighting controls that must be used in commercial and industrial buildings. LPD refers to the spatial average power consumption of the installed luminaires in a building or in a space and is expressed in units of watts per square feet of floor area (W/ft^2). In residential buildings, the maximum LPD is not typically standardized, but the minimum efficacy of lamps is often given, in addition to prescribing some requirements for lighting controls.

The LPD cannot be arbitrarily low. The Illuminating Engineering Society (IES) defines recommended illumination levels for a large variety of visual tasks, and building codes for commercial and industrial buildings take these recommendations into account. In order to reduce energy use and costs, the trend over the past decade has been for builders to lower the LPDs to the point that the International Association of Lighting Designers (IALD) has published a statement indicating that they do not support any further lowering of the LPDs beyond ASHRAE Standard 90.1-2010 (IALD, 2011). Additional lowering of lighting power densities would only be acceptable if the illumination levels remain unchanged, which requires an increase in efficacy of the light source. The position expressed by IALD is based on the performance of currently available technology, which is commonly used as a criterion for changes in building energy codes.

FINDING: Given the currently available lighting technologies, LPD allowances for commercial buildings have reached their practical lower limits, according to lighting professionals. In the long term, SSL may permit LPD allowances in building codes to be reduced further.

State Building Codes

Although states are required by federal law (EPACT 92) to either adopt the latest version of a model building energy code or develop one that is considered equivalent to such an energy code, there is no penalty for not complying with this requirement. As of late 2011, about half of the states have adopted a commercial building energy code corresponding to ASHRAE Standard 90.1-2007, and nearly the same number have adopted a residential model building code corresponding to 2009 IECC.[8] However, the 2010 version of ASHRAE Standard 90.1 offers significant energy savings over its predecessor, as shown in determinations performed by PNNL. Large architectural engineering firms design buildings at least to the requirements of the latest standards. However many design-build contractors, who provide the bulk of the smaller buildings, typically minimize the initial cost of the building, resulting in lower performance. Furthermore, enforcement of building energy code requirements is sometimes inadequate or inconsistent at the state level. Even in California, where the energy code process is among the best in the nation, the California Energy Commission lacked enforcement authority until 2011, when the California

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[7] Texas HB 2510, 82(R) Sess. (2011) (signed into law June 17, 2011, effective January 1, 2012); H. 3735, South Carolina General Assembly, 119th Session, 2011-2012 (introduced February 11, 2011, pending in state senate at end of session).

[8] However, states are not required to meet ASHRAE Standard 90.1-2007 until July 20, 2013, 2 years after DOE issued a final determination on 90.1-2007 and the 2009 International Energy Conservation Code. They are not required to comply with 90.1-2010 until October 19, 2013.

legislature passed a law (SB 454[9]) granting the commission such authority.

FINDING: Minimum building energy standards and model codes are steadily improving. Nevertheless, their adoption, as well as uniform and effective enforcement of adopted energy codes, would result in significant energy savings.

PNNL has historically been tasked by DOE to perform a "determination" of the energy savings effect of a new version of building codes for commercial buildings. PNNL determined that a commercial building complying with the 2010 standard is approximately 18.2 percent more energy efficient than one complying with the same standard from 2007 (DOE, 2011e). Lighting has played a key role in achieving this result through the reduction of maximum allowed LPDs, as well as the increased mandatory requirements for lighting controls. The goal for the 2015-2016 code cycle is to improve commercial building energy efficiency by 50 percent over the 2004 standard, and the long-term DOE vision is to achieve marketable "net zero" energy commercial buildings by the year 2025 (DOE, undated). To achieve this result, buildings will have to have on site "renewable" energy generation that on average is greater than or equal to the energy consumption of the building over the course of a year.

The model residential building code requires 50 percent of the permanently installed luminaires to use "high-efficacy" lamps. High efficacy is defined in IECC[10] in a way that, in practical effect, the residential building must use either CFLs or SSL products. The 2012 version of IECC increases this requirement to 75 percent of the permanently installed luminaires, and Maryland was the first state to adopt that version in December 2011. Title 24 of the California Code of Regulations requires the use of high-efficacy light sources in some rooms while giving the user a choice of high-efficacy light sources or any light sources operated on lighting controls (other than a manual switch) for other rooms.

The current approach of the model residential energy code to lighting has some important limitations. First, the codes specify the energy efficiency of installed lighting but do not address the total number of luminaires nor how the lighting is used. Moreover, the trend in IECC to require an increasing percentage of high-efficacy light sources in residential new construction may have unintended consequences in terms of the number of lamps installed or how they are used, at least in the short term when LED lamps are not yet appropriate for all residential applications. Moreover, as discussed later in this chapter, there is broad consumer dissatisfaction with CFLs.

An alternative is to follow the California example and give the home owners the option of using either high-efficacy lamps or standard lamps with appropriate lighting controls.

FINDING: Model energy codes for residential buildings only address the efficacy of light sources, not their number or their use. The approach taken by the California residential energy code may be more likely to improve energy efficiency.

Specifications for High-Performance Buildings

High-performance buildings are designed to use sustainable materials, consume less energy than other buildings, and conform to "Green Codes" or High-Performance Building Standards.[11] High-performance buildings focus on reducing or eliminating the waste at the building level.

The new trend is to shift attention from LPDs to actual energy use as well as focusing on controls as a way to eliminate wasted energy. A recent, thorough assessment of the energy savings potential from lighting controls shows that the biggest opportunities for savings come from reducing lighting power use by "tuning," or setting the illumination level appropriately for the visual task, occupancy sensing (which turns off lighting when there are no people present), and daylighting (reducing electric lighting power in response to available daylight) (Williams et al., 2012). Using all of these lighting control strategies offers an average opportunity for energy savings in the range of 25 to 40 percent.

Figure 2.2 illustrates the relationship between light output and electrical power required to produce that light output. The quantities are shown as relative light output and relative power, and one can see that in each case, as light output is reduced, the electrical power required to produce that light output also decreases. In the case of incandescent and halogen lamps, the reduction of power is slower than with the other light sources. SSL shows the most linear response between light output and electrical power. When lighting control strategies are fully employed in a building, the installed LPDs (as represented by the right end point of the curves) become less relevant.

Some industry sources (e.g., NEMA) have concluded that regulation at the component level will not achieve net-zero energy buildings, so in order to achieve the goal set by DOE to get there by 2030, a systems approach is needed. It is noteworthy, therefore, that some residential "green codes" still express a preference for high-efficacy lighting in general, and sometimes for SSL products in particular. The approach in lighting requirements for residential buildings may need to change in view of this goal.

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[9] See http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0451-0500/sb_454_bill_20110216_introduced.pdf.

[10] High-efficacy lamps are compact fluorescent lamps, T-8 or smaller diameter linear fluorescent lamps, or lamps with a minimum efficacy of 60 lumens per watt for lamps over 40 watts; 50 lumens per watt for lamps over 15 watts to 40 watts; and 40 lumens per watt for lamps 15 watts or less (ICC, 2012).

[11] Such standards include, for example, ASHRAE 189.1: Standards for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings; and International Green Construction Code™ (IgCC) published by the International Code Council.

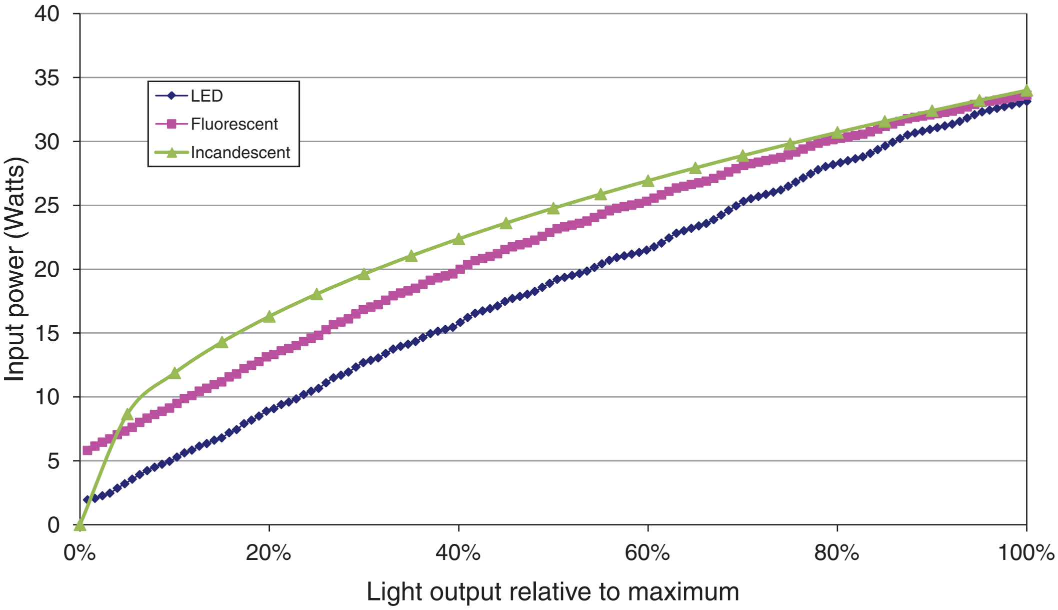

FIGURE 2.2 Typical power draw as a function of light output for dimmable incandescent, fluorescent, and LED luminaires with maximum rated power of approximately 34 watts.

INCENTIVE PROGRAMS

Various incentive programs have also played an important role in encouraging the adoption of more energy efficient lighting. The most prevalent and high-profile incentive programs have been provided by electric utilities, which have actively supported the use of more energy efficient lighting as part of their DSM and energy conservation campaigns. For example, electric utilities across the nation have actively promoted CFLs with consumer incentive programs, including giveaways, direct install products, discounted prices, and rebates (Vestel, 2009). These utility incentive programs increased consumer awareness of more energy efficient products (such as CFLs) (Sandahl et al., 2006). However, the programs also encountered some limitations, including the frequent reliance on low-quality, low-price CFLs that may have reinforced negative attitudes toward this technology by consumers (Sandahl et al., 2006). In addition, providing consumers with energy efficient lamps for free or at greatly reduced prices might create unrealistic expectations about lower future costs for such lighting (Sandahl et al., 2006).

Some retailers have also implemented their own incentive programs for efficient lighting. For example, Walmart, the nation's largest retailer, committed to selling 100 million CFLs (Barbaro, 2007). It was able to achieve this 3 months ahead of schedule because of an aggressive in-store campaign and devoted shelf space as well as partnership with DOE, Environmental Defense, and a number of other organizations to promote energy efficiency.

In addition to incentives that are available from electric utilities and retailers, the federal government has made available tax deductions to commercial building owners when they undertake energy efficiency improvements beyond minimum code requirements. EPACT (05) authorized the Energy Efficient Commercial Building Tax Deduction, creating Section 179D of the Internal Revenue Code (26 United States Code, Section 179D). According to this part of the Code, a taxpayer who owns, or is a lessee of, a commercial building that achieves reductions to 50 percent below the level set by ANSI/ASHRAE/IESNA Standard 90.1-2001 is eligible for a tax deduction of up to $1.80 per square foot, and $0.60 if lesser reductions are realized (IRS, 2012). Buildings designed to have lighting power density at least 25 percent below the baseline established by Standard 90.1-2001 are eligible for a tax deduction of $0.30 per square foot of floor space that is renovated. For public buildings, the tax deduction is available for the design teams. The original law was extended in 2008 until December 31, 2013 (GSA, 2011).

Finally, DOE has created incentives for the design and manufacture of more efficient lamps by offering a prize, called the Bright Tomorrow Lighting Prize or the "L Prize," for the manufacturer that can design an LED lamp that meets specified performance criteria.[12] As mandated by EISA 2007, DOE is offering this prize initially to manufacturers that develop and plan to manufacture at a reasonable cost energy efficient replacement technologies for "two of today's most widely used and inefficient technologies, 60 W incandescent lamps and [parabolic aluminum reflector] (PAR) 38 halogen lamps" (DOE, 2009). It was announced in August 2011 that Philips Lighting North America had won the L Prize in the 60 W category.

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[12] See http://www.lightingprize.org/index.stm.

FINDING: Non-regulatory incentive programs may play an important role in the adoption of energy efficient lighting technologies.

RECOMMENDATION 2-6: The Department of Energy, in consultation with the Department of the Treasury, should conduct a study to determine the effectiveness and impacts of incentive program designs in fostering adoption of efficient lighting technologies.

INTERNATIONAL REGULATION

Many nations are in the process of phasing out traditional incandescent lamps in favor of more energy efficient lamps (Figure 2.3). Cuba and Australia were the first nations to phase out incandescent lamps. New Zealand joined its neighbor Australia in June 2008 by announcing that country's intention to phase out incandescent lamps and later joined with Australia to develop a common minimum efficacy standard for these lamps, AS/NZS 4934.2(Int):2008, which was later replaced by AS/NZS 4934.2:2011. However, public opinion and a change in government in New Zealand led that country in March 2011 to repeal the ban announced in 2008. The European Union began a phase-out of incandescent lamps on September 1, 2009.

In November 2011, China announced that it will phase out incandescent lamps within 5 years. Canada also adopted a phase-out of incandescent lamps starting in January 2012, but in October 2011 the Canadian government announced that the phase-out in that country will be delayed by 2 years, expressing concerns about "the availability of compliant technologies and perceived health and mercury issues, including safe disposal for compact fluorescent lamps," and will now begin in January 2014 (Thompson, 2011).

FINDING: Other countries are following similar regulatory pathways as the United States in phasing out incandescent lamps, although at different schedules and with some delays.

In contrast to the convergence in lighting product regulations, building regulations are less uniform around the world, and thus far there have been no internationally recognized building standards. Significantly, the International Commission on Illumination or CIE (Commission Internationale d'Eclerage) announced in 2011 that it is starting a new technical committee to develop recommendations for international building standards.

COMPACT FLUORESCENT LAMP CASE STUDY

The U.S. experience with CFLs provides a useful case study that offers some pertinent lessons for LED lighting. The CFL is much more energy efficient than the incandescent lamp, and it also lasts much longer. The incandescent lamp converts only 0.2 to 2.6 percent of electricity consumed into useful light (the rest is wasted as heat) and has a typical lifetime between several hundred and a few thousand hours (median of about 1,000 hours). The CFL, on the other hand, has an efficiency of approximately 13 percent (five-fold better than the incandescent lamp) and has a reported lifetime ranging from 3,000 to 30,000 hours (median around 10,000 hours) (Azevedo et al., 2009). The Congressional Research Service estimates that a typical 100 W incandescent lamp used $18.30 in energy per year compared to only $4.90 for an equivalent CFL lamp (Logan, 2008). The CFL thus provides great potential to save energy, money, and reduce environmental consequences, such as CO_2 emissions, from generating the electricity needed to operate the light.

While fluorescent lights have been widely used in commercial and industrial applications since the 1950s, they were not appropriate for most residential applications until the advent of the CFL. The first spiral tube CFL was created in 1976, but they were not commercially available on a widespread basis until the 1990s—when they were made feasible by technological advances such as the ability to cost-effectively manufacture lamps consisting of tightly coiled gas-filled fluorescent tubes and the introduction of small electronic ballasts (Sandahl et al., 2006; Logan, 2008).

The initial consumer uptake of CFLs in the 1980s and 1990s was slow and was much lower in the United States than other industrial nations (LRC, 2003; Sandahl et al., 2006). Various utility energy efficiency programs gave away or substantially discounted CFLs in the 1990s, but these programs were generally unsuccessful in building consumer demand for CFLs. Many of the CFLs distributed in these programs were of low quality (e.g., poor CRI, unmet projected lifetime, lack of cold temperature operation, delay to full brightness, inability to dim, inability to fit in many lamp harps), reinforcing negative stereotypes of CFLs (Sandahl et al., 2006). Moreover, the free or near-free distribution of millions of CFLs created an expectation that CFLs were inexpensive, causing consumer backlash when higher quality and more realistically priced lamps were offered for sale once the giveaway programs ended (Sandahl et al., 2006).

The market share of CFLs grew rapidly in the early 2000s as utilities and other entities aggressively promoted consumer switch-over to CFLs. For example, the EPA and a large number of participating manufacturers, retailers, and utilities launched a national media campaign in 2001 promoting CFLs (Sandahl et al., 2006). Today, the majority of U.S. households have used or are currently using at least one CFL (APT, 2010). The market share for CFLs hit a peak of approximately 20 percent in 2007 but then declined in 2008 and 2009 to approximately 15 percent of the U.S. market, due in part to the recession, but also likely in part due to reduced incentive programs (Swope, 2010). This market penetration of CFLs has resulted in an expected decline in overall replacement shipments, as the CFL's longer life has reduced the frequency in which lamps must be replaced (APT, 2010).

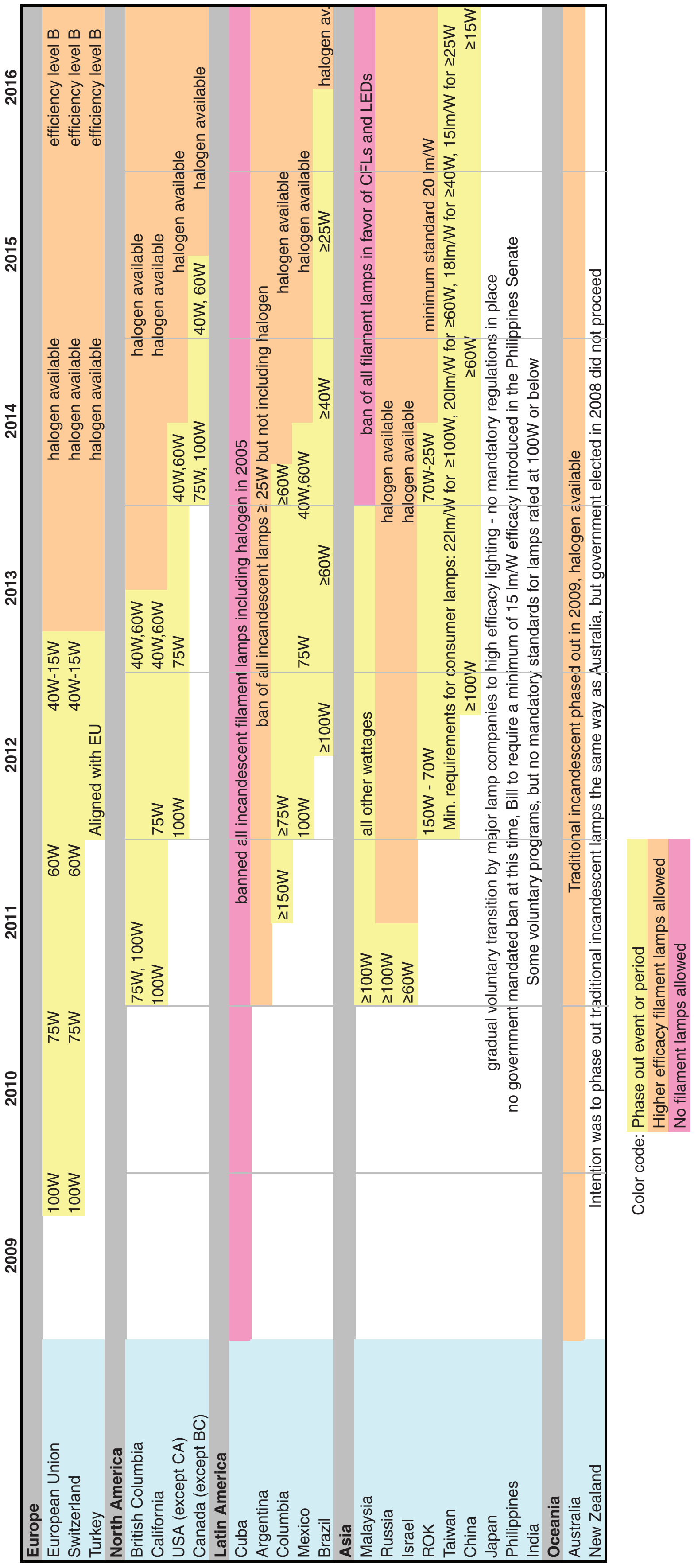

FIGURE 2.3 Schedule for phase-out of incandescent lamps worldwide as of December 2011.

The ENERGY STAR® program has also helped to enhance the quality and environmental benefit perceptions of CFLs. ENERGY STAR® launched a CFL program in 1999 that set design specifications for lamps that would qualify for ENERGY STAR® labeling, which had a beneficial effect in promoting the production and sale of high-quality, energy efficient CFLs (Sandahl et al., 2006). These specifications for program-compliant CFLs have been strengthened several times since the launch of the program in 1999. Nearly 300 million ENERGY STAR®-certified CFLs were sold in the United States in 2007 (Logan, 2008).

EISA 2007 has the potential to significantly increase market demand for CFLs as the traditional incandescent lamp is gradually phased out for general service applications by the legislation. Virtually every other industrial nation has adopted similar measures to phase out incandescent lamps (see Figure 2.3; Waide, 2010). Amendments to California's Title 24 energy code requirements in October 2005 required dedicated non-screw-based, energy efficient luminaires in most new residential applications, which again provided a regulatory boost to CFLs, although in this case for the linear pin-based CFLs with a separate ballast rather than the screw-in spiral CFLs being developed to substitute for traditional incandescent lamps.

Despite this progress, the CFL has encountered a number of problems that have presented a significant obstacle to its market growth and adoption. One problem is that consumers associate negative connotations with the word "fluorescent," likely a residue of the "unfriendly" and flickering fluorescent tube lighting used in many commercial establishments (LRC, 2003; Brodrick, 2007). Another problem, noted in the above discussion on DSM, has been the poor or inconsistent quality, reliability, and durability of some CFL lamps. For example, many of these cheaper lamps had inconsistent performance and produced low-quality light (Sandahl et al., 2006; Logan, 2008). Exaggerated product claims had a lasting detrimental impact on consumer interest and confidence in CFLs (Sandahl et al., 2006). Some cheaper CFLs even had to be recalled because they presented a fire danger (CPSC, 2010). Many consumers who were early adopters of CFLs ended up removing them from their homes because of the disappointing performance (Broderick, 2007). In many cases, CFL products were used as screw-in replacements for various types of incandescent bulbs, such as the PAR lamp, used in recessed, downlighting applications. Lacking the internal reflector, the retro-fitted, omni-directional CFL in some cases would result in lower efficacy (lumens per watt) of the luminaire. A similar problem occurred in surface-mounted downlights, where the lamp was indiscriminately matched with the luminaire's optical components.

In addition, some CFLs have not lived up to their advertised extended lifespan. For example, one analysis of the Program for the Evaluation and Analysis of Residential lighting (PEARL) found that 2 to 13 percent (depending on brand) of CFLs failed early, and half of reflector CFLs used in recessed lighting had dimmed by at least 25 percent by halfway through their rated lifetime (Angelle, 2010). Another study performed for the California Public Utilities Commission found that the average useful life of a CFL in California was 6.3 years, considerably shorter than the projected useful life of 9.4 years (Smith, 2011). Moreover, factors such as frequently turning the light on and off can substantially degrade the longevity of a fluorescent lamp (DOE, 2011c). Given that the extended useful life of CFLs is one of their primary selling points, the early burnout of many lamps was "especially vexing" (Broderick, 2007). While substantial improvements have been made in the quality and reliability of CFLs, by engineering improvements in both the lamp and ballast design (Sandahl et al., 2006), there remains significant variation in product quality that continues to hamper consumer confidence (Logan, 2008).

Some consumers have expressed dissatisfaction with the quality of light from CFLs. These consumer concerns include the following: CFLs have a slower ramp-up to full luminous output compared to the standard incandescent lamp; most CFLs are not dimmable; and, most significantly, some consumers perceive the quality of light from CFLs as inferior to traditional lighting sources, with frequent complaints that the light is "too dim," "harsh and unflattering," "too blue," or otherwise "not right" (APT, 2010; Logan, 2008; Rice, 2011; Sandahl et al., 2006; LRC, 2003; Scelfo, 2008). Although manufacturers of CFLs have invested considerable R&D effort to improve the performance of CFLs, adverse consumer perceptions can be long-lasting and hard to reverse.

Environmental and health concerns have also been an important factor in the uptake of CFLs. Each CFL contains a small amount of mercury (generally 3-5 mg per lamp), which, if accumulated in landfills or other inappropriate disposal routes, could total a significant amount of mercury released to the environment, creating both an environmental and occupational exposure risk (Aucott et al., 2003). Only 2 percent of residential users and just under 30 percent of businesses properly recycle their CFLs, even though some state laws mandate recycling of fluorescent and a number of retailers and other entities have launched free recycling programs (Bohan, 2011; Silveira and Chang, 2011). Nevertheless, EPA and others have pointed out that CFLs may still result in a net decrease in mercury releases into the environment because the mercury released from CFLs, especially if handled and disposed of properly, would be less than the amount of mercury emissions that would result from coal-fired power plants if powering all incandescent lamps (ENERGY STAR®, 2010).

Some states have adopted regulations for recycling or disposal of mercury-containing light. For example, the Massachusetts Mercury Management Act, adopted in 2006 (Chapter 109 of the Acts of 2006), prohibits the disposal of mercury-containing lamps in the trash or other unapproved sites and requires manufacturers of such lamps to implement a plan for educating users about recycling "end of life" lamps. The Massachusetts law also establishes recycling targets for mercury-containing lamps that reached 70 percent by December 2011. Similarly, Maine requires (Chapter 850, Section 3A) any type of mercury-added lamp used in commercial, industrial, or residential applications to be treated as hazardous waste, which requires that all such lamps be treated, disposed, or recycled at an authorized destination facility. The State of Washington adopted legislation in 2010 (ESSB5543) that established a producer-financed product stewardship program for the collection, recycling, and disposal of mercury-containing lamps that must be implemented by 2013, after which no CFLs may be placed in the garbage.

Moreover, there is also concern about individual lamps breaking in residential use, and the EPA recommends special precautions in using and disposing of CFLs if they break (EPA, 2011a), which may alarm some consumers. The European Union's Scientific Committee on Health and Environmental Risks (SCHER) calculated that ambient room exposures to mercury are in the range of or exceed the occupational exposure limit (100 $\mu g/m^3$), but because that exposure limit is based on the safe level of *lifetime* exposure, the expert group concluded that adults would not be harmed by mercury exposures from a broken CFL lamp (SCHER, 2010). Various unconfirmed allegations in the media about other potential health impacts of CFLs, including migraine headaches, skin problems, epileptic seizures, and cancer, have further increased public anxiety about the "unfamiliar" CFLs (Ward, 2011).

Consumer confusion and uncertainty have also been impediments to CFL uptake (Sandahl et al., 2006). Some specific examples included uncertainty about whether CFLs could be used in existing luminaires, confusion caused by the use of different names to describe CFLs, the lack of ability to compare different lighting technologies in terms of watts and lumens, and the inability to communicate different color options (Sandahl et al., 2006; Broderick, 2007). Consumers were more comfortable with performance descriptions that were framed in terms of comparisons with existing, familiar products (Sandahl et al., 2006). More generally, there also is considerable inertia in the consumer demand for lighting, with many consumers displaying strong preferences for lamps that are most similar to the type they have been using previously. Thus, as the incandescent lamp is gradually phased out under the EISA 2007 timeline, many consumers will switch to halogen lamps rather than CFLs, even though CFLs generally provide a greater energy efficiency advantage.

Initial price has also been a problem for CFL uptake (LRC, 2003; Sandahl et al., 2006; APT, 2010). Even though CFLs save consumers money in the long-run because of lower energy use and longer lifespan, consumers are particularly sensitive to the higher up-front costs of CFLs, as is the case with many other energy efficient products, an effect described as the "energy paradox" of the very gradual diffusion of energy-conservation technologies (Jaffe and Stavins, 1994). The Government Accountability Office (GAO) estimates that the higher up-front cost of a CFL would be recovered in 2 to 7 months because of the higher energy efficiency and lower replacement costs of CFLs, but consumers are disproportionately influenced by the higher initial cost (Logan, 2008). Consumers apply a very high implicit discount rate—as high as 300 percent compared to the typical 2.5 to 10 percent used in most economic analyses—that deter consumer purchases of energy efficiency technologies that may cost more up-front but save money over their lifetime because of lower energy and replacement costs (Azevedo et al., 2009). This inflated consumer discount rate is attributed to a number of factors, including lack of knowledge about cost savings, disbelief about lifetime savings, and lack of expertise in addressing the time value of money (Azevedo et al., 2009).

In addition, substantial variation in CFL pricing, including the availability of inexpensive subsidized lamps, creates consumer confusion and beliefs that higher-priced CFLs are over-priced (Sandahl et al., 2006). Empirical studies indicate that many consumers are unaware of the lower operating costs of CFLs, as well as their environmental benefits (Di Maria et al., 2010; LRC, 2003). Better communication initiatives—such as clearer labels emphasizing lower lifetime costs and the trade-offs between initial and operating costs, as well as various types of consumer education campaigns, have been suggested as necessary to help consumers understand the energy saving and environmental benefits of CFLs (Di Maria et al., 2010).

Mandating technology change through legislation without any concerted effort to educate and prepare consumers, not unexpectedly, creates a political backlash, with the perceived shortcomings of the CFL serving as a key catalyst to much of the controversy and opposition. (See further discussion of this issue in Chapter 6 in the section "Role of Government in Aiding Widespread Adoption.") Some consumers are stockpiling incandescent lamps (O'Donnell and Koch, 2011), in many cases after trying and rejecting CFLs, and the public resistance to the switchover is likely to grow as more consumers become aware of the legislative consequences as they began to take effect on January 1, 2012. Some politicians have decried the "light bulb ban" and criticized the attempt to impose those "little, squiggly, pigtailed" CFLs on an unreceptive public (Rice, 2011). The EISA 2007 mandate has become a lightning rod for contested national political debates on the role of government in society and consumer freedom. Legislation has been introduced to overturn the phase-out of the incandescent lamp, but none has succeeded to date, although some have received significant and even majority support. For example, the U.S. House of Representatives passed an amendment in July 2011 that would prohibit DOE from spending any funds on implementing the lighting efficiency standards (Howell, 2011). As noted above, similar bills have been introduced in state legislatures in South Carolina and Texas (Simon, 2011).

FINDING: Disposal of mercury-containing CFL lamps and perceived health impacts are causing concern by some citizens and states. Federal legislators and other actors promoting CFL lamps failed to adequately anticipate these perceived risks and concerns.

RECOMMENDATION 2-7: Policy makers should anticipate real or perceived environmental, health, and safety issues associated with solid-state lighting technologies and prepare to address such concerns proactively.

FINDING: The experience with CFLs provides a number of lessons for SSL, including the following: (1) the quality, reliability, and price of initial products will be a critical factor in the success and consumer uptake of the product; (2) market introduction and penetration take time; (3) manufacturers and others should take care not to over promise; (4) consumer education is critical; and (5) ENERGY STAR® and other credible performance standards can play important roles in raising quality and confidence.

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3

Assessment of LED and OLED Technologies

Both inorganic and organic light-emitting diodes (LEDs) offer dramatically new sources of illumination with the potential of greater efficiency, longer lifetimes, exceptional control over the colors generated, and differing form factors. In aggregate, these sources promise to redefine how lighting that is both economically and energy efficient can be integrated into our daily lives. Inorganic LEDs, fabricated from light-emitting semiconductors, leverage a great deal of fabrication and manufacturing equipment developed for electronic semiconductor devices. Although red, green, and yellow LEDs have been available since the 1970s, the advent of high-brightness blue LEDs in 1993 made high-efficiency white lighting sources possible. There has been continual progress in the wall plug efficiency of these lighting sources, resulting in current values of ~150 lumens per watt (lm/W) for commercial samples and the best in-lab values of 254 lm/W (Cree, 2012). Organic LEDs (OLEDs) for lighting can build on manufacturing experience gained from the recent and large-scale production of OLED displays—which in 2012 represent a $3 billion market. Today white OLEDs with color rendering indices greater than 80 have been reported (i.e., they can be made to emit with almost any color; therefore generation of high-quality white light is easily achieved) with greater than 100 lm/W efficacy (D'Andrade et al., 2008; Reineke et al., 2009). Figure 3.1 illustrates the progress in lighting efficiency and the role that LEDs and OLEDs have played in driving that progress. The succeeding sections of this chapter will provide a basic introduction to both LED and OLED technologies and will discuss the major challenges for each technology in achieving widespread, low-cost, higher-efficiency lighting sources. The technical details that underlie performance of LEDs and OLEDs have important impacts on the efficacy and reliability of the performance of the total lighting system and also determine the subtleties of color quality of the lighting. Ultimately, understanding these details will allow better strategies for developing lower-cost manufacturing technologies. Although specific findings and recommendations are integrated into the entirety of this chapter, some of the committee's major findings and recommendations are stated at the outset of this chapter to provide some perspective for the reader and to set the tone for the rest of the chapter.

FINDING: LEDs and OLEDs are complementary lighting sources that can together offer a wide range of lighting solutions. OLEDs can provide large-area diffuse lighting, while, in the same venue, LEDs form intense point sources, useful for spot illumination and downlighting. The committee finds value in supporting rapid developments in both technologies, because they both represent large possible markets, new applications, and tremendous energy savings.

FINDING: LED and OLED efficiency and performance are still limited by fundamental materials issues. Improvements in efficiency at the device and materials level, as targeted by the Department of Energy (DOE) solid-state lighting (SSL) roadmap, will have a "lever effect"—influencing the design, performance, and cost of the luminaires. Therefore, improvements in efficiency and performance of the entire SSL system are linked to further fundamental investigations in core technology on emitter materials.

While inorganic LEDs have been manufactured and widely available commercially for some time, there is as yet no commensurate large-scale manufacture of OLEDs. Nevertheless, LED yield, cost, and performance would still benefit enormously from further fundamental exploration and improvements in the basic technology of materials growth.

FINDING: Current LED dies used in SSL lighting suffer from inhomogeneities in the light output, color, and operating voltage that necessitate "binning" (hence testing) of dies from a single wafer. This variability severely constrains the yield of the manufacturing process and raises the cost of the technology. These inhomogeneities are in turn related to fundamental materials and materials growth issues.

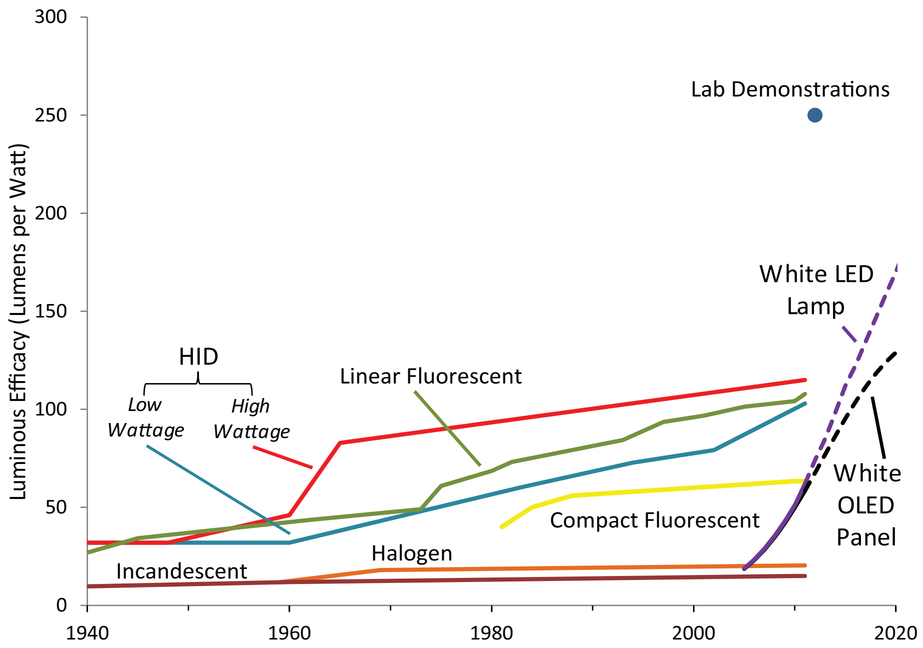

FIGURE 3.1 Progress in lighting efficacy. SOURCE: DOE (2012b, p. 38).

RECOMMENDATION 3-1: The Department of Energy should continue to make investments in LED core technology, aimed at increasing yields, and in fundamental emitter research to increase efficacy, including improvements in the controlled growth and performance of the emitter material. DOE should carefully consider the range and depth of funding in its portfolio of investments in these areas, given the existing technological challenges, in order to determine how the targeted goals of device performance can indeed be met.

The remainder of this chapter will provide an introduction to both inorganic and organic LEDs in a parallel approach. The LED and OLED primers will first focus on the basic device structure and metrics of device performance. This will be followed by discussions on the control of the color output of these devices and the important influence of materials on device performance. Because OLEDs for SSL have not yet been scaled up for large-scale manufacture, the discussion for OLEDs will also encompass issues of reliability and manufacturabililty. The chapter will conclude with a comparison and summary of promises and challenges for both technologies.

AN LED PRIMER

Introduction

Semiconductor LEDs are a special kind of electronic device that emits light upon the application of a voltage across the device. Silicon (Si) is probably the best-known semiconductor material and the basis of the integrated circuits that underlie the fast and compact electronic devices, such as computers and cell phones, that are so critical to our daily lives. LEDs are based on a semiconductor material comprised of several different elements. This material is known as a *compound semiconductor*. The tremendous power of semiconductors lies in their ability to take on a wide range of conductivities, from metallic to insulator. This is brought about by "doping" the semiconductor with other elements that will donate either positively or negatively charged carriers to achieve a desired conductivity.

Semiconductors can also absorb and emit light, and the relevant wavelengths are related to the *bandgap* of the semiconductor (see Box 3.1). The general process for light emitted in this manner is referred to as *electroluminescence*. The first high-efficiency light-emitting devices were developed in the 1960s utilizing gallium arsenide (GaAs), aluminum gallium arsenide ($Al_xGa_{1x}As$), gallium phosphide (GaP), and gallium arsenide phosphide ($GaAs_xP_{1-x}$) (Hall et al., 1962; Nathan et al., 1962; Pankove and Massoulie, 1962; Woodall et al., 1972; Herzog et al., 1969). GaAs and AlGaAs LEDs produced light with *infrared wavelengths*, ~850 nanometers (nm), while the gallium phosphide-based LEDs produced light in the red and green wavelengths. In the early 1990s, efficient blue LEDs based on III-nitride materials began to appear based on the work of Akasaki et al. (1992) and Nakamura et al. (1994). (The III refers to elements in the third column of the periodic table, indicating that these LEDs can be comprised of alloys of aluminum nitride (AlN), gallium nitride (GaN), and indium

BOX 3.1
Light Emission Mechanism

Figure 3.1.1 gives a simple description of the basic light-emission process. Electrons fill up energy states in a *valence band*, which is separated in energy from a *conduction band* by an *energy gap,* with energy E_g (where there are generally no allowed states in which electrons can reside). Providing energy to an electron in the valence band can promote that electron to the higher-energy conduction band, also creating a *hole* (lack of electron) in the valence band. The electron can subsequently return to its lower-energy state: in *radiative recombination*, the electron returns to the valence band and releases a *photon* with the energy of the photon approximately equal to the energy E_g. In an LED, *radiative* recombination is the desirable outcome for an "energized electron," but there are also numerous non-radiative recombination processes where the electron or hole may be trapped at defects or imperfections in the material. Such imperfections limit the efficiency of the light generation and, therefore, of the LED.

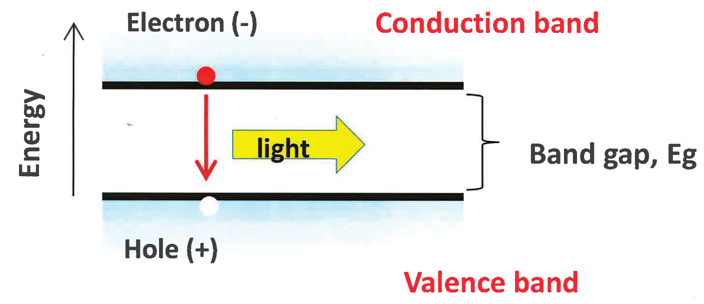

FIGURE 3.1.1 Light emission process.

nitride (InN)). The bandgaps of these III-nitrides produce light emission across a range of wavelengths spanning the infrared to ultraviolet (UV) parts of the spectrum. The III-nitride LEDs have had an unusually rapid development and huge impact on appearance of SSL. Although the first GaN LED was reported by Pankove et al. (1971), almost two decades transpired before substantial further progress was made by Akasaki and Nakamura. Akasaki demonstrated that high crystal quality GaN could be grown by metal organic chemical vapor deposition (MOCVD) using a novel low-temperature buffer (Amano et al., 1986). In 1992, Nakamura, working at Nichia, developed an industrially robust process for p-doping of GaN that led to the first high-brightness blue LEDs. This provided the understanding of the mechanisms that had limited the conductivity of P-type material and allowed for the first time the fabrication of low-voltage p-n junction LEDs and eventually led to the commercialization of high-brightness blue and white LEDs for SSL. The wider bandgaps of the III-nitrides enabled the development of efficient LEDs that emit light at blue wavelengths, which together with green and red LEDs provided the basis for white light as well as full-color displays. The nitride blue emitters can also be coupled with phosphors to generate white light, which is currently the dominant approach to an SSL technology. The later introduction of blue LEDs, compared to their green and red counterparts, is the result of materials issues that are still of importance today: the lack of a well-matched material (substrate) upon which to form the LED structures and some difficulties in controlling the electrical properties of the material. Nonetheless, the III-nitride materials have been pivotal in the success of inorganic SSL, and thus the committee will focus on LEDs formed from those materials. There are several good reviews of LED device technology (see, for example, Schubert [2006]) as well as III-nitride materials technology (Pankove and Moustakas, 1998)).

The LED Device Structure

The basis of the LED device is a *p-n junction diode*, shown schematically in Figure 3.2. As the name implies, there is a junction between the N-type material (rich in electrons) and P-type material (rich in holes). Under forward bias (positive voltage applied to the P-region and negative voltage applied to the N region) large numbers of electrons are injected into the N region and large numbers of holes are injected into the P region.

Current flows in the device and the large number of injected electrons and holes can combine radiatively, producing significant light emission. The basic structure is modified in actual LEDs to (1) improve the efficiency of injection of electrons and holes and to (2) "localize" the electrons and

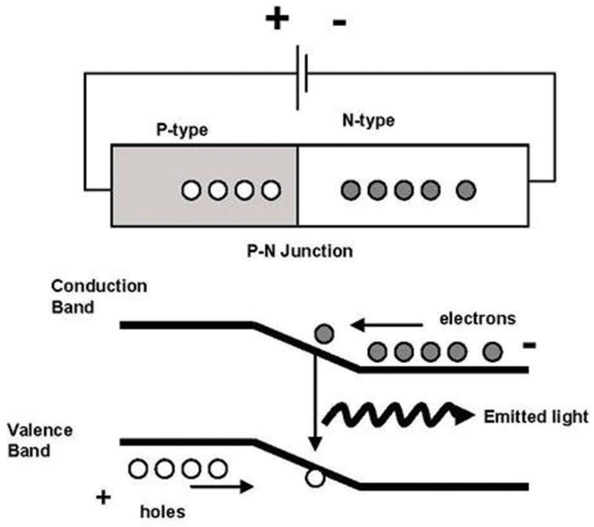

FIGURE 3.2 Schematic of p-n junction diode.

holes and improve the likelihood of radiative recombination. This localization is accomplished by introducing *quantum wells* in the region of the junction. These are thin slivers of lower bandgap-materials that, as their name implies, serve as wells that confine pools of electrons and holes to increase the probability that they will recombine radiatively.

The external view of the typical LED structure is given in Figure 3.3, showing the N-type GaN, the InGaN quantum wells, and the P-type GaN. Most GaN LED devices are formed on a sapphire substrate through the MOCVD process. Typically, one 4-inch-diameter sapphire wafer can produce 5,000 individual devices or "dies." The 16 percent mismatch in natural lattice size between the sapphire substrate and the GaN overlayers has important consequences on device performance and on the uniformity of the dies grown from a single wafer. This is further discussed in the section "Materials Issues." In order to connect the device to the outside world, metal contacts must be deposited by evaporation on the N and P regions. Figure 3.3 shows these metal contacts, as well as the transparent and conductive indium tin oxide (ITO) layer that extends the top-side electrical contact over the device surface. Both the sapphire substrate and the ITO spreader contact are transparent to the emitted light, as is necessary for the light to leave the device. High-quality electrical contacts are important to reduce loss due to resistance (R) to current flow (I) in the contact region. This is even more important when the device is operated at high currents or current densities, because loss of power due to resistive heating scales as I^2R. In the III-nitride materials, it is a challenge to dope the materials to a sufficient level so that resistances are low, particularly for P-type materials. The formation of the device structure shown in Figure 3.3 is just a starting point for the fabrication of the final solid-state "light-bulb." An individual device must be further "packaged" to better control its chemical, thermal, and electrical environment and to better integrate it into the final luminaire.

The LED Module

The LED package is the structure in which the LED chip is mounted and through which access to the LED terminals is provided. It is an important part of the finished device. The package serves the following functions: (1) it passivates or protects the active semiconductor material from degradation due to the environment (principally moisture); (2) it integrates an optical lens structure, which determines the optical emission pattern of the structure; (3) it removes heat from the device, protecting against degradation due to overheating; and (4) it protects the device from electrostatic discharge

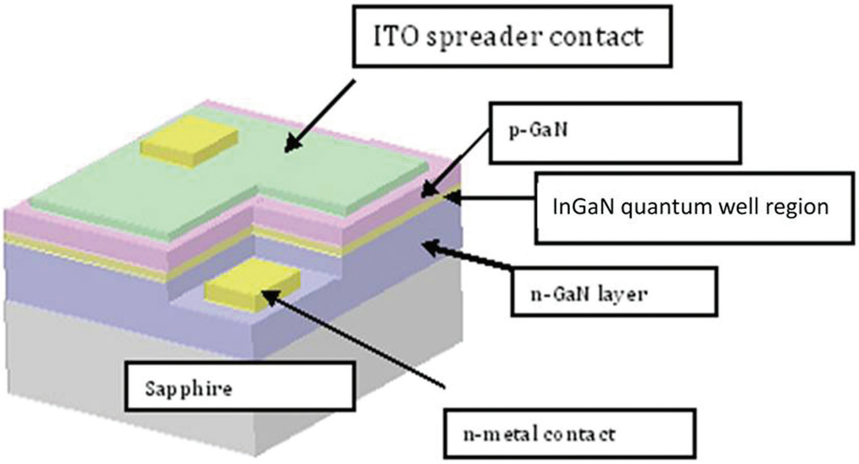

FIGURE 3.3 A typical GaN LED chip.

failure. The packaging processes include placement of the device in the chip carriers, attachment of the optical lens, as well as electrical and optical device testing and "binning." Because of the variability in the color accuracy, color quality, and color stability (see section "Controlling the Color Output of the LED"), each device must be individually tested and placed in *performance bins*. In addition, if phosphor coatings are used in connection with the LED to control the output color, the phosphor must be added to the device or package.

A schematic of a typical LED package is shown in Figure 3.4. The LED semiconductor chip or "die" is bonded to a ceramic substrate, which provides mechanical support and thermally connects the LED to a thermal pad on the bottom of the substrate. An electrical interconnect layer connects the LED chip to the voltage leads on the bottom of the substrate (one of the voltage leads, the cathode, is shown). A silicone lens above the LED extracts the light that is generated within the chip. Also shown is a transient voltage suppressor (TVS) chip which protects the LED chip against electrostatic discharge events.

Metrics of Device Performance

Efficiency is an important metric of LED device performance, and some insights into efficient operation can be gleaned by tracing the life cycle of the LED operation beginning with the injection of electrons and holes, shown in Figure 3.2, leading to the generation of photons within the device, and culminating with the emission (or extraction) of the photons from the device. A simple summary of the total external quantum efficiency (EQE or η_{EQE}) of an LED can be expressed as:

$$\eta_{EQE} = \eta_{IQE} \cdot \eta_{out}$$

where η_{IQE} is the internal quantum efficiency, and η_{out} is the outcoupling (or light extraction) efficiency, which will be further discussed below.

Internal Quantum Efficiency

Not all electrons and holes that are injected into the LED (e.g., from a battery) will produce photons; for example, defects in the LED material can trap an electron or a hole, and prevent the formation of a photon. The percentage of photons generated, relative to current (of electrons or holes) that is injected into the device is reflected in the IQE. η_{IQE} can be maximized by using quantum well structures as described above, by utilizing defect-free semiconductor material, and by ensuring high-quality, very-low-resistance metal contacts to the device. η_{IQE} also sensitively depends on the quality of the LED material. Because the quantum well composition and strain varies with the desired emission wavelength, η_{IQE} varies with wavelength. Although η_{IQE} of today's best LEDs

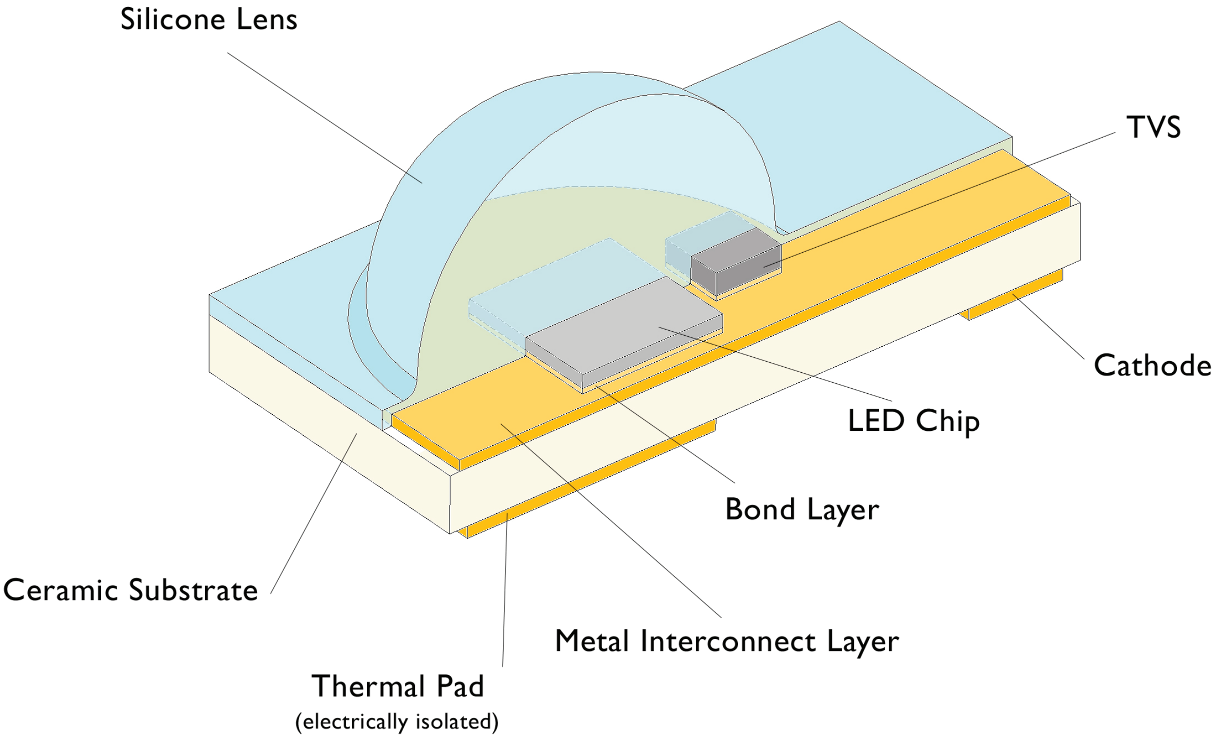

FIGURE 3.4 Schematic of an LED module. NOTE: TVS = transient voltage supression. SOURCE: Figure provided courtesy of Sudhir Subramanya, Philips Lumileds Lighting Company.

has reached as high as 80 percent for blue LEDs and 38 percent for green LEDs (DOE, 2011a, p. 71), equal efficiency of LEDs at all colors is important, and further improvements toward 100 percent η_{IQE} will require far better control of the material defects.

Current and Thermal Droop

Two of the most important issues holding back efficiency at high illumination levels is the droop in efficiency as the LED is driven at higher currents (e.g., operation at 100 A/cm^2 compared to operation at 35 A/cm^2 (DOE, 2011a, Table A1.2, p. 71), and the effect of temperature. These issues are known in the industry as "current droop" and "thermal droop." The causes and solutions to current droop are still not widely known. Thermal droop is influenced by the choice of III-nitride alloy bandgaps and the active layer design, which is limited to thin quantum wells. As was discussed above, η_{IQE} of green LEDs is much lower than that of blue LEDs. Similarly, the "droop" at higher current operation is more pronounced for green LEDs. All major LED companies have active research in these areas.

Outcoupling (or Light Extraction) Efficiency

Once the photons have been formed in the LED structure, care must be taken to ensure that they will exit the device. The ratio of photons leaving the device to the number generated within the device is called the outcoupling (or light extraction) efficiency. Because the LED material has a higher index of refraction (n ~ 2.5) than air (n = 1), most photons incident on the GaN-air interface will be internally reflected and trapped within the LED structure or absorbed (lost) by other materials comprising the device (see Figure 3.5). A thin metal film can serve as a mirror to direct the light out through the "front surface" of the LED. The internal reflection and trapping of the light can be mitigated by forming a *rough*, rather than smooth top LED surface; one way of achieving this is through the immersion of the device structure in a simple wet chemical etchant (Fujii et al., 2004). Such techniques can improve the extraction efficiency from a few percent to values of 80 percent (Krames et al., 2007). Finally, the external power efficiency (η_P) is defined as the ratio of the total optical power output of the LED to the electrical power input. Low resistive power loss, high η_{IQE}, and good design to maximize η_{out} produce high power efficiency in LEDs. Maximizing the power efficiency not only increases the efficacy of the LED but also reduces the heat removal problem.

FINDING: Efficient operation of LEDs depends on a number of critical factors related to materials defects, structure, and strain. Such factors not only limit device efficiencies, but also lead to thermal and current droop; all have a major impact on the cost and performance of LED lighting.

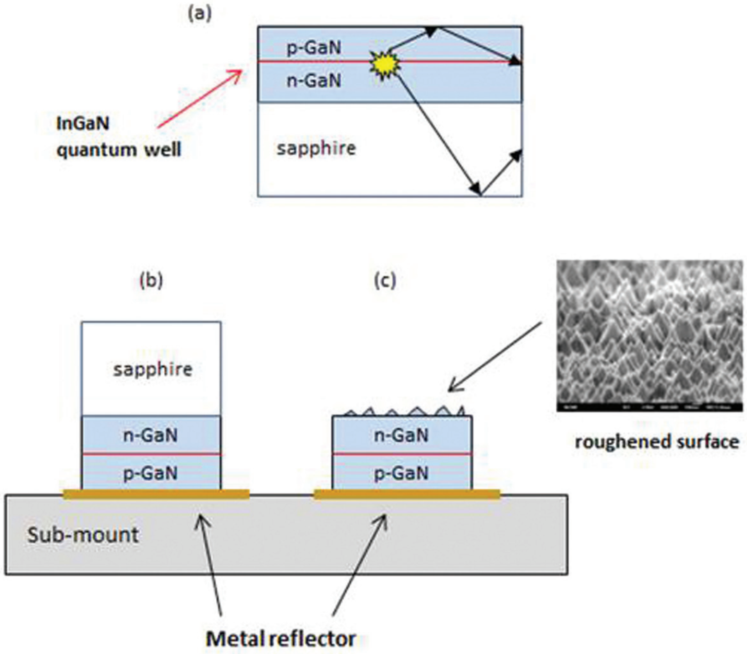

FIGURE 3.5 Improving light extraction efficiency. (a) Much of the light emitted from the quantum well is internally reflected (not extracted). (b) Flipping the LED and placing it above a reflective surface helps to direct the light outwards. (c) Removing the sapphire substrate and then roughening the top of the LED surface. NOTE: p-GaN is P-type (i.e., positive) gallium nitride material (rich in holes); n-GaN is N-type (i.e., negative) gallium nitride material (rich in electrons).

CONTROLLING THE COLOR OUTPUT OF THE LED

An important metric of LED device operation is the control over the accuracy, quality, and stability of its color or peak emission wavelength. Three well-established approaches to generating white light using LEDs are shown in Figure 3.6. These include a blue LED with yellow phosphors; an ultraviolet (UV) LED with blue and yellow phosphors (or red, green, and blue phosphors); and a device that combines red, green, blue LEDs.

The color of emitted light from an LED depends on the structure and composition of the LED. Achieving a desired photon frequency (hence color) from an LED requires sensitive control over the thicknesses and material composition of the LED.

Quantum Well Thickness and Composition

The active layers of the current blue LEDs used in SSL are extremely small, 3 nm thick, which classifies them as quantum wells. In other words, these nanostructures fall in the class of devices in which the light generation mechanism is controlled at the atomic level. Small changes in the indium composition and well thickness affect the emission wavelength and width of the emission. Currently, blue LEDs have a peak wavelength of 455 nm and a width of 15 nm. Any changes in the peak position or width can visibly affect the hue of white light obtained. The MOCVD deposition machines used in the manufacture of the LEDs have a huge influence on the uniformity of the wavelength and yield of white LEDs (see the section “Materials Growth”). One way to improve the color consistency and make wider, more reproducible quantum wells is to look at alternative substrates for the growth of the GaN LED structures.

FINDING: The color output of LEDs is extremely sensitive to the control of materials composition and thicknesses of the LED structure, which in turn are influenced by the control of the MOCVD growth process.

Use of Phosphors

Another means of controlling the LED color output is through the use of phosphors. The phosphors absorb the (typically) blue light from the GaN LED and re-emit light at longer wavelengths. The phosphors are chosen so that the combination of the direct light from the LED and the light emitted from the phosphor will produce the desired white light. A selected few phosphors have garnered considerable attention, including for example rare-earth (RE) doped yttrium aluminum garnets (YAG:RE, $Y_3Al_5O_{12}$(RE)). The cerium-doped YAG can absorb blue and UV light and emit it as yellow light with high efficiency. A critical aspect of this process is that the higher-energy light (e.g., UV or blue) is being converted into lower energy (e.g., yellow or red). As a consequence, LEDs emitting red light—the color having the lowest energy in the visible spectrum—cannot be used with phosphors to generate white light; instead, a short-wavelength UV, violet, or blue LED is required (Denbaars et al., 2013).

Phosphors are typically directly added on top of the LED in the encapsulation material, which is either silicone or epoxy-based. The uniformity of the phosphor coating and mixture selection can drastically affect the efficacy and qual-

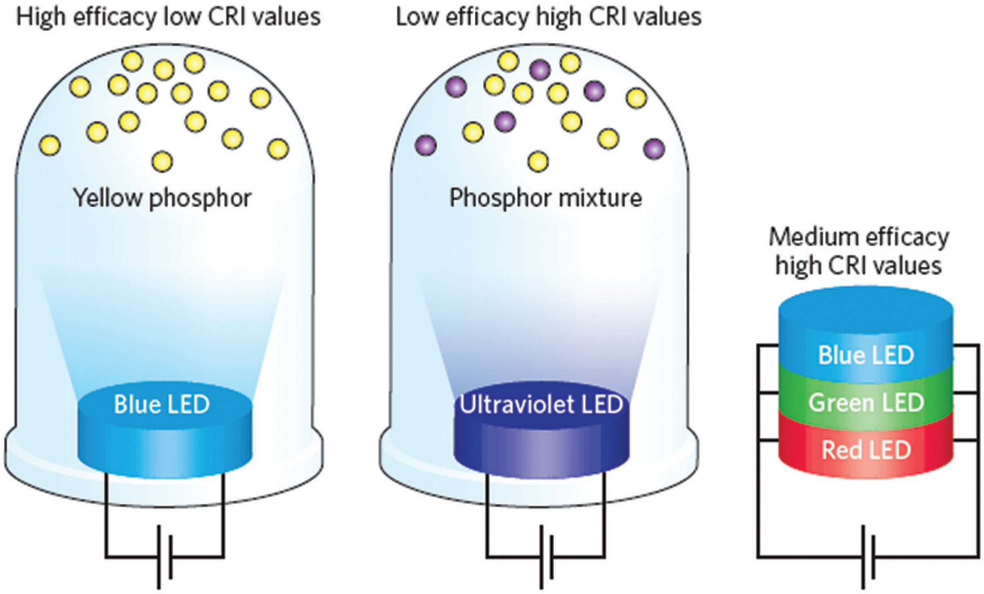

FIGURE 3.6 Three types of white LEDs for lighting: (a) blue LED plus yellow phosphors, (b) ultraviolet LED plus three phosphors, (c) three LEDs: red, green, blue connected in parallel. SOURCE: Pimputkar et al. (2009). Reprinted by permission from Macmillan Publishers Ltd.

ity of light. For example, the use of just a yellow-emitting YAG phosphor with a single blue GaN LED results in high luminous efficacies but relative poor quality (color rendering index, CRI < 75) light. This has led to the perception that all LED lighting is blueish-white and cold. UV LEDs with phosphor mixtures provide a better CRI value, but at the expense of poorer efficacy. A combination of three (or more) LEDs having different wavelengths (red, green, and blue) may be used if one wishes to dynamically control white light. This approach may lead to higher efficacies than the UV-phosphor LED. In addition, moving the phosphor layer away from the chip and tailoring the optics between the LED chip and the remote phosphor layer has resulted in significant improvement in light output and luminous efficacy (Narendran et al., 2005).

General Considerations: Mixed LEDs or Phosphors?

Using narrowband (colored) components to create white light, like the examples in Figure 1.9 in Chapter 1, allow manufacturers to manipulate the luminous efficacy of radiation (LER) and color qualities of a light source depending on their goals and priorities. At these relatively early stages of the technology, there are a number of technical difficulties with the use of multi-color LEDs (red, green, blue; red, green, blue, yellow) to produce a white source in SSL products. If one of the colored components ages differently from the others or responds to heat differently, the color properties of the light source will change. Furthermore, inadequate mixing of the light will result in colored shadows. Nonetheless, multi-color LED lighting has some advantages. The spectrum can be tuned to optimize LER. A wide range of chromaticities can be achieved by adjusting the relative intensities of the component colors. In fact, some SSL products currently on the market allow users to adjust the chromaticity—a heavily marketed feature (Philips Solid-State Lighting Solutions, 2012)—and some in the industry believe that eventually all consumers will expect their lighting products to offer such functionality (Thompson et al., 2011).

Even though entire portions of the visible spectrum are missing from such light sources, narrowband multi-color lights can achieve good (three components) or excellent (four or more components) color rendering. These types of lights can even exhibit some desirable color-rendering properties that broadband light sources cannot, such as inducing increases in the colorfulness/vividness of object colors beyond what the CRI deems to be "perfect." Research on this effect suggests that people find these slightly enhanced object colors to appear more attractive (Jost-Boissard, 2009).

Phosphor white LEDs have a clear ease-of-use advantage and dominate the current SSL general illumination market. Although the resultant products do not offer the same flexibility in chromaticity as those from multi-color white LEDs, the phosphors themselves are available in a wide range of chromaticities. Color rendering varies depending on the particular phosphor involved, but can be disappointing, particularly compared to incandescent-based light sources. Over the past few years, manufacturers have found that adding some additional energy in the long (red) wavelengths, either with a red LED or remote phosphor, vastly improves the color quality of typical white phosphor LEDs (Hum, 2011). This solution is now widely used.

Quantum Dot "Phosphors"

There has recently emerged another interesting approach for the color control of both LEDs and OLEDs involving semiconductor nanocrystals or "quantum dots." These materials are governed by the light emission mechanism described earlier, but these semiconductors, like the phosphors, can also absorb higher-energy photons and emit photons of lower energy or longer wavelength. What is distinctive about these chemically synthesized materials, with diameters of a few nanometers, is that the size of the nanocrystals will influence the wavelength of emission. Initial work on CdSe nanocrystals began in the late 1980s (Brus, 1991): the color tunability of these structures, their small size, the relative ease of production, and their optical robustness encouraged researchers to utilize these quantum dots in a variety of applications, such as selective tagging and in vivo imaging of features in cells (Michalet et al., 2005). Although much further assessment will be required to understand the full potential of this technology, initial results look promising.

FINDING: A number of approaches have successfully been used to achieve and modulate color rendition for LED lighting. Phosphor-converted and color-mixed LEDs show promise but face different challenges. The ultimate choice of approach will depend on a multiplicity of issues regarding sensitivity of color control, efficiency, reliability, manufacturability, and cost.

RECOMMENDATION 3-2: The Department of Energy has provided excellent guidance in its roadmap targets for both phosphor-converted and color-mixed light-emitting diodes. Core investment in these technologies should be continued, with consideration for promising new technologies (e.g., quantum dot layers replacing phosphors).

MATERIALS ISSUES FOR WHITE LEDS

Materials issues in white LED technology affect the cost, yield, and reliability of the resulting luminaire at the most fundamental level. A particularly critical issue is that the current white LED materials substrate and growth technology do not produce LED devices that are uniform with respect to their color quality or efficiency. This in turn places an additional burden on the evaluation of individual devices: "Variability in lumen output, correlated color temperature (CCT), and forward voltage, is currently handled by test-

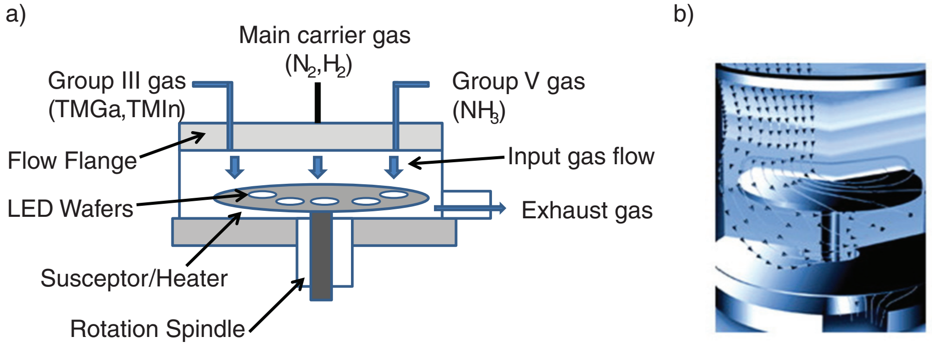

FIGURE 3.7 Schematic of an metal organic chemical vapor deposition system. Panel (b) is a three-dimensional diagram of the gas flow around and under the wafer stage. Panel (b) image courtesy of Veeco Instruments Inc. NOTE: TMGa = trimethyl gallium; TMIn = trimethyl indium.

ing each package and placing it into a specific performance bin" (DOE, 2009, p. 15). The technology of growth of LED devices and the choices of substrates for that growth form the early components of LED manufacturing and can have a profound "lever effect" with long-term implications for device yield and reliability (DOE, 2011b, p. 14).

There are two principal approaches to mitigation or elimination of the materials-related cost and performance issues. The first approach is to improve the uniformity of the epitaxial growth process. In the second approach, a fundamental breakthrough in native GaN substrate technology would allow the elimination of a vast number of crystal defects and would revolutionize the materials growth process. The two approaches are discussed below and build on an understanding of the MOCVD growth process, which is one of the steps in forming the LED devices.

Materials Growth: Mechanisms, Reactors, and Monitoring

As was made evident in the preceding section, the formation of the materials that comprise the LED plays a critical role in determining the color output and the efficiency of the device. Sensitive control over the composite layers of the crystalline LED device structure, some of which are only nanometers in thickness, is achieved through the use of *epitaxial* growth processes. In these processes, a single-crystal material (the overlayer) is grown on a crystalline substrate, and there is a registry, or relationship, between the structure of the overlayer and the substrate. The most commonly used process is MOCVD. These complex MOCVD machines are basically very sophisticated "ovens" used to produce the wafers that are later fabricated into individual LED chips. The typical MOCVD machine costs more than $2 million and can carry out growth on 60 2-inch wafers at a time.

Technology leadership in this field is still based in the United States (VEECO, Applied Materials) and Europe (AIXTRON). In MOCVD technology, ammonia gas and trimethylgallium (called a metal organic gas) are combined in a stainless steel growth chamber. In order for the reaction between ammonia and trimethylgallium to occur, forming the GaN material, the sapphire substrate must be heated to temperatures of about 1,000°C. This is done using a heated metal plate (called a susceptor). There are several possible configurations for this growth system; however, MOCVD growth based on a vertical rotating disk design has had broad acceptance. The generic rotating disk design is shown in Figure 3.7. The sample sits on the rotating disk, which is also a susceptor. Gases are injected vertically into and through a showerhead, and the high-speed rotating disk produces stable gas flow, aiding the uniformity of the material composition produced. The MOCVD technology can be used for all of the III-nitride materials (Ga, In, Al) utilizing a specific metal organic gas for each element (for example, trimethyindium for indium compounds and trimethyaluminum for aluminum compounds). Therefore, all of the elements of the LED structure can be grown in a single run. MOCVD technology has the following several advantages: (1) the ability to grow all of the III-nitride materials and alloys, (2) the ability to produce abrupt junctions between dissimilar regions of materials, and (3) the ability to produce thin (almost single atom layer) quantum well regions.

Prior research on MOCVD technology has established the fundamental understanding of reactor design and scale-up. Excellent numerical codes are available to simulate the gas flow and gas chemistry in the reactor. Therefore, scale-up in reactor size to accommodate larger substrates (and potentially lower-cost manufacturing) should be straightforward. The major challenge in MOCVD technology is control of this complicated growth process over the entire area of the substrate. Complicating the issues of MOCVD control and monitoring for the III-nitride materials is the substantial material differences between the overlayers (GaN LED structure) and the substrate (sapphire). The low thermal conductivity of the sapphire means that substrate and overlayer might not be at the same temperature during the growth process. It is therefore important to accurately measure the temperature of the *surface* of the growing material. The substrate and the overlayer have different *thermal coefficients of expansion*, producing a strain at the interface between the substrate and overlayer that can result in a curvature or "bowing" of the wafer. The curvature is accentuated by the mismatch in lattice constant between the sapphire and the LED overlayers (see section below). This curvature in turn aggravates non-uniformity in temperature and the flux of materials seen by each wafer. The most important issue for the MOCVD growth of nitride LEDs is control of the growth temperature. Wafer temperature is important for determining the growth rate as well as the composition of the indium-containing layers in the structure. Even small changes in temperature are enough to change the optical emission (color) of the LED.

The technology that has been developed to accomplish monitoring of MOCVD is based largely on optical reflectivity. Early technology development was supported by DOE through Sandia National Laboratories (Sandia National Laboratories, 2004) and has resulted in a U.S.-based start-up company, k-space Associates, that manufactures MOCVD monitoring products. There is a similar company in Europe, LayTec, which manufactures similar technology. Both k-Space[1] and LayTec[2] have developed specific systems, which can in "real time" monitor either the wafer temperature or the growth rate or the curvature (hence the strain) of the growing layer. However, a complete picture of the state of the reactor, and therefore of the material being grown, requires information about *all* of these parameters. It is possible to incorporate several of these monitors into a single reactor, but this requires the careful design of the reactor to best accommodate and integrate the monitors. In addition, careful cross-calibration of the monitor outputs with the actual grown materials is required in order to extract meaningful data about the monitored growth conditions and the actual material characteristics. There are currently no systems, which can *directly* monitor the composition of the growing film. Initial efforts have been made to implement many of systems with feedback reactor control (Haberland, 2008). However, for commercial reactors only wafer temperature has been implemented as part of the control loop.

Current sapphire substrates are 4 inches in diameter. As the production reactors scale up to 8-inch-diameter sapphire substrates, the interrelated problems of substrate temperature, wafer bow, and change in materials composition can only get worse. In order to achieve the desired wafer yield, optical monitoring needs to continue to develop. Goals for future optical monitoring system include the following: (1) integration of growth rate and wafer bow measurements with reactor control in commercial systems, (2) development of tools to make real time composition measurements on the growing layers, and (3) development of tools that will provide full wafer maps of the important parameters (temperature, composition, strain, and growth rate).

FINDING: Production-scale MOCVD growth of LEDs is a complex process. The uniformity and yield of the structures grown (and hence of the optical performance of the LEDs) is strongly and negatively affected by small variations in the MOCVD growth process. The thermal and lattice mismatch between substrate and overlayer exacerbates the sensitivity of the growth process. Further difficulties of growth control are anticipated with use of substrates with increased diameter.

RECOMMENDATION 3-3: The Department of Energy should fund research to develop instrumentation for in situ monitoring and dynamic control of the metal organic chemical vapor deposition growth process.

The Search for an Improved Substrate

Epitaxial growth processes work best when the substrate (e.g., sapphire) that serves as the template for the material growth has a structure (lattice constant) that matches that of the finally formed material. Without the one-to-one registry of the overgrown material to the template, there will be a strain in the overlayer that may eventually give rise to dislocations and defects in the material (10^7 to 10^8 cm^{-2} dislocations in the best case for GaN on sapphire). Such defects will compromise the performance and reliability of the devices formed from the material, and this in turn leads to "uncertainty in the long-term performance of the luminaire system" and "makes it difficult to estimate and warrant the lifetime of LED-based luminaires" (DOE, 2012a, p. 30).

Thus, a key issue in the growth of III-nitrides is the *lack* of a native or lattice-matched substrate. Currently, the substrates used for the III-nitrides are sapphire, SiC, or Si; at the moment, there are no GaN substrates of suitable size and quality available. Were they available, they might provide a better match to the overlayer III-nitride material, within the limitations imposed by different lattice constants for InGaN, GaN, and so forth. Besides improvement in device efficiency and reliability, a better thermal match between the substrate and overlayer would reduce wafer bowing, increasing the yield of fabricated devices.

From the discussion above it is easy to see that there is a great impetus for the development of GaN native substrates—among which is the growth of GaN bulk substrates. DOE is considering several competing technologies for substrates. There are a variety of approaches to the growth of GaN bulk substrates, which have been recently reviewed in a special issue of the *Proceedings of the IEEE* and in other journals (Avrutin et al., 2010; Ehrentraut and Fukuda, 2010; Paskova et al., 2010). Further progress in the formation of GaN bulk substrates has considerable technological challenges; furthermore, GaN substrates will have to compete with the lower-cost availability of (lattice-mismatched) substrates such as 8-inch sapphire.

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[1] See, for example, Data Sheets KSA 400, KSA MOS, KSA Rate Rat Pro, and KSA BandiT (k-Space Associates, 2012).

[2] See, for example, Application Notes 49, 53, 45, 50, and 34 at http://www.laytec.de/compounds-applicationnotes.html.

However, the committee believes that a breakthrough in native GaN substrate technology would allow the elimination of a vast number of crystal defects, revolutionize the materials growth process, and have profound benefits for LED efficiency, reliability, and yield. DOE workshop participants speculate that "in principle, the use of a GaN substrate, if it were available at reasonable cost, might simplify the buffer layer technology (thinner buffer layers with shorter growth times) and allow flat, uniform epiwafers to be manufactured" (DOE, 2012a, p. 35.).

FINDING: Significant improvements in LED efficiency, yield, and reliability are possible by using GaN substrates and latticed-matched epitaxial growth processes. Currently, there are no viable techniques for producing high-quality, low-cost GaN substrates. While realization of low-cost GaN substrates is not assured, the potential payoff of this research is immense.

RECOMMENDATION 3-4: The Department of Energy should make a long-term investment in the development and deployment of gallium nitride substrates.

CHALLENGES AND PROMISES FOR LEDs

The development of III-nitride LED technology has brought many surprises to the semiconductor community. Never before have production devices been formed in a materials system in which the light-emitting layers were produced on non-native substrates with thermal and lattice mismatch. Although GaN-based devices have worked well enough to initiate a lighting revolution, materials issues have re-emerged as defining elements in the technology. As has been discussed above, current devices suffer from a high concentration of defects and dislocations that limit the internal quantum efficiency achievable.

The DOE (2011a) roadmap goals relating to device efficiency, shown in Table 3.1, can only be achieved by substantial improvements in the control and quality of the materials growth and in the reduction of defects that arise through the growth and fabrication processes, which are aggravated by the strain between substrate and overlayers. Moreover, improvements in the basic technology that forms the starting materials of the LEDs will have a profound feed-forward effect that will influence yield, and thus cost, at every stage of the LED package formation and performance. For example, strain between the substrate and the overlayer results in the non-uniformity of LED characteristics across wafers, leading to the wasteful practice of "binning." Fluctuations in the composition of the LED layers, and particularly in the quantum well region, compromise control over the LED emission wavelength. Defects have an impact on the electrical resistance of the LEDs, increasing power dissipation and limiting higher-temperature performance, as well as lifetime. Limitations at the device level necessitate compensating solutions (e.g., heat sinking) at the packaging level, which may increase the overall cost. For example, Krames et al. (2007) have calculated that an improvement in IQE from 2010 values (Table 3.1) to 2020 values could result in a fourfold reduction in the amount of wasteful heat generated in a 70 lm/W device. The ancillary issues of increased device lifetime and reliability will also have an impact on cost.

TABLE 3.1 Internal Quantum Efficiency Values of Light-Emitting Diodes

Metric(s)	2010 Status	2020 Target(s)
IQE at 35 A/cm^2	80% (blue) 38% (green) 75% (red)	90% (blue, green, red)
EQE at 35 A/cm^2	64% (blue) 30% (green) 60% (red)	81% (blue, green, red)
Power Conversion Efficiency @ 35 A/cm^2	44% (blue) 21% (green) 33% (red)	73% (blue, green, red)
Relative EQE at 100 A/cm^2 versus 35 A/cm^2 (droop)	77%	100%

SOURCE: DOE (2011a, Table 2.1, p. 71).

Thus, investments in improving the control and uniformity of the epitaxial growth process can have a profound effect on long-term device performance, reliability, and cost. Improvement in the cumulative manufacturing yield of the LED module, currently in the range of 50 to 70 percent to more than 95 percent, will further lower the cost and improve the quality of SSL. But although not directly shown in the projection of LED package costs (Figure 3.8), improvements in the cumulative yield will benefit enormously from improvements in the earlier part of the manufacturing process, such as improved uniformity in the epitaxial process. These improvements will exercise a "lever" effect on the cumulative yield and have a large impact on the final device cost and selling price through improved binning yield (DOE, 2011b).

FINDING: LED efficiency and performance is still limited by materials issues. Improvements in efficiency at the device level, as targeted by the DOE SSL roadmap, will have a "lever effect," influencing design, performance, and cost of the luminaires. Improvements in efficiency and performance are linked to further fundamental investigations in core technology on emitter materials.

RECOMMENDATION 3-5: The Department of Energy should continue to make investments in light-emitting diode core technology and fundamental emitter research. Its portfolio of investments in these areas should be extensive enough to ensure that the targeted goals of device performance can indeed be met.

Unit	2010	2012	2015	2020
Price ($/klm)	18	7.5	2.2	1
Efficacy (lm/W)	96	141	202	253

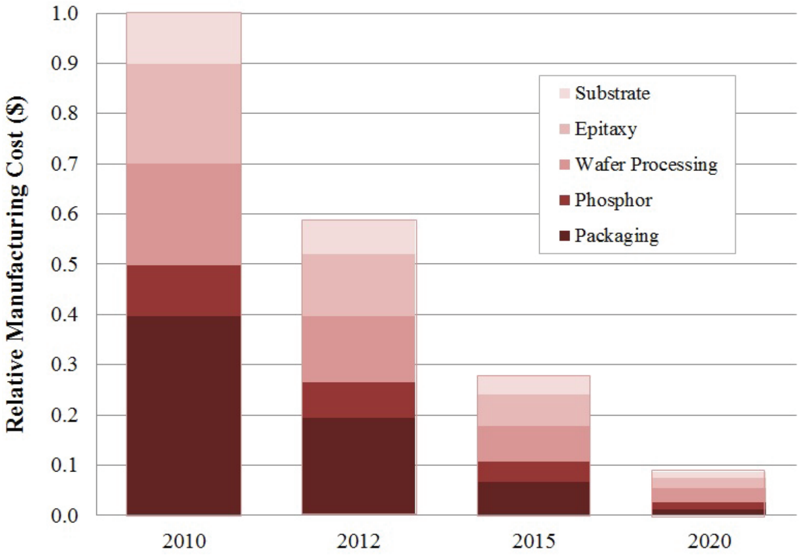

FIGURE 3.8 Light-emitting diode package cost trends. SOURCE: DOE (2011b).

AN OLED PRIMER

Introduction

OLEDs are a new source of illumination wherein light is emitted uniformly over a large planar surface. They are primarily deployed today in very large numbers for displays on handheld appliances such as smart phones. The excitement surrounding OLED technology stems from several unique aspects of its manufacture and performance. They are inherently ultrathin film devices that can be deposited on any smooth substrate such as glass, flexible metal foil, or even plastic, and the devices themselves have very high performance: 100 percent internal quantum efficiency, custom tunable color from the blue to the near infrared, and extremely low temperature rise, even when operated at very high brightness. In contrast to the inorganic semiconductor materials used for LEDs, organic materials are predominantly carbon-based, much the same as inks used in printing or dyes used to color fabrics. Hence, in principle they are abundant, inexpensive, and may have limited negative environmental impact. In addition, the materials used in fabricating OLEDs are used in very small quantities and are deposited over large areas using low energy consumption processes owing to their low sublimation temperatures. While there are currently no significant concerns regarding the toxicity of materials used in OLEDs and their packages, the committee can well appreciate that for any technology, what can begin as minor concerns can become more significant as volume of deployment increases. Hence, it may be necessary to monitor the potential negative toxic and environmental effects that OLED lighting may have as the technology becomes adopted to ensure that risks associated with their use is minimal.

The OLED Device Structure and Operation

The first organic light-emitting device was demonstrated in the 1960s by Pope et al. (1963) and later by Helfrich and Schneider (1965). Sandwiching the organic material anthracene between contact electrodes, blue light was emitted at a relatively high efficiency (a few percent). Unfortunately, the voltage required was very high (~500 V). This situation changed dramatically in 1987 with the first low-voltage OLED. With an efficiency of approximately 1 percent, the voltage was dropped to <10 V, suggesting that a new and potentially efficient light source had been demonstrated (Tang and VanSlyke, 1987). While their first commercial applications of OLEDs have been in ultrathin, full color displays, their currently extremely high efficiency has led laboratories worldwide to explore their applicability as lighting sources.

A simplified OLED structure is shown schematically in Figure 3.9, where the nomenclature used is typical of that used in OLEDs. Here, "ETL" is the organic electron

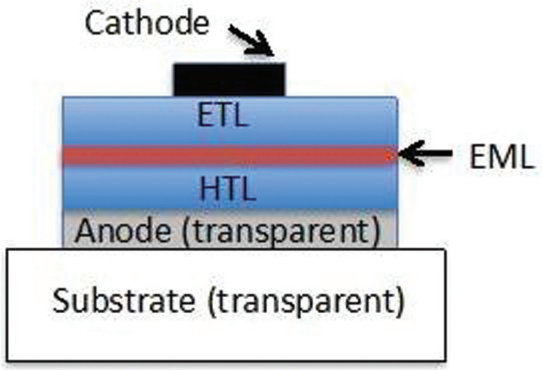

FIGURE 3.9 Archetype organic light-emitting diode structure. SOURCE: Willner et al. (2012). ©IEEE (2012). Reprinted, with permission from *Proceedings of the IEEE*.

transport layer that moves electrons from the cathode metal contact to the light emissive layer, or "EML." This layer is typically composed of two different molecules, a charge conductive "host" molecule into which is doped a molecule at very small concentration (~1 to 8 percent by weight) that gives off light of the desired color (or wavelength) under excitation from electrons and holes in the device. This dopant is called the light emissive "guest." The "HTL" is the hole transport layer whose purpose is to transport positively charged "holes" from the anode contact to the EML. The transparent conducting anode through which the light is viewed is invariably composed of ITO, and the cathode is a metal (such as aluminum doped with lithium) capable of forming an ohmic contact with the ETL for the efficient injection of electrons. Typical OLED structures used in high-efficiency and high-reliability applications are considerably more complex than the structure shown in Figure 3.9. However, in all cases, the total thickness of organic layers rarely exceeds 100 nanometers (1 nanometer = 10^{-7} centimeter) (Willner et al., 2012). The committee also notes that in contrast to LEDs, OLEDs can be made integral to the luminaire rather than being added to it, in contrast to all alternative lighting solutions. This structural adaptability provides new design possibilities for SSL.

The mechanism for light emission in organic, thin-film OLEDs (Box 3.2) is fundamentally different than in inorganic semiconductor LEDs described earlier in this chapter. When an electron and its oppositely charged counterpart, the hole, are conducted to the same molecule within the EML, they put the molecule into an excited state. This excitation is maintained for a brief period of time (from nanoseconds to microseconds). While it exists, the excitation can hop from molecule to molecule, which are very densely packed within the EML. This mobile excitation (called an "exciton") eventually decays by the recombination of the electron and the hole (i.e., the electron "falls into" the hole that is located on the same molecule as the electron). This decay process often emits light whose energy is equal to that of the difference in energies between the electron and hole. By changing the composition or structure of the molecule, the wavelength (color) of light emission can be varied. In fact, small chemical modifications can change the color emission from the ultraviolet, through the blue and green, to the red. In all cases, the light emission can be extremely efficient, with 100 percent conversion of electrons to photons having been reported across the visible light spectrum (Willner et al., 2012).

Metrics of Device Performance

In a manner similar to the calculation of the EQE of an inorganic LED, the EQE of an OLED depends on both an intrinsic efficiency, for the material and device, and an outcoupling or extraction efficiency, where

$$\eta_{EQE} = \phi \bullet \gamma \bullet \eta_{out} \cdot \chi \qquad (3.1)$$

where ϕ is the absolute efficiency of a molecule to emit light once excited, γ is the probability that every injected electron and a hole can simultaneously exist on a light-emissive molecule, η_{out} is the outcoupling efficiency to be discussed below, and χ is the ratio of emissive molecular excited states that an electron and hole can reside on in a single molecule to the total number of possible excited states. χ is also known as the excited state ratio. For the best emissive molecules, $\phi = 1$, which is often the case with state-of-the-art materials. Furthermore, $\gamma = 1$ in properly engineered device structures.

The power efficiency (η_P) of the light source is its most important operational parameter. Here the optical power out per the input electrical power is related to the quantum efficiency following the formula:

$$\eta_P = \theta \eta_{EQE} \frac{V_\lambda}{V} \qquad (3.2)$$

Here, θ is the overlap of the light source with the spectral sensitivity of the eye, and V_λ is related to the energy of the emitted photon. The operating voltage of the OLED is V—clearly the power efficiency decreases as V increases. For a given device geometry, the operating voltage is related to the device drive current and thus also has an important influence on the device lifetime.

In conventional OLEDs fabricated on glass substrates, through mechanisms similar to those in inorganic LEDs, much of the emitted light is trapped within the glass substrate or absorbed in the layers that comprise the device (see Figure 3.10), resulting in an extraction or outcoupling efficiency of only ~20 percent. However, low-cost schemes have been reported that can increase this efficiency to 40 to 60 percent (see below). Nevertheless, one of the grand challenges facing OLEDs is how to extract more of the emitted light in a cost-effective and highly efficient manner. This will

BOX 3.2
How Light Is Emitted in OLEDs

Shown in Figure 3.2.1 is a pictorial view of the light-emitting layer in an organic light-emitting diode (OLED). This layer is typically sandwiched between electron and hole transporting layers. The blue background represents the thin film that is comprised of a molecular species that transports the charges injected from contacts at the boundaries of the OLED itself. The red dots are the dopant molecules that are interspersed at low density within the charge transporting matrix. These dopants can either be fluorescent molecules or phosphorescent molecules. Phosphorescent molecules can produce devices with the highest internal quantum efficiency. The inset on the lower left shows a typical phosphor molecule. It can be very inexpensive and is only used in trace amounts. Ultimately, it consists of carbon, nitrogen, and hydrogen atoms (open circles) that are bonded together (lines) along with a heavy metal atom (typically iridium) in its center (red dot). Light emission occurs when an electron injected from the cathode travels to the same molecule as the hole (positive charge) injected from the anode, forming a mobile excitation or “exciton.” Light is then generated when the electron and hole (or exciton) recombine on the edges of the dopant molecule. This emission process is depicted by the yellow burst around the dopant molecule in the emitting region. By varying the structure of the molecule, the entire visible and near-infrared spectra can be accessed.

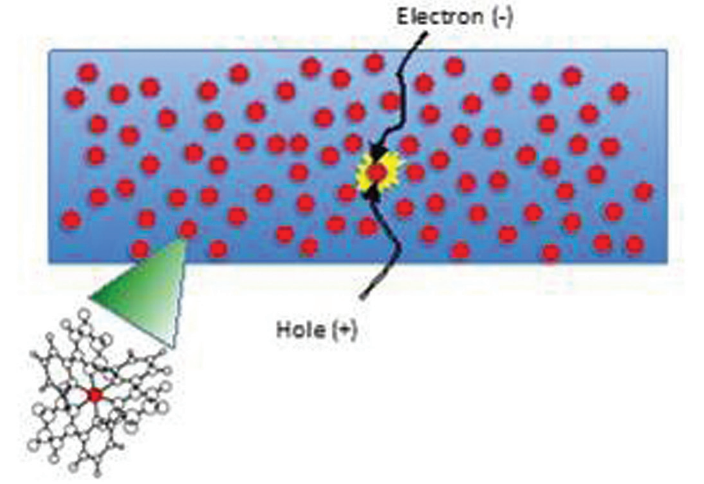

FIGURE 3.2.1 Pictorial view of the light-emitting layer of an OLED.

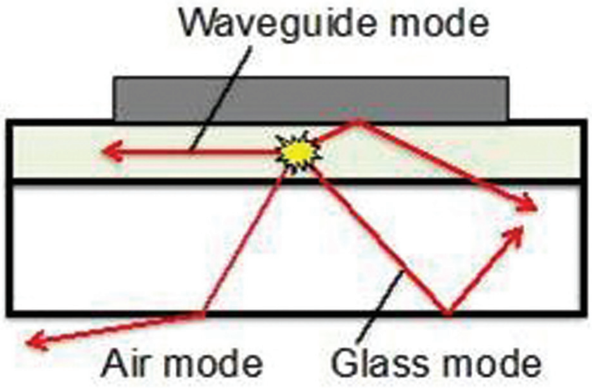

FIGURE 3.10 Illustration of the optical pathways taken by a photon following emission from a luminescent molecule (shown as yellow star).

be discussed further in the section on necessary technology developments.

Finally, the excited state ratio is $\chi = 0.25$ for fluorescent emitting molecules, and $\chi = 1$ for phosphors, as will be discussed in the following section (Baldo et al., 1999b). Putting all of the efficiencies together, it is demonstrated that η_{EQE} is 20 to 60 percent in the very best cases. Even with these limitations, the power efficiency of phosphorescent white organic light-emitting devices can exceed 150 lm/W, making them especially attractive for use as efficient lighting sources.

CONTROLLING THE COLOR OUTPUT OF THE OLED

For OLEDs, changing the composition of the molecular components of the material influences the wavelength (color) of the light emitted. White light is generated by mixing red, green, and blue emission from different regions of the OLED. That is, the emission spectrum of a particular molecule is insufficiently broad to efficiently generate the desired broadband white radiation to produce high-quality illumination, so the use of several different molecular species within the emission region of the OLED is required to achieve the desired white spectrum.

A given molecule within an EML will emit with a well-defined spectral shape. Hence, unlike the case for inorganic LEDs, binning is not needed to select those devices that emit at the appropriate wavelength. However, the white balance or chromaticity is ultimately determined not only by the well-defined spectra of the constituent molecules in the EML, but also by the details of the device structure, which may vary from run to run. Hence, several schemes have been developed for lighting applications that are both efficient and have a stable, predictable, and highly controllable white chromaticity. The highest performance is achieved using a variant of one of the three designs shown in Figure 3.11—the striped, white OLED (WOLED), the fluorescent/phosphorescent (F/P) WOLED, and the stacked WOLED (SOLED). The latter design is most effective in achieving long lifetime and high brightness and can be combined with the F/P design as well as others for illumination purposes.

Striped WOLEDs

The simple design of the striped WOLED places stripes of red (R), green (G), and blue (B) PHOLEDs (phosphorescent OLEDs) side by side. The R-G-B pattern is repeated on a very small scale so that the separate colors cannot be resolved by an observer. By injecting current into each stripe, the viewers will perceive the mixture of the three primary colors, which will appear white. An advantage of this design is that each of the three color elements can be separately optimized to emit with 100 percent internal efficiency, and variation of the current through each of the elements can be used to tune the color, from their constituent color to any desired white chromaticity. A disadvantage is the complexity of driving the WOLED with three different current sources.

F/P WOLEDs

The F/P WOLED is based on the recognition that approximately 25 percent of the color content of white light is blue. To achieve lower voltage operation and perhaps longer lifetime, which is currently limited by phosphorescent blue EMLs (see Box 3.3), and because 25 percent of the injected charge forms fluorescent states, this device uses a fluorescent blue segment and harvests the remaining green and red excited states using phosphorescent (i.e., heavy-metal-atom containing) molecular compounds. In principle, this particular device has the lowest drive voltage and hence highest efficacy of all alternative architectures. The F/P design can also be incorporated into stacked and striped architectures. Hence, the device still achieves 100 percent internal quantum efficiency because all excitons are harvested by a combination of blue fluorescent dopants and red and green phosphors.

Stacked WOLEDs

The compact SOLED design stacks two or three white-emitting segments, with each segment separated by a very thin and transparent "charge generating layer." In this case, a single injected electron can recombine with a positively charged hole in each segment, generating a photon. Thus, a 2 to 3 times higher quantum efficiency is achieved with this device compared to the other designs, but at 2 to 3 times higher voltage (where the multiplier is equal to the number of elements in the final stack). Hence, the efficacy of this device is no higher than that of the other designs shown, but there are significant benefits of increased device lifetime.

For example, the SOLED of Figure 3.11 comprises a B PHOLED as one stacked element and an R-G PHOLED as the second element. Other examples of SOLEDs include a complete white-emitting phosphorescent R-G-B EML in each element. This three-element SOLED is known as a W-W-W SOLED, as shown in Figure 3.11.

Finally, the committee notes that there are several other approaches to generating white light. Two alternatives that are often pursued are to use very broadly emitting white

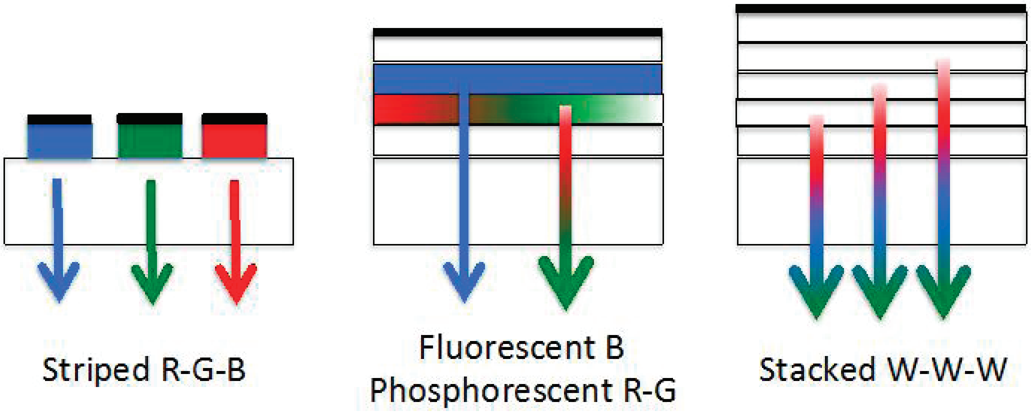

FIGURE 3.11 Three examples of white organic light-emitting diode designs.

BOX 3.3
OLED Drive Voltage

According to Equation 3.2, the white organic light-emitting diode (WOLED) efficacy (i.e., power efficiency) is inversely proportional to the total voltage dropped across the device. Low-voltage operation is, therefore, desirable for high efficacy (and also results in lower electrical power dissipation); because the conductivity of organic materials is low, this requires the use of thin device layers. Unfortunately, such thin layers can also decrease device yields, because any flaws in the film (e.g., pinholes, clusters, etc.) can lead to shorts between the closely spaced electrodes (typically, the organic layers are ~100-200 nm thick in total). A particular constraint for low voltage operation resides with OLEDs emitting in the blue, requiring at least ~3.5 V to excite the emitting (dopant) molecule. To transfer the excitation from the host material to the dopant molecule requires ~3.5 V for *fluorescent emission* in the blue, but >4 V to achieve *phosphorescent emission* in the blue. As discussed earlier, the excited state ratio, χ is only 0.25 for fluorescent-emitting molecules, but *fortuitously*, only 25 percent of the color content of white light is blue. Thus using *fluorescent* molecules for blue OLED emission allows a lower-voltage operation.

Another effective means for decreasing voltage is to increase the conductivity of the charge transporting layers using conductivity-enhancing dopants (Blochwitz et al., 1998; D'Andrade et al., 2008; Pfeiffer et al., 2002). This strategy has been successfully pursued by Novaled and the COMEDD Fraunhofer Institute in Dresden, Germany.

OLEDs (e.g., emission from a single molecular species that spans an unusually broad spectrum or uses a blue OLED to "pump" red and green organic phosphors located external to the OLED pump). Unfortunately, in both cases the efficiency is considerably less than direct PHOLED emission and, hence, are generally not viewed as adequate for meeting the stringent demands of advanced SSL sources.

MATERIALS FOR OLEDS

All current significant manufacturing of OLEDs employs small-molecular-weight organic materials. These materials consist of a single molecular unit with a well-defined number of constituent atoms. This is in contrast to polymers that are chains of units of indeterminate length and, hence, number of atoms. Polymers are typically used in plastics, whereas small molecules are used as pigments in common dyes for clothing, ink-jet printing, and so on. Small-molecular-weight organic compounds are commonly deposited from the vapor phase (i.e., either vacuum thermal evaporation (VTE) or organic vapor phase deposition (OVPD); Shtein et al., 2002), although, like polymers, they can also be deposited from liquid solution.

Note that the demands placed on the deposition process (and tools) are quite high. As discussed above, a typical high-performance OLED display consists of at least five layers, with the thickness of the entire stack seldom exceeding 100 nm. White-emitting OLEDs used in lighting applications have at least double this number of layers. Hence, deposition must occur over very large substrate surfaces (exceeding 1 m^2 in production environments), with minimum individual layer thicknesses of ~5-10 nm. To maintain device performance uniformity, layer thickness variations of only a few percent are tolerable across the entire substrate surface. Fortunately, in-line VTE and OVPD have been proven to achieve these demanding specifications in display production facilities, suggesting that such targets are realizable for lighting as well.

To produce high-quality, long-lived devices, it is imperative that the organic materials, most of which are easily synthesized using well-known methods, be highly purified prior to use. That is, small concentrations of molecular impurities can lead to rapid degradation in device performance, and hence considerable steps must be taken to ensure their purity. High purity is achieved by evaporation of the volatile (and lightweight) impurity molecules in a vacuum system that exhausts the volatile evaporants.

The layering of numerous materials with different functions needed to confine both charges and photons (see Figure 3.9) is a relatively simple task when deposition occurs from the vapor phase, and given that the process generally occurs in vacuum, this too aids in the prolonged operational lifetime of the OLEDs. As will be discussed below, extended lifetimes, particularly of the blue emitting molecules, remains a challenge.

In addition to polymer and small-molecular-weight OLEDs, as mentioned in the section "How Light Is Emitted," there are two systems of emissive dopants available: those that emit from fluorescent molecules and those from phosphorescent molecules. Note that while fluorescent devices (Tang and VanSlyke, 1987) can have a theoretical maximum emission efficiency of only 25 percent (because $\chi = 25$ percent in Equation 3.1, in this case), phosphorescent devices can have 100 percent internal quantum efficiency. This implies that PHOLEDs are ideal for both displays and lighting. Following the demonstration of "electrophosphorescence" using metalorganic compounds (Baldo et al., 1998, 1999a) in 1998, the materials have found widespread adoption in all OLED devices currently introduced into the market.

As shown in Table 3.2, extremely high-efficiency emitting molecules (with 100 percent IQE) are available for emission across this entire spectral region.

Several other materials are used in high-efficiency PHOLED structures beyond the simplified design shown in Figure 3.9, including the conductive host, the electron and

TABLE 3.2 Representative Commercial Phosphorescent Molecules and Their Corresponding PHOLED Performances

			Operating Lifetime (hours)	
PHOLED Performance at 1000 cd/m^2	CIE 1931 Chromaticity Coordinates	Luminous Efficiency (cd/A)	L95	L50
Deep red	(0.69, 0.31)	17	14,000	250,000
Red	(0.69, 0.34)	24	25,000	600,000
Red	(0.64, 0.36)	30	50,000	900,000
Green-yellow	(0.46, 0.53)	72	70,000	1,400,000
Green	(0.34, 0.62)	78	18,000	400,000
Light blue	(0.18, 0.42)	47	600	20,000

NOTE: Results are for bottom-emitting structures (with no cavities). Lifetime data are based on accelerated current drive conditions at room temperature without any initial burn-in. L95 and L50 are the time to which the luminance has decreased to 95 percent and 50 percent, respectively, of initial values.
SOURCE: Universal Display Corporation (undated).

hole transporting molecules, and the exciton blocking layer (EBL). This EBL layer, positioned at the cathode-side of the EML, is required in PHOLEDs because of their long excited-state lifetimes and corresponding diffusion length. The EBL prevents diffusion of the excited states to the cathode contact where they may quench before they can radiatively emit light. Hence, the use of an EBL has greatly increased the efficiency of PHOLEDs such that 100 percent IQE is routinely obtained using optimized materials sets.

KEY ISSUES FOR IMPROVED DEVICE PERFORMANCE

Light Outcoupling

Perhaps the largest efficiency gain that has yet to be achieved is through increased light outcoupling from the substrate. As noted in Equation 3.1 and the ensuing discussion, only 20 percent of the light emitted by the WOLED is coupled into the air and is, therefore, viewable if the device is deposited on a conventional glass substrate. The remainder is trapped in the glass, or is absorbed by the materials that comprise the device, as shown in Figure 3.10. Outcoupling of light in OLEDs is particularly difficult when compared with LEDs because of the large areal dimension and integrated form factor of the OLEDs. That is, they are "area" rather than "point" lighting sources, whereby a large surface area must be coated with emitting materials to generate the desired level of illumination. As noted above, this is a generally desirable feature because the lighting source (the OLED) and the luminaire form a single *integrated* unit. Yet, it also poses challenges because there is little access to the light trapped within the substrate and emissive layers. Numerous outcoupling efforts have therefore explored ways of cost-effectively harvesting a greater proportion of the trapped light (Wang et al., 2011).

There are three principal optical pathways an emitted photon can take. The first is the air mode: i.e., the light that escapes from the substrate and can be viewed as useful light. As noted above, only 20 percent of the light is emitted into air modes because of total internal reflection when conventional, low-cost glass substrates are employed. A large remaining fraction (again about 20 percent) of the light is trapped in the glass substrate (glass modes). And finally, 33 percent of the light is emitted along the plane of the organic thin films, forming waveguide modes. Other losses due to absorption in the organic or transparent conducting oxide anode layers, as well as excitation of so-called plasmons at the metal cathode surface, can also lead to reductions in efficiency.

Because of the relative sizes of the effects and ease in modal access, most efforts have been directed at eliminating glass and waveguide modes. The effective elimination of these losses can result in a tripling of the external efficiency from 20 to 60 percent.

Any practical solution of the outcoupling problem must be extremely low cost to implement, and it must not affect the wavelength or angular intensity distribution of the emitted light. With these considerations in mind, glass modes are most effectively eliminated by the attachment of microlens arrays onto the substrate/air surface (Möller and Forrest, 2001; Sun and Forrest, 2008). Microlenses are typically 5-10 µm diameter transparent hemispheres that can be made by molding into large plastic sheets (see Figure 3.12, for example). This omnidirectional, wavelength-independent solution has been shown to increase the efficiency of the OLEDs by nearly a factor of 2 (with external efficiencies as high as 40 percent measured). Alternative solutions for extracting glass modes include roughening of the glass surface, placing OLEDs on the surfaces of plastic blocks with tapered edges, or using high index of refraction plastic substrates and a large hemispherical lens.

Extracting waveguide modes (i.e., that light emitted within the organic layers themselves and propagating in the plane of the substrate) that consume 33 percent of the emission is more difficult. It needs to be done very near to the point of emission (i.e., at the location of the excited molecular dopant) to avoid losses due to waveguiding within the absorptive organic or transparent conducting oxide anode layers. Such solutions, therefore, must be integrated into the

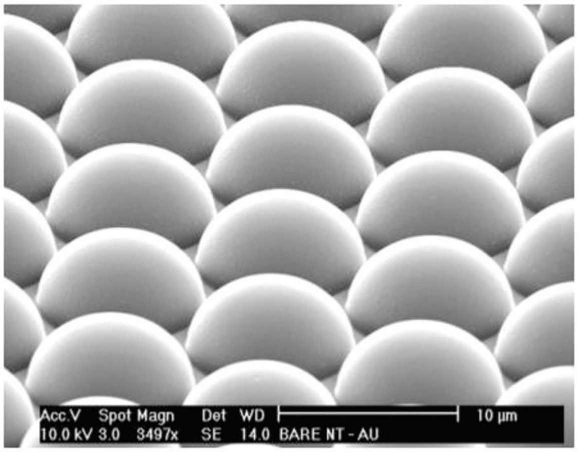

FIGURE 3.12 Polymer sheet of 5 µm diameter microlenses attached to the glass surface of an OLED. Outcoupling enhancements of a factor of 2 are possible using this approach. SOURCE: Sun (2008). Reprinted by permission from Macmillan Publishers Ltd.

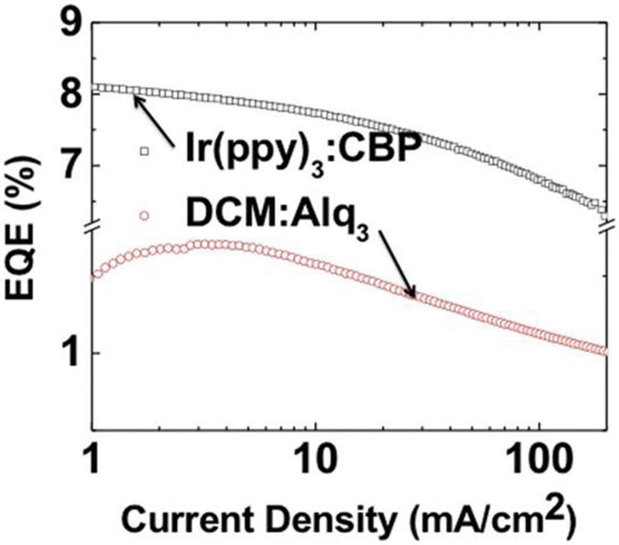

FIGURE 3.13 Efficiency droop in phosphorescent OLEDs (black rectangles) and fluorescent OLEDs (red circles).

OLED structure itself without degrading device performance in other, unintended ways.

Generally, to couple waveguide modes into the glass or air, there must be a surface texture inserted at the transparent anode/organic interface. The length scale of the texture cannot be on the order of the emission wavelength; otherwise, an undesirable angular dependence of emission wavelength (i.e., color) and/or intensity may result. Low-index grids consisting of a dielectric such as silicon dioxide residing at this interface have been shown to outcouple almost all of the waveguide modes without significant losses (Sun and Forrest, 2008). The openings in the grids are typically 5 µm, with grid lines of only 1 µm. Combining the grid with the microlenses shown in Figure 3.12 has resulted in the demonstration of 34 percent external efficiency.

FINDING: A number of promising approaches have been developed to increase outcoupling efficiency.

RECOMMENDATION 3-6: The Department of Energy should focus on efforts that result in significant light outcoupling enhancements for OLED that are low-cost to implement and are independent of both wavelength and viewing angle.

OLED Efficiency Droop

As in the case of LEDs, OLEDs also suffer a loss of efficiency as the current (and corresponding brightness) is increased. This is readily apparent in Figure 3.13 where the external quantum efficiencies of archetype fluorescent and phosphorescent devices are shown as functions of drive current. This droop is fundamentally related to the molecular excited state (exciton) that, when de-excited, emits light. At very high intensity, a substantial fraction of the emitting molecules in the EML are excited. When the excitation migrates from molecule to molecule, it has a possibility of colliding with another excitation on the same molecule or on an electron or hole that is transiting the EML. This collision results in the loss (or de-excitation) of one of the two excited states, ultimately resulting in the loss of efficiency. This process is known as “exciton annihilation.” Importantly, this same process leads to the degradation of the molecules and hence a decrease in OLED operational lifetime, as discussed below. Hence, it is essential to find device architectures that minimize exciton annihilation processes. One method to effect this is, for example, extending the thickness or grading the dopant concentration within the EML. However, little work has been done to date to reduce or even eliminate droop.

One important difference between OLEDs and LEDs, however, is that in the former case, there is no thermally driven droop effect. That is, as the temperature is varied, the efficiency characteristics in Figure 3.13 are largely unaffected.

FINDING: OLEDs show a decrease in efficiency as the current is increased. This results in a reduction in efficiency at high brightness.

RECOMMENDATION 3-7: The Department of Energy should support research to understand the fundamental nature of efficiency droop at high currents in organic light-emitting diodes and to seek means to mitigate this effect through materials and device architectural designs.

ISSUES FOR OLED DEVICE RELIABILITY AND MANUFACTURING

OLED Reliability

As in all electronic devices, there are numerous sources of OLED degradation that limit the operating lifetime of the lighting source. These mechanisms fall into two categories: extrinsic and intrinsic, or fundamental. Typically, the usable lifetime of a device is indicated by the time to which the light output has dropped to a given percentage of initial luminance (L_o) (see Table 3.2). Typically, lighting requires qualification to at least the so-called L70 limit set forth in the industry standard, LM-80, issued by the Illumination Engineering Society (2008). For displays, a differential luminance loss of only 10 percent on a highly used area of the display field is easily perceptible, rendering the appliance useless. Once again, experience being gained in the large-scale deployment of reliable displays has promoted the advances in lighting applications as well. However, in the case of white light sources, their exceptionally high surface brightness (typically 3,000 cd/m^2 compared to 100 cd/m^2 required for displays) places additional stress on the devices that results in a shortened lifetime. Furthermore, the differential aging of one color component versus another leads to perceptible and unacceptable shifts in the CRI or luminaire color temperature over time.

The primary extrinsic source of aging in OLEDs is degradation of materials and cathode interfaces due to exposure to moisture and oxygen (Burrows et al., 1994). For this reason, packaging of OLEDs is important in controlling the local environment. OLEDs are sealed against ambient ingress by packaging in an ultrahigh purity nitrogen environment. A conventional package consists of a glass substrate and a metal back cap that has a slight recess filled with a dessicant such as BaO to scavenge any residual oxygen or moisture in the package. The seal is typically made using a bead of UV-curable epoxy. Although it is by no means a perfect seal, the long-term degradation of most OLEDs is extended to well within acceptable industrial standards. Other routes to extrinsic failure include incorporation of impurities from source materials and chemical reactions in the guest-dopant conductive layer. All such extrinsic mechanisms can be reduced to acceptable levels through the proper handling and purification of source materials and by careful selection of materials sets for a particular OLED structure.

FINDING: The lifetime of OLEDs is very sensitive to extrinsic factors such as exposure to air and moisture. The low-cost fabrication of large area OLED lighting sources requires a high degree of fabrication competency that can ensure package hermiticity along the entire large package periphery and scavenge excess water and oxygen that might have been enclosed during the package manufacture.

RECOMMENDATION 3-8: To create a highly environmentally robust organic light-emitting diode (OLED) lighting technology, the Department of Energy should invest in materials and packaging technologies that make OLEDs resistant to degradation over their long operational lifetimes. In particular, important areas for investment include finding low-cost means to eliminate glass as a primary package constituent, devising molecules and device architectures that are resistant to degradation on exposure to atmosphere, and developing sealing technologies that are fast, precise, and robust to bending.

As can be observed in Table 3.2, both red- and green-emitting PHOLEDs used in analogous display applications have lifetimes of several hundreds of thousands to millions of hours. Devices emitting with these colors, therefore, significantly exceed the lifetimes required for practical lighting sources. However, blue PHOLEDs have a significantly shorter lifetime. Early blue failure is not due to environmental factors, but rather to properties *intrinsic* to organic molecules (Giebink et al., 2008). The principal intrinsic failure mode is excited state-charge and excited state-annihilation reactions that occur when, at the molecular scale, a charge ends up on an excited molecule (Giebink and Forrest, 2008)—a process similar to that responsible for a decrease in quantum efficiency as current is increased (see Figure 3.13). Today, the useful life of blue phosphorescent devices is only approximately 10,000 to 20,000 hours (Table 3.2), also setting the limit for the lifetime of white lighting sources. Fluorescent blue-emitting materials have somewhat longer lifetimes because of the very short existence of the blue fluorescent excited state (~nanoseconds) compared to that of blue phosphorescence (~tens of microseconds). Hence, the less efficient fluorophores support annihilating collisions with charges and other excited states for durations that are far shorter than for phosphors, increasing the operational lifetime of the device.

One significant challenge that must be overcome to ensure the widespread deployment of WOLEDs for lighting, therefore, is to increase the lifetime of the blue-emitting element to hundreds of thousands of hours. As noted, use of fluorescent blues is one avenue for improvement, as is designing phosphorescent blue molecules that have shorter excited state emission times. Further techniques might include extending the thickness of the blue EML, thereby reducing the density of excited molecules at high brightness. Indeed, the SOLED architecture does this effectively by distributing several of the blue-emitting regions within the several elements in the stack. Finally, white light does not require the use of deep blue (i.e., high-energy) emission. Rather, light blue (cyan) emission is desirable for this application. Because this is a lower energy of emission, the problem is partially resolved simply by the judicious choice of blue-emitting wavelength. Nevertheless, more rapid degradation of blue intensity versus red or green inevitably leads to color shifting during the operational lifetime of the WOLED that must ultimately be minimized.

To summarize the operational lifetimes of both single element and stacked OLEDs, a comparison is shown in Figure 3.14. The advantage to using a SOLED that distributes the EML between elements, while reducing operating current to achieve a desired brightness, is readily apparent.

Finally, the committee notes that elevated temperature can significantly reduce the OLED operational lifetime. At surface luminances of 8,000 cd/m^2, it has been found that a 10°C increase in temperature reduces the lifetime by as much as 30 percent (see panel a of Figure 3.15). Fortunately, because OLEDs are highly distributed lighting sources, their temperature rise during operation is minimal (Levermore et al., 2012). Indeed, with proper packaging, the rise in temperature even at high surface luminances of 3,000 cd/m^2 can be less than 1°C using only natural convection present in the ambient surrounding the fixture, as shown in panel b of Figure 3.15.

FINDING: OLEDs are area light sources, and their rise in temperature, even at the highest drive currents (and hence brightness), is minimal. This is a major distinction from LEDs, which are intense point light sources and, hence, operate at high temperatures that require extensive heat sinking and care in their installation. Nevertheless, OLED operational lifetime is very sensitive to temperature increases. As the room temperature rises, the OLED lifetime can be expected to be noticeably decreased.

RECOMMENDATION 3-9: The Department of Energy should support the pursuit of material sets and device architectures that would increase the useful operational lifetimes of high-intensity white organic light-emitting diodes.

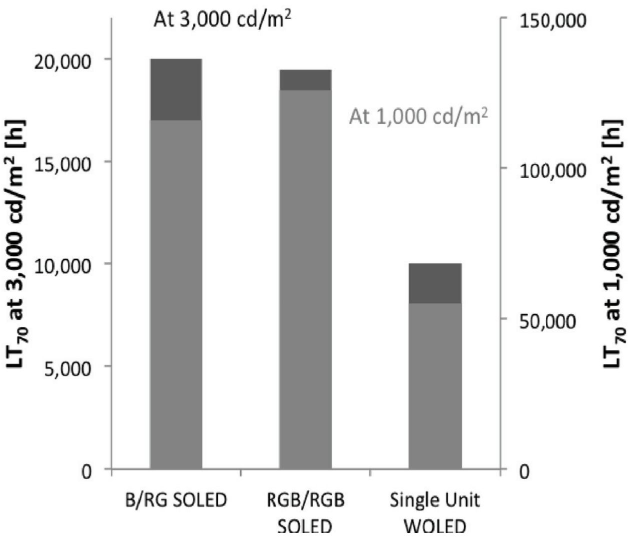

FIGURE 3.14 Comparison of lifetimes of three different white PHOLED emitters at two different surface luminance intensities. SOURCE: Courtesy of Universal Display Corporation.

Manufacturing Issues

There is as yet no large-scale manufacture of OLED lighting; however, major growth in OLED display technologies may provide both infrastructure and cost reduction and, thus, important incentives for the further development of manufacturing for OLED-based SSL. As of this writing, one company alone, Samsung Mobile Displays (SMD), is producing 30 million such displays per month, with plans to scale these devices to larger, three-dimensional displays. SMD's major competitor in this space is LG Display, along with a handful of other display companies in Asia of varying

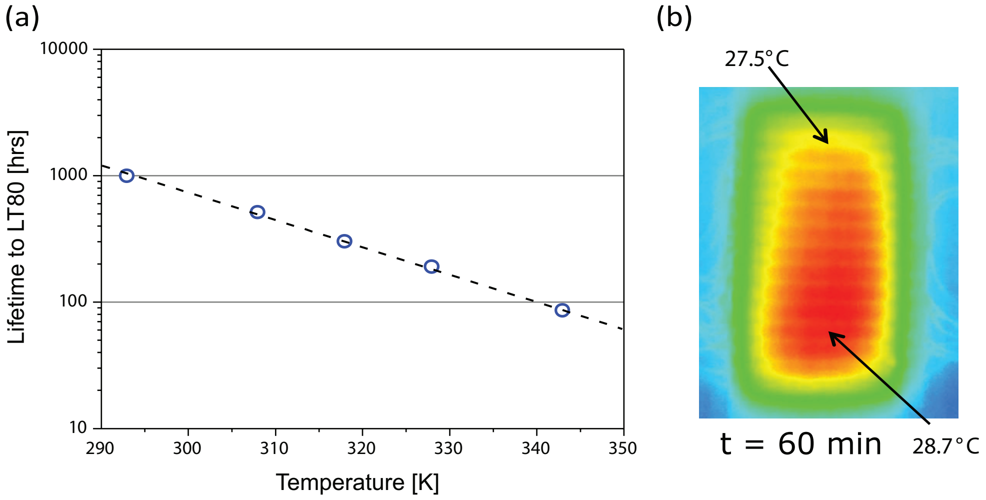

FIGURE 3.15 Time to LT80 for a white PHOLED with an initial surface luminance of Lo = 8,000 cd/m^2. (b) Infrared image showing the surface temperature of a 7 cm × 15 cm panel as in (a) after 60 min operation in a 24°C ambient temperature. SOURCE: Levermore et al. (2012).

sizes. All of this manufacturing, today occurring on Gen 5.5 (1,300 × 1,500 × 0.6 mm) mother glass substrates, is resulting in a precipitous decrease in the cost of OLED technology, while increasing performance, as the industry grows, thereby positioning these early-entry companies to become competitive in producing low-cost, ultrahigh efficiency, easily dimmable OLED sources for the consumer lighting market. Indeed, several companies are concerned only with the lighting applications of OLEDs (i.e., not their uses in displays), such as General Electric, Osram, Moser-Baer, and Philips.

Equipment makers, providing key infrastructure that is required to provide a strong growth in manufacturing, are also starting to take notice of the possibilities for large, developing markets in OLED displays and lighting. Chief among the OLED manufacturing equipment suppliers is Aixtron, SE, the largest producer of MOCVD equipment for LED lighting, which also produces (on still a small scale) organic vapor phase deposition systems for OLEDs. Applied Materials is the world's largest supplier of equipment for low-temperature polysilicon deposition on glass substrates used as active matrix display drivers (Nathan et al., 2005), and its division Applied Films supplies in-line deposition sources for front-plane OLED display materials deposition. The committee notes, however, that the current lack of a complete tool set for manufacture of OLEDs remains a limiting factor in their widespread and low-cost deployment as lighting sources.

SUMMARY OF OLED CHALLENGES

Based on the foregoing discussion, phosphorescent WOLEDs provide an unusual opportunity to complement LEDs as an important solution for areal SSL. Yet there remain significant barriers to their adoption, and as a result their development still lags that of inorganic LEDs as the preferred white illumination source

The committee's findings and recommendations on the major challenges that should be the focus of near-term investment are given below.

Cost Reduction

FINDING: This is potentially the single most important metric to meet in OLED lighting. It requires simplification of device structure, use of ultralow-cost substrates such as metal foils, development of replacements for costly transparent anodes (current technology is indium tin oxide), low-cost encapsulation technologies, and so on. Also, investment in equipment infrastructure is essential for the success of low-cost, manufacturable products. In-line vacuum deposition sources, roll-to-roll processes on flexible substrates, ultrahigh-speed organic vapor phase deposition, and in situ encapsulation techniques will all require substantial infrastructure development.

RECOMMENDATION 3-10: The Department of Energy should aggressively fund the development of all possible routes leading to significant (100×) cost reduction in organic light-emitting diode lighting sources.

Extended Operational Lifetime

FINDING: Extending the lifetime of blue phosphorescent OLEDs is a primary area where investment will have substantial payoff. It involves a combination of advances in the development of new materials, device architectures, encapsulation, and contact technologies, as well as a fundamental advance in the understanding of degradation processes. Interactions between the phosphor and the conductive host will have an influence on mitigating *efficiency droop*, or the de-excitation of the molecules in the OLED. The mechanisms for thermally induced degradation also require clarification. Encapsulation compatible with flexible, lightweight substrates is also an important area of development.

RECOMMENDATION 3-11: Given the interactions between the phosphor and the conductive host molecules, the Department of Energy should direct studies for determining what chemical structural combinations lead to the most robust materials sets. Fundamental studies of the degradation mechanisms should be carried out both at room and elevated temperatures. Research on understanding contact and ambient degradation routes and their minimization should also be supported.

Low-Cost Light Outcoupling

FINDING: Increased outcoupling remains the single most beneficial route to increasing device efficiency from the current 100 lm/W to nearly three times that value. Methods to achieve this should be inherently very low cost and deployable over very large areas, even in the context of roll-to-roll manufacture. The outcoupling technology should have the additional attributes of being wavelength and intensity independent, and the light source should exhibit no color shifts as the viewing angle is varied from normal to highly oblique. Clearly, a viable outcoupling technology should not otherwise impact or degrade OLED performance.

Addressing the critical challenges for OLED lighting should enable the realization of increased power efficacy and the realization of the targets set by DOE, as shown in Table 3.3.

SUMMARY AND COMPARISON OF LED AND OLED SSL

The LED and OLED technologies explored in this chapter provide new, energy-efficient approaches to lighting with exceptional control over the chromaticity and the quality of the light produced. As shown in Table 3.3, both technolo-

TABLE 3.3 Comparison of Lighting Sources by Various Metrics

	Incandescent	Fluorescent	LEDs	OLEDs
Efficacy (lab demo)			231 lm/W – white 150 lm/W – warm white	100 lm/W
Efficacy (commercial)	17 lm/W	100 lm/W	100-120 lm/W – white	50 lm/W panel
CRI	100	80-85	85 – white 95 – warm white	Up to 95
Form factor	Heat generating	Long or compact gas filled glass tube	Point source high-intensity lamp	Large area thin diffuse source Flexible, transparent
Safety concerns	Very hot	Contains mercury	Very hot operation	None to date
Lifetime (hours)	1,000	20,000	50,000	30,000
Dimmable?	Yes, but much lower efficacy	Yes, efficiency decreases	Yes, efficiency increases	Yes, efficiency increases
Noise	No	Yes	No	No
Cost ($/klm)	0.50	1.0	7.0	100-250

gies have enjoyed an unprecedented rapid progress in luminous efficacy. However, the comparison of lighting source technologies in Table 3.3 shows that substantial challenges remain for LEDs and OLEDs, not only in performance, but also in cost. The strong demand for high-power, efficient lighting sources propelled the III-nitride LEDs into the commercial sector despite the relative immaturity of the component materials and the known existing defects and variations in the devices. Despite the continuous progress in the wall-plug efficiencies of inorganic LEDs, issues of yield and cost will ultimately determine the long-term success of this technology, and these in turn are strongly influenced by some fundamental materials challenges.

OLEDs can be designed and fabricated with exceptionally high internal efficiencies, rendering virtually any desired color, but there has not yet been a sufficient manufacturing infrastructure established to understand the practical issues and costs of scaling up this device technology into a practical and ubiquitous lighting source. Considerable additional efforts are needed to optimize light extraction, extend device lifetimes, reduce the roll off in efficiency at high brightness, and improve operational lifetime. The inorganic LEDs form "point-sources" of light while OLEDs lend themselves to unusual, conformable, and flexible form factors, offering diffuse lighting over large areas. Thus, the two technologies provide complementary lighting solutions, depending on particular lighting applications and venues. Investments in fundamental advances in OLED materials and device architectures, at this stage, may be the deciding factors in their ultimate success and the widespread adoption of this very promising lighting technology. On the other hand, the inorganic LEDs have already made the transition to widespread manufacturing and commercialization, yet still face substantial challenges to longer-term success. Issues of higher efficiency and more robust and reliable operation at lower cost similarly require continued investments into the technology, both at the fundamental level of materials and device improvement, as well as at the level of manufacturing and systems-level improvements.

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4

Assessment of Solid-State Lighting Products

INTRODUCTION

Lighting products used in illumination or luminaires are used to illuminate an environment with electric light sources. Generally, a product has, at a minimum, a fixture envelope, a light source, and an electrical connection to a power source. Examples include downlights, troffers, outdoor area and streetlight luminaires, under-cabinet luminaires, chandeliers, and others. The interest in using white solid-state light sources for illumination applications started in the mid-1990s. Today, the technology, specifically the inorganic light-emitting diode (LED), has matured to a point that these solid-state lighting (SSL) products, both luminaires and integral replacement lamps (i.e., those containing the electronics for the replacement lamp that are not otherwise present in the incumbent luminaire), are able to compete well with some traditional technologies in certain applications.

Even though the replacement lamp is a subcomponent of a luminaire product, in some sense the replacement lamp is also a self-contained product. Therefore, in this chapter we call both the complete luminaire and the integral replacement lamp a product. Ultimately, the lighting product's (i.e., the luminaire's or the integral replacement lamp's) performance in a given application is what matters most to the purchasers and end users of that product. In this chapter we look at each subcomponent of a lamp or luminaire and its performance and then address the luminaire and integral lamp products and issues related to their overall performance. This chapter addresses only products that produce white light, created by either mixing color (red, green, blue, yellow) or down-converting with a phosphor.

TYPES OF SSL PRODUCTS

Typically, an SSL product consists of several subcomponents, including:

- An LED, an LED array, an integral lamp, or an organic LED (OLED) panel;
- Secondary optics to control the distribution of the light;
- Heat sink, thermal management components, or thermal interface material (TIM); and
- Driver and control devices.

Figure 4.1 illustrates these components for a screw-base A-lamp LED replacement.

Some luminaires integrate the light source(s) with the luminaire envelop and other product components, meaning the light source cannot be easily removed and replaced or repaired. Some luminaires with integrated light sources are considered retrofit luminaires and are to be used in whole product replacement. Other luminaires have replaceable lamps (with a screw base or pin base), including A-lamps, linear fluorescent lamps (LFLs), compact fluorescent lamps (CFLs), multifaceted reflector (MR) and parabolic aluminized reflector (PAR) lamps, and others. Figure 4.2 illustrates a luminaire with integrated light sources and a luminaire with a replaceable lamp.

Luminaires with integrated light sources offer a number of advantages compared to luminaires with replaceable lamps. The luminaire designer/manufacturer has more control over the entire product (e.g., electronic components, thermal management design, optics, etc.) and can select the components to optimize performance. In contrast, a developer of replacement lamps must consider all of the possible luminaires within which a product may be installed and design a product to optimize compatibility rather than performance.

LED Replacement Lamps

After the phase-out of certain types of incandescent lamps between 2012 and 2014, consumer choices for replacing these types of screw-in lamps will include higher efficacy halogen incandescent lamps, CFLs, and LED lamps. Many SSL product manufacturers are producing screw- and pin-based lamp products to replace incandescent, halogen, com-

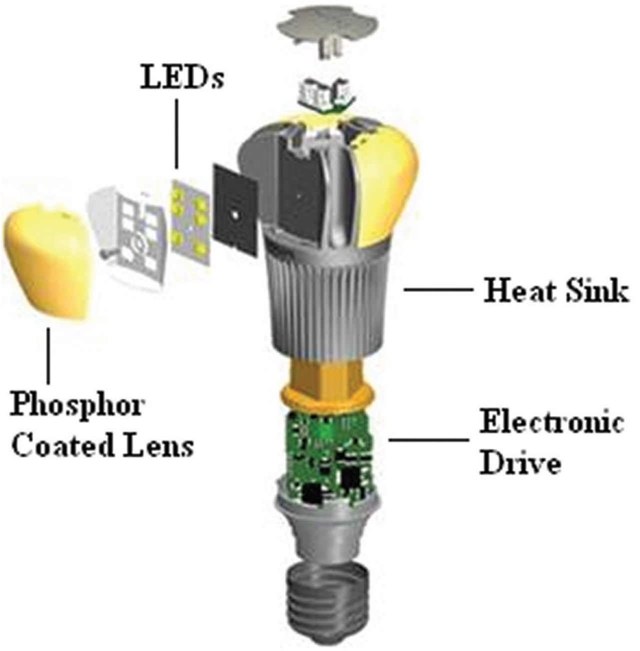

FIGURE 4.1 An LED equivalent of a screw-base A-lamp showing the component parts. Courtesy of Philips Lighting.

pact and linear fluorescent, and metal halide lamps. This is an appealing market segment for several reasons. The large number of available sockets appeals to the manufacturing community, and the lower investment required to try these products by directly replacing the older lamp in the existing luminaire appeals to the consumer. Although the LED chips themselves are manufactured by a small number of multinational companies, the assembly of an LED lamp resembles that of any electronic equipment. The investment needed to set up an assembly line is relatively modest, and therefore a very large number of companies can and have entered the industry. The approximately 4 billion medium screw-base sockets in U.S. households represent a very attractive potential market, so the industry development has happened very quickly, in the span of only a few years. At the same time, the industry[1] is scrambling to develop meaningful safety and performance standards, and product quality varies over a wide range.

Figure 4.3 through Figure 4.5 illustrate examples of LED replacements for incandescent A-lamps, PAR lamps, and linear fluorescent lamps. The lamp on the left of Figure 4.3 uses the remote phosphor concept where the blue LEDs excite the orange phosphor cover (which emits white light), and the lamp on the right uses two phosphor white LEDs[2] placed within an envelope that mimics an incandescent A-19 lamp.

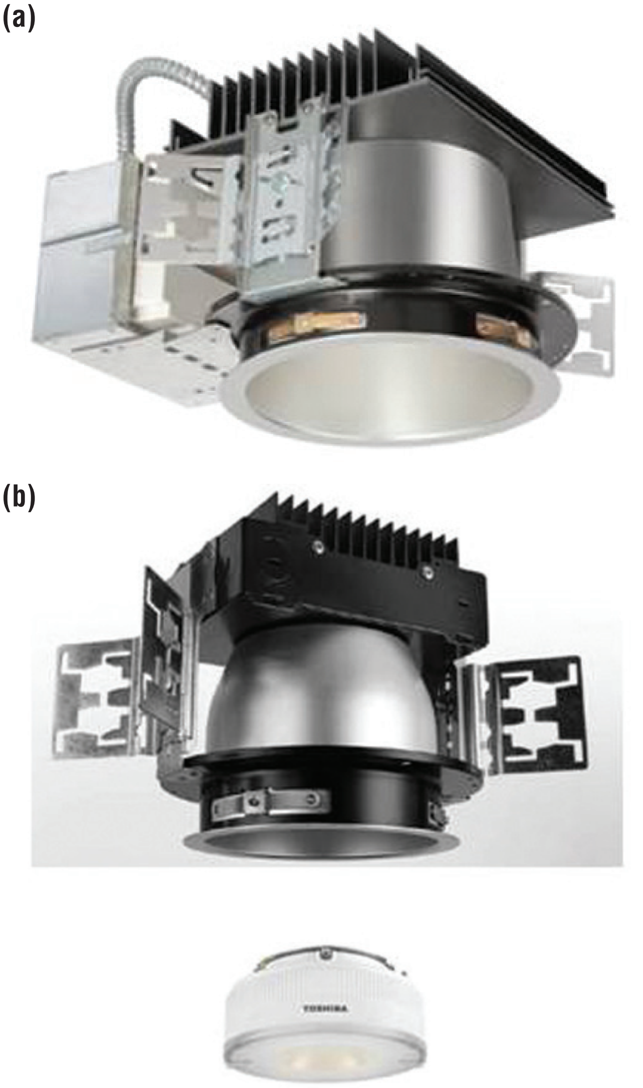

FIGURE 4.2 Two types of LED luminaire: (a) with integrated LED light source; (b) with replaceable LED module. Courtesy of Toshiba.

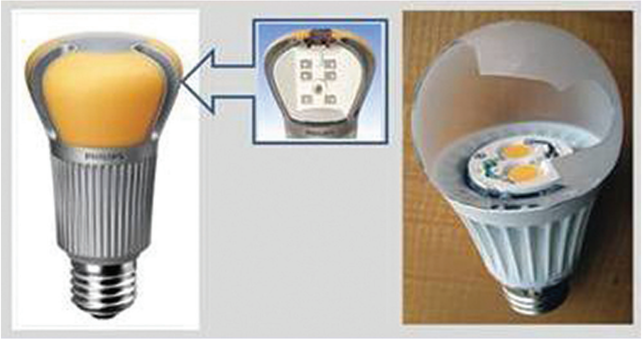

FIGURE 4.3 Sample LED replacement lamps for incandescent A-19 lamps. Courtesy of Philips Lighting.

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[1] Primarily the National Electrical Manufacturers Association (http://www.nema.org) and the Zhaga Consortium (www.zhagastandard.org).

[2] See the discussion of white phosphor LEDs in the subsection of Chapter 3, "Use of Phosphors."

FIGURE 4.4 Sample LED replacement lamp for incandescent parabolic aluminized reflector lamps. Courtesy of OSRAM SYLVANIA and Paul Kevin Picone/PIC Corp.

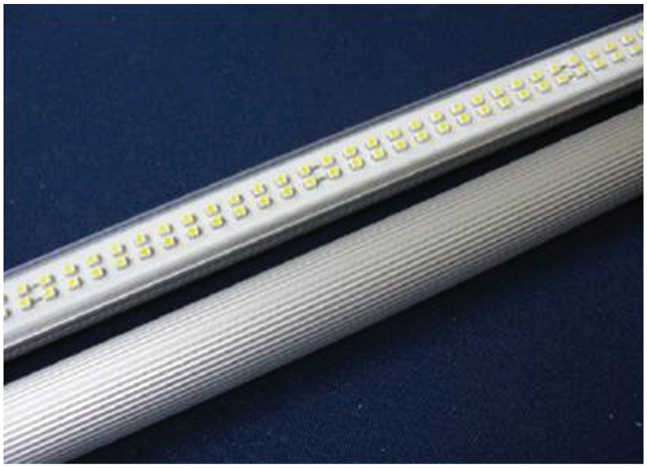

FIGURE 4.5 Sample LED replacement lamp for linear T8 fluorescent lamp. Courtesy of Pacific Northwest National Laboratory.

The luminous efficacy of LED replacement products has improved over the past several years and is expected to continue, as illustrated in Figure 3.1 of Chapter 3. Figure 4.6 illustrates examples of performance data for replacement LED-integral lamps (A-lamp, PAR lamp, and linear lamps), reported in 2011. The efficacy values of these replacement lamps are in the range of 40 to 110 lumens per watt (lm/W). Several LED replacement A-19 and PAR lamps are showing very promising results in terms of efficacy.

A few LED replacements for 4-foot linear fluorescent tubes have performance similar to traditional fluorescent lamps, but for many of them the total light output is substantially lower, and the spatial distribution of light is far more concentrated than that of the conventional fluorescent lamps. The narrow spatial distribution and relatively low luminous flux mean that closer spacing of luminaires would be required to achieve the same lighting environment as produced by conventional fluorescent lamps.

There are many challenges for making reliable replacement A-19 lamp replacements. An LED replacement lamp for an incandescent A-lamp requires squeezing all the needed components, LEDs, driver, heat sink, etc., into a light-bulb sized package as shown in Figure 4.3. Heat dissipation is very challenging and could affect the reliability of the LED lamp. At the present time, in early 2012, it is difficult to make long-life, reliable, LED replacements for incandescent A-19 lamps greater than 75 W because of thermal management challenges. There are some high-power PAR replacement lamps that use active cooling in which a fan is employed to move air and remove heat by convection. However, active cooling usually is not desirable in lighting products because of additional failure modes and audible noise issues. Realizing these limitations, an industry group, Zhaga Consortium,[3] is developing a standard for a better socket for replacement lamps with better heat dissipation characteristics, among other attributes. Even though the new socket may help lamps and luminaires in the future, it will not help replacement lamps for existing luminaires. Many of the LED A-19 replacement lamps currently in the market (early 2012) cannot be considered as true replacement for the following reasons:

- LED replacement lamps have a larger geometric shape than the incandescent lamp they are meant to replace and may not fit into a luminaire that was designed for incandescent A-19 lamp.
- The spatial beam distribution of the LED replacement lamps is not similar to that of the lamps they are designed to replace. For example, in a common table lamp, LED replacement lamps often will cast light in a more upward direction, leaving the tabletop surface below relatively dark.
- Although a wide variety of LED replacement lamp products are commercially available, their initial purchase price is much higher than that of competing lamp technologies. However, the “Lighting Facts” labels that appear on lamp packages provide consumers an estimate of annual operating costs, which allows rough calculation of payback times.

Retrofit Luminaires

Retrofit luminaires are SSL products that fit into the spaces occupied by existing luminaires but require complete removal of the existing luminaire for installation. Common types of retrofit luminaires are those for recessed housings, 2′ × 2′ or 2′ × 4′ recessed troffers, high-bay luminaires, track

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[3] “Zhaga is a consortium, a cooperation between companies from the international lighting industry. The cooperation is governed by a consortium agreement that defines rules regarding confidentiality, intellectual property, and decision making. Zhaga enables interchangeability of LED light sources made by different manufacturers. This simplifies LED applications for general lighting” (Zhaga Consortium, 2012).

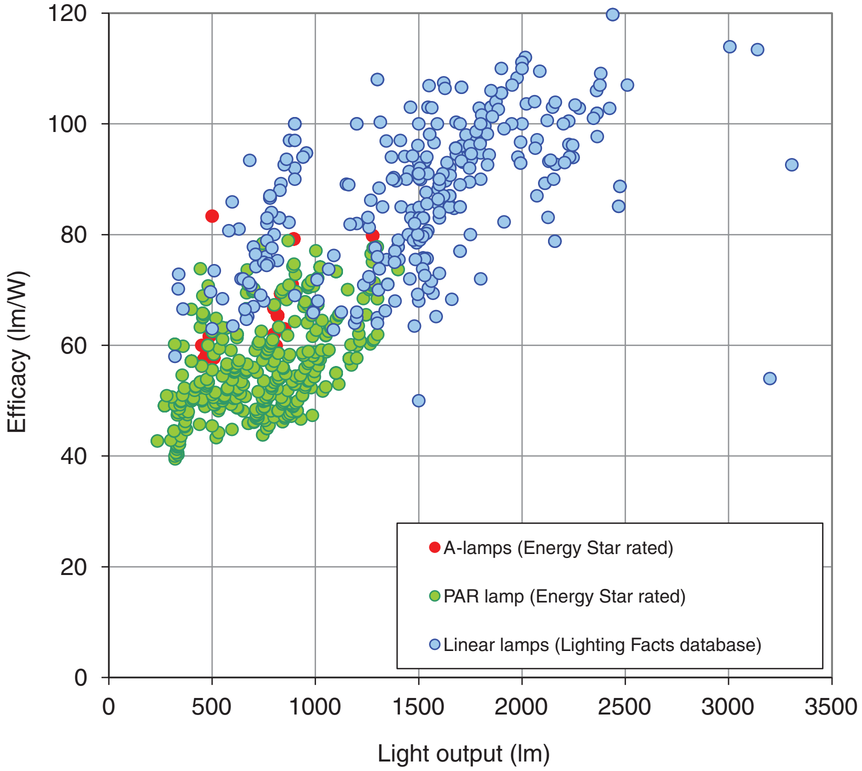

FIGURE 4.6 Performance data for LED replacement lamps. SOURCE: See http://www.energystar.gov, http://www.lightingfacts.com.

lighting products, pendant lights, and roadway luminaires. Although less constrained by "existing holes in the ceiling," other LED products that might be categorized as retrofit luminaires include under-cabinet lights, showcase lights, pathway lights, and rope lighting products. These products take on similar forms to existing non-SSL luminaires.

Of this category of products, the most attention has been paid to SSL roadway lighting luminaires. While most of these luminaires produce luminous flux comparable to incumbent technologies, a few are significantly dimmer (National Lighting Product Information Program, 2010; DOE, 2012). Some of the advantages of LEDs, such as long life, high performance in cold environments, and robustness, make SSL very attractive for many roadway applications. As with replacement lamp products, however, the spatial distribution of light is very different from many SSL roadway luminaires than from other types of light sources. This is frequently a disadvantage, because consumers expect a replacement product to behave identically to the preceding technology. Some outdoor luminaires have significant glare, which is not desirable.

One advantage is that the LED luminaire has the opportunity to direct light more toward the task, thus reducing wasted light and helping to control light pollution.

Another application where retrofit luminaires with LED have done well is recessed cans. Websites including those of the ENERGY STAR® program, U.S. Department of Energy's Lighting Facts, CALiPER, and Gateway programs are places where one can gather information regarding the performance of commercial LED lighting luminaires (Next Generation Luminaires, 2012; DOE, 2012). Figure 4.7 illustrates examples of 2011 performance data for downlight luminaires for commercial lighting applications. As seen, in 2011, the luminaire efficacies of ENERGY STAR®-rated LED downlights are in the range 35 to 85 lm/W. In comparison, CFL and halogen downlights are in the range of 10 to 30 lm/W.

Even though LED luminaires have greater luminous efficacy than traditional light source luminaires, LED luminaires can have greater lamp to lamp color variation, glare, and flicker and cannot be dimmed.

FINDING: While the majority of LED products in the marketplace have better luminous efficacy than traditional lighting technologies, for many of them, other quality factors, such as useful life, color appearance and rendering properties, beam distribution, flicker, and noise, may be inferior to traditional lighting products. Even though the optimistic view is that energy has been saved by using SSL technologies, if other factors such as system life, lamp-to-lamp color variation, glare, flicker, and dimming, do not meet user expectations, they could slow down market adoption of SSL technologies.

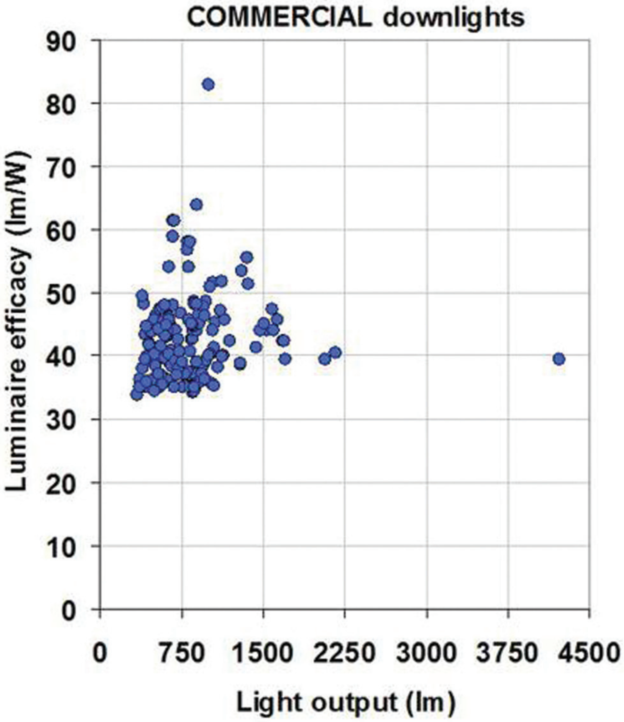

FIGURE 4.7 Sample performance in 2011 of commercial LED downlights. SOURCE: See http://www.energystar.gov.

As with most SSL lighting products, retrofit luminaires have higher initial costs than competing technologies. However, they are becoming more widely used in applications where maintenance costs are high.

Subcomponents of an SSL Product

SSL products in the commercial market employ a variety of LED white light sources, including an array of phosphor-converted LEDs (blue LED chips covered by a coating of phosphor); an array of cool white (i.e., high color temperature) LEDs combined with red LEDs to create a warmer white and feedback control to maintain light output and color; and an LED array with a mixture of multicolored (red, green, blue, etc.) LEDs. These LEDs or LED arrays are mounted on a heat sink to minimize the heat at the LED junction(s) and are powered by an electronic driver that produces power of the form required by the LED. In some cases, secondary optics are used to direct the beam in a specific manner. If the LEDs are packaged as an integral lamp to replace a traditional light source, the lamp envelope (i.e., glass bulb) is designed to mimic the form of the traditional source and includes a specific connector (e.g., an American National Standards Institute (ANSI) standard base).

This section analyzes these subcomponents, their state of the art, and what improvements are needed to produce products with the performance and price necessary for widespread adoption.

LED and LED Array

As described in Chapter 3, white LEDs are commonly made by dispersing phosphor(s) in the encapsulant surrounding the blue (or near-ultraviolet) LED chip. The process of combining phosphors with the LED chip has evolved over the years. Some packages still use the original method of mixing phosphor(s) into an epoxy or silicone medium. Other packages use a layer of phosphor conformally coated on the chip, while newer LED packages and products consist of phosphor layer(s) separated from the LED chip(s), commonly referred to as a remote-phosphor LED or product (Hoelen et al., 2008; Narendran et al., 2005). Remote phosphor-type LEDs minimize heat-induced efficiency loss in phosphors (provided the phosphor conversion efficiency is not very low as well as the absorption of phosphor-converted photons by the blue LED chip). An LED array is created by mounting and interconnecting individual LED devices on a printed circuit board, which is then connected thermally to the heat sink.

OLED Panel

A unique feature of OLED lighting is that the device itself can form the installable fixture because of its ability to be fabricated on any particular substrate or shape. Indeed, OLEDs can be fabricated directly on plastic blocks, flexible metal or plastic foils, or glass. In its configuration as an area lighting source, as discussed in Chapter 3, the luminaire itself operates without a significant increase in temperature above the room ambient. That is, in appropriately packaged devices, at a high surface luminance of 3,000 cd/m^2, the luminaire temperature rise can be only a few degrees centigrade, creating no local or distributed heat load on the room environment.

Secondary Optics

In an LED lighting product, secondary optics are needed to tailor the output beam of a lighting product. LED products commonly designed for illumination applications have LEDs arranged in several different ways together with secondary optics. These designs include an LED array placed inside reflector(s) and behind total internal reflection (TIR) lenses. These methods help the collection and distribution of light in a specific manner. Refractive optics, commonly referred to as lenses, reflective optics, or reflectors, are generally designed as non-imaging optics to be used in illumination products for beam shaping. Researchers have designed and used complex optics to achieve difficult beam shapes (Tsais and Hung, 2011).

Typically, no secondary optics are required for OLED panels.

Reliability of Optics

Lens materials are usually made from glass, polymers, epoxies, or silicones. Material selection is very important, especially when designing long-life products. Some optical materials degrade when exposed to radiation (more specifically, short wavelengths like ultraviolet (UV) and "blue" radiation) and heat. This spectrally dependent light output deterioration is one of the main ways that LEDs degrade.

Thermal Management

Thermal management is very important to enable reliable, long-life LED products, and the thermal management components in an LED product constitute a large fraction of product cost. A high-temperature LED junction can negatively impact LED life and optical performance, and as discussed in Chapter 3 in the section "An LED Primer," this places considerable demands on the plastic lens and encapsulant material. At higher p-n junction temperatures, the amount of photons emitted decreases and the spectral power distribution shifts to longer wavelengths. Furthermore, the degradation of the encapsulant and the LED chip, over time, decreases the luminous flux. Electrical energy not converted to light contributes to the heat at the p-n junction. To keep the LED junction temperature low, all heat transfer methods, including conduction, convection, and radiation, must be considered. Heat conducted to the environment from the p-n junction encounters several interfaces and layers. Therefore, to keep the junction temperature low, the thermal resistance of every layer and interface must be very low.

Thermal Management Component and Strategies

An LED chip is typically encapsulated in a transparent material, such as epoxy, polymer, or silicone. These materials have very low thermal conductivities. As a result, the majority of the heat produced at the p-n junction is conducted through the metal substrate below the chip and not through the transparent encapsulant. Usually, a high-power LED is mounted on a metal-core printed circuit board (MCPCB). When creating a product, an LED (or an array of LEDs) mounted on an MCPCB is attached to a metal heat sink using a TIM. Usually these heat sinks have extended surfaces, such as fins, which dissipate the heat to the environment by convection and radiation. Currently, a few manufacturers have started to mount the LED directly onto the heat sink to further reduce the thermal resistance from the junction to the environment and also to reduce the overall cost.

Common thermal interface materials are solder, epoxy, thermal grease, and pressure sensitive adhesive. Parameters that can influence thermal resistance include: surface flatness and quality of each component, the applied mounting pressure, the contact area, and the type of interface material and its thickness. Adding conducting particles and carbon nanotubes (CNTs) to TIM to reduce thermal resistance has been studied (Fabris et al., 2011).

Most manufacturers exploit both conduction and convection methods to reduce LED junction temperature. Usually the heat sinks have a very large metal surface area, and, as a result, the integral lamp or the entire luminaire is much heavier than its traditional counterpart. Figure 4.8 shows typical weights for incandescent, CFL, and LED lamps of different types.

To make the weight of LED products comparable to traditional lamps, lightweight materials, like polymers and composites, with very high thermal conductivity are needed. The thermal conductivity of plastic materials can be increased by using fillers such as ceramics, aluminum, graphite, and so on. Injection-molded polymer parts of high thermal conductivity are an economical approach for cool-

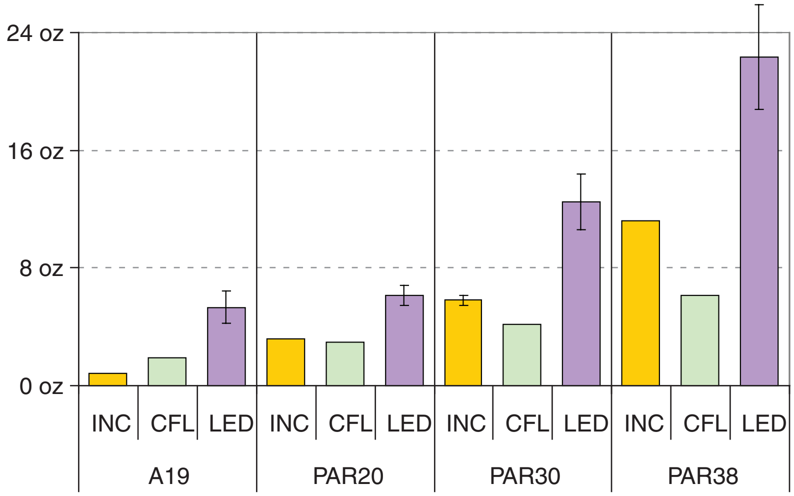

FIGURE 4.8 Weight comparisons among incandescent (INC), compact fluorescent (CFL), and LED lamps for A19, PAR20, PAR30, and PAR38 lamp types. SOURCE: Narendran (2012).

ing high power LED products. Some also have investigated techniques such as heat pipes, like those used in computers, to keep LED junctions cooler.

While these passive cooling methods work well for certain types of SSL products, higher power LED lighting products (1,500 lumens and above) pose significant thermal management challenges. Passive heat sinks are not sufficient to keep the LED junction sufficiently cool. Therefore, to achieve desired lumen values in a small form factor (e.g., A-lamp, PAR lamp, MR 16, etc.), active cooling may be required to dissipate the heat. Even though mechanical fans have been used in some high-power LED lighting products (Ecomaa Lighting Inc., undated; Peters, 2012), they are not desirable for many reasons, including short life, acoustic noise, attraction of dust, and increased energy use. Over the past several years, other active cooling techniques have been investigated for managing the heat in high-power electronics, including synthetic jet and piezoelectric fan technologies. Synthetic jet technology uses a moving diaphragm that produces air movement by suction and ejection of air. Rapidly fired pulses of air are directed to where cooling is needed, such as heat sink fins, to improve cooling efficiency. Piezoelectric fans have several advantages, including longer life, lower acoustic noise, and lower power demand (Zhang et al., 2011). These techniques have shown promise and are worthwhile for further development for high-power LED cooling (Acikalin et al., 2007). Even though active cooling may be necessary for some products in some applications, for the majority of the applications, passive cooling is more desirable.

There is a strong interaction among LED device efficacy, the requirement placed on the thermal management system, and the cost of SSL. Increased efficacy reduces the heat generated per lumen, allowing either a shrinking of the necessary heat sink, and thus a reduction in cost and weight, or an increase in lumen output for the same physical luminaire.

FINDING: LED efficacy strongly leverages cost, physical size, and weight of SSL luminaires.

RECOMMENDATION 4-1: The Department of Energy should place a high priority on research directed at increasing the efficacy of LEDs.

Thermal Management for OLEDs

One of the advantages of OLEDs is that the thermal management challenge is less stringent than for LEDs because their heat density is very low because of their large surface area. Indeed, it is found that at a surface luminance of 3,000 candlea per square meter (cd/m^2), OLED panels typically operate in room environments cooled only by natural convection, at 5-7°C above room temperature. However, many applications require high-intensity spot sources. In fact, very high luminances (>10,000 cd/m^2) have been demonstrated for OLEDs, but, unfortunately, their operational lifetime scales roughly inversely with current (and therefore, brightness). Also, it is known that for every 10°C increase in temperature the OLED lifetime decreases by approximately 30 percent (see Chapter 3). Hence, thermal degradation becomes a limitation at very high brightness. Up until now, this has prevented the application of OLEDs to high intensity or specular lighting applications. Further research, however, directed at developing molecular materials and device architectures that are more robust and, therefore, can more easily withstand these extreme operating conditions can result in a much expanded application domain for OLEDs. Continuous improvements in brightness and lifetime, however, are being made by researchers across the globe. If such high-brightness-spot OLED sources are successfully developed, the other useful features of this lighting technology may eventually dominate the SSL market.

FINDING: OLEDs are typically low-intensity, large-area lighting sources. However, numerous applications require more intense, specular lighting as afforded by LEDs. The lifetime of OLEDs are negatively impacted by high currents used to generate high brightness.

RECOMMENDATION 4-2: The Department of Energy should invest in research that can lead to small area but high-intensity lighting systems with organic light-emitting diode for use in directional illumination applications.

Electronic Drivers

The light output of an LED is proportional to its drive current, which is typically direct current (dc), and this current is supplied at a relatively low voltage. To provide the appropriate dc current and voltage, an electronic circuit known as a *driver* is inserted between the alternating current (ac) line voltage and the LED. This electronic driver can be incorporated within a lamp product, as for the A-lamp LED replacement, or as a separate device located external to the luminaire.

Integral Drivers in LED Replacement Lamps

The LED replacement lamp has an integral driver, illustrated in Figure 4.1, that enables the lamp to be connected directly to the line voltage socket. The medium screwbase lamp offers very little space for the built-in or integral driver, so thermal challenges for the electrical components can be significant. The drivers utilize electrolytic capacitors for energy storage on the dc side of their ac-to-dc converters, and they are likely going to be the weakest link in these products and limit the product lifetime. The maximum temperature ratings of these capacitors are typically in the 105°C to 125°C range, at which temperature their life ratings are 5,000 to 10,000 hours. Each 10°C reduction in operating temperature increases the capacitor life by roughly a factor of 2, giving the driver designer the challenge to maximize the driver life while also providing the required output power. This challenge is the hardest for drivers that are integral to screw-based lamps, because they cannot be moved far from the heat source.

For these reasons, the rated wattage of available LED lamps is still fairly small. The luminous efficacy of the LED devices has increased to a point where a lamp with a light output equal to a 60 W incandescent lamp consumes only 10 W. However, because of the thermal challenges, a 100 W equivalent lamp has not yet become available. As a result, screw-in LED lamps that are used as incandescent replacements in existing installations are at present limited to the lumen output of a 60 W incandescent lamp, although a 75 W equivalent has recently been made available.

Non-Integral Drivers

Commercial-grade LED luminaires are not constrained to use any particular form factors for the components. This is because luminaire replacement in commercial buildings is easier in dropped ceiling-type construction where there is ample room for luminaire housing and components, and replacement is, therefore, more readily performed. The drivers in these luminaires are typically separate from the LED module, and the luminaire may be designed so as not to present a thermal problem for the drivers. There is a trend in the industry to design “universal” drivers that produce either constant voltage or constant current output to the LED with input voltage ranging from 100 Vac to 277 Vac, which covers almost all global requirements. Having said that, today manufacturers of these drivers—quite often the same companies that also produce ballasts for fluorescent lamps—produce a wide array of products with differing specifications, while they are jockeying for market position. Standardization in the industry has started in some areas (see, for example, NEMA (2010a) and emerging standards by the Zhaga Consortium (2012)), especially for the interconnections between different components within the SSL luminaire (e.g., for standardizing electrical, mechanical, and thermal connections of the LED luminaire, including the LED module, the heatsink, the driver, and any lighting controls).

Most currently available drivers for interior lighting applications have relatively low output power, up to around 40 W. Some higher-output drivers, typically rated around 100 W, do exist for outdoor and industrial high-bay applications. It is likely that higher-output drivers will be needed in both interior and exterior applications in the future, when higher-light-output LED modules become available. The construction complexity of these products is similar to electronic ballasts for fluorescent lighting, and their assembly can be performed anywhere in the world. The potential number of different output configurations of LED drivers is much larger than for fluorescent lamps, mainly because fluorescent lamps are quite standardized, while LED designs are not. This may lead to fragmentation in the market in the short term, with manufacturers of the different component parts of an LED luminaire forming loose alliances to make certain that the products work together. It is also reasonable to expect a high level of obsolescence of driver designs, with older designs being replaced by those having different features during the time that the industry remains without standards. Indeed, the early designs from different manufacturers have been quite unique and not compatible with one another, so direct replacement of components within the LED luminaire, and sometimes even the replacement of the entire luminaire, can be challenging. Leading companies have recognized the need to rapidly develop standards, at least for the interconnections between the various components within the LED luminaire. As a result, the Zhaga Consortium was formed to develop these standards.

FINDING: Because of the large number of different ways to construct an LED lamp, industry has recognized the need for some levels of standardization and has organized to develop such standards.

The long expected life of an LED light engine will put pressure on the driver designer to produce designs that have equally long life ratings. Just as with integral drivers in incandescent replacement lamps, the weakest link in a non-integral LED driver is the electrolytic capacitor that is used for energy storage in the ac-to-dc converter that is part of the driver. Research into other types of energy storage devices, perhaps ceramic capacitors with high capacitance and small size, may become necessary, and funding for it should be considered. Another way to solve this problem may be to create a new building infrastructure, where the ac-to-dc conversion is performed centrally, nearer to the utility entrance to the building. This enables the building to use only a few larger power ac-to-dc converters that may not be as cost constrained as in the case when the conversion is performed in every luminaire. At least one industry group, the EMerge Alliance,[4] has been formed to investigate the possibility of a new electrical infrastructure and start the development of standards in this area. This application is currently limited to commercial buildings that use a dropped ceiling consisting of a ceiling grid and ceiling tiles, because it is envisioned that the elements of the ceiling grid are going to become the electrical conductors.

Drivers for OLEDs

The driver industry for OLEDs is at its infancy. It can reasonably be expected that the driver would look similar to, if not be the same as, a driver for LEDs, because the electrical requirement of both light engines are very similar. However, only a few experimental OLED luminaires have been produced so far, and experience driving them is limited. Both

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[4] Further information is available at http://www.emergealliance.org.

LEDs and OLEDs are current-driven devices and can work using either dc or ac supplies. Given that the line source is an ac voltage supply, the OLED driver must convert voltage to current. Luminance then, is controlled by the current in a nearly linear fashion. Hence, there is a roughly linear dependence of luminance on current. The current-versus-voltage (I-V) characteristic of an OLED follows a power law, $I \sim V^m$, where the dimensionless ratio $m = B/T$ has values between 3 and 7. Here, B is a constant, and T is the temperature. This is in contrast to that of an LED, where $I \sim \exp(-AV/T)$, where A is a constant. Hence, as an LED brightness increases, the voltage required to achieve a given brightness changes. However, given the relatively constant temperature characteristic of OLED operation, the voltage-to-luminance conversion required in the driver is simplified compared to that of an LED, which requires aggressive cooling to remove heat at the highest brightness. However, these products are far from being ready for any kind of standardization.

Nevertheless, the large capacitance of an area device, coupled with a somewhat different current-voltage relationship for OLEDs versus LEDs present as yet largely unexplored challenges in the development of versatile, efficient, and electronically robust control electronics for the former technology. Given the relatively early stage of development of OLED lighting, it is important that issues of lighting control be investigated earlier rather than later to understand what challenges must be met to produce low-cost control systems. In particular, the unusual form factor of OLEDs suggest that there might be opportunities for integrating such electronics in unusual ways with the luminaires that will provide advantages over conventional SSL and other lighting systems.

FINDING: OLEDs are still in their infancy. While the driver electronics may have many similarities to that of LEDs, there are some essential differences in their operating performance because of the large capacitive load presented by OLEDs.

LIGHTING CONTROLS

Lighting controls for electric lighting have existed almost as long as incandescent lamps themselves in the form of switches and rheostat dimmers that were used primarily in theatrical applications. The modern lighting control industry had its beginning in the early 1960s, when the first wallbox[5] solid-state dimmer for incandescent lamps was commercialized. Since that time, several lighting control devices have been developed by many companies, such as automatic time switches and sensors that are used for detecting the presence of people (“occupancy sensors”) or ambient levels of daylight (“photosensors”). These devices do not connect directly to the luminaire, so the development of SSL technology has practically no effect on the design of the former or compatibility with SSL luminaires.

In the case of incandescent or incandescent halogen lamps, the lighting control device that connects directly to the luminaire is either a switch or a dimmer. Switches are available in two forms, mechanical and electronic. A mechanical switch consists of metal switch leaves that open to form an “air gap” (a physical disconnect) to disrupt electric current to the luminaire and turn the lights off. The actions of opening and closing the switch leaves cause electric arcs to be formed that typically last no longer than a few milliseconds, but over time this arcing causes the switch contacts to erode, thus eventually causing the switch to fail. The introduction of electronic ballasts for fluorescent lighting in the 1980s was followed by some reports of switch failures, which were the result of increased “inrush current” during switch turn-on compared with traditional lighting loads. This led the industry to develop a switch-ballast compatibility standard (NEMA, 2011), which is in use today. SSL drivers that meet that standard are not expected to cause problems with mechanical switches.

Electronic switches also exist in the market. These are used especially in components that are part of a lighting product, in so-called smart switches or smart dimmers. Such devices use a semiconductor switch, typically a device called a TRIAC, which can be turned off without creating an airgap to the load. This technology is useful especially in wallbox switches that may be remotely turned on and off, for example, by using a sensor or handheld device. Typical electrical wiring practices do not bring a neutral wire to the wallbox, and, therefore, the microcontroller that controls the operation of the smart switch or dimmer has to be kept “alive” by allowing a small amount of current to pass through the lighting load when the lamps are in the off state. (Without such current, the microcontroller would shut off, and there would be no way to turn the switch or dimmer on.) For conventional lamps this “keep alive” current does not cause inconvenience to the end user because incandescent or fluorescent lights do not emit any light when the current is that small. However, more care has to be taken in the design of controls for SSL devices. Because of the low wattage of the lamps, even small currents can cause visible light output, often in the form of flickering when the lights are intended to be off. The small current charges the capacitors typical in the design of the drivers for these lamps, and the capacitors in some designs discharge periodically through the lamps, causing the flicker. Industry standards are being developed to address this issue, but there are SSL control products on the market today that cause this problem.

Dimmers for incandescent lighting are available with analog and digital designs. The analog designs are similar to mechanical switches in the sense that they employ a mechanical switch producing an airgap when the dimmer is off. However, digital dimmers are in this sense essentially the

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[5] The term *wallbox* refers to a wall-mounted electrical box that houses the wiring connections for electrical devices such as light switches, light dimmers, and receptacle outlets.

same as electronic switches, and flickering in the off state is observed with some SSL lamps.

Additionally, incandescent dimmers can also be categorized into two main types: "leading edge" (also called forward phase-cut) and "trailing edge" (also called reverse phase-cut). The former uses a TRIAC as the semiconductor switch, and the vast majority of incandescent dimmers in residential buildings are of this type because of the lower cost of the design. The TRIAC is turned on when it receives an electrical pulse at its "gate" (one of the terminals of the device) and stays on until the electric current falls below the TRIAC's "holding current" very near the end of the half cycle of the ac wave form, which in the United States operates at 60 Hz and ideally (and very closely in practice, too) has the form of a sine-wave. The earlier the TRIAC is turned on in the half cycle, the brighter the lamp operates. The resulting voltage waveform at the lamp is illustrated in Figure 4.9. The design of the dimmer converts the user action—such as moving a slider up and down—to the proper timing of this TRIAC gate pulse. The operation of the TRIAC is illustrated in Figure 4.9. Electronic switches that employ a TRIAC simply turn it on at the beginning of the half cycle to operate the lamp at full on.

The TRIAC works very well with incandescent lighting because the TRIAC's holding current (below which the TRIAC will not remain on) is much smaller than the current in even the lowest wattage incandescent lamps, such as a 25 W lamp. However, with CFLs, and even more so with SSL devices that require very low power, the current required to operate the lamps may be smaller than the holding current, and this can lead to observations of flickering or other improper operation. In addition, other problems have been observed with keeping the TRIAC reliably in conduction with certain LED lamps. In some cases, the problems manifest themselves when the total load (number of lamps) is actually *increased*, meaning that the minimum load requirement in an incandescent dimmer is not the only condition that needs to be satisfied. Leading edge dimmers that are used in commercial grade lighting controls sometimes provide a continuous gate signal rather than a pulse, and this action is very successful in keeping the TRIAC on even with smaller loads. Additionally, trailing edge dimmers, which use transistor switches that require a continuous signal to keep them on and are not characterized by a holding current, may also avoid this problem. Trailing edge dimmers were originally designed for low-voltage (incandescent) lighting using an electronic transformer to step the 120 Volts ac (Vac) line voltage to the 12 Vac required by the lamps. These transformers were developed to make them lighter, smaller, and also often less expensive than core and coil wound transformers, and they utilize capacitors on the "front end" for energy storage inside the device. When a capacitor suddenly experiences a high voltage, a large inrush of current occurs, and many such electronic transformers are not compatible with leading-edge dimmer designs. Trailing edge designs reverse the process of switching by turning the transistors on in the beginning of the half cycle and turning them off at some point before the end of the half cycle. Front end capacitors do not cause problems for this mode of operation, so these types of dimmers are more compatible with SSL drivers such as those used in medium screw-base incandescent replacement lamps.

The lighting controls industry is developing new dimmer designs specifically for LED lamps that are used as replacements for incandescent lamps. It is reasonable to expect that the lamps will operate well with the new designs, but the industry has estimated that there are more than 150 million leading-edge dimmers installed in U.S. homes, and it is probably impractical to expect to replace them all as LED lamps become more popular. NEMA (2010b) has developed a new standard, NEMA SSL 6-2011, to address the retrofit issue,

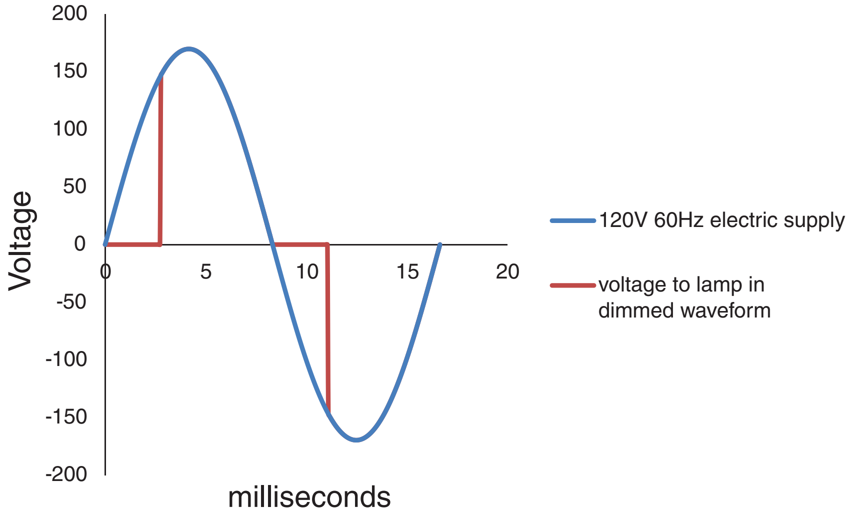

FIGURE 4.9 Waveforms illustrating leading-edge dimming control.

and lamps that are designed to comply with this voluntary standard should operate with the existing dimmers and avoid such problems as flickering. Such controls, however, may not provide the same low-end dimming range that consumers are used to with incandescent lamps. In addition, the U.S. Environmental Protection Agency has asked the industry to develop a testing standard for ENERGY STAR® lamps regarding compatibility with controls.[6] Together, these initiatives should mitigate most of the compatibility problems, or at least provide consumers reasonable options. Finally, NEMA and the Zhaga Consortium have started another standard development (NEMA SSL 7-2012) to address the need for future LED lamps and future dimmer designs to provide significantly better dimming performance. These standards will place new requirements on both the lamp and the dimmer design.

In addition to controlling light levels through dimmers as described above, there are other industry standard "protocols" to provide dimming signals to luminaires. These include 0 to 10 volts DC signals where higher voltages correspond to higher light levels, digital standards such as Digital Addressable Lighting Interface (DALI),[7] wireless standards such as Zigbee, and various proprietary standards by individual manufacturers. In each of these cases, the luminaire contains a separate fluorescent or high-intensity discharge (HID) ballast or a separate driver for SSL products that has been designed to be compatible with whichever method of signaling is used. This means that the method of signaling the dimming information is decoupled from the actual dimming function performed by the ballast or driver, and there is no need for new compatibility standards.

With the phase-out of incandescent lamps taking place in Europe, there has been a proposal to develop a new standard for communicating dimming information on the power line (the so-called "power line carrier" method) to CFL and LED lamps that would replace incandescent lamps. This is thought to be necessary by some industry representatives because phase-cut dimming is interpreted to be permissible by European standards only when used with incandescent lamps (International Electrotechnical Commission, 2009). The new standard is now under development, and some people in the industry expect it to be published in late 2012 or early 2013. This would also mitigate any concerns about total harmonic distortion (THD) and power factor (PF) that have been expressed by power utilities. For more detail, see the discussion below, "Electric Power Quality."

FINDING: LED replacements for incandescent lamps may not work with all existing control infrastructure, especially dimmers.

RECOMMENDATION 4-3: Industry should develop standards for LED drivers and future generations of lighting controls that will ensure that all LEDs that are designated "dimmable" work well with all new dimmers in the future. In the meantime, SSL products should indicate on their labels that they may not function correctly with presently installed controls.

LED lamps offer an additional control opportunity, that of controlling the color of the light output. There have been some proprietary products in the market that offer this control function,[8] but no industry standards are yet under development. It is not yet clear how much value the market gives to such color control, so the development of these standards may not happen in the immediate future, if at all. The functionality will probably begin with luminaires that have a separate driver using digital communication (such as an enhanced DALI that includes additional control functions or wireless protocol). Whether screw-in incandescent lamp replacements ever develop this functionality remains to be seen.

An important difference between incandescent lamps and both CFLs and LEDs under dimming conditions is that incandescent (and halogen) lamps become warmer, exhibiting a color shift (in terms of color temperature, measured in Kelvin) toward the red, when dimmed. The other light sources do not inherently change their color temperature, which is often viewed as an undesirable feature by residential consumers. Humans are biologically biased to prefer red light in lower ambient conditions because of the same shift in sunlight toward the late evening hours. With proper controls and devices emitting the appropriate colors, LED lamps and luminaires can mimic the color shift performance of incandescent lights when dimmed in this manner. It should be noted that there is at least some patent protection[9] for this functionality, possibly leading to limited choices for consumers.

STANDARDS AND REGULATIONS

LED Product Measurement and Performance

Standards play an important role in the development and deployment of new technologies as discussed in the Chapter 5 section, "Testing and Measurement Standards." During the past several years, several standards have been created, most notably IES LM-79, "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products" (IES, 2008a) and IES LM-80, "Approved Method: Measuring Lumen Maintenance of LED Light Sources" (IES, 2008b), the latter used in conjunction with IESNA TM-21 to extrapolate estimates of lumen maintenance. More

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[6] Alex Baker, personal communication with Nadarajah Narendran, Committee on Assessment of Solid State Lighting, August 2012.

[7] See IEC 62909.

[8] See for example controls offered by Philips (Color Kinetics).

[9] See for example U.S. Patents 7,038,399; 7,014,336; and 6,636,003.

standards are needed to resolve unknowns that will otherwise be left to consumers and other lighting decision-makers.

Difficulties can arise with standards when the test conditions do not match those of the installed application. As an example, downlight luminaires are typically measured according to the IES LM-79 standard that requires the surrounding ambient temperature to be at 25°C. In practice, the ambient temperature generally will be higher when the light source is recessed in a luminaire. In addition, the temperature is dependent on where the luminaire is located and will be higher on upper floors where the fixture is surrounded by insulation material. This potential for higher ambient temperatures was less of an issue in the past when downlights used incandescent and halogen technologies whose performance was less sensitive to changes in temperature. But in the case of LEDs, increases in junction temperature can alter the performance. Past studies have shown that in some cases the light output reduction from the product is significant, more than 30 percent (Narendran et al., 2008), versus the LM-79 data sheet. Practitioners expecting a certain performance may be disappointed if they strictly rely on the product's LM-79 data. While the use of testing standards has worked for incumbent lighting technologies, LM-79 may not work for SSL products because of the latter's sensitivity to heat. Test procedures specific to the application environment are an ideal solution but much more costly than a single procedure for all applications. A compromise solution would be for manufacturers to publish data with de-rating factors for use in typical applications.

Another important aspect of standards is their quality; that is, their ability to produce reliable and realistic information about performance. Today manufacturers commonly use the IES LM-80 procedure to test the lumen depreciation of individual LEDs, but then use those data to rate the entire product life. (Labeling programs also use LM-80 test data.) In reality, a product has many more components than just the LED. Electronic drivers with electrolytic capacitors are known to have a short life, especially at high temperatures. Products claiming a life of 25,000 to 50,000 hours may not live up to such claims as a result. LM-80 test results are more appropriate for LED package manufacturers to provide to product manufacturers, not to product end users. Even though white papers have started to point out this issue (Next Generation Lighting Industry Alliance, 2011) and research is under way to develop test procedures to predict whole product life more accurately (Davis, 2012; Lighting Research Center, 2012), early adopters of LED lighting may be disappointed when products do not live up to the claims on their labels, based as they are on LM-80 results. Some SSL product manufacturers have started offering warranties for their products. This too is challenging because the terms and conditions for product replacement or cash reimbursement can be difficult to define and settle.

Other examples of industry challenges with standards include the current color standards (e.g., ANSI C78.377) that were borrowed from the CFL industry. Manufacturers grouping LEDs to single bin for a given correlated color temperature (CCT) product according to American National Standards Institute (ANSI) C78 tolerance area may find the color variation between LEDs very large, to a point that it is not acceptable for general lighting applications. Presently, some manufacturers are using tighter bins to avoid visible color difference between products.

FINDING: Additional standards or revisions to standards are needed to resolve unknowns that will otherwise be left to consumers and other lighting decision-makers to resolve, specifically test procedures and/or de-rating factors that account for higher temperature environments, where performance may vary from LM-79 data, and alternatives to LM-80 that can predict whole product life more accurately. In the case of the latter, research is under way to develop test procedures to predict whole product life more accurately.

RECOMMENDATION 4-4: (a) Manufacturers should publish data for photometric quantities and life per industry standards and de-rating factors for use in typical applications. (b) IESNA should develop a test procedure to predict whole product life more accurately. (c) ANSI should revise the color binning standard to ensure imperceptible color differences between two adjacent light sources.

Electric Power Quality

In the United States, power quality is a subject of voluntary industry standards, except for electromagnetic compatibility of some lighting equipment, which is regulated by the Federal Communications Commission (FCC) at frequencies corresponding to radio and television transmissions.

The Institute of Electrical and Electronics Engineers (IEEE) sets voluntary standards for distortion of the voltage waveform in the utility supply to buildings (IEEE 519) in order to ensure that electrical and electronic equipment in the building has a reasonably clean supply of power (correct frequency, voltage, and lack of distortion). Distortion of the sinusoidal voltage waveform is of most concern and is expressed in terms of a parameter known as "total harmonic distortion" (THD),[10] which is typically limited to about 5 percent. On the other hand, industry voluntary standards set limits to the distortion in the current waveform drawn by the equipment connected to the electric supply. The distortion is

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[10] Total harmonic distortion (THD) of the supply voltage is equal to the square root of the sum of the squares of the amplitudes of the voltage harmonic frequencies above 60 Hz divided by the amplitude of the fundamental 60 Hz voltage. A high THD (>33 percent) causes problems in three-phase power systems, because usually the dominant harmonic current is the third harmonic. The third harmonic currents add in the neutral wire of the electrical system, and in cases of high THD one can have a situation where the current flowing in the neutral wire exceeds the rating of the wire, causing overheating.

expressed as THD limits for the current, calculated in the same way as for the supply voltage; for commercial and industrial lighting equipment, the THD limit is set at approximately 30 percent by ANSI standards. For fluorescent and HID lamp ballasts these limits are defined in ANSI C82.77-2002. The displacement of the current waveform is expressed in terms of PF, which is usually defined as the ratio of the real electric power flowing in the product to the apparent power.[11] ANSI standards and other voluntary standards also define PF limits for lighting equipment, typically 0.9 for commercial and industrial equipment. These limits have been in place for several decades and, because of a lack of reported problems, seem to be appropriately set. There are currently no THD or PF standards for SSL products, so it would seem appropriate that similar limits be set for SSL drivers for commercial and industrial applications as for fluorescent ballasts. It should be noted, however, that, for residential lamps with integral ballasts and medium screw bases, ANSI C82.77-2002 specifies very loose standards—PF is required to be greater than 0.5 and THD less than 200 percent. Note, however, that the PF for an incandescent lamp is 1 (i.e., “perfect”) and its THD is 0. Therefore, the impact of the residential standard has been minimal as the penetration of screw-base CFLs is limited. As LED lamps become more ubiquitous as replacements for discontinued incandescent lamps, the effects of the liberal PF and THD limits may not be so benign. The ANSI standard for residential screw-base lamps should match that of commercial and industrial applications, as for fluorescent ballasts.

Modern lighting equipment, such as electronic ballasts for fluorescent lighting or drivers for SSL devices, also generate some electrical energy in the radio frequency bands. These types of equipment are termed unintentional radiators by the FCC, and the FCC sets limits for the conducted (i.e., along the electrical wires) and radiated (i.e., into the air) emissions of such equipment.[12] Separate limits are set for residential and non-residential applications, with the residential limits being significantly stricter than non-residential ones, presumably to protect the consumer’s ability to receive AM radio broadcasts in the home.

In the European Union, the Low Voltage Directive (2006/95/EC) of the European Parliament sets limits for PF, THD, and radio frequency emissions for lighting equipment and does so by reference to standards published by the International Electrotechnical Commission (IEC) and the Comité International Spécial des Perturbations Radioélectriques (CISPR; in English, Special International Committee on Radio Interference). All of these limits are mandatory in member countries, and the PF and THD limits tend to be stricter in Europe (THD limits for current are in the range of 30 percent) than they are in the United States and apply to a broader class of lighting products, such as lighting controls. On the other hand, CISPR does not distinguish between residential and non-residential emission limits, and the European requirement falls between the FCC’s residential and non-residential limits. Other countries typically follow either the European model or the U.S. model.

Historically, there has been a tug of war between the electric utilities and the lighting industry about the importance of stricter limits on power quality metrics, in particular on THD and PF, because of concerns about incompatibility between an increasing number of electronic loads in buildings. However, the reported number of incidents claiming poor performance because of power quality problems has remained low, while the number of installed electronic ballasts has increased. Electronic ballasts, introduced to the market in the 1980s, now account for more than 80 percent of sales of all linear fluorescent lamp ballasts in the United States. The current limits, therefore, appear to be appropriate.

FINDING: There are existing standards for THD and PF for electronic ballasts for linear fluorescent lamps, but at present there are no such residential standards for LED drivers that are external to the lamp. Standards for low-wattage, integrally ballasted CFLs with medium screw bases in residential applications allow low PF and high THD.

RECOMMENDATION 4-5: For external solid-state lighting drivers in general, industry should adopt the same total harmonic distortion and power factor standards that are in place for electronic ballasts for linear fluorescent lamps. Industry should revisit the standards for low-wattage medium screw-base lamps to determine their impact on power quality before applying them for light-emitting diode lamps, and these standards should match those for commercial and industrial applications.

SSL PRODUCT COSTS

A recent limited survey of consumer prices for a variety of lamp types (A19, MR16, PAR20, and PAR38) at a Home Depot store in New Jersey indicates that the initial cost of LED lamps ranges from 3.5 times to 15 times (PAR38) that of halogen lamps (PAR20). However, when the total cost of ownership is calculated using an electricity rate of

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[11] The *power factor* (PF) of the equipment is equal to the electric power dissipated in the equipment expressed in watts divided by the product of the amplitude of the supply voltage and the amplitude of the electric current drawn by the equipment expressed in volt-amperes. In the past when most ballasts used in lighting were magnetic coils, the main effect to reduce PF came from the phase angle difference between the supply voltage and the current drawn by the equipment, which is why PF can be thought of as the displacement of the current relative to the voltage. With modern electronic ballasts this effect is smaller, and increasing THD also decreases PF. For example, in the absence of any displacement PF, a THD of about 44 percent corresponds to a PF of 0.9.

PF is of particular interest to the electric utilities because they bill their customers based on delivered real power. However, the transmission line capacity is expressed in terms of amperes of current, so a low PF product will limit the utility’s ability to generate revenue.

[12] 47 CFR Part 15 and 47 CFR Part 18.

TABLE 4.1 Consumer Prices for a Variety of Lamps—Incumbent and Likely LED Replacement

	Halogen Incandescent					LED					Summary		
Lamp Type	Power (W)	Price (incl. 7 percent sales tax)	Life (h)	Cost to Own[a]	10,000 hr Cost[b]	Power (W)	Price (incl. 7 percent sales tax)	Life (h)	Cost to Own[a]	10,000 hr Cost[b]	Savings Over 10,000 hrs	Savings (%)	Initial Cost Ratio
A19	43	$1.75	1,000	$6.48	$64.85	12	$16.02	10,000	$29.22	$29.22	$35.63	55	9.1
MR16	50	$6.66	2,000	$17.66	$88.28	10	$26.72	10,000	$37.72	$37.72	$50.56	57	4.0
PAR20	50	$6.76	3,000	$23.26	$77.54	8	$23.51	10,000	$32.31	$32.31	$45.23	58	3.5
PAR38	90	$3.83	2,000	$23.63	$118.15	18	$56.68	10,000	$76.48	$76.48	$41.68	35	14.8
T3	150	$4.42	2,000	$37.42	$187.10	not available					not applicable		

[a] Energy rate $0.11/kWh.

[b] Not including labor to install lamp(s).

$0.11/kWh, LED lamps save between 35 and 58 percent over 10,000 hours of operation, which corresponds to about 10 years in typical residential use. Table 4.1 summarizes the results of this survey. The LEDs that were chosen for this comparison are the closest available in light output to the halogen lamps that they would replace. The "cost to own" is the price of the lamp plus the energy cost over the lifetime of the lamp. This calculation is limited to 10,000 hours, even though most of the life ratings shown on the LED packaging are actually longer than that. The initial price ratio in the final column is just the ratio of the prices of one LED to one halogen lamp (measuring "sticker shock") even though more than one halogen lamp needs to be purchased to reach 10,000 hours of use. Finally, it is also worth noting that LED alternatives are not available for all lamp types at this time, such as the T3 tubular lamp that is used for example in some bathroom vanity lights and floor lamps. A calculation of life-cycle costs of LEDs and various fluorescent lamps, taking account of discount factors and expected improvements in LED performance, is included in Chapter 6.

FUTURE OPPORTUNITIES

Purchasing a product while the technology is still evolving is always challenging, especially when the life of the product is very long. Having said that, people are now accustomed to upgrading computers and cell phones in 2 to 5 years because they see value in the new product's functions. The same cannot be said for lighting. Until now, people have typically changed a light bulb only when the previous one has failed. Unless the payback period is very short, many would find it difficult to justify investing in LED lighting products as replacements for traditional light bulbs, as promoted by the SSL industry. As a result consumers take a "wait and see" approach, even though the currently available LED products could save them significant amounts of energy.

Nevertheless, SSL offers new methods to light our spaces. SSL technologies can be embedded into many types of architectural elements due to their small size and long life to meet the needs of desired tasks or ambiance for the occupant. Responding to this opportunity, researchers and industry groups have been attracted to the concept of creating mini direct current (dc) grids within buildings for lighting and some appliances (as well as power production from photovoltaic systems) while maintaining an alternating current (ac) power grid to transmit power from the generation site to end-user sites without much loss (EMerge Alliance, 2012; Narendran, 2012; Thomas et al., 2012).

A dc-powered SSL infrastructure that allows for rapid reconfigurations of lighting systems using LED-lighted panels that snap in and out of a modular electrical grid, makes it as easy to redesign lighting as to move furniture, providing value to the end users. Such concepts not only allow for greater energy savings, but also can improve lighting in our built environments.

FINDING: The power requirements and flexible physical configurations of SSL make attractive the concept of a new dc building lighting infrastructure.

RECOMMENDATION 4-6: The SSL industry should collaborate with other industries such as building materials and construction to explore the challenges and potential benefits of developing and adopting standards for a new dc electrical infrastructure.

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5

Solid-State Lighting Applications

INTRODUCTION

Solid-state lighting (SSL) is a new technology, not simply a refinement of an existing one. New materials and technologies are not only offering substantial improvements in efficiency compared with conventional incandescent lighting, but also opportunities to put light in new and sometimes startling places and modes that are only beginning to emerge in a rapidly changing field. But it also presents significant challenges to end users, designers, the lighting industry, and regulating authorities as they try to cope with the implications of this change in a very basic service.

Incorporating SSL products in a home or office is not always simply a matter of unscrewing one lamp and screwing in another, because they are significantly different in form and function, as described in Chapter 4. At the current stage of development, these new light sources (currently comprising light-emitting diodes (LEDs) and organic LEDs (OLEDs)) have been highly successful for some applications, show promise in many more, and have serious problems that need addressing before they can be used in yet other applications.

SSL is becoming more popular with end users and designers. The general public's perception is that LEDs are more energy efficient and "advanced." Users' expectations are that the SSL quality will be as good as standard lighting products. They also expect that SSL can be applied to existing electrical distribution systems with no problems, which is not always the case.

Advantages of SSL include the following: small size, ease of control, uni-directional distribution, cool beam and color rendering that can be very high and comparable to high fluorescent lamps with high color rendering index (CRI), lower energy use compared to incandescent lamps, high performance in cold environments, long life, and new form factors. Current challenges with SSLs include cost, system and controls compatibility, heat management, power quality, the failure process, color consistency, and glare issues.

Whereas SSL lamps have relatively low lumen output (approximately equivalent to a 60 W incandescent) and the majority produce a unidirectional beam, the best applications currently are those in which the light source is close to the task, lower lumen output is sufficient, and directionality is important. Examples of these best applications are task, undercabinet, track, wall washing, surface grazing, step lights, semi-recess, lower light output street and area lighting, and color changing theatrical lighting.

Challenging applications include omni-directional lighting (e.g., such as those applications for the linear fluorescent lamps) and high output. Examples of these are fluorescent lamp replacements and high output downlights. Street and area lighting is improving dramatically, but high light output and glare are still an issue with poorer quality luminaires.

At this stage of development, the challenges outweigh the advantages for many applications. Of course, what is a challenge in one application can be an advantage in another. However, product development is very active, and the trends are toward decreased cost, better glare control, and better color rendering and color consistency. Standards, guidelines, and better designer/user education are needed to help make SSL ready for successful applications in large-scale markets. The outdoor and residential markets currently offer the greatest opportunities for large-scale deployment because commercial and industrial applications already have low cost and relatively efficient fluorescent and high-intensity discharge (HID) lamps.

This chapter outlines the types of applications where SSLs have been incorporated and evaluates their current status.

OVERVIEW OF APPLICATION TYPES

Residential

Residential lighting typically consists of recessed downlights, wall sconces, pendants or chandeliers, track lighting, table and floor lamps, and undercabinet and task lighting. Lighting levels are lower than in commercial or industrial applications. Color, brightness, dimming capability, and appearance are extremely important.

Residential users expect SSL to look and act just like their incandescent counterparts. Such attributes as smooth dimming with existing residential dimmers, absence of flicker, absence of radio interference, great color rendition, and equal light output and similar brightness to incumbent lighting technologies will all be imperative for the successful SSL introduction into the residential market. Users also expect to be able to use the new lamps without having to replace existing luminaires (i.e., fixtures using screw-in lamps).

SSL is easily controlled in principle. Dimming is readily available, but flicker, so called "pop-on" effects and lower end drop-out are still apparent in some products. Pop on occurs in two ways: (1) when a preset dimming control is used and lights do not turn on to their pre-set dimming level, but first come on (near) full and then dim down automatically to the preset level and (2) when a slide (or rotary) dimmer is used, lights do not turn on at the low end, but require the slider to be raised to a relatively high level to start the lamp, before dimming to a lower level can be achieved. Lower end drop-out occurs when lights are dimmed but turn off before reaching the desired low level. All of these are symptoms of incompatibility between the LED lamp driver electronics and incandescent dimmers and can be mitigated when the drivers are designed for better compatibility using an industry standard such those of the National Electrical Manufacturers Association (NEMA) on SSL 6 (see Chapter 4). Alternatively, the dimmer can be replaced with a new-generation device that is being designed to operate LED lamps. Existing incandescent dimmers may not work with LED replacement lamps (even though the LED lamps are labeled "dimmable"). In some cases, the dimmers may have to be replaced.

FINDING: Replacing incandescent or fluorescent lamps with LED lamps provides an opportunity to greatly reduce power load and increase lamp life. They can also turn on instantly and are able to dim. The market for these lamps will only expand as the light and color quality improve and the costs are reduced.

If SSL meets the above performance criteria, then long life and low energy use will attract users. If SSL does not meet the criteria, then disappointment and frustration will damage the market, as happened with compact fluorescent lamps (CFLs) (see Chapter 2). Appropriate policies, regulations, and educational campaigns can help avoid this result.

Commercial

Ambient lighting in commercial sites has been traditionally supplied with linear fluorescents in either recessed troffers, recess parabolics, semi-recess indirect, or pendant mounted with direct/indirect distribution.[1] All of these provide uniform omni-directional light distribution, creating uniform ambient lighting.

Accent lighting adds visual interest to an area and is frequently implemented with track lighting supplied with tungsten halogen or ceramic metal halide lamps. Ceramic metal halide track lighting is used in many grocery stores because of the higher light output.

Task lighting offers higher lighting levels for specific areas and has been traditionally supplied with tungsten halogen or CFLs. Task lighting is used primarily in office areas in the form of under-shelf or free-standing desktop luminaires.

In most commercial applications, the lighting system is expected to last for many years, requiring very little maintenance with easy accessibility. Occupants expect controls to perform daylight dimming, occupancy/vacancy sensing, scene controls, and manual dimming.

SSL is becoming more common in commercial applications, especially for use with surface grazing (wall washing, white board lighting, and cove lighting). SSL is ideal for task or personalized lighting and for accent or track lighting. The more difficult applications are general omni-directional ambient lighting now supplied by fluorescent luminaires. The one exception is lower light output, semi-recessed indirect luminaires, which are becoming popular for ambient lighting.

FINDING: The best LED applications take advantage of the directional light put out by LEDs, such as downlights, wall washers, and grazing and accent lighting.

FINDING: Omni-directional LED lamps are not as efficient as linear fluorescent lamps. In order to become a viable replacement alternative for linear fluorescent lamps, SSL products need to improve efficacy, become more omni-directional, and reduce initial cost in order to compete with fluorescent lamps.

Total harmonic distortion (THD) of the line current and the power factor (PF) of the LED lamps are serious concerns. Most existing commercial buildings have 120/208 or 277/480 volt three-phase electrical distribution systems, where three phases share a neutral. If the THD is too high, the neutral conductor may be overloaded, especially in existing buildings with older electrical distribution systems. In new construction, the most recent National Electrical Code recommends separate neutrals for each circuit to avoid this problem. This issue is discussed in more detail in Chapter 4,

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[1] A *troffer* is "a long, recessed luminaire installed with the opening flush with the ceiling." A *pendant* is "a luminaire that is hung from the ceiling by supports." A *parabolic* is "a luminaire with the light source at or near the focus of a parabolic reflector producing near-parallel rays of light." Both troffers and parabolics are installed as recessed luminaires. Indirect lighting involves "luminaires that distribute 90 to 100 percent of the emitted light upward" (ANSI/IES, 2010).

where recommendations are made for SSL devices. It should also be noted that when replacement dimmable LED lamps are installed in existing luminaires, many of the existing incandescent dimmers may cause lamp flickering (this issue is also discussed in detail in Chapter 4). Pop-on dimming effects are very similar to those in residential applications and have been discussed above.

FINDING: SSL must have power quality standards to mitigate against high THD, low PF, and repetitive peak current issues.

FINDING: New dimmers must be able to operate LED luminaires and lamps smoothly without perceptible flicker and should be available to dim from 100 percent power to 1 percent power.

Industrial

Industrial applications typically use a combination of high bay luminaires (directional downlights) or low bay luminaires (omni-directional downlights). Task lighting is also used for specific applications where higher light levels are required, such as in manufacturing facilities. Long-lasting light sources are required for reliability and safety, especially in 24-hour facilities. Controls have typically not been expected in industrial sites but are becoming more popular, especially in applications where daylight can supplement the light level, allowing energy reduction by dimming the interior lights.

Traditionally, high ceilings and harder access has lead many industrial sites to higher-wattage, standard HID luminaires. Standard HID luminaires provide higher light output than fluorescents, but do not last as long (having roughly two-thirds the life). Also, HID lamps have a slow start, requiring several minutes to achieve full light output, making them harder to control with occupancy sensing or daylight on/off switching.

SSL applications are more difficult for industrial applications because of high light level requirements. Also, heat management is difficult in high ceilings where ambient temperatures are higher. In some settings, the failure process may be an issue, because SSLs gradually lose luminous flux rather than burn out. If these issues can be solved, then SSL could provide lower maintenance costs and controllability.

Power quality issues are similar to the commercial applications.

FINDING: Industrial applications of SSL products will require higher light output for ambient lighting because of their use in high ceiling applications.

Outdoor Lighting

Roadway and area lighting appear to be one of the fastest growing application markets for SSL. The requirements in such applications for lower light levels (compared to interior applications); larger luminaires with non-confined mounting, mostly open to air, which enhances heat dissipation; performance at cold temperatures; and long life have made SSLs attractive to this rapidly growing market. Traditional outdoor luminaires have used HID lamps, mostly high-pressure sodium (HPS), where the lamp is located inside the luminaire reflector. This configuration has the advantage that the arc tube brightness is typically not viewed by motorists or pedestrians. HPS luminaires have a narrow spectral distribution, which provides poorer color rendering properties than white light sources such as metal halide, induction, and SSL. HID life is mid-range, requiring lamp replacement approximately every 2 to 3 years.

SSL luminaires are uni-directional, unlike HID luminaires, which are more omni-directional. The advantage of using omni-directional HID luminaires is they offer glare control and a soft gradient edge. The disadvantage is that the light from an HID luminaire is harder to control, providing higher lighting levels directly below the luminaire and requiring a large reflector system to control light spillage. The uni-directional properties of SSL mean it can direct light exactly where it is required without unwanted higher light levels below the luminaire while having more light in-between luminaires, which improves overall uniformity. But glare can be greater with the SSL luminaires if the light sources are not shielded with a lens or redirected and diffused by a reflector.

The American Medical Association has issued a policy that states, “Many older citizens are significantly affected by glare as the eye ages, leading to unsafe driving conditions; and glare light is also light trespass and is intrusive and unwanted in households and dwellings; and light trespass has been implicated in disruption of the human and animal circadian rhythm, and strongly suspected as an etiology of suppressed melatonin production, depressed immune systems, and increase in cancer rates such as breast cancers” (Motta, 2009).

FINDING: Discomfort or disability glare can be an issue with directional LED luminaires. Luminaires must be designed so as not to increase glare potential compared to their HID counterparts.

Heat still needs to be managed, especially if the luminaires are left on during the day because of a malfunctioning photocell. However, the superior performance of SSLs at cooler temperatures is an advantage for some applications, such as roadway lighting and signals.

Currently, white LED modules always include a blue LED, which raises environmental concerns similar to those for the short wavelength components of metal halide and fluorescent lighting. These concerns include photobiological effects and increased skyglow[2] (IDA, 2010; Wright, 2011). These effects are most pronounced when lighting is energized all night long.

FINDING: LED white light products produce light in spectral regions that may create environmental and health concerns. These concerns should be recognized in the design and application of LED luminaires.

The long life promised by SSL luminaires has the potential to reduce maintenance, offering not only replacement savings, but also higher reliability. However, SSLs typically do not burn out, but only reduce their light output. So in some applications there may be a liability risk if the SSL is functioning but not producing the expected luminosity. Reduced light output occurred in the past with mercury vapor lighting.

Outdoor SSL luminaires may be dimmed if adaptive standards were to be applied. Adaptive standards are the practice of reducing lighting levels during periods of low activity, such as in the middle of the night when many establishments are closed. This practice is very popular in Europe and is now being introduced into North America through recommendations of the Illuminating Engineering Society (IES) (IES and IDA, 2011). Adoption of such practices would provide communities and property owners the flexibility to reduce lighting levels during periods of low activity, or during peak demand periods, thus saving energy.

Several cities, such as New York City, San Francisco, Oakland, San Jose, and others have performed extensive LED street lighting demonstration projects (DOE, 2012a) as part of the U.S. Department of Energy's GATEWAY demonstration program.[3] In all of these projects, the predicted and measured energy use and maintenance are lower than for conventional lighting, but illuminance levels are also lower compared to existing HPS street lighting. Additional added benefits include reductions in sky glow and light spillage. Some cities, such as San Jose (Figure 5.1) and Anchorage, conducted controlled public surveys to obtain community feedback on the LED street lighting (Clanton and Associates and VTTI, 2009, 2010). The public preferred the warmer color temperature LED, even at lower lighting levels, compared to the existing higher wattage low pressure sodium (LPS) and HPS street lighting (Gibbons and Clanton, 2011).

FINDING: Exterior lighting is a prime candidate for early adoption of SSL because of the lower lighting levels required in such applications and the optical control, long life, and dimmability characteristics of SSL.

SSL APPLICATION ADVANTAGES

While some of the advantages of SSL are immediately obvious, others are still only possibilities. As new technologies and luminaires are developed, new applications will also emerge, leading to unexpected opportunities in lighting design. Current SSLs offer small size, ease of control, unidirectional light, cool beam, superior color, low energy use, and long life. OLEDs promise entirely new form factors, a prospect that opens up a whole new realm of possible applications. Also, because of control compatibility, SSL can further reduce energy through dimming strategies.

Small Size

The compact size of the SSL modules offers opportunities to put lighting in areas that previously had restricted luminaire size. But the challenge of managing the heat generated by the LED has prevented a desired reduction in the size of the light source needed for high lumen output. As modules become more efficacious, the size can shrink even more. Shrinking size will allow more opportunities for replacement of additional types of lamps such as high-output MR-16 lamps (see Chapter 1). The MR-16 is an important lamp for retail, hospitality, and residential applications.

Inherent Controllability

SSL products have instant on and off operation without the requirement for a warm-up time, an attribute that is in contrast to that of HID and CFLs. With a dimmable driver, SSL products can be dimmed over a wide range of luminous flux in a smooth manner. Dimming below 10 percent is only available with a select number of drivers but is desirable (see Chapter 4). Smooth dimming is also available with some SSL screw-in incandescent replacement lamps. The appropriate choice of dimmers and drivers for SSL will enable control compatibility, which is critical for intelligent energy control systems.

Some control systems can change the color of light by varying the intensity of different colored LEDs in a red, green, blue system (i.e., one which produces white light by combining red-, green-, and blue-component LEDs). These are currently used mainly in special effects lighting, but have the potential for applications in commercial and high-end residential markets. For example, retail venues might wish to vary the color of light in a display to emphasize a product's features.

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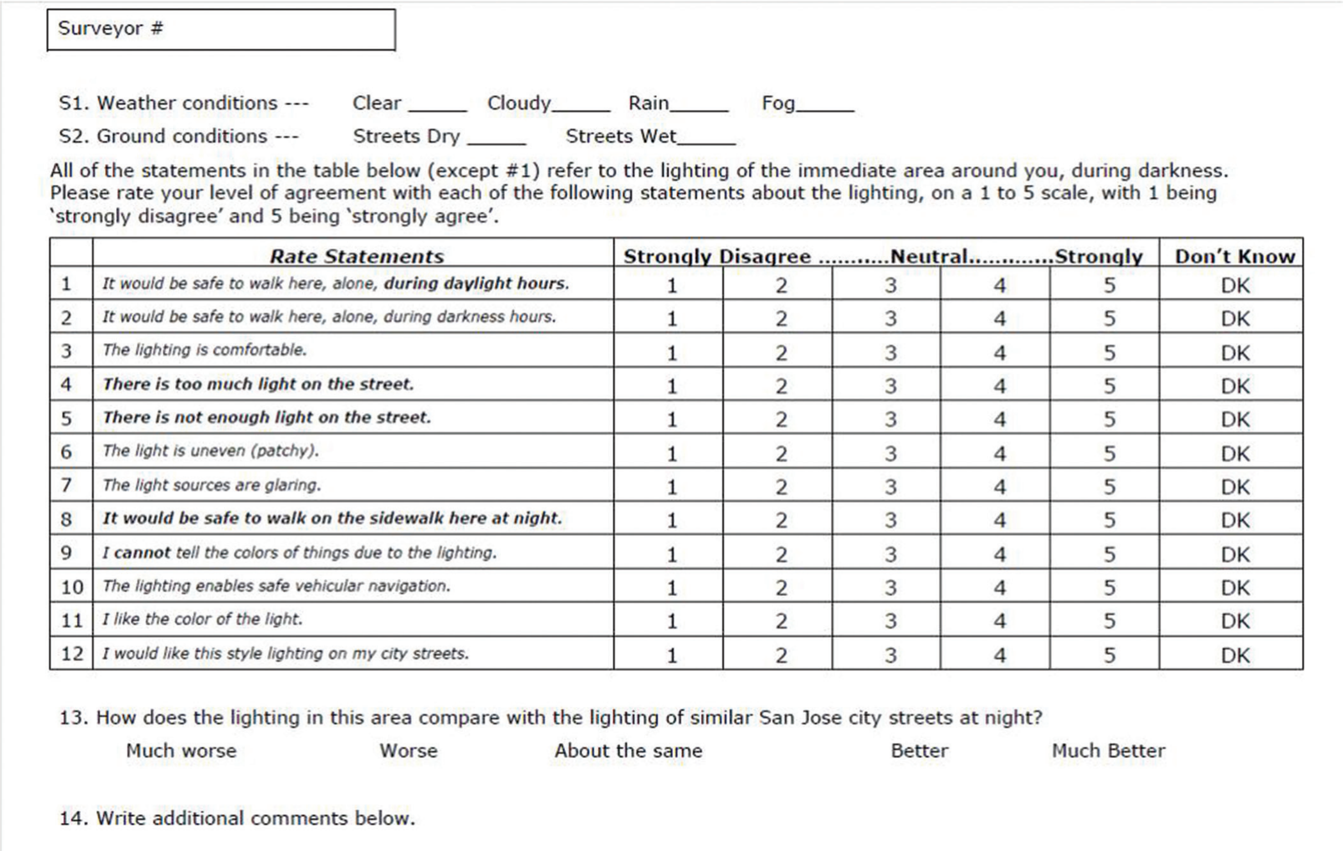
[2] *Skyglow* is the result of blue light being absorbed or scattered in the atmosphere resulting in a loss of visibility of the night sky, which is of special concern to the astronomy community.

[3] DOE GATEWAY demonstrations have the objective to showcase LED products for general illumination. DOE publishes detailed reports and briefs on completed projects. The reports include analysis of data collected, projected energy savings, payback analysis, and user feedback. Adapted from http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html.



Surveyor #

S1. Weather conditions --- Clear _____ Cloudy_____ Rain_____ Fog_____

S2. Ground conditions --- Streets Dry _____ Streets Wet_____

All of the statements in the table below (except #1) refer to the lighting of the immediate area around you, during darkness. Please rate your level of agreement with each of the following statements about the lighting, on a 1 to 5 scale, with 1 being 'strongly disagree' and 5 being 'strongly agree'.

	Rate Statements	**Strongly Disagree ....Neutral............Strongly**					**Don't Know**
1	*It would be safe to walk here, alone,* ***during daylight hours.***	1	2	3	4	5	DK
2	*It would be safe to walk here, alone, during darkness hours.*	1	2	3	4	5	DK
3	*The lighting is comfortable.*	1	2	3	4	5	DK
4	***There is too much light on the street.***	1	2	3	4	5	DK
5	***There is not enough light on the street.***	1	2	3	4	5	DK
6	*The light is uneven (patchy).*	1	2	3	4	5	DK
7	*The light sources are glaring.*	1	2	3	4	5	DK
8	***It would be safe to walk on the sidewalk here at night.***	1	2	3	4	5	DK
9	*I* ***cannot*** *tell the colors of things due to the lighting.*	1	2	3	4	5	DK
10	*The lighting enables safe vehicular navigation.*	1	2	3	4	5	DK
11	*I like the color of the light.*	1	2	3	4	5	DK
12	*I would like this style lighting on my city streets.*	1	2	3	4	5	DK

13. How does the lighting in this area compare with the lighting of similar San Jose city streets at night?

Much worse Worse About the same Better Much Better

14. Write additional comments below.

FIGURE 5.1 Subjective lighting survey used by the city of San Jose, California. SOURCE: Clanton and Associates and VTTI (2010).

Directional Distribution

SSL has unique uni-directional distribution characteristics, providing excellent beam control and allowing the fabrication of luminaires that are ideal for long-distance light distributions. For instance, an entire building façade can be grazed with luminaires located at one level. Accent lighting in retail stores can produce high-quality illumination with little energy. SSL has the potential to put light where it is needed with minimal light spillage, but without appropriate optics it can exhibit a sharp cutoff in illuminance with an abrupt termination of the lighted area. For instance, without appropriate optics roadway lighting may not light the adjacent sidewalks. This attribute of SSL emitters may also make for difficulties in the development of omnidirectional lamps replacements for fluorescent and incandescent lamps. In the future this problem could be solved by proper optical designs.

Cool Beam

Because the LED does not emit infrared light as does an incandescent lamp, the beam of light is cool. This makes it ideal for reducing heat on retail products and art work and in other heat sensitive applications. SSLs based on LEDs are currently used in museums (e.g., in Portland, Oregon) and in refrigerated display cases (e.g., Albertsons Grocery in Eugene, Oregon) (DOE, 2012a). Newer domestic refrigerators are also using LEDs for interior lights.

Color Characteristics

SSL has the potential for superior chromaticity and color rendering. As discussed in Chapters 1 and 3, the spectral output of SSL products can be tuned to create virtually any desired chromaticity. This is required in all applications where the users typically compare the lighting color to recognizable sources such as daylight or an incandescent lamp.

In addition to achieving excellent color rendering, some SSL sources can create desirable effects, such as increasing the saturation of object colors. Opportunities exist to select spectral distributions for specific applications, such as rendering artwork, or narrow spectral distribution, such as amber LED (i.e., LED lights without the blue component) for lighting beach boardwalks near turtle hatching areas where young turtles are at risk because they are attracted to blue light similar to the ocean effervescence (Longcore and Rich, 2005).

Long Life

When SSL is properly operated within its temperature and operating current ranges, it has a relatively long life, which reduces maintenance and improves reliability. Because SSL may not burn out but only decrease in light output, there is a potential liability issue if light output drops below design levels. Proactive maintenance strategies can be developed to alert users through intelligent controls when SSL drops below 70 percent of initial light output. SSL drivers can be made to adjust operating current so that when lamps are new, the operating current is lower. As lamps age, the operating current increases to maintain consistent light output. Near the end of usable life, indicators may be used to signal low light output.

Luminaires with Entirely New Form Factors

Luminaires of entirely new form factors may be developed to take advantage of the unique attributes of LEDs and OLEDs. For instance, neither replacement lamps nor retrofit luminaires capitalize on the very small size of individual LEDs. This characteristic alone, if fully exploited, has the potential to completely change where and how electric lighting is used. The controllability of LEDs is also only beginning to be explored. Common lighting controls now are limited to dimming, occupancy/motion sensing, and daylight sensing. The next generation of SSL luminaires will be able to do those things and perhaps much more: change color, change color rendering properties, and so forth. Because the ability to control different light properties is determined by the components in the product, controls will most likely be considered integral parts of the luminaires. OLED's unique properties naturally lend themselves to out-of-the-box thinking, and truly novel luminaire designs may emerge with new OLED products. Other applications may include lighted surfaces such as walls, ceilings, and furniture systems.

Adoption of these new and novel types of luminaires would require the most risk and investment by consumers. If a consumer were to become dissatisfied with a very innovative SSL luminaire, reverting to other lighting technologies would be difficult and expensive. Installation of highly innovative luminaires in existing buildings may necessitate major retrofit work. Thus it is likely that early adoption of such luminaires will be in new construction projects that pay attention to lighting design from the early stages of architectural planning.

A small sampling of these types of forward-looking luminaires has been developed. One interesting example is a closet rod embedded with LEDs, which becomes luminous when the closet door is opened (Reo, 2011). This custom-made product illustrates a clever use of controls and great attention to putting light where it is actually needed in a closet. Future lighting may emphasize flexibility and multi-function, as illustrated by a multi-functional OLED luminaire, which consists of multiple, movable OLED panels (Figure 5.2). It is possible that future lighting will make luminaires invisible, as is done by some LED products that are small and thin and intended to be installed in small crevices and recesses in the built environment.[4] At this stage, it is impossible to predict all of the forms that future SSL luminaires will assume.

FIGURE 5.2 Example of multi-panel OLED (Canvis™ Twist by Acuity Brands). SOURCE: See http://www.acuitybrandsoled.com/creations/canvis-twist/.

FINDING: Were OLEDs to become commercially viable, they would provide an opportunity to change the form factors of how luminaires are designed with smaller sizes, less material, and fewer physical constraints and offer an ability to change from traditional-looking luminaires to internally lighting surfaces and materials.

SSL APPLICATION CHALLENGES

As with any new technology, the early adopters have highlighted areas in which further improvements are needed to make SSLs fully equivalent across the whole spectrum of lighting applications. Whenever a new technology is introduced, dissimilarities are noticed. For example, when the CFL was introduced to replace the incandescent lamp, users were unhappy with the flickering, slow start-up, color, light intensity, noise, radio static, and lack of dimming. It will be important not to make the same mistakes with SSL introduction (see the Chapter 2 section, "Compact Fluorescent Lamp Case Study").

At this point, the major challenges to full acceptance of SSL are cost, system and control compatibility, and heat management. These issues are not well understood by most end users, so it falls to the lighting industry to improve

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[4] See, for example, http://www.youtube.com/watch?v=_8e4iYlNyZI> and www.edgelighting.com.

components and to other professionals to establish standards and recommendations that will ease the introduction of SSL.

Cost

The cost for SSL luminaires needs to be reduced for them to be readily accepted. As noted in Chapter 2, it took a combination of technical advances to improve quality and incentive programs to overcome the initial reluctance to adopt CFLs, and their initial cost is still an inhibiting factor.

Both initial and replacement costs are major considerations, particularly for SSL luminaires. Many SSL components are integral with the luminaire, making component replacement difficult if not impossible. Instead of replacing a lamp, the entire luminaire would need to be replaced should one of these integral components fail. Progressive manufacturers now construct luminaires for easy component replacement, including such features as removable optical cartridges and quick connects to drivers. Also, driver lives are dependent on operating temperature but, nonetheless, are increasing to match the life of the SSL luminaire (Figure 5.3).

While cost is still a significant barrier to more rapid introduction of SSLs, the expectation is that with the current rate of progress, they will become a cost-effective option in the near future (Bland, 2011).

System and Controls Compatibility

Lighting controls can include dimming, occupancy controls, and color control. Current SSLs do not always gracefully mesh with existing installations. One great challenge for designers is selecting compatible drivers for the SSL luminaires. This is also related to dimming compatibility issues. Different drivers have unique operating currents and operational characteristics. If a driver is not compatible, luminaires can flicker, have shorter lives, or not operate at all. Most quality manufacturers now supply the drivers with their luminaires, which avoids confusion.

Drivers must also be compatible with new and existing control systems. Currently, some integrated drivers have power quality problems such as high THD of the line current and low PF. A designer must obtain the list of compatible drivers from the control manufacturer—a method of selection that is awkward, adds design time, and adds difficulty when SSL equipment is substituted for standard fixtures. A NEMA standard for controls, drivers, and SSL compatibility could streamline this process.

Heat Management

Heat management is a huge challenge with SSL applications (see Chapter 4). Luminaires must dissipate heat adequately to maintain life and light output expectations. For SSLs, mounting details can add heat management complexity. For instance, operating temperatures can rise if SSL luminaires are mounted in a confined space, adjacent to insulation, in high temperature environments, or where the heat otherwise cannot be dissipated. An example would be a recessed downlight adjacent to insulation in a nonconditioned area. Another example would be one in which MR16 lamps are installed in open air luminaires where the only heat sink is the socket connection. As operating temperatures increase, life and light output decrease. Non-LED luminaires have an easier chance of dissipating heat compared to LED lamps, where the heat sink is limited to the socket size and cooling fins around the lamp. OLED luminaires do not have as significant heat management issues as LED (refer to Chapter 3) at room temperatures and below, which facilitates installations in more varied environments.

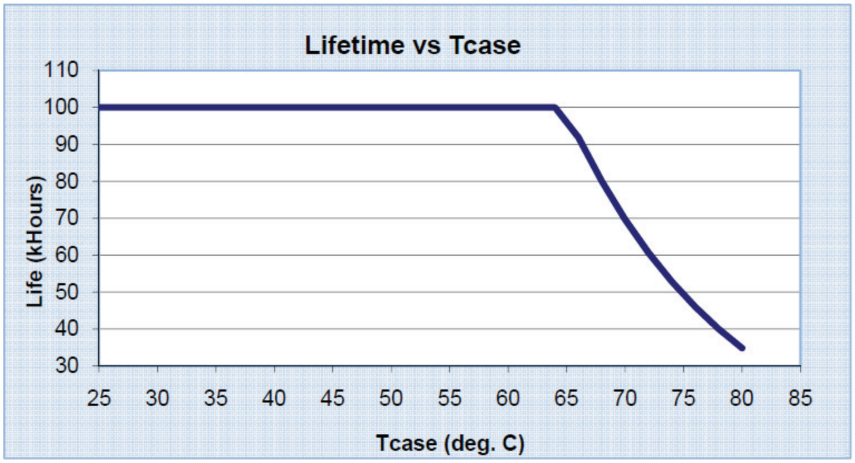

FIGURE 5.3 LED driver life of Philips “Xitanium” driver versus case temperature. SOURCE: Philips Lighting North America (2012).

FINDING: Replacing existing incandescent lamps with LED lamps in existing luminaires may under certain conditions cause the LED to overheat. Examples include downlights adjacent to insulation or in enclosed luminaires. This is true also of the use of SSL in industrial applications having higher ambient temperatures. LED lamp heat management needs to be addressed for all such applications.

Power Quality

SSL products, similar to fluorescents and HID, contain electronic components and without appropriate design can produce poor power quality and exhibit, for example, high THD and low PFs. This is a similar set of issues encountered by early deployments of electronic and hybrid ballasts for compact fluorescents and linear fluorescents lamps. High THD can cause flickering and excess current on shared neutral conductors. Low PF results in line currents higher than necessary to supply the required power.

SSL drivers, similar to fluorescent electronic ballasts, can cause radio interference, which can be annoying, especially to residential users. SSL drivers are required by the Federal Communications Commission to adhere to similar protocols as electronic ballasts in order to avoid these problems.[5] This includes the integral drivers in SSL lamps.

Related to power quality, issues such as dimmer range and reliability, maximum/minimum units required on a control, repetitive peak voltage, and in-rush current can cause significant problems if not properly addressed (see "Electric Power Quality" in Chapter 4).

Failure Process

As an SSL product ages, its output gradually declines. It does not simply go dark, but its lumen output declines over time. This could be a liability issue in some applications where a specific level of illumination is required. One promising option to address this is incorporating a driver that will increase the operating current as the LEDs age to keep the luminaire at its specified output.

Lighting Quality Issues

If SSL is to compete successfully, then its lighting quality should be equal to or better than non-SSL luminaires (IES, 2011, p. 7.64; IALD, 2006). Lighting quality issues include quantity of light, lighting ambiance, glare reduction, and color rendering and consistency (ALA, IES, IALD, 2010).

Light Quantity

When a user installs SSL, they expect that the light will be equivalent to (seem the same as) an incandescent of the specified equivalent wattage. The quantity of light (i.e., the luminous flux measured in lumens) is the easiest metric to use, because it is easily predicted and measured. SSL has been successful in producing a quantity of light similar to standard luminaires in the lower lighting level environments. High lighting levels are currently harder to achieve because of the amount of heat management required with the additional wattage. As SSL modules become more efficacious, higher lighting levels will be achievable that do not encounter these problems in operation.

Lighting Ambiance

Whether a scene is pleasant, spacious, intimate, or dramatic depends on the luminance balance within the scene (IES, 2011, p. 4.26) and how light is layered. For instance, spaciousness is implied when walls and ceilings are evenly lighted. Pleasant scenes may have non-uniform lighting with stronger accent lighting and peripheral wall emphasis (Flynn and Spencer, 1977; IES, 2011). SSLs based on LEDs perform well for surface grazing for walls and ceiling coves and for accent lighting. Applications of SSLs based on OLEDs include lighted surfaces in addition to luminaires.

Examples of installations having lighting layers include uniform ceiling brightness balanced with select wall washing and occasional accent lighting; personal work areas may have under-shelf lighting with adjustable task lighting. All of these layers should be separately controlled to provide the desired luminance balance. The light output of SSL products can be very directionally controlled and, thus, has unique advantages in providing layers of light, especially for surface ambient, accent, and task lighting.

Brightness and Glare

Because SSL lighting is uni-directional, it has the possibility of high brightness, giving luminaires the potential of producing glare if not controlled properly. Luminaires can limit brightness through optical systems either at the module level or within the reflector and lens design. Methods include the use of remote phosphor modules or diffusing lenses or by indirectly lighting via reflectors or surfaces so the individual LEDs are not visible.

Color Rendering, Appearance, and Consistency

To see colors as intended, the lighting system must produce a desired spectral distribution. Lower color temperatures are associated with "warmer" looking light, appropriate in residential, hospitality, and retail applications. Higher color temperature represents "cooler" looking light, which is appropriate in commercial and industrial applications. Exterior applications show a preference for lower color temperatures (Clanton and Associates and VTTI, 2009, 2010).

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[5] See discussion in Chapter 4, "Electric Power Quality."

An LED produces light in a narrow spectrum. In order to produce white light from a single LED module, the module is phosphor-coated. Another method of producing white light is combining several different color LEDs. Color rendering, and color rendering indexes, are harder to apply to LED luminaires than standard luminaires (see Chapter 1). Not all LED lamps available in the current market have good color rendering properties. Higher color temperature LED modules are more efficacious, encouraging their application. But the cooler color (bluish tint) associated with them may not be as readily acceptable to users (Clanton and Associates and VTTI, 2009; Clanton and Associates, VTTI, ETA, 2010). SSL luminaires need to increase the efficacy for color temperatures below 3,800 K in order to satisfy user preference for the lower correlated color temperature (CCT) (Figure 5.4).

One significant issue is the consistency of SSL luminaires' color appearance. If LEDs from different bins are used in the same luminaire or in similar luminaires side by side, the light outputs will not match in color appearance (i.e., the CCT). This is an issue not only during initial installation, but also in deployment because of aging and replacement of luminaires. SSLs need to be consistent between products and guaranteed to provide color-consistent replacement modules in the future.

FINDING: Many LED lamps currently available do not have the same light output and color rendering properties as incandescent lamps. SSL products with improved light output that are color consistent from product to product will be needed for the public to readily accept these as replacements for incumbent lighting technologies.

EVALUATING SSL LIGHTING APPLICATIONS

SSL lighting applications are currently intended to duplicate or be similar to incandescent and fluorescent lighting. SSL has many unique qualities that have not been present before in lamp technology, and these may result in new applications in the future. The attributes of SSL make possible new ways of lighting such as uniform surface washing and grazing, close-to-task effectiveness, and surface integrated light. Tunable spectral distribution adds flexibility for color adjustments.

The current status of SSL applications is summarized below. This is, of course, a snapshot of a moving target, as the field is changing rapidly.

Best. Because the current LED products have relatively low lumen output, the best current applications for SSL are those in which the light source is close to the task and the required lighting levels are low. Examples of these are task

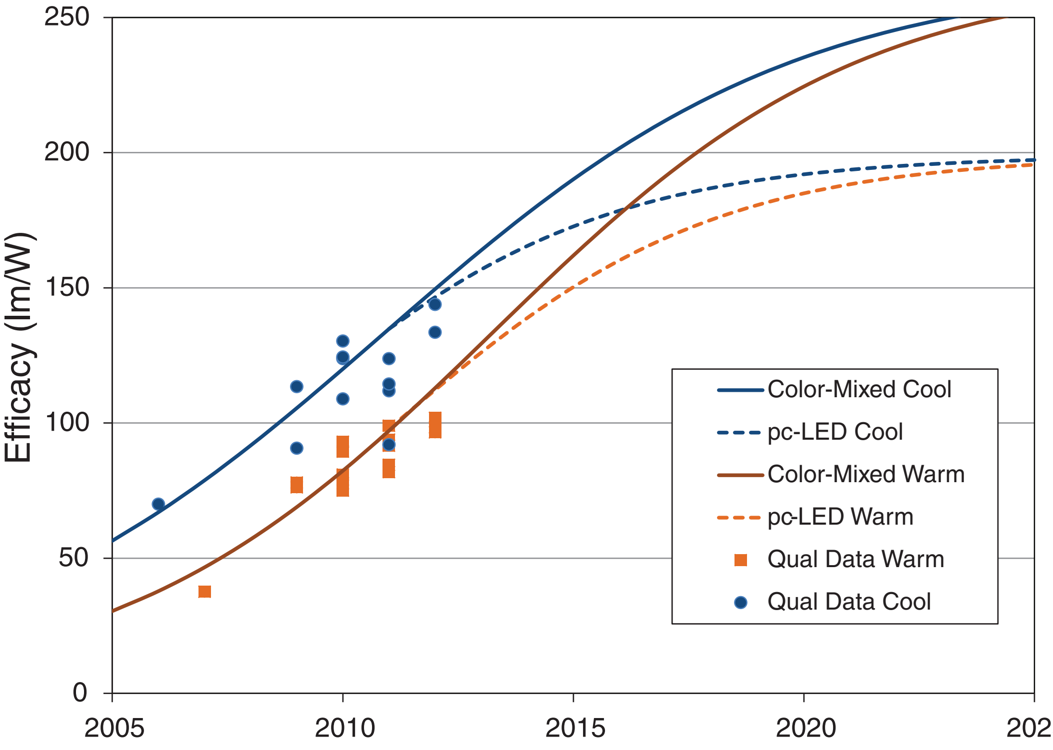

FIGURE 5.4 Current and projected efficacies. NOTE: pc-LED = phosphor-converted LED; lm = lumen; W = watt; Qual = qualified data point having satisfied the criteria for cool white (color rendering index (CRI) of 70-80, correlated color temperature (CCT) of 4,746-7,040 K) or warm white (CRI of 80-90, CCT of 2,580-3,710 K). Results are for 25°C package temperature and are normalized to current densities of 35 A/cm^2. SOURCE: DOE (2012b).

(Figure 5.5), under-cabinet or under-shelf, step lighting, and wall washing (Figure 5.6) and cove grazing.

Emerging. Emerging SSL applications include higher output directional lighting. Because heat management may be an issue with higher output lumen packages, higher-efficacy lamps will help with these applications. Examples are accent lighting, downlighting (Figure 5.7), large area grazing, and street (Figure 5.8) and area lighting.

Difficult. Difficult SSL applications include omnidirectional lighting. Because LED modules are unidirectional, it is difficult to fabricate luminaires that render them omni-directional. For fluorescent replacements, LEDs offer little advantage if any, and at higher initial cost. Replacements for high wattage A-lamps (i.e., 100 W and higher) are not yet available.

Unique. When commercially available, OLEDs will facilitate applications with new form factors, which is enabled by the manner in which the OLED is essentially the luminaire

FIGURE 5.5 Example of task lighting. “Equo LED Desk Lamp” by Koncept Technologies, Inc. SOURCE: Next Generation Luminaires, PNNL.

FIGURE 5.6 Example of wall washing. “Stile Styk” by STILE, a brand of SPILIGHTING, Inc. SOURCE: Next Generation Luminaires, PNNL.

FIGURE 5.7 Example of downlighting. Sea Gull Lighting/Juice-Works. SOURCE: Next Generation Luminaires, PNNL.

FIGURE 5.8 Example of street lighting (“RoadStar” by Philips Roadway Lighting). SOURCE: Next Generation Luminaires, PNNL.

(with the addition of a driver). Examples of new form factors include lighted surfaces and objects, which eliminates traditional luminaire aesthetics. Some new forms include foils and moldable and conformable materials. Both OLEDs and LEDs could be used, for example, in a recessed cavity or in places where, for reasons of repair and maintenance, it would otherwise be awkward to install a luminaire.

Both LED and OLED applications may use dynamic controls with spectral distribution tuning, allowing, for example, cooler color temperature appearance during the day and warmer color temperature appearance in the evening. In areas where spectral distribution restrictions are required, such as in environmentally sensitive areas or in areas where melatonin suppression is avoided (i.e., places of sleep for residential and healthcare properties), dynamic tuning could provide solutions.

Post-Occupancy Assessment

Post-occupancy assessment (POA) is a valuable tool, especially when deploying a new or emerging technology. POAs can provide valuable positive and negative feedback from users to manufacturers, lighting designers, utilities for rebate programs, and to the Department of Energy's (DOE's) SSL programs. Organized POAs may discover an issue that requires mediation before it becomes an established association with SSL, such as dimmer compatibility. Assessments can gather opinions on lighting quality, performance, longevity, economic value, and general expectations. Specific issues may include glare, color, dimming, and flicker.

POAs should be performed in both the commercial and residential applications with subjective evaluations given to the end users. Additionally, issues such as energy use, power quality, longevity, and maintenance could be gathered from building managers and utility groups.

There are several existing POA formats such as Berkeley's Center for the Built Environment "Occupant Indoor Environmental Quality (IEQ) Survey,"[6] but none of them delves into specific SSL issues.

TESTING AND MEASUREMENT STANDARDS

Because of the different spectral, electrical, and thermal characteristics of LEDs, OLEDs, and SSL products, existing standards to measure the photometric properties (i.e., measures of perceived light intensity) and colorimetric properties (i.e., measures of perceived color characteristics) of other lighting technologies frequently cannot effectively be used for SSL. For instance, the temperature of an LED package will affect measurements of light output, lifetime, and color. In such cases, the applicability of a measurement will depend on the effectiveness of the thermal management of that LED package in its ultimate application. Because of this, standards for SSL focus on different stages of the integration of complete lighting products, including LED packages, LED arrays and modules, LED light engines, and integrated LED lamps and luminaires. Additional standards focus on terminology.

Within documentary standards, test and measurement standards simply detail how a device or product is to be measured but do not indicate the desirable results of those measurements. A lighting product does not adhere to a measurement standard; the manner in which its characteristics are measured does. Performance standards, on the other hand, set rules and/or give permissible ranges of measurement outcomes. A lighting product would be said to adhere to a certain performance standard if it met the latter's requirements. Safety standards, including electrical safety and photobiology (the effects of light on organisms, often concerned with the potential for light sources to damage the human eye), are one type of performance standard.

A number of standards development organizations are involved in recommending test procedures for the measurement of LEDs, OLEDs, and SSL products. The Illuminating Engineering Society of North America (IES), a professional organization dedicated to advancing the art, science, and practice of lighting, has been one of the leaders in the development of standards specifically for SSL and is accredited by the American National Standards Institute (ANSI). ANSI establishes the consensus procedures that are the basis for the development of American National Standards[7] and is the U.S. representative to the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO). The IEC is an international consensus standards organization for electrotechnology. The International Commission on Illumination (CIE) is recognized by ISO and the IEC as an international standards body. Its activities include the development of standards and procedures for the measurement of light and publication of standards and technical reports related to light and lighting. NEMA is primarily a trade association for the electrical manufacturing industry but is also an ANSI-accredited standards development organization. The Underwriters Laboratory is ANSI-accredited and sets safety standards for lighting products.

Test and measurement standards for SSL are rapidly being developed, both within the United States and internationally. Because of the volume of standards produced and frequent new publications, an exhaustive discussion of standards will not be included here. Instead, a few important areas of testing and measurement of SSL are highlighted.

The United States has taken early leadership on several influential standards, such as IES LM-79-08 "Electrical and Photometric Measurements of Solid-State Lighting Products," which specifies the procedures for measuring total luminous flux, electrical power, luminous efficacy, and chromaticity of SSL integral lamps and luminaires (IES,

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[6] See http://www.cbe.berkeley.edu/research/survey.htm.

[7] Further information is available at http://web.ansi.org/about_ansi/faqs/faqs.aspx?menuid=1.

2008). Despite rapid progress, a number of important test and measurement standards still need to be developed for SSL to be successful.

There is currently no way to measure or estimate the lifetime of SSL luminaires. LEDs do not typically "burn out" or abruptly fail at end-of-life, like an incandescent lamp. Instead, they get dimmer over time, the speed of which depends on exposure to heat and other variables. Standards have made progress on measuring and predicting lumen maintenance (the relationship between temperature, operating time, and light output) for individual LED packages, but the life of an integral lamp or luminaire is determined by more than the LEDs. For example, the failure of an electrical component or darkening of an optical component may limit the lifetime of an SSL luminaire. Predicting and measuring the lifetime of the integration of varying subcomponents makes this topic very technically complicated.

FINDING: There is no standardized method for measuring the lifetime of SSL products.

The CRI is the internationally accepted metric for the evaluation of a light source's color rendering abilities (CIE, 1995) and was developed in response to the advent of fluorescent lamps. Fluorescent lamps had spectral power distributions (SPDs) unlike anything the lighting industry had used before, and the quality of color rendering from these light sources was highly variable. The calculation of the CRI requires only the spectral power distribution of the light source of interest and is basically a series of colorimetric simulations. In these simulations, the appearance of a predefined set of reflective samples (object colors) is compared when illuminated by the test source and when illuminated by a reference illuminant (blackbody radiator or daylight simulator). If the samples appear identical in both cases, the test lamp would receive a general CRI (R_a) of 100. Deviations in the appearance of the test sample colors lower the score. A number of flaws of the CRI have been recognized for years, but the problems have not been considered important enough to warrant change (CIE, 1999). The problems of the CRI include the use of outdated and obsolete colorimetry (the math used to calculate the appearance of the reflective samples), a set of reflective samples that do not detect certain color rendering problems, and, according to some, an underlying definition of color rendering that does not correspond to actual users judgments of color rendering quality (Davis and Ohno, 2009).

For much of the history of electric lighting, a small number of very large companies produced nearly all of the light sources sold in the world. Each of these companies had the resources and expertise to understand the limitations and flaws in their measurements and ensure that metrics did not lead them to inadvertently create poor products. However, the lighting industry has changed considerably, largely because of SSL. Many smaller companies are now developing lighting products, some with very little experience in lighting, and the metrics used to evaluate light sources need to give users accurate predictions of performance. Furthermore, the problems of the CRI are particularly pronounced for some SSL sources (CIE, 2007). For example, certain LED spectra can render the reflective samples of the CRI very well, but render other object colors poorly.

There is now widespread agreement that a new method is needed to evaluate the color rendering quality of light sources (CIE, 2007), and many different approaches and methods have been proposed (reviewed in Davis and Ohno, 2009; Guo and Houser, 2004). DOE has publicly supported one proposed metric (DOE, 2010), the Color Quality Scale (CQS) (Davis and Ohno, 2010). Although it still uses the CRI, it is the current standard. A technical committee in the CIE was formed in 2006 to recommend a new procedure for evaluating the color rendering of light sources. Because the CIE committee consists of a diverse international group of stakeholders, consensus has not yet been achieved. This is problematic for SSL manufacturers, particularly small companies incapable of performing detailed colorimetric simulations, as they optimize their products to the metric.

FINDING: The CRI does not always yield results that predict or evaluate performance well, so manufacturers cannot rely on it to guide product development.

DOE has actively supported the consensus process for the development of testing and measurement standards. DOE has provided experts and supported their work time for numerous SSL standards committees. The agency also organized and sponsored an SSL standards workshop, as well as several related round-table meetings. Furthermore, DOE uses its demonstration projects to provide input on additional needed standards and provides financial support to the U.S. national committee of the CIE. DOE also funds measurement and standards research at the National Institute of Standards and Technology.

The Commercially Available Light-Emitting Diode Product Evaluation Reporting (CALiPER) component of the DOE program includes verification testing that produces extensive data on individual products. DOE funds independent laboratories to conduct the testing, each focused on one product type (e.g., high-bay luminaires; small replacement lamps (MR16, PAR lamps, and so forth)). The testing follows the IESNA LM-79-08 method of electrical and photometric measurements to verify that lamps are performing according to specifications.

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6

SSL Large-Scale Deployment

INTRODUCTION

The widespread adoption of solid-state lighting (SSL) will necessitate further technological and scientific advances to improve product quality and reduce costs and also require greater dissemination of product information to support consumer purchases. This chapter identifies the barriers faced by industry to the widespread deployment of SSL products and analyzes the role that governments and partnerships can play in bringing reliable and competitively priced SSL products[1] to market. Consideration is also given to the time line and the quantifiable benefits for the commercialization of SSL products as replacements for current incandescent and halogen lamp (i.e., light bulb) technology.

Consumers need assurances that the SSL products they purchase will meet their lighting needs as advertised to avoid some of the early deployment problems associated with the introduction of compact fluorescent lamps (CFLs). Problems encountered during the introduction of CFLs are discussed in Chapter 2 and again later in this chapter, as are the lessons learned for the introduction of SSL products.

Also examined in this chapter is the role of support for consumer purchases in the form of financial incentives (or giveaways) by utilities and state energy efficiency programs and the establishment of more stringent lighting requirements in new construction and building retrofits to stimulate market demand to support SSL industry development in the United States. To avoid problems experienced with the introduction of CFLs, government and industry both have a role to play in helping achieve scientific breakthroughs, developing standards, supporting consumer purchases with financial incentives, and having a viable disposal plan in place to address safe disposal of end-of-life SSL products to support adoption, as discussed in more detail later in this chapter.

SSL costs must come down in all major cost categories, including materials use, yield, wafer processing, assembly, and packaging to reduce the cost of SSL products at the point of purchase. This chapter further discusses those categories of cost along the value chain that need to be addressed to improve the value proposition of higher quality light, longer product life, and overall lower life-cycle cost compared to current lighting products on the market.

SSL products to date have been successful in penetrating the vehicle and traffic signal lighting markets, retail and refrigerated displays, and electronic and entertainment markets. However, the performance of SSL products needs to improve, and costs need to come down to further penetrate the residential, commercial, and industrial lighting replacement market, which is the largest potential market for SSL. The cost of organic light-emitting diodes (OLEDs) must be substantially reduced before OLED lighting products penetrate the lighting market. The replacement markets also hold the most promise for the greatest energy savings and environmental benefits from SSL use, consistent with the Department of Energy's (DOE's) SSL program objective and funding priorities.

SSL Industry and Markets

At this time, the United States is lagging behind other countries in SSL manufacturing volume, and most manufacturing is located in the Far East.[2] The SSL lighting industry is intertwined with the electronics industry, and light-emitting diodes (LEDs) are used not only for general lighting but also in many other applications, including backlighting of liquid crystal display (LCD) TVs, laptop computers, and handheld devices. One analysis of the LED market revenues for all such applications approached $10 billion globally in 2010, and sales of packaged LEDs rose 55 percent in 2010 with sales of 81 billion units (Young, 2011). LEDs fabricated of gallium nitride (GaN) were principally responsible for this

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[1] Including those based on light-emitting diodes (LEDs), organic LEDs (OLEDs), and, potentially in the future, semiconductor lasers.

[2] Market shares are as follows: United States and Europe, 23%, Japan, Korea, Taiwan, and China, 72% (Young, 2011).

growth, rising 67 percent and now accounting for 79 percent of the LED market. LED backlighting for LCD television screens is now the leading market for LEDs, accounting for 27 percent of the inorganic LED sales, and is the fastest growing LED market today. Total revenues from sales of backlighting rose 84 percent in 2010 and accounted for 70 percent of inorganic LED sales (Young, 2011). Lighting, automotive, and signage applications of LEDs enjoyed a greater than 20 percent growth in the past year to slightly less than $2 billion (Young, 2011; Bhandarkar, 2011). IMS Research estimates that the North American lighting market has close to 4 billion incandescent lamps, 1.6 billion CFLs,[3] 1.65 billion fluorescent lamps, 200 million HID lamps, and just over 500 million halogen lamps (Young, 2011). McKinsey (2011) studied the global market for lighting in all applications and found that in 2010 LEDs for general illumination captured 7 percent (roughly €3 billion) of the market for new installations and 5 percent (€0.3 billion) of replacements.

U.S. participation in SSL research and development (R&D), manufacturing, and sales is currently well behind other developed countries. Japan is a leader in the LED industry in production and in public funding for R&D. Suppliers such as Nichia, Toyoda Gosei, Sharp, Rohm, Panasonic, Toshiba, and Citizen reside in Japan. More than 20 national universities in Japan have strong R&D efforts, which surpass the number in the United States. Currently, LED lighting is being subsidized by the Japanese government in order to reduce electricity use, in part in response to the devastation to the country's electricity supply (25 percent reduction) caused by the Sendai earthquake and tsunami of 2011. LED lighting sales in Japan are estimated to top $1 billion in 2011, making Japan the largest market for LED lighting products. The LED adoption rate for new lamp purchases has already reached 40 percent and is projected to exceed 50 percent in Japan by 2012.

In June 2011, a new national energy-saving program was launched by the South Korean government aimed at achieving a 100 percent conversion rate to LED lighting in buildings owned by the South Korean government, as well as a 60 percent penetration of all lighting applications nationwide by 2020. To support this initiative, the Korean government will provide $185 million in funding support in 2012 and 2013 for LED point-of-purchase rebates. Samsung, LG, and Seoul Semiconductor are crucial players in helping reach these goals. These companies already offer a broad range of LED products for the domestic market. Samsung announced a 60 watt (W) equivalent LED lamp at less than $20 in 2011. Seoul Semiconductor was the fourth largest LED manufacturer in 2010 (Bhandarkar, 2011). China is currently a net importer of LED lighting for notebook backlights and automobile headlights. However, China intends to be a major producer of LEDs by 2015, and large capital investments by LED makers are now being heavily subsidized by the Chinese government (Young, 2011). Until July 2011, metal organic chemical vapor deposition (MOCVD) equipment was subsidized 50 percent by the Chinese government. More than 200 MOCVD systems were purchased under this subsidization program. However, it is now being discontinued until further demand for LED lighting is demonstrated. Motivated by the potential for large energy savings using SSL, LEDs are a targeted technology in China's 5-year plan. Started in 2009, the plan is focused on the development of a sustainable LED industry. The Chinese central government's objective is to consolidate the industry with five or six major players, all of which would be able to compete globally with the intention of becoming low-cost manufacturers by 2015; with China being the largest consumer of LEDs with a market reaching $74 billion by that same year. China has announced its intent to phase out incandescent lamps by 2016 starting with those over 100 watts in October 2012 (Reuters, 2011).

Mobile OLED displays are now being manufactured almost exclusively in Korea and the Far East for handheld electronic device applications such as smart phones. It is expected that display manufacturers in Japan, Korea, and China will move to larger displays, where OLEDs are very attractive alternatives to liquid crystal displays (LCDs). Although displays are a highly commoditized product, their relative price elasticity compared to general lighting makes displays the ideal first application for OLEDs. Larger companies like GE, Philips, Osram Sylvania, and Samsung are all developing OLED technology for lighting applications, with Moser-Baer, located in New York, being the first commercial entry into OLED lighting manufacturing.

Several large U.S.-based corporations and numerous medium-size lighting and start-up companies participate in the SSL market. These companies hold world-class positions and employ tens of thousands of people in the United States. In the LED chip market, Cree Inc., and Philips-Lumiled are among the top 10, based on worldwide revenue. Both companies still manufacture in the United States and produce revenues of the order of $1 billion annually. Some of the world's leading LED manufacturing equipment suppliers reside in the United States, with VEECO and Applied Materials being leading MOCVD reactor suppliers. Numerous substrate equipment suppliers and fabrication and test companies play a critical role in the SSL supply chain. The LED lamp and luminaire markets have numerous medium and small companies providing LED lamps and luminaries.

OLEDs have also been the subject of a growing manufacturing base over the past decade in the commercialization of color mobile displays. Mobile display production in 2011 was estimated at approximately 3 million displays per month for Samsung alone (Wall Street Journal Asia, 2011). Leveraging this early manufacturing experience, several

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[3] The term *CFL* applies to not only the twisted fluorescent replacement for incandescent A-lamps, but also "folded" fluorescent lamps, e.g., GE's Biax lamp. These do not share the problems associated with the twisted CFL.

manufacturers are now developing OLEDs for general lighting applications because of their potential for high efficacy, large area coverage, and conformable configurations. At present, however, OLEDs have some shortcomings for general lighting applications, as discussed in Chapter 3, such as very high cost compared to LEDs and to other lighting technologies.

BARRIERS AND THE SSL VALUE CHAIN

Despite the rapid increase in manufacturing and sales of SSL products based on LEDs, barriers remain to be overcome for them to dominate the lighting market. Efforts focused on materials research and overcoming manufacturing challenges to improve SSL products and reduce costs are essential. Barriers exist all along the SSL value chain, depicted graphically in Figure 6.1. The value chain identifies at a high level the market activities and participants comprising the lighting industry. Activities include, but are not limited to: R&D; patenting and licensing intellectual property; the making of specialty manufacturing tools required in commercial-scale SSL component and product manufacturing; manufacturing itself; product assembly; component and product distribution, wholesaling, and retailing; and various light form applications in the consumer market. Market participants include all those individuals, businesses, and organizations participating in some aspect of the lighting market just described, including the lighting design community and consumers.

The industry value chain shown in Figure 6.1 is depicted as consisting of three major categories of activities (upstream, midstream, and downstream) and is used to organize the discussion in this chapter around the barriers that need to be overcome for widespread SSL adoption. First are upstream market activities, including basic and applied R&D, performance standards setting, and determining the best ways to test products. Second are the midstream activities that focus on manufacturing and the movement of product to major wholesalers and retailers, also including associated sales force education and training on the benefits of SSL. Third are downstream activities that include decision-making on particular lighting applications and end-user purchases and the offering of any purchase support programs offered by utilities or other entities to support widespread adoption of SSL. There are barriers to full-scale deployment at each point along the value chain that will be discussed below.

UPSTREAM OPPORTUNITIES AND CHALLENGES

R&D challenges to improving the efficacy, reliability, and color quality of SSL products while reducing the cost are many, as noted in preceding chapters of this report. While challenges for improving SSL products to support widespread adoption can be generalized, some challenges are unique to specific end-use sectors and applications, including residential, commercial, industrial, and general illumination and niche applications. Upstream barriers include but are not limited to the following:

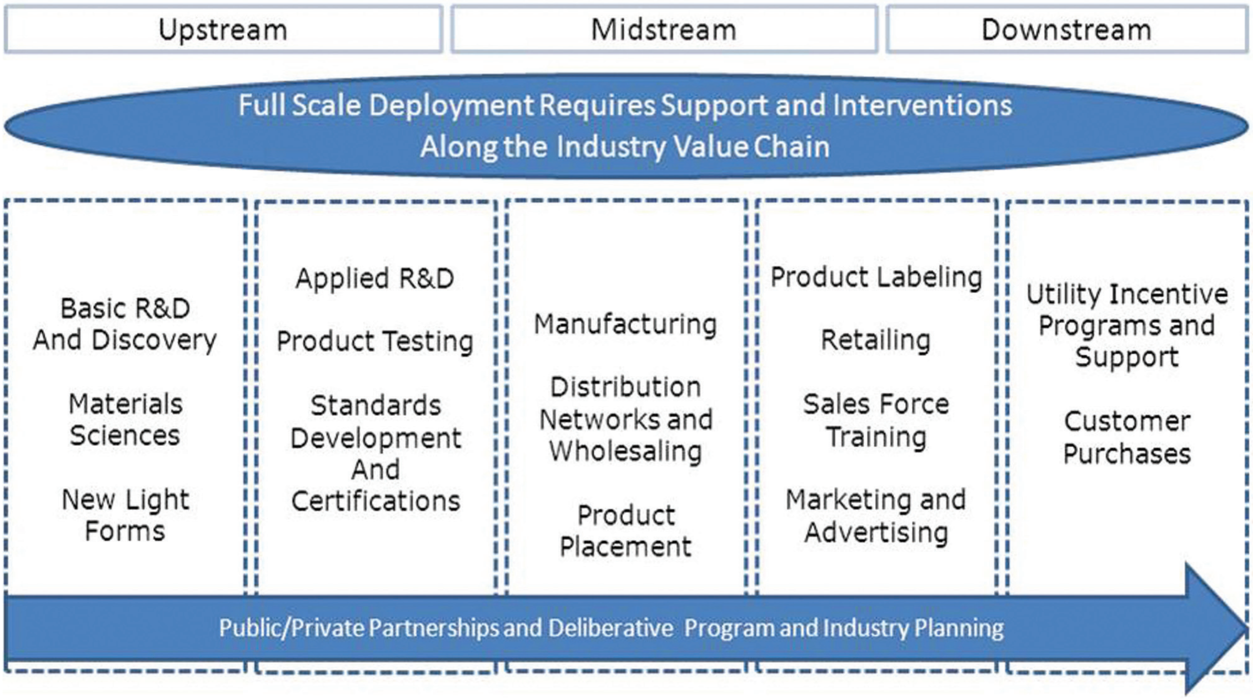

FIGURE 6.1 Solid-state lighting industry value chain.

1. Potential for inferior product quality compared to other illumination alternatives if sufficient scientific breakthroughs are delayed;
2. Bulky and heavy product designs due to SSL heat sink requirements;
3. Uncertain product lifetime, insufficient warranties, and lack of expedited testing procedures;
4. Costly product design and engineering, including choice of rare earths, wafer, and substrate design; and
5. Costly packaging and components and product manufacturing.

For uniform and consistent adoption of SSL, improvements need to occur upstream quickly to ensure that the market is not tainted early with inferior products and that SSL products continue to come down the cost curve.

Research and Development

Several upstream R&D needs must be addressed if widespread adoption is to occur. For example, LED R&D support is needed for improving the yield, efficiency, and operation at high power and high temperatures. One specific development, discussed in Chapter 3, is the development of low-cost, high-quality substrates for GaN for the growth of lattice-matched LED structures. The removal of such defects as would occur due to lattice mismatch in LEDs should increase reliability, yield, and efficiency. Improving LED light output and color is also important because most LED lamps currently available do not have the same light output and color rendering properties as incandescent lamps, and those that do have lower efficacies.

New dimming switches (“dimmers”) will need to be developed. As is the case with some CFLs, existing dimmers used with incandescent luminaires may not work with LED replacement lamps because of perceptible flicker, no smooth dimming, radio interference, and insufficient loading (dimmers require a minimum load). Even though LED lamps are labeled “dimmable” they are not universally dimmable by the myriad of dimming systems currently available. Consumers accustomed to incandescent dimming might notice and be bothered by the fact that LED lights do not get warmer in color as they dim.

LED lamp heat management needs to be improved. Even though heat management requirements are much less for LEDs than for incandescent lighting, both the point heat source nature of LEDs and the thermal sensitivity of the device create a thermal management challenge. If LEDs and OLEDs are to compete with fluorescent lamps and other light forms, particularly in the commercial sector, efficacy must be improved. And because many applications require an omni-directional lamp, the unidirectional emission from the LED must be modified by lamp design to become more omni-directional.

MIDSTREAM OPPORTUNITIES AND CHALLENGES

Midstream market activities, as defined for the SSL industry and depicted in Figure 6.1, include all of the means and processes for moving products from R&D and smaller-scale manufacturing to full-scale manufacturing and, ultimately, to architects, engineers, lighting designers, contractors, and retailers for sale to and use by consumers. This definition is broader than what might typically be defined as midstream because of the heavy emphasis in the SSL industry value chain on continued R&D and smaller-scale manufacturing, which in this case is included as an upstream activity. Midstream activities are also defined to include product labeling for consumer information and for marketing and advertising, which includes ENERGY STAR® and related labeling systems, such as the Northeast Energy Efficiency Partnership’s DesignLights^{TM} Consortium, established outside of the federal government.

Midstream market actors principally include distributors, designers, and contractors responsible for designing and installing lighting in commercial and industrial buildings, and lighting contractors and electricians serving the residential sector. Midstream labeling efforts help facilitate and inform decision-making by these market actors. The barriers and challenges to widespread adoption in residential, commercial, and industrial sectors, while generally similar, can also be quite different. The lighting systems design and product decision makers are different for each sector, and decision makers in each sector have a different level of knowledge and experience with SSL technology. Bringing information to all lighting decision makers uniformly and consistently through ENERGY STAR® or other labeling programs has proved valuable in deploying new lighting technologies, whether for CFLs in recent years or SSL today. Examples highlighting the success and value of labeling programs are discussed below and later in this chapter.

General midstream barriers include, but are not limited to, the following:

1. Risks associated with moving from demonstrations and niche market product manufacturing to full-scale standardized product manufacturing;
2. Availability of SSL products on the market in retail and other outlets with still uncertain product demand;
3. Lack of availability of some SSL products and light forms (not a full array of lighting solutions yet available);
4. Lack of awareness of applications and benefits of SSL by architects, design engineers, building professionals, and consumers; and
5. Lack of information and training of wholesalers and retailers on various SSL light forms, product applications, performance, and costs, which impede stocking decisions, product placements, and sales emphasis.

SSL Manufacturing

SSL manufacturing refers to the full range of activities and materials use, including intellectual property and labor to produce SSL products for sale, including for use in televisions, mobile devices, and signage, as well as end-use lighting products for general illumination in buildings. Each SSL product has its own set of manufacturing challenges, and LED and OLED technologies, in particular, as emphasized in previous chapters, present different challenges and opportunities for use in general illumination and specialty lighting and for lowering energy use and costs.

LED Manufacturing Yield

The low yield of high-efficiency LED devices with proper color and the fact that they are grown on relatively small substrates is what makes LEDs relatively expensive. The substrates (sapphire or silicon carbide) are typically 2 to 4 inches in diameter compared to 12 inches typically for silicon. The LED devices are sold to manufacturers for assembly into luminaires (i.e., SSL products). Some LED manufacturers, however, are vertically integrated and make the LED package and their own varied lighting devices and luminaires. All LED-based luminaires require optics to distribute the light, a large heat sink to remove the heat, and driver electronics to control the current input. The cost and assembly of these components is similar to other commonly used electronic devices, such as hand-held games and cell phones, where cost is dependent on manufacturing volumes and component size. As with other electronics, competition and progression along the learning curve associated with moving to higher-volume manufacturing will bring down the cost and price to consumers.

Another important benefit of improving the crystal growth and substrates is the effect on greater yields. The yield of high-efficiency LEDs at the proper wavelengths is relatively low under current design and manufacturing processes. Low enough, in fact, that manufacturers are "binning" their product. After testing, manufacturers put the product in bins each with a range of wavelengths and efficiencies and sell them to consumers at different prices. Binning is used when the yield is low and manufacturing processes do not have sufficient quality controls in place to ensure a consistent and uniform product. For most all other semiconductor devices, manufacturers have detailed sampling and testing of devices from large lots. Device functionality is also sampled and tested. Devices are typically made and sold to a given specification. Improved epitaxial growth technology should eliminate binning and substantially improve yields and lower costs. Improvements in LED efficacy, and thus efficacy of luminaires, will also result in lower cost and as a result increased SSL adoption.

Early manufacturing challenges need to be overcome, particularly if the United States wants to be home to a successful SSL manufacturing base. The risk of not manufacturing SSL products in the United States is one of continuing to import technology, intellectual property, and product and, thus, export money and jobs overseas. The U.S. LED manufacturing base, although substantially smaller than that of Japan or Korea, is still a multibillion-dollar industry and will at some point produce higher yields and higher efficiencies. The very large industry efforts currently under way, coupled with legislation that requires higher lighting product efficacies, with time should allow attractively priced lighting products to be available in the marketplace that meet the mandated U.S. efficacy standards.

LED Efficacy

The relatively high cost of general illumination LED lamps and luminaires today is due to the recently established manufacturing base and not necessarily to suboptimal designs and low yield, both of which will improve with time and from the natural learning curve associated with manufacturing electronic products. In addition, current LED products suffer from relatively low efficacy compared to their potential efficacy. LED luminaires require large heat sinks to maintain temperature and large electronic components to carry high currents. Higher-efficiency LEDs will contribute to a lower heat load, which would in turn substantially reduce the cost of the luminaire by reducing the size and cost of the heat sink and supporting electronics. Improving LED efficiency can lower luminaire costs by an amount roughly equal to the efficiency improvement and allow for smaller, lighter designs that are more attractive to consumers. Improvements in efficiency will come with scientific research and breakthroughs.

FINDING: To make LED-based luminaires and lamps at high efficacies (notionally those exceeding 150 lumens per watt) at prices lower than fluorescents, technological and manufacturing breakthroughs will be needed.

RECOMMENDATION 6-1: The Department of Energy should concentrate its funding on light-emitting diode core technology and fundamental emitter research that have the potential to lower costs of solid-state lighting products.

OLEDs

SSL products based on LEDs and OLEDs can fill separate lighting niches. Based on current experience, there do not appear to be any fundamental reasons why OLED lighting cannot become cost competitive with LEDs as engineering, design, and manufacturing infrastructure and experience with OLEDs are improved. The multiyear learning curve and multibillion dollar manufacturing base in Asia for OLED displays should significantly reduce costs and make the manufacture of OLED-based general lighting devices more attractive.

The manufacturing experience gained as OLEDs have emerged as an increasingly important display technology provides manufacturers with the experience and confidence to move this technology, with its unique features, into the lighting market in the near future (Willner et al., 2012). OLED displays have a much higher selling price than do light sources, and OLED costs will have to be substantially reduced for OLED lighting products to be viable in the market place. In this context, Universal Display Corporation in Ewing, New Jersey, provides significant intellectual property to the industry with their holdings of more than 1,000 patents covering many of the key technologies that are required to make high-efficiency OLED displays and lighting sources. In addition, Novaled in Germany has important intellectual property in low-voltage, high-efficiency OLED technology that may prove significant for lighting applications. Other chemical companies, notably Idemitsu Kosan, PPG (in Pittsburgh, Pennsylvania), and BASF, also have a portfolio of materials that they provide to the display industry. Intellectual property and manufacturing development is currently emerging as a global industry whose center is in Asia, but significant market strengths and players are also located in the United States and Europe.

Equipment manufacturers, which provide the key infrastructures needed for sustained growth in manufacturing, are also starting to take notice of the possibilities for potentially large developing markets for OLED displays and lighting. Aixtron, AG, the largest producer of MOCVD equipment for LED lighting, also produces (on still a small scale) organic vapor phase deposition systems for OLEDs. Applied Materials is the world's largest supplier of equipment for low-temperature polysilicon deposition on glass substrates used as OLED display drivers. Its division, Applied Films, supplies in-line deposition tools for "front-plane" OLED display materials deposition. ULVAC in Japan provides many OLED display manufacturers with evaporation systems, whereas Angstrom Engineering is a leading supplier of laboratory tools used in OLED device experimentation across North America. Most OLED display manufacturers have no single source for deposition tools, and work is continuing to engineer low-cost, scalable, and high-throughput methods to deposit and pattern organic thin films. It should be noted, however, that the current lack of a complete tool set for the manufacturing of OLEDs remains a limiting factor in their widespread and low-cost deployment as lighting sources. (See Chapter 3 for the committee's recommendations on where DOE should invest to enable widespread deployment of OLED SSL.)

Materials

There should be no impediments to the deployment of LED and OLED lighting products due to availability of starting materials. Gallium, one of the two components in the material set of the most commonly used LEDs, is a byproduct of aluminum manufacturing and is abundantly available. LEDs are manufactured with very small amounts of phosphor containing rare earths to create the color balance needed for efficient white output, as described in Chapter 3. The rare earths in phosphors, however, are in short supply globally and are mainly sourced today from China. If other supplies are not developed or the rare earths become much more expensive, then other alternatives need to be found to make white-light LEDs. DOE and the lighting industry disagree on the severity of this problem, and the potential consequence is that product supply might be in jeopardy if the industry view proves correct.[4,5] High-efficacy white-light LEDs can be manufactured with red, green, and blue LEDs, in which case phosphor is not required. In addition, quantum dots can be used to replace the phosphor, as discussed in Chapter 3. In the case of OLEDs, the materials are carbon-based and closely related to dyes used in paints and inks. Hence they are widely available, easy to synthesize, and typically inexpensive. Also, there do not appear to be toxicity issues in organic materials used in lighting that would impede their widespread commercial distribution.

Testing and Standards

Performance

As new and innovative products move to market, it becomes increasingly important that performance testing be standardized so as not to impede adoption. Currently the testing method for LED-based emitters—the so-called LM-80 standard (IES, 2008)—specifies data collection at various intervals over a 6,000-hour time period to evaluate lumen maintenance. Doing this requires 8 months of real-time testing to introduce a new product. The standard places a significant burden on new technology, for which new and improved product introductions face market pressure to occur at a faster pace.

The current standard for forecasting lumen maintenance, TM-21 (IES, 2011), which specifies no greater than 30 percent diminution in light output (the so-called "L70" point) in 25,000 hours of operation, appears to be more than adequate to meet market demand. In addition, efforts to increase efficiency should extend the LED lifetime even further by decreasing the operating temperature and removing process-related defects. Currently, the lifetime of luminaires will be limited by the lifetime of the supporting electronics and not the LEDs themselves (Next Generation Lighting Alliance and DOE, 2010). The reduced electric current requirements for more efficient LEDs should also have a beneficial effect on extending the lifetime of the supporting electronics.

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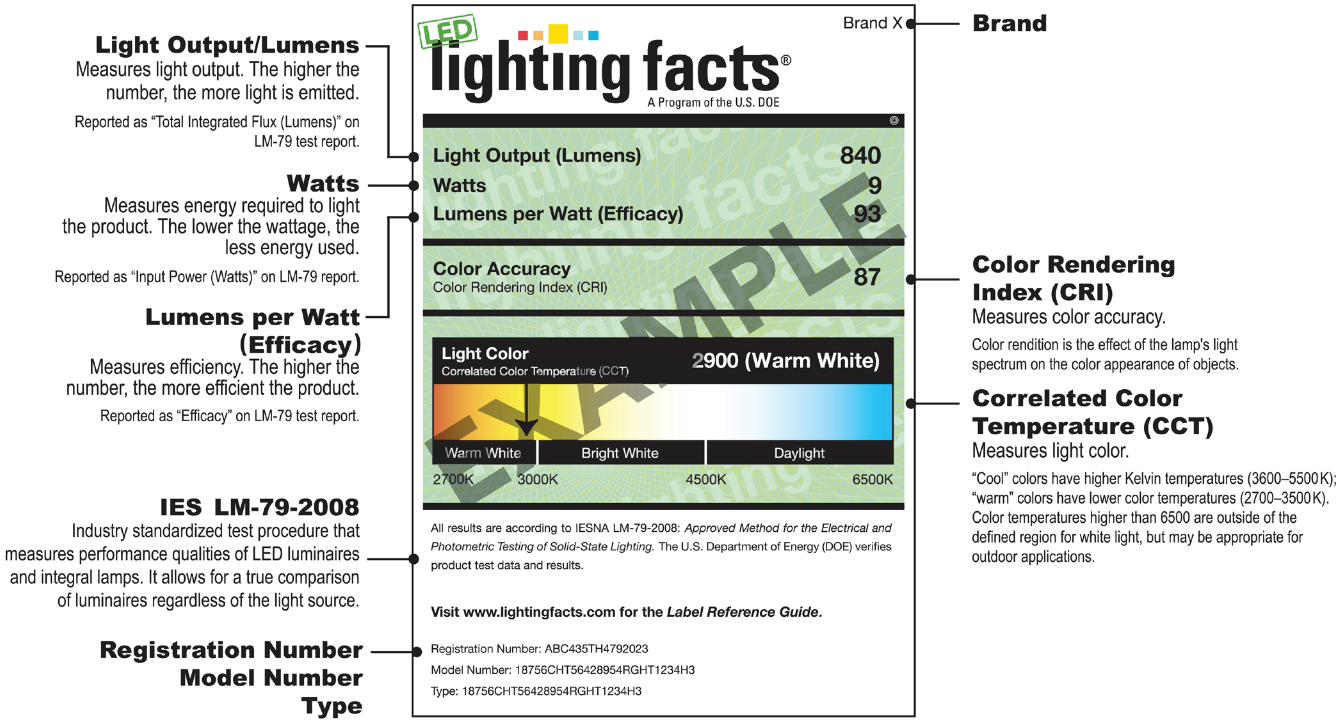
[4] DOE New Critical Materials Strategy, released December 15, 2010, see http://energy.gov/articles/energy-department-releases-new-critical-materials-strategy.

[5] NEMA letter to DOE, November 28, 2011. Available at http://www.nema.org/policy/paegs/rulemaking-comments.aspx.



LED lighting facts®
A Program of the U.S. DOE

Brand X

Light Output (Lumens)	840
Watts	9
Lumens per Watt (Efficacy)	93
Color Accuracy Color Rendering Index (CRI)	87
Light Color Correlated Color Temperature (CCT)	2900 (Warm White)

All results are according to IESNA LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting.* The U.S. Department of Energy (DOE) verifies product test data and results.

Visit www.lightingfacts.com for the *Label Reference Guide.*

Registration Number: ABC435TH4792023
Model Number: 18756CHT56428954RGHT1234H3
Type: 18756CHT56428954RGHT1234H3

Light Output/Lumens
Measures light output. The higher the number, the more light is emitted.
Reported as "Total Integrated Flux (Lumens)" on LM-79 test report.

Watts
Measures energy required to light the product. The lower the wattage, the less energy used.
Reported as "Input Power (Watts)" on LM-79 report.

Lumens per Watt (Efficacy)
Measures efficiency. The higher the number, the more efficient the product.
Reported as "Efficacy" on LM-79 test report.

IES LM-79-2008
Industry standardized test procedure that measures performance qualities of LED luminaires and integral lamps. It allows for a true comparison of luminaires regardless of the light source.

Registration Number
Model Number
Type

Brand

Color Rendering Index (CRI)
Measures color accuracy.
Color rendition is the effect of the lamp's light spectrum on the color appearance of objects.

Correlated Color Temperature (CCT)
Measures light color.
"Cool" colors have higher Kelvin temperatures (3600–5500K); "warm" colors have lower color temperatures (2700–3500K). Color temperatures higher than 6500 are outside of the defined region for white light, but may be appropriate for outdoor applications.

FIGURE 6.2 Lighting Facts Label. SOURCE: DOE and NGLIA.

FINDING: There are currently no industry-accepted accelerated life tests for SSL products, which slows the development and deployment of new reliable products.

RECOMMENDATION 6-2: The Department of Energy should continue efforts to help develop accelerated life tests for luminaires and LEDs.

Labeling of SSL Products

Several efforts are under way to standardize the information provided to consumers who purchase (or who consider the purchase) of SSL products. In December 2008, DOE, in collaboration with the Next Generation Lighting Industry Alliance (NGLIA), started a voluntary program known as SSL Quality Advocates. Members of this program pledge to use the "Lighting Facts Label" depicted in Figure 6.2, for SSL products in order to accurately communicate key performance characteristics of SSL devices to consumers and retailers.[6] The Lighting Facts Label is designed to help retailers and utilities compare qualities and benefits of similar products. Although it is not designed to be affixed to product boxes, it could appear on the product that is purchased by consumers or in retail displays.

The Federal Trade Commission (FTC) published a final rule on July 19, 2010, that required all medium screw-base lamps, including incandescent, compact fluorescent, and LED lamps, to carry their version of a lighting facts label. This label is intended to give individual consumers more information about the lighting products they are purchasing and will be on each replacement lamp box. An example of this label is shown in Figure 6.3. This rule went into effect on January 1, 2012. The voluntary DOE label will not be used on products that require the FTC label, in order to avoid confusion. Both labels are limited in information content, for example, no information of dimming capability or expected lifetime is given, both of which are important features for the buyer to consider.

While labels help communicate to consumers the performance of lamps they are considering purchasing, they do little to help them understand the choices that they have after the phase-out of general service incandescent lamps, which began January 1, 2012. The FTC label, for example, does not show how a particular lamp compares with other lamps on the market and does not indicate whether the lamp is dimmable. Furthermore, while both the DOE and FTC labels provide information on color quality, there are few studies elucidating people's preference across different attributes of lighting technologies (brightness, color, lifetime, and price, for example) to help guide how labels and communications could be more helpful to consumers purchasing decisions.

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[6] For more information, see http://www1.eere.energy.gov/buildings/ssl/advocates.html.

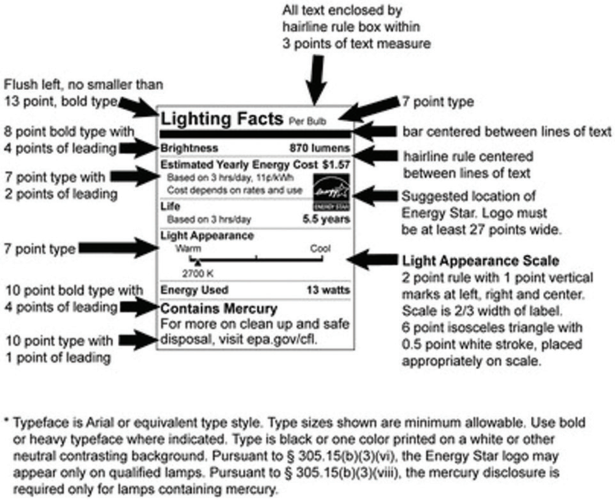

FIGURE 6.3 Lighting Facts Label. SOURCE: Federal Trade Commission.

FINDING: The labels designed by DOE and FTC for lamp packages help consumers better understand the characteristics of the product they are purchasing, but important information is missing from the labels that would help consumers to better differentiate products and assign value to the products.

RECOMMENDATION 6-3: The Federal Trade Commission should conduct a study in 2014, 2 years after introduction of the label, to determine the effectiveness of the labeling and whether it could be improved by additions and/or changes.

The Energy Independence and Security Act of 2007 (EISA 2007) provided an authorization of $10 million for each of the fiscal years 2009 to 2012 for public awareness. It appears that this money has not been appropriated, however, to help the education process.

FINDING: The move to new lighting is changing the entire vernacular used for lighting. It is going to be critical to label products in a clear way and educate retailers, consumers, lighting designers, and contractors on the opportunities and challenges with these new lighting technologies. To this end, EISA 2007 authorized $10 million a year to advance public awareness, but this money has not been appropriated.

RECOMMENDATION 6-4: The Department of Energy and lamp manufacturers and retailers should work together to ensure that consumers are educated about the characteristics and metrics of the new technology options.

As discussed in the Chapter 2 section "Current Federal and State Programs," the Environmental Protection Agency (EPA)-led ENERGY STAR® program is a voluntary labeling program designed to promote energy efficient appliances and other end-use products.

ENERGY STAR® labeling for lighting products applies to residential applications and, to the extent these are part of federal procurement activities, to commercial applications. Industrial applications do not currently fall within the scope of ENERGY STAR®. As a result, ENERGY STAR® does not provide the information and labeling that would enable lighting decision makers in the commercial sector (beyond federal procurements) and the industrial sector to make informed choices easily. This may significantly limit the impact of ENERGY STAR® overall in improving lighting efficiency in these sectors and impede widespread deployment of SSL technologies. Other programs, such as the Northeast Energy Efficiency Partnership DesignLights™ Consortium (DLC) initiated in 2009, partially fill this gap, but not as comprehensively or with as high a profile as the ENERGY STAR® program would (and does for residential sector applications).

The DLC is comprised of utility companies and energy efficiency program administrators throughout the United States interested in providing incentives for high-performing LED products that meet individual sponsor criteria. The DLC claims that its qualified products list includes only high-quality, high-performance, tested, and verified LED products. The qualified products list is used by program administrators to determine the products to include in their programs for consumer rebates.[7]

DOWNSTREAM OPPORTUNITIES AND CHALLENGES

Downstream market activities include all means and processes employed to support end-user purchases of lighting products, which can include some later-stage, midstream activities, such as training of retail sales staff, technical support for distributors, design professionals and contractors, and information dissemination to support consumer purchases. More typically, downstream activities are consumer focused and intended to encourage and support consumer purchases. Such support can be in the form of financial incentives to consumers or product "giveaways" or incentives to retailers to increase the percentage of SSL products available for purchase. The main downstream barriers include, but are not limited to, the following:

1. Higher first-cost of SSL products and systems, absent utility rebates or other government or manufacturer incentives, compared to conventional lighting;
2. Lack of consumer awareness and undervaluing the benefits of SSL;
3. Skepticism regarding SSL performance claims without sufficient field-testing;

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[7] Further information is available at http://www.designlights.org/.

4. Lack of utility financial incentives or government support for consumer purchases;
5. Uncertainty about SSL product use and replacement opportunities; and
6. Uncertainty associated with handling and disposal of toxins contained in SSL products at their end of life and the potential for future government regulations regarding safe disposal.

Downstream barriers, while generally similar among sectors and building type, affect decisions differently across the residential, commercial, and industrial sectors. This is because the decision maker for lighting choices differs in each sector, and the barriers are more difficult to overcome in one sector than in another. For example, the residential sector is characterized by thousands of point-of-purchase outlets, including small local retail establishments, big box stores, department stores, lighting showrooms, hardware stores, grocery stores, and local convenience shops. Each carries a wide variety of lamps, and most do not have sales staff that are knowledgeable about the characteristics of particular lighting products to aid consumers with their purchase. Moreover, consumers generally do not concern themselves with lighting characteristics—cost is a primary driver of lighting purchase decisions.[8] Providing information about lighting choices for residential purchases also differs. Utility bill stuffers and utility-sponsored in-store advertising, as well as collaborative labeling efforts like ENERGY STAR® and the DLC-qualified products list, aid utilities in determining for which products to provide incentives. Multifamily residential buildings have their own unique challenges, particularly where renters do not make lighting purchases but, rather, the building owner or a management company has this responsibility. In this case, cost is the primary driver for lamp purchases.

Commercial sector lighting decisions in new buildings are made by architects, engineers, and lighting designers working primarily with large building projects and by contractors and distributors whose primary focus is on smaller buildings. While final lighting decisions belong to the building owner, information and lighting systems options are provided by the lighting design community. Providing SSL information to architects, engineers, and lighting designers is therefore critical to widespread deployment of SSL in new construction.

The building retrofit market is different from the new construction market with respect to the activities and actors involved in lighting decisions. Major retrofit and renovation lighting decisions are most often made by contractors and energy services companies. Often, energy services companies (ESCOs) are also the primary contractors used by utilities for implementing lighting efficiency programs in building renovations and retrofits. Utility program activities and information targeted to ESCOs and contractors is important in the retrofit market.

Industrial sector lighting applications require large amounts of ambient light. Industrial buildings are less homogeneous than commercial buildings and often require specialty and task lighting. Such buildings and lighting systems are typically designed by facility designers specializing in industrial and facility applications, usually working in concert with manufacturers.

Utility-Administered Programs and Partnerships

Electric utilities have long played a role in incenting energy efficient product purchases by consumers—in part at the direction of their regulators or in response to state law and in part as a response to their customers' vocal support for such incentives and programs. Several successful programs are currently being offered by utilities to encourage purchase of SSL. As found by GSD Associates in its review of the Small Commercial Lighting Program administered by the New York State Energy Research and Development Authority (NYSERDA) (GSD Associates, 2005), training activities, technical support, and incentives encourage contractors, distributors, designers, and other trade allies to design and install lighting projects that result in better lighted spaces, which allow people to see more easily and which cost less to operate.

The small commercial market segment, although difficult and costly to reach through such programs, has been persuaded by this program to install energy efficient lighting. Large projects tend to have design teams and architects involved in project design and implementation, while smaller projects are often installed by lighting contractors with products selected by the contractor, distributor, or manufacturer's representative. By focusing outreach and information dissemination on these mid-market actors, program efforts can influence the practice of designing, specifying, and installing lighting for small commercial buildings—ultimately providing effective, energy efficient lighting to an increasing portion of the market.

Utility incentive programs working in concert with programs like the DLC help spur consumer demand for LED products and support manufacturers' interest in providing market-ready retail products. As an example, each year the Long Island Power Authority's (LIPA's) Energy Efficient Products Program (Box 6.1) works with lighting manufacturers and retailers to coordinate incentive programs that promote specific ENERGY STAR®-qualified products. In October 2010, LIPA announced a campaign encouraging customers to switch to energy-saving lighting by offering

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[8] While a high-performance lighting system typically has a payback of 4 to 8 years, a building owner's expectation for payback is shorter—around 2 years. A common problem in commercial buildings is that the person responsible for the operating budget is not the same as the person responsible for the construction budget. The decision to go ahead with a more expensive but better performing system would have to be made at a higher level in the organization, where other priorities often preclude sufficient attention to the building energy performance. In residential construction, the limiting factor often is available capital for the construction of a high-performance home.

BOX 6.1
The Value of Partnership in Rebating LED Purchases—Long Island Power Authority

Because of the success of the Long Island Power Authority's (LIPA's) initial LED fixture markdown, LIPA approved additional funding through 2011. The Energy Efficient Products Program in 2011 added LED bulbs to the product mix and established a sales goal of 25,000 ENERGY STAR®-qualified LED products. Through October 2011, a total of 31,326 products were sold through the LIPA markdown program of which more than 26,000 have been downlights—and sales through year-end 2011 were in excess of 37,000. Because of the early success of this program, both Cree, the manufacturer, and Home Depot, the retailer, provided rebates of their own, bringing the promotional retail price to just under $25. In 1 month following these added rebates, sales increased by more than 200 percent.

a discount on ENERGY STAR®-qualified LED recessed downlights. This promotion began as a pilot offering, when Home Depot began carrying one of the first ENERGY STAR®-qualified LED downlights. The retail price for this luminaire was $49.97, and with a $15 discount from LIPA, customers could purchase the luminaire for $34.97.

In addition to those sold at Home Depot, LIPA's Energy Efficient Products Program has allocated funding for more than 77,000 ENERGY STAR®-qualified LED lamps and luminaires to be sold at Costco, Sam's Club, and 15 independent electrical distributors across the Long Island service area. LIPA's Energy Efficient Products Program provides site visits to enrolled retailer partners and place point of purchase materials that call out the product's energy savings and promotional pricing provided by LIPA. Field representatives on LIPA's behalf provide training to the sales force at each location that joins the program. The program also provides retailer in-store promotions complete with light displays to educate consumers on the ENERGY STAR®-qualified LED products and demonstrate the energy efficient lighting products and their dimming capabilities. LIPA also promotes LEDs with bill inserts, newsletters, and print ads in local newspapers.[9]

National Grid offers a similar rebate and support services program in its New England service area, which covers several states (Box 6.2). This cross-state program is helpful in stimulating industry interest in serving the broader regional market. The market potential for ENERGY STAR®-qualified LED products is high, with opportunities for lamps, retrofit kits, and luminaires. Recent technology additions by GE and Philips now have cost-effective general ambient lighting solutions on the market for table lamps, whereas previously the LED market had been focused more on downlighting.

BOX 6.2
The Value of Partnership in Rebating LED Purchases—National Grid

National Grid has been promoting emerging solid-state lighting (SSL) technologies through its residential and commercial energy efficiency programs since 2007. Like most efficiency programs the goals are energy savings facilitating the introduction and sustainability of emerging technologies in the marketplace. To that end, National Grid is an active participant in the ENERGY STAR® SSL Lighting Program and Northeast Energy Efficiency Partnership DLC. National Grid has seen its program savings attributed to SSL increase over the past several years. Incentives are offered for a wide range of SSL products that are listed by ENERGY STAR® and the DLC. It is expected that up to 10 percent of the savings through its lighting programs could be attributed to SSL by the end of 2012. Most savings are derived through "downstream" incentives provided directly to the end-user for purchasing and installing solid-state lighting products. Starting in late 2010 for residential downlight retrofits and expanded to commercial reflector/directional lamps in 2011, National Grid has been offering "upstream" incentives to retailers and distributors for select solid-state lighting products. These upstream programs are targeting end-users that would otherwise purchase halogen-based incandescent products.

Reducing the price of SSLs for retail purchases has been shown to increase sales, as illustrated in Figure 6.4—showing monthly sales and price data compiled by Philips—which shows a significant increase in sales as LED prices fell.

LED End-of-Life Issues

One of the fundamental advantages of SSL is that the light-emitting structure does not contain materials that exceed existing U.S. regulatory toxicity levels. This is in contrast to other lighting systems that can contain highly toxic materials like mercury. However, other materials that are used in the white LED device packaging may have high levels of toxicity. Because these materials do not directly affect the fundamental light generation mechanisms, it is theoretically possible that substitution materials can be found and used to address toxicity issues. It is important to identify potential toxins in SSL and their role in the device's operation and use.

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[9] LIPA's LED program is continuing in 2012 with a goal of 52,500 products (lamps and luminaires) and a budget of $787,500.

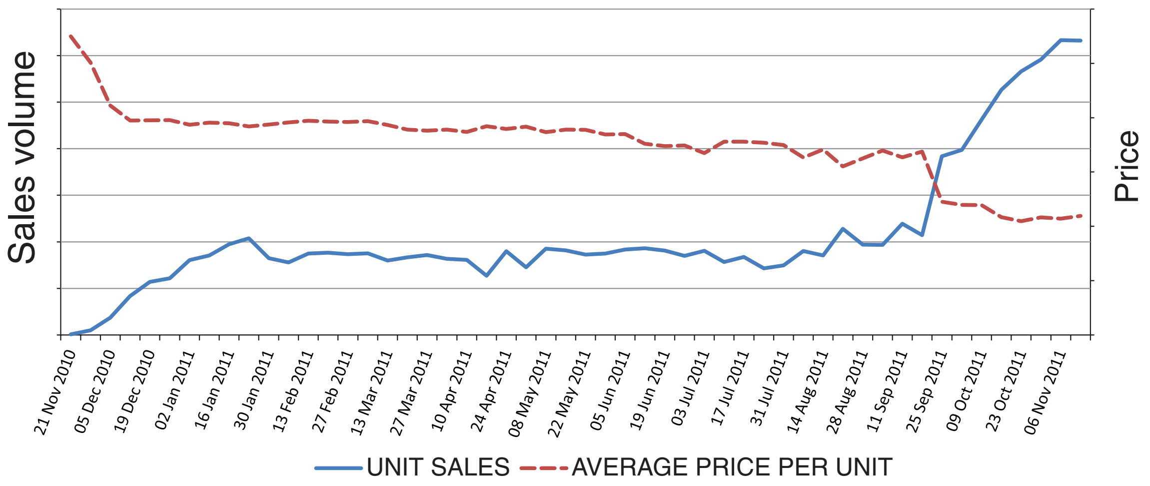

FIGURE 6.4 LED sales and price relationship. Courtesy Philips Lighting.

A recent study by researchers at the University of California, Davis (Lim et al., 2011), focused on the potential metallic toxins in LEDs. The study found that other than arsenic and some metals, the materials found in LEDs do not pose serious health risks. Among the LEDs tested, white LEDs appeared to be the safest for the environment because of the absence of toxic substances. LED lighting does not contain mercury, which is a miniscule component in all fluorescent lighting products.

Other potential toxicity issues can originate from the polymers used for the plastic lenses/encapsulate or from the phosphor used to generate white light. It is important to note that while this study found for blue/white LEDs that toxic levels for copper, silver, and nickel are exceeded, based on California's Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65), currently no federal regulations are violated by the levels of any material in white light LEDs. Furthermore, in LED-based lighting components only lead was found to be in the European directive Restriction of Hazardous Substances, and lead levels for this standard were not exceeded. Current SSL products appear to be in compliance with current environmental regulations, thus disposal should not impede widespread deployment. As regulations and materials used in manufacturing change, there needs to be continued study and vigilance so that disposal does not become an issue.

RECOMMENDATION 6-5: The Environmental Protection Agency in conjunction with the Department of Energy should conduct a study to understand the environmental impacts of SSL and to determine potential disposal strategies, if necessary, that should be developed as SSL deployment develops.

SSL COST AND ENERGY SAVINGS POTENTIAL

SSL Energy Savings Potential

The United States electricity consumption was 3,754 TWh in 2010, and lighting electricity consumption in all sectors accounted for roughly 19 percent of U.S. total electricity use.[10] DOE's estimates for lighting electricity use, by sector and technology type, in 2010 are shown in Table 6.1.

It is anticipated that the adoption of SSL will lead to large energy and attendant cost savings. Nonetheless, there is some uncertainty of just how large these savings might be. In this section, the committee reviews estimates prepared for DOE and also provides its own estimates.

A recent study performed for DOE by Navigant analyzed 12 markets for SSL, including four applications in general illumination; [11] four applications in outdoor lighting;[12] and four applications in consumer electronic displays (Navigant Consulting, 2011).[13] The study found the greatest savings potential to be in general illumination, where LEDs are estimated to have saved 0.38 TWh of electricity in 2010 alone because of the replacement of incumbent technologies with LEDs. The study estimates that if the four general illumination applications switched entirely to LEDs, savings could reach 133 TWh per year.

The Navigant study further estimates that the maximum theoretical energy estimated savings for all niche

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[10] EIA, 2012, Electricity sales and revenue data, available at http://www.eia.gov/electricity/sales_revenue_price/ index.cfm.

[11] These applications were as follows: (1) PAR, BR, and R shaped; (2) MR16; (3) 2-ft by 2-ft Troffer luminaires; and (4) general service A-type.

[12] These included roadway lighting, parking facilities, other area and flood lighting applications, as well as lighting outside residences.

[13] These included television displays, desktop monitor displays, laptop displays, and mobile handset displays.

TABLE 6.1 Estimates for Lighting Electricity Consumption in 2010 by Sector and Technology Type (in terrawatt-hours (TWh) per year)

	Residential	Commercial	Industrial	Outdoor	All Sectors
Incandescent	136	15	0	4	156
Halogen	12	15	0	1	28
Compact fluorescent	15	16	0	1	32
Linear fluorescent	10	250	23	10	294
High intensity discharge	0	49	35	98	183
LED	0	3	0	2	5
Miscellaneous	1	0		1	3
TOTAL	175	349	58	118	700

SOURCE: DOE (2012).

TABLE 6.2 Average Efficacy, Power, Daily Usage, and Lamps Per Household in 2010

	Incandescent	Halogen	CFLs	Linear Fluorescents	HID	LED	Other
Efficacy (lm/W)	12.1	14.3	52.1	67.3	62.4	40.7	37.5
Average wattage (W)	56	65	16	24	126	11	54
Average usage (h/day)	1.8	1.9	1.8	1.9	2.5	2.1	1.4
Average number of lamps per building	31.8	2.3	11.7	5.1	0	0.1	0.4

SOURCE: DOE (2012).

market applications[14] from 100 percent LED replacement is 263 TWh per year. A previous report (Navigant Consulting, 2006) projected that electricity savings from LED adoption by 2027 could be larger than the energy used to illuminate all homes in the United States today (NRC, 2010).

The committee developed its own estimates of energy savings potential that might result from different scenarios for the transition to LEDs for general illumination purposes in the U.S. residential and commercial sectors and outdoor applications. These estimates and their derivation are discussed in the following sections.

Potential Energy Savings for the Residential Sector

Today the residential sector accounts for 39 percent (1,446 terawatt-hours [TWh]) of U.S. electricity use.[15] Approximately 12 percent of residential electricity use is to power lights (DOE, 2012). Approximately 78 percent of lighting electricity use is attributable to incandescent lamps. For the committee's estimates, the baseline assumptions for lighting technology characterization and lighting energy use in the residential sector rely on the 2010 U.S. lighting market characterization from DOE. Estimates from DOE's market characterization for average efficacy, power, daily usage, and lamps per house in 2010 are shown in Table 6.2 for each technology type.

For the residential sector, it was assumed that usage patterns (hours per day for each technology type) will remain the same during the 2012-2020 time period. This excludes any potential direct "rebound effects"[16] associated with lighting energy use or other changes in consumer behavior. It is further assumed that the demand for illumination (measured in lumens) will be proportional to population growth. Using these assumptions, residential lighting use would grow from roughly 173 TWh in 2010 to 187 TWh in 2020 in the base case (Table 6.3), where the base case does not account for the impact of EISA 2007.

The first scenario estimates the impacts of EISA 2007 standards. Given the limits for rated lumen ranges and

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[14] Niche-application lighting includes under-cabinet kitchen lighting, under-cabinet shelf-mounted task lighting, portable desk task lights, outdoor wall-mounted porch lights, outdoor step lights, outdoor pathway lights, and recessed downlights, as defined for ENERGY STAR® Program Requirements for Solid State Lighting Luminaires Eligibility Criteria.

[15] EIA, 2012, Electricity sales and revenue data: http://www.eia.gov/electricity/sales_revenue_price/index.cfm.

[16] *Rebound effects* include the following consumer responses to an increase in energy efficiency. The *direct* rebound effect means that efficiency gains lead to a lower price of energy services, leading to an expanded or intensified use of the energy consuming products or services. For example, when consumers switch from incandescent lamps to compact fluorescents, they may leave their lights on for more hours than they did previously because their operation costs less. The *indirect* rebound effect reflects the case where an additional income that is freed up by saving energy costs can be used for other energy- or carbon-intensive consumption. For example, the income gained by installing an efficient furnace and insulating one's house could be bundled into additional air travel, leading possibly to an overall increase in energy consumption and greenhouse gas emissions (adapted from the definitions in Sorrell, 2010).

TABLE 6.3 Residential Electricity Consumption, Due to Lighting, as Estimated by the Committee

Year	BAU (TWh)	Scenario 1 (TWh)	Scenario 2 (TWh)
2010	173	173	173
2011	174	174	174
2012	176	176	176
2013	177	177	177
2014	178	107	56
2015	180	108	53
2016	181	109	50
2017	183	110	48
2018	184	110	46
2019	186	111	45
2020	187	112	44

NOTE: BAU = business as usual; TWh = terawatt-hours.

maximum rated wattages (see Chapter 2), these standards are only expected to substantially impact general illumination in the residential sector starting in 2014 (see Chapter 2 for the detail on EISA standards for general illumination). It is assumed that residential illumination services will be provided with the maximum allowed wattage while providing the same level of illumination. As a result, this scenario provides an estimate of the technical potential energy savings that can be anticipated as a result of EISA implementation.[17] Under this scenario, lighting technologies (whether CFLs or LEDs) would replace standard incandescent lighting starting in 2014, leading to residential electricity use of 112 TWh in 2020. Savings are estimated at 514 TWh between 2012 and 2020 (or an average of 57 TWh per year).

A more aggressive scenario was also developed in which LED lamp efficacy would continue to evolve according to projections in DOE's *Solid-State Lighting Research and Development: Manufacturing Roadmap* (DOE, 2011), shown in Table 6.4. The values in the table were depreciated by 24 percent to take account of the higher operating temperature. DOE does not report projections for overall lamp efficacies—only packaged device efficacies. Thus, a package-to-lamp efficacy ratio of 42 percent is assumed—which reflects the ratio between 2010 package efficacies and the efficacy for LED lamps reported in the DOE 2010 market characterization. Under this aggressive scenario, cumulative savings from 2012 to 2020 could reach 939 TWh (an average of 103 TWh savings per year).

Potential Energy Savings for the Commercial Sector

Baseline assumptions for average efficacy, power, usage, and lamp counts in the commercial sector are shown in Table 6.5 for each technology.

TABLE 6.4 Projections for LED Package Efficacies Used in the Committee's "Aggressive Scenario"

Year	Efficacy
2010	96
2012	141
2015	202
2020	253

NOTE: Projections are taken from DOE (2011, p. 24) and are for device temperatures of 25° C.

Using similar scenarios as those used to estimate residential sector savings, commercial lighting use would grow from roughly 347 TWh in 2010 to 406 TWh in 2020 in the base case. The base case does not account for the impact of EISA 2007. The committee estimates that the EISA 2007 standards will save 60 TWh between 2012 and 2020. A more aggressive scenario was also developed in which LED package efficacy would continue to improve according to the projections in Table 6.4, again depreciated to take account of the operating temperature. Under this aggressive scenario, widespread adoption of LEDs could lead to cumulative savings from 2012 to 2020 of 771 TWh (an average of 86 TWh savings annually) (see Table 6.6).

Residential and Commercial Energy Consumption Surveys

The Residential Energy Consumption Survey (RECS), the Commercial Energy Consumption Survey (CEBCS),[18] and the Manufacturing Energy Consumption Survey (MECS) have been the primary sources of data for estimating the nation's lighting energy use. These surveys were designed to be nationally representative of U.S. residential, commercial, and manufacturing building energy use and expenditures, and are administered by the Energy Information Administration (EIA). Since the late seventies, CBECS and RECS surveys have been conducted every 4 years. MECS was developed in the mid-1980s and has been conducted once every 4 years on average since its inception.

While RECS data are available for 2009, the most recent CBECS data available are from the 2003 edition of the Survey. EIA reports, "the 2007 data did not yield valid estimates of building counts, energy characteristics, consumption, and expenditures."[19,20] These data collection errors have since

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[17] Technical potential does not take into account different rates of adoption to technology turnover; it assumes the baseline technology is replaced by the efficient one overnight.

[18] CBECS includes all buildings in which at least half of the floor space is used for a purpose that is not residential, industrial, or agricultural. Thus, it includes also schools, correctional institutions, and buildings used for religious worship, in additional to "commercial" buildings.

[19] Available at http://www.eia.gov/emeu/cbecs/. Accessed May 24, 2011.

[20] EIA reports that because of the use of "a cheaper but experimental survey frame and sampling method by EIA's prime contractor, design errors in the construction of the method and selection of common building types, and an inability to monitor and manage its use in a production survey environment." Available at http://www.eia.gov/emeu/cbecs/. Accessed May 24, 2011.

TABLE 6.5 Average Efficacy, Power, Daily Usage, and Lamps Per Building in 2010

	Incandescent	Halogen	CFLs	Linear Fluorescents	HID	LED	Other
Efficacy (lm/W)	11.7	16.3	55.2	76.6	75.2	55.8	66.2
Average wattage (W)	53	68	19	37	350	12	11
Average usage (h/day)	10.4	12.4	10.4	11.1	11.1	20.8	14.8
Average number of lamps per building	14.1	8.7	39.3	301	6.3	6.9	0.1

SOURCE: DOE (2012).

TABLE 6.6 Commercial Electricity Consumption, Due to Lighting, As Estimated by the Committee

Year	BAU (TWh)	Scenario 1 (TWh)	Scenario 2 (TWh)
2010	347	347	347
2011	377	377	377
2012	381	381	381
2013	384	380	384
2014	387	379	337
2015	390	382	312
2016	393	385	292
2017	397	389	278
2018	400	392	268
2019	403	395	261
2020	406	398	257

NOTE: TWh = terawatt-hours; BAU = business as usual.

been corrected for the 2011 edition of CBECS. Without further support for data collection, policy makers and the lighting industry generally are left to rely on a nearly decade old survey data. The results of the survey, in either case, because of data limitations and the frequency of collection, are of little use to energy modelers and policy makers. EIA could ask consumers to fill out tables similar to Table 6.7, which uses the room types from DOE's 2010 Lighting Market Characterization study (DOE, 2012). The list of data and questions provided below is illustrative and not exhaustive.

Questions related to lighting use that EIA might consider asking CBECS survey respondents include the following:

1. The percentage of the square footage in buildings that are lighted when the building is operating under normal use conditions.
2. The best estimate of the percentage of square feet lighted for each room (space) identified in Table 6.7.
3. The percentage of room area in square footage, lighted during off hours—hours when the building is not in normal operating use, excluding the space lighted by emergency lighting.
4. The types of lighting used to light space in the building: fluorescent lighting other than CFLs; CFLs; incandescent lamps other than halogen lamps; halogen lamps; high-intensity discharge (HID) lights, such as high-pressure sodium, metal halide, or mercury vapor; and other types of lighting.
5. The type of lamp if "other" is identified in (4) above.
6. Questions about the percentage of floor space lighted by the types of lighting just identified, keeping in mind the following:
   a. The lighted portion of the floor space, so these percentages must add up to at least 100, but because more than one type of lamp can light the same area, it is also possible for them to add up to more than 100; and
   b. The percentage of the lighted area in the building lighted by each lighting technology, e.g., fluorescent lighting; compact fluorescent lighting; incandescent lamps; halogen lighting; HID; and other lighting types.

FINDING: Without appropriate data on consumer lighting use, it is difficult to establish an appropriate baseline of energy use in lighting and benchmark energy lighting efficiency.

RECOMMENDATION 6-6: The Energy Information Administration should collect data on energy demand for lighting through the Residential Energy Consumption Survey, the Commercial Energy Consumption Survey, and the Manufacturing Energy Consumption Survey. These efforts need to be pursued on a consistent basis and should consider adding questions that would increase the accuracy and usefulness of the data. In addition, detailed lighting market characterization based on nationally representative surveys, such as the 2001 Lighting Market Characterization from the Department of Energy, need to be pursued every 5 years. It would be helpful if these surveys are available before this study is updated in 2015.

Relative Cost Savings

Annualized Life-Cycle Cost of Lighting

The committee has developed a first-order comparison of the consumer life-cycle costs of light. The following assumptions are used: a retail electricity price of 0.11$/kWh and a 10 percent discount rate reflecting the implicit discount

TABLE 6.7 Suggested Design to Be Used in Future RECS to Assess Lighting Energy Consumption and Usage Patterns

Number of lamps used less than 1h/day:	Incandescent	Halogen	Compact Fluorescent Lamps	Linear Fluorescent	HID	LED	Other
Basement(s)							
Bathroom(s)							
Bedroom(s)							
Closet(s)							
Dining Room(s)							
Exterior(s)							
Garage(s)							
Hall(s)							
Kitchen(s)							
Laundry / Utility Room(s)							
Living / Family Room(s)							
Office(s)							
Other							

NOTE: Similar tables using other usage intervals (1 to 4 h/days, 4 to 12 h/days, and more than 12h/day).

rate of the consumer. The latter is in general higher than the market rate and the social discount, both utilized in analyses of public investment (Azevedo et al., 2009; Frederick et al., 2002). The committee employed two scenarios for daily usage of lights: 3 h/day and 10 h/day. The committee selected these two usage scenarios for two reasons: first, because they are representative of average daily usages in the residential and commercial sectors, and second, the results are found to be very sensitive to the number of hours of use. For each scenario, it is assumed that a 60 W incandescent lamp would be replaced by another lighting technology while the same energy service is provided (850 lumen). The level of the energy service and the baseline power for the incandescent lamp does not change the overall results for this assessment.

The committee assumed efficacies, lifetime, and cost per thousand lumen values shown in Table 6.8. The committee used the figures from DOE (2011) for efficacy and lifetime of warm and cool LEDs, and scaled them so that for year 2012 they are in reasonable alignment with the efficacies and lifetimes of LEDs that can currently be purchased by consumers in retail stores. These same scaling factors were used for years 2015 and 2020, resulting in the following weighting factors for cool and warm LEDs: lifetime factor of 0.5, efficacy factor of 0.51, and a markup factor for price of 3. This further translated into lifetimes and efficacies for LEDs that are half of the goals reported by the SSL roadmap, and capital expense costs per thousand lumen that are three times what is reported in the SSL roadmap.

The results of the analysis in the 3 h/d usage scenario are shown in Figure 6.5 and for the 10 h/d scenario in Figure 6.6.

TABLE 6.8 Assumptions Used in Calculation of Cost in Figures 6.5 and 6.6

		Efficacy (lm/W)	Lifetime (h)	Lamp Cost ($/lamp)	Service Cost ($/thousand lm)
Incandescent		14	2,000	0.5	0.5
Compact fluorescent lamp (CFL)		69	8,000	4.4	4.3
Fluorescent tube (T12)		69	5,000	2.0	2.0
Fluorescent tube (T8)		92	12,000	2.0	2.0
Fluorescent tube (T5)		104	20,000	2.0	2.0
Solid-state lighting (system level, warm white)	2012	72	25,000	23.0	22.5
	2015	103	25,000	6.7	6.6
	2020	129	25,000	3.1	3.0
Solid-state lighting (system level, cool white)	2012	90	25,000	18.4	18.0
	2015	114	25,000	6.1	6.0
	2020	132	25,000	3.1	3.0

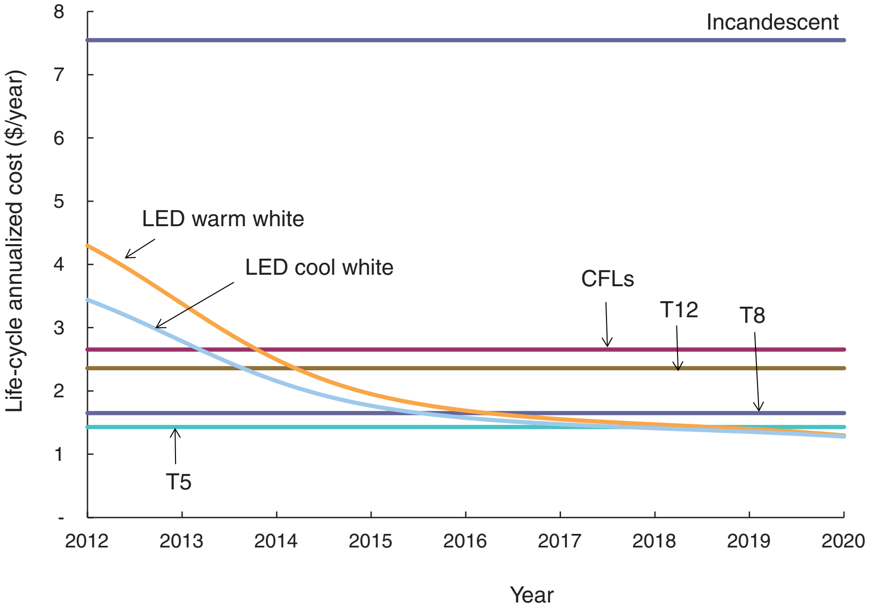

FIGURE 6.5 Annualized life-cycle costs of lighting technologies for 3 h/day usage scenarios. A 10 percent discount rate and an electricity price of $0.11/kWh are assumed.

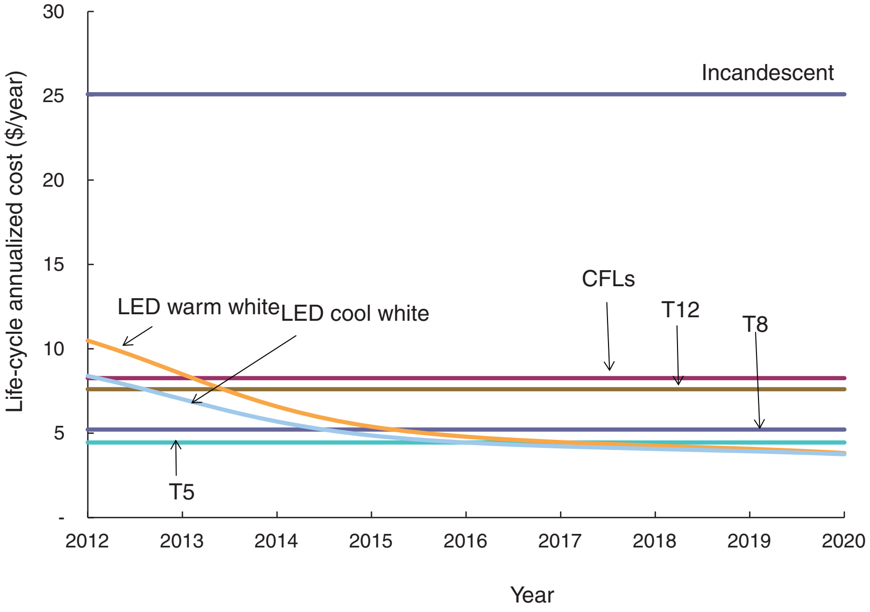

FIGURE 6.6 Annualized life-cycle costs of lighting technologies for 10 h/day usage scenarios. A 10 percent discount rate and an electricity price of $0.11/kWh are assumed.

FINDING: On a life-cycle basis, warm and cool white LEDs are already cheaper than incandescent lighting and will likely be comparable to that of fluorescent lighting technologies in the near future. For applications where the daily usage is larger than 10 h/d, cool white LEDs have now a similar consumer cost to CFLs or T12.

ROLE OF GOVERNMENT IN AIDING WIDESPREAD ADOPTION

Government can have a role to play in spurring technological innovations and development as well as new product introduction for products that offer economic, environmental, energy, and national security benefits to the nation.

SSL technology, when fully deployed, offers all of these benefits. The federal government and many state governments provide R&D support, manufacturing support, and information resources to market participants, including consumers, to advance the public good. Industry, health and safety, and environmental regulations also play a role in directing industry behavior as it conforms to meeting stated public policy goals.

Outreach and Communication on Implementing Standards

Chapter 2 reviewed targets and timetables set by various bodies around the globe for the implementation of more efficient lighting products for illumination. In many cases such targets and timetables are mandated by law, such as in EISA 2007. Some states were permitted to accelerate these timetables, and California issued a fact sheet discussing its early adoption.[21] This section reviews the efforts made in communicating the implications of these standards to the consumer public.

The phase-out of incandescent lamps in the European Union began on September 1, 2009.[22] At that time, the European Commission had not issued any guidance documents to consumers about the choices they would have after the transition date. There are no official estimates of the percentage of the European population in September 2009 that was aware of the changes in available products, but the European Lamp Companies Federation (ELC) estimates that more than half of the adult population was aware that changes were coming. This is largely the result of the media and retailers themselves in various European countries informing the consumers of the change. It should be noted, however, that some of the information provided was found by ELC to be inaccurate. Negative reactions were experienced in many countries, and it was not until a year later that the European Commission finally published its consumer guidance on its website where readers in Europe are now able to find it in their own language. ELC estimates that the total amount of money that the European Commission has spent on consumer awareness programs such as this is approximately half a million Euros. The member countries have not funded local language programs, at least not on a systematic scale. Much like in the United States, halogen incandescent lamps and LEDs are also available to consumers and meet the legislative requirement. Nonetheless, the European Union recognized the need for government intervention to aid in the lighting transition. The United States is the only country in the world where such significant changes in consumer choices of lamps has taken place without the government first making efforts to build awareness with the consumer.

An effective program for communicating to consumers about the incandescent lamp phase-out was launched by the Australian government. After Cuba instituted an import ban of filament lamps in 2005, Australia was the first country to announce, in February 2007, that incandescent lamps were going to be phased out in that country starting with an import ban in February 2009 and ultimately leading to a sales ban in November 2009. While the total amount of money that the Australian government has spent on consumer education is not publicly available, the federal and state governments in Australia collaborated with industry, retailers, and other stakeholders to produce in-store banners and other point-of-purchase materials intended to give guidance to the public about lamp choices. One such example is shown in Figure 6.7.

The Australian government also produced training manuals for electrical contractors to explain the new regulations and to teach the basics of lighting energy efficiency. The acceptance of these regulations has been high, and the overwhelming majority of media reports have been positive and in support of the regulations.[23] In other examples around the world, New Zealand joined Australia in June 2008 by announcing its intention to phase out incandescent lamps. The government of New Zealand worked with Australia to develop a common minimum efficacy standard for these lamps.[24] However, public opinion and a change in government in New Zealand led that country in March 2011 to repeal the ban. There is some speculation that the minimum standard may be re-introduced in New Zealand now that the election period is well over. The Canadian government announced in October 2011 that the phase-out in that country will be delayed by 2 years and will now begin in January 2014. Brazil is currently considering regulations similar to those in the United States and is watching developments in other countries closely. China recently announced that it will phase out 100 W incandescent lamps starting October 1, 2012 (Taylor, 2011).

On the other hand, the market share of incandescent lamps in Japan's residential market has for a long time been much lower than in other countries, even without government regulation or intervention. The traditionally high electricity rates have contributed somewhat to Japanese consumers voluntarily using fluorescent lighting in their homes, and after the 2011 earthquake and tsunami, as a result of extensive news coverage and government outreach to the public, the adoption of even higher efficiency LED lamps has accelerated.

Discussion

These examples suggest that national governments can greatly help increase public acceptance of higher-efficiency products with positive and proactive messaging. And conversely, by remaining passive, government can turn the public against such efforts. The committee found that in

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[21] See http://ww.energy.ca.gov/lightbulbs/lightbulb_faqs.html.

[22] European Commission Regulation 244/2009.

[23] Email communication with Bryan Douglas, Chief Executive Officer, Lighting Council Australia.

[24] AS/NZS 4934.2(Int):2008, which was later replaced by AS/NZS 4934.2:2011.

The right choice will save you money

- Together we spend around $900 million each year on lighting our homes
- Simply by switching to energy efficient light globes you can cut your lighting costs by up to 80%
- By choosing an energy efficient light globe, each of us can change the Globe™ today

A joint initiative of Australian, State and Territory Governments www.changetheglobe.energyrating.gov.au

FIGURE 6.7 Australian lighting information brochure. SOURCE: Reproduced by permission of the Commonwealth Department of Climate Change and Energy Efficiency, Australia.

California, media coverage has been fair and balanced and informative as to what the new standards really mean for consumers. As described in greater detail in Chapter 2, the rollout of CFLs encountered many problems. Foremost among them was the lack of a robust public education campaign to prepare consumers for this new technology. Related to this problem was the failure to consider and give sufficient weight to consumer expectations and reactions to this new lighting technology in terms of lighting quality, reliability, costs, and durability. Finally, there was an absence of any serious effort to proactively anticipate and attempt to address foreseeable problems with the technology that may be important to consumers, such as the objectionable color temperature, the potential for mercury pollution, and the inability to dim many CFLs. The lessons of CFLs have played out in other types of technology introductions, such as the transition to digital TV (see Box 6.3).

FINDING: As discussed in this chapter and in previous chapters, demonstration, outreach, and public and industry education programs are important for widespread adoption of SSL products and can help to avoid the problems encountered during the introduction of CFLs.

RECOMMENDATION 6-7: The Department of Energy should take a leadership role, in partnership with the states and industry, to examine and clearly identify opportunities for demonstration, outreach, and education so that its activities in support of SSL deployment are most valuable.

BOX 6.3
Lessons to Avoid: The Digital TV Example

The transition to digital television (DTV) provides a relevant analogy and some potentially useful lessons for the transition to solid-state lighting (SSL). As is the case with SSL, DTV offers important benefits and advantages over existing technologies, but because of public unfamiliarity with the new technology, consumer demand was "latent." Another similarity is that the successful deployment of DTV required action by several different industries that are not linked or coordinated, as is the case with SSL.

While DTV depended on the combined actions of equipment manufacturers, broadcast channels, and content providers, SSL requires synchronized action by lamp and fixture manufacturers, retailers, utilities, builders, and designers. Finally, both DTV and SSL raise challenging issues as to the appropriate role of government, industry, and other players in promoting a nascent technology that may not achieve an optimal pace and scale of market penetration relying on market forces alone. The Federal Communications Commission (FCC) and Congress mandated that all broadcast TV channels switch to digital broadcasts by a specified date, which after several delays and extensions, ended up being June 12, 2009.

The DTV transition resulted in substantial public and industry confusion, frustration, and resistance, as well as repeated delays, even though it ultimately succeeded. Perhaps the greatest problem was the failure of government to anticipate and address the public response to the technology change that many perceived as being forced upon them.

The federal government also failed to accurately anticipate how companies in the various industry sectors would respond to the DTV mandate. There were performance problems with DTV, such as the "digital cliff" that resulted in the complete loss of a signal when there was any interference, which was not communicated well to customers (Hart, 2008). There was also a failure to consider the environmental implications of suddenly making millions of analog TV sets obsolete, many of which ended up in landfills (Palm, 2009). The Government Accountability Office criticized the federal government for failing to have a comprehensive plan for the DTV transition (GAO, 2007).

Federal Facilities

The federal government is a major consumer of products that use and supply energy. In 2008, the federal government used 1.1 percent of the 99.3 quadrillion Btu of energy used in the United States (PCAST, 2010). The government owns or operates 3.5 billion square feet of buildings space and a fleet of 600,000 vehicles. Most federal government buildings are under the jurisdiction of the Department of Defense (DOD) and the General Services Administration (GSA). Executive Order 13514 was issued on October 5, 2009, to encourage the federal government to use its purchasing power to accelerate the introduction of more energy efficient technologies in its facilities. There have also been recent studies from the President's Council of Advisors on Science and Technology (PCAST, 2010) and the National Research Council (NRC, 2011) recommending the government use its purchasing power. The PCAST study recommended that "the Office of Management and Budget (OMB) should develop criteria for determining life-cycle costs and for including social costs in evaluating energy purchases" (PCAST, 2010, p. 20) for its building assets.

DOD and GSA are taking steps to align themselves with the Executive Order. In the Office of the Secretary of Defense (OSD) the Under Secretary for Acquisition, Technology, and Logistics has responsibility for overall energy use. On May 5, 2011, a memorandum to the facility directors of each of the services was issued describing the Defense Logistics Agency's sustainability and energy efficiency policy. This included a schedule of technologies, including LEDs, necessary to meet the 2015 goal to reduce energy density by a minimum of 50 percent compared to ASHRAE Standard 90.1 2010, as discussed in Chapter 2. Although OSD issued the overall policy, it is up to the services and ultimately the base commanders for implementation. The base commander is responsible for the final purchasing decision. The bases are currently being required to reduce their energy consumption by 10 percent.

Except for DOD facilities, GSA owns, leases, and operates all of the federal government facilities except for those of the National Institutes of Health, the Environmental Protection Agency's (EPA's) laboratories, and the Veteran's Administration's hospitals, to name a few. Approximately 50 percent of GSA space is owned, while the rest is leased space. Of 9,000 properties in 2,800 communities, about 8,000 are leased properties. Most of these are 10,000 square feet or less and are often part of a larger building. These 8,000 buildings use less than 50 percent of the energy used in federal government buildings. GSA is implementing a program that all owned or leased buildings over 10,000 square feet will have to incorporate energy efficient products during build or retrofit. They are converting the prescriptive standards to performance standards for specific services and components. GSA will not dictate the technologies to be used to meet the target.

FINDING: Government agencies that manage building assets can play a larger role in helping the deployment of energy efficient SSL.

RECOMMENDATION 6-8: The Office of Management and Budget should develop criteria for determining life-cycle costs and for including social costs in evaluating energy purchases and incorporating this methodology into agency procurements.

Public Funding of Applied Energy R&D

To highlight the role public funding can play in supporting industry development, one can look at the role DOE had in advancing energy technologies and helping move them in to the marketplace.

A study by the NRC assessing the benefits and costs of DOE's R&D programs in fossil energy and energy efficiency reported that, in the aggregate, the benefits of federal applied energy R&D exceeded the costs but observed that the DOE portfolio included both striking successes and expensive failures (NRC, 2001). Follow-up studies by the NRC to develop a methodology for estimating the prospective benefits of DOE R&D efforts determined that future success will depend on a number of factors, "including uncertainty about the technological outcome of a program, uncertainty about the market acceptance of a technology, and uncertainty about future states of the world" (NRC, 2005, p.2). DOE's SSL program has sponsored more than $120 million R&D activities over the past 10 years. While DOE is the primary funding agency for SSL, the Office of Science and the Advanced Research Projects Agency-Energy (ARPA-E) have also provided funding for some novel programs. With the exception of DOE and ARPA-E funding and some states funding, there has been very little investment in SSL by other governmental entities.

Large academic programs at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI), California Lighting Technology Center (CLTC) at University of California, Davis, and the Solid State Lighting and Energy Center (SSLEC) at University of California, Santa Barbara, have established strong public-private partnerships. Numerous other U.S. universities have strong research efforts in LED lighting. In terms of scientific publications, the United States, Japan, and China are leading globally.

Although it is difficult to assign benefits to collaboration, these processes can directly lead to technological breakthroughs and advance innovations.

In 1998, NYSERDA funded creation of the LRC at RPI. NYSERDA helped establish the LRC through a competitive grant solicitation. NYSERDA and Niagara Mohawk (now National Grid) helped establish the LRC's Partners Program beginning in 1988, and the number of partners has grown over time to a high of 15, in 2003, from government, utilities, manufacturers, and foundations from around the world. Today the LRC has 35 full-time faculty and staff and 15 graduate students conducting a range of research activities, including lighting technology, design, and human factors, to influence lighting practice through multidisciplinary research, demonstration, and education. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) was established in 2002 by the LRC as a collaboration of global private- and public-sector organizations (25 members in 2012) to specifically address the needs of SSL to gain acceptance for general illumination purposes through research and education.

In a similar vein, the California Lighting Technology Center (CLTC) at the University of California, Davis, a collaborative effort among the California Energy Commission, the DOE, and the National Electrical Manufacturers Association (similar to the LRC), was established in 2003 to "stimulate, facilitate, and accelerate the development and commercialization of energy-efficient lighting and daylighting technologies" (UC Davis, undated). CLTC works within the SSL value chain making key market connections by providing practitioners hands-on opportunities to learn about energy efficient lighting technologies and lighting design approaches. In addition, CLTC coordinates outreach and support efforts downstream, with existing utility-based energy centers, offering touring exhibits, demonstration materials, and technical assistance in the adoption of emerging technologies.[25]

UNINTENDED CONSEQUENCES

Supporting the widespread adoption of SSL requires the identification and consideration of possible unintended consequences in the application of such a new technology. The original goal for both industry and government in the development of SSL products was to save energy. It is worth noting, however, that seldom has a type of electric light source been discontinued during the more than 100-year-old history of electric lighting. The sulfur lamp from the 1990s, once installed to light the outside walking areas of DOE's Forrestal Building, is one of the very few examples. Even though the high-wattage metal halide lamp was introduced in the 1950s to replace the need for inefficient mercury vapor lamps, it is only now—60 years later—that the mercury vapor lamp is finally being phased out.

One of the consequences of introductions of new light sources has been the ability to light new applications, leading to a higher overall lighting energy use. In the case of SSL, one can already anticipate the more widely spread lighting of such applications as stairs on staircases (to improve safety), under-cabinet and cabinet lighting (for aesthetics as well as visibility), or closet bars (for special effect), just to name a few.

Finally, today's SSL products still typically have lower luminous flux than many of the light sources that they are intended to replace. The initial applications of these light sources in interior spaces may, therefore, be weighted more heavily than anticipated on the side of new applications that were never lighted before, raising the possibility of increased energy use for illumination.

CONCLUSION

Widespread adoption of SSL is dependent on a number of critical developments. The industry, still in its infancy, requires continued public and private funding and support for basic R&D to improve the efficacy, reliability, and color quality of SSL while simultaneously reducing costs. For SSL technologies to be deployed successfully in the lighting retrofit and replacement markets and in new building construction, several issues need to be addressed. First, SSL needs significant technological breakthroughs to improve products and lower costs. Second, the benefits of SSL in retrofit applications and in new lighting forms need to be well articulated and accurately assessed, based on rigorous and valid testing and in-field verification. Third, consumers need to have access to information relevant to inform decisions when selecting lighting solutions; products also need to be readily available where consumers shop. Lastly, public policy and public-private partnerships need to be focused to address needs as they exist and emerge along the industry's value chain, as depicted in Figure 6.1.

The introduction of new technologies in the lighting sector is relatively rare. As we consider the deployment of SSL solutions, lessons can be drawn from the problematic introduction of CFLs for homes and businesses. As detailed in Chapter 2, first generation CFL products were expensive, had poor color rendering, started dim and achieved full brightness only after several minutes, and often flickered, creating poor and inconsistent illumination. Like CFLs, SSL can substitute for conventional screw-base lamps, including incandescent and HID lamps and will soon be able to replace linear tube fluorescent lighting. SSL can also complement conventional lighting by adding accent and point source effect lighting in buildings and in architectural illumination, as discussed in Chapter 5. While the largest market for SSL in the near term is replacing screw-base lamps in residential and commercial applications, complementary and new SSL light forms offer a pathway to gain a foothold into new lighting markets. While the screw-base replacement lamp market might be the most profitable for the lighting industry in the near term in the residential sector, greater energy savings potential exists in making product for the commercial sector. This could include replacement and new construction markets as well as new light forms, which can change the way consumers use and perceive lighting in buildings. New light forms can produce energy savings but will likely not reduce energy use if they are complementary to or used in new construction unless they otherwise displace conventional lighting. To avoid the fits and starts associated with creating a sustainable consumer market for SSL, thought

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[25] Further information is available at http://cltc.ucdavis.edu.

needs to be given to the types and kinds of support needed for widespread adoption of SSL along the lighting industry value chain.

RECOMMENDATION 6-9: Government and industry should continue to provide support in a cooperative and comprehensive manner to upstream, midstream, and downstream market actors and should support market activities evenly.

DOE's efforts in helping advance SSL technology and manufacture in the United States and educating the lighting product community, including researchers, manufacturers, distributors, and sellers, have been judiciously chosen and well executed. For widespread SSL deployment to be successful and for consumer expectation to be met regarding SSL products, the much larger task of making the public aware of the major differences between incandescent and solid-state technology needs to be addressed. The lighting product and design community, working in concert with DOE, could best accomplish this task; however, if DOE takes on a leadership role, it will need additional funding and some direction from Congress to undertake this activity. Another source of funding for increasing public awareness might be the electric power industry, to help encourage the faster deployment of very energy-efficient LED lighting and avoid the backlash associated with CFL deployment.

With continued U.S. government support and funding and DOE leadership, the promise of low-cost and very efficient SSL could be realized, lowering U.S. energy needs and allowing the United States to be a significant SSL manufacturer and technology provider.

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7

Findings and Recommendations

CHAPTER 1

FINDING: A light source need not emit energy at every visible wavelength in order to achieve high color quality (see Figure 1.9). An understanding of the spectral power distribution's effects on luminous efficacy and the color properties of a light source will enable SSL developers to optimize energy efficiency while maintaining good color quality.

CHAPTER 2

FINDING: While it is difficult to discern the contribution of public policies on the adoption of energy efficient products, it is likely that a sizable fraction of the decrease in per capita energy consumption may be attributable to such policies, judging from a study of changes in energy consumption in California. However, the actual impact of any specific policy instrument is difficult to disentangle as is the impact on any one type of household energy use.

FINDING: Improvements in energy efficiency of lighting products have been brought about by a combination of legislation, regulation, RD&D funding, consensus standards, industry programs and initiatives, incentive programs, and market forces.

RECOMMENDATION 2-1: The Department of Energy should develop a study to quantify the relative impact of different policy interventions on the benefits of adopting efficient lighting.

FINDING: DOE has done an impressive job in leveraging a relatively small level of funding to play a leading role nationally and internationally in stimulating the development of SSL.

FINDING: In recent years, DOE has recently expanded its portfolio to include R&D into manufacturing projects, largely at the direction of Congress in the FY2009 ARRA funding and the FY2012 appropriations bill.

FINDING: The percentage of matching funds from R&D grant recipients was 18 percent for FY2011 funds. Ten years ago, for FY1999 to FY2001, it had been roughly 40 percent. It has declined in the past few years, particularly in the Product Development category.

RECOMMENDATION 2-2: The Department of Energy's solid-state lighting program should be maintained and, if possible, increased.

RECOMMENDATION 2-3a: The Department of Energy should seek to obtain 50 percent cost-sharing for manufacturing research and development projects, as was done with the projects funded by the American Recovery and Reinvestment Act.

RECOMMENDATION 2-3b: As part of the next mandated study of the Department of Energy Solid State Lighting program in 2015, an external review should be conducted to provide recommendations on the relative proportions of funding that should be dedicated to core technology, product development, and manufacturing projects, and what the targeted level of matching funding should be in each of these three funding categories.

FINDING: DOE's waiver of Bayh-Dole for projects funded by the SSL R&D program is discouraging some universities and small companies from participating in the program.

RECOMMENDATION 2-4: The Department of Energy should consider ending its waiver of Bayh-Dole for SSL funding.

FINDING: A technology-neutral specification for lighting would “raise the bar” for energy efficiency without putting the government in the position of picking and choosing which technologies should be included in ENERGY STAR®. Rather, those technologies that meet the specified criteria (e.g., luminous efficacy, color temperature, color rendering) would qualify for ENERGY STAR® labeling.

RECOMMENDATION 2-5: The Environmental Protection Agency should develop technology-neutral specifications for lighting that are based on performance rather than the type of lamp to provide the most objective and even-handed standards for energy efficiency.

FINDING: The ENERGY STAR® program provides useful information to residential consumers on energy efficient lighting products. While the ENERGY STAR® program also has a commercial and industrial segment, that program focuses on overall building efficiency rather than the certification and labeling of individual products (with the exception of luminaires in commercial buildings subject to federal procurement). Many other government and industry organizations address lighting product standards for the commercial sector.

FINDING: The EISA 2007 requirements for phasing out inefficient lighting have sparked significant resistance by some legislators, states, and citizens in advance of the implementations of the requirements.

FINDING: Given the currently available lighting technologies, LPD allowances for commercial buildings have reached their practical lower limits, according to lighting professionals. In the long term, SSL may permit LPD allowances in building codes to be reduced further.

FINDING: Minimum building energy standards and model codes are steadily improving. Nevertheless, their adoption, as well as uniform and effective enforcement of adopted energy codes, would result in significant energy savings.

FINDING: Model energy codes for residential buildings only address the efficacy of light sources, not their number or their use. The approach taken by the California residential energy code may be more likely to improve energy efficiency.

FINDING: Non-regulatory incentive programs may play an important role in the adoption of energy efficient lighting technologies.

RECOMMENDATION 2-6: The Department of Energy, in consultation with the Department of the Treasury, should conduct a study to determine the effectiveness and impacts of incentive program designs in fostering adoption of efficient lighting technologies.

FINDING: Other countries are following similar regulatory pathways as the United States in phasing out incandescent lamps, although at different schedules and with some delays.

FINDING: Disposal of mercury-containing CFL lamps and perceived health impacts are causing concern by some citizens and states. Federal legislators and other actors promoting CFL lamps failed to adequately anticipate these perceived risks and concerns.

RECOMMENDATION 2-7: Policy makers should anticipate real or perceived environmental, health, and safety issues associated with solid-state lighting technologies and prepare to address such concerns proactively.

FINDING: The experience with CFLs provides a number of lessons for SSL, including the following: (1) the quality, reliability, and price of initial products will be a critical factor in the success and consumer uptake of the product; (2) market introduction and penetration take time; (3) manufacturers and others should take care not to over promise; (4) consumer education is critical; and (5) ENERGY STAR® and other credible performance standards can play important roles in raising quality and confidence.

CHAPTER 3

FINDING: LEDs and OLEDs are complementary lighting sources that can together offer a wide range of lighting solutions. OLEDs can provide large-area diffuse lighting, while, in the same venue, LEDs form intense point sources, useful for spot illumination and downlighting. The committee finds value in supporting rapid developments in both technologies, because they both represent large possible markets, new applications, and tremendous energy savings.

FINDING: LED and OLED efficiency and performance are still limited by fundamental materials issues. Improvements in efficiency at the device and materials level, as targeted by the Department of Energy (DOE) SSL roadmap, will have a “lever effect”—influencing the design, performance, and cost of the luminaires. Therefore, improvements in efficiency and performance of the entire SSL system are linked to further fundamental investigations in core technology on emitter materials.

FINDING: Current LED dies used in SSL lighting suffer from inhomogeneities in the light output, color, and operating voltage that necessitate “binning” (hence testing) of dies from a single wafer. This variability severely constrains the yield of the manufacturing process and raises the cost of the technology. These inhomogeneities are in turn related to fundamental materials and materials growth issues.

RECOMMENDATION 3-1: The Department of Energy should continue to make investments in LED core technology, aimed at increasing yields, and in fundamental emitter research to increase efficacy, including improvements in the controlled growth and performance of the emitter material. DOE should carefully consider the range and depth of funding in its portfolio of investments in these areas, given the existing technological challenges, in order to determine how the targeted goals of device performance can indeed be met.

FINDING: Efficient operation of LEDs depends on a number of critical factors related to materials defects, structure, and strain. Such factors not only limit device efficiencies, but also lead to thermal and current droop; all have a major impact on the cost and performance of LED lighting.

FINDING: The color output of LEDs is extremely sensitive to the control of materials composition and thicknesses of the LED structure, which in turn are influenced by the control of the MOCVD growth process.

FINDING: A number of approaches have successfully been used to achieve and modulate color rendition for LED lighting. Phosphor-converted and color-mixed LEDs show promise but face different challenges. The ultimate choice of approach will depend on a multiplicity of issues regarding sensitivity of color control, efficiency, reliability, manufacturability, and cost.

RECOMMENDATION 3-2: The Department of Energy has provided excellent guidance in its roadmap targets for both phosphor-converted and color-mixed light-emitting diodes. Core investment in these technologies should be continued, with consideration for promising new technologies (e.g., quantum dot layers replacing phosphors).

FINDING: Production-scale MOCVD growth of LEDs is a complex process. The uniformity and yield of the structures grown (and hence of the optical performance of the LEDs) is strongly and negatively affected by small variations in the MOCVD growth process. The thermal and lattice mismatch between substrate and overlayer exacerbates the sensitivity of the growth process. Further difficulties of growth control are anticipated with use of substrates with increased diameter.

RECOMMENDATION 3-3: The Department of Energy should fund research to develop instrumentation for in situ monitoring and dynamic control of the metal organic chemical vapor deposition growth process.

FINDING: Significant improvements in LED efficiency, yield, and reliability are possible by using GaN substrates and latticed-matched epitaxial growth processes. Currently, there are no viable techniques for producing high-quality, low-cost GaN substrates. While realization of low-cost GaN substrates is not assured, the potential payoff of this research is immense.

RECOMMENDATION 3-4: The Department of Energy should make a long-term investment in the development and deployment of gallium nitride substrates.

FINDING: LED efficiency and performance is still limited by materials issues. Improvements in efficiency at the device level, as targeted by the DOE SSL roadmap, will have a "lever effect," influencing design, performance, and cost of the luminaires. Improvements in efficiency and performance are linked to further fundamental investigations in core technology on emitter materials.

RECOMMENDATION 3-5: The Department of Energy should continue to make investments in light-emitting diode core technology and fundamental emitter research. Its portfolio of investments in these areas should be extensive enough to ensure that the targeted goals of device performance can indeed be met.

FINDING: A number of promising approaches have been developed to increase outcoupling efficiency.

RECOMMENDATION 3-6: The Department of Energy should focus on efforts that result in significant light outcoupling enhancements for OLED that are low-cost to implement and are independent of both wavelength and viewing angle.

FINDING: OLEDs show a decrease in efficiency as the current is increased. This results in a reduction in efficiency at high brightness.

RECOMMENDATION 3-7: The Department of Energy should support research to understand the fundamental nature of efficiency droop at high currents in organic light-emitting diodes and to seek means to mitigate this effect through materials and device architectural designs.

FINDING: The lifetime of OLEDs is very sensitive to extrinsic factors such as exposure to air and moisture. The low-cost fabrication of large area OLED lighting sources requires a high degree of fabrication competency that can ensure package hermiticity along the entire large package periphery and scavenge excess water and oxygen that might have been enclosed during the package manufacture.

RECOMMENDATION 3-8: To create a highly environmentally robust organic light-emitting diode (OLED) lighting technology, the Department of Energy should invest in materials and packaging technologies that make OLEDs resistant to degradation over their long operational lifetimes.

In particular, important areas for investment include finding low-cost means to eliminate glass as a primary package constituent, devising molecules and device architectures that are resistant to degradation on exposure to atmosphere, and developing sealing technologies that are fast, precise, and robust to bending.

FINDING: OLEDs are area light sources, and their rise in temperature, even at the highest drive currents (and hence brightness), is minimal. This is a major distinction from LEDs, which are intense point light sources and, hence, operate at high temperatures that require extensive heat sinking and care in their installation. Nevertheless, OLED operational lifetime is very sensitive to temperature increases. As the room temperature rises, the OLED lifetime can be expected to be noticeably decreased.

RECOMMENDATION 3-9: The Department of Energy should support the pursuit of material sets and device architectures that would increase the useful operational lifetimes of high-intensity white organic light-emitting diodes.

FINDING: This is potentially the single most important metric to meet in OLED lighting. It requires simplification of device structure, use of ultralow-cost substrates such as metal foils, development of replacements for costly transparent anodes (current technology is indium tin oxide), low-cost encapsulation technologies, and so on. Also, investment in equipment infrastructure is essential for the success of low-cost, manufacturable products. In-line vacuum deposition sources, roll-to-roll processes on flexible substrates, ultrahigh-speed organic vapor phase deposition, and in situ encapsulation techniques will all require substantial infrastructure development.

RECOMMENDATION 3-10: The Department of Energy should aggressively fund the development of all possible routes leading to significant (100×) cost reduction in organic light-emitting diode lighting sources.

FINDING: Extending the lifetime of blue phosphorescent OLEDs is a primary area where investment will have substantial payoff. It involves a combination of advances in the development of new materials, device architectures, encapsulation, and contact technologies, as well as a fundamental advance in the understanding of degradation processes. Interactions between the phosphor and the conductive host will have an influence on mitigating *efficiency droop*, or the de-excitation of the molecules in the OLED. The mechanisms for thermally induced degradation also require clarification. Encapsulation compatible with flexible, lightweight substrates is also an important area of development.

RECOMMENDATION 3-11: Given the interactions between the phosphor and the conductive host molecules, the Department of Energy should direct studies for determining what chemical structural combinations lead to the most robust materials sets. Fundamental studies of the degradation mechanisms should be carried out both at room and elevated temperatures. Research on understanding contact and ambient degradation routes and their minimization should also be supported.

FINDING: Increased outcoupling remains the single most beneficial route to increasing device efficiency from the current 100 lm/W to nearly three times that value. Methods to achieve this should be inherently very low cost and deployable over very large areas, even in the context of roll-to-roll manufacture. The outcoupling technology should have the additional attributes of being wavelength and intensity independent, and the light source should exhibit no color shifts as the viewing angle is varied from normal to highly oblique. Clearly, a viable outcoupling technology should not otherwise impact or degrade OLED performance.

CHAPTER 4

FINDING: While the majority of LED products in the marketplace have better luminous efficacy than traditional lighting technologies, for many of them, other quality factors, such as useful life, color appearance and rendering properties, beam distribution, flicker, and noise, may be inferior to traditional lighting products. Even though the optimistic view is that energy has been saved by using SSL technologies, if other factors such as system life, lamp to lamp color variation, glare, flicker, and dimming, do not meet user expectations, they could slow down market adoption of SSL technologies.

FINDING: LED efficacy strongly leverages cost, physical size, and weight of SSL luminaires.

RECOMMENDATION 4-1: The Department of Energy should place a high priority on research directed at increasing the efficacy of LEDs.

FINDING: OLEDs are typically low-intensity, large-area lighting sources. However, numerous applications require more intense, specular lighting as afforded by LEDs. The lifetime of OLEDs are negatively impacted by high currents used to generate high brightness.

RECOMMENDATION 4-2: The Department of Energy should invest in research that can lead to small area but high-intensity lighting systems with organic light-emitting diode for use in directional illumination applications.

FINDING: Because of the large number of different ways to construct an LED lamp, industry has recognized the need for some levels of standardization and has organized to develop such standards.

FINDING: OLEDs are still in their infancy. While the driver electronics may have many similarities to that of LEDs, there are some essential differences in their operating performance because of the large capacitive load presented by OLEDs.

FINDING: LED replacements for incandescent lamps may not work with all existing control infrastructure, especially dimmers.

RECOMMENDATION 4-3: Industry should develop standards for LED drivers and future generations of lighting controls that will ensure that all LEDs that are designated "dimmable" work well with all new dimmers in the future. In the meantime, SSL products should indicate on their labels that they may not function correctly with presently installed controls.

FINDING: Additional standards or revisions to standards are needed to resolve unknowns that will otherwise be left to consumers and other lighting decision makers to resolve, specifically test procedures and/or de-rating factors that account for higher temperature environments, where performance may vary from LM-79 data, and alternatives to LM-80 that can predict whole product life more accurately. In the case of the latter, research is under way to develop test procedures to predict whole product life more accurately.

RECOMMENDATION 4-4: (a) Manufacturers should publish data for photometric quantities and life per industry standards and de-rating factors for use in typical applications. (b) IESNA should develop a test procedure to predict whole product life more accurately. (c) ANSI should revise the color binning standard to ensure imperceptible color differences between two adjacent light sources.

FINDING: There are existing standards for THD and PF for electronic ballasts for linear fluorescent lamps, but at present there are no such residential standards for LED drivers that are external to the lamp. Standards for low-wattage, integrally ballasted CFLs with medium screw-bases in residential applications allow low PF and high THD.

RECOMMENDATION 4-5: For external solid-state lighting drivers in general, industry should adopt the same total harmonic distortion and power factor standards that are in place for electronic ballasts for linear fluorescent lamps. Industry should revisit the standards for low-wattage medium screw-base lamps to determine their impact on power quality before applying them for light-emitting diode lamps, and these standards should match those for commercial and industrial applications.

FINDING: The power requirements and flexible physical configurations of SSL make attractive the concept of a new dc building lighting infrastructure.

RECOMMENDATION 4-6: The SSL industry should collaborate with other industries such as building materials and construction to explore the challenges and potential benefits of developing and adopting standards for a new dc electrical infrastructure.

CHAPTER 5

FINDING: Replacing incandescent or fluorescent lamps with LED lamps provides an opportunity to greatly reduce power load and increase lamp life. They can also turn on instantly and are able to dim. The market for these lamps will only expand as the light and color quality improve and the costs are reduced.

FINDING: The best LED applications take advantage of the directional light put out by LEDs, such as downlights, wall washers, and grazing and accent lighting.

FINDING: Omni-directional LED lamps are not as efficient as linear fluorescent lamps. In order to become a viable replacement alternative for linear fluorescent lamps, SSL products need to improve efficacy, become more omni-directional, and reduce initial cost in order to compete with fluorescent lamps.

FINDING: SSL must have power quality standards to mitigate against high THD, low PF, and repetitive peak current issues.

FINDING: New dimmers must be able to operate LED luminaires and lamps smoothly without perceptible flicker and should be available to dim from 100 percent power to 1 percent power.

FINDING: Industrial applications of SSL products will require higher light output for ambient lighting because of their use in high ceiling applications.

FINDING: Discomfort or disability glare can be an issue with directional LED luminaires. Luminaires must be designed so as not to increase glare potential compared to their HID counterparts.

FINDING: LED white light products produce light in spectral regions that may create environmental and health concerns. These concerns should be recognized in the design and application of LED luminaires.

FINDING: Exterior lighting is a prime candidate for early adoption of SSL because of the lower lighting levels required in such applications and the optical control, long life, and dimmability characteristics of SSL.

FINDING: Were OLEDs to become commercially viable, they would provide an opportunity to change the form factors of how luminaires are designed with smaller sizes, less material, and fewer physical constraints and offer an ability to change from traditional-looking luminaires to internally lighting surfaces and materials.

FINDING: Replacing existing incandescent lamps with LED lamps in existing luminaires may under certain conditions cause the LED to overheat. Examples include downlights adjacent to insulation or in enclosed luminaires. This is true also of the use of SSL in industrial applications having higher ambient temperatures. LED lamp heat management needs to be addressed for all such applications.

FINDING: Many LED lamps currently available do not have the same light output and color rendering properties as incandescent lamps. SSL products with improved light output that are color consistent from product to product will be needed for the public to readily accept these as replacements for incumbent lighting technologies.

FINDING: There is no standardized method for measuring the lifetime of SSL products.

FINDING: The CRI does not always yield results that predict or evaluate performance well, so manufacturers cannot rely on it to guide product development.

CHAPTER 6

FINDING: To make LED-based luminaires and lamps at high efficacies (notionally those exceeding 150 lumens per watt) at prices lower than fluorescents, technological and manufacturing breakthroughs will be needed.

RECOMMENDATION 6-1: The Department of Energy should concentrate its funding on light-emitting diode core technology and fundamental emitter research that have the potential to lower costs of solid-state lighting products.

FINDING: There are currently no industry-accepted accelerated life tests for SSL products, which slows the development and deployment of new reliable products.

RECOMMENDATION 6-2: The Department of Energy should continue efforts to help develop accelerated life tests for luminaires and LEDs.

FINDING: The labels designed by DOE and FTC for lamp packages help consumers better understand the characteristics of the product they are purchasing, but important information is missing from the labels that would help consumers to better differentiate products and assign value to the products.

RECOMMENDATION 6-3: The Federal Trade Commission should conduct a study in 2014, 2 years after introduction of the label, to determine the effectiveness of the labeling and whether it could be improved by additions and/or changes.

FINDING: The move to new lighting is changing the entire vernacular used for lighting. It is going to be critical to label products in a clear way and educate retailers, consumers, lighting designers, and contractors on the opportunities and challenges with these new lighting technologies. To this end, EISA 2007 authorized $10 million a year to advance public awareness, but this money has not been appropriated.

RECOMMENDATION 6-4: The Department of Energy and lamp manufacturers and retailers should work together to ensure that consumers are educated about the characteristics and metrics of the new technology options.

RECOMMENDATION 6-5: The Environmental Protection Agency in conjunction with the Department of Energy should conduct a study to understand the environmental impacts of SSL and to determine potential disposal strategies, if necessary, that should be developed as SSL deployment develops.

FINDING: Without appropriate data on consumer lighting use, it is difficult to establish an appropriate baseline of energy use in lighting and benchmark energy lighting efficiency.

RECOMMENDATION 6-6: The Energy Information Administration should collect data on energy demand for lighting through the Residential Energy Consumption Survey, the Commercial Energy Consumption Survey, and the Manufacturing Energy Consumption Survey. These efforts need to be pursued on a consistent basis and should consider adding questions that would increase the accuracy and usefulness of the data. In addition, detailed lighting market characterization based on nationally representative surveys, such as the 2001 Lighting Market Characterization from the Department of Energy, need to be pursued every 5 years. It would be helpful if these surveys are available before this study is updated in 2015.

FINDING: On a life-cycle basis, warm and cool white LEDs are already cheaper than incandescent lighting and will likely be comparable to that of fluorescent lighting technologies in the near future. For applications where the daily usage is larger than 10h/day, cool white LEDs have now a similar consumer cost to CFLs or T12.

FINDING: As discussed in this chapter and in previous chapters, demonstration, outreach, and public and industry education programs are important for widespread adoption of SSL products and can help to avoid the problems encountered during the introduction of CFLs.

RECOMMENDATION 6-7: The Department of Energy should take a leadership role, in partnership with the states and industry, to examine and clearly identify opportunities for demonstration, outreach, and education so that its activities in support of SSL deployment are most valuable.

FINDING: Government agencies that manage building assets can play a larger role in helping the deployment of energy efficient SSL.

RECOMMENDATION 6-8: The Office of Management and Budget should develop criteria for determining life-cycle costs and for including social costs in evaluating energy purchases and incorporating this methodology into agency procurements.

RECOMMENDATION 6-9: Government and industry should continue to provide support in a cooperative and comprehensive manner to upstream, midstream, and downstream market actors and should support market activities evenly.

Glossary

A-lamp: An A-lamp is what most individuals think of when they hear the term "light bulb." A19 is the most common form factor used in residential applications. Most of these are what are known as medium screw-base A19 lamps, which describes the sockets with which the lamps are compatible. These include most typical incandescent lamps and many compact fluorescent lamps.

avoided cost: The incremental cost to an electric power producer of generating or purchasing a unit of electricity or capacity or both.

ballast: An electronic device that converts incoming electricity to the proper voltage and current required to start and maintain the operation of a lamp.

bandgap: The energy gap between a semiconductor's valence and conduction bands. The valence band is the highest energy level occupied by an electron, while the conduction band is the lowest unoccupied level. External energy is necessary to excite an electron through the bandgap from the valence band to the conduction band.

binning: General term for the production and sorting methodologies used by LED makers to ensure that the LEDs they manufacture conform to stated specifications for forward voltage, color, and luminous flux. (Philips Color Kinetics, 2010)

Btu: The British thermal unit is the traditional standard of measure for the quantity of heat required to raise the temperature of 1 lb of water by 1°F.

candela (cd): The SI unit of luminous intensity (i.e., flux per unit solid angle). A common candle will typically have luminous flux of about 1 candela.

chromaticity: The color of emitted light as perceived by the human visual system. The most common system for specifying and communicating chromaticity is with CIE 1931 (x,y) chromaticity coordinates.

color quality: The combination of chromaticity and color rendering properties of a light source that users judge to be pleasing.

color rendering: The appearance of colored objects illuminated by a source.

color rendering index (CRI): The internationally accepted metric for the evaluation of a light source's color rendering abilities. The calculation of the CRI requires only the spectral power distribution of the light source of interest. The appearance of a predefined set of reflective samples is compared when illuminated by the test source and when illuminated by a reference illuminant.

conduction band: See *band gap*.

control circuitry: Electronic components designed to control a power source by adjusting output voltage, current, or duty cycle to switch or otherwise control the amount and characteristics of the electrical energy delivered to a device. Control circuitry does not include a power source. (ANSI and IES, 2010)

cool white: Light described as "cool" has a coordinated color temperature (CCT) at the high end of the CCT spectrum. It is usually perceived as slightly blue.

correlated color temperature (CCT): The temperature of the blackbody radiator whose emitted light would appear to most closely match that of the source.

die: A small block of light-emitting semiconducting material on which a functional LED circuit is fabricated. (ANSI and IES, 2010)

dimmer: A device capable of adjusting the level of light output from a lamp.

downlight: A small, direct lighting unit that directs light downward and can be recessed, surface mounted, or suspended. (ANSI and IES, 2010)

driver: A device comprised of a power source and control circuitry designed to operate an LED package (component), array (module), or lamp. (ANSI and IES, 2010)

electroluminescence: The emission of light from a phosphor excited by an electromagnetic field. (ANSI and IES, 2010)

encapsulant: A material used for encapsulating a device. In the case of LEDs, the encapsulant typically surrounds the chip and must be capable of withstanding constant optical radiation and elevated operating temperatures without loss of transparency.

energy gap: See *band gap*.

epitaxy: The growth of one thin film layer using the crystalline structure of the preceding layer as a template.

exciton: An excitation of a molecule when an excited electron and hole are loosely bound together. This excitation is mobile and eventually decays by the recombination of the electron and the hole.

fluorescence: The emission of light as a result of, and only during, the absorption of radiation of shorter wavelengths. (ANSI and IES, 2010)

fluorescent lamp: A tubular electric lamp that is coated on its inner surface with a phosphor and that contains mercury vapor whose bombardment by electrons from the cathode provides ultraviolet light, which causes the phosphor to emit visible light either of a selected color or closely approximating daylight. (California Energy Commission, 2002)

footcandle (ftc): A lumen per square foot; a unit of illuminance. While commonly used, it is not an SI unit. The corresponding SI unit is lux.

glare: The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted; it may cause annoyance, discomfort, or loss in visual performance or visibility. (ANSI and IES, 2010)

halogen lamp: A type of incandescent lamps in which the tungsten filament has been enclosed in a capsule containing a halogen gas, typically bromine.

high-intensity discharge (HID) lamps: Electric lamps with tubes filled with gas and metal salts. The gas initiates an arc, which evaporates the metal salts, forming a plasma. These lamps are generally used to light large spaces or roadways. Mercury, metal halide, and high-pressure sodium lamps are examples of specific types of HID lamps.

illuminance: The total luminous flux incident on a surface per unit area. Commonly referred to as brightness, it indicates how bright an illuminated space is. Illuminance depends on the luminous flux of the light sources, their distances from the illuminated surface, and some of the reflectance properties of nearby surfaces.

incandescence: The self-emission of radiant energy in the visible spectrum, due to the thermal excitation of atoms or molecules. (ANSI and IES, 2010)

incandescent lamp: A light source that generates light by passing an electric current through a thin filament wire (usually tungsten) to a temperature of approximately 2,500-3,000 kelvin (K) where the filament glows or incandesces.

internal quantum efficiency (IQE): The percentage of photons generated relative to the current (of electrons or holes) injected into a device.

lamp: A replaceable component that produces light. The term lamp can refer to an incandescent bulb, a CFL bulb, or an LED replacement bulb.

light-emitting diode (LED): A p-n junction semiconductor device that emits optical radiation under an applied voltage. The optical emission may be in the ultraviolet or infrared wavelength regions as well as visible light. (Industrial Fiber Optics, 2004)

LED array: An assembly of LED packages or dies that are intended to connect to an LED driver, created by mounting and interconnecting individual LED devices on a printed circuit board, which is then connected thermally to the heat sink.

LED package: The LED package is the structure in which the LED chip is mounted and through which access to the LED terminals is provided. The assembly typically includes one or more LED dies with electrical connections and may include an optical element as well as thermal, mechanical, and electrical interfaces. (ANSI and IES, 2010)

LED lamp, integrated: An integrated assembly composed of LED packages or LED arrays, LED driver, ANSI standard base and other optical, thermal, mechanical, and electrical components. The device is intended to connect directly to the branch circuit through a corresponding ANSI standard socket. (ANSI and IES, 2010)

LED lamp, non-integrated: An assembly comprised of an LED array or LED packages and ANSI standard base. The device is intended to connect to the LED driver of an LED luminaire through an ANSI standard socket and not to the branch circuit directly. (ANSI and IES, 2010)

LED light engine: An integrated assembly comprised of LED packages or LED arrays, LED driver, and other optical, thermal, mechanical, and electrical components. The device is intended to connect directly to the branch circuit through a custom connector compatible with the LED luminaire for which it was designed and does not use an ANSI standard base. (ANSI and IES, 2010)

lighting power density (LPD): The spatial average power consumption of the installed luminaires in a building or in a space. It is expressed in units of Watts per square feet of floor area (W/ft^2).

lumen (lm): A measure of the amount of light, or luminous flux, emitted by a source per unit time.

lumen maintenance: The relationship between temperature, operating time, and light output.

luminance: A measure of the amount of light per unit area of a surface. The luminance of an illuminated object is dependent on both the incident illuminance and the reflectance of the object. Luminance is the common measure of the intensity of displays. Lighting products available in variable-sized flat forms, such as sheets or tapes, often report luminance because luminous flux depends on the surface area of the product.

luminous efficacy: The luminous efficacy of a lamp is the ratio of the luminous flux to the total electrical power consumed by the lamp.

luminous flux: The quantity of visible light emitted by a source per unit time. Luminous flux is measured in lumens.

luminous intensity: The luminous flux per unit solid angle (i.e., in a specific direction) expressed in candela. Luminous intensity magnitude results from luminous flux being redirected by a reflector or magnified by a lens.

lux (lx): A lux is defined as a lumen per square meter and is the SI unit of illuminance.

Metal Organic Chemical Vapor Deposition (MOCVD): A method used for the growth of single crystal materials. During MOCVD, the wafer/substrate is exposed to metal-organic precursor gases (e.g., ammonia, trimethylgallium, and trimethylaluminum) at elevated temperatures. These gases then react, depositing a high-quality film (e.g., AlGaN) on the substrate.

N-type material: A semiconductor rich in (negatively-charged) electrons.

organic light-emitting diode (OLED): Organic (carbon-based) molecules can behave similarly to inorganic semiconductors; an OLED is an LED made from an organic semiconductor. In contrast to an LED, which is a point source, OLEDs are made in sheets and act as a diffuse area light source. In addition to lighting, they are used prominently in displays for TVs and cell phones.

organic vapor phase deposition: A method of deposition wherein an organic material is heated in the presence of an inert carrier gas. The carrier gas is saturated by the evaporated organic material before flowing toward the substrate onto which the organic molecules are then deposited.

P-type material: A semiconductor rich in (positively-charged) holes.

p-n junction diode: When a p- and n-type semiconductor come in contact, they create a junction known as a diode. The diode will selectively pass current from one material to the other. In an inorganic LED, the diode structure creates a region at the junction interface where electrons recombine radiatively with holes and emit light.

performance bins: See *binning*.

phosphor: A material that absorbs and re-emits light at a lower energy. Phosphor coatings are commonly used with LEDs—for example, a blue LED coated with a yellow phosphor will emit both blue light (from the LED) and yellow light (from the phosphor after absorbing some of the LED's light), which can appear white. Common phosphors used in LEDs include rare-earth doped yttrium aluminum garnets, or YAG:RE.

photobiology: Photobiology is the study of the effect of light on biological organisms.

photosensor: A device capable of detecting the amount of light present. In lighting, it is often used as a way of maintaining a constant level of illuminance in an environment.

pop-on effect: A rapid increase in brightness before dimming. Pop-on effects occur either (1) when lights do not turn on to their pre-set dimming level but first come on (near) full and then dim down automatically to the preset level, in the case of a preset dimming control; or (2) when lights do not turn on at the low end, but require the dimmer to be raised to a relatively high level to start the lamp, before dimming to a lower level can be achieved, in the case of a slider or rotary dimmer.

power factor (PF): The ratio of electrical power dissipated by a piece of equipment to the line power drawn.

power quality: The degree to which an electrical system functions as intended, with low levels of electrical noise and steady voltage output up to a specified load.

power source: A transformer, power supply, battery, or other device capable of providing current, voltage, or power within its design limits. This device contains no additional control capabilities. (ANSI and IES, 2010)

power supply: An electronic device capable of providing and controlling current, voltage, or power within design limits. (ANSI and IES, 2010)

quantum well: A layered structure designed to confine electrons or holes to a plane.

remote phosphor: A remote phosphor is a phosphor that is not put in intimate contact with the LED chip but rather secondary optics for the packaged LED.

retrofit luminaire: A luminaire with an integrated lamp. They are designed to fit into the spaces occupied by existing luminaires, but require complete removal of the existing luminaire for installation.

roll-to-roll processing: The process of creating a large quantity of electronic devices on a flexible substrate. This manufacturing process is typically imagined for OLEDs and organic photovoltaics to drive the cost down, because both technologies are capable of being grown at low temperatures onto flexible substrates.

semiconductor: A semiconductor is a material characterized by its ability to conduct a small electrical current. Intrinsically, it has far fewer carriers than a metal and is typically doped with other materials to pass large currents.

skyglow: The result of blue light being absorbed or scattered in the atmosphere resulting in a loss of visibility of the night sky, which is of special concern to the astronomy community.

Spectral Luminous Efficiency Function (V_λ): A model depicting the relationship between wavelength of light and the relative sensitivity of the human visual system.

thermal coefficient of expansion: The rate at which a material expands/contracts as it is heated/cooled.

total harmonic distortion (THD): The amount of distortion on the voltage supply line at frequencies above the fundamental (60 Hz) carrier frequency. A high THD (>33 percent) causes problems in three-phase power systems, because usually the dominant harmonic current is the third harmonic. The third harmonic currents add in the neutral wire of the electrical system and in cases of high THD one can have a situation where the current flowing in the neutral wire exceeds the rating of the wire, causing overheating.

troffer: A long, recessed lighting unit usually installed with the opening flush with the ceiling. (ANSI and IES, 2010)

vacuum thermal evaporation: A method of deposition in which a material is heated in vacuum, evaporating from the source and then condensing on the substrate.

valence band: See *band gap*.

visible spectrum: The band of electromagnetic radiation that can be detected by the human eye, encompassing wavelengths between 380 nm (violet) and 750 nm (red).

warm white: Light described as "warm" has a coordinated color temperature (CCT) at the low end of the CCT spectrum. It is usually perceived as slightly yellow.

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Appendixes

A

Committee Biographical Information

JOHN G. KASSAKIAN (NAE), *Chair,* is professor of electrical engineering and former director of the Massachusetts Institute of Technology (MIT) Laboratory for Electromagnetic and Electronic Systems. His expertise is in the use of electronics for the control and conversion of electrical energy, industrial and utility applications of power electronics, electronic manufacturing technologies, and automotive electrical and electronic systems. Prior to joining MIT, he served in the U.S. Navy. Dr. Kassakian is on the boards of directors of a number of companies and has held numerous positions with the Institute of Electrical and Electronics Engineers (IEEE), including founding president of the IEEE Power Electronics Society. He is a member of the National Academy of Engineering (NAE), a Life Fellow of the IEEE, and a recipient of the IEEE's William E. Newell Award for Outstanding Achievements in Power Electronics (1987), the IEEE Centennial Medal (1984), and the IEEE Power Electronics Society's Distinguished Service Award (1998). He has served on a number of National Research Council (NRC) committees, including the Review of the Research Program of the FreedomCAR and Fuel Partnership and the Committee on Light-Duty Vehicle Technologies Improve Fuel Economy. He has an Sc.D. in electrical engineering from MIT.

INÊS AZEVEDO is the executive director of the Center for Climate and Energy Decision Making at Carnegie Mellon University (CMU) and an assistant research professor with CMU's Department of Engineering and Public Policy. Dr. Azevedo's research interests lie at the intersection of environmental, technical, and economic issues, such as how to address the challenge of climate change and to move toward a more sustainable energy system. In particular, Dr. Azevedo has been looking at how energy systems are likely to be shaped in the future, which requires comprehensive knowledge not only of the technologies that can address future energy needs but also of the decision-making process followed by different agents in the economy. Her dissertation looked at these issues as they relate to the development and deployment of solid-state lighting (SSL) technologies. Dr. Azevedo received her B.Sc. in environmental engineering from IST University in Portugal, her M.Sc. in engineering policy and management of technology from IST, and her Ph.D. from CMU in engineering and public policy.

NANCY E. CLANTON is founder and president of Clanton & Associates, a lighting design firm specializing in sustainable design. She is a fellow of the Illuminating Engineering Society of North America (IESNA) and is a LEED-accredited professional. Ms. Clanton serves as chairperson for the IESNA Outdoor Environmental Lighting Committee, the IESNA/IDA Model Lighting Ordinance Task Force, and the IESNA Mesopic Committee. She is a past member of the board of directors of the International Association of Lighting Designers and the International Dark Sky Association. Additionally, she serves as a member of the advisory committee of *Environmental Building News*, the Professional Advisory Board for the Engineering Department at the University of Colorado, Boulder, and the U.S. Green Building Council. Ms. Clanton is a topic editor for the *IESNA Lighting Handbook,* 9th edition, and her committee was responsible for the production of the IESNA Recommended Practices on Outdoor Lighting. She was group leader for the "Greening of the White House" initiative and received the 1999 Contribution to the Built Environment Award from the Colorado North Chapter of the American Institute of Architects (AIA). In 2001 Ms. Clanton served as a final editor for the Advanced Lighting Guidelines written by the California Energy Commission. She speaks throughout the nation on topics relating to sustainable design, energy efficiency, and light pollution. Her firm's lighting design projects reflect her sustainable philosophy, and 10 of their projects have been named to the AIA Committee on the Environment Earth Day Top Ten List. Projects for which Clanton & Associates designed the lighting are LEED rated, and several current projects are registered, certification pending. She obtained her bachelor of science degree in architectural engineering, illumination emphasis, from the University of Colorado, Boulder, and she is a registered professional engineer in the states of Colorado and Oregon.

WENDY DAVIS is an associate professor and director of the Illumination Design Program in the Faculty of Architecture, Design and Planning at the University of Sydney. She previously (2004-2011) worked as a vision scientist in the Lighting and Color Group at the National Institute of Standards and Technology (NIST). Dr. Davis's research addresses lighting and color, with a particular focus on quality issues in emerging and next-generation energy efficient lighting technologies. With a colleague at NIST she developed the Color Quality Scale (CQS) to evaluate the color rendering properties of light sources for general illumination. This work led to her 2009 U.S. Department of Commerce Silver Medal Award for Scientific/Engineering Achievement for "developing measurement methods and technical standards to accelerate the commercialization of energy-efficient, solid-state lighting products." Dr. Davis chairs the International Commission on Illumination (CIE) technical committee 1-69, "Colour Rendition by White Light Sources," and is a member of the IESNA Color Committee. She earned her Ph.D. and M.S. degrees from the University of California, Berkeley, in vision science and her B.A. in psychology and physiology from the University of Minnesota.

PAUL A. DeCOTIS is vice president of power markets at Long Island Power Authority where he oversees strategic resource planning; fuel, energy, and capacity purchases and sales; power project development and management; and participation in the region's wholesale power markets. Prior to this Mr. DeCotis was deputy secretary for energy in New York, serving as senior energy advisor to Governor Spitzer and Governor Paterson. He was also chair of the State Energy Planning Board and previously served as director of energy analysis for the New York State Energy Research and Development Authority where he oversaw corporate strategy and planning, forecasting and analysis, and energy program evaluation. Prior to this, Mr. DeCotis was chief of policy at the State Energy Office. Until his appointment as deputy secretary, he was president of a management consulting business specializing in executive and board development, strategy, and mediation. Since 1985, he has served as an adjunct faculty member at several colleges and universities, including Cornell University, Rochester Institute of Technology, and the Sage Graduate School at Russell Sage College. Mr. DeCotis is a member of the NRC Board on Energy and Environmental Systems, board member of U.S. Offshore Wind Collaborative, board member of the Clean Energy States Alliance, editorial board member of the *Energy Efficiency Journal*, executive committee member of the New York State Reliability Council, New York's representative to the Eastern Interconnection States Planning Council, and a member of other boards and committees. He has served on and chaired many professional organizations and associations and has extensive community service experience. Mr. DeCotis has published dozens of articles and professional papers on energy and industry matters. He received his bachelor of arts in international business management from the State University College at Brockport, his master of arts in economics from the University at Albany, and his M.B.A. in finance from the Sage Graduate School at Russell Sage College.

STEVEN P. DenBAARS (NAE) is a professor of materials and co-director of the Solid State Lighting Center at the University of California, Santa Barbara (UCSB). Specific research interests include growth of wide-bandgap semiconductors (GaN based) and their application to blue light-emitting diodes (LEDs) and lasers and high-power electronic devices. This research has led to the first U.S. university demonstration of a blue GaN laser diode. Dr. DenBaars has performed cost evaluations of LED technologies over the past 23 years and is active in LED research and development as well as commercialization. He is also engaged in the international SSL community. In 1994 he received an National Science Foundation (NSF) Young Investigator award. He has authored or co-authored more than 580 technical publications, 270 conference presentations, and 35 patents. Prior to joining the faculty of UCSB, Dr. DenBaars was a member of the technical staff at Hewlett-Packard's Optoelectronics Division, which was involved in the growth and fabrication of visible LEDs from 1988-1991. In 2012 he was elected to the National Academy of Engineering. He received a Ph.D. in electrical engineering and an M.S. in materials science from the University of Southern California (USC) and a B.S. in materials and metallurgical engineering from University of Arizona.

MICHAEL ETTENBERG (NAE) is managing partner at DOLCE Technologies, a company that commercializes technologies invented at leading universities, such as Princeton and Columbia. He retired from Sarnoff Corporation (formerly RCA Laboratories) after 35 years, ending as senior vice president in charge of all of Sarnoff's device research, including a small silicon integrated circuit fabrication, TV displays, optoelectronics, and cameras. Dr. Ettenberg was elected to membership in the National Academy of Engineering for his work on optoelectronic components, including the evolution of practical and reliable semiconductor lasers. He also has extensive experience with III-V materials and optoelectronic devices. He developed the dielectric mirrors used on all of today's laser diodes. Dr. Ettenberg has published 110 papers and has been awarded 35 patents, mainly in the area of optoelectronics. He also was president of the IEEE Lasers and Electro-Optics Society and was a member of the Defense Science Board. He received his B.S. from the Polytechnic Institute of Brooklyn and his M.S. and Ph.D. from New York University.

STEPHEN FORREST (NAE) is the vice president for research at the University of Michigan as well as the William Gould Dow Collegiate Professor of Electrical Engineering and Computer Science and professor in the Materials Science and Engineering Department and the Physics Department. In 1985, Dr. Forrest joined the Electrical Engineering and Materials Science Departments at USC where he worked on optoelectronic integrated circuits and organic semiconductors. In 1992, he became the James S. McDonnell Distinguished University Professor of Electrical Engineering at Princeton University. He served as director of the National Center for Integrated Photonic Technology and as Director of Princeton's Center for Photonics and Optoelectronic Materials. From 1997 to 2001, he served as the chair of the Princeton's Electrical Engineering Department. In 2006, he rejoined the University of Michigan as vice president for research. He is a fellow of the American Physical Society (APS), IEEE, and the Optical Society of America and a member of the National Academy of Engineering. He received the IEEE/Lasers Electro-Optics Society (LEOS) Distinguished Lecturer Award in 1996-1997, and in 1998 he was co-recipient of the IPO National Distinguished Inventor Award as well as the Thomas Alva Edison Award for innovations in organic LEDs. In 1999, Dr. Forrest received the MRS Medal for work on organic thin films. In 2001, he was awarded the IEEE/LEOS William Streifer Scientific Achievement Award for advances made on photodetectors for optical communications systems. In 2006 he received the Jan Rajchman Prize from the Society for Information Display for invention of phosphorescent organic light emitting diodes (OLEDs) and is the recipient of the 2007 IEEE Daniel Nobel Award for innovations in OLEDs. Dr. Forrest has authored approximately 465 papers in refereed journals and has 203 patents. He is co-founder or founding participant in several companies, including Sensors Unlimited, Epitaxx, Inc., Global Photonic Energy Corp., Universal Display Corp., and ASIP, Inc., and is on the board of directors of Applied Materials and PD-LD, Inc. Dr. Forrest received his B.A. in physics from the University of California, Berkeley, and his M.S. and Ph.D. from the University of Michigan.

PEKKA HAKKARAINEN is corporate vice president at Lutron Electronics. Dr. Hakkarainen has developed an expertise in the performance of fluorescent and halogen lamps in dimming conditions as well as co-developed an integrated daylighting system involving electric lights and window shades. He is a member of IESNA and currently chairs the lighting Systems Division of the National Electrical Manufacturers Association (NEMA). He has chaired several IESNA and NEMA committees and served on numerous other industry committees and advisory groups. Dr. Hakkarainen received his B.A. and M.A. in mathematics from Cambridge University, England, and a Ph.D. in plasma physics from MIT.

EVELYN L. HU (NAS/NAE) is the Gordon McKay Professor of Applied Physics and Electrical Engineering in the Harvard University School of Engineering and Applied Sciences. Prior to her appointment at Harvard, Dr. Hu was the scientific co-director of the California Nanosystems Institute, a University of California, Los Angeles-UCSB collaborative California Institute for Science and Innovation. Her research focuses on high-resolution fabrication of compound semiconductor electronic and optoelectronic devices, candidate structures for the realization of quantum computation schemes, and novel device structures formed through the heterogeneous integration of materials. Recently her work has involved the interaction of quantum dots in high Q microdisk and photonic crystal cavities. Dr. Hu is a member of the American Academy of Arts and Sciences, the National Academy of Sciences, the National Academy of Engineering, and the Academica Sinica. She is a recipient of the American Association for the Advancement of Science (AAAS) Lifetime Mentor Award and was named an NSF Distinguished Teaching Scholar. She was named the 2005 UCSB Faculty Research Lecturer. She is a fellow of the IEEE, APS, and the AAAS, and holds an honorary doctorate of engineering from the University of Glasgow. From 1975 to 1981, Dr. Hu was a member of technical staff at Bell Laboratories at Holmdel, New Jersey. From 1981 to 1984 she served as a supervisor for VLSI patterning processes at Bell Laboratories at Murray Hill, New Jersey. In 1984 she joined UCSB as a professor of electrical and computer engineering. She received her B.A. in physics (summa cum laude) from Barnard College and her M.A. and Ph.D. in physics from Columbia University.

GARY MARCHANT is a professor of law and executive director and faculty fellow of the Center for Law, Science, and Innovation in the College of Law at Arizona State University (ASU). He is also a senior sustainability scientist at ASU's Global Institute of Sustainability. Dr. Marchant teaches environmental law, science and technology, genetics and the law, and environmental justice. Prior to joining ASU, he was a partner at the Washington, D.C., office of the law firm of Kirkland and Ellis, where his practice focused on environmental and administrative law. He received his B.Sc. and Ph.D. in genetics from the University of British Columbia, his M.P.P. from the Kennedy School of Government of Harvard University, and his J.D. from Harvard Law School.

NADARAJAH NARENDRAN is director of research at the Lighting Research Center (LRC) and professor in the School of Architecture at Rensselaer Polytechnic Institute. He spearheads LRC's SSL program with concentrated research efforts in the areas of LED lighting performance, packaging, and application. He is a fellow member of IESNA and organizes the Alliance for Solid-State Illumination Systems and Technologies. He has been awarded the Taylor Technical Talent Award for Best Technical Paper from the IESNA and the Pew Teaching Leadership Award. Dr. Narendran received a B.S. in physics from the University of Peradeniya, Sri Lanka, and a Ph.D. and M.S. in physics from the University of Rhode Island.

MAXINE SAVITZ (NAE) is a retired general manager of technology partnerships at Honeywell, Inc. Dr. Savitz is currently vice president of the National Academy of Engineering. She has managed large R&D programs in the federal government and the private sector. Some of her positions include the following: chief, Buildings Conservation Policy Research, Federal Energy Administration; professional manager, Research Applied to National Needs, National Science Foundation; division director, Buildings and Industrial Conservation, Energy Research and Development Administration; deputy assistant secretary for conservation, U.S. Department of Energy; president, Lighting Research Institute; and general manager, Ceramic Components, AlliedSignal, Inc. (now Honeywell). She has extensive technical experience in materials, fuel cells, batteries and other storage devices, energy efficiency, and R&D management. She is a member of the National Academy of Engineering and has been, or is serving as, a member of numerous public- and private-sector boards and has served on many energy-related and other NRC committees. She has a Ph.D. in organic chemistry from MIT.

MICHAEL G. SPENCER is a professor of electrical engineering at Cornell University. His research interests are in the epitaxial and bulk growth of compound semiconductors, such as GaAs, SiC, and AlN, microwave devices, solar cells, and electronic materials characterization techniques (including deep level transient spectroscopy and photoluminescence). Dr. Spencer's particular interest has been in the correlation of device performance with material growth and processing parameters. His recent work has emphasized wide bandgap materials, and his group was the first to produce conducting AlN and thick films of beta SiC grown by the bulk sublimation technique. He is a recipient of the Presidential Young Investigator Award (1985), the Alan Berman Research Publication Award from the Naval Research Laboratories (1986, for research leading to the first identification of a self interstitial defect in AlGaAs), the White House Initiative Faculty Award for Excellence (1988), a distinguished visiting scientist appointment at Jet Propulsion Laboratories (1989), and a NASA Certificate of Recognition (1992). Dr. Spencer is on the permanent committee for the Electronic Materials Conference and the Compound Semiconductor Conference, and he also helped initiate and form the International Conference on Silicon Carbide and Related Materials. He is one of the directors of the NSF-sponsored National Nanofabrication network. Dr. Spencer received his B.S., M.Eng., and Ph.D. from Cornell University.

B

Committee Activities

FIRST COMMITTEE MEETING
MAY 12-13, 2011, WASHINGTON, D.C.

Status of Solid State Lighting: Philips' Perspective
Jim Gaines, Philips LED Lamps and Systems

A Lighting Designer's Perspective on the Emerging Role of SSL Technologies in Design for the Built Environment
Randy Burkett, FIALD, IES, LC; Randy Burkett Lighting Design

Challenges in Mass Adaption of LED Lighting
Gerry Negley, CREE LED Lighting

Advanced Solid State Lighting
Keith R. Cook, Philips Washington Government & Industry Affairs

Briefing on DOE Solid-State Lighting Program
James R. Brodrick, Ph.D., U.S. Department of Energy

SECOND COMMITTEE MEETING
JULY 27-28, 2011, WASHINGTON, D.C.

Status of LED Lighting—Market Development and Forecast
Vrinda Bhandarkar, Strategies Unlimited

Solid State Lighting: Outlook for National Lighting Energy Use
Jennifer Amann, LC; American Council for an Energy-Efficient Economy

ENERGY STAR® Lighting: An Update on the New Program
Alex Baker, MSc, LC, IES; Environmental Protection Agency

Presentation [untitled]
Eric Haugaard, BetaLED by Ruud Lighting, Inc.

LED Innovations in Luminaries
Steve Oh, Philips Lighting

OLED Luminaries
Peter Y. Ngai, PE, FIES, LC; Acuity Brands Lighting

Io Light for a Brighter Future™
Ann Reo, Cooper Industries

THIRD COMMITTEE MEETING
SEPTEMBER 26-27, 2011, WOODS HOLE, MA

Phase II: Emerging Ecosystems of Solid State Lighting
Makarand H. Chipalkatti, OSRAM Sylvania

Presentation (no title)
Jonathan Linn and Susan Coakley, Northeast Energy Efficiency Partnerships

Quantum Dot Technology for Solid State Lighting
Seth Coe-Sullivan, QD Vision

Energy Efficiency Programs and Solid State Lighting. A Presentation for the National Academy of Sciences Solid State Lighting Committee
Eileen Eaton, Consortium for Energy Efficiency

Presentation (no title)
Mike Hack, Universal Display Corporation

Retrofit LED Drivers
Anthony Sagneri, OnChip Power

OLEDs for Lighting
Joseph Shiang, GE Global Research

FOURTH COMMITTEE MEETING
DECEMBER 1-2, 2011, WASHINGTON, D.C.

SSL Manufacturing Issues—Prospects for Cost Reduction
Steve Bland, SB Consulting

NAS Assessment of Solid State Lighting
Jed Dorsheimer, Canaccord Adams

FIFTH COMMITTEE MEETING
FEBRUARY 1-2, 2012, IRVINE, CA

No open sessions this meeting.

C

Acronyms and Abbreviations

Alq_3	tris(8-hydroxyquinoline) aluminum
ANSI	American National Standards Institute
ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BES	basic energy sciences
BTP	Building Technologies Program
Btu	British thermal unit
BULB Act	Better Use of Light Bulbs Act
CBECS	Commercial Buildings Energy Consumption Survey
CBP	4,4-*N*,*N*-dicarbazole-biphenyl
cd	candela
CFL	compact fluorescent light
CIE	International Commission on Illumination (Commission Internationale d'Eclerage)
CISPR	Special International Committee on Radio Interference (Comité International Spécial des Perturbations Radioélectriques)
CLTC	California Lighting Technology Center
CNT	carbon nanotube
CRI	color rendering index
DALI	Digital Addressable Lighting Interface
DCM	4-(dicyanomethylene)-2-methyl-6-(dimethylaminostyryl)-4*H*-pyran
DLA	Defense Logistics Agency
DLC	DesignLights™ Consortium
DOD	Department of Defense
DOE	Department of Energy
DSM	demand side management
DTV	digital television
EBL	exciton blocking layer
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EML	light emissive layer
EPA	Environmental Protection Agency
EPACT	Energy Policy Act
EPCA	Energy Policy and Conservation Act
EQE	external quantum efficiency
ERDA	Energy Research and Development Administration
ETL	electron transport layer
FCC	Federal Communications Commission
FEA	Federal Energy Administration
ftc	footcandle
FTC	Federal Trade Commission
GAO	Government Accountability Office
GSA	General Services Administration
HID	high-intensity discharge
HTL	hole transport layer
HVPE	hydride vapor phase epitaxy
IALD	International Association of Lighting Designers
ICC	International Code Council
IEC	International Electrotechnical Commission
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
IQE	internal quantum efficiency
Ir(ppy)_3	*fac* tris(2-phenylpyridine) iridium
ITO	indium tin oxide
L Prize	Bright Tomorrow Lighting Prize

LBNL	Lawrence Berkeley National Laboratory
LED	light-emitting diode
LER	luminous efficacy of radiation
LFL	linear fluorescent lamp
LIPA	Long Island Power Authority
lm	lumen
LPD	lighting power density
LRC	Lighting Research Center
LUMEN	Lighting Understanding for a More Efficient Nation
lx	lux
MCPCB	metal-core printed circuit board
MECS	Manufacturing Energy Consumption Survey
MOCVD	metal-organic chemical vapor deposition
MR	multifaceted reflector
NAECA	National Appliance Energy Conservation Act
NEEP	Northeast Energy Efficiency Partnerships
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
NRC	National Research Council
NYSERDA	New York State Energy Research and Development Authority
OLED	organic light-emitting diode
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
OVPD	organic vapor phase deposition
PAR	parabolic aluminized reflector
PCAST	Presidential Council of Advisors on Science and Technology
PF	power factor
PHOLED	phosphorescent organic light-emitting diode
PNNL	Pacific Northwest National Laboratory
QD	quantum dot
R&D	research and development
RD&D	research, development, and demonstration
RECS	Residential Energy Consumption Survey
RGB	red, green, blue
RGBY	red, green, blue, yellow
RoHS	restriction of hazardous substances
SBIR	Small Business Innovation Research
SCHER	Scientific Committee on Health and Environmental Risks
SOLED	stacked organic light emitting diode
SPD	spectral power distribution
SSL	solid-state lighting
THD	total harmonic distortion
TIM	thermal interface material
TIR	total internal reflection
TWh	terawatt-hours (10^{12} watt-hours)
UV	ultraviolet
VTE	vacuum thermal evaporation
WOLED	white organic light-emitting diode
YAG	yttrium-aluminum garnet