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Solid-State Lighting

2017 Suggested Research Topics Supplement:

Technology and Market Context

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Disclaimer

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List of Acronyms

Abbreviation	Definition
$/klm	U.S. dollars per kilolumen
3-D	3-dimensional
A/cm^2	amperes per square centimeter
AC	alternating current
AlGaN	aluminum gallium nitride
AlInGaN	aluminum indium gallium nitride
AlInGaP	aluminum indium gallium phosphide
AlN	aluminum nitride
ANSI	American National Standards Institute
app	software application
ASP	average selling price
BLE	Bluetooth Low Energy
BR	bulged reflector
Btu	British thermal unit
°C	degrees Celsius
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	correlated color temperature
cd/m^2	candelas per square meter
CFL	compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage
CLTB	connected lighting test bed
cm-LED	color mixed-LED
COB	chip-on-board
CRI	color rendering index
CSA	China Solid State Lighting Alliance
CSP	chip scale package
CWF	cool white fluorescent
DC	direct current
DLC	DesignLights Consortium
DMX	digital multiplex
DOE	U.S. Department of Energy
Duv	distance from the blackbody locus in u-v colorspace
EESL	Energy Efficiency Services Limited
EQE	external quantum efficiency
EQE/IQE	extraction efficiency
EU	European Union
FCC	Federal Communications Commission
FOA	funding opportunity announcement
FP-7	Seventh Framework Programme
FWHM	full width at half maximum

FY	fiscal year
GaAs	gallium arsenide
GaN	gallium nitride
HID	high intensity discharge
HPS	high-pressure sodium
HVAC	heating, ventilation and air conditioning
hy-LED	hybrid LED
IEA	International Energy Agency
IES	Illuminating Engineering Society
IHS	Information Handling Services Markit Ltd.
III-N	III nitride material
III-V	III-V semiconductor material
InGaN	indium gallium nitride
IoT	Internet of things
IP	Internet protocol
IQE	internal quantum efficiency
IR	infrared
ITO	indium tin oxide
K	Kelvin
klm/m^2	kilolumen per square meter
KrW	Korean Won
L1	Level 1
L2	Level 2
L70	duration of lumen maintenance to 70% initial brightness; operational lifetime
LBNL	Lawrence Berkeley National Laboratory
LCA	life-cycle assessment
LED	light-emitting diode
LER	luminous efficacy of radiation
lm/m^2	lumens per square meter
lm/W	lumens per watt
LSRC	LED Systems Reliability Consortium
LT50	lifetime to 50% of the initial luminance
LT80	lifetime to 80% of the initial luminance
mAh	milliamp hour
MC-PCB	metal-core printed circuit board
MEMS	microelectromechanical systems
Mg	magnesium
MLA	micro-lens array
MOCVD	metal organic chemical vapor deposition
MR	multifaceted reflector
MW	megawatt
NGLIA	Next Generation Lighting Industry Alliance
NIST	National Institute of Standards and Technology

nm	nanometer
OLED	organic light emitting diode
PAR	parabolic aluminized reflector
PCB	printed circuit board
PCE	power conversion efficiency
pc-LED	phosphor-converted LED
PDMS	polydimethylsiloxane
Pd	palladium
PECVD	plasma enhanced chemical vapor deposition
PLC	powerline communication
PNNL	Pacific Northwest National Laboratory
PoE	power over Ethernet
PPER	photosynthetic photon efficacy of radiation
Pt	platinum
QY	quantum yield
R&D	research and development
R2R	roll-to-roll
R9	Color fidelity test standard for red content not used in calculations of CRI
RGB	red, green and blue
RGBA	red, green, blue and amber
RYGB	red, yellow, green and blue
SSL	solid-state lighting
TADF	thermally activated delayed fluorescence
TAKT	process cycle time
TBtu	trillion British thermal units
THD	total harmonic distortion
TiO_2	titanium dioxide
TLED	tubular LED
TWh	terawatt-hours
UDC	Universal Display Corporation
UV	ultraviolet
V	volt
VLC	visible light communication
W	Watt
W/m^2	watts per square meter
W/mK	watts per meter kelvin
W/mm^2	watts per square millimeter
YAG	yttrium aluminium garnet
ZESCO	Zambia Electricity Supply Corporation
ZrO_2	zirconium dioxide
μm	micrometer
Δu'v'	magnitude of color shift in the CIE 1976 chromaticity diagram (u', v')
Ω/□	resistivity per unit area

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Executive Summary

Solid-state lighting (SSL) technology and pricing have advanced significantly in the past decade, to the point where it is the best option for almost every lighting application. SSL technology offers clear energy savings, reduced cost of ownership, and even improved lighting performance compared to conventional lighting products. Even so, it is the early phases of the market and technology transition to light-emitting diode (LED) lighting. Though the rate of progress in LED lighting technology has been impressive, opportunities for significant improvements in source efficacy can still be achieved through ongoing research and development (R&D), and there is a compelling case to do so. If LED products were to meet medium- and long-term SSL Program efficacy targets, the United States would see 5.1 quadrillion British thermal units (Btus),[a] or quads, of annual energy savings from LEDs in 2035 [1].

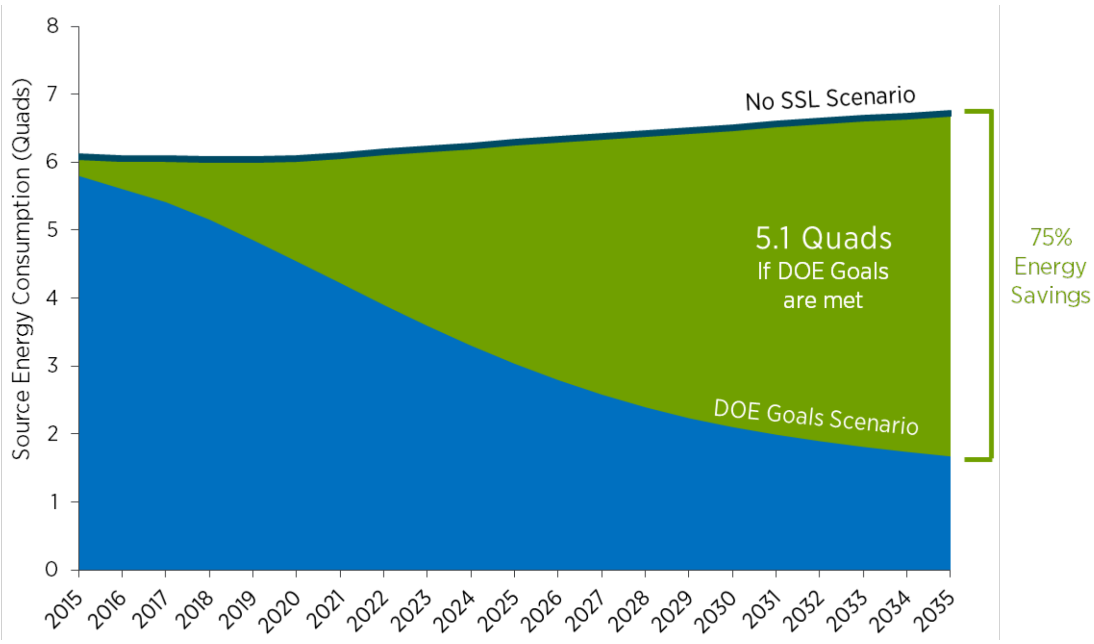

Figure E.1 DOE SSL Program Goal Scenario Energy Savings Forecast for the U.S. from 2015 to 2035

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

Other aspects of lighting performance, such as color quality, optical control, efficient delivery of light, and integration of lighting into buildings, can also still be improved while providing additional levels of energy savings. New functionality of lighting products that was not possible with previous lighting technologies, is being developed that can enable new applications and increase the value of lighting systems. For example, active color tuning enables new benefits, such as lighting that can be tuned to engage human physiological responses. Integration of sensors, controls, and communications also allows lighting systems to be part of the Internet of things (IoT), which will unlock enormous additional value for lighting systems through data mining and analytics.

a 1 Btu is equal to 1,055 joules, and 1 TBtu is equal to 1.055 petajoules.

Organic light-emitting diode (OLED) technology still faces challenges in reducing cost and in commercializing the high-efficacy performance that has been demonstrated in the lab. However, the technology offers intriguing benefits in terms of brightness, form factor, and effective delivery of lighting that could complement LED lighting solutions. While LED sources are by nature small and bright, OLED sources are large and diffuse, which means they can be deployed very close to the task without creating uncomfortable glare. OLEDs have the potential of being manufactured through very low-cost continuous, roll-to-roll (R2R) type deposition processes, offsetting the materials cost inherent with these lower brightness sources.

As these technology developments are ongoing, manufacturers are working to supply SSL products to replace or retrofit conventional lighting products that are in a vast number of "sockets" worldwide. There are an estimated 45 billion lighting sockets in the world [2], and this number is expected to increase through population growth, construction in the developing world, and growth of new lighting applications, such as indoor horticulture. To fill these sockets is a massive manufacturing challenge, but also an opportunity to provide energy and cost-saving lighting products and systems with increasing value. In addition, SSL technology provides an opening to develop domestic manufacturing infrastructure to create SSL products for the long term.

The opportunities and challenges for SSL can generally be described in terms of:

- Improvements to system efficiency,
- Better understanding of lighting applications to optimize the effectiveness of delivered light,
- Improved manufacturing technologies for SSL products, which reduces costs while improving product quality and consistency, and encourages domestic job growth,
- Reduction of barriers to adoption.

This document, the *SSL 2017 Suggested Research Topics Supplement: Technology and Market Context*, describes these opportunities and highlights the critical R&D topics necessary to make advancements. This document supplements the *2017 SSL Suggested Research Topics* document, which describes specific research topics suggested for support by DOE SSL Program Stakeholders from academia, National Laboratories, and industry. The DOE SSL Program continues to set aggressive performance and cost targets for LED and OLED lighting technology and provide R&D funding and research activities in support of reaching these targets. The funding support from DOE provides resources to tackle very challenging fundamental research and scientific inquiry. One such issue is understanding and solving current density droop or green gap efficiency in LEDs, which industry alone has been unable to solve. DOE funding support has also allowed industry to pursue risky technology areas, such as quantum dot integration into LED products or development of OLED light extraction technology, which are beyond what one company can support with internal R&D resources. DOE support is critical to achieving the ultimate potential for SSL technology, including maximized source and system efficacy, low purchase price, optimized light utilization, and integration with connectivity and control systems.

The DOE SSL Program has developed a comprehensive R&D strategy to support advancements in both LED and OLED technology for maximum ultimate energy savings. This Supplement was developed with community experts through inputs received at roundtable meetings, held in September and October 2016, and at the DOE SSL R&D Workshop, held in January 2017. The plan reflects SSL stakeholder inputs on key R&D topics that will improve efficacy, remove barriers to adoption, and add value to SSL. The discussions in this document provide context about the changing lighting market and cover critical R&D needs for LED and OLED technologies that can be applied across the SSL value chain.

The current critical R&D challenges identified during the Roundtable and Workshop discussions are summarized below.

LED-Based Lighting R&D Suggestions

- **Emitter Materials** – emitters across the spectrum that demonstrate advancements in peak efficiency and stable efficiency at high drive and temperature operating conditions. Includes novel device structures such as tunnel junction LEDs.

- **Downconverters** – narrow red, green, and tunable downconverters. Improved matrix integration and improved optical control at the downconverter-matrix level.

- **Encapsulation** – LED package encapsulants and phosphor matrices that enable higher LED operating temperature, increased light output, and more efficient package light extraction without degrading package stability.

- **High Efficacy Prototypes** – achieve maximum LED efficacy and embed additional luminaire functionality into packages, e.g., light engines including sensors, connectivity, power supply, optical functionality, etc.

- **Advanced LED Lighting**– develop entirely novel, fully optimized concept luminaires or lighting system architectures that take advantage of the unique properties of LEDs to demonstrate improved efficacy, performance, connectivity, and advanced lighting values, e.g., human physiological benefits.

- **Power Electronics** – advancements in LED power supplies that enable peak driver efficiency across multiple channels and full operating range. Also includes advancements in system reliability, form factor, and critical components.

- **Advanced Manufacturing** – novel technologies and approaches that enable on demand lighting product production with low part count and flexibility to create a wide range of lighting products types.

OLED-Based Lighting R&D Suggestions

- **Stable, Efficient White Devices** – research into emitter systems (i.e., emitters, hosts, transport materials) designed to simultaneously achieve long lifetimes and high efficacy, particularly for blue emitters, or into OLED stack materials (i.e., transparent conductors, charge generation layers, and other layers) to improve optical and electrical performance of the OLED stack.

- **Fabrication Technologies** – novel approaches and advancements in materials deposition, device fabrication, or encapsulation for high-performance OLED panels are desired.

- **Light Extraction and Utilization** – explore novel solutions that will allow for substantial improvements in panel efficiency by extracting light trapped in organic/anode wave-guided modes and/or reducing surface plasmonic losses. The ability to control the distribution of the emitted light would provide additional value.

- **OLED Prototype Lighting Platforms** – demonstrate OLED lighting platforms that highlight capabilities of OLED lighting technology. OLED platforms should combine one or more high performance OLED panels with custom driver electronics to achieve efficient, long-life systems.

Lighting R&D Suggestions (LED and OLED)

- **Physiological Impacts of Light –** understanding human physiological responses to light that enable development of lighting products to improve wellbeing, increase productivity, and minimize negative impacts of electric lighting while also saving energy in the application.

- **Lighting Application Efficiency –** research to understand effective delivery, control, and utilization of light for specific lighting applications.

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1 Introduction

The Department of Energy (DOE) Solid-State Lighting (SSL) Program was created in response to Congressional direction described in Section 912 of the Energy Policy Act of 2005, which directs DOE to *"Support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light-emitting diodes."* The DOE SSL Program has developed a comprehensive research and development (R&D) strategy to support advancements in SSL technology and maximize energy savings. The specific goal of the R&D Program is:

By 2025, develop advanced SSL 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% with appropriate application spectrum.

In order to maximize energy savings, the DOE SSL R&D Program supports foundational R&D topics with benefits that apply across the value chain and is R&D that is not typically undertaken within the lighting industry. DOE supported R&D advances understanding of underlying physical phenomena, explores completely new technical and fabrication approaches, reduces the development risk with new technologies, and/or develops understanding of application benefits that complement and increase the energy savings potential for SSL.

This document, the *SSL 2017 Suggested Research Topics Supplement: Technology and Market Context (formerly titled the DOE SSL R&D Plan)*, is updated annually and is a consolidation of the DOE SSL Multi-Year Program Plan and the DOE SSL Manufacturing R&D Roadmap that DOE published prior to 2015.[2] The DOE SSL R&D Plan provides analysis, context, and direction for ongoing R&D activities to advance SSL technology and increase energy savings.

This document reflects ongoing progress toward DOE SSL goals and the shifting R&D priorities that will have the biggest impact on achieving the program goals. Details on the legislation and policies defining the program are not included in this document, but may be found on the SSL website at https://energy.gov/eere/ssl/about-solid-state-lighting-program and https://energy.gov/eere/ssl/partnerships.

[2] Previous documents are available at: http://energy.gov/eere/ssl/technology-roadmaps

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2 Impacts of Solid-State Lighting

SSL offers vast opportunity to improve the efficiency, performance, and value of lighting by creating new applications and benefits. The initial motivations for the pursuit of light-emitting diode (LED) and organic light-emitting diode (OLED) technology were the promise of high-source efficacy and the prospects of leveraging semiconductor manufacturing processes. Industry experts held that high-volume processing technologies from the semiconductor industry could be applied for LEDs, and roll-to-roll (R2R) processing technologies for OLEDs. While there is still considerable room for improvement, SSL is already fulfilling its promise as it continues to demonstrate improved efficacy over conventional lighting sources, reduced total cost of ownership that enable payback within reasonable time periods, and new features including spectral tunability, advanced controls, and connectivity. These attributes have led to rapid adoption of SSL, already resulting in significant energy savings. In addition to improved source efficacy, SSL can be more effective in delivering light when and where it is needed, representing an additional level of energy savings that is just beginning to be understood. As the technology has developed, it has become clear that the impacts of SSL will go far beyond energy savings alone. It has the potential to have profound beneficial impacts on the environment, horticulture, transportation safety, human health, and productivity, all of which can be realized while saving significant amounts of energy compared to conventional lighting technologies.

SSL holds the promises of ongoing energy savings and new lighting value, but continued R&D is required to fully realize these promises. Key impacts of SSL will be discussed in the following sections.

2.1 How Is SSL Different from Conventional Light Sources?

Light generated by LED or OLED sources is the same as any other light that we perceive. However, SSL sources have a few key features that open a vast array of new values that were not previously possible. The key features of LED based lighting are:

- **Spectral Control:** LEDs and phosphors can emit light across the visible spectrum, including ultraviolet (UV) and infrared (IR). Combinations of different LEDs and/or phosphors create the ability to engineer the spectra for the demands of the application. This enables delivery of just the right spectrum of light for the application.

- **Intensity Control:** LEDs are inherently dimmable, and multi-channel LED sources enable dimming of individual LEDs, which may include different colors of LEDs, or LEDs aimed in different directions. This enables active tuning of spectrum or direction for some LED lighting products.

- **Optical Distribution:** The bright output, small source size, and directional nature of LEDs means that the optical distribution of LED lighting products can be well controlled with small, relatively low-cost optics, enabling light to be delivered only where it is needed for the application.

OLEDs also have demonstrated these types of spectral control and intensity control. Additional OLED features include:

- **Low luminance:** The low brightness of OLED sources allows them to be placed close to the lighted task, improving the lighting performance and efficiency of delivery of the light to the task without glare.

- **Thin Form Factor:** OLED sources can be very thin and, potentially, conformable or bendable enabling new lighting layout and locations.

SSL products can demonstrate all these important features while also performing at high efficacy levels, well beyond what conventional light sources can achieve. These features enable new aspects of efficiency in terms of delivering the right light (spectrum) in the right place (optical control) at the right time (intensity control). These features also enable new lighting capabilities that address physiological responses for health and productivity, horticulture lighting engineered to provide the appropriate spectrum at the right time to maximize plant productivity, lighting for safer roadways, and many more high-value lighting applications.

2.2 Energy Savings

LED lighting is already saving lighting consumers a significant amount of energy due to improved source efficiency compared to conventional lighting technologies. Current LED lighting products have form factors, light distributions, and light output levels that allow for direct replacement for existing, lower efficiency conventional lighting products, thus resulting in rapid adoption for significant energy savings. While SSL performance has already led to meaningful energy savings, there is still considerable room for efficacy improvement for both LED and OLED technology, as discussed in Sections 4 and 5.

The next generation of energy savings from SSL will come from application efficiency, which at its simplest, can characterize the efficient delivery of light from the light source to the lighted task. However, application efficiency can also take into account the effectiveness of the light spectrum for the lighting application, and the ability to actively control the source to minimize energy consumption when the light is not being used. The final factor in energy savings is adoption. Consumers need to buy and use SSL sources to replace less efficient sources in order to save energy. As with the introduction of any new technology, particularly on the scale of the lighting market, there will be barriers to adoption. Understanding these barriers and actively working to mitigate them will directly result in increased energy savings. These three aspects of energy savings – source efficiency, application efficiency, and barriers to adoption – will be discussed in the following sections.

2.2.1 Source Efficiency

With efficacies of certain products getting beyond 150 lumens per watt (lm/W), LED products can be more efficient than incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs), linear fluorescent luminaires, and high-intensity discharge (HID) sources. However, consumers often opt for lower cost, lower efficacy products over higher priced, top-of the-line products. Table 2.1 shows a comparison between the price and performance of top-performing SSL products available in 2016 and products typically purchased in 2016; Table 2.2 shows the price and performance of the best-in-class conventional lighting technologies. Together these tables illustrate that the top-performing LED products are already more efficient than incumbent technologies, but have higher purchase prices. On the other hand, LED products typically purchased in 2016, which were priced lower, have lower efficacies that are closer to those of the best-in-class incumbent competitors. This indicates that there is still work to be done to simultaneously improve efficiency and drive down the cost of LED products to make them more attractive to the general public. In addition to efficacy/cost tradeoffs, LED lighting manufacturers can choose to trade efficacy for lifetime, color quality, light distribution, and other performance attributes.

Table 2.1 Comparison Among Typical and Top-Performing SSL Products

2016 SSL Product Type	Top Performing Products* Luminous Efficacy (lm/W)	Top Performing Products* Price ($/klm)	Top Performing Products* Usable Life (L70)† (hours)	Typical Products** Luminous Efficacy (lm/W)	Typical Products** Price ($/klm)	Typical Products** Usable Life† (hours)
LED A19 Lamp (Dimmable, 2700 K)	100	$14	25,000	79	$9	22,000
LED PAR38 Lamp (3000 K)	88	$20	25,000	68	$18	25,000
LED T8 Tube (4000 K)	149	$13	50,000	109	$8	50,000
LED 6” Downlight (3000 K)	86	$80	50,000	58	$26	50,000
LED Troffer 2' x 4' (3500 K)	129	$51	50,000	100	$27	50,000
LED High/Low-Bay Fixture (4000 K)	136	$21	60,000	113	$14	60,000
LED Street Light (5000 K)	118	$37	60,000	103	$27	50,000
OLED Luminaire (3000 K)††	-	-	-	43	$756	40,000

Notes:

* The 90th percentile of either ENERGY STAR®-qualified products (for LED A19, PAR38, and 6” downlight) or DesignLights Consortium-qualified products (for LED tube, troffer, high/low-bay, and streetlight) was used to characterize the efficacy of “top-performing” products, and then average price was found for products at this efficacy point.

** Lawrence Berkeley National Laboratory (LBNL) conducted a consumer survey finding that more than 80% of respondents purchased a lamp at or below the 25th percentile price, and more than 90% purchased at or below the median price. From the survey, LBNL concluded that the mean and median are volatile metrics that represent the tail of the purchase distribution and that the 25th percentile of their web-scraped data best represents the characteristic price for LED lamps [3]. Based on this assessment, the 25th percentile was used to characterize the typical purchase price for LEDs, and the average efficacy was found for products matching this price point.

† For non-SSL technologies, the lifetime values mark the end of life of the product due to failure. Because LEDs undergo gradual lumen depreciation in addition to catastrophic failure, L70 values, the time at which products produce 70% of initial light level, are given to define the useful lifetime of the LED and OLED products [3].

†† Based on Acuity Brands Luminaires’ Chalina 5-Panel Brushed Nickel OLED Pendant available from Home Depot in May 2017 (product first released in 2015) [4].

Table 2.2 Price and Performance of Best-in-Class Conventional Lighting Technologies

Product Type	Luminous Efficacy (lm/W)	CCT (correlated color temperature)	Usable Life (hours)	Price ($/klm)
Incandescent A19	15	2760	1,000	$0.63
Halogen A19	20	2750	8,400	$2.50
CFL A19 Replacement	70	2700	12,000	$2
CFL (Dimmable) A19 Replacement	70	2700	12,000	$10
Linear Fluorescent System*	108	4100	25,000	$4
HID (High-Watt) System*	115	3100	15,000	$3
HID (Low-Watt) System*	104	3000	15,000	$4

* Includes ballast losses

There is still significant room for improvement in terms of performance and price for LED-based SSL products. The analysis in Section 4.1 shows that 255 lm/W is an achievable performance target for LED packages enabling luminaires with efficacy around 225 lm/W. Excellent progress toward this target has been demonstrated in the laboratory and in commercial LED packages.

Figure 2.1 suggests that LED luminaires will offer improvements of up to 100 lm/W over the best efficacies possible for incumbent technologies. OLED technology is still in its infancy but promises high efficacy and low cost, as well as new options for form factor and light distribution. Section 5.1.1 analyzes how OLED technology could reach 190 lm/W while offering a low-brightness and low-glare light source.

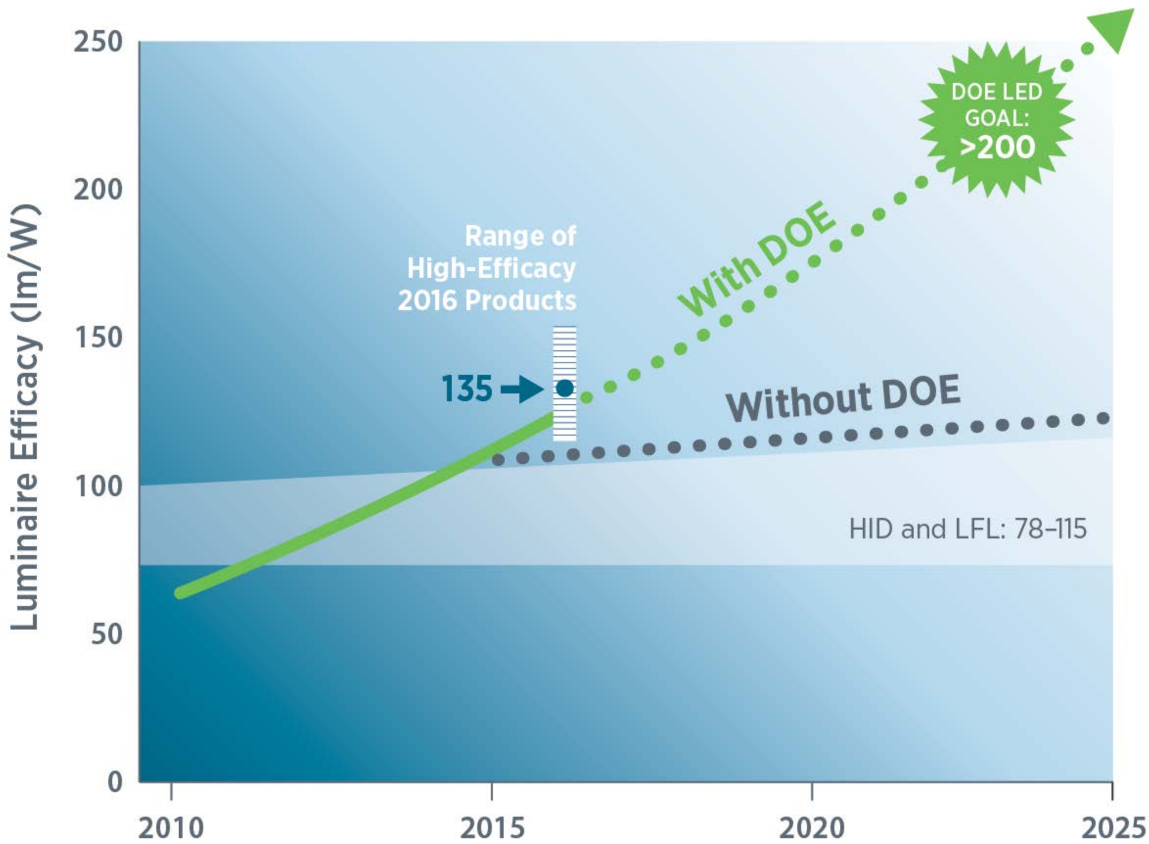

Figure 2.1 Comparison of LED and Incumbent Light Source Efficacies for HID and Linear Fluorescent Troffer Lighting

Source: LED Lighting Facts® Product Database, 2016

2.2.2 Application Efficiency

Lamp and luminaire source efficiency are important indicators of the energy efficiency of a lighting system, but they do not tell the whole story. The full efficiency of a luminaire is also defined by how efficiently the light is delivered to the target area, how effectively the color of the emitted light matches the needs of the application, and how effectively the light intensity is controlled. Each lighting application has its own requirements, and how effectively and efficiently the lighting system achieves the requirements defines the application efficiency.

For typical indoor lighting, the intent of the lighting is to enable vision, visual acuity, and possibly, non-visual physiological stimulation. Depending on the application, the intent of indoor lighting may be even more refined than this, with requirements such as high color fidelity, tuned spectra for lighting-specific colors, or more. Other applications will have different objectives for the lighting. Outdoor lighting is often intended for roadway and pedestrian safety. Horticultural lighting is intended to provide fuel and signaling to plants for effective growth.

Three additional advances are necessary to maximize application efficiency as efficient light sources alone are not sufficient. These three advances are summarized here and detailed in other sections of this report. First, a deeper understanding of the requirements of the application, including the physiological responses of the recipient of the light (discussed in Section 3.3) is essential to make full use of the technical capabilities of SSL technologies for optimized lighting effectiveness and energy savings. Second, tailoring the optical distribution of light (spectral, intensity, spatial) to the application – perhaps in real time – is important to only create the type of light required by the application and to direct it only where it is needed. Third, developing new ways of measuring how well the light has in fact been tailored to the application – again perhaps in real time – is vital to maximize application efficiency. This third advance is especially important because it can help drive the other two advances. Preliminary measurements can help lighting architects and engineers more intelligently design systems/components that tailor light to the application.

In matching source efficiency to application efficiency, the productivity of the application might be enhanced significantly, a benefit that goes beyond energy savings. For example, improved matching of the spectral distribution of light to the human day/night circadian cycle could improve sleep patterns, with benefit to human wellbeing that cannot be measured simply as an increase in "application efficiency."

2.2.3 Barriers to Energy Savings

SSL products can only deliver energy savings and improved productivity if they are being installed. While the energy savings and application benefits of SSL technology have been described, consumers must feel confident in the technology in terms of claimed energy savings, compatibility with existing fixtures and switches, and reliability. In addition, the cost of energy saving lighting products must not be out of reach for the users. Current barriers of first cost, reliability, and compatibility are being overcome and consumers are gaining the confidence required to adopt this technology. A brief overview of each of these aspects is discussed below.

- **First Cost –** The primary barrier to adoption for SSL products has been the price of LED and OLED lighting products, though prices have dropped rapidly over the past few years. SSL products remain more expensive than incandescent light sources, but have come down to as low as $2 to $3 per lamp for standard replacement products. However, these lower cost products, while still superior to conventional lighting products, may trade low price for reduced efficacy, lifetime, light distribution, and/or color quality. Even with somewhat higher prices, LED products exhibit clear reduction in total cost of ownership, when taking into account the energy and maintenance costs associated with the product.

- **Reliability** – LED lighting products can clearly be more reliable than conventional lighting technologies, yet individual LED products may not meet the user's reliability expectations due to the use of low cost materials, designs, or manufacturing processes. The long life of LED technology requires new techniques to project and communicate lifetime. The 70% lumen depreciation point of the LED has been used as a proxy for lifetime. However, this point only considers degradation in the LED source and does not account for other, more likely points of failure such as the power supply. (This is covered in more detail in Section 3.1.3.)

- **Compatibility –** The first generation of SSL products needs to be compatible with existing building infrastructure and controls to enable rapid adoption and increased consumer familiarity and comfort with the technology. However, LED products can have different light levels, optical distribution, and color qualities that make the replacement process less straightforward. In addition, LED products might not be compatible with all existing dimmers or power supplies (ballasts). Eventually, new form factors and lighting layouts that better align with the technology will be introduced to maximize the application benefits and increase energy savings. Through the DOE SSL R&D Program, scientists at Pacific

Northwest National Laboratory (PNNL) have performed research on many aspects of LED lighting compatibility including dimmers, controls, and general compatibility through the GATEWAY program.[3] The GATEWAY program improves consumer confidence and spurs adoption by documenting specific aspects of SSL technology, which provides an information resource for potential users of SSL technology.

- **Technology Understanding and Uncertainty –**There have been a number of situations where concerns about LED lighting impacts on the environment, aesthetics, or physiological impacts have caused delays or cancellation of SSL lighting installations. However, with its spectral and optical control, LED lighting is the only lighting technology that can be optimized to minimize environmental concerns, improve aesthetics, and mitigate negative physiological impacts. A better understanding of all these considerations at the application level is necessary to alleviate concerns and ensure the appropriate product is selected. LED lighting offers the flexibility to maintain or improve the lighting performance while still delivering energy savings.

Although these barriers can discourage adoption, LED lighting technology is rapidly gaining market share. These barriers do not represent fundamental limitations to SSL technology, but rather are normal resistance to the disruption of a large, entrenched market. As LED and OLED technology continue to improve and mature, the significance of these barriers will be further reduced.

2.3 U.S. Manufacturing and Jobs

The United States has played an important role in global lighting manufacturing since Thomas Edison established the Edison General Electric company in 1890, which then merged with Thomson-Houston Company two years later to become the General Electric we know today [5]. The U.S. lighting industry has evolved to tackle each lighting technology as it was born, from incandescent to CFL, linear fluorescent to HID, and now the industry has shifted once again to tackle SSL.

2.3.1 Domestic Lighting Manufacturing

The DOE 2017 SSL R&D Workshop in Long Beach, CA, included a panel “Thinking Ahead for Domestic SSL Manufacturing,” which brought together leading domestic manufacturers to discuss how they are positioning themselves for the future. The common thread among manufacturers was that LED lighting has enabled so many more choices, e.g., color rendering index (CRI), correlated color temperature (CCT), dimming, trim color, and connectivity, etc., and that to meet customers’ expectations, manufacturers must be able to quickly produce exactly what customers want. Manufacturers represented on the panel have different ways of approaching this problem, but the general trend is to make individual lighting systems tailored to a specific customer order. This approach benefits U.S. manufacturers supplying the U.S. market, because it requires luminaire manufacturing to take place near the end user.

2.3.2 U.S. Lighting Manufacturing Status

The DOE SSL R&D Program recognized early on that without focused action, U.S. leadership in SSL technology would not necessarily translate into domestic manufacturing operations and jobs. In 2009, the DOE initiated support of SSL advanced manufacturing R&D, which for a time included an annual meeting on SSL Manufacturing R&D and posting an annually updated SSL Manufacturing R&D Roadmap.[4]

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3 For more information, see: https://energy.gov/eere/ssl/gateway-demonstration-special-reports

4 Since 2015, the SSL Manufacturing Workshop has been folded into the annual SSL R&D Workshop, and the contents and updates of the SSL Manufacturing Roadmap are now included in this document. The final SSL Manufacturing R&D Roadmap (August, 2014) can be found at: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf.

Since 2009, the DOE SSL R&D Program has supported numerous advanced manufacturing R&D projects that have resulted in development of new production tools, new production techniques, and new SSL products. The objectives of the SSL manufacturing R&D portion of the DOE SSL Program are to reduce SSL product cost, improve SSL product consistency, and encourage domestic SSL manufacturing infrastructure and capabilities that support domestic production and job creation. Today, with the help of DOE SSL R&D, the United States is highly competitive for SSL product design and production [6]. Ongoing support of SSL R&D by DOE will support continued U.S. SSL technology leadership with the result of increased production of high-value SSL products in the United States.

At the LED chip and package level, two of the top LED package manufacturers worldwide are based in the United States: Cree and Lumileds. While these manufacturers perform most of their packaging outside the United States, the performance-defining manufacturing process for their high-value products — the metal-organic chemical vapor deposition (MOCVD) crystal growth of the LED wafer — is done in the United States. This process contains sensitive intellectual property that, if lost, would erode the competitive advantage enjoyed by domestic LED manufacturers in terms of LED efficiency and manufacturing yield. However, the semiconductor packaging supply chain and infrastructure has been solidly in Asia for decades. Technology developments, particularly in terms of automated, wafer-level packaging for specific processes necessary for LED packaging, could stimulate bringing LED packaging to the United States, but R&D breakthroughs would be necessary to advance these technologies.

Many of the largest domestic lighting manufacturers are in the process of shifting their products lines entirely to SSL technology. This shift has required their workforces to transition from metal working and fabrication skillsets to electronics, optics, thermal management, and system integration. With the further introduction of connected lighting, additional skillsets of software, circuit design, and communication protocols must be included in the design and manufacturing workforce. The United States has always had a robust group of smaller luminaire manufacturers participating in the lighting market alongside the largest lighting manufacturers. As LED component products have stabilized and matured, these companies can continue to develop luminaire products using readily-available LED packages, modules, and light engines. LED lighting technology offers the opportunity for smaller luminaire manufacturers to develop specialized and differentiated lighting products to fulfill an almost limitless number of lighting market niches.

As new aspects of SSL technology and applications emerge (e.g., connected lighting, horticultural lighting, and lighting that engages physiological responses), more manufacturing capacity and more lighting professionals with expertise in these areas will be required. SSL is expected to become the dominant lighting technology within a few years, and all jobs in the lighting sector of the economy will be considered SSL jobs. In 2015, it was estimated that 327,288 people are employed in “efficient lighting” jobs within the United States [7]. However, with the market transition to SSL technology, the distinction between “conventional” lighting jobs and “energy efficient lighting” jobs will no longer exist. These jobs include not just product design and manufacturing, but also lighting design, specification, procurement, and sales professionals.

2.4 Environmental Sustainability

The higher efficacy of SSL lighting systems is projected to save a significant amount of energy, as shown in Figure 2.9. This savings has direct benefits in terms of energy cost savings and improved energy security for the United States [8]. In addition, new levels of control of the spectrum, optical distribution, and intensity of the emitted light can minimize the impact of artificial lighting on the ecosystem.

The DOE-sponsored life-cycle assessment (LCA) conducted in 2013 showed that, compared to conventional lighting, LED products reduce the total life-cycle energy consumption, including energy consumed during manufacturing, transportation, and use of the products [8]. Continued advancements in LED efficacy and lifetime have roughly halved the life-cycle energy consumption compared to LED products five years ago. The LCA study also showed that SSL can reduce energy use from lighting and maintain performance levels without using large amounts of toxic or scarce materials.[5] Unlike fluorescent lighting technology, LEDs and OLEDs do not require mercury or lead, and they make much more effective usage of rare-earth materials. The DOE LCA showed that in terms of air, resource, water, and soil impacts, LED-based SSL has a far less negative impact than incandescent lighting, and as LED technology has improved, it has lower impact than CFLs. The LCA study concluded that LED-based SSL already represents an advancement in sustainability for lighting, and the advantages will continue to grow as further improvements in efficiency are realized.

Although LED-based SSL products are already demonstrating improved sustainability, additional efforts can be pursued to further limit environmental impacts. The following are some of the initiatives being pursued within the LED lighting industry:

- **Reducing the ecological impacts of providing light at night**. For example, tailoring the spectra of LED products has enabled outdoor lighting designed to minimize disruption of sea turtle hatching.[6] Controlling the optical distribution of light along with the use of controls could also minimize the impact of night lighting on migratory birds, who can be confused by night lighting. In an effort to further understand the impacts of light on animals and identify other opportunities for LED products, DOE organized a meeting in April 2016 with animal researchers, LED technologists, and lighting impact researchers to discuss animal responses to light, and produced a summary report of the discussions.[7]

- **Minimizing light pollution from outdoor area lights**. The DOE SSL R&D Program recently released a report "An Investigation of LED Street Lighting's Impact on Sky Glow."[8] The report analyzed the impacts on sky-glow of typical LED roadway lighting spectral power densities, reduction in total light, and reduction in the amount of light emitted upward from typical roadway lighting. The report found that while broad spectrum (white) lighting does scatter more in the atmosphere, the reduced light outputs and eliminated uplight enabled by LED technology results in a net reduction of sky-glow.

- **"Dematerializing," or reducing the amount of material used for SSL products**. With thoughtful new design, there is an opportunity to dramatically reduce the amount of materials – particularly energy-intensive materials such as aluminum – required for an LED lamp or luminaire products. Improving lighting form factors, integration, and ease of installation can also reduce waste in the installation or retrofit process.

- **Understanding the product life cycle** to allow for reusing, recycling, or salvaging of luminaires or components at the end of product life [9].

- **Improving manufacturing efficiency** through yield improvements, material utilization, and equipment energy usage.

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[5] LEDs enable a dramatic reduction of the use of rare-earth metals for lighting in line with the DOE Critical Materials Strategy available at: http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

[6] For more information on approved Sea Turtle Lighting please see: http://www.myfwc.com/wildlifehabitats/managed/sea-turtles/lighting/

[7] The summary report for the Animal Responses meeting can be found at: https://energy.gov/eere/ssl/downloads/2016-animal-responses-light-meeting-report.

[8] The report "An Investigation of LED Streetlighting's Impact on Sky Glow" can be found at: https://energy.gov/sites/prod/files/2017/05/f34/2017_led-impact-sky-glow.pdf

2.5 Global Lighting Market

There is a vast global opportunity for SSL products. Rising electricity prices and the desire for energy independence are causing the global lighting market to shift toward energy-efficient light sources. Even in emerging economies such as in India, the lighting industry now focuses almost all its R&D activities and new manufacturing facilities on SSL. Consumer acceptance of LEDs has been enhanced by the improvements in the quality of light and rapid price reductions.

Many of the leading lighting companies recently report that LED lamps and luminaires represent more than 50% of their revenues, including Acuity Brands (67%), OSRAM (65%), Philips (61%), Hubbell (55%), and Zumtobel (73%) [10] [11] [12] [13] [14]. Strategies Unlimited estimate that at the end of 2016, LED lamps comprised 11% of the global installed lamp base. As seen in Figure 2.2, it forecasts that penetration of the global installed base will reach 50% around 2022 [2].

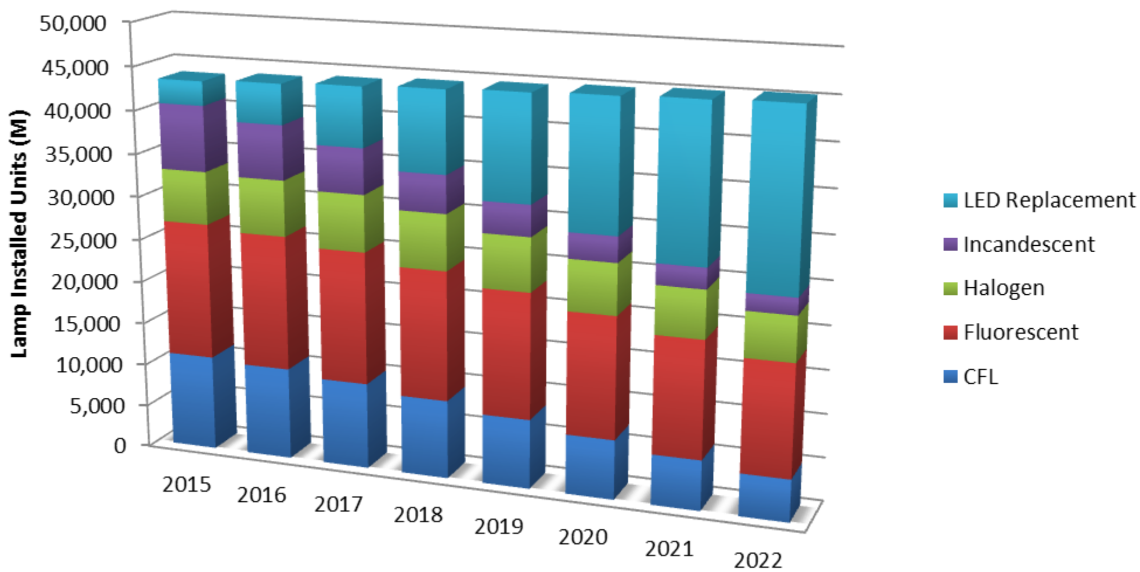

Figure 2.2 Evolution of the Global Installed Lamp Base by Lighting Technology

Source: Philip Smallwood, Strategies Unlimited, Strategies in Light, Anaheim, CA, March 2017 [2]

Figure 2.3 shows the anticipated growth in LED lamp sales, by lamp type, and the fall in the average selling price (ASP) of LED lamps.

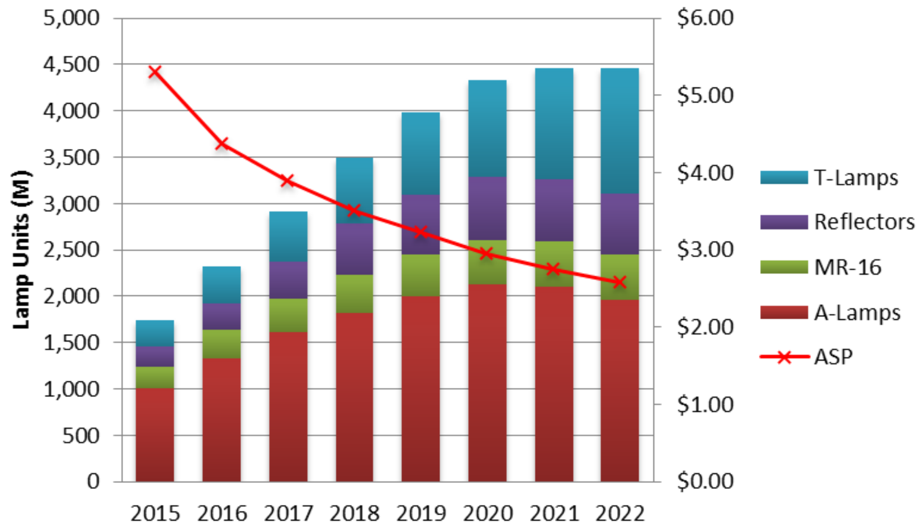

Figure 2.3 Global LED Lamp Shipments by Lamp Type

Source: Philip Smallwood, Strategies Unlimited, Strategies in Light, Anaheim, CA, March 2017 [2]

Because of the fall in ASP, the revenues from LED lamp sales are expected to peak in 2019 at about $12 billion. The anticipated peak in unit sales reflects the longer lifetime. Figure 2.4 shows that in most applications the operational lifetime of LEDs is now longer than the average replacement cycle for lighting systems.

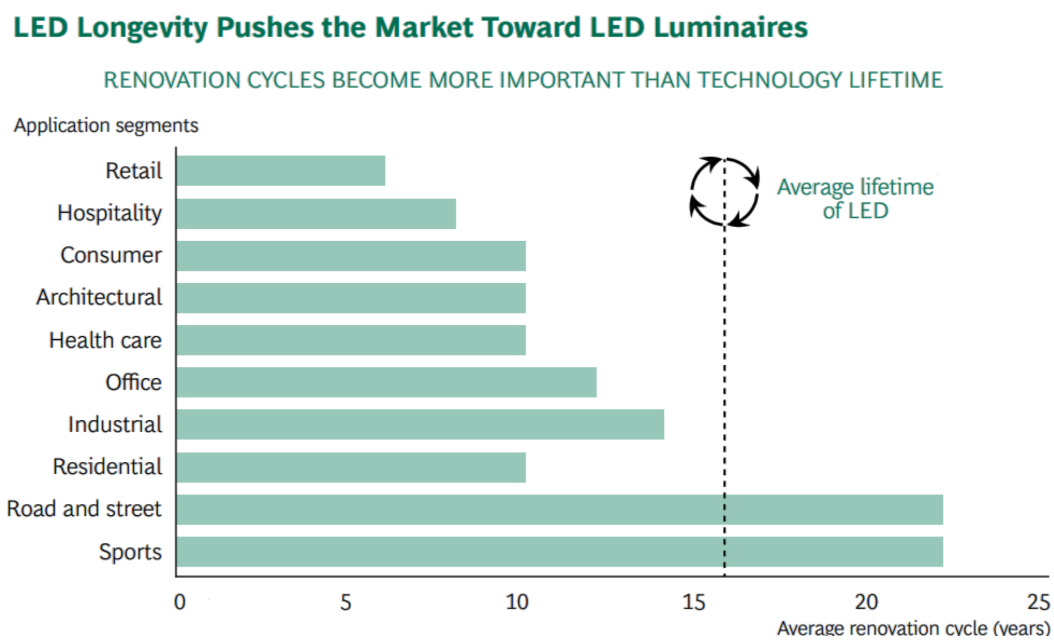

Figure 2.4 Renovation Cycles for Lighting Applications

Source: Boston Consulting Group, "How to Win in a Transforming Lighting Industry," November 2015 [15]

The intense price competition in the markets for light sources and lamps has led many companies to begin providing complete lighting systems and services. However, the analysis by Boston Consulting Group shown in Figure 2.5 forecasts that sales of luminaires will remain the largest source of revenues through 2020 and will be dominated by SSL-based fixtures [15].

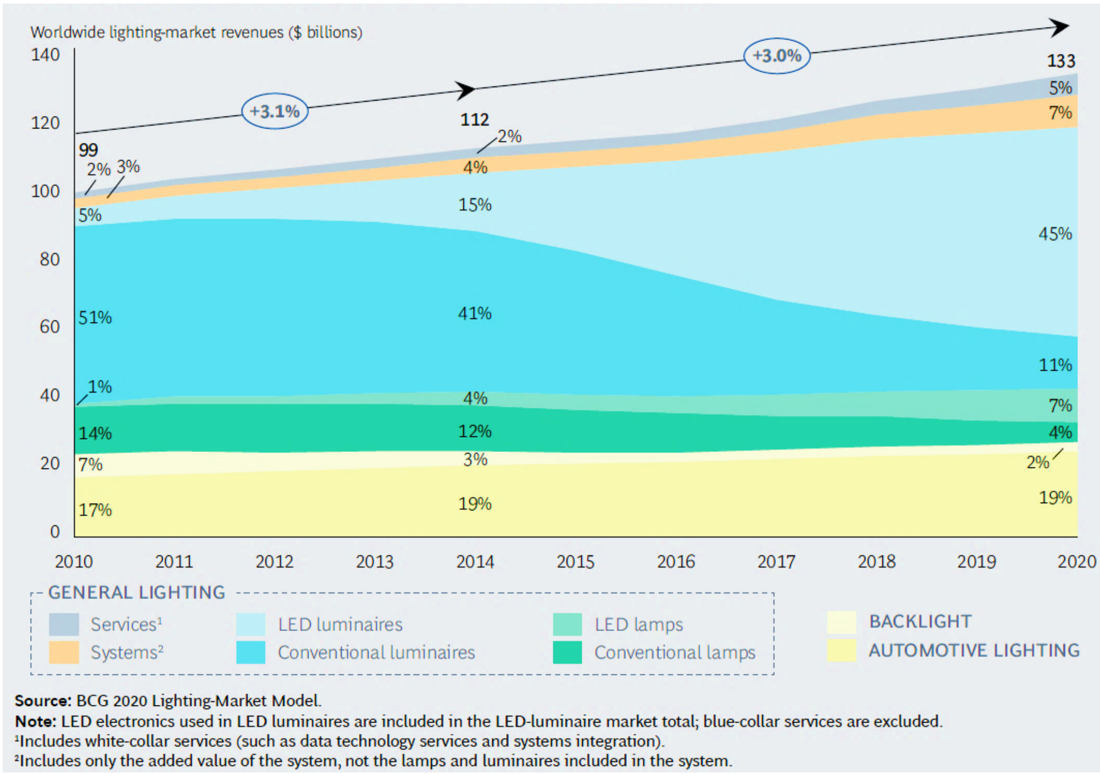

Figure 2.5 Global Lighting Revenues from 2010 to 2020

Source: Boston Consulting Group, "How to Win in a Transforming Lighting Industry," November 2015 [15]

According to Strategies Unlimited, revenues of LED packages for general lighting applications in 2016 grew by 7% to $5.7 billion, while sales for signs grew by 8% to $2.2 billion and for automobile lights by 9% to $2.1 billion. The markets for these three applications are expected to grow through 2021, as shown in Figure 2.6 [2].

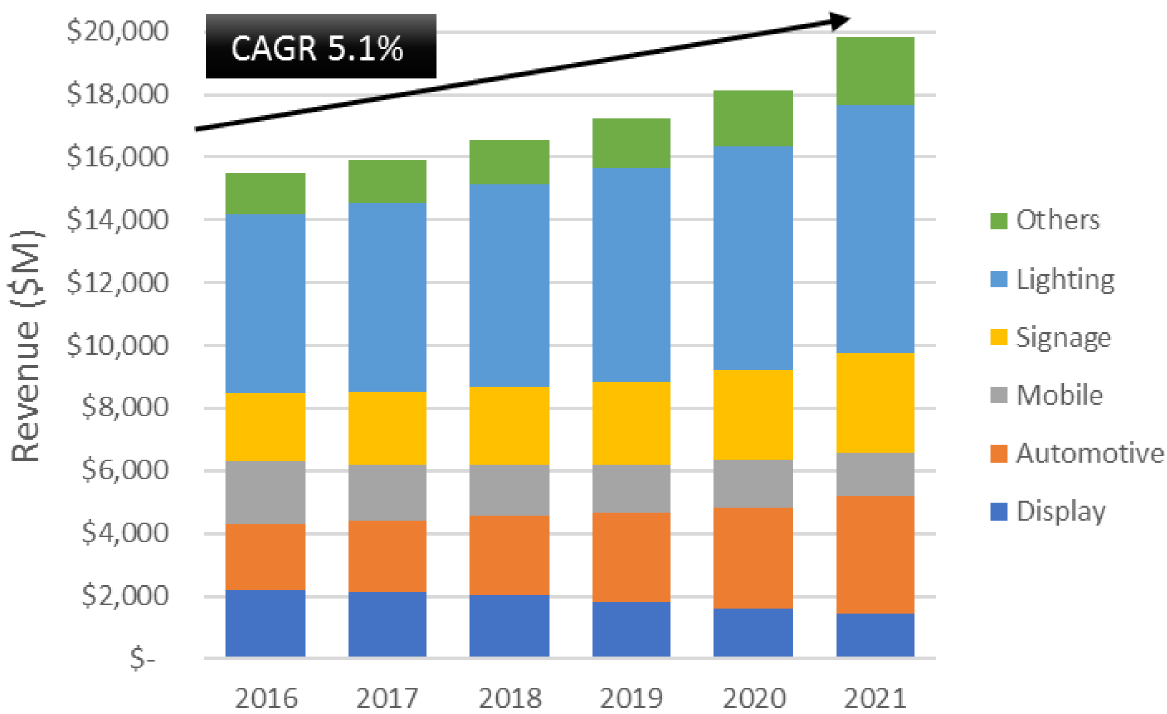

Figure 2.6 Sales Revenues and Compound Annual Growth Rate (CAGR) for LED Packages by Application from 2016 to 2021

Source: Philip Smallwood, Strategies Unlimited Strategies in Light, Anaheim, CA, March 2017 [2]

2.5.1 United States

The DOE SSL Program supports numerous analyses to determine the status and potential of SSL in the U.S. lighting market. Each year, DOE alternates between producing a "snapshot" of the current LED installed base[9] and a forecast of the future U.S. lighting market;[10] each serves as an input for the other. While a high-level overview of the U.S. lighting market will be provided in this section, readers are encouraged to visit https://energy.gov/eere/ssl/market-studies to view these full reports.

Status

By the end of 2016, there were 874 million cumulative LED unit installations in the United States, more than double the number of LED unit installations in 2014. These LED installations contributed 469 trillion British thermal units (TBtu) of energy savings, which is equal to an annual cost savings of about $4.7 billion [16]. Table 2.3 provides a detailed breakout of the installations and energy savings by application.

9 Most recently, the "Adoption of Light-Emitting Diodes in Common Lighting Applications," published August 2017
10 Most recently the "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," referred to as the DOE SSL Forecast, published September 2016.

Table 2.3 LED Installations and Energy Savings by Application

Application	2016 LED Installed Penetration (%)	2016 LED Units Installed* (Millions)	2016 Energy Savings (TBtu)
A-Type	13.5%	436	99.1
Decorative	6.7%	58.9	10.3
Directional	15.3%	82.4	37.9
Small Directional	47.6%	21.0	35.6
Downlighting	19.8%	137	92.5
Linear Fixture	6.0%	68.0	62.0
Low/High Bay	9.4%	8.6	46.4
Total Indoor	12.3%	812	384
Street/Roadway	28.3%	12.5	14.9
Parking Garage	32.5%	8.5	14.4
Parking Lot	26.2%	7.1	18.6
Building Exterior	31.2%	18.1	14.0
Total Outdoor	29.7%	46.1	61.9
Other	7.7%	15.6	12.4
Connected Controls	<0.1%	4.0	11.4
Total All**	12.6%	874	469

Source: DOE SSL Program, Adoption of Light Emitting Diodes in Common Lighting Applications, August, 2017 [16]

* Installations are the total cumulative number of LED lamps and luminaires that have been installed as of 2016.

** Values may not add due to rounding.

Despite recent progress, there is still a long way to go, as Figure 2.7 shows. Nearly all indoor applications have seen less than 20% penetration of LED lighting products, and the penetration in the linear fixture and low/high-bay applications is less than 10%.

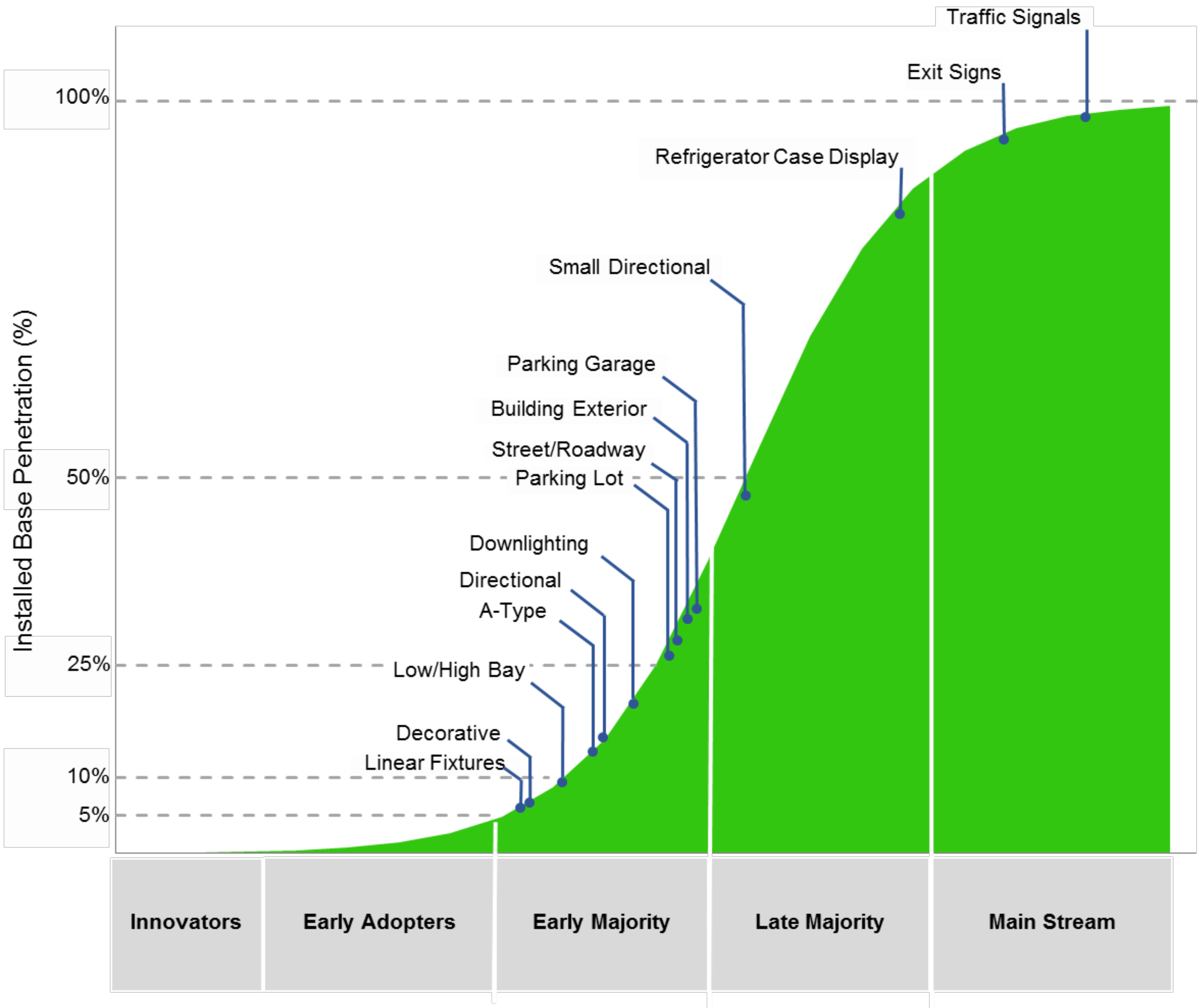

Figure 2.7 2016 Penetration Rates of LED Lighting Applications

Source: DOE SSL Program, Adoption of Light Emitting Diodes in Common Lighting Applications, August, 2017 [16]

With more than three billion A-type lamps in use, general service lamps made up nearly half of all U.S. lighting unit installations; however, a large number of installations does not necessarily translate directly to the best opportunity for energy savings. As shown in Figure 2.8, the energy savings opportunity depends on the number of installations, the number of hours each installation is operated, and the energy efficiency improvement offered by LEDs compared to the incumbent technologies with which they are competing. For this reason, linear fixture and low/high-bay applications, which are used more heavily in commercial and industrial spaces and characterized by long operating hours, contributed equal or greater energy savings compared to A-types in 2015 despite fewer total installations (1.1 billion and 90 million, compared to 3 billion, respectively) and lower LED penetration (3.2% and 3.7% compared to 6.0%, respectively). Linear and low/high bay applications are also predicted to contribute significantly to future LED energy savings, (discussed in the following section), and have therefore been identified as key applications by the program.

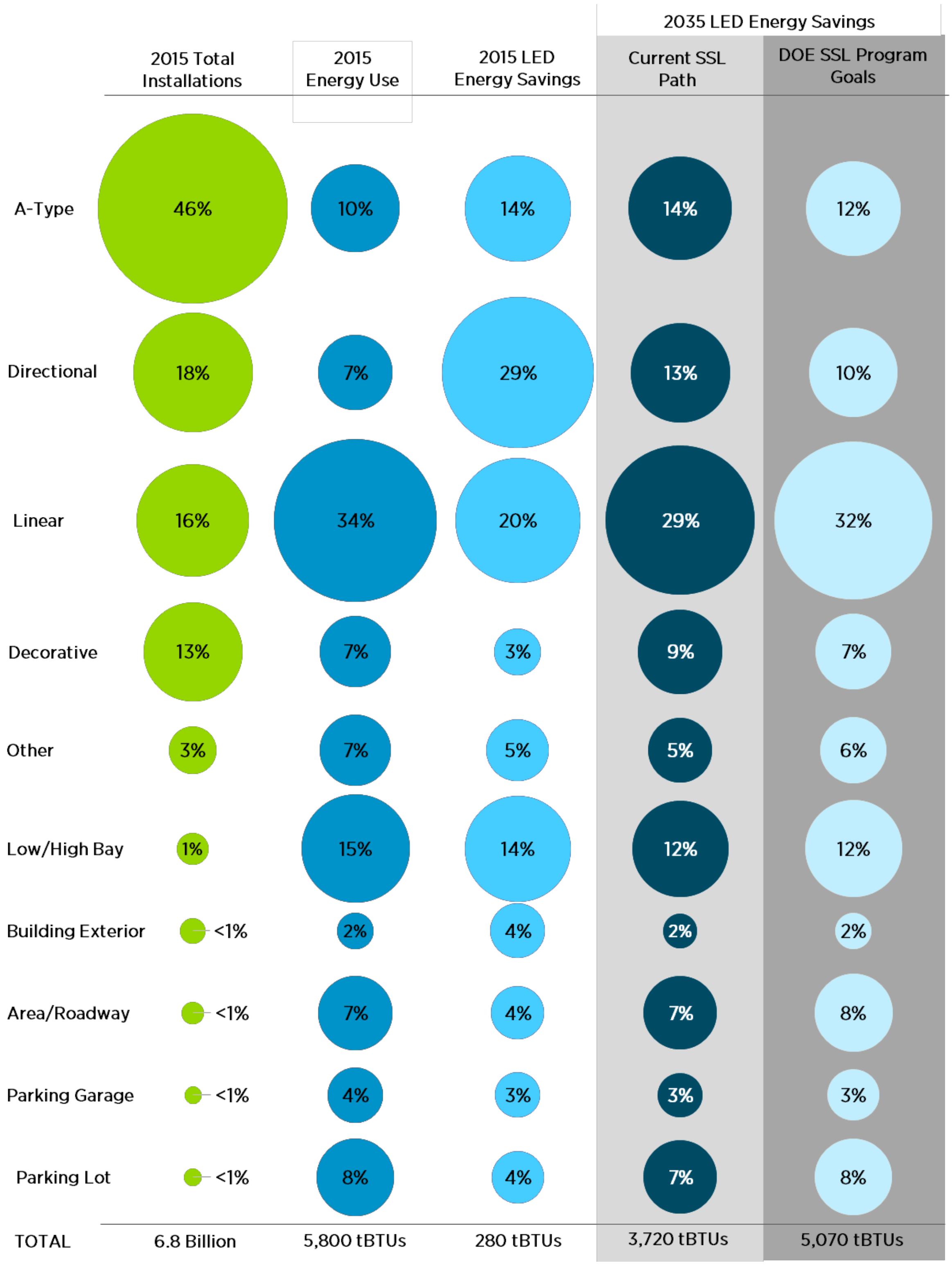

Figure 2.8 Total 2015 U.S. Lighting Installations, Energy Consumption, and LED Energy Savings

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

Forecast

Forecasts of LED adoption in the United States are similar to global forecasts, in that LEDs account for a small but increasing share of the lighting market. The DOE 2016 SSL Forecast suggested that SSL could account for 86% of installed lighting in the United States by 2035 [1].

The DOE SSL Program Goals scenario is based on aggressive price and performance projections derived from reaching DOE SSL program goals. By 2035, meeting the DOE SSL program goals would yield a total of 5.1 quads of energy savings annually [1]. As shown in Figure 2.9, this represents 75% energy savings over the scenario in which SSL did not exist.

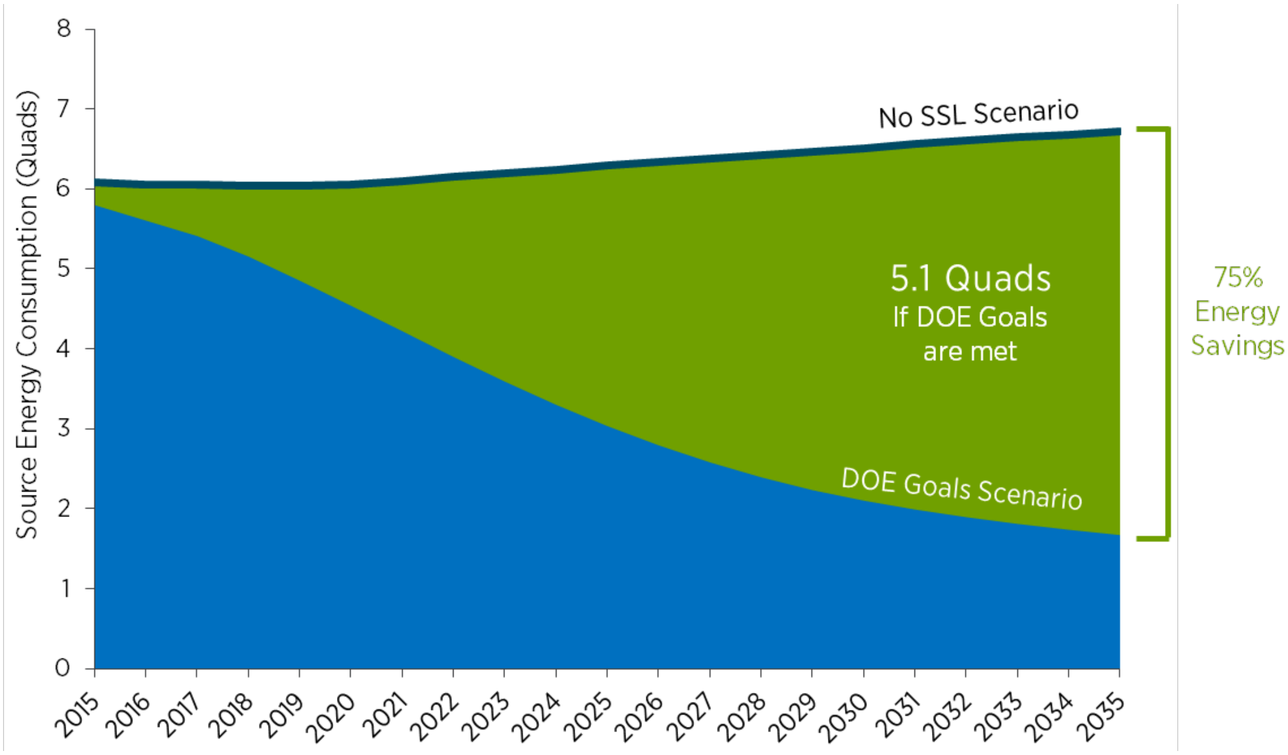

Figure 2.9 DOE SSL Program Goal Scenario Energy Savings Forecast for the U.S. from 2015 to 2035

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

Figure 2.10 shows the resulting cumulative energy savings from 2015 through 2035 for both the Current Path and DOE SSL Program Goals scenarios. If DOE SSL Program Goals are met, LEDs would enable an additional 20 quads of energy savings through 2035 over the Current Path, which is enough energy to power 90% of U.S. homes for one year. This demonstrates that SSL provides an unprecedented opportunity to reduce electricity consumption, thereby saving money and improving domestic energy security. It also illustrates the importance of the DOE SSL Program R&D priorities and milestones to help realize aggressive price and performance improvements.

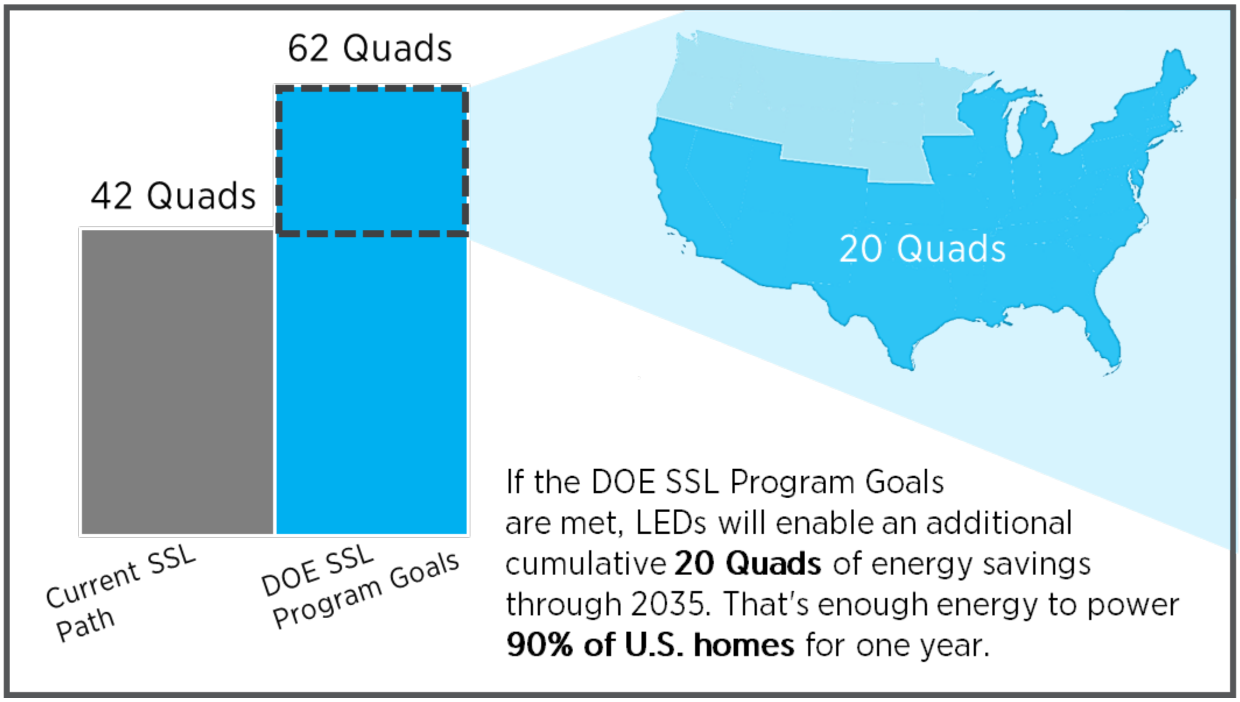

Figure 2.10 U.S. Cumulative Energy Savings Forecast from 2015 to 2035

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

2.5.2 Europe

Information Handling Services Markit Ltd. (IHS) estimates that in 2016, 20% of lamps sold and 10% of luminaires sold in Europe were LED-based, and that 8% of lamps and 9% of luminaires installed in Europe were LED. The IHS forecast for both unit sales and unit installations through 2024 is shown in Figure 2.11. LEDs are expected to make up an increasing percentage of unit sales, reaching 72% of lamps and 87% luminaires by 2024. These sales are projected to contribute to an increasing number of LEDs in the installed base, such that 53% of lamps and 58% of luminaires will be LED in 2024 [17]. Regulations within the European Union (EU) have helped clear the way for LEDs. Restrictions on sales of incandescent lamps within the EU were first introduced in 2009; however, an exception was allowed for halogen lamps [18]. The exception was terminated for directional lamps in September 2016; the ban on omnidirectional halogen lamps will go into effect on September 1, 2018 [19].

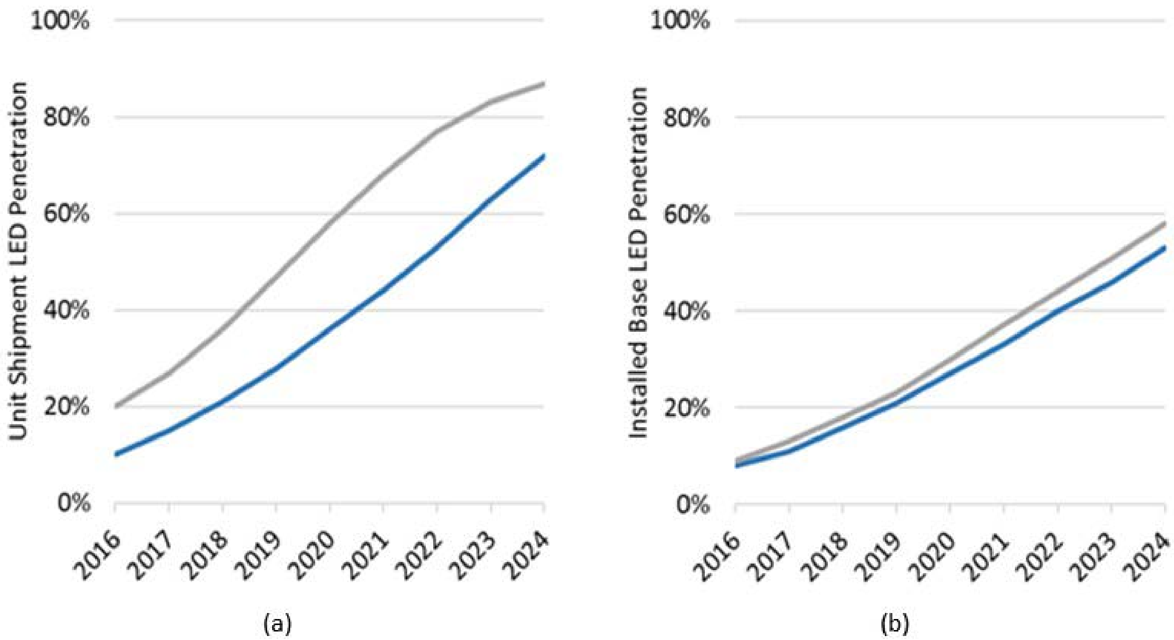

Figure 2.11 Forecast of SSL Market Penetration in Europe: (a) Unit Sales, and (b) Installed Base

Source: IHS Markit, "IHS Markit Lighting Intelligence Service: Lighting," 2017 [17]

Lamp production in Europe has traditionally been dominated by OSRAM, Philips, and the Thorn division of Zumtobel. While Zumtobel is managing the transition to SSL within its existing corporate structure, both OSRAM and Philips are in the midst of significant reorganization. The luminaire business is very fragmented, with the ten largest vendors capturing less than 50% of the market.

OSRAM Licht has sold its general lighting business (LEDVANCE) to a Chinese consortium, which is dominated by MLS Lighting [20]. In the fiscal year 2016, LEDVANCE contributed revenues of €1.9 billion (approximately $1.7 billion US), while revenues from the remaining OSRAM operations were €3.8 billion (approximately $3.4 billion US) [20, 21]. Looking to the future, OSRAM is investing heavily in R&D and is expanding its manufacturing of LED chips in Malaysia [22]. Philips has announced its intention to sell an 80% interest in its Lumileds Division, which manufactures LED chips and includes the Philips Automotive Lighting Division [23]. Philips split off its remaining lighting operations through a public offering of 20% ownership. Since the initial stock market listing, the parent company, Royal Philips, has reduced its share in Philips Lighting to 55% [23].

Much of the collaborative R&D in Europe has been coordinated through the Seventh Framework Programme (FP-7) and Horizon 2020 programs funded by the EU.[11] The typical project involves both industry and universities or research institutes and lasts for about three years.

Table 2.4 contains a list of European SSL projects that were active in the past year.[12] These R&D programs provide insight into European priorities, which include LED and OLED materials and system integration for new lighting values.

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[11] For more information about these programs, please see: http://cordis.europa.eu/home_en.html

[12] Funding levels are the EU contribution in Euros (€); as of May 2, 2017 €1 was equivalent to $1.09

Table 2.4 European SSL Projects Active in 2016 and 2017

Project Name	Funding (Millions)	Project Goals
OpenAIS	€10.8	To add value through the more efficient use of the building, reduction of carbon footprint, and increased comfort and well-being. To facilitate smooth and effective interaction of the lighting system with other functions in a building such as heating, ventilation, and air conditioning (HVAC), security and access control. To guarantee extensibility and security of the system architecture.
HI-LED	€3.5	To advance the state of the art of SSL through research on innovative light engines that take advantage of full control of light. For incorporated intelligence to enable responsive fine tuning of spectral properties in real time, as well as precise dimming capabilities.
LBNL	€3.15	To achieve progresses beyond the state-of-the-art LED in terms of size (area and thickness), flexibility, efficiency, lighting quality, beam-shaping, lifetime, added intelligence, production and production/installation costs by integrating light management structures combined with new color-changing coatings containing organic fluorescent dyes with heat management solutions, LED chips, and multispectral sensors for intelligent color-sensing feedback.
LEDLUM	€4.1	To develop a highly integrated cost competitive light engine technology platform for SSL, connected directly to the electrical power grid. For the new platform to reduce size by 90%, material cost by more than 50% and losses by 20% compared to state-of-the-art solutions.
NANPHOM	€1.5	To exploit new ways of controlling the emission characteristics of nanophosphors, surpassing the limits imposed by conventional optics, through new optical design based on multilayers, surface textures and nano-scatterers of controlled composition, size and shape.
SHINING	€1.5	To develop low-cost LEDs based on solution-processed semiconductors, through the synthesis of new perovskite nanostructures, combined with advanced spectroscopic characterization and device development.
PHEBE	€3.9	To develop innovative, high-efficiency, blue emitters for white OLEDs, which will create a major breakthrough in the cost performance of OLED lighting. The focus will be on thermally activated delayed fluorescence (TADF).
ALABO	€3.9	To develop organic electronic building elements on flexible substrates with monolithically integrated barrier foils as substrate for use in photo-voltaic panels and OLEDs.
HyperOLED	€4.0	To develop materials and matching device architectures for innovative, high performance, hyper-fluorescence OLEDs, by combining TADF molecular hosts with novel shielded fluorescence emitters, targeting saturated blue emission of very high efficiency, especially at high-brightness levels.
Excilight	€3.9	To set up a network to train 15 Early Stage Researchers in the development and application of exciplex and TADF emitters, who can apply their expertise directly in future positions.
FLEXOLIGHTING	€4.4	To spur innovations in materials, processes, and device technology for OLED lighting with the intention of building a European supply chain. Specific targets include: panel cost less than €10/kilolumen, efficacy exceeding 100 lm/W, lifetime over 1000 hours at 97% initial luminance of 5,000 candelas per square meter (cd/m2), consistent color coordinates and CRI over time, and minimizing the environmental impact of the materials and lighting systems.
PI-SCALE	€14.0	To integrate existing infrastructures into a "European flexible OLED pilot line," which will operate in an open access mode and serve customers from along the value chain with individual product designs, validation of upscaling concepts, and system-level flexible OLED integration.

2.5.3 China

China plays several important roles in the transformation of the lighting industry. China's consumption of electricity is about 50% higher than that of the United States. The Chinese government is concerned about the environmental effects of power generation as well as the cost of building additional power plants [24, 25]. About 14% of China's electricity consumption is used for lighting, so China has incentive to be a large consumer of energy efficient lighting products [26]. China is also a major manufacturer of LED packages and lighting products, as summarized in a report in 2016 published by the China Solid State Lighting Alliance (CSA) [27]. Production of LED lamps and luminaires grew in 2016 by 33% to 8 billion units, and half were sold domestically [28]. SSL adoption, in terms of sales, increased from 33% in 2015 to 42% in 2016 and has reduced the electricity use for lighting by 140 terawatt-hours (TWh) to 800 TWh [29].

In 2016, the value of LED exports to the United States rose by 17% to $2.4 billion, and the total revenue of LED lighting exports was about $10.6 billion [28]. China is a major supplier of LED packages, including low and mid-power packages and high-brightness packages. With expected LED price increases, Chinese orders for new MOCVD production tools are anticipated. While much of the total LED production capacity is located in China, a large portion of this capacity is not suitable for lighting caliber LEDs, which have more rigorous requirements for efficiency, consistency, and reliability than other applications such as indicators and displays. Consolidation of the SSL industry in China continued in 2016, which should generally improve LED performance and increase interest in innovation.

Chinese manufacturers have a strong presence at all levels of the LED lighting manufacturing value chain. At the LED chip level, LEDInside estimates that approximately $2 billion worth of LED chips were produced in China [30]. At the package level, manufacturers sold $7.5 billion worth of packages, 75% of which were produced by Chinese-owned companies. Although the share of all LED packages manufactured in China by foreign-owned companies is only around 25%, more of these are intended for lighting applications. The production of lamps and luminaires in China is growing rapidly – by 34% in 2016 – and is now worth approximately $30 billion, according to the CSA [31]. The national objective is to double the production of lighting products over the next five years, enabling annual energy savings of 340 TWh.

2.5.4 India

India has an ambitious commercialization and industrialization program that is severely constrained by the shortage of electricity. In 2009, the Indian Ministry of Power set up Energy Efficiency Services Limited (EESL), a joint venture of NTPC Limited (India's largest power utility), Power Finance Corporation, Rural Electrification Corporation, and POWERGRID (responsible for the interstate transmission of electricity) to facilitate implementation of energy efficiency projects. Since its conception, EESL manages the purchase and distribution of replacement lamps and street lights.

Following local trials by EESL, in January 2015 Prime Minister Norendra Modi launched a national program for LED-based residential, commercial, and street lighting as a key component in the drive toward energy efficiency [32]. The project had four main goals:

1. To reduce the imbalance between electricity demand and supply, thereby avoiding the need for new production plants
2. To reduce the impact of coal-burning power plants on air pollution in major cities
3. To reduce the burden of electricity bills on all Indian consumers
4. To revitalize the lighting industry by adopting new technology and training new manufacturing skills.

The focus of the new government program was on three applications [33]:

1. Self-ballasted replacement lamps: Primarily focused in the residential market, which is still dominated by incandescent lamps. The goal is to replace more than 700 million lamps in the next 3 years.

2. Downlights: Aimed at showrooms, shop windows, and offices where the poor color quality of CFLs has led to these applications being dominated by inefficient halogen lamps. The goal is to introduce 50 million LED lamps in these applications.

3. Roadway and street lights: Targeted to replace most of the 35 million existing street lights in the next few years.

The program is well underway; more than 237 million LED replacements for incandescent bulbs have been distributed through the EESL's program, which allows customers to purchase lamps with a minimal down payment and then pay the remainder through monthly installments along with their electric bill [34]. The lamps were purchased by EESL through a series of tenders, with prices for an 800 lm bulb falling from 310 rupees (US$5) in 2014 to 38 rupees (US$0.60) in 2016 [35]. The resulting annual energy savings are estimated at more than 30 TWh [34].

Regional and local governments have also promoted the adoption of LED streetlights and replacements for fluorescent tubes. LED tubes are being distributed at prices between 200 and 250 rupees (US$3 to US$4). Installation of streetlights has been slowed by financing and infrastructure challenges. By May 2017, 2.1 million streetlights had been installed. While this was double the number of installations seen through May 2016, is still far from the 35 million target set out in Prime Minister Nodi's 2015 program [36].

Manufacturing domestically in India is strongly encouraged, although most LED chips and packages are currently imported. India has had a large capacity to produce incandescent lamps and CFLs, and much of this is being converted to make LED products. Current capacity to manufacture LED lamps is around 30 million per month, with about half these lamps being allocated to the government distribution programs [34]. According to EESL, more than 330 million LED lamps had been sold by the Indian lighting industry through March 31, 2017 [34].

2.5.5 Off-Grid Communities in the Developing World

Today, there are 1.2 billion people worldwide living without access to the power grid, and about half of these people reside in Sub-Saharan Africa, where the installation of high-quality lighting is constrained by the availability of reliable sources of electricity [37]. Solar-powered lighting provides the entry point to electrical access for many families. Solar-powered SSL is affordable, even offering long-term financial benefits, as savings on the purchase of candles or kerosene can enable the purchase of small solar systems that support lighting, cell phone charging, and perhaps small appliances.

In addition to the financial savings, solar-LED lighting offers environmental and health benefits. Fuel-based lighting (e.g., kerosene lamps) contributes to air pollution, and is particularly dangerous due to the risk of fires and toxicity of the fuel, which contains a high proportion of heavy particulates. A 2014 study published by the United Nations Environment Programme cited safer living conditions and support for new forms of employment as potential benefits of switching from fuel-based lighting to solar SSL [38]. Specifically, one estimate found that 38 jobs are created for every 10,000 people living off-grid for whom stand-alone solar LEDs are suitable. Extending that figure to the 112 million households globally that lack electricity access, are unlikely to be connected to the major grid, micro-grids, or are able to afford more extensive solar systems, the uptake of solar-LED lighting has the potential to create 2 million new jobs [39]. This number far exceeds the 150,000 jobs associated with fuel-based lighting, and half of the jobs would be created in Africa [39].

While solar-powered SSL offers the potential to bring reliable lighting to people across the world, the remainder of this section will focus on the progress in expanding access to lighting in Africa. According to the International Energy Agency (IEA), 632 million residents of sub-Saharan Africa (65% of the population) have no access to the electrical grid, and the supply of electricity to many of those who do is unreliable [40]. A list of qualified off-grid SSL products is available from the Lighting Africa website.[13] The solar products that have been added during 2016 and 2017 produce between 23 and 230 lumens for periods of 3.9 to 18 hours before recharging. The lights contain between 1 and 36 LEDs and mostly draw power at 3.2 to 3.7 volts (V) from batteries with storage capacity of 470 milliamp hour (mAh) to 4900 mAh. Warranties vary between 1 and 3 years, and most lamps maintain their light output when under full charge to more than 95% of the initial level after 2,000 hours of operation. Efficacy varies from 50 lm/W to over 150 lm/W, and the average efficacy is close to 100 lm/W.

Annual sales of qualified solar lamps in Africa are currently estimated to be 4 million per year [41]. The major barrier to faster adoption has been the shortage of financing to set up the necessary distribution infrastructure and to provide loans for potential customers. The cost of solar panels and batteries has not been falling as rapidly as that of the LED light sources. Thus, a major contribution that the SSL industry can make would be to increase the efficacy of the LEDs to more than 200 lm/W, which would halve the necessary capacity of the panels and batteries or double the light output of the solar lamps.

For grid-connected lighting, many African governments have in the past subsidized the purchase of CFLs to replace incandescent bulbs in order to reduce the load on electrical grids. Programs are now underway to promote the adoption of LED lights. For example, the state-owned Zambia Electricity Supply Corporation (ZESCO) estimates that if all households and industries switch to LED bulbs, the nation can reduce its load by up to 200 megawatts (MW), which is about 30% of its energy deficit. ZESCO will spend a total of US$20 million to distribute 5 million free LED bulbs in exchange for conventional ones in the first half of 2017 [42].

2.6 Virtuous Cycles of Science, Technology, and Societal Benefit

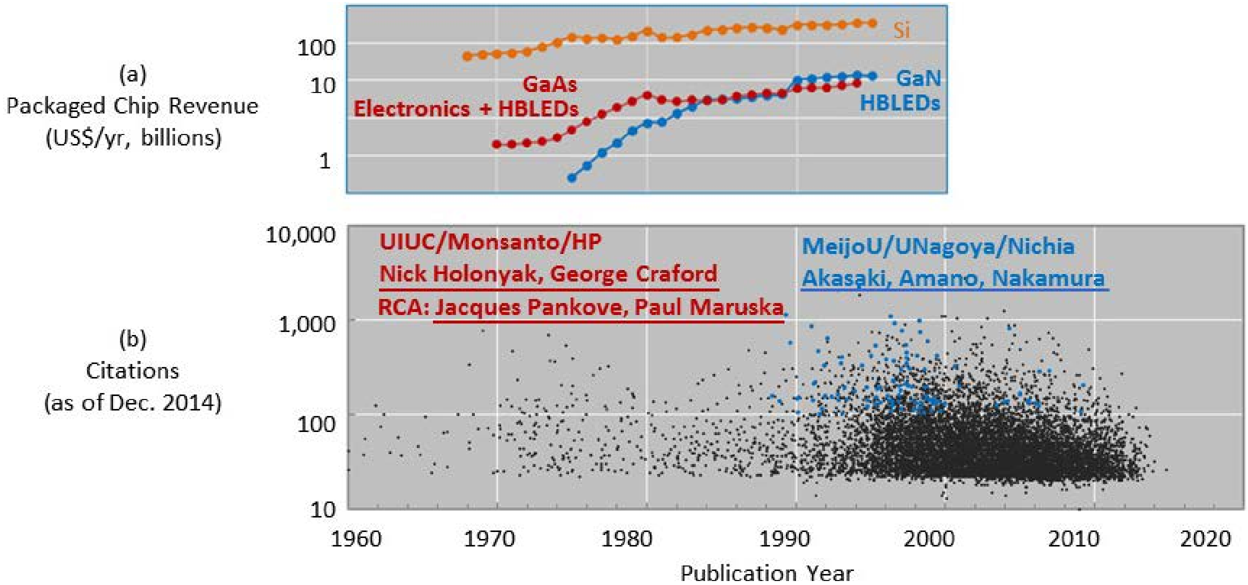
The path of development and use of SSL technologies is recent, ongoing, and provides an example of the positive interrelationships among scientific understanding, tool and technology development, and societal benefit. These interrelationships are seldom linear; sometimes scientific understanding leads and enables; sometimes tools and technologies lead and enable; and sometimes societal use and behavior leads and enables. But when they all interact with and feed off each other, they create powerful virtuous cycles of progress and innovation [43]. This is especially evident in semiconductors. The interactive progress in semiconductor science, technology and societal use/behavior has transformed and continues to transform our scientific understanding of the universe and the powerful information technologies that are now ubiquitous in our daily lives and societal use.

SSL is the most recent example of such a virtuous cycle in semiconductors. The core invention of the blue LED was followed by deeper scientific understanding of aluminum indium gallium nitride (AlInGaN) materials chemistry and physics, the underlying semiconductor material system for the blue LED. It was also followed by the tremendous societal benefit associated with its rapid adoption, which in turn provided a powerful motivation and platform for the continuing scientific understanding and technological development of this material system. The simultaneous evolution of the science and technology and of the blue LED market is illustrated in Figure 2.12.

Note that, in the larger context of this virtuous cycle of science, technology, and societal use, the DOE SSL R&D program is small. On the one hand, it must rely heavily for its success on advances outside its program. Yet, on the other hand, it plays a critical role in catalyzing key advances throughout the cycle, particularly those that are too risky and pre-competitive for individual companies to support on their own, but that are

[13] For the list of qualified off-grid SSL products see: https://www.lightingafrica.org/products/

potentially transformative. The DOE SSL Program also plays a critical role in identifying key scientific and technical challenges that constrain the performance or value of SSL solutions.



Notes:

(a) Neither the GaN nor the GaAs data include laser diodes.

(b) Earlier foundational work in visible LEDs was in GaAs- and GaP-based materials, at the University of Illinois by Nick Holonyak and his students, and at Monsanto and HP by George Craford and his colleagues. Subsequent foundational work in GaN-based materials was at RCA by Jacques Pankove, Paul Maruska and their colleagues. The Nobel-Prize-winning work of Akasaki, Amano and Nakamura in the late 1980s and early 1990s led to dramatic changes in the field. Their work, which catalyzed an explosion of research, is represented by the blue dots.

Figure 2.12 (a) Package Chip Revenue by Semiconductor Material, and (b) Citation History of Publications in the Science and Technology of Gallium Nitride (GaN)-Based Materials

Source: GaN data courtesy of Bob Steele and Strategies Unlimited; gallium arsenide (GaAs) data from Strategy Analytics; Silicon (Si) data from World Semiconductor Trade Statistics. Citation data from Tsao, J.Y., Han, J., Haitz, R.H. and Pattison, P.M., 2015. The Blue LED Nobel Prize: Historical context, current scientific understanding, human benefit. Annalen der Physik, 527(5-6).

2.6.1 The SSL Core

The virtuous cycle within the SSL core areas of energy-efficient white lighting (societal use), blue LEDs (technology), and AlInGaN materials chemistry and physics (science), is illustrated in Figure 2.13. The three vertical legs of the prism are time lines of key achievements in these core areas. The left green leg is a timeline of achievements in the core science and understanding – broadly speaking, AlInGaN materials chemistry and physics. The front blue leg is a time line of achievements in the core tools and technology associated with the blue LED. The right red leg is a time line of achievements in societal use and behavior associated with white lighting for illumination of the human environment. Note that, for simplicity, extreme selectivity has been exercised in the choice of achievements. The achievements begin only with the work that was awarded the 2014 Physics Nobel Prize, even though that work rested on the shoulders of important work by earlier giants; only subsequent achievements from the core areas most well recognized by their communities through papers with major citation impact or now well-established product categories and markets are included. The dates are approximate, based on publication dates of key papers or introduction dates of key product categories.

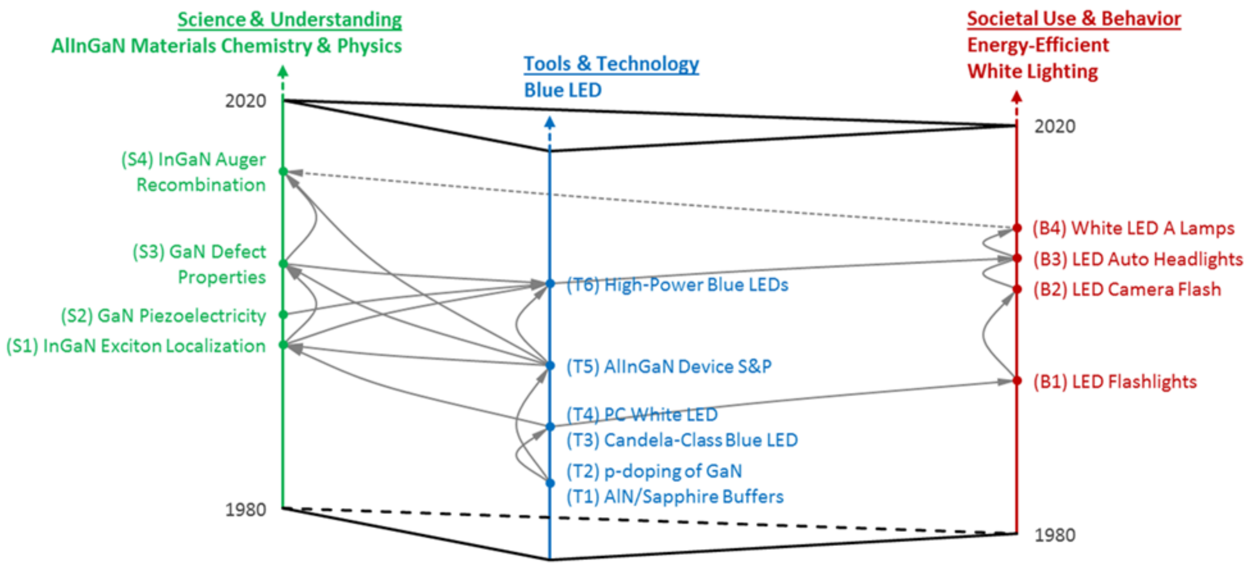


Figure 2.13 SSL's Virtuous Cycle of Science, Technology and Societal Use Within Its Core Areas: energy-efficient white lighting (societal use), blue LEDs (technology), and AlInGaN materials chemistry and physics (science). Note that, for simplicity, we have been extremely selective in our choice of achievements.

By the time of the late 1980s, silicon (Si) and the "conventional" III-V[14] technologies had become fairly sophisticated, though wide bandgap III-N alloys remained elusive. The major challenges included: no substrate that was reasonably lattice-matched to gallium nitride (GaN) to keep dislocation density acceptably low (seemingly a must for any minority carrier device); and no dopant process for low-sheet-resistance p-layers. Indeed, by the 1980s the challenges seemed insurmountable, and most researchers had abandoned the field. Two pivotal breakthroughs in the late 1980s and early 1990s to reinvigorate this field of research: the development of aluminum nitride (AlN) and GaN buffer layers on sapphire with reduced dislocation densities [44]; and a method to activate p-type magnesium (Mg) doping of GaN [45]. These two breakthroughs in turn led to two breakthrough device technologies: the candela-class blue LED and the white phosphor-converted LED (pc-LED) [46, 47, 48]. It also led to a rich set of ancillary GaN device synthesis and processing technologies, including sophisticated MOCVD epitaxy tools and processes, necessary for fabrication of these devices [49].

These early device technologies led to the white light products such as white LED flashlights and, later, white LED camera flashes. Those white light products were not very powerful, certainly not "general illumination" class, but they fed important stepping stone societal uses en route to general-illumination-class white lighting. At the same time, these early device technologies motivated the deeper scientific understanding of AlInGaN materials chemistry and physics. Just as importantly, they enabled the fabrication of the materials and heterostructures on which increasingly "clean" experiments could be performed and similarly clean scientific understanding could be gained. Indeed, the ability of state-of-the-art semiconductor device technologies to reveal previously hidden phenomena so that they can be the object of clean scientific study has been a common theme in the virtuous cycle between semiconductor science and technology. In Si and gallium arsenide (GaAs) materials and heterostructures, the ability to fabricate ultra-pure heterostructures enabled the high-mobility two-dimensional electron gases that then led to the observation of the integer and fractional quantum Hall effects, resulting in two sets of physics Nobel Prizes [50, 51, 52, 53]. In indium gallium nitride (InGaN)

[14] Semiconductors consisting of elements from groups III and V of the periodic table. "III-N" semiconductors consist of a group III element and nitrogen.

materials, similarly, it was the Nobel-Prize-winning fabrication breakthroughs of buffer layers and p-type doping in GaN that led to the observation of an unexpected resistance of InGaN quantum-well luminescence to defects, and ultimately its scientific explanation in terms of InGaN exciton localization [54].

Along with deeper scientific understanding of InGaN exciton localization came deeper scientific understanding of the role of GaN piezoelectricity and GaN defect properties in mediating luminescence properties [55, 56]. That deeper scientific understanding, along with continuing advances in AlInGaN device synthesis and processing technologies, then led to new architectures for high power blue LED technologies [57]. These high power blue LED technologies, combined with the earlier stepping stone white light products, enabled higher power white light products, such as white LED auto headlights and energy-efficient white LED A-lamps. The downward cost pressure associated with products and markets provided a large motivation to drive the blue LEDs at higher and higher current densities, to reduce costs per lumen, and this drew attention to the physical phenomenon called efficiency droop. This, along with the earlier understanding of defects, helped spur the scientific experiments that determined that a substantial part of efficiency droop can be attributed to InGaN Auger recombination [58].

Of course, the virtuous cycle of interactions among science, technology, and societal use is much denser than can be depicted in Figure 2.13, in which only a very small set of achievements are depicted. But even with this small set of achievements, one can see how dense and important the interactions have been. Moreover, as discussed throughout this supplement, the SSL core is hardly done, with significant challenges and opportunities that will feed the virtuous cycle in the future.

2.6.2 Beyond the SSL Core

Section 2.6.1 described the virtuous cycle *within* the SSL core: energy-efficient white lighting for general illumination (societal use), blue LEDs (technology), and AlInGaN materials chemistry and physics (science). In fact, each of these core areas has itself spawned new virtuous cycles and broader synergies that overflow *beyond* the SSL core. These broader synergies are illustrated in the three panels of Figure 2.14.

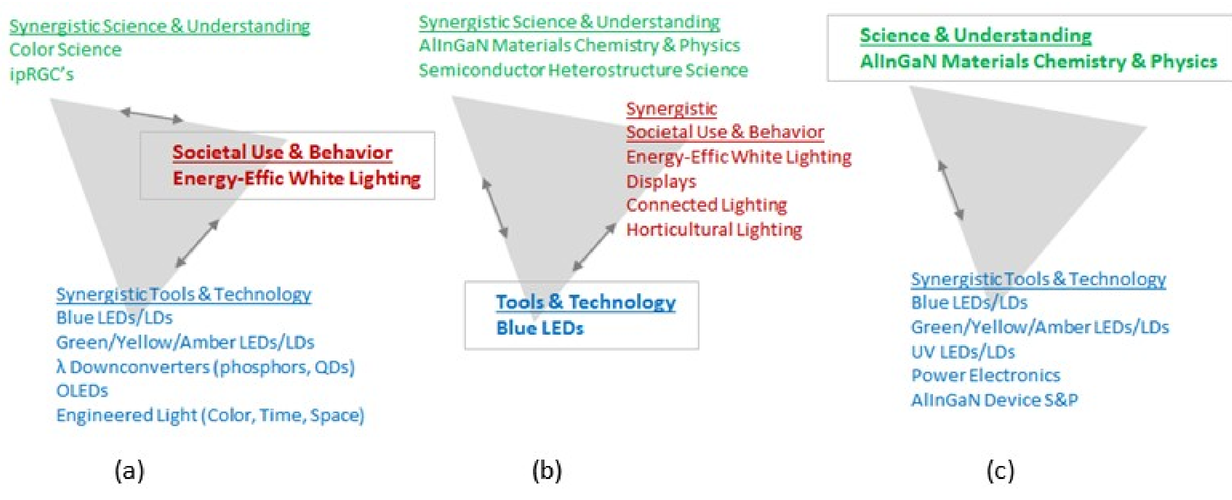


Figure 2.14 Science, Technology, and Societal Uses Synergistic with the SSL Core:
(a) White lighting is synergistic with many areas of science beyond AlInGaN materials chemistry and many technologies beyond the blue LED. (b) The blue LED is synergistic with many areas of science beyond AlInGaN materials chemistry and physics and many uses beyond white lighting. (c) AlInGaN materials chemistry and physics is synergistic with many technologies beyond the blue LED.

Synergies with White Lighting

For white lighting to realize its potential in terms of cost-effectiveness and utility, many areas of science beyond AlInGaN materials chemistry and physics, and many technologies beyond the blue LED, have been important to explore, as illustrated in Figure 2.14(a). With respect to synergistic areas of science, note that white light used for general illumination interacts first with the environment but then ultimately with one of two human photoreceptor channels. The first of these channels is the visual imaging channel, which originates in the rods and cones in the fovea of the human eye, and the science of which has been critical to understanding how best to tailor the use of the white light. The second of these channels is the non-visual channel that originates in the intrinsically photoreceptive retinal ganglion cells discovered only in the past 15 years [59].

With respect to synergistic areas of technology, perhaps the most important is alternate materials and architectures for green/yellow/amber light emission – either direct emission from a semiconductor or indirect emission via wavelength downconversion of higher to lower energy photons.

For direct emission from a semiconductor, many advances have been made in the SSL core area of AlInGaN materials. However, there have also been advances in non-AlInGaN materials, particularly in organic LEDs. Indeed, OLEDs are themselves the result of a long history of their own interplay between science and technology. The conduction of electricity by polymers was demonstrated in 1862 by Letheby, and electroluminescence from organic molecules was observed in the 1950s by Andre Bernanose. More recently, key progress in light production through fluorescence from small organic molecules was made by Ching Tang and Steve Van Slyke at Eastman Kodak in 1987 [60], and efficient light production from polymers was reported in 1990 by the team at Cambridge University led by Richard Friend and Jeremy Burroughes [61]. The route to a further four-fold enhancement in efficacy was demonstrated in 1998 through a collaboration between Princeton University and the University of Southern California; they showed that the introduction of phosphorescent molecules containing heavy atoms could lead to extraction of light from triplet excitations [62]. Substantial increases in the conductivity of polymers were acknowledged by the award of the 2000 Nobel Prize for Chemistry to Heeger, MacDiarmid and Shirakawa "for the discovery and development of conductive polymers."

For indirect emission via wavelength downconversion, there have been advances both in "conventional" phosphor materials as well as in emerging quantum dot materials. Conventional phosphor materials include those, like yttrium aluminum garnet (YAG), developed in the 1960s and 70s for cathode ray tube displays and scintillators, as well as the more recent development in 2004 of a red phosphor in a completely new material system (the nitridosilicates), a pivotal advance [63]. Quantum dot materials were of purely scientific interest at first, as "artificial atoms" with discrete electronic states and sharp luminescing transitions between them, but are now being taken seriously for SSL, particularly because of their wavelength tunability and narrow emission linewidth [64, 65, 66].

Fortuitously, these synergistic technology areas highly desirable for white lighting are also highly desirable for displays, a societal use superficially very different from white lighting for illumination. Indeed, because displays can support higher costs of light (per lumen) than general illumination can, they are driving the development of both OLEDs and quantum dot (QD) wavelength downconverters. It can be anticipated that, as OLEDs and QDs are increasingly inserted into displays, they will become more sophisticated, their performance will improve, and their manufacturing costs will decrease. Though white lighting is in some ways more demanding than displays in requiring lower cost points and higher lumen outputs, nonetheless the learning curves of OLEDs and QDs as used in displays will benefit their possible eventual use in white lighting.

Synergies with Blue LED Technology

As blue LED technology has evolved, many areas of science beyond AlInGaN materials chemistry and physics, and many societal uses beyond white lighting, have been important to explore, as illustrated in Figure

2.14(b). With respect to synergistic areas of science, blue LED technology is fundamentally a semiconductor device technology based on AlInGaN materials, thus the intersection of AlInGaN materials chemistry and physics and semiconductor heterostructure science have been critical for blue LED technology, as discussed in Section 2.6.1.

There are many synergistic societal uses of blue LED technology, and this is a major reason it is considered such a seminal invention. Energy-efficient white lighting for general illumination is one, of course. En route, as discussed above, a major intermediate stepping stone has been displays at all size scales: small displays for smart phones and mobile applications; medium-size displays for televisions and computer monitors; and large displays for outdoor video screens. Because LEDs are a solid-state light source, lighting is becoming smart, “connected” and part of the Internet of Things [67]. Horticultural lighting is yet another application that blue/white LEDs are beginning to penetrate, and that may grow considerably in importance as indoor farming close to urban populations becomes increasingly attractive.

Synergies with AlInGaN Science

For AlInGaN materials chemistry and physics to realize its potential, many areas of technology beyond the blue LED have also been important to explore, as illustrated in Figure 2.14(c). Note that broader areas of societal use are not listed, even though there are many. Nonetheless, even limiting to synergies with broader areas of technology, the opportunities are already quite large. The SSL core area of the blue LED has of course been the main synergistic technology, but the blue laser diode has also been synergistic. Note that the blue laser diode has itself been critical to optical storage (Blu-ray discs), even as it is now being considered for SSL. Also, light emitters at wavelengths other than blue, but nonetheless based on AlInGaN materials, are also synergistic. These include green/yellow/amber and UV LEDs and laser diodes, green/amber/red to fill in the “green/yellow/amber gap” and create white light without Stokes losses, and UV for manufacturing and biocide applications.

Power and extreme-environment electronics are an emerging area for GaN and aluminum gallium nitride (AlGaN) materials, both of which benefit from their overlap with AlInGaN science. This area may someday be comparable to the blue LED in market size and reach, with a wide range of applications: alternating current (AC) and direct current (DC) power supplies, DC/AC power inverters, and power switching for the smart power grid of the future [68].

Finally, note that AlInGaN device synthesis and processing technology is both an enabler for the heterostructures necessary to advance AlInGaN materials chemistry and physics, but also benefits from it.

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3 Directions in Lighting

3.1 Lighting Performance and Design

SSL offers a new range of features and design flexibility. SSL products can be designed to emit almost any spectrum of visible light; this ability to dynamically tune the emitted spectrum of an LED or OLED lighting source can unlock a host of features for SSL lighting beyond energy savings. Two new applications that are enabled by LED color tunability and spectral engineering include lighting for human health and productivity and horticultural lighting.

The unique properties of LEDs and OLEDs allow for new lighting form factors that can change the way lighting is integrated into buildings. SSL is not limited to the conventional bulbs or fixture sizes, but instead provides new integration opportunities such as working with DC microgrids to minimize AC/DC conversion losses at each fixture or when using renewable energy sources. Additionally, as a semiconductor light source, SSL brings the ease of connected lighting to buildings. In terms of illumination properties SSL light sources have inherent advantages; LEDs sources can provide very directional optical distribution, and OLEDs bring a low-glare, low-illuminance light source.

As product developers, architects, and lighting designers fully embrace the possibilities of SSL technologies, new product form factors, lighting layouts, and construction integration approaches will emerge, which will fully optimize SSL technology for source efficiency as well as for optimized utilization efficiency, building and construction efficiency, and human health and productivity.

3.1.1 Tailored Light: Spectral, Intensity, and Spatial Control

As discussed in Section 2.2.2, each lighting application has its own requirements, and how effectively and efficiently the lighting system achieves the requirements defines the application efficiency. To maximize application efficiency, sources of light whose various distributions (spectral, intensity, spatial) can be tailored to the application, perhaps in real time, are required.

Spectral engineering has been a central theme of SSL since its beginning – with significant attention paid to its most common metrics, lumens, CCT and CRI. But this is just the beginning, and many applications will benefit from more finely controlled spectral engineering, not only for reducing the energy required for the application, but also for improving the productivity of the application. Using a tailored spectrum for the application maximizes the effectiveness of the lighting by ensuring that the necessary components of the spectrum are present for the specific lighting application. Additionally, damaging or unnecessary portions of the visible spectrum can be omitted or reduced. This concept is still relatively novel for general illumination applications, as it was the advent of SSL that made effectively controlling the spectrum possible. For most lighting applications, the optimum spectrum is not well understood, and significant research will be necessary to develop this understanding.

Controlling intensity also enables improved effectiveness and reduced energy for lighting. When there is sufficient daylighting or no one is present, lighting products can be dimmed or turned off to save energy. Light levels also can be controlled throughout the day to match outdoor light levels, thereby triggering physiological responses and improving the effectiveness of lighting systems. Lighting products can also be designed with intensity control of individual LEDs or groups of LEDs, which enables white or color tuning. Plus, products can even be engineered to provide active control of the spatial distribution of the light as with the OSRAM Omnipoint concept discussed in Section 4.2.2.

Spatial engineering is the final and equally important leg in the trio of tailored light. LED lighting systems, with their improved optical control and spatial engineering, have demonstrated they can often use less total light to achieve the prescribed illuminance levels. For outdoor applications, this is achieved through improved optical control, which reduces overlighting and non-useful, off-target lighting (which is manifested as light trespass or uplight that is emitted into the atmosphere and serves no purpose and increases sky-glow). Figure 3.1 demonstrates a specific example of improved light utilization of LED-based outdoor lighting fixtures. In this example, a parking lot lighting retrofit using Cree LED-based fixtures demonstrated a 66% reduction in energy usage compared with HID fixtures, due to improved efficiency and reduced total light generation. In addition, significantly more of the parking lot area is illuminated, which is advantageous for both driver and pedestrian safety.

Figure 3.1 Cree Edge Area Square, Edgewater Marketplace, Edgewater, CO

Source: John Edmond, Cree Inc., SSL R&D Workshop, San Francisco, CA, January 2015 [69]

3.1.2 Lighting Integration into Buildings

Most LED lighting technologies have been engineered to address nearer-term market opportunities in the form of replacement lamps and retrofit luminaires. There are approximately 45 billion sockets in the world, so these form factors represent an enormous market and energy savings opportunity [2]. The lamp and retrofit form factors also promote rapid customer acceptance by offering product familiarity and providing similar usability to existing products. However, typical lamp form factors are not ideal for integration of LED packages into a lighting product. There is no natural thermal path to conduct heat away from the LED packages; the LED package light distribution is not ideal for many applications; and integrating power supplies into individual lamps can be costly and inefficient. LED product integrators have done a remarkable job developing products that surmount these challenges, but legacy form factors fail to exploit the unique features and design flexibility associated with LED technology and will always require LED technology to be forced into a sub-optimal form factor.

Retrofit luminaires allow for greater flexibility because they typically have a larger volume for integration enabling more optimized and cost-effective integration of LED lighting products. The drawback is that the lighting layout and required light distribution for the retrofit luminaire is often defined by the legacy technology that is being replaced, rather than by what could be optimally achieved if the entire lighting system was reconsidered with LED properties in mind. Similarly, how a retrofit luminaire fits and connects into the building is defined by legacy lighting technologies. For example, LED products will require less depth and volume in recessed lighting applications allowing for more compact building architectures that require less in the way of building materials. The electrical connection of lights can potentially be improved through the use of DC grids in the building, thus removing the requirement for full AC to DC conversion at each LED lamp or luminaire. This can also facilitate direct connection to renewable energy resources, such as solar or wind power and their battery systems without requiring DC to AC conversion and then conversion back to DC for the LED operation.

Taking advantage of the inherent properties of LED and OLED lighting not only can lead to new form factors that can transform how light is integrated into buildings, but it can also lead to designs that improve delivered efficiency in the application. By designing the luminaire to put a greater percentage of light to the target area, the overall light required to reach the required illuminance levels can be reduced, improving light utilization. For example, the small source size of LEDs can enable improved optical control and directionality; conversely the large source size of OLEDs in conjunction with low brightness and low glare can enable their use very close to the task area. Maximizing light utilization for both LED and OLED sources will require a move beyond legacy form factors such as the light bulb and the recessed luminaire, and toward form factors that maximize application efficiency as well as optical, electrical, and thermal efficiency.

OLEDs are not readily able to replicate most lamp and luminaire form factors, which is both a disadvantage and an advantage. While this creates a barrier for near-term adoption of OLED technology, it also accelerates the development of fully optimized lighting systems and applications that are in alignment with the unique features of this technology (e.g., large area, low brightness, thin form factor, and non-planar surfaces). Ultimately, some combination of large area, low brightness OLED sources with directional LED sources could be an approach that maximizes the features of both lighting technologies and optimizes the lighting design.

An example of this complementary approach is from Acuity Brands. Acuity announced the development of Duet SSL™ Technology, blending the use of OLED and LED light sources in the same luminaire, optimizing both to produce refined photometric performance, improved lighting quality, and increased cost effectiveness. As shown in Figure 3.2, downward-facing OLEDs are incident on the task surface, while LEDs face upward and provide general illumination that can reflect off the ceiling to light the space. This combination utilizes the soft diffuse glow of OLEDs where the light interacts with the user, and LEDs provide cost-effective supplementary lumens to fully light the space.

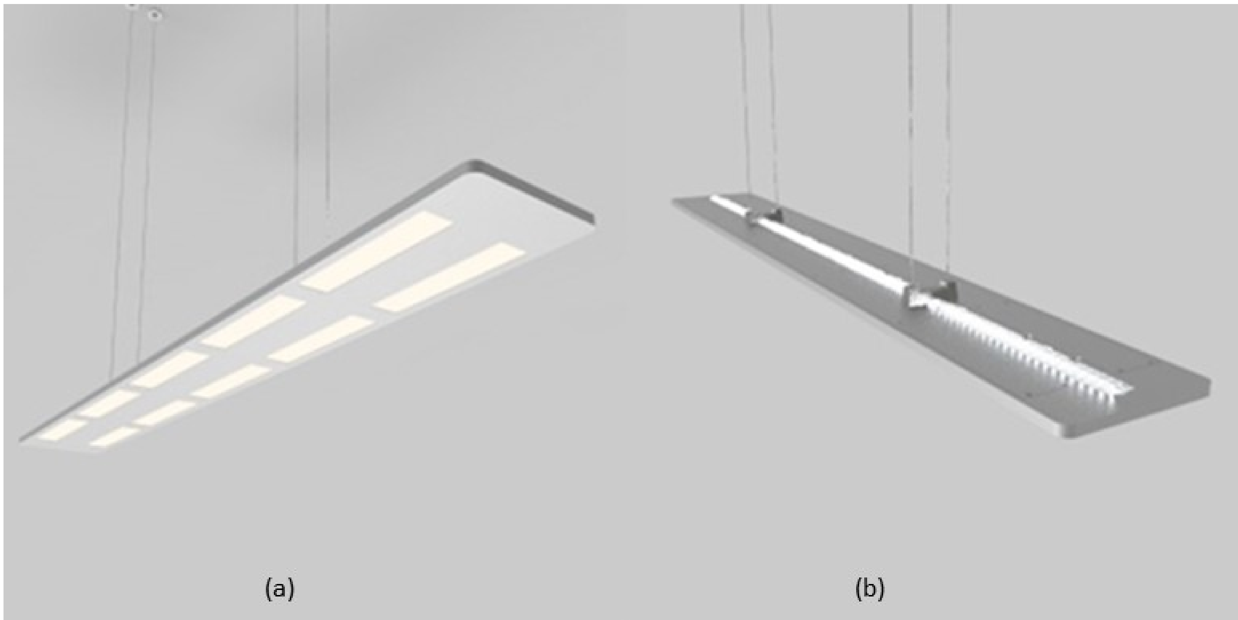


Figure 3.2 Duet SSL Concept Luminaire
with (a) OLEDs Producing Downward Illumination to Light the Task Area, and (b) LEDs on Top to Produce Light That Fills the Room

Source: Acuity Brands, Olessence OLED/LED Specifications, 2016 [70]

3.1.3 Reliability

LEDs are the heart of SSL lighting products. They provide long lifetimes that last well beyond 50,000 hours of operation, much longer than most conventional light sources. The end of life for all lighting technologies is signaled by the loss of light, but this may be less evident for LED luminaires, in which the light output may continuously fade or the color may slowly shift, to the point where these events constitute practical failure.

When integrated lamps and luminaires first appeared on the market, it was assumed that the lumen depreciation of the LED packages could be used to estimate the degradation characteristics of the integrated lighting product. While the lifetime of an LED source is one important indicator of LED luminaire life, lifetime claims should consider the whole luminaire system, not just the LEDs. Electronics failures in the driver or degradation of optical components can often occur long before LED lumen depreciation causes failures. A system reliability model that integrates the failure mechanisms in the various luminaire subsystems would create a much more accurate lifetime claim from LED luminaire manufacturers.

To address the challenge of developing accurate lifetime claims, the DOE SSL Program formed an industry consortium with the Next Generation Lighting Industry Alliance (NGLIA), the LED Systems Reliability Consortium (LSRC). This consortium aims to coordinate activities and foster improved understanding. Work by the LSRC and other funded R&D by the DOE SSL Program is focused on understanding the various degradation mechanisms to enable the development of new models so that system reliability can be confidently understood, modeled, predicted, and communicated.

Lumen Maintenance

LED packages rarely fail abruptly (i.e., suddenly stop emitting light), but rather experience parametric failures such as degradation or shifts in luminous flux, color point (chromaticity coordinates), CRI, or efficacy. Of these parametric shifts, lumen depreciation in the LED source has received the most attention because it was thought to be the prime determinant of lifetime for the complete product. Although research shows this is not the case, lumen maintenance is still used as a proxy for LED lamp or luminaire lifetime ratings, largely due to the availability of standardized methods for measuring and projecting LED package lumen depreciation.

The useful life of an LED package is often cited as the point in time where the luminous flux output has declined to 70% of its starting value, or L70. For products with lifetimes of many years or even decades, failures may be very slow to appear under normal operation. In 2008, the Illuminating Engineering Society (IES) published IES LM-80, an approved method for measuring the lumen maintenance of solid-state (LED) light sources, arrays, and modules [71]. The LM-80-08 procedure required measurements of lumen output and chromaticity for a representative sample of products to be taken at least every 1,000 hours, for a minimum of 6,000 hours.

Many researchers have put a great deal of effort into devising a way to project the time at which L70 will be reached for an LED package in a luminaire, and IES has documented a forecasting procedure, IES TM-21 [72], which uses the LM-80 test data for the lumen maintenance projections (a minimum of 6,000 hours of test data is required). The LM-80 data (luminous flux vs. test hours) for the LEDs tested is averaged and an exponential curve fit is applied to the data; the results of the curve fit are used to calculate a lumen maintenance lifetime projection. This technical memorandum stipulates that any projection may not exceed a set multiple (depending on sample size statistics) of the actual hours of LM-80 testing data taken, which helps avoid exaggerated claims.

It should be noted that LM-80 measurements are taken with the LED packages operating continuously in a temperature-controlled environment, where the solder point and ambient air temperature are at equilibrium. This does not necessarily reflect real-world operating conditions, so there may not be a perfect match between predictions based on laboratory test results and practical experiences with lamps and luminaires in the field. Nevertheless, lumen maintenance projections can help sophisticated users compare products, as long as their limitations are properly understood.

The impact of LED package design and materials of construction on performance, color quality, lumen maintenance and color shift, have been investigated for a variety of LED packages. Different LED package platforms (detailed in Section 4.1) have different intrinsic characteristics based on materials of construction and manufacturing processes. At high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate, leading to lumen depreciation and color shift. More information on package degradation mechanisms and their impact can be found in LSRC's recently published paper, "LED Luminaire Reliability: Impact of Color Shift" [73].[15]

Color Shift

While lumen maintenance has dominated discussions about LED lifetime, color stability (also known as chromaticity stability) is another important performance attribute that can be a barrier to purchase or can result in unmet expectations. Color shift occurs in traditional lighting technology, but has gained more attention with LED lighting due to the long operating life of 10 years or more in many applications. Traditional lighting technology (halogen, fluorescent or metal halide) also experiences color shifts, and relamping every few years is required to mitigate the impact of color shift.

The importance of chromaticity stability varies by application, and it may be more detrimental than lumen depreciation for some applications. For example, a high degree of chromaticity stability is crucial for light sources in a museum or retail store, but less important for street lighting. Chromaticity stability of the lamps

[15] The report "LED Luminaire Reliability: Impact of Color Shift" can be found at: https://energy.gov/eere/ssl/downloads/led-luminaire-reliability-impact-color-shift.

and luminaires is important where multiple lamps or luminaires are being used to wash a wall, or where objects are being evaluated based on color, such as in a hospital or factory.

The color of light can be represented using chromaticity coordinates to describe its hue and saturation. A pair of chromaticity coordinates corresponds to a unique color of light; two sources with the same chromaticity coordinates should theoretically appear the same. Chromaticity diagrams representing the different color space have been developed and standardized by the Commission Internationale de l'Eclairage (CIE). The most commonly used chromaticity diagrams are the CIE 1931 chromaticity diagram using (x, y) coordinates to specify chromaticity, and the CIE 1976 chromaticity diagram using (u', v') coordinates. To date, the industry generally quantifies chromaticity shift using Δu'v', which describes the magnitude of chromaticity shift, but does not capture the direction of the shift. (The actual chromaticity coordinates u' and v' are required to know the direction of the chromaticity shift.) The point at which a chromaticity shift becomes noticeable and results in parametric failure will depend on the lighting application. If the chromaticity change occurs slowly over a very long period (e.g., 25,000 hours), it may not be objectionable in the case where the light sources shift by the same magnitude and in the same direction (but this is unlikely in practice).

Chromaticity stability can vary based on LED lamp or luminaire product design with several factors affecting the resulting performance. Ambient air temperature, drive current, and the design of the lamp or luminaire's thermal management system can influence the junction temperature of the LED, which in turn, can affect its output characteristics. Of greater concern for long-term chromaticity stability is the effect that high operating temperatures can have on certain package and optical materials. Depending on the design of the LED package, the phosphor layers may settle, curl, delaminate, or otherwise change the number of photons that are converted to white. This behavior can occur even in the absence of high ambient temperatures. Likewise, other materials in the optical path, such as silicones or plastics, may discolor over time. In addition, materials such as glues or chemicals may diffuse into the LED package and affect chromaticity stability. Temperature fluctuations during operation may also intensify degradation mechanisms for some LED products.

There are no official standards limiting the amount of acceptable chromaticity shift in LED lighting products, but different certifications have established requirements. For example, to qualify for the ENERGY STAR label, 9 out of 10 samples of an LED lamp must have a measured chromaticity shift (Δu'v') less than 0.007 over the first 6,000 hours of operation. For applications that require high chromaticity stability, a specification may be established on a project-by-project basis. Beyond the lack of agreement on acceptable levels of chromaticity shift, there is no standard methodology for projecting future chromaticity maintenance using standard test procedures as there is for projecting LED package lumen maintenance. Furthermore, there are no established methods for accelerated testing, leaving each manufacturer to develop its own testing methodologies and predictive modeling approaches. A consensus methodology for predicting chromaticity shift will be a challenge as different materials of construction and manufacturing processes can affect the results; however, an IES committee is working to come to accord on this pressing issue (TM-31) [74].

Factors affecting chromaticity point stability in LEDs include aging-induced changes in the emitter, phosphor, encapsulant materials, and plastic resin. Emitters can exhibit decreases in radiant flux over time; phosphors can experience decreases in quantum efficiency or shifts in emission spectrum due to oxidation; encapsulants can exhibit cracking, oxidation and yellowing, or changes in index of refraction; and resins can discolor and absorb photons, as illustrated in Figure 3.3. Higher temperatures will accelerate these degradation mechanisms leading to greater color shift, though the magnitude of the color shift as a function of temperature will vary with packaging materials and manufacturing processes. As with lumen maintenance behavior, if the LEDs are operated at low drive currents and lower than normal operating temperatures, these materials changes leading to chromaticity shift will be very slow to develop, if they occur at all.

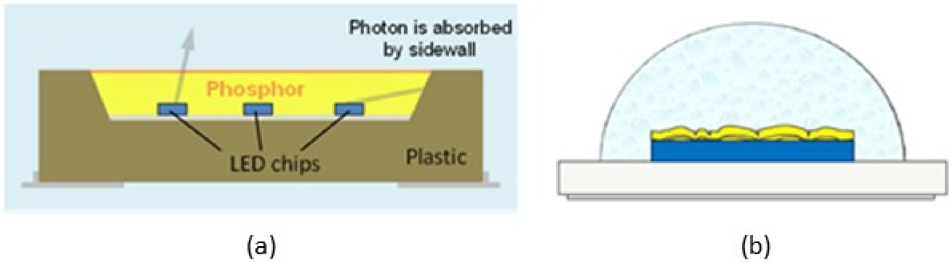
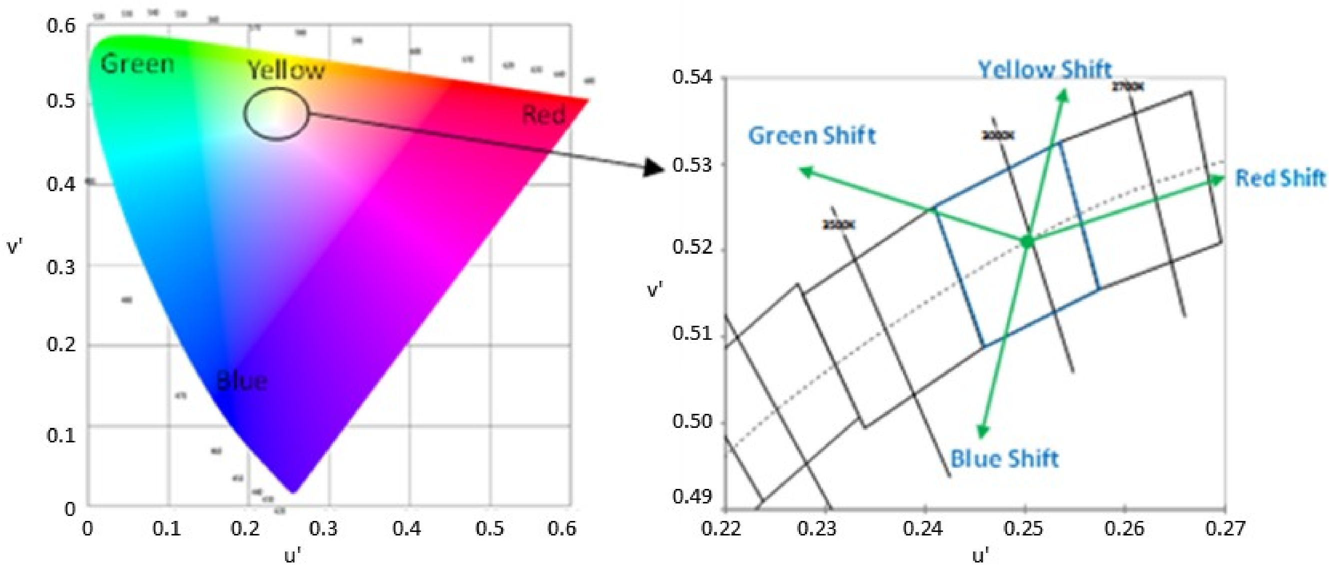


Figure 3.3 LED Package Schematics Showing Cases of Color Shifting:
(a) sidewall discoloration in a mid-power package that absorbs long-path length blue photons resulting in an overall blue chromaticity shift, and (b) phosphor delamination in a high-power package leading to a yellow shift due to the longer path-length through the phosphor when it delaminates

Source: Monica Hansen, Strategies in Light, Las Vegas, NV, February 2015 [75]

The resulting direction of chromaticity shift depends on the dominant degradation mechanisms occurring in the package, which in turn depends on the packages materials and methods of construction. The chromaticity shifts can be toward the yellow, blue, green, or red colors using the CIE 1976 chromaticity diagram as illustrated in Figure 3.4. Different package platforms have shown distinct differences in the chromaticity shift signatures. Four main chromaticity-shift modes were identified and caused by changes in the LED packaging materials, including the behavior of the LED chip, the phosphor and silicone binder, as well as the plastic molding used as in the package body. More details on the color shift mechanism can be found in the DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) report titled "Chromaticity Shift Modes of LED PAR 38 Lamps Operated in Steady-State Conditions."[16]

[16] DOE's CALiPER report titled "Chromaticity Shift Modes of LED PAR 38 Lamps Operated in Steady-State Conditions" can be found at: https://energy.gov/sites/prod/files/2016/03/f30/caliper_20-5_par38.pdf



(a) (b)

Figure 3.4 The 1976 CIE Chromaticity Diagram (u', v') Detailing Color Shifts:
(a) the white chromaticity region (denoted by the black circle) and the common directions of chromaticity shift in LED packages, and (b) zoomed-in image of the white chromaticity bins (black circle)

Source: Monica Hansen, Strategies in Light, Santa Clara, CA, March 2016 [76]

Luminaire Reliability

As integrated lamps and luminaires appeared on the market, it was first assumed that one could project the LM-80 test data obtained on LED packages to describe the degradation characteristics of the integrated product. When LEDs are installed in a luminaire or system, many additional factors can affect the rate of lumen depreciation or lead to catastrophic failure. These include temperature extremes, humidity, chemical incursion, voltage or current fluctuations, failure of the driver or other electrical components, damage or degradation of the encapsulant material covering the LEDs, damage to the interconnections between the LEDs and the fixture, degradation of the phosphors, and yellowing of the optics. In addition, abrupt, semi-random, short-term failures may be observed due to assembly, material, or design defects.

Further research has shown that electronic or driver failures, solder joint failures, or degradation of optical components can often occur long before LED package lumen depreciation results in failure. More information about observed system level failures can be found in LSRC's "LED Luminaire Lifetime: Recommendations for Testing and Reporting" [77].

LED luminaire failures can be parametric (lumen depreciation or chromaticity shift) or catastrophic (no light output). Both types of failure modes need to be considered when life testing LED systems. Continuous testing often leads to the emergence of parametric failure, though catastrophic failures can occur when the testing includes on-off cycling due to thermal expansion, which can lead to strain and breakage in different components or solder joints [78]. A study on LED A-lamps showed that lamps under life testing performed with on-off cycling showed a shorter time to failure relative to continuous life testing. In addition, many lamps failed catastrophically before L70 values were reached – in this case due to solder joint failures and driver electronics failures [79]. The way A-lamps will perform in the field also will strongly depend on the application, whether they are in a downlight fixture or table lamp, but more complete life testing protocols would help identify potential sources of catastrophic failure that may lead lower lifetimes than projected L70.

Today, many manufacturers have developed proprietary means to estimate product life for their own designs using data on principal components such as the LED package, driver, and optical components, which allows an estimate of the overall luminaire performance. While such practices exist for specific product lines and applications, there is no industry-consensus protocol at this time. Understanding the cause of system failures – elevated temperatures, thermal cycling, surge events, repeat switching, etc. – requires the development of test methods to mimic these system failures in a "reasonable" amount of time to create failure distribution. Developing better testing methods to accurately predict system lifetimes is still an important area that requires more effort.

3.2 Connected Lighting

SSL is creating an opportunity for a whole new lighting system paradigm by the broad transition of lighting infrastructure to inherently controllable SSL systems. The convergence of SSL, low-cost sensors, smartphones and apps, and the Internet of things (IoT) is expected to enable new lighting system functionality and an unprecedented exchange of data among lighting and other building systems, the Internet, and other devices. The ubiquity of lighting in the built environment (in overhead locations) provides a unique and valuable opportunity to create a dense grid of networked data collection nodes in and near buildings. Such connected lighting systems, i.e., networked devices with sensors, can become key data-collection platform in buildings and in cities, thereby providing a backbone for the fast-emerging IoT, and enabling a unique array of services, benefits, and revenue streams that would take lighting well beyond its traditional definition and greatly enhance its value. Connected lighting systems deliver improved lighting quality and energy performance, and can improve the energy performance and management of other building systems, space utilization, and additional functions that have yet to be identified. Further, it is likely that these capabilities will offer benefits that match or exceed the value of the energy savings they deliver.

3.2.1 Lighting Controls

Lighting control has the potential to deliver significant energy savings by adjusting the amount and type of light to the real-time needs of a particular space and its occupants. SSL products are poised to be the catalyst that unlocks the energy savings potential of lighting controls due to their unprecedented controllability and increasing degrees of automated configuration – facilitated by embedded sensors and intelligence, as well as by other features and capabilities that leverage the data they collect. Lighting systems that can leverage occupancy sensing, daylight harvesting, high-output trim, personal area controls, or any combination of these approaches have been shown to provide energy savings of as much as 20% to 60% of SSL power consumption, depending on the application and use-case [80].

While many products for controlling light have been commercially available for quite some time, their deployment and resulting energy savings have been limited due to their complex configuration, high cost, limited interoperability among devices from competing manufacturers, and a narrow range of people who know how to efficiently design, install, commission, and operate them.

Table 3.1 shows the installed stock in various building sectors and what type of controls system are installed. The net effect is that there remains an enormous amount of energy that could be saved just with the proper and persistent use of lighting controls – let alone what could be saved with broader deployment. Data is the fuel that is powering data analytics (e.g., space utilization, location services), and delivering significant value to lighting systems that can overcome past cost and complexity barriers for the adoption of advanced lighting controls.

Table 3.1 2015 Installed Stock Penetration of Lighting Controls in Buildings

Installed Stock Penetration (%)	Commercial	Residential	Industrial	Outdoor
None	68%	86%	94%	41%
Dimmer	3%	11%	4%	<1%
Daylighting	<1%	<1%	<1%	39%
Occupancy Sensor	6%	<1%	2%	<1%
Timer	4%	<1%	<1%	20%
Energy Management Systems	15%	<1%	<1%	<1%
Multi	4%	<1%	<1%	<1%
Connected	<1%	<1%	<1%	<1%

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

3.2.2 Sensor Integration

The deployment of a dense network of sensors is key to delivering the value of data analytics to the end user. Lighting happens to be one of the best places to install sensors as it generally covers every square foot of real estate and provides accessibility to power. The SSL community has benefited from mobile phone industry driving the miniaturization and cost reduction of sensors, allowing integration of low-cost, compact sensor packages directly in the luminaire, as seen in Figure 3.5.

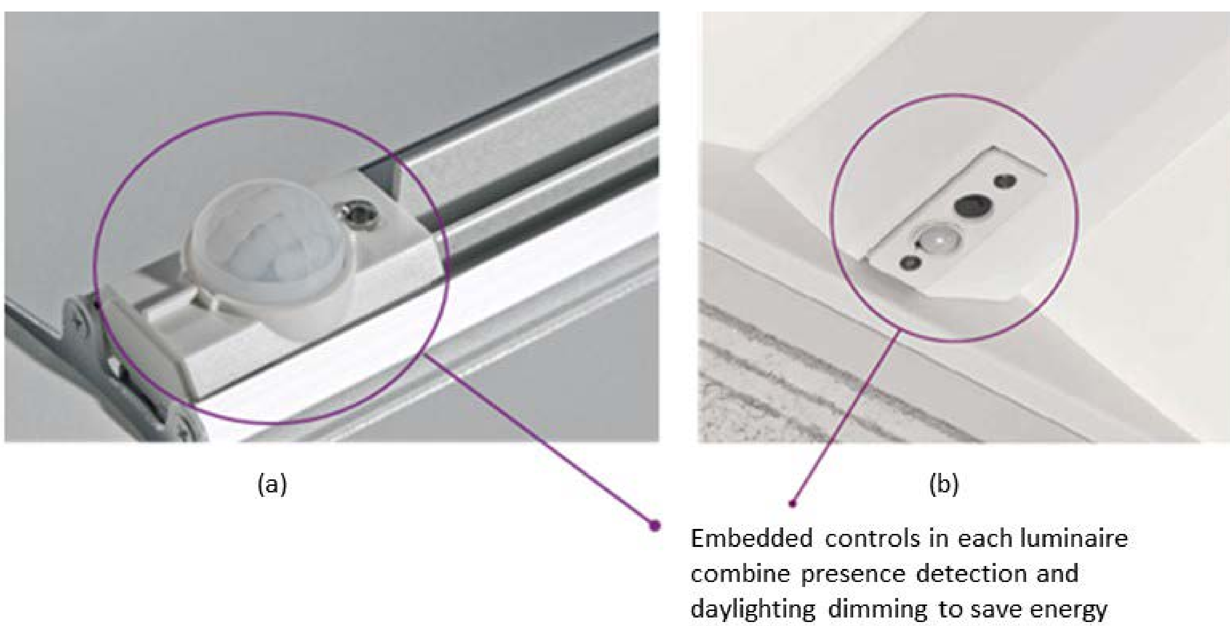


Figure 3.5 Sensor Package Integration into LED Luminaires

Sources: (a) Cree SmartCast Technology [81], and (b) Philips, SpaceWise Office Brochure [82]

A lighting-based advanced sensor network can provide a vast array of data from the building environment (e.g., energy usage, temperature, daylighting) or building activity (e.g., occupancy and asset location and movement). This information can be used to improve energy savings through daylight harvesting, occupancy detection, demand response programs, time-of-day dimming schedule, and real-time energy savings reporting. Other information can lead to better utilization and maintenance of the building including advanced occupancy detection, light-level stability, personalized setting profile, and fixture outage reporting.

However, that potential is still on the table, as technology developers jostle with competing ideas for how much to collaborate within their industry and how much to compete. As controls have become increasingly important, a number of lamp and luminaire manufacturers, either on their own or in partnership with a controls company, have begun integrating control devices into their lighting products. Some examples of luminaires with fully integrated lighting controls include Cree's SmartCast and Philips' SpaceWise. Cree's SmartCast lighting controls technology platform provides occupancy sensing and daylight-harvesting capabilities in addition to field-tunable color temperature. The luminaires are equipped with occupancy and ambient light sensors, dimming controls, and are interconnected with a wireless mesh. The scheme enables automated commissioning of fixtures within a room using a Cree remote control.[17] Philips' SpaceWise lighting controls technology provides a similar solution, with embedded sensors and wireless controls that provide plug-and-play mesh network capabilities with automated grouping of luminaires to create central zones, automated calibration, and daylight commissioning.[18]

Some manufacturers integrate a broader range of building management solutions into the same systems that provide lighting controls (using advanced sensor packages embedded in LED lighting fixtures). For example, Enlighted's Energy Manager analyzes data harvested by advanced sensors.[19] In addition to being the collection point for the energy, occupancy, and environmental data captured by the sensors, Energy Manager provides a web-based user interface for managing the lighting system and optimizing building system performance. With insights from real-time data, facilities managers can make informed adjustments to energy use or improve comfort in individual areas.

3.2.3 Communications

The use of wireless communication technologies (e.g., Bluetooth or Zigbee) to enable connected LED lighting systems has become increasingly common in recent years. The prevalence of smartphones and tablets has also changed the way people want to control lighting. With this increased integration of wireless connectivity, lighting is becoming easier to configure and control. For example, users can control the lighting in their building space through a software application that can be downloaded on a smartphone or tablet.

In addition to wireless technologies, power over Ethernet (PoE) is a wired solution gaining more consideration for lighting connectivity. PoE technology offers the ability to provide both low-voltage DC power and communication through the Ethernet cable. PoE technology offers noteworthy contrasts with wireless approaches for connected lighting systems. While mobile devices inherently require wireless technologies, general lighting devices typically have fixed locations and do not necessarily require wireless. PoE technology has the benefit of carrying power and data over a single cable, and reducing demand for wireless communication bandwidth. However, the primary benefit of wireless technology for lighting (and other building devices) is reduced installation costs – particularly in retrofits – from not having to run new wire to carry control signals and other data. A challenge for PoE has been the ability to deliver sufficient power for a lighting network. However, steadily improving LED efficacies has reduced the power required for lighting

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17 For more information on Cree SmartCast please see: http://www2.cree.com/smartcast-landing-page

18 For more information on Philips' SpaceWise please see: http://www.usa.lighting.philips.com/products/product-highlights/spacewise-wireless-lighting-controls.html

19 For more information on Englighted's Energy Manager please see: http://www.enlightedinc.com/system-and-solutions/iot-system/energy-manager/

applications, and recent advances in PoE technology have yielded substantial increases in the amount of power that can be delivered to a networked device over a single cable.

As a result of these advancements, PoE technology proponents such as Cisco, predict lighting will go the same path as other technologies that converged with Internet protocol (IP) workplace service – e.g., telephony, security, and building management systems based on a building automation and control network. An illustration of the convergence of services on a single IP network – described as a Digital Ceiling by Cisco – is shown in Figure 3.6. A significant number of major LED manufacturers have introduced PoE connected lighting systems in the past year, with more promising to announce in the near future, making this a potentially disruptive technology.

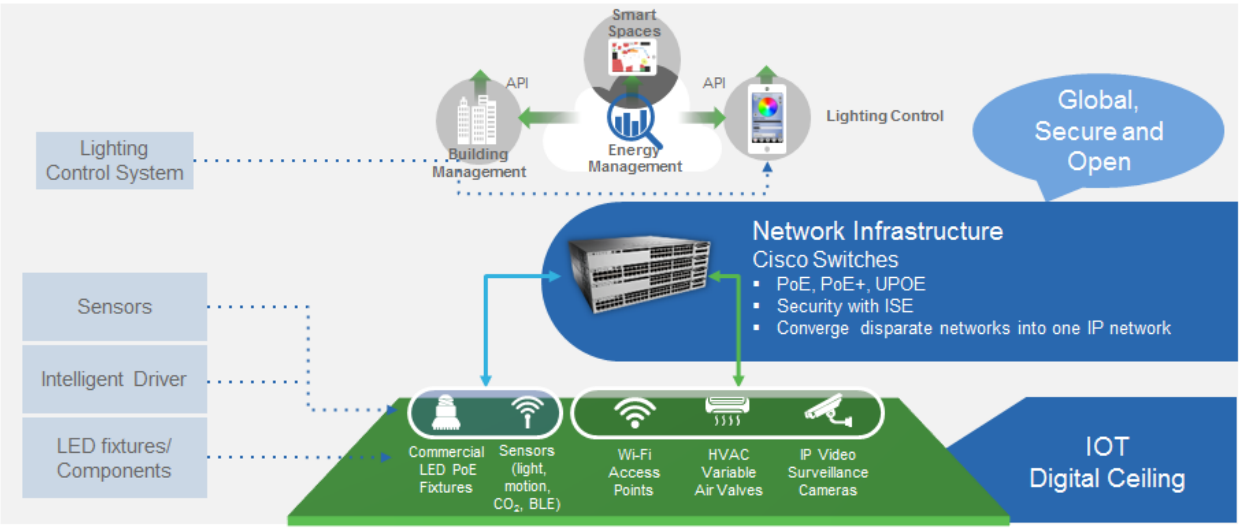

Figure 3.6 Schematic Illustration of an IoT Digital Ceiling Architecture for Buildings

Source: Wen-Lin Tsao, Cisco, DOE SSL R&D Roundtable, Washington, DC, September 2016 [83]

3.2.4 Interoperability

Just as SSL technology brought many new players (e.g., semiconductor manufacturers and microelectronic system developers) to the lighting industry, the coming intersection of lighting, communication networks, big data, and advanced analytics – facilitated by the IoT – will significantly alter the lighting industry landscape. The challenge is agreeing on common platforms and protocols, which will unlock the full potential of IoT by enabling the exchange of useable data among lighting systems, other building and control systems, and the cloud. Enabling the right level of interoperability is crucial for devices, applications, networks, and systems to work together reliably and to securely exchange data.

Traditionally, there has been little-to-no interoperability between competing lighting-control devices and systems, as manufacturers have focused on developing and promoting their own proprietary technologies or their own version of industry standards. Use of proprietary hardware and software essentially forces the users to source all products from a single vendor to ensure interoperability. Because user needs are likely to change over time, heavy reliance on a single supplier increases user risk when considering new installations by creating dependency on a vendor that may not be able to support these changing needs. In such situations, the user is faced with the decision to start over or live with an existing, increasingly unsuitable system.

A connected lighting system comprises many layers of communication, including the physical and data link layers (where data are created), the transport and network layers (where data are routed) and the application layer (where data are understood). In systems, interoperability may be partitioned by gateways, which translate between different protocols. As shown in Figure 3.7, one approach to interoperability may enable data exchange between luminaires and sensors, while another enables data exchange between luminaires and controllers, and yet another provides a simple communication pipeline between a central management system and the gateway to a field device network. Specifically, application-level interoperability is needed to ensure that devices and systems can not only "hear" each other, but can also understand what is being said. Many existing lighting protocols focus on lower-level interoperability, which is akin to ensuring that multiple parties can dial in to a teleconference without first making sure that they all speak a common language. If they do not, information cannot be exchanged without a translator.

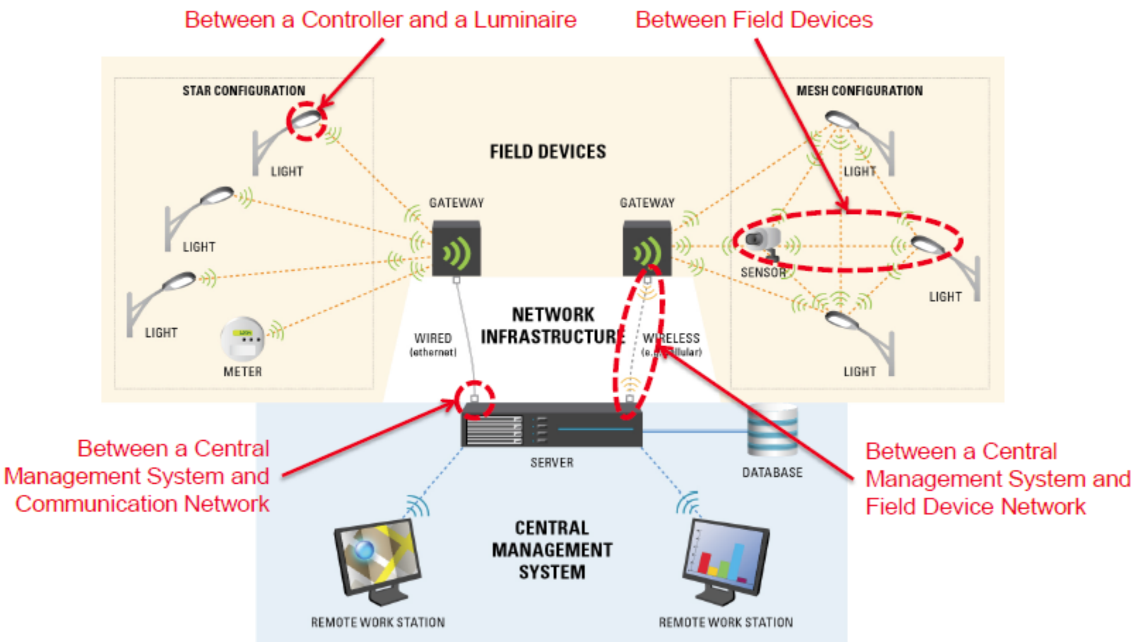

Figure 3.7 Lights, Sensors, Meters, Gateways, and Management Systems Working Together

Source: Michael Poplawski, PNNL, DOE SSL Market Development Workshop, Detroit, MI, November 2014 [84]

Standardized communication protocols can help increase interoperability and offer simpler system integration. Such standards can lead to more choices for customers among competing vendors, reducing investment risks from future dependence on a single vendor. Standardized communication protocols also can benefit the vendors because they support market growth, which benefits all players in the market. A number of consortia are working to establish common specifications and standards that support increased interoperability, including the Open Connectivity Foundation, the TALQ Consortium, oneM2M, Bluetooth special interest group, the Industrial Internet Consortium, and the Zigbee Alliance. As with the development of computing technologies, these groups are taking different approaches or addressing different parts of the puzzle. There is currently little interoperability in commercially available connected lighting systems.

DOE intends to help industry consortia unlock the full potential of connected lighting by supporting the development of increasing levels of interoperability. While interoperability may be perceived to be less important for relatively small, self-contained lighting systems (e.g., those servicing a single conference room or building floor), the challenges will increase over time as more systems become interconnected in support of initiatives such as net-zero building, smart city, smart grid, and intelligent transportation.

Interoperability also remains a key hurdle for home energy management systems, along with the cost of those systems. Home management integration through systems like Wink, Belkin's WeMo, and Apple's Homekit allow consumers to control most home devices using one simple interface. For example, the Wink Hub allows a diverse collection of smart products to speak the same wireless language so that they can be easily controlled from a single Wink software application. The Wink software application (app) allows users to monitor and control energy use for the devices within their home. Other home integration systems available behave in a similar manner. Most connected lighting products require a bridge or hub to connecting with a local Wi-Fi network (e.g., Philips Hue, GE Link, Cree Connected). Interoperability among home automation systems could simplify use and promote the acceptance of advanced lighting controls and home energy management systems.[20]

3.2.5 Connected Lighting Test Bed

As LED technology matures, maximizing the energy savings from connected LED lighting systems will become increasingly dependent on successful integration into the built environment. The DOE SSL Program is working closely with industry to identify and collaboratively address the technology development needs of connected lighting systems. Central to DOE's efforts in this area is a connected lighting test bed (CLTB), designed and operated by PNNL to characterize the capabilities of market-available connected lighting systems. The results of these studies will increase visibility and transparency on the capabilities and performance of new devices and systems, and create tight information feedback loops to inform technology developers of needed improvements as it relates to DOE priority areas of energy reporting, interoperability, configuration complexity, cybersecurity, and key new features.

The CLTB has infrastructure that enables the efficient installation of indoor and outdoor lighting devices. Two ceiling grids are available for installing indoor lighting luminaires. The height of each is vertically adjustable, to enable easy installation and set varying luminaire heights. The grids have plug-and-socket interfaces to enable easy electrical connections, and circuit-level power and energy metering in the electrical panels that serve them. The CLTB also has dedicated infrastructure for street lighting luminaires; again, plug-and-socket interfaces enable easy electrical connections.

To enable the testing of multiple devices and systems, the CLTB includes a software interoperability platform that allows installed lighting devices and systems not natively capable of exchanging data with each other to be able to communicate. Multiple commercially available indoor and outdoor connected lighting systems have been installed in the CLTB, incorporated into the software interoperability platform, and made available for connected lighting systems and other studies.

3.2.6 Connected Lighting Applications

With their sensor networks, connected lighting systems allow for data collection and exchange in ways not previously possible, and allow building owners/operators to manage and understand their physical environment to enable greater productivity, efficiency, energy savings, and security. This has led to increased availability of lighting devices and systems that can report their own energy consumption and the development of indoor positioning in heavy-traffic buildings such as retail stores and airports. Connected lighting systems also have the potential to develop a new source of broadband communication called Li-Fi, which modulates light to transmit data. Cities across the nation are setting up connected lighting platforms utilizing street lights as a backbone for access nodes and sensor deployments. Connected lighting is also being combined with spectral tuning in a variety of settings, with the goal of improving mood, productivity, and health.

Energy Monitoring

Energy reporting is critical for lighting systems, for the simple reason that it is not possible to effectively manage what cannot be measured. Connected lighting systems can help building owners to understand how a

[20] Please refer to the following websites for more information on the mentioned products:
Wink: http://www.wink.com/; Belkin's WeMo: http://www.belkin.com/us/Products/home-automation/c/wemo-home-automation/; Philips Hue: http://www2.meethue.com/en-us/;GE Link: http://gelinkbulbs.com/; Cree Connected: http://creebulb.com/products/standard-a-type/connected-60-watt-replacement-soft-white-led-bulb

space is being utilized by its occupants and to deploy adaptive lighting strategies that increase lighting energy efficiency. Data-driven energy management can significantly reduce energy consumption and enable new market opportunities, such as pay-for-performance energy efficiency initiatives, energy billing for devices currently under flat-rate tariffs, verified delivery of utility-incented energy transactions (e.g., peak and other demand response), lower cost and more accurate energy-savings validation for service-based business models, and self-characterization of available (i.e., marketable) “building energy services.”

This real-time information can help project the annual return on investment that will be realized from replacing traditional lighting systems with connected LED lighting. Figure 3.8 shows an example of the Energy Manager system by Enlighted, with the energy usage plotted as a function of date range and the impact of sensing and scheduling on energy consumption. DOE is interested in the opportunity to facilitate and develop transactive energy markets with such data; a variety of market actors, including building owners looking to realize the value of available – and perhaps marketable – building-energy services also may be interested. DOE is working with industry partners to help identify and evaluate ways to leverage the broad availability of energy use data, and to identify cost-effective techniques for measuring the energy consumption of installed lighting systems.

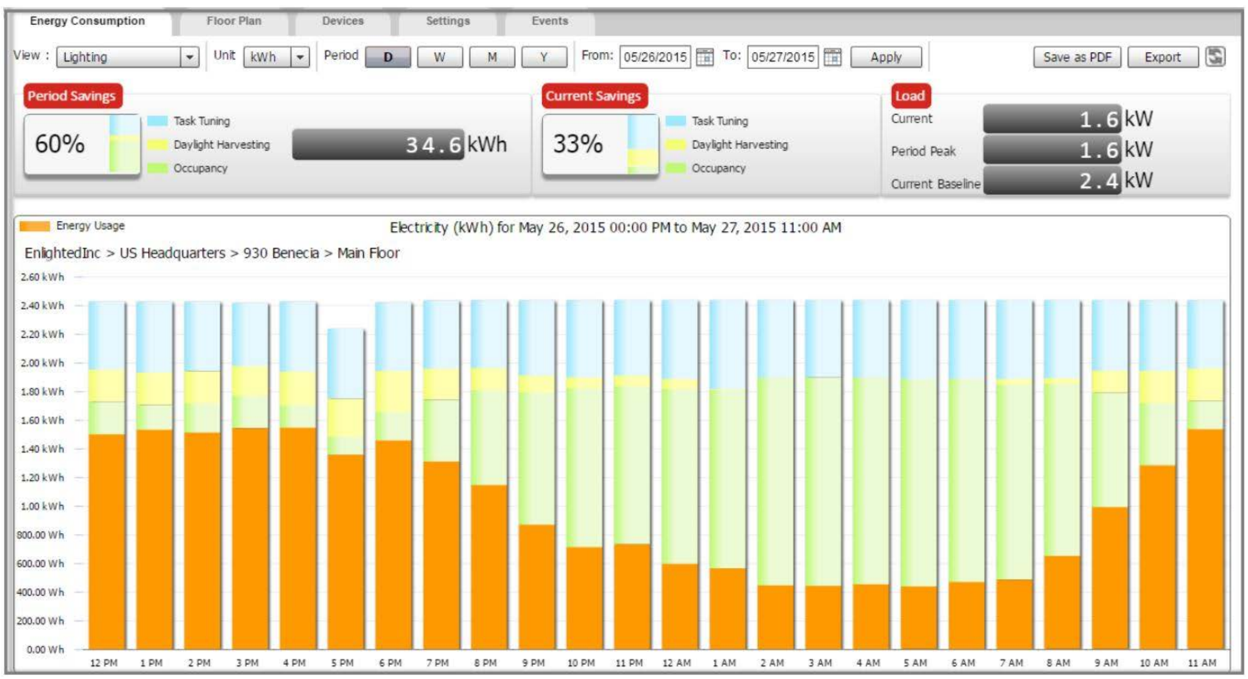

Figure 3.8 Example implementation of Enlighted Energy Manager Software Showing Energy Usage Mapping in a Building

Source: Enlighted, Energy Manager Specification Sheet [85]

Smart Cities

The installation of LED street lights can provide cities with substantial savings through increased energy efficiency, decreased maintenance costs, and longer lifetimes. They can also serve as a platform to integrate a sensor network that provides value-added features to the city (illustrated in Figure 3.9). A dense sensor network could provide a city data on variables such as air quality, weather events, security, parking space availability, and traffic patterns. Street light poles are the ideal platform for collecting data by adding environmental sensors and security infrastructure, such as surveillance equipment or acoustic sensors to detect gun shots in real time and notify police. Leveraging this data through an intelligent platform, LED street lights can act as a wireless communications network that would be more costly if developed separately. Data can be sent to a centralized data management platform, which can be accessed by customized dashboards for city staff to provide information and controls appropriate to their responsibilities.

LED lighting has already proven to save cities money via increased energy efficiency over the incumbent high-pressure sodium (HPS) used in street lighting. Connected street lighting systems offer the ability for city officials to implement adaptive lighting strategies (e.g., having the street light at 100% brightness when it turns dark and gradually dim to 50% in the middle of the night and return to full brightness in the early morning for commuters) that deliver further energy savings. Connected street lights may also provide the city the location of each light pole to better manage the assets, particularly when there are failures.

Figure 3.9 Services that Can be Provided to a City when Utilizing LED Lighting Street Lights Integrated with Sensors

Source: Himamshu Prasad, GE Lighting, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [86]

Indoor Positioning

Connected SSL systems are already being used as a platform for indoor positioning in retail and other heavy-traffic buildings, by using Bluetooth and/or visible light communication (VLC) to provide personalized location-based services for occupants via a mobile app. Beacons embedded in LED luminaires allow for the monitoring and analysis of building use and traffic, which can lead to operational efficiencies, enhanced safety, and increased revenues in spaces such as airports, shopping malls, logistics centers, universities, and healthcare facilities.

Several lighting manufacturers have lighting products that incorporate VLC and Bluetooth Low Energy (BLE) beacon technology into luminaires for use by retailers. Retailers use the luminaires to transmit location-specific data to shoppers, such as discount coupons or where in the store to find products. The customer benefits through the receipt of targeted information or product promotions, and the retailer benefits from knowledge of customer flow and product interest. The ability to develop a source of recurring revenue from this feature changes the economics of LED adoption for the retailer by accelerating the return on investment. In addition to app-based services for customer use, beacons embedded in LED luminaires allow for indoor analytics that can measure people passing by and entering a store or building. These location-based analytics allow users to visualize how many people in a building are first-timers, repeat customers, and how long they are staying. The use of beacons to locate smartphones through BLE or Wi-Fi signal pings provides valuable information about traffic flow and dwell time in certain locations. The benefits to this granularity in building traffic can help businesses understand how to identify peak traffic hours, adjust staffing needs, maximize the value of repeat customers, and draw customers inside.

Broadband Communications Using VLC

The opportunity to provide new sources of broadband communication using VLC may be important in the future to help cope with the continuing rise of global mobile data traffic. The increasing number of wireless devices that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth. VLC requires improvements to enable faster data transmission speeds to address one of the challenges for data transfer with lighting. More research is required to improve the modulation speeds of the LEDs, which would increase transmission speed and make this added communication functionality valuable. Increasing transmission speed may require the exploration of laser diodes or superluminescent diodes, which both have faster modulation speeds, for lighting. Other system-level challenges include developing the ability to handoff the Li-Fi signal as users move between luminaires, because line of sight is required for VLC, and requiring that the luminaires have wired connections to a high-speed data network.

3.2.7 Security

As more devices are becoming part of a connected world, the benefits come with security risks, as demonstrated by a few publicized cases in which firewalls have been breached by hacking into lighting products [87]. An Internet-connected lighting system can provide hackers entry points to everything behind the network firewall, e.g., a home computer, a retailer's payment terminals, or a government office’s sensitive database. Studies found that even the most basic security practices that could have prevented these breaches were often not followed, including the lack of encryption and authentication, the use of clear-text protocols to transmit sensitive information (e.g., passwords), and the use of default passwords in customer environments [87]. Because of these potential vulnerabilities, it is imperative that manufacturers integrate security into their product and software development lifecycle right from the start.

Connected lighting systems and other IoT systems require further work in integrating end-to-end security. Figure 3.10 shows some common defense strategies for IoT systems and devices to protect and maintain data privacy and to avoid crippling important control systems with denial of service attacks. Lighting fixtures must have authentication and security certificates for each node and the sensor data needs to be “signed” to make sure it is coming from the correct sensor. In many cases, IoT systems will not be a single-use, single-ownership solution. The devices and the control platform where data may be collected and delivered can have different ownership, policy, managerial and connectivity domains. Consequently, devices may be required to provide access to a number of data consumers and controllers, while still maintaining privacy of data where that is required among those consumers. Information availability with simultaneous data isolation among common customers is critical. Securing user data and privacy, ensuring availability, and protecting network-connected devices against unauthorized access will be crucial to companies wanting to gain and maintain trust with connected lighting buyers.

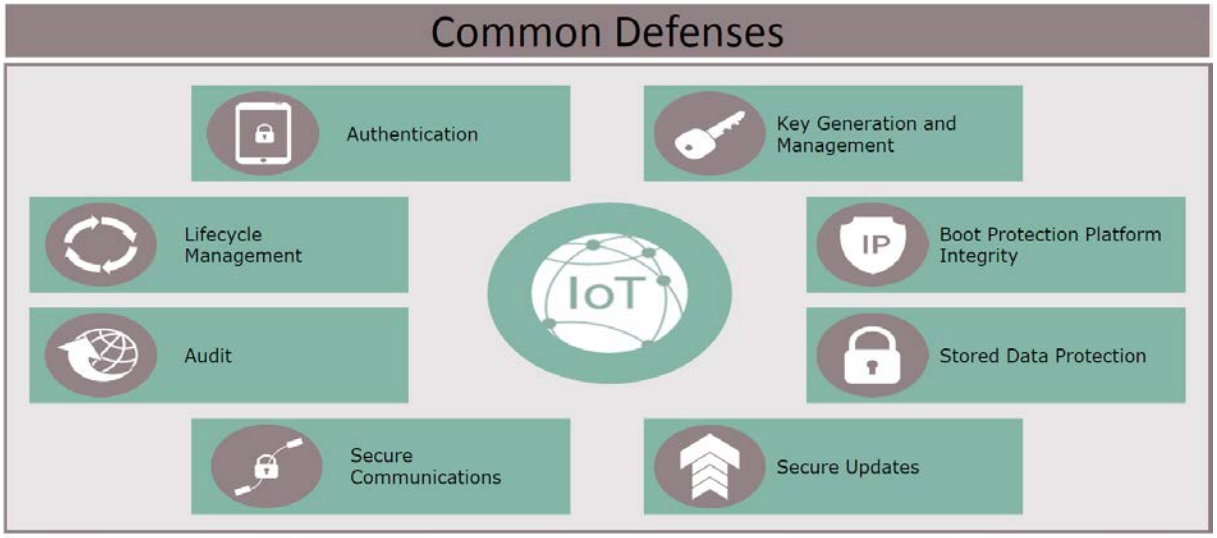

Figure 3.10 Common IoT Defense Strategies

Source: Michael Armentrout, Strategies in Light, Anaheim, CA, March 2017 [88]

3.2.8 Conclusion

DOE intends to help develop connected lighting technology primarily because it enables even deeper energy savings than those achievable by simply converting from conventional to SSL sources. Those deeper energy savings are made possible not only from the advanced lighting control potential of connected systems, but also from improved operation of other end uses such as HVAC systems, reduced transportation energy (from outdoor connected lighting systems), and other value propositions that will likely emerge as the incremental cost of providing that energy management capability falls. Connected lighting systems promise to provide value far beyond energy savings, such as the location services for retailers. Those additional services have the potential to add value, revenue streams, and functions that may partly or even completely offset the cost of providing improved energy management services, making the energy management services low cost or potentially free, depending on how costs of additional functionality are allocated among potential services.

DOE is working with industry partners to help accelerate the development of connected lighting systems that 1) allow luminaire systems to self-measure and report energy use, 2) have a high degree of application-level interoperability, and 3) are easier to configure, commission, and maintain than is common in current lighting systems. As part of that focused effort, DOE is conducting a series of connected lighting workshops, focused on facilitating and encouraging collaborative industry efforts in these areas.[21] Those workshops will also be used to help identify high-priority R&D investments needed by both the public and private sectors.

3.3 Health and Productivity – Physiological Responses

As described in Section 3.1.1, LED lighting products can be designed to emit almost any spectrum of visible light. Newer commercial products such as the Philips Hue and specialty products such as the Telelumen Light Replicator can provide active control of the emitted spectrum with varying degrees of spectral resolution and intensity control. In addition, new products offer active control of the CCT of the white light from the luminaire to trigger human physiological responses. However, while LED products can have a tailored

[21] More information on Connected Lighting Workshops, which have been held in November 2015, June 2016, and June 2017, can be found at: https://energy.gov/eere/ssl/workshops

spectrum, most LED lighting products do not yet have active control of the emitted spectrum. The ability to dynamically tune the emitted spectrum of an LED or OLED lighting source and the broad range of instantaneous intensity control are distinguishing features of the technology and can add value to SSL beyond energy savings. New applications enabled by LED color tunability and spectral replication include lighting for human wellbeing and horticultural lighting for improved productivity.

The ability to tailor the spectrum is leading to a better understanding of the most appropriate light for performing a specific task, optimizing horticultural productivity, and positively affecting human physiology, as well as developing new applications. Enabling dynamic control of the emission spectrum can provide further value by allowing the spectrum to change over time in response to changing lighting demands.

While the impact of lighting on horticulture, physiological responses, and productivity is becoming better understood, it is important to acknowledge that much of the supporting research for these effects is at an early stage and that additional research is necessary to fully understand these biological responses. LED technology can support these efforts by offering a new high-resolution tool for better research and understanding of all biological impacts of lighting. In particular, human physiological impacts of lighting, both positive and negative, need to be well understood and controlled to maximize the benefits from lighting, and lighting manufacturers should be careful to claim only well-supported, understood, and verifiable physiological benefits from their products.

3.3.1 Human Physiological Responses to Light

Humans are continuously exposed to natural and electric lighting, all of which has some effect on our physiology, regardless of the source. Recent research has advanced the understanding that light not only enables vision, but also is a critical signal to our biological systems, affecting circadian rhythms, pupillary response, alertness, and more, as illustrated in Figure 3.11 [59]. Light has been shown to be an effective treatment for a variety of conditions, such as seasonal affective disorder and dementia [89].

Importantly, the non-image-forming photoreceptor system in our eyes is different from our visual system. Although it shares some of the same photoreceptors, it has its own unique spectral and temporal response to light. The non-image-forming photoreceptor has a peak sensitivity to blue light and controls the release of melatonin. When humans are exposed to light with a high blue content, such as sunlight at mid-day, melatonin release is suppressed. Control of blue light is therefore important for light and health, but further research is necessary to fully understand the impacts.

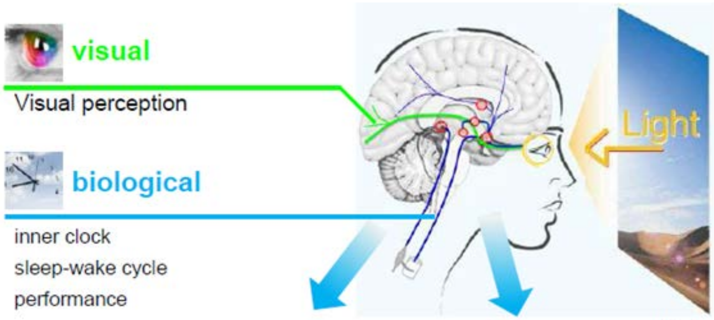

Figure 3.11 How Light Affects Biological Systems

Source: Andreas Wojtysiak, OSRAM, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [89]

Case studies have shown that certain tuning the spectrum of the lighting throughout the day can lead to improved alertness and productivity, and can help synchronize our internal circadian clock. Light levels in the morning can clearly indicate to our inner clock that the day has begun and that the body should be awakened. This activation phase requires light with a high blue content as shown in Figure 3.12. During the evening, it is desirable to reduce the amount of blue light in the spectrum because it suppresses the production of melatonin and makes falling asleep more difficult.

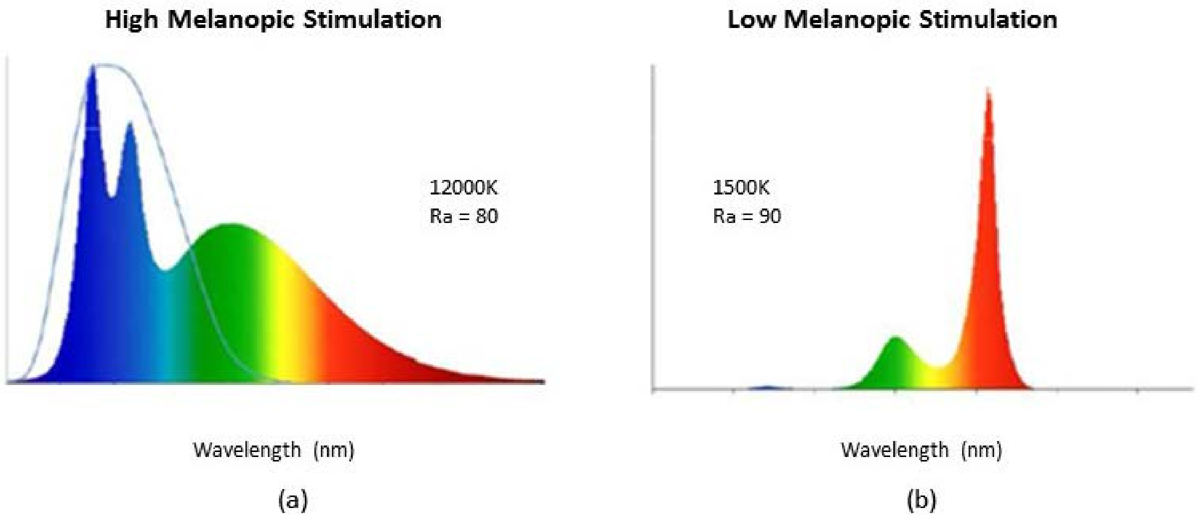

Figure 3.12 (a) Daytime Activation by Light, and (b) Less Circadian Light Effects in the Evening and Night

Source: Andreas Wojtysiak, OSRAM, DOE SSL R&D Workshop, San Francisco, CA, January 2015 [89]

Researchers have shown that spectral tuning [89]:

- Improves classroom alertness for students
- Promotes daytime activity, alertness, and better sleep at night for the elderly (nursing homes)
- Assists chronic pain therapy through structuring the day and stabilizing sleep/wake cycles
- Increases evening and nocturnal relaxation and morning activation for passengers in an aircraft cabin
- Reduces the duration of time of therapy to relieve unipolar depression.

The physiological impacts described above could be harnessed to improve wellbeing of those under the lights and effectiveness of lighting systems. It is too early to tell how big of an impact these features may have, but even slight improvements in workforce productivity could justify the added expense of integrating personal controls for dimming or implementing a changing white color spectrum and intensity throughout the day. LED technology can enable the control of the light output, spectrum, and light distribution to implement such a system.

A suggestion from stakeholders at both the DOE SSL R&D Workshop and the DOE SSL Roundtable meetings was for DOE to support R&D on the topic of human physiological responses to light. With the building blocks offered by SSL technology (i.e., LEDs, phosphors, and controls), it is now possible to directly engage human physiological responses to improve wellbeing and productivity. However, lab-based studies need to be replicated and confirmed within more realistic lighting contexts, and the benefits need to be clearly validated for the specifically claimed responses. The results of these studies can then be translated into best practices for lighting design and efficient product solutions can be developed that provide both the desired physiological response and good efficiency.

While expenditures on energy are far greater than the costs of buying and installing lighting systems, perhaps the greatest opportunity for the lighting industry is to realize the potential for increases in productivity. These can come directly from improved lighting in the workplace or indirectly, for example, by facilitating access to education and healthcare in developing countries [90]. The impact of lighting on the global economy, as estimated by the International Solid-State Lighting Alliance (ISA), is shown in Figure 3.13.

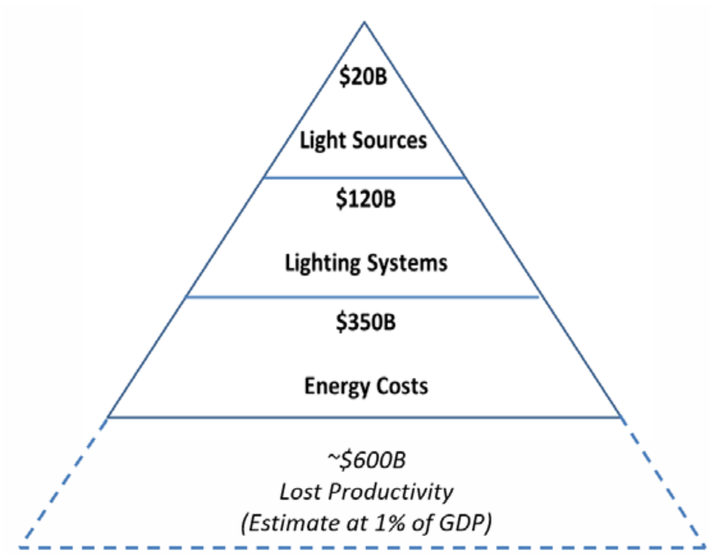

Figure 3.13 Impact of Lighting on the Global Economy in 2014

Source: International Solid-State Lighting Alliance, Global Solid State Lighting Industry Status Report and Market Trends, 2014 [90]

3.3.2 Horticulture

Horticulture lighting is an increasingly important application that takes advantage of the spectral tailoring and tuning, intensity control, and light distribution control offered by SSL sources. Light-regulated plant attributes, including flowering, branching, plant height, biomass accumulation, plant immunity and defense, stress tolerance, and phytoceutical production, are influenced by changes in the spectrum of light. This can then influence various aspects of plant growth, such as the size of the plant, germination process, flowering, vegetation, and even nutritional value [91].

While blue and red regions of the spectrum are the primary spectral regions for photosynthetic activity, as shown by the chlorophyll curves in Figure 3.14, there is debate in the horticultural community as to the role of green light as well. In many controlled environments, plants grow just fine under the almost entirely green spectrum of HPS lights. The optimum spectra and light levels and durations for specific growth periods of specific plant species is an active topic of research.

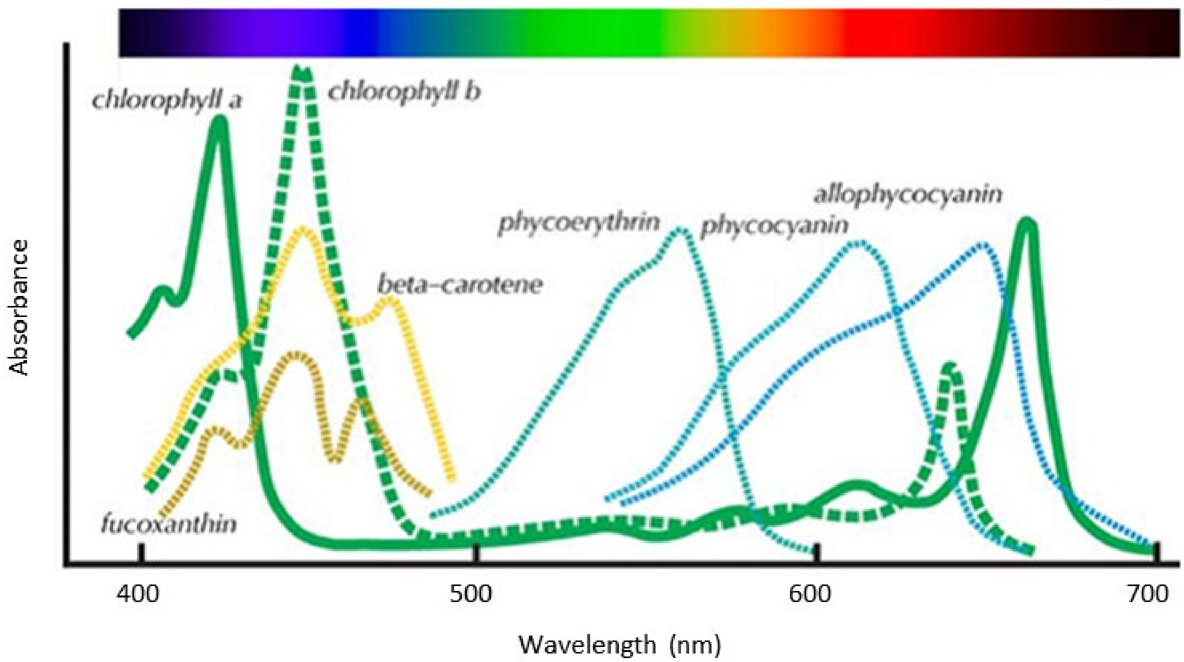

Figure 3.14 Absorption Spectrum of Various Plant Pigments

Source: Lincoln Taiz et al., “Plant Physiology and Development,” 2014 [92]

Plant pigments absorb across the visible spectrum, including the green region, as shown in Figure 3.14. Research at Rensselaer Polytechnic Institute has demonstrated the ability to tailor the spectra to improve the nutritional value of plants. For example, anthocyanin, a flavonoid pigment, is responsible for the red color of red lettuce and is thought to have a variety of health benefits including improving eye health, heart health, and cognition [91]. Red lettuce grown under lamps of varying spectral output produced different amounts of anthocyanin, as shown in Figure 3.15.

Figure 3.15 The Influence of Spectra from Cool White Fluorescent (CWF) and LED Lights on Anthocyanin Production in Red Lettuce

Source: Tessa Pocock, Rensselaer Polytechnic Institute, SSL Technology Development Workshop, Portland, OR, November 2015 [91]

Understanding the specific lighting needs for horticultural crops can enable more efficient and effective growth and control of the ultimate product. This understanding, along with continued advancements in LED efficiency and reductions in cost of LED lighting products, can improve the economics for all types of controlled environment agricultural: greenhouse, indoor, and indoor vertical. Potential benefits for controlled environment agriculture enabled by LED technology, include:

- Reduced energy consumption
- Reduced water consumption
- Localization of food supplies
- Reduced chemical requirements
- Increased nutritional value of crops
- Improved control of the growth process

The performance of horticultural lighting products is characterized by different metrics than general illumination products. General illumination product performance is centered around lumens (which are defined by the human eye response) as well as color quality metrics such as CRI and CCT, which ensure the light quality is suitable for the application. The standard for horticultural lighting is to characterize the light output in terms of number of photons within the photosynthetic active region, 400-700 nanometer (nm) (disregarding the energy or color of the photon), and to further characterize the color quality in general terms of color bands or color ratios. Table 3.2 details the corresponding metrics for general illumination and horticultural illumination.

Table 3.2 Corresponding Metrics (and Units) for General Illumination and Horticultural Illumination

	General Illumination	Horticultural Lighting
Output	Lumens (lm)	Photosynthetic Photon Flux (µ-moles/second)
Efficacy	Lumens/Watt (lm/W)	Photosynthetic Photon Efficacy (µ-moles/joule)
Illuminance	Footcandles (lm/ft^2) or Lux (lm/m^2)	Photosynthetic Photon Flux Density (µ-moles/second·m^2)
Efficacy of Radiation	Luminous Efficacy of Radiation (LER) (lm/Optical Watt)	Photosynthetic Photon Efficacy of Radiation (µ-moles/second Optical Watt)

While the metrics for characterization are different for general illumination and horticultural lighting, they can be calculated from the same radiometric measurements of the lighting product. Similarly, lighting professionals can apply the same lighting design practices for greenhouses and indoor farms as they do for general illumination, once the lighting requirements of the crop are defined.

Each year this document describes efficacy projections for LED and luminaires in terms of lm/W with specified color qualities. These projections are further detailed in Figure 4.4 on page 61. Using the same projections for advancements in efficiency of LEDs, projections for horticultural efficacy advancements are described in Figure 3.16. Some integrated horticultural LED lighting products claim efficacy levels of around 2.5 µ-moles/J, which matches well with performance estimates based on individual LED package performance while accounting for typical luminaire losses. Note that these projections use fixed operating conditions for the LEDs of 25°C and 35 amps per square centimeter (A/cm^2) drive current. In practice, LEDs are often operated at higher temperatures, which decreases efficiency, and/or lower current densities, which improves efficiency.

Figure 3.16 shows that there is a drop-off in efficacy when using phosphor converted white LEDs compared to color-mixed (cm) LEDs. However, as with general illumination efficacy, hybrid approaches using both phosphor conversion and direct emitting red LED can fall between the two curves and provide the benefits of both approaches. The saturation values for the two curves in Figure 3.16 are estimates of the maximum photosynthetic photon efficacies of LEDs consistent with the targeted efficiencies of LEDs in the color mixed LED (cm-LED) architecture discussed in Section 4.1.4. Note that these are lower than the maximum calculated efficacy for a given spectrum with perfectly efficient sources, which would be analogous to luminous efficacy of radiation (LER) for general illumination. As with LER, the photosynthetic photon efficacy of radiation (PPER) could be multiplied by the efficiency of the LED sources (including optical and power supply losses) to determine the actual efficacy of the system.

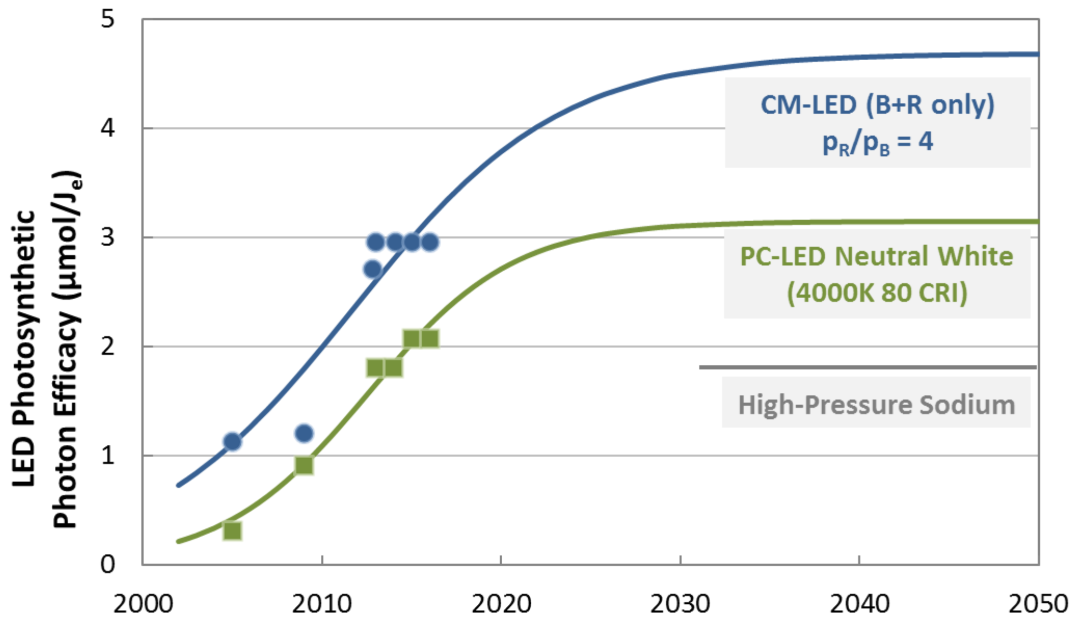

Figure 3.16 LED Photosynthetic Photon Efficacy (or LED Photosynthetic Efficacy of Source) for a Typical Pc-LED Architecture with a Neutral White Color Temperature and for a Hypothetical Cm-LED Architecture Containing Only Blue (455 nm) and Deep Red (665 nm) LEDs With an Optical Power Ratio of 1:4

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4 LED Technology and Manufacturing Status, Opportunities, and Challenges

LED lighting technology has improved dramatically over the past decade to achieve among the highest efficiencies of available white light sources. Improvements in manufacturing have enabled LED products to achieve a low enough cost to drive measurable LED adoption in all general illumination applications. Despite this progress, further improvements are possible and desirable. LED lighting efficiency and other features, such as color quality, light distribution, form factor, and architectural integration, have room for further improvement. The manufacturing technology for LED lighting also can be improved to reduce cost and increase market penetration, resulting in the greatest possible energy savings for the nation.

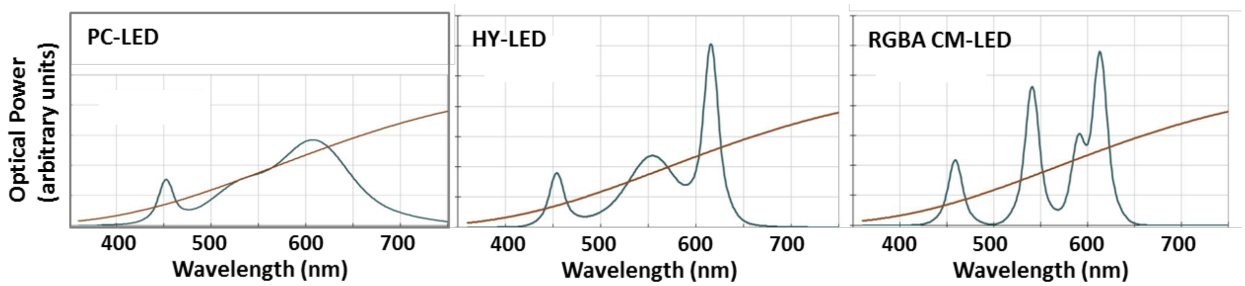
The following sections explore the current status, performance improvement opportunities, and challenges for LED technology. The key challenges currently facing LED technology also represent some of the greatest opportunities for performance gains. The following sections identify eight key opportunities/challenges. The sections cover both the LED package, which creates the white light, and the LED luminaire, which houses the LED package and provides the appropriate interface between the electrical supply, mechanical integration, thermal handling, and optical distribution.

4.1 LED Package Technology

This section describes three common architectures for generating white light; the simulated optical power spectra for these three architectures are shown in Figure 4.1. The pc-LED is based on a blue LED to pump yellow-green and red wavelength optical downconverters (typically phosphors), thus producing white light. The hybrid LED (hy-LED) is based on a blue LED used to pump a yellow-green wavelength downconverter, then the blue and yellow-green light is mixed with light from a red LED to again produce white light. The primary colors that compose a red, green, blue, and amber (RGBA) color-mixed LED combine to produce white light.

Throughout this section, quantitative analyses of the three architectures are described by separating their overall efficiencies into sub-efficiencies associated with the various source colors, and then re-assembling them into white light using an optical modeling worksheet.[22] The analyses reveal the relative impacts of various sub-efficiency losses imposed on the different architectures, and the corresponding opportunities for targeted improvements. These sub-efficiency breakouts and efficiency roll-ups are detailed later in this section, in Table 4.1 and Table 4.2.

[22] Simulator developed by Yoshi Ohno at the National Institute of Standards and Technology (NIST) (version 7.5).



Note: In all cases, the peak wavelengths and relative intensities are those which maximize LER for a 3000K CCT (warm white), a "standard" CRI R_a of 80 and a CRI associated with the ninth, deep-red Munsell color sample $R_9 > 0$. The spectral widths of the various source colors correspond to the current state-of-the-art. Overlaid on each spectrum is the spectrum from an incandescent blackbody source at 3000K.

Figure 4.1 Typical Simulated Optical Power Spectra for the Three White-Light LED Package Architectures Considered

For all three white-light architectures, four important performance characteristics, when optimized (especially simultaneously), can introduce efficiency penalties: drive current density, operating temperature, CCT, and CRI. The tradeoffs for each, as well as the values chosen for the following analyses, are described below:

1. **Drive current density (35 A/cm^2).** Drive current determines the amount of luminous flux being generated in the package. Top-bin commercial LED packages can achieve luminous efficacies of 200 lm/W, but only by operating at lower current densities, which results in less overall luminous flux being generated in the package, and thus a higher cost per lumen. Packages driven at a higher current density produce more lumens; however, due to a phenomenon known as efficiency droop, the efficiency of blue LEDs decreases at higher current densities, as shown in Figure 4.2(a). For normalization purposes, all analyses in this section are for packages driven at 35 A/cm^2.

2. **Junction temperature (at room temperature, 25 degrees Celsius (°C)).** This is the temperature during which operation occurs at the junction between the p- and n-type semiconductors that form the diode. This junction temperature, T_j, affects the efficiency of the device. As shown in Figure 4.2(b), the relative lumen output (and therefore efficiency) decreases with increasing junction temperature. This phenomenon, known as thermal droop, is likely to grow in importance. For consistency with previous years' data and targets, the following analyses emphasize operation under standard room-temperature conditions (T_j equal to 25°C). However, because LED packages can be driven "hard" (35 A/cm^2 and higher), they also often run "hot" (T_j much greater than 25°C). Therefore, their hot performance is often of greater interest than their room-temperature performance, which is why many LED manufacturers test LEDs at 85°C. The junction temperature is affected by the package design, including thermal handling materials, drive current, and ambient temperature.

3. **Correlated color temperature (warm white, 3000K).** Achieving higher efficiencies has been more challenging for warm white LEDs than for cool white LEDs due to the relative inefficiency of the red downconverters. However, advancements driven by the push to increase the efficiency of warm white LEDs will also likely benefit cool white LEDs. Though warm white is currently more "challenged" than cool white, the maximum luminous efficacies of radiation achievable for warm is somewhat higher than that for cool white. As can be seen in Figure 4.3(a), maximum luminous efficacies of radiation for CRI 80 are slightly higher for warm (about 414 lm/W at 3,000K) than for cool (about 390 lm/W at 5700K) white. This is because the human eye is more sensitive to red than to blue light.

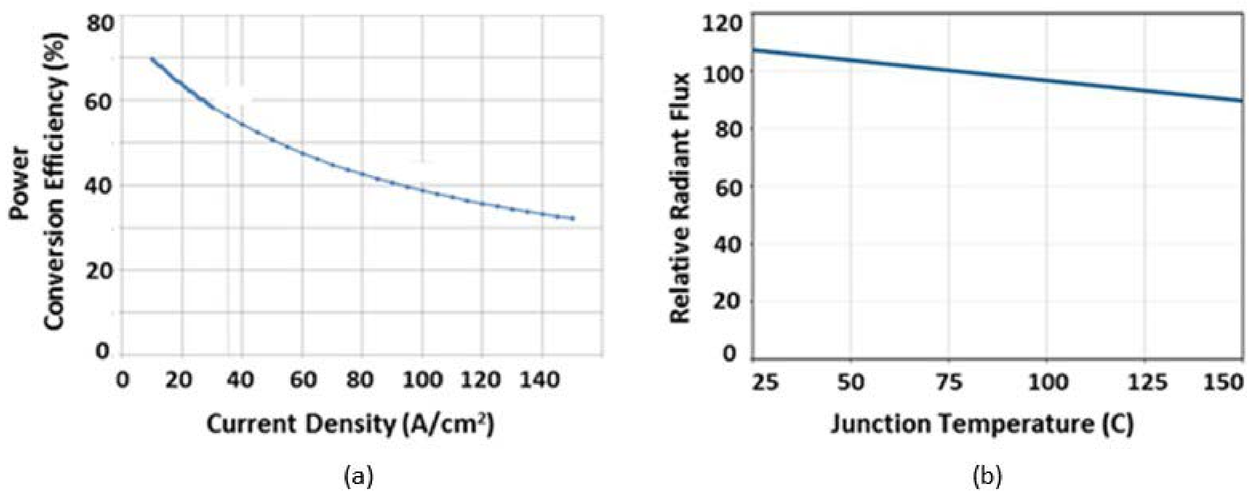


Figure 4.2 Two Types of Efficiency Droop: (a) Current Efficiency Droop, and (b) Thermal Efficiency Droop

Source: Cree Inc, XLamp XT-E Datasheet [93]

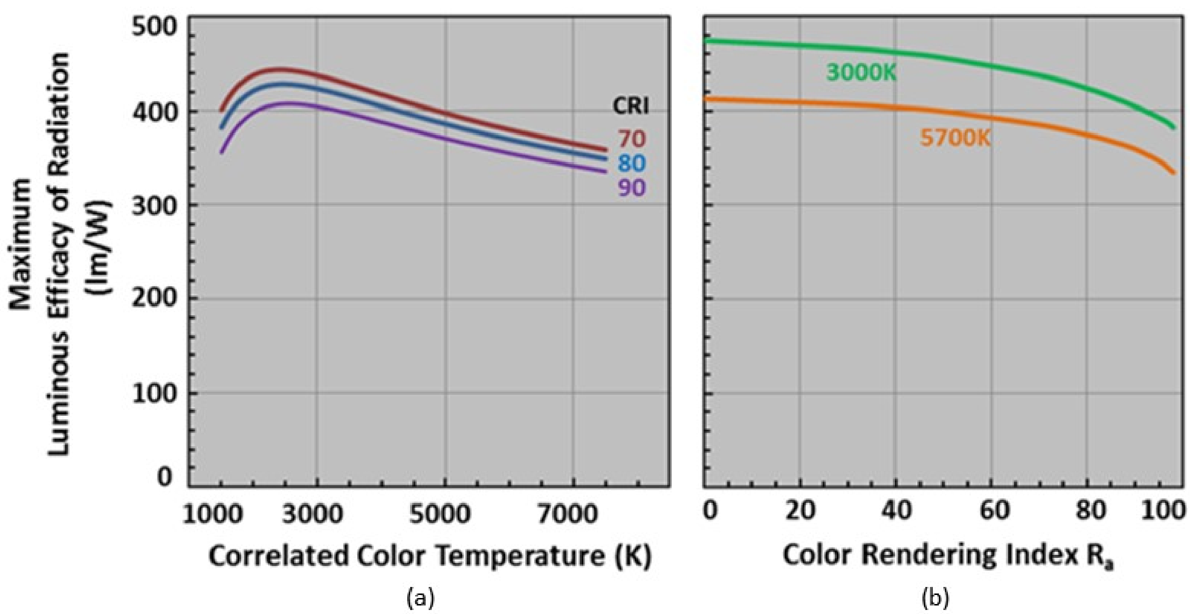


Figure 4.3 Theoretical Limits to White Light Luminous Efficacies of Radiation
vs. (a) CCT for a Given CRI, and (b) CRI for a Given CCT

Source: Hung and Tsao, "Maximum White Luminous Efficacy of Radiation Versus CRI and Color Temperature: Exact Results and a Useful Analytic Expression," June 2013 [94]

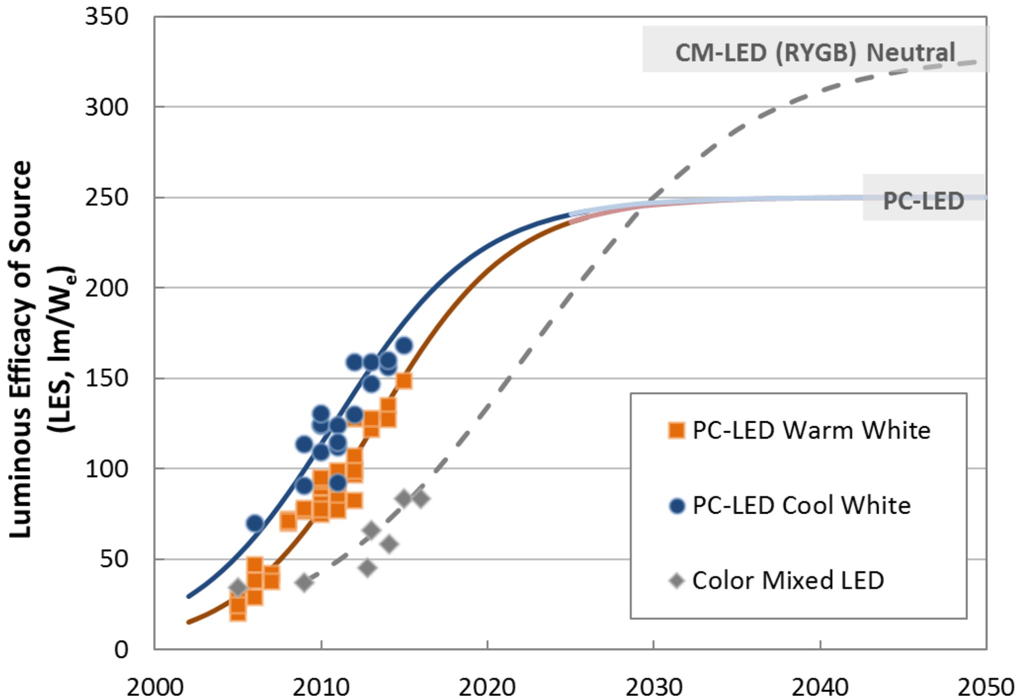
4. **Color rendering (R_a equal to 80, R_9 greater than 0).** There is an inverse relationship between luminous efficacy and color rendering quality. As seen in Figure 4.3(b), increasing CRI from 80 to 90 decreases the maximum achievable luminous efficacy by 10%. Practical data suggests the drop to be significantly higher in the pc-LED architecture, in the range of 15 to 25%, due to deficiencies and broad peak widths in the red phosphors. To satisfy the majority of applications for white light, relatively high color rendering quality, i.e., a "standard" CRI, R_a of 80 and an R_9 value greater than zero is desired.[23] However, some sectors of the market increasingly demand even higher color rendering quality. Furthermore, the meaning of color rendering quality is itself an active area of study. It is likely that new measures will someday replace or at least augment the standard CRI in ways which depend on the illumination application. For example, IES recently articulated TM-30, a new method for evaluating color rending that includes both a "fidelity index" and a "gamut index [95]."

4.1.1 Pc-LED Architecture: Current Status

The pc-LED architecture was the first and is by far the dominant white light architecture. It has three major advantages over the other architectures: simplicity (only one LED type), temperature robustness (the InGaN blue LED and YAG phosphor downconverters can operate at relatively high temperatures), and color stability (the fractions of red, green, and blue source colors are determined during manufacture by the phosphor optical density and are relatively stable over time).

Figure 4.4 shows a history of the luminous efficacy of pc-LEDs since the DOE SSL Program began and the progress that has been made. In just 10 years, luminous efficacies have increased by a factor of more than three, from less than 50 lm/W to approximately 150 lm/W (at 35 A/cm^2). The principal reason has been improvement in blue LED efficiency, although improvements also have been made in phosphors (efficiency and wavelength match to the human eye response) and package (optical scattering/absorption) efficiency.

[23] The standard CRI (R_a) is a measure of the ability of a source to accurately render a set of eight standard color samples R_1 to R_8 (CIE 1995), but fails to measure the ability to render saturated colors, especially red, which is represented by color sample R_9. A value for R_9 is therefore often included with CRI to quantify the ability of a source to render red colors. For example, the ENERGY STAR specifications calls for R_9 greater than or equal to 0, but some specifications bodies are starting to consider higher values, with the California Energy Commission voluntary specifications calling for R_9 greater than or equal to 50.



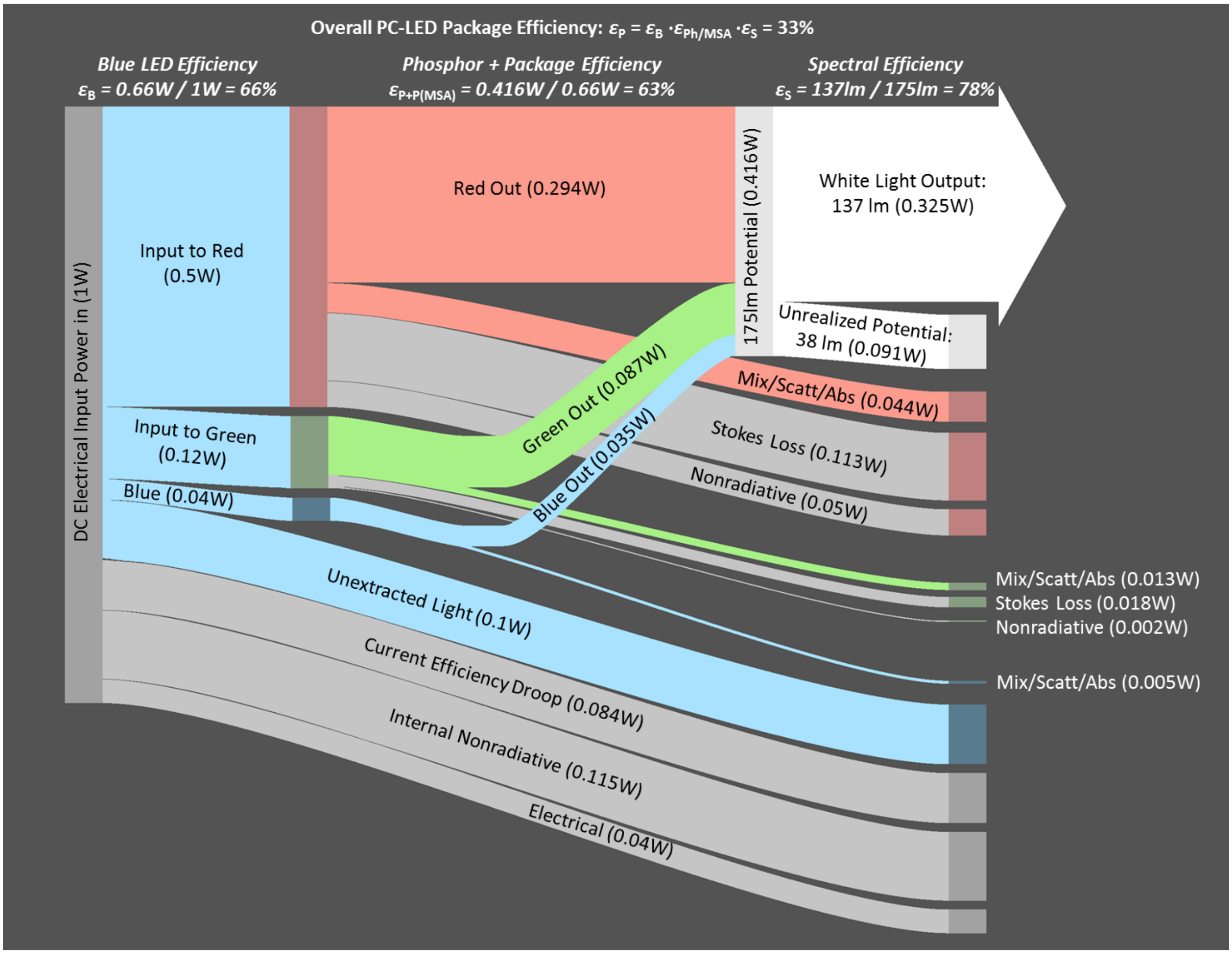
Note:

Blue = cool white (5700K) data (circles) and logistic fit (line); orange = warm white (3000K) data (squares) and logistic fit (line). Year 2016 commercial products reach approximately 160 lm/W for cool white and approximately 140 lm/W for warm white. Approximate long-term-future potential efficacies of the pc-LED white light architecture are their values after saturation, depicted as beginning in the years 2020-2025. The long-term-future potential efficacy of the red, yellow, green and blue (RYGB) cm-LED architecture is shown as the dashed grey curve. As discussed in the text, as with many "disruptive innovations," the cm-LED architecture currently has lower performance than the current dominant pc-LED architecture, but it has the potential in future years to leapfrog beyond.

Figure 4.4 Efficacies of Commercial LED Packages Measured at 25°C and 35 A/cm^2 Input Current Density

Despite these improvements, there is much further to go. As illustrated by the saturation values of the blue and orange curves in Figure 4.4, luminous efficacies of approximately 255 lm/W are practically possible for pc-LEDs, a factor 1.6x beyond the current state-of-the-art. To help visualize where this factor might come from, Figure 4.5 shows an estimated electricity-to-visible-light power-flow diagram for a current LED warm white light state-of-the-art commercial pc-LED package, in which a hypothetical 1 W (0.35 A x 2.85 V) is injected into the blue LED package at the left of the diagram, and 137 lumens of white light emerges from the pc-LED package at the right.

The blue LED converts the 1 W of electrical power with an efficiency of 66% into 0.66 W of blue optical power. The blue LED loses 34% or 0.34 W of that electrical power to a combination of electrical resistance losses, internal quantum efficiency (IQE) losses due to non-radiative recombination of injected electrons and holes at low current density, efficiency droop due to operation at higher (35 A/cm^2) current density, and losses due to incomplete extraction of blue light from the high-index InGaN semiconductor material.



Note:

The diagram gives estimates for how 1 W = 0.35 A x 2.85 V of DC power is distributed into various useful and non-useful (loss) streams en route to being converted into white light. The colors of the various streams indicate the type of power they contain: gray for electronic excitations, colored for light at various red, green and blue (RGB) wavelengths, and white for white light formed from a combination of colors. For each loss stream, values indicate both its absolute power as well as the percentage it represents of its immediately preceding parent stream.

Figure 4.5 Electricity-to-Visible-Light Power-Flow Diagram for a 2016 State-of-the-Art Warm White Commercial PC-LED Package

Source: Tsao, Coltrin, Crawford, and Simmons, "Solid-State Lighting: An Integrated Human Factors, Technology, and Economic Perspective," July 2010 [96]

The green and red phosphors convert the 0.66 W of blue optical power with an efficiency of 63% into 0.416 W of blue (0.035 W), green (0.087 W), and red (0.294 W) optical power. En route, the phosphors lose 37% or 0.244 W of the initial blue optical power to a combination of IQE losses, a fundamental Stokes deficit, and mixing/scattering/absorption losses. IQE losses occur due to non-radiative recombination of electrons and holes excited in the phosphors. There is a fundamental Stokes deficit due to the lower energies of green and red versus blue photons. Losses also occur as the green, blue, and red photons mix, scatter in, and occasionally get absorbed within the LED package.

Finally, the 0.416 W of white optical power, distributed spectrally in a 20 nm full width at half maximum (FWHM) blue LED band, a 100 nm FWHM green phosphor band, and an 80 nm red phosphor band, yields a lumen output of 137. The maximum LER of white optical power at this CRI (80) and CCT (3000K), when optimally distributed into three or four narrower (less than 20 nm) bands in the blue, green and red, is approximately 414 lm/W. Thus, 0.416 W of white optical power, if spectrally redistributed, could potentially give 175 lumens (0.416 W x 414 lm/W). The spectral efficiency of the LED package is thus 78% (137 out of a maximum of 175 lumens).

Taken together, the current overall LED warm white, state-of-the-art, commercial package efficiency is 33%, and is equal to the product of the blue LED efficiency (66%), phosphor and mixing/scattering/absorption efficiency (63%), and white light spectral efficiency (78%).

These estimates of sub-efficiency breakdowns and overall efficiency roll-ups are for warm white. Historical and current commercial pc-LED efficacies are somewhat higher for cool white because they require a lower optical power fraction of red light, and red light contributes more losses in the pc-LED architecture than either blue or green. The most important loss contribution is its Stokes efficiency loss (25% for the red, in contrast to 15% for the green and 0% for the blue). The second most important loss contribution is the 15% to the white light spectral efficiency loss, because the current 80 nm FWHM-wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive, as discussed in Section 3.3.1.

4.1.2 Pc-LED Architecture: Opportunities and Challenges

As discussed above, the current state-of-the art commercial pc-LED, with a luminous efficacy of approximately 137 lm/W, is about 33% efficient. Because of the fundamental Stokes efficiency loss associated with this architecture, 100% efficiency is not possible. As indicated in Table 4.1 and Table 4.2, even if all other losses were eliminated, the current pc-LED with its current spectral distribution of optical power can at most have a luminous efficacy of approximately 220 lm/W (LER × Stokes losses). This can be improved through improved spectral distribution of optical power, as discussed in more detail below, but it is not likely that all other losses will be eliminated. Thus, a luminous efficacy of 255 lm/W, or an efficiency of 61%, is considered to be the “upper pc-LED potential,” and is indicated as such by the saturation values in Figure 4.4 that are depicted as beginning in years 2020 through 2025.

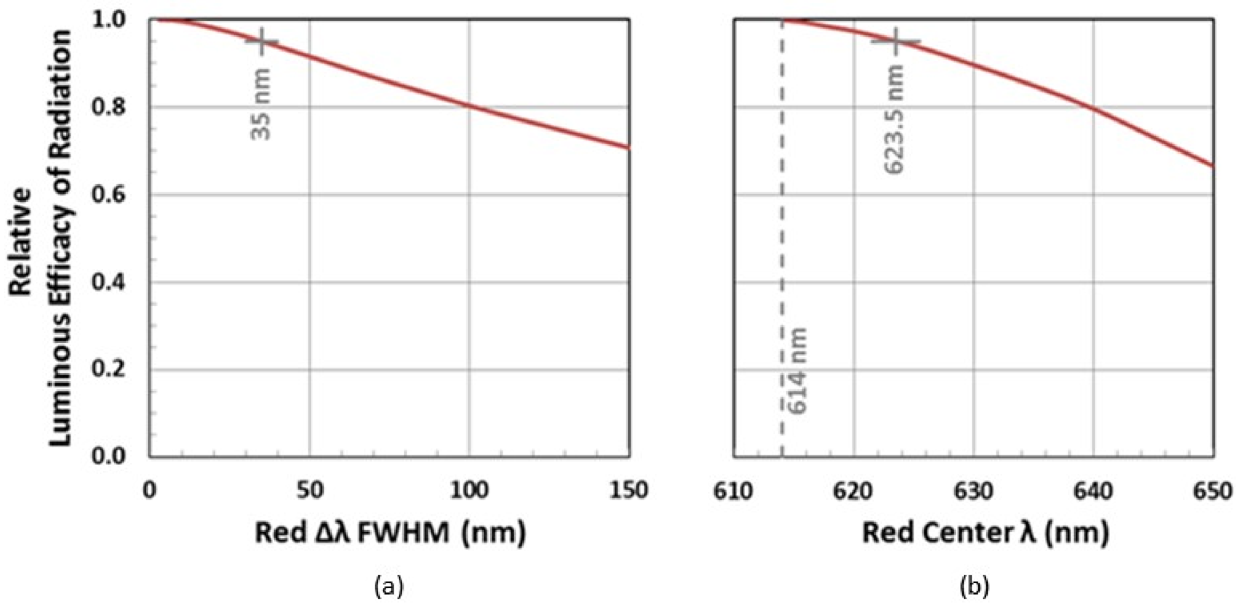
This upper pc-LED potential can be considered approximately equal for warm and cool white. This is because warm white requires a higher optical power fraction of red than blue light, which leads to two offsetting effects. On the one hand, the human eye is more sensitive to red than to blue light, so warm white light will have an intrinsically higher LER than cool white light. On the other hand, in the pc-LED architecture, red light has a higher Stokes deficit than blue light, so warm white light will have an intrinsically lower phosphor plus mixing/scattering/absorption efficiency than cool white light. These effects offset each other, with the net result being approximately similar potential efficacies.

For both warm and cool white, there is significant opportunity: 255 lm/W is considerably higher than the current state-of-the-art for both warm white (137 lm/W) and cool white (168 lm/W) at typical current densities. To achieve such a high luminous efficacy, improvements will be required, ranging from continuing to improve the IQE of the green and red phosphors, modestly narrowing the linewidth of the green phosphor emission to 50 nm FWHM or so, and improving the electrical efficiency of the blue LED. Three particularly important opportunities (and challenges) can be identified, as evidenced in Figure 4.5, Table 4.1, and Table 4.2.

Opportunity/Challenge: Light extraction and mixing/scattering/absorption efficiency improvement. As can be seen from Figure 4.5, Table 4.1 and Table 4.2, a significant fraction (approximately 13%) of blue LED light is not extracted from the blue LED, and an equally significant fraction (approximately 13%) of white (blue, green, and red) light is not extracted from the white light package due to mixing/scattering/ absorption losses. Taken together, minimizing these two loss channels represents a major opportunity for efficiency improvement. For both loss channels, the fundamental challenge is the high refractive indexes of the InGaN semiconductor that emits blue light and of the phosphors and encapsulants that absorb the blue light and mix/scatter the subsequent white light. The combination of high refractive indexes and scattering cause light to be trapped inside the white light package, and the long residence time of the light ultimately leads to optical absorption. Some of that absorption (e.g., blue light by the blue LED, or blue/green/red light by the green/red phosphors) might be recycled by photon re-emission, but most is lost to parasitic absorbers (e.g., metal contacts, interface states, heavily doped radiatively dark semiconductor layers). One challenge is to develop ways in which light can be made to escape from both the blue LED and white light package much faster, preferably during the first pass. Examples of possible solutions include lower refractive index materials, novel micro- and nano-optical shapes or geometries, or coherent or partially coherent directed beams. Another challenge is to develop architectures and materials that minimize parasitic absorbers, or at least the degree to which light interacts with parasitic absorbers.

Opportunity/Challenge: Red downconverter linewidth reduction.

As mentioned earlier, the current 100 nm FWHM wide red phosphor emission linewidth causes a significant spillover of light into the deeper red, where the human eye is less sensitive, and is a significant contributor to the spectral inefficiency of current pc-LED white light. As seen in Figure 4.6(a), relative LER is higher with narrower red linewidth, increasing by 15%, from 80% to 95%, as the linewidth decreases from the current 100 nm FWHM to 35 nm FWHM. It is important to note that the improvement continues as linewidth continues to narrow to even less than 35 nm, with no penalty in color rendering quality. The challenge is thus to develop new red downconverters – phosphors, quantum dots, etc. – with narrower emission linewidths, while maintaining high (greater than 90%) internal radiative quantum efficiency. For on-chip (rather than remote) phosphor applications, robustness at high (85°C) operating temperatures and high impinging optical flux (1 watt per square millimeter, W/mm^2) saturation are also critical. Finally, as narrower linewidth red wavelength downconverters are explored, their center emission wavelength is also important. As can be seen in Figure 4.6(b), relative LER is higher the closer the center emission wavelength is to 614 nm. A center wavelength of 623.5 nm would incur a 5% efficiency penalty, and a center wavelength of 630 nm would incur a 10% efficiency penalty. There have been recent developments in the field of narrow red downconverters. GE continues to release lighting products that feature its narrow red phosphor, “PFS,” under their “Tri-Gain” brand. These lights exhibit excellent color quality and high efficacy due to the narrow red emission spectrum of the phosphor. Similarly, Lumileds has commercialized mid-power LED packages that use its “SLA” phosphor to provide narrow red emission and enable good color quality and high efficacy. More recently, Lumileds has used on-chip quantum dots from Pacific Light Technologies in mid-power LED packages to provide narrow red emission. The quantum dot LEDs have shown acceptable stability in the on-chip configuration and are close to commercialization. While great breakthroughs have been made with narrow red emitters, they still do not demonstrate the necessary stability for application with high brightness LEDs.



Note:

Relative white light LER as the (a) FWHM linewidth of the red phosphor increases, for a given red center wavelength of λ = 614 nm, and (b) red center wavelength increases, for a given FWHM linewidth of Δλ = 7 nm. In both cases, the blue and green linewidths were fixed at 20 nm and 50 nm FWHM, but their center wavelengths were allowed to vary so as to optimize LER while maintaining Ra = 80 and R9 > 0. The 95% efficiency points are indicated: FWHM of 35 nm and center wavelength of 623.5 nm.

Figure 4.6:Relative White-Light Luminous Efficacy of Radiation

Source: Calculations based on White Light Simulator in “Color rendering and luminous efficacy of white LED spectra,” Yoshihiro Ohno, October 2004 [97]

Opportunity/Challenge: Blue LED efficiency droop.
The efficiency of blue LED has improved enormously, but it is still highest at low current densities. The current “best” research has seen LED packages exceed 80% efficiency, but only at relatively low current densities. At the higher current densities desirable for low cost of light to drive higher market penetration, the LED efficiencies decrease. This so-called “efficiency droop” from about 10 A/cm^2 to 35 A/cm^2 is about 10%, and to 100 A/cm^2 is about 15%. The challenge will be to circumvent the key physical mechanism responsible for efficiency droop, Auger recombination. Auger recombination is a non-radiative carrier recombination process which increases nonlinearly with carrier density and hence current density. Possible approaches to circumvent Auger recombination losses include: increasing the rate of competing radiative recombination (either through composition/geometry engineering or through use of alternative recombination mechanisms such as stimulated emission in laser diodes) or decreasing carrier densities (either through band-structure/transport engineering or through alternative geometries such as stacked active regions connected via tunnel junctions). The key to any of these approaches is to understand and control the complex epitaxial materials synthesis process in order to maintain the material quality that has been painstakingly engineered into current LED structures [98].

4.1.3 Emerging Hy-LED Architecture: Status, Opportunities, and Challenges

Hy-LED architecture is the combination of a blue LED, a yellow-green phosphor, and a red LED to produce white light. This is a non-standard but emerging white light architecture. For example, in the Cree TrueWhite and OSRAM Brilliant Mix technologies, greenish-white light (deliberately shifted off the black body curve toward the green) from a pc-LED is mixed with a pure red component from a red LED.

This architecture has a significant efficiency advantage over the more standard pc-LED architecture because the red LED incurs no Stokes deficit in generating red light, and red LEDs have intrinsically narrow linewidths with little spillover into the deep red where the human eye is relatively insensitive. A luminous efficacy of about 280 lm/W, or an efficiency of around 68%, is considered to be the hy-LED upper potential. In contrast, the pc-LED upper potential is only 255 lm/W, and could be closer to 220 lm/W if narrower red phosphor linewidths are not achieved.

However, while the efficiencies can be higher, this architecture also has two major disadvantages, both associated with the current aluminum indium gallium phosphide (AlInGaP) technology used for the red LED. First, the thermal efficiency droop associated with these AlInGaP-based red LEDs is much greater than that associated with InGaN-based blue LEDs. Their very different thermal behavior requires a control system to maintain a consistent color point, which adds complexity and cost to the lighting system. It is expected that tunable-CCT sources, which are of increasing interest for human-centric lighting, will drive down the cost of such control systems, possibly minimizing this disadvantage in the future. Second, AlInGaP-based red LED efficiencies decrease the shorter their red wavelengths, as illustrated in the spectral power densities for various LEDs in Figure 4.7. At 614 nm, which can be considered the ideal red peak for lighting as it is just long enough to provide good color rendering quality but just short enough for good sensitivity by the human eye (reasonably high LER), state-of-the-art research LED external quantum efficiencies (EQE) are only about 25%. Thus, this architecture faces a number of challenges, two of which are the same as those for the pc-LED architecture: light extraction and mixing/scattering/absorption efficiency improvement and blue LED efficiency droop. Most importantly, it faces the challenge of improving the red LED.

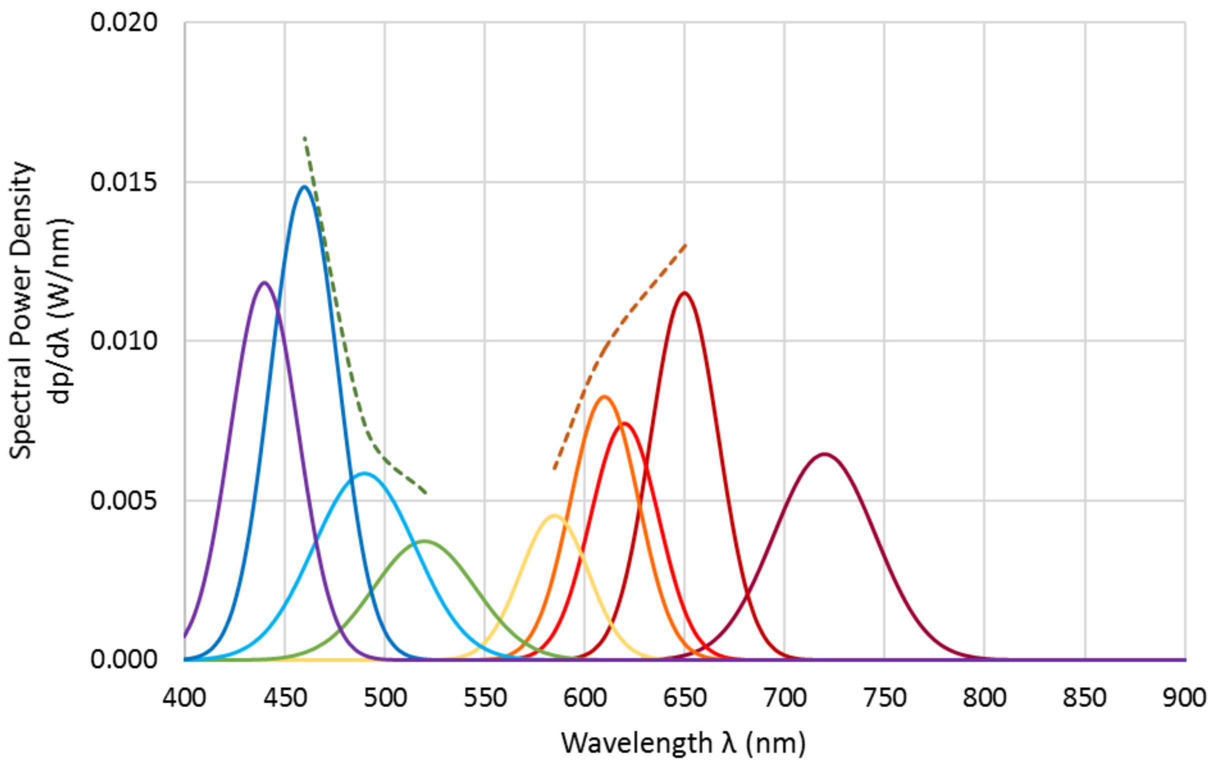


Figure 4.7 Spectral Power Densities of State-of-the-Art Commercial LEDs vs. Wavelength.
Dashed lines are guides to the eye, illustrating the "green gap:" the decrease in efficiency from the blue to the green-yellow and from the red to the green-yellow.

Source: Spectral power densities were calculated from the efficiencies, center wavelengths and spectral widths given in Lumileds LUXEON Rebel Color Line Product Datasheet, 2017 [99]

Opportunity/Challenge: Red LED efficiency improvement.
This is an important but tough challenge. Replacing even an ideal narrow linewidth red phosphor in a pc-LED architecture with a high-efficiency red LED at 614 nm in a hy-LED architecture would enable approximately 10% improvement, and replacing a non-ideal wide-linewidth red phosphor in a pc-LED architecture would enable approximately 25% improvement. The key challenge is to overcome what appear to be fundamental limits associated with AlInGaP materials: an unfavorable band structure in the shallow red both for carrier transport/confinement and radiative carrier recombination (due to a direct to indirect bandgap crossover). A novel variant of AlInGaP, or a different material system entirely (e.g., InGaN), may provide a solution. The full exploitation of composition and band-structure engineering in semiconductor materials is often limited by strain issues associated with lattice mismatches to common substrates; however, recent research breakthroughs may have overcome these issues including metamorphic epitaxy (in which strain-induced defects are minimized through gradual shifting of lattice constants) and nano-compliancy (in which strain is accommodated through nano-geometries). SSL would benefit from more complete understanding of these research breakthroughs and their application to red LEDs. The development of novel substrates that are lattice-matched to material compositions of interest for 614 nm red LED emission may also reap benefits.

4.1.4 Hypothetical RYGB CM-LED Architecture: Opportunities and Challenges

The four-color RYGB cm-LED architecture, in which all colors are generated by direct LEDs, can be considered the ultimate embodiment for white light architecture. There would be no wavelength down-conversion, and therefore no phosphor conversion or Stokes losses. As indicated by the dashed grey line in Figure 4.4, its ultimate upper potential might be on the order of 330 lm/W, limited only by the anticipated 80% to 90% efficiencies of the LEDs themselves and for the losses when mixing of their pure source colors to create white light. Note, this is a classic case of the “disruptive” innovations discussed by Clayton Christensen in “*The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*” [100]. From steel minimills to personal computers to cellular telephones, a technology that is currently inferior develops slowly at first. Eventually, because of its better *long-term* potential, it emerges as the “winning” technology. This of course does not always happen, but when it does it can be transformative. In our case, the cm-LED architecture currently has lower performance than the current dominant pc-LED architecture, but has the potential in future years to leapfrog well beyond.

There are various cm-LED possibilities that can be considered: three-color red, green and blue (RGB); four-color RYGB (or RGBA); and perhaps even five-color RYGCB. This section looks at four-color RYGB, because it gives higher ultimate efficiency, better color rendering, and more flexibility for chromaticity tuning and hence for smart lighting (and implications for human comfort, health, and productivity) than three-color RGB. Five colors are not considered, as a fifth color adds only negligibly to efficiency, color rendering quality, and chromaticity tuning flexibility.

This architecture can be considered somewhat hypothetical. Though there are specialty products that make use of this architecture, the low efficiencies of green and amber LED sources and thermal stability of red and amber AlInGaP-based LED sources limit their performance. In particular, the green and amber LEDs, with ideal wavelengths at approximately 540 nm and 575 nm respectively, are right in the middle of the so-called “green gap.” Efficiency reduces as the green emission wavelengths are approached, both from the short wavelength and long wavelength sides. While performance of InGaN-based blue and violet LEDs has advanced rapidly over the past couple of decades with IQEs at low current densities now approaching 95%, increasing the Indium composition to provide emission in the green spectral region results in a rapid reduction in efficiency. For example, shifting the wavelength from 450 nm (blue) to 500 nm (cyan) results in a halving of power conversion efficiency (PCE); a further shift to 525 nm results in an additional halving.

Opportunity/Challenge: Green/Amber LED efficiency improvement.
The realization of efficient LEDs in the green gap (e.g., green and amber) is a key technical challenge, and solutions have been elusive. Mounting evidence suggests that performance of green LEDs is limited by efficiency droop, just like in blue LEDs, caused by Auger recombination. Therefore, fundamental research in

droop mitigation strategies should benefit both blue and green LEDs [81]. Another issue to be resolved is the strain associated lattice mismatches between InGaN (with a high enough indium fraction to emit in the green and amber) and common substrates. It may be possible to leverage research breakthroughs for longer wavelength InGaN LEDs (e.g., metamorphic epitaxy and nano-compliancy). If InGaN could be made to emit efficiently in the red, then green and amber performance should benefit as well. Moreover, there is evidence that the low efficiency of green LEDs is in large part because efficiency droop is more pronounced in the green than in the blue. Therefore, improved understanding of droop and ways to circumvent it in the blue might have broader ramifications to the green.

The efficiency of wavelength downconverted amber LEDs are significantly higher than those of direct amber LEDs, even after accounting for the additional Stokes losses associated with wavelength down-conversion. This shows that the development of efficient narrow band downconverter material when combined with very high PCE blue InGaN LEDs would be an important intermediate step toward a cm-LED approach to white lighting. Table 4.1 presents a summary of the different sub-efficiencies for blue, green, amber, and red light sources (both phosphor converted and direct emitter if applicable).

Table 4.1 Present and Future Target Sub-Efficiencies for Blue, Green, Amber, and Red Light Sources, with Estimated Package (Optical Mixing/Scattering/Absorption) Efficiency for White Light Package

Properties of colored sources and their mixing to produce white light				Units	Present 2016	Future (Targets) 2018	2020	2025	Goal
Blue Source	LED or LD	Efficiencies	Electrical efficiency		0.96	0.97	0.98	0.98	0.98
			Internal quantum efficiency at 0 A/cm2		0.88	0.91	0.94	0.97	0.98
			Efficiency droop at 35 A/cm2		0.90	0.93	0.96	0.98	0.99
			Extraction efficiency		0.87	0.89	0.90	0.92	0.95
			LED efficiency	WPE	0.66	0.73	0.80	0.86	0.90
		Spectral Properties	Wavelength (center)	nm	459	459	459	459	459
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	43	43	43	43	43
Green Sources	LED or LD	Efficiencies	LED efficiency	WPE	0.26	0.33	0.39	0.50	0.86
		Spectral Properties	Wavelength (Center)	nm	530	535	540	540	540
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	566	602	630	630	630
	Phosphor	Efficiencies	Internal quantum efficiency		0.98	0.98	0.98	0.98	0.98
			Stokes efficiency		0.85	0.85	0.85	0.85	0.85
			Phosphor efficiency		0.83	0.83	0.83	0.83	0.83
		Spectral Properties	Wavelength (center)	nm	540	540	540	540	540
			Wavelength (FWHM)	nm	100	80	70	50	50
			Luminous efficacy of radiation	lm/W	486	486	499	552	552
Amber Source	LED or LD	Efficiencies	LED efficiency	WPE	0.08	0.15	0.22	0.25	0.86
		Spectral Properties	Wavelength (Center)	nm	587	575	575	575	575
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	534	611	611	611	611
Red Sources	LED or LD	Efficiencies	LED efficiency	WPE	0.44	0.50	0.60	0.65	0.86
		Spectral Properties	Wavelength (Center)	nm	615	615	615	615	615
			Wavelength (FWHM)	nm	20	20	20	20	20
			Luminous efficacy of radiation	lm/W	304	304	304	304	304
	Phosphor	Efficiencies	Internal quantum efficiency		0.90	0.93	0.95	0.95	0.95
			Stokes efficiency		0.75	0.75	0.75	0.75	0.75
			Phosphor efficiency		0.68	0.69	0.71	0.71	0.71
		Spectral Properties	Wavelength (center)	nm	612	615	615	615	615
			Wavelength (FWHM)	nm	80	60	30	30	30
			Luminous efficacy of radiation	lm/W	313	314	308	304	304
Package (optical mixing/scattering/absorption) efficiency					0.87	0.89	0.90	0.93	0.95

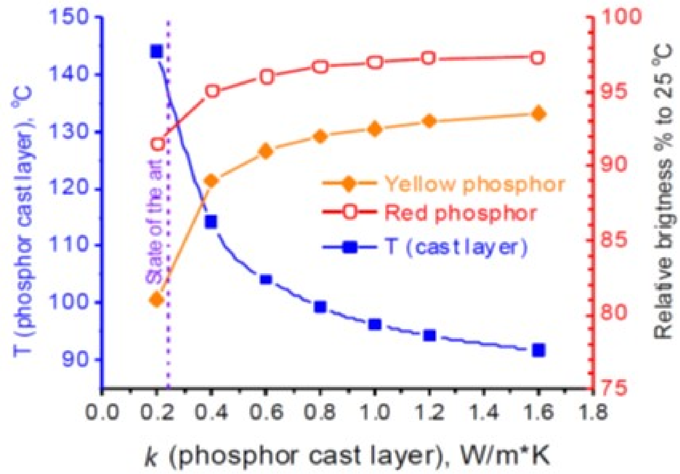
Table 4.2 Present and Future Target Rolled-Up Efficiencies for White Light Packages
for the Three White Light Architectures: Pc-LED, Hy-LED, RGBA Cm-LED Rolled-Up Efficiencies Are Based on the Sub-Efficiencies Listed in Table 4.1

Properties and effiacies of white light produced by package				Units	Present	Future (Targets)			
					2016	2018	2020	2025	Goal
Warm White: CCT=3000, R_a~80, R_9>0	Phosphor Converted PC-LED	Source power fractions of white	Blue		0.08	0.09	0.10	0.12	0.12
			Green		0.21	0.36	0.45	0.42	0.42
			Red		0.71	0.55	0.45	0.47	0.47
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	256	281	300	306	306
			LER (spectral losses)	lm/W	323	354	372	381	381
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	137	175	208	237	255
		White Efficiencies	Source (no Stokes)		0.53	0.62	0.69	0.77	0.83
			Stokes		0.79	0.79	0.81	0.80	0.80
			Spectral		0.78	0.85	0.90	0.92	0.92
			Actual		0.33	0.42	0.50	0.57	0.61
	Hybrid HY-LED	Source power fractions of white	Blue		0.09	0.09	0.09	0.12	0.12
			Green		0.49	0.49	0.48	0.42	0.42
			Red		0.42	0.42	0.43	0.47	0.47
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	335	335	337	343	343
			LER (spectral losses)	lm/W	374	374	376	381	381
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	166	189	215	243	285
		White Efficiencies	Source (no Stokes)		0.49	0.56	0.64	0.71	0.83
			Stokes		0.90	0.90	0.90	0.90	0.90
			Spectral		0.90	0.90	0.91	0.92	0.92
			Actual		0.40	0.46	0.52	0.59	0.69
	Hypothetical Color Mixed RGBA CM-LED	Source power fractions of white	Blue		0.13	0.14	0.14	0.14	0.14
			Green		0.29	0.24	0.27	0.27	0.27
			Amber		0.20	0.20	0.15	0.15	0.15
			Red		0.38	0.42	0.44	0.44	0.44
		White Luminous Efficacies	Fundamental (Stokes+spectral losses)	lm/W	390	400	400	400	400
			LER (spectral losses)	lm/W	390	400	400	400	400
			Max LER (no losses)	lm/W	414	414	414	414	414
			Actual (source+Stokes+spectral losses)	lm/W	92	119	154	186	327
		White Efficiencies	Source (no Stokes)		0.23	0.30	0.39	0.46	0.82
			Stokes		1.00	1.00	1.00	1.00	1.00
			Spectral		0.94	0.97	0.97	0.97	0.97
			Actual		0.22	0.29	0.37	0.45	0.79

4.1.5 LED Package Encapsulation

The performance of pc-LEDs depends not only on the LED emitter, but also on the rest of the packaging materials. The properties of the encapsulant impact the resulting thermal and optical properties of the LED package. The low thermal conductivity of current silicone encapsulants can lead to heating of phosphor particles and rapid degradation of conversion efficiency when the LED is driven under high current conditions. The Stokes losses from the conversion of blue light to white results in 20% to 30% of the absorbed energy to be lost as heat. The resulting heat from the phosphor particle reduces its efficiency if it cannot be conducted away. The silicone encapsulant has a thermal conductivity of approximately 0.2 watts per meter kelvin (W/mK), which is not sufficient to conductor the heat from the phosphor. This results in a higher phosphor temperature and lower efficiency. Increasing the thermal conductivity to 1 W/mK can lower the phosphor layer temperature by 50°C or more, which can lead to phosphor efficiency improvements of 10% or more during standard operating conductions of the LED package, as seen in Figure 4.8.

(a)



(b)

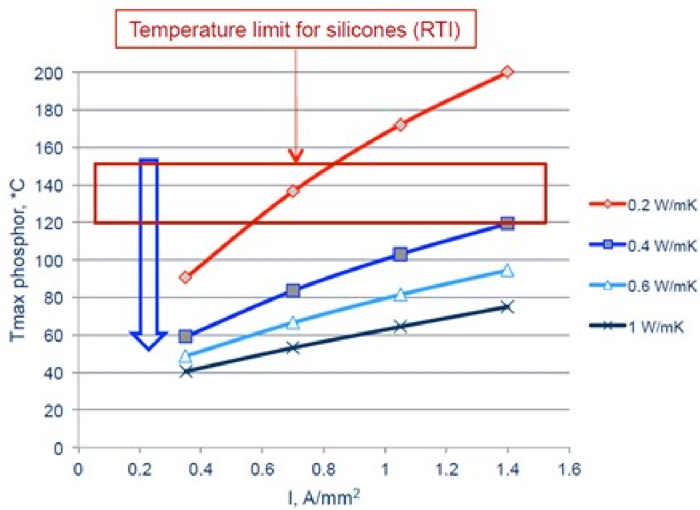


Figure 4.8 (a) The temperature of the phosphor layer as a function of thermal conductivity and the impact to the relative brightness of LED phosphors and (b) the temperature of the phosphor layer decreases with increasing thermal conducivity of the encapsulant.

Source: Michael Bockstaller, Carnegie Mellon University, SSL R&D Workshop, Raleigh, NC, February 2016 [101]. Figures courtesy of OSRAM Sylvania

Increasing the refractive index of LED encapsulants can also improve the light extraction out of the package, thereby leading to higher efficiencies. The higher the refractive index, the more light can be coupled from the chip. Methods to increase the refractive index involve adding more phenyl end groups to the silicone molecular backbone (phenyl-based chemistry) compared to the methyl-based silicones. The methyl silicones used in blue LED packages have a refractive index of 1.4; phenyl silicones commonly used in white pc-LED packages have a refractive index of 1.55. There is a practical limit to adding phenyl end groups; when too much phenyl content is added the stability of the silicone decreases under LED optical flux densities and temperatures, essentially creating an upper limit at the 1.55 refractive index available today [102]. Adding high refractive index nano-fillers such as titania or zirconia have potential, though their integration into the polymer chains is critical for performance and is still an area of intense research.

Opportunity/Challenge: High thermal conductivity and refractive index encapsulants.
The poor thermal conductivity in silicone encapsulants presents an opportunity to improve the resulting pc-LED efficiency by reducing the thermal droop in the phosphor particles and even in the LED emitter. Progress in improving thermal conductivity has been slow. Thermal transport of hybrid materials (e.g., high thermal conductivity additives in a silicone resin) presents an opportunity for improvement through engineering the thermal conductance of the polymer/particle matrix. Reducing the scattering cross-section of particle fillers can enable higher optical transparency at higher inorganic loading. Moving this concept to the extreme by using inorganic encapsulants, such as low melting point glasses, is another potential path towards improving refractive index and thermal stability.

4.1.6 Overall Conclusions and Future Prospects

Comparing the pc-LED, hy-LED and cm-LED architectures (as shown in Table 4.2), the following conclusions can be drawn:

- The pc-LED architecture has room for further improvement from the current status of approximately 140 lm/W to a potential of 255 lm/W. This may be accomplished by improving optical light extraction and package efficiencies from approximately 75% to 95%, narrowing the red phosphor emission linewidth to about 35 nm FWHM, and reducing blue LED efficiency droop from 10% to 20% down to 5% (in the 35-100 A/cm^2 range).

- The hy-LED architecture has somewhat more room for improvement, from the current status of approximately 160 lm/W to a potential of 280 lm/W, but with additional difficult challenges: improving the efficiency (from approximately 20% to 80%) and thermal stability of the red LED at the 614 nm wavelength range that is ideal for white lighting.

- The cm-LED architecture has the most room for improvement, from the current status of 90 lm/W to a potential of 330 lm/W, but with the addition of the most difficult challenge: improving the efficiency of the green, amber *and* red LEDs.

As the future unfolds, performance characteristics are anticipated to become more demanding, which will have implications on which white light architecture is preferred, and for the relative importance of different routes for improving efficiency.

First, baseline current densities of 35 A/cm^2 and operating temperatures of 25°C are somewhat arbitrary. In practice, the higher the operating temperature that can be tolerated, the higher the allowable current density; and the higher the current density, the lower the cost of light (with both of these relationships mediated by current efficiency and thermal efficiency droop). Operating current densities of 100 A/cm^2 and higher and operating temperatures of 85°C and higher, are both desirable.

Second, as more is learned about the influence of light on humans and human productivity, various spectral characteristics of light may become more important. Higher color rendering quality as measured by CRI may become more significant. Many applications already demand CRI 90 over CRI 80. Other spectral features, including those discussed above in conjunction with the new IES TM-30 guidelines, may need to be controlled.

Progress toward either high efficiency-high current density, or low cost will help to improve all of these attributes. Efficiency improvement is perhaps the most key, as it increases lumen output per package (and thus decreases cost per lumen) and decreases the waste heat that must be removed (which in turn decreases package cost and decreases cost per lumen indirectly). As current density increases so does lumen output per LED, and thus decreases cost per lumen. Achieving low cost will create margin for more complex device designs for higher efficiency or current density.

4.2 LED Luminaire Technology

While the LED package is at the heart of the overall system that produces and delivers white light to the environment and ultimately to the human user, it is surrounded on either side (input and output) by components that collectively make up the luminaire. In this section, these components are discussed, along with their impact on the efficiency of the overall white light production and delivery system.

4.2.1 Luminaire Light Production Efficiency: Progress, Opportunities, Challenges

The white light production efficiency of an LED luminaire can only be as high as the efficiency of the LED package. The other pieces of the luminaire – the power supply and electrical driver on the front end, the mechanical and thermal-management structure, and the optical diffusing and/or directing on the back end – can only contribute additional losses. Progress in (and future targets for) the various efficiencies associated with these pieces of the luminaire, i.e., the driver efficiency, the luminous efficacy of the LED package at room temperature (25°C), thermal efficiency droop due to higher operating temperature (85°C), and the fixture (optical) efficiency, are indicated in Table 4.3.

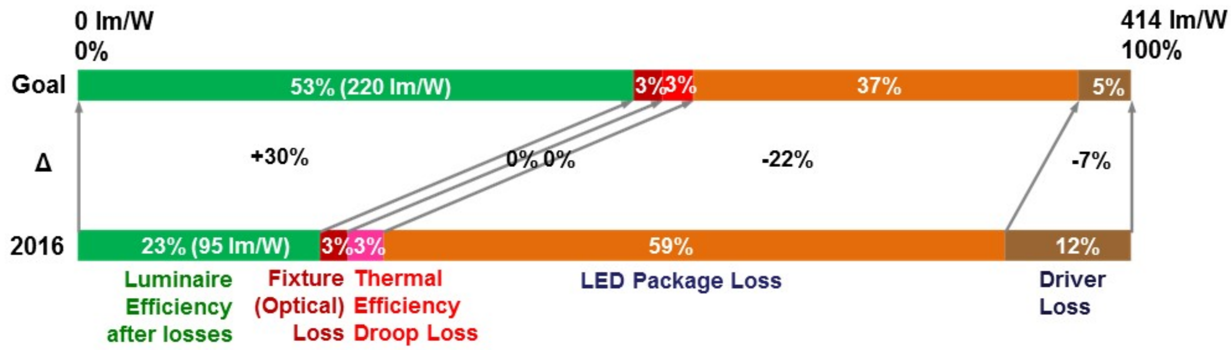
Table 4.3 Breakdown of Warm-White* LED Luminaire Efficiency Projections.
Package Luminous Efficacies Are Based on the Rolled-Up Efficiencies Listed in Table 4.2.

Efficiency Channel	2016	2018	2020	2025	Goal
Package Efficacy Projection** (lm/W)	137	175	208	237	255
Thermal Efficiency Droop (increased T_{op})	88%	91%	93%	95%	95%
Driver Efficiency	88%	91%	93%	95%	95%
Fixture/Optical Efficiency	90%	92%	94%	95%	95%
Overall Luminaire Efficiency	70%	76%	81%	86%	86%
Luminaire Efficacy† (lm/W)	95	133	169	203	218

* Warm-white packages and luminaires have CCT=3000K and CRI=80.
** Package efficacy projections are for the warm-white pc-LED, per Table 4.2
† Luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.

Table 4.3 estimates best case efficiencies, not average efficiencies. In any particular application, they may not be achievable. There is a wide range of lighting applications, and the luminaire is the final custom element that tailors how the white light fits into the application, resulting in a wide range of luminaire types. The brightness, size, direction, and diffuseness of the final beam; the aesthetics, shape, size, and cost of the fixture and overall luminaire; and the environment with which the luminaire must be compatible and integrate are considerations that lead to a much wider proliferation of luminaire types than of LED package types. In addition, many luminaires use LED packages operated at current densities below 35 A/cm^2, so the efficacy of the package can be higher than the levels described in both Table 4.2 and Table 4.3. These factors create a range of varying efficiency levels that roll up into a large range of product performance levels.

Moreover, the market is also in the middle of an important transition from luminaires intended for use with lamps, to those designed around LED packages. A steady growth in the use of integrated LED luminaires is anticipated, due to the efficiency and performance benefits that cannot be achieved in legacy lamp form factors.



Note:

From right to left, the percentage losses incurred from various channels in the conversion of electricity to visible light for commercial state-of-the-art luminaires, with the final percentage of the original electricity converted to visible light in green at the left. The 100% mark corresponds to an approximate theoretical maximum LER of 414 lm/W. The lower bar is current 2016, the upper bar is long-term goal, performance, the Δ's in the middle are the percentage changes due to potential improvements of the various channels. The improvement in the LED package is based on the rolled-up efficiencies listed in Table 4.2.

Figure 4.9 Losses Incurred in the Conversion of Electricity to Visible Light

The opportunities for improved efficiencies associated with luminaire components are indicated in Figure 4.9. Following the figure, two priority R&D opportunities are discussed, with an emphasis on integrated luminaires.

Opportunity/Challenge: Electrical Driver.

On the front end is the power supply that converts alternating current (AC) line power to a voltage and current compatible with the LED packages, and may incorporate such control functions as dimmability. A variety of driver configurations accommodate different numbers of LED packages, varied circuit architectures, and various voltage levels of either AC or DC input. The various driver topologies and LED drive schemes, functionality, size, and cost will dictate the exact performance of the driver. Table 4.3 provides a representative driver efficiency, though some topologies today show higher performance and some show worse. Perhaps the weakest feature of drivers is not performance, but reliability. Driver reliability is the weakest link among all components in the luminaire. A significant opportunity/challenge is to improve reliability of the driver, including fundamental reliability limitations of many of the subcomponents of this driver. There is also an opportunity to improve driver performance in terms of efficiency and flicker while the driver is operating at a dimmed setting. There is the further opportunity to embed additional control and communication functionality within the driver to enhance energy savings and functionality of the luminaire. An additional level of control could be the ability to better address and control individual strings of LEDs while maintaining a compact form factor and low cost.

On the back end of the light generation process is the mechanical, thermal management, and optical structures that are used to integrate LED packages into the larger luminaire. The optimized integration of the full luminaire, taking into consideration electrical, thermal, and optical integration, while also creating new value within a specific lighting application and saving energy, is a bigger picture opportunity/challenge. This opportunity/challenge encompasses many of the preceding topics and is identified as a priority research topic.

With respect to thermal management, unlike traditional incandescent lamps, LED sources do not radiate heat, so any heat generated by inefficiencies must be dissipated through conduction in the luminaire itself. The operating current of the LED package and the ambient temperature then determine the operating temperature of the LED package. As illustrated in Figure 4.2(b), thermal efficiency droop represents the drop-in efficiency of the LED as it is operated at an elevated temperature. Improved thermal handling and/or reduced operating current will result in a lower operating temperature of the LED and, in turn, higher LED efficiency. Luminaire developers have found that removing thermal interfaces within the luminaire thermal path can improve the thermal handling of the luminaire and improve LED efficiency.

With respect to optical efficiency, the optical system in the luminaire can make use of many permutations of lenses, reflectors, optical mixing chambers, remote phosphors, and diffusers, depending on the lighting application, the desired optical distribution, and the form factor of the lighting product. Well-designed luminaires in certain applications can experience less than 10% optical losses, and new approaches may reduce this further. In general, the fewer and smaller the LED packages with smaller etendue, the more efficient the optical system can be. In the limit of laser diodes, optical systems that are extremely efficient, as well as novel (e.g., the possibility of ultra-thin edge-lit waveguide geometries), can be envisioned.

Although much of the focus in luminaire development has been for pc-LED architectures, extremely good performance has been demonstrated for hy-LED architectures. In 2013, Philips announced the realization of a prototype 200 lm/W tubular LED (TLED) lamp with CCT in the 3000K to 4500K range, with CRI and R_9 greater than 80 and 20, respectively [103]. In 2014, Cree announced a 3,200 lumen concept luminaire delivering in excess of 200 lm/W at 80 CRI at thermal equilibrium while remaining within the American National Standards Institute (ANSI) color specification for 3000K [104]. Also in 2014, OSRAM announced a prototype 3,900 lm LED tube similar to Philips' but with an efficacy of 215 lm/W, or 205 lm/W when combined with a control unit, at 3000K and a CRI of 90 [105]. These R&D prototypes meet the 2020 target shown in Table 4.2 and demonstrate that significantly better performance can be obtained through careful system optimization of a holistic design approach. The use of red LEDs does increase cost and create system complexities in terms of color stability with temperature and time and for design of the power supply. So, while initial prototypes demonstrate the promise of the approach, practical barriers remain.

Opportunity/Challenge: Integration of LED luminaire functionality.
An emerging opportunity/challenge is the integration of existing and new luminaire functionality into smaller and lighter form factors, perhaps pushing some functionality down into the LED package. Sensors are one such functionality. With the advent of connected lighting, lighting fixtures may well become the most ubiquitous grid-connected "thing," and the use of the IoT for environmental control (including lighting control) will require sensors of all types. Programmable directionality is another such functionality. As discussed in the next section, there is room for improvement with respect to how the light is used, and controlled placement of light would enable significant advance in that efficiency.

Optical beam shaping is another functionality. Some street light designs have integrated specific lens functionality into the primary optic/encapsulant of the LED package, thereby removing the secondary optic and eliminating optical losses at the additional interfaces. The electrical driver is another such functionality, and there is even the possibility of monolithic integration of GaN-based drive electronics with GaN-based LEDs. Finally, simply making luminaires small may enable greater flexibility and density of luminaire placement, which in turn will enable lighting architects to more flexibly control lighting scenes and provide denser geographic coverage of sensors.

4.2.2 Luminaire Light Distribution

After light is produced by the luminaire, light must be delivered to the environment and ultimately to the user. Whereas the previous section discussed the light production efficiency, this section focuses on the application efficiency with which light is used, with a focus on spatial engineering and distribution of the light.

In an absolute sense, the "spatial" efficiency with which electric light is used is exceedingly low. In typical use, the fraction of photons leaving a lamp that finally strike the retina of a human eye is likely less than one millionth, even in an enclosed space such as an office. The loss factors include less than 100% reflectance of non-white objects being illuminated, the small entrance aperture and field of view of the human eye relative to the area and solid angle of the illuminated space, and less than 100% of the time rooms (or portions of rooms) are occupied or viewable while illuminated.

It is not possible to eliminate all of these loss factors. However, the ability to dynamically control the light distribution or "beam" from a fixture would help building users to reduce these loss factors, as well as to change and repurpose a space quickly and with ease. In building environments where the use of a given space is not the same over the course of a year, e.g., retail displays, it can be costly and time consuming to redesign the lighting in the space. Installation of variable beam angle light fixtures is challenging and requires setting up motorized gimbals, which are challenging to control remotely and are heavy to install in the ceiling. The ability to remotely control the direction and light distribution from the fixture in a compact, lightweight form factor would greatly improve the use of building spaces in certain sectors such as retail and hospitality. The following discussion includes five examples of technologies being explored for the spatial engineering of light.

A first example of a beam control technology is the OSRAM OmniPoint concept, a remotely manageable lighting system (luminaire, driver, and software application) that enables users to instantly shape the light output (i.e., beam angle, direction, distribution, shape, and intensity) with a touch screen wireless interface. As shown in Figure 4.10(a), the luminaire consists of an array of individually controlled LEDs aiming out of a small aperture, which allows one luminaire to serve as ambient and/or accent light for a space on demand. The user interface, shown in Figure 4.10(b), allows users to select portions of the space for ambient or accent lighting, as well as to control lighting intensity. This offers significant improvement over traditional lighting systems that would require manually adjusting multiple fixtures on the ceiling [106].

(a) (b)

Figure 4.10 The (a) OSRAM OmniPoint Luminaire and (b) User Interface

Source: Jerry Ryu, OSRAM Sylvania, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [106]

While the Omnipoint is a key demonstration on what is possible with a flexible luminaire design, it uses a large number of LEDs oriented in different directions that are simply turned on and off depending on the light distribution requirement. This requires using numerous LED packages and control channels, which adds to the system cost and complexity. An optical beam control technology that can easily change the beam orientation, size and shape is desirable. Several areas of research in different technologies address this need – from microelectromechanical systems (MEMS) to liquid crystal and liquid lenses and beyond into metamaterials.

A second example of beam control technology is liquid crystal lenses, which align the liquid crystal molecules in a shaped electric field to create a variable refractive index over the flat lens surface. These liquid crystal molecules have a different refractive index in different orientations (along the long axis and short axis). As the electric field is applied to the molecules, they orient and result in a variable refractive index gradient across the surface to match the electric field strength gradient. Figure 4.11 shows a schematic of the liquid crystal lens.

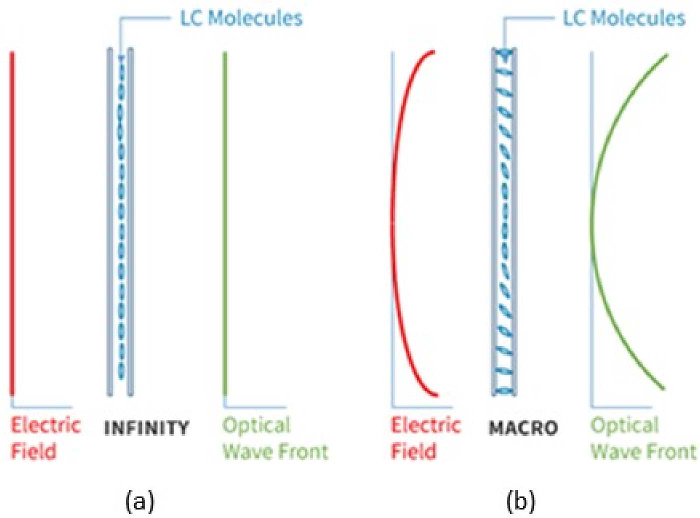


Figure 4.11 Schematic of Liquid Crystal Lens and the Impact on an Optical Wave Front
from an Electrical Field of (a) Constant Gradient, and (b) Variable Gradient

Source: LensVector, How it Works, 2017 [107]

A third example of beam control technology is electrowetting, another method to change the shape of a lens by applying an electric field to shape a liquid interface. A planar liquid lens is created by enclosing two immiscible liquids between two plates to form a lens cell, as illustrated in Figure 4.12. A non-polar oil is immersed in an actuating liquid such as water, and is surrounded by ring-shaped electrodes covered by a hydrophobic layer. When a voltage is applied across the electrode, it induces a change in the contact angle for the fluid on the surface resulting in a change in shape of the oil droplet that forms the lens. The focal length of the lens varies with the different oil dimensions. The challenge with electrowetting is creating a cell large enough for beam steering in an LED luminaire.

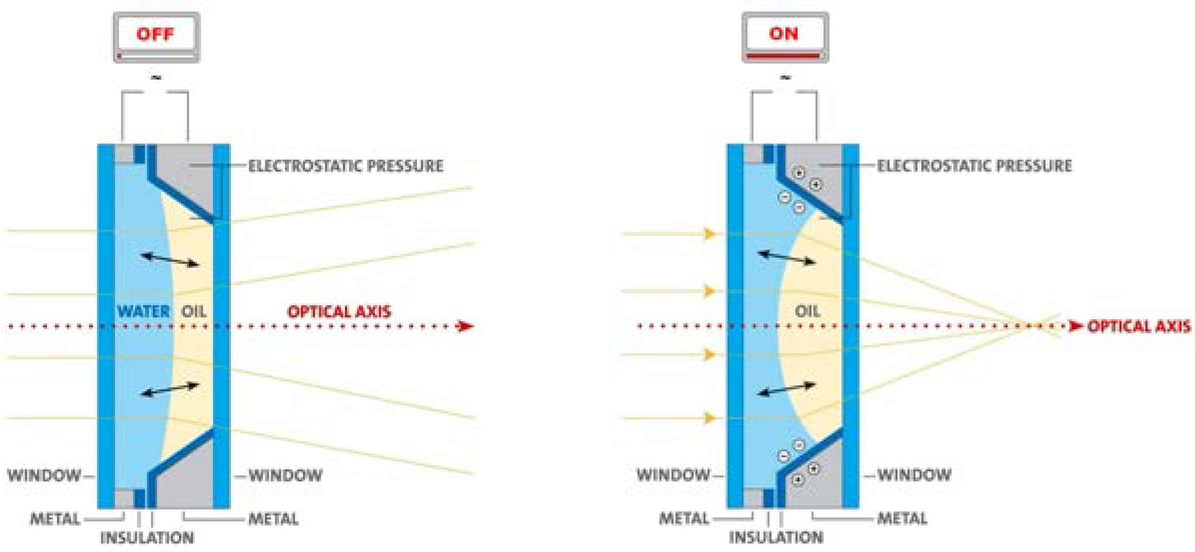
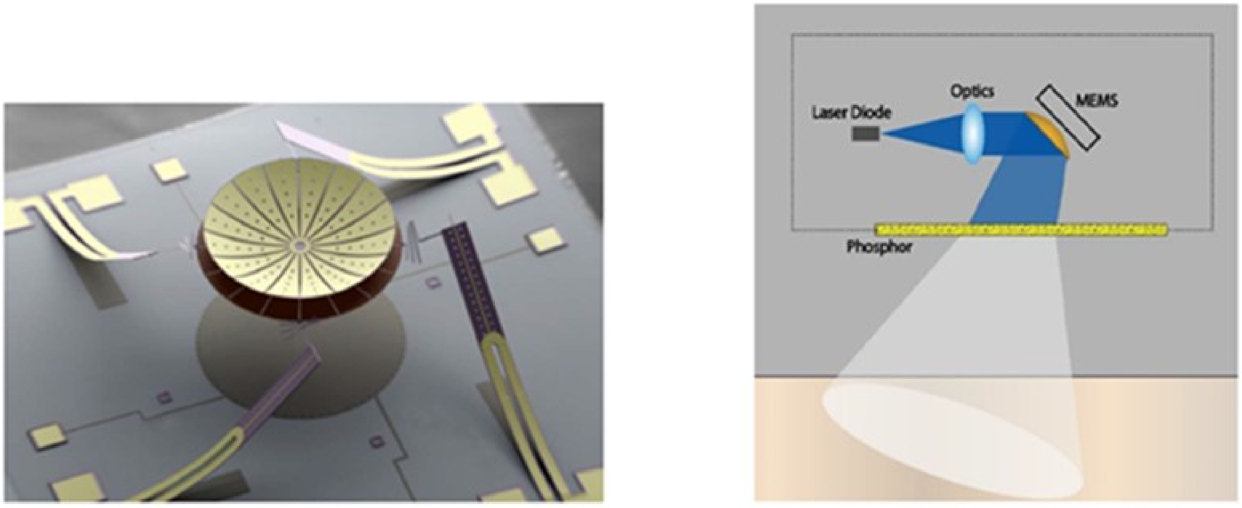


Figure 4.12 Illustration of Liquid Lens Operation via Electrowetting

Source: Varioptic, Liquid Lens for Auto Focus [108]

A fourth example of beam control technology is controllable micromirrors based on standard MEMS manufacturing processes that electronically adjusts the beam position and profile in a package that is 10x smaller than existing mechanical adjustment systems. A MEMS based mirror can provide a directionality that spans up to 80° and can be adjusted in milliseconds. Some of the challenges are the system integration of a MEMS micromirror package and achieving a sufficiently low cost. Figure 4.13 shows an image of a fabricated micromirror and a schematic of integration into a lighting system to provide beam steering.



(a) (b)

Figure 4.13 (a) MEMS Micromirror, and (b) Schematic of the Use of a MEMS Micromirror in a Lighting System

Sources: (a) David Bishop, Boston University, DOE SSL R&D Roundtable, Washington, DC, September 2015 [109], and (b) Helux Lighting

A fifth example of beam control technology is metamaterials, an emerging area of research with exciting possibilities. The introduction of dielectric metamaterials and metasurfaces for the development of embedded optics could allow for control of directionality and extraction efficiency through controlled, coherent light scattering with lower optical absorption losses than associated with more traditional metal-based metamaterials. Metalenses with variable focus or conformal lenses have potential to lead to new dynamic beam steering capabilities with LED lighting. Assemblies of light emitters and metamaterials could provide monolithic devices with embedded optical control. More research is needed to find materials that exhibit a high refractive index, as optical metamaterial research is new and has been focused on applications outside of the visible spectrum.

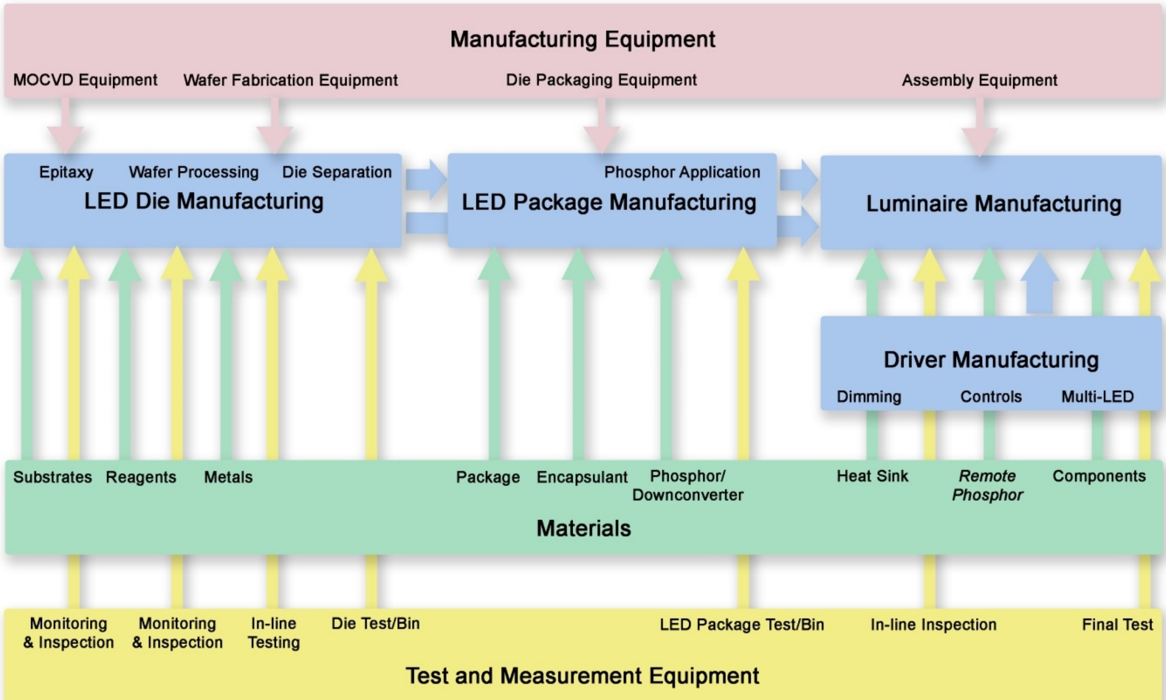
These examples are an indication of the directions in research for new dynamic beam control technologies. Successful dynamic beam control and spatial engineering of light will provide powerful lighting options for improved application efficiency and productivity, including flexible building spaces with low infrastructure costs.

4.3 Manufacturing Technology Status

4.3.1 Supply Chain Outline

Understanding and managing the manufacturing supply chain is critical to the success of any manufacturing operation. In a general sense, the LED manufacturing processes can be defined by a sequence of relatively independent manufacturing steps. These steps are supported by the supply of manufacturing equipment, materials, and testing equipment. The combination of the manufacturing processes, equipment, materials, and testing constitute the manufacturing supply chain.

The supply chain shown in Figure 4.14 represents the current situation for LED-based SSL manufacturing, but the supply chain is ever-changing and will continue to evolve and mature. For example, a vertically integrated manufacturer might currently handle some of these processes internally; however, as the manufacturing industry matures, it is common for the supply chain to become more disaggregated for optimum manufacturing efficiency. In addition, the manufacturing supply chain will be affected by developments in technology and product design, as well as by product distribution, including geographical or regulatory considerations.



Note:

The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow as indicated by the relevant arrows.

Figure 4.14 LED-Based SSL Manufacturing Supply Chain

The manufacturing process for LED-based luminaires begins with LED die manufacturing, consisting of growth of the LED wafer by MOCVD, processing of the LED wafer by mostly conventional semiconductor processes, and separation of the LED wafer into individual LED chips. The next step is typically to mount the LED die into LED packages, including the deposition of phosphor material to convert the blue LED emission to white light. Finally, the LED packages are integrated with a driver, heat sink, optical components, and mechanical elements to form the end luminaire or lamp product. The manufacturing process is constantly evolving as individual elements are refined or removed, new elements are developed, or new process sequences are introduced. Ultimately the optimum process flow for a particular product will depend on a detailed system-level optimization.

4.3.2 LED Package Manufacturing

Manufacturing Methods

The LED die manufacturing process comprises epitaxial growth of the active device layers on the substrate, processing of the semiconductor wafer to define individual devices, dicing of the wafer to produce individual die, and mounting of the resulting die in packages that provide mechanical support along with thermal and electrical contacts.

The LED package no longer is the dominant cost element within the LED-based luminaire; it represents a smaller fraction of the cost, from approximately 18% in a replacement lamp to 7% or less in an LED indoor or outdoor fixture. Efforts to reduce costs while continuing to improve performance will require concerted action throughout the manufacturing supply chain, including higher quality and lower cost raw materials; improved epitaxial growth equipment and processes; optimized wafer-processing equipment; and more efficient packaging methods, materials, and equipment.

Market demand is growing for integrated light engines comprised of LEDs and the driver. The different integration levels are illustrated in Figure 4.15. Level 1 (L1) refers to the packaged LED; Level 2 (L2) refers to components such as LEDs or driver electronics mounted on a board; and Level 2+ (L2+) refers to various higher levels of integration such as LEDs with optical elements. L2 and L2+ integration is desirable for some luminaire manufacturers as it simplifies the value chain and their manufacturing process. Careful system optimization at L2 enables tailoring LED operating conditions, optimizing the number of packages employed, and simplifying the L2 configuration for lower manufacturing cost while retaining quality and reliability. This can lead to reduced system size and/or cost, which is valued by customers.

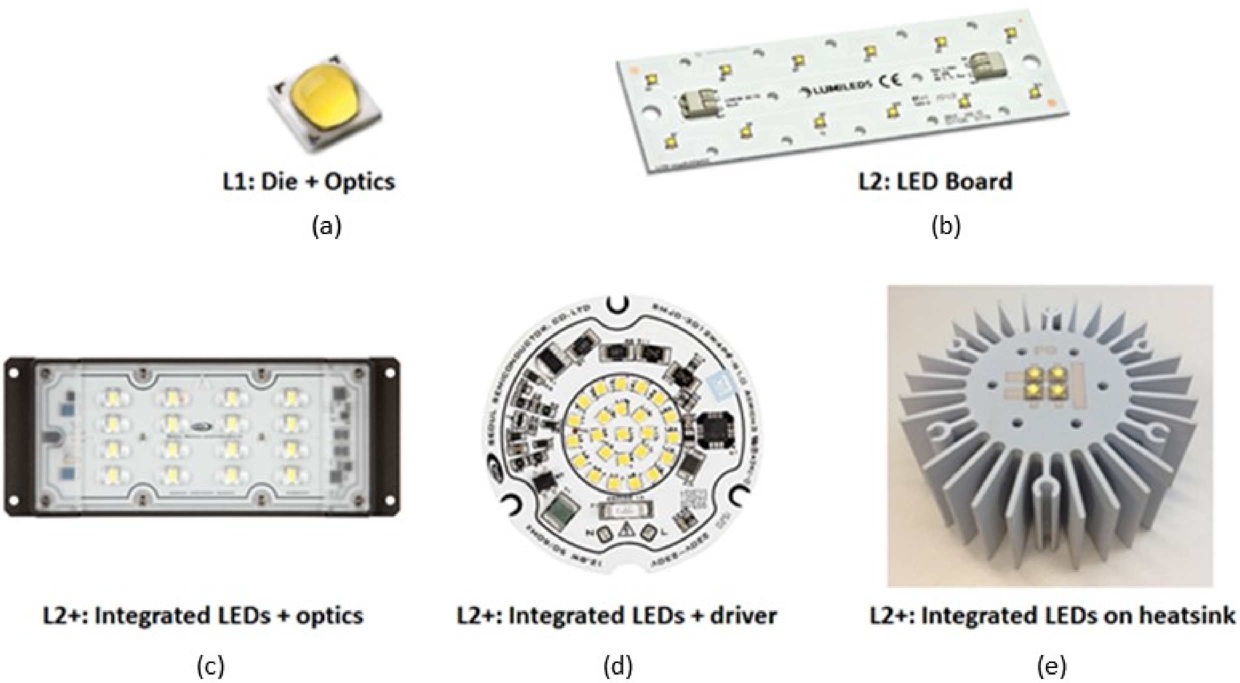


Figure 4.15 Integration Path for LED Components

Sources: a) Lumileds, LUXEON T Datasheet, 2015 [110]; b) Lumileds, LUXEON XR-TX Datasheet, 2016 [111]; c) Seoul Semiconductor, Acrich2.5 Datasheet, 2015 [112]; d) Seoul Semiconductor, Acrich3 Datasheet [113]; e) Frost & Sullivan, Chip on Heat Sink Technology, 2013 [114]

Package Diversity

The variety of LED packages for general illumination has exploded in recent years from a few types of 1 W class packages to a huge number of form factors, lumen levels, voltages, optical patterns, and physical dimensions. An LED manufacturer may have 50 different package families, and each family has multiple variants based on lumen output, forward voltage, CCT, CRI, and binning tolerance. This package diversity has given luminaire manufacturers the freedom and flexibility to use LEDs best suited for the targeted lighting application and market.

Four main LED package platforms (shown in Figure 4.16) have emerged:

1. High-power packages (1 to 5 W) typically used in products requiring small optical source size (e.g., directional lamps) or high reliability (e.g., street lights)
2. Mid-power packages (0.1 to 0.5 W) typically used in products requiring omnidirectional emission (e.g., troffers, A-type lamps)
3. Chip-on-board (COB) packages typically used in products needing high lumens from small optical source or extremely high-lumen density (e.g., high-bay lighting)
4. Chip scale packages (CSPs), also called package-free LEDs or white chips, have gained attention as a compact, low-cost alternative to the high-power and mid-power platforms.

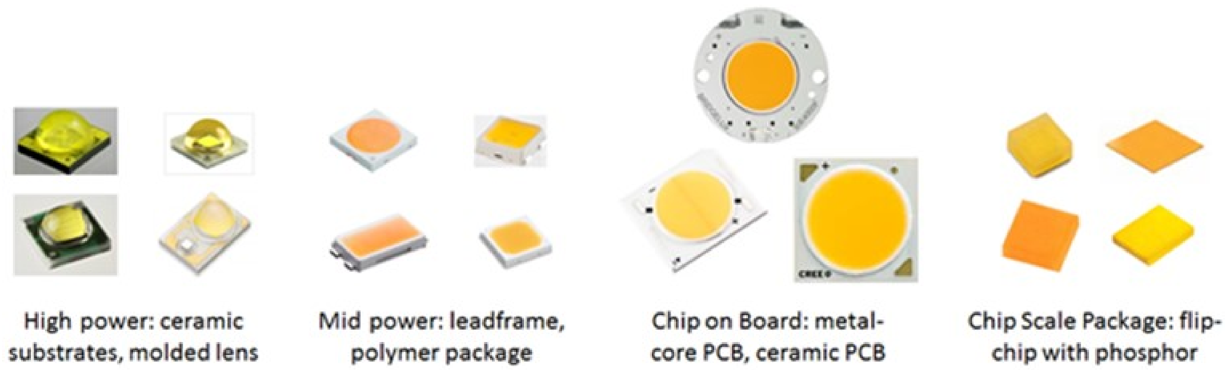


Figure 4.16 Examples of High-Power, Mid-Power, Chip-on-Board and Chip Scale LED Packages

High-power packages provide high efficacy, high luminous flux, and good reliability based on their thermal management and optical design. The design typically consists of a large die (1 to 4 mm^2), or even multiple die for a high-power array, mounted onto a ceramic substrate for thermal management. The phosphor is applied to the chip and then a hemispherical silicone lens or flat lens is over-molded onto the package. In addition to the large die, some high-power package designs use numerous small die in series to create a high voltage package architecture that, when grouped with a boost driver topology, can yield system efficiency improvements.

Mid-power packages were originally used in display and backlighting applications, but found their way into general lighting applications in 2012 as chip performance improvements led to viable lumen levels. Mid-power LEDs are low-cost, plastic molded lead frame packages that typically contain one to three small LED die. The die are mounted on a silver-coated metal lead frame surrounded by a plastic cavity. The cavity is filled with phosphor mixed in silicone to act as the downconverter and encapsulant. Mid-power LEDs have gained favor over high-power LEDs in some applications due to their low cost, which improves the lumens per dollar metric of the system.

COB arrays typically use a large array of small die mounted onto a metal-core printed circuit board (MC-PCB) or a ceramic substrate. The LEDs are then covered with a phosphor mixed silicone. COB arrays provide high lumen output (up to 14,000 lumen) from a small optical source area and are typically used in high-bay lighting and low-bay lighting. With a good thermal substrate, these COB arrays can have the same color and lumen stability associated with high power packages as long as the operating temperature is kept within specification. Their ease of use in luminaire manufacturing appeals to some smaller luminaire manufacturers who do not have the surface mounting equipment to assemble discrete packages onto MC-PCBs.

CSP LEDs have gained prominence recently due to their lower cost from minimizing materials and manufacturing steps, as well as their small footprint allowing for tighter packing in a luminaire. The number of CSP product offerings continues to grow, as does the number of manufacturers offering this LED product type. The majority of CSP products use flip-chip die as a base, onto which the phosphor and encapsulant is applied, as illustrated in Figure 4.17(a). Eliminating wire bonding and removing the need for lead frames or ceramic substrates, allows for a more compact size and reduced cost. The CSP manufacturers apply a conformal phosphor coating directly onto a blue flip-chip LED die, which provides luminous flux on five sides and at wider angles. Recent examples of CSP LED products include a variety of sizes to meet the different lighting application needs to replace the mid-power, high-power, and small COB packages, as shown Figure 4.17(b).

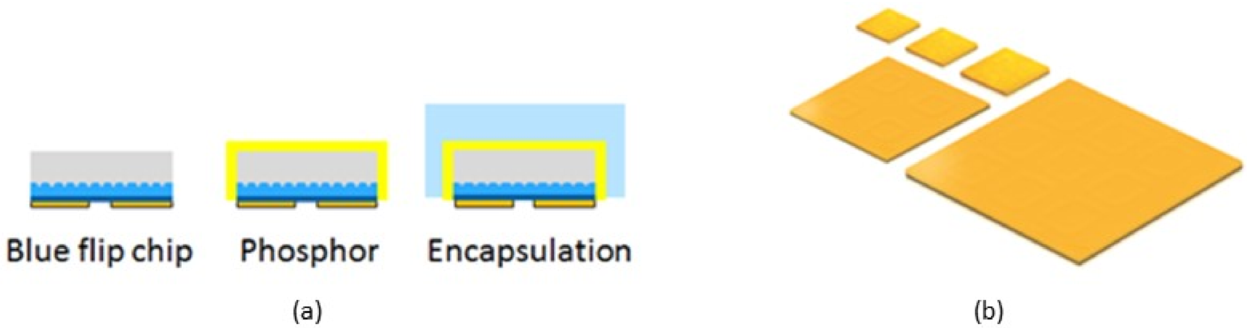


Figure 4.17 (a) CSP Manufacturing Approach, and (b) Recent Example of the Scalability of Commercial CSPs

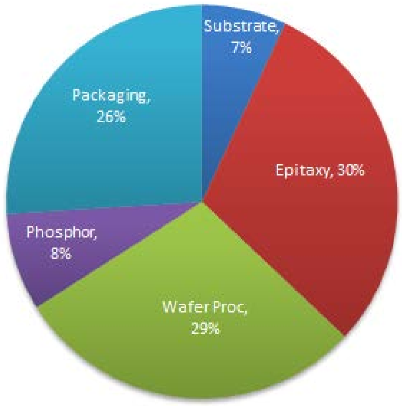
Source: (a) Shatil Haque, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [115], and (b) Samsung Newsroom, May 2016 [116]

While CSPs offer the potential for significant system cost savings, there are various performance tradeoffs, such as thermal impacts from eliminating the high conductivity ceramic substrate, and optical losses associated with moving from a large dome primary lens to a conformal cubic encapsulant. In addition, other manufacturing challenges remain when integrating small CSPs onto Level 2 PCBs including:

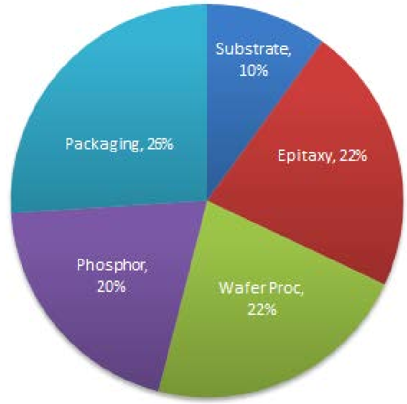
- Higher precision manufacturing is required for alignment of much smaller CSP on PCB due to rotation and tilting.
- Control of radiation pattern can limit chip packing density and affects secondary optics design.
- Increased levels of electrostatic discharge protection is required, because CSP devices do not have integrated Zener diodes for electrostatic discharge protection.
- Handling of packages must be optimized to avoid destroying the phosphor layer, because direct handling of the phosphor layer is unavoidable.
- Accurate testing of the smaller CSP size create handling challenges in the test and sort equipment typically used for surface-mount technology lines.

LED Package Costs

The typical cost breakdown for a high-power and mid-power LED package is shown in Figure 4.18. The data for a high-power package assumes high-volume manufacturing of 1 mm^2 die on 100 mm diameter sapphire substrates, and packaging the die in ceramic packages to produce warm white pc-LED lighting sources. The data for a medium-power, warm white pc-LED package assumes a 0.5 mm^2 die packaged in a plastic leaded chip carrier package of similar dimensions. The cost breakdown for the high-power LED package is largely unchanged compared with 2016, although there is an overall cost reduction of around 20%, which is largely associated with reductions in raw materials costs and yield improvements. The die cost and package cost are much lower for the mid-power package, while the phosphor is still applied over a similar area; therefore, its relative importance to the overall cost increases. Typically, the mid-power package cost will be 5-10x less, depending on die area, and this is reflected in a similar price differential.



High-Power LED Package



Mid-Power LED Package

Figure 4.18 Typical Cost Breakdowns for High-Power and Mid-Power LED Packages

Source: Inputs from DOE SSL Roundtable and Workshop attendees

Figure 4.18 indicates that no single cost element dominates for high-power or mid-power LED packages. Packaging remains the largest cost element, but wafer processing costs are similar and epitaxy costs are not far behind. These breakdowns suggest the need for a more holistic approach to cost reduction.

It is expected that the high-power LED package cost will continue to come down over time as volumes continue to ramp up. The relative contribution from substrate, epitaxy, and wafer processing should see a decrease as wafer size increases over this period, while the relative contribution from packaging and phosphor content will rise.

There is plenty of room for innovation in this area, and DOE anticipates many different approaches to cost reduction, including the following:

- Increased equipment throughput
- Increased automation
- Improved testing and inspection
- Improved upstream process control
- Improved binning yield
- Optimized packages (e.g., simplified designs, lower cost materials, and multi-chips)
- Higher levels of component integration (hybrid or monolithic)
- Chip-scale and wafer-scale packaging

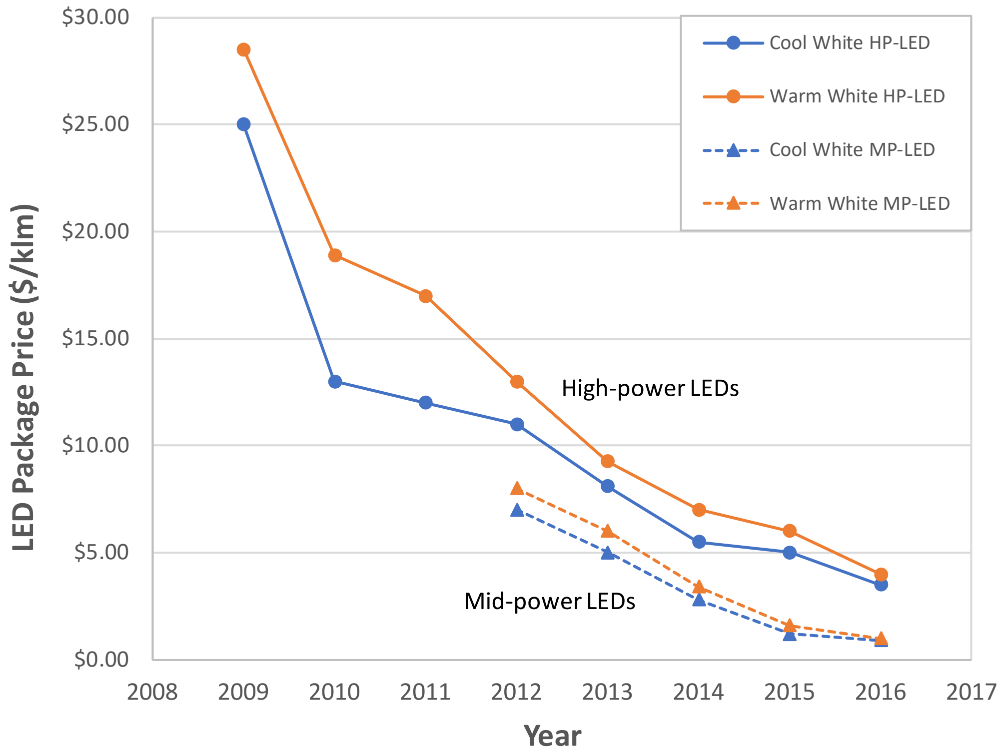
Mid-power packages, however, have reached prices that are close to the raw materials cost due to the intense competition and oversupply in this market segment since 2014. A number of LED chip manufacturers and packagers have been raising prices of mid-power packages to rebound margins from the rock-bottom level they reached recently. The rising cost of raw materials such as printed circuit boards and gold wire has kept manufacturers from continuing the pricing wars to survive in the fierce competition. It is expected that going forward, high-power LED package price erosion will continue, though mid-power package prices will slowly rise.

LED Package Prices

In the past, LED package prices have tended to dominate the cost breakdown for an LED-based lamp or luminaire; however, rapid price reductions have occurred over the past few years, along with the introduction of plastic packaging materials and chip scale packaging methods.

The price estimates in this section represent typical retail prices for LED packages purchased in quantities of 1,000 from major commercial distributors such as Digi-Key, AVNET, Mouser, and Future Electronics. Each LED manufacturer produces variants for each package design covering a range of color temperatures and lumen output levels. Data are selected based on available datasheets and represent devices in the highest flux bins where this is reported (taking the average value within that bin) or typical flux values for the total available distribution. Chosen devices fall within specified ranges of CCT and CRI. In all cases, the price is expressed in units of U.S. dollars per kilolumen ($/klm).

The price per kilolumen was fairly stable in 2016 for mid-power packages, though price continued to decline for high-power packages at a steady rate. The evolution of LED package price is illustrated in Figure 4.19. High-power packages have prices of approximately $3.5/klm for cool white and $4/klm for warm white, while the mid-power LED packages are available as low as $0.9/klm (cool white) and $1.0/klm (warm white). The maximum efficiencies seen in high-power LEDs are not available for purchases at the very low prices seen in mid-power LED. The mid-power packages at these low prices often had efficacies between 120-130 lm/W, while the efficacies for the high-power packages surveyed were between 140-150 lm/W at these prices. Note that higher package efficacies of 168 lm/W (cool white) and 137 lm/W (warm white, 80 CRI) at a current density of 35 A/cm^2 were identified for high-power LED packages readily available in mass production during 2016, though pricing listed in Figure 4.18 represented high-volume LED product models. The price difference between warm white and cool white packages has decreased and can be almost negligible for a number of LED packages families. Warm white packages have been approximately 10% higher but that premium is expected to decrease over time as the cost of phosphors continue to come down.



Note: Cool white packages assume CCT=5700K and CRI=70; warm white packages assume CCT=3000K and CR=80.

Figure 4.19 Price for High-Power and Mid-Power LED Packages

The price–efficacy projections from Figure 4.4 and Figure 4.19 are summarized in Table 4.4. The price projections have been adjusted to account for the lower prices associated with mid-power package designs. Similarly, the efficacy projections have been adjusted to reflect the slower than projected progress, especially for cool white products.

Table 4.4 Summary of LED Package Price and Performance Projections

Metric	2014	2016	2018	2020	2025
Cool White Efficacy (lm/W)	158	168	194	218	240
Cool White Price ($/klm)	1.4	0.9	0.6	0.45	0.3
Warm White Efficacy (lm/W)	131	137	175	208	237
Warm White Price ($/klm)	1.7	1.0	0.7	0.45	0.3

4.3.3 LED Luminaire Manufacturing

Manufacturing Methods

Manufacturing an LED luminaire involves combining the LEDs with mechanical and thermal components (e.g., the heat sink), optical components to tailor the light distribution, and LED driver electronics. LED die or packages are a critical component of all LED-based luminaires, and luminaire manufacturing revolves around integrating the LED source with the other luminaire components to achieve the required form factor and the optimum balance between cost, performance, product consistency, and reliability. The balance of these features and necessary tradeoffs depends on the lighting application, the customer profile, the incumbent lighting performance, and cost. For example, a 6-inch downlight for the residential market can provide 67 lm/W, whereas a higher end commercial downlight from the same manufacturer can reach 100 lm/W at the same color temperature and CRI. The difference in these two models is a factor of design choices for the product requirements for those applications. A lower cost downlight will have fewer LEDs, which in turn are driven at higher currents to achieve the lumen output required, thus pushing the efficacy lower due to current density droop at higher drive currents.

Reducing the number of LEDs can lower costs at the expense of efficacy, but there are further consequences to consider: higher drive currents lead to higher temperatures in the package, which in turn leads to earlier lumen degradation and color shift, thus affecting the luminaires reliability performance and warranty life. This describes just one tradeoff with the LED source design. Further subsystem design choices such as heatsink, and driver and optics designs lead to additional tradeoffs. Understanding all the nuanced performance tradeoffs and impacts on product design and manufacturing costs determines the efficacy, CCT, CRI, warranty life, and cost points at which different luminaire products are brought to market. Lighting quality features such as high CRI, color tuning, dimmability, and longer L70 lifetimes come at a higher cost. Lamps that have lower first cost are generally not dimmable or have the longer lifetimes or high CRI metrics. This illustrates why there is no one size fits all lighting product. The value of efficiency, color quality, or lifetime vary for different applications and affect what customers are willing to spend for those benefits.

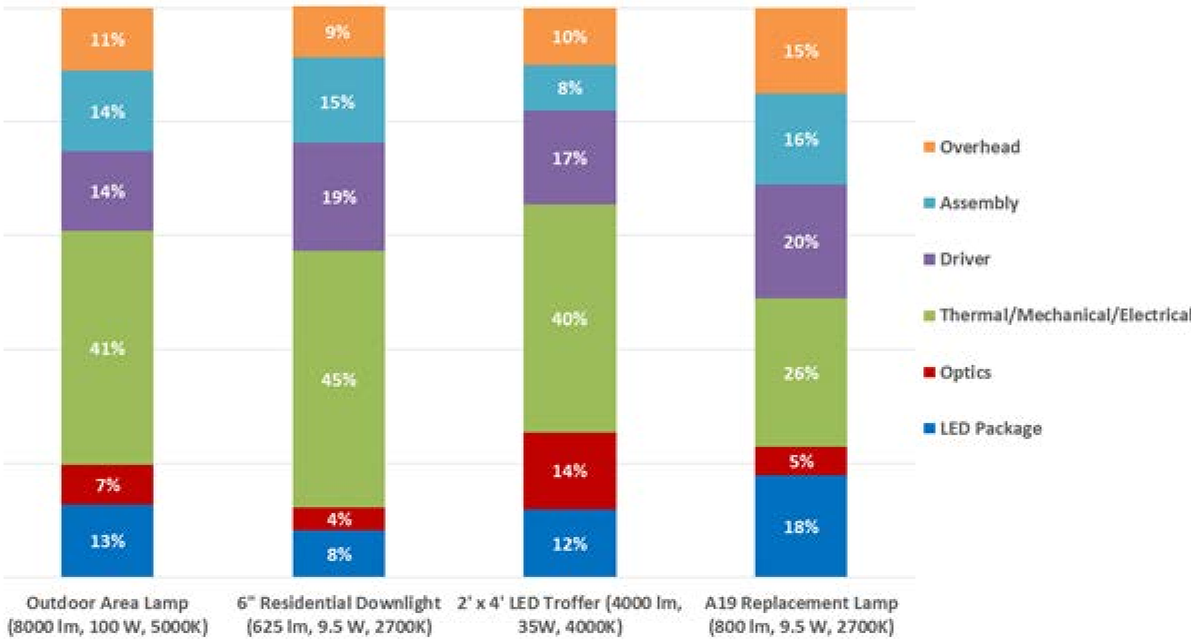
The fact that some form factors have lower efficacy than others does not necessarily indicate that certain LED lighting product classes cannot be made as efficient or reliable as other LED lighting products. Instead, this could reflect a specific tradeoff the manufacturer selected for the end-use case. There are certain cases, such as etendue limited lighting designs required for narrow spot lights, that can have efficacy limitations compared to large area light sources such as troffers (due to the small source size required to achieve small spot sizes), but these efficacy limitations are not fundamental in many designs.

LED-based replacement lamps and LED luminaires have a similar level of integration, but lamps use a standard electrical interface for use within conventional lighting fixtures. Manufacturing of LED-based lighting products shares little in common with conventional lighting products because conventional lighting technologies tend to be based around the fixture-plus-lamp paradigm, with the manufacturing of each part handled completely separately, and often by separate companies. The integrated nature of an LED-based lighting product, where fixture, light engine, and driver electronics are typically combined in a single unit, significantly complicates the manufacturing process. Luminaire manufacturers have successfully addressed the challenge by introducing manufacturing technologies more commonly seen in the consumer electronics industry, simplifying the materials and manufacturing processes, introducing system-level design optimization methodologies (including design for manufacturing and design for assembly), and developing improved testing capabilities.

LED Luminaire Costs

The typical cost breakdown for a lamp or luminaire will vary depending on the lighting application and fixture size. Figure 4.20 shows a comparison of the cost breakdown for an outdoor area lamp, indoor residential downlight, an LED troffer, and A19 replacement lamp. This comparison reveals that relative costs for different form factors can vary considerably. A noticeable trend in recent years is how fast relative LED package cost is dropping in both luminaires and lamps.

Overhead costs also represent a real cost element, especially for LED A19 lamps, and should be included in the cost charts along with the bill of materials. The overhead included in the cost charts refers to manufacturing engineering, product development, documentation, packaging, in-line and compliance testing, shipping, and distribution. The retail price will include an additional channel margin of approximately 25% to 30%.



Note: This represents a typical manufacturing cost breakdown; however, different luminaire manufacturers have varying cost breakdowns depending on their business models.

Figure 4.20 Comparison of Cost Breakdown for Different Lighting Applications in 2016

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

Early in the development of LED lamps and luminaires, the cost of the LED packages dominated the total product cost, but this is no longer the case due to the lower prices and wide availability of lighting class LED packages. For most luminaire products, the dominant subsystem cost has become thermal/mechanical/electrical, which represents the housing, heat sinking elements, electrical connectors, and mechanical fasteners. Moving forward, the cost of LED packages will continue to drop and stabilize, so future cost reduction must be achieved by focusing on optimization of the complete system rather than focusing on any specific cost element.

While a straight cost down process is one approach to reducing luminaire cost, system redesigns —changing the amount and type of components in a system — are a more common way to make greater jumps in cost reduction. This system redesign approach also affects the relative subsystem cost over time as different design approaches to achieving good optical, electrical, and thermal performance will affect the component costs and therefore their ratios. Manufacturers continue to seek manufacturing approaches that can enable cost reduction without degrading system performance in terms of efficacy, lifetime, color quality, etc. The key cost drivers for each major element of the LED supply chain are summarized in Table 4.5.

Table 4.5 The LED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers		
Equipment Suppliers	Epitaxial growth	• Uniformity • Throughput	• Reagent usage efficiency	• In situ monitoring/ Process control
	Wafer processing	• Throughput	• Automation	• Yield
	LED packaging	• Throughput	• Flexibility (packaging materials and package types)	
	Luminaire assembly	• Throughput	• Automation	• Chip scale packaging
	Test and inspection	• Throughput	• Accuracy	• Reproducibility
Materials Suppliers	Substrates	• Diameter	• Quality	• Standardization
	Chemical reagents	• Quality/Purity	• Bulk delivery systems	• In-line purification
	Packaging	• Standardization	• Ceramics processing	• Plastic formulations
	Phosphor	• Quality/Efficiency • Consistency	• Stability (thermal and optical flux)	• Reliability
	Encapsulation	• Quality	• Stability (thermal and optical flux)	• Processability
Die Manufacturing		• In-line inspection/ • Process Control	• Yield • Testing	• Throughput • Capital costs
Package Manufacturing		• Modularization • In-line inspection/ • Process control	• Labor content • Testing • Standardization	• Yield • Throughput
Luminaire Manufacturing		• Automation/Labor content • In-line inspection/ • Process control	• Testing • (performance and compliance)	• Modularization • Throughput

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5 OLED Technology and Manufacturing Status

A highlight in 2016 was the announcement of the availability of Brite2 panels from OLEDWorks [117], the first new product arising from its acquisition of the manufacturing line in Aachen, Germany, previously owned by Philips. These panels provide excellent color, with a CRI above 90 and R_9 above 70. At the standard luminance of 3,000 cd/m^2, efficacy is 63 lm/W and the L70 is 50,000 hours. The R2R line built by Konica Minolta in Japan has not yet been brought into high-volume production, and LG withdrew several of its most innovative products in 2016. However, in spring 2017, in preparation for the completion of a new manufacturing line at Gumi in Korea, LG published documents describing an impressive array of new panels and luminaires [118]. First O-Lite reported panels with 70 lm/W efficacy and announced a new line of specialty products with tailored spectra and no flicker, promoted as "healthy" lighting for families with small children, but these will have little impact on general lighting or energy savings [119].

On the research side, a DOE project between Acuity and OLEDWorks has shown that it is possible to provide intelligent controls to individual OLEDs in a multi-panel luminaire, but further progress is needed to reduce the cost and increase the efficiency of the drivers [120]. The unification of the OLEDWorks and Philips teams has clarified some of the obstacles that need to be overcome in raising panel efficacy to over 100 lm/W. The implementation of reliable encapsulation techniques has been accelerated due to the growing interest in flexible OLED displays, but significant challenges remain for lighting applications. Steady progress has been reported on development of internal light extraction structures, with enhancement factors reaching 2.5 in laboratory experiments. Developments in materials have focused on oriented emitting molecules, and IR-based phosphorescent alternatives such as thermally activated delayed fluorescence (TADF) or platinum/palladium (Pt/Pd)-based phosphorescent emitters.

DOE published three evaluations of OLED products in 2016. A Gateway Demonstration in the office of Aurora Lighting Design (shown in Figure 5.1) concluded that "OLEDs provide comfortable direct view because of low surface luminance (less than 3,000 cd/m^2) and a light distribution that produces high vertical illuminances on surfaces (such as walls) and excellent facial modeling, with soft light that reduces harsh shadows from objects" [121]. In May 2016, DOE published a review of the performance of available commercial luminaires along with comprehensive evaluations carried out by PNNL [122]. The CALiPER Report in September 2016 presented the results of further tests carried out at PNNL and RTI International [123].

Figure 5.1 Acuity OLED Luminaires in Offices

Source: PNNL, "OLED Lighting Products: Capabilities, Challenges, Potential," May 2016 [122] Photos courtesy of Aurora Lighting Design

5.1 OLED Panels

This section describes OLED panel performance in terms of efficacy, lifetime, and color quality. A breakdown of each performance criteria is provided, and key technical challenges and goals are discussed. The performance goals are compared to recent data that illustrate the efficacy tradeoffs that are made to realize desirable lifetime, color quality, and unique form factors. Features that differentiate OLEDs from other efficient light sources are being developed and are continually expanding OLED product offerings. Targets are suggested for future performance increases.

5.1.1 OLED Panel Efficacy

In the transition from the Brite 1 to Brite 2 panels, OLEDWorks achieved an increase in efficacy of 35% to reach 63 lm/W along with a substantial improvement in color quality [124]. The CALiPER test confirmed that the LG panels incorporated in luminaires by Acuity have efficacy of 55 lm/W. The efficacies of the panels available from suppliers in Japan, such as Lumiotec, Kaneka, Konica Minolta and Pioneer, remain below 50 lm/W. First O-Lite has announced the availability of panels with efficacy of 70 lm/W, but their performance has not yet been confirmed [125].

The new catalog from LG promises 3-stack rigid panels that will deliver 90 lm/W with CRI of 93 and CCT at 3000K [126]. Six sizes are listed, in circular, square, and rectangular shapes. Production is scheduled for the third quarter (Q3) of 2017, but delays due to problems in factory construction or yield optimization are possible. For customers who prefer a higher CCT, 2-stack versions will be offered at 4000K with efficacy at 75 lm/W. Although flexible panels are still included in the catalog, their efficacy will remain at 50 to 55 lm/W.

The remainder of this section examines four factors that govern the panel efficacy and identifies opportunities for further research.

5.1.2 Spectral Efficiency

Opportunity/Challenge: Red emitter with narrow spread in wavelength.
The improvement in color balance and color gamut that was achieved in the transition from Brite 1 to Brite 2 led to a reduction in the LER from 336 lm/W to 302 lm/W. This was primarily due to enhanced emission in the near-IR region. The emission spectra of the Brite 2 panel at different driving currents is shown in Figure 5.2 alongside a typical LG panel emission spectra.

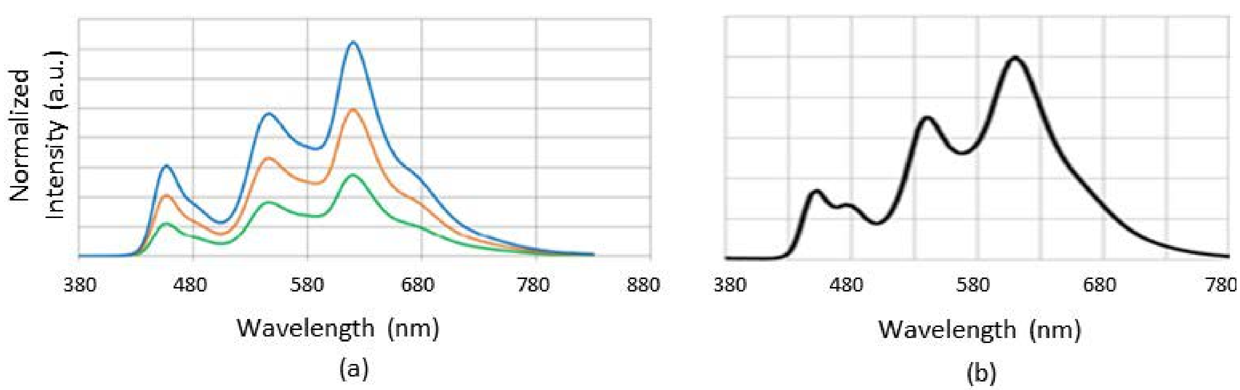


Figure 5.2 Emission Spectra for (a) the Brite 2 FL300 at Different Driving Currents, and (b) a Typical LG Panel

Sources: (a) OLEDWorks, Brite 2 FL300 Datasheet, September 2016 [124], and (b) LG, OLED Light Panel User Guide, April 2017 [127]

The IR tail in the LG panel is not so prominent, but the efficacy of both might be improved by the availability of a red emitter with a narrower spectral peak. Note that the spectrum of the Brite 2 panel varies little with the driving current.

5.1.3 Electrical Efficiency

Electrical efficiency is determined by comparing the drive voltage to the energy (in electron volts) of the emitted photons. This component is usually improved in stacked devices, as a lower potential difference can be applied across red, yellow, or green layers compared to the blue layer. The current density required in multi-stack devices is also less than that for 1-stack devices. Thus, as illustrated in Figure 5.3, while a drive voltage of 3.4 V may be needed to produce luminance of 3000 cd/m^2 for a 1-stack, the same output can be achieved with 6.4 V with a 2-stack and 8.5 V with a 3-stack.

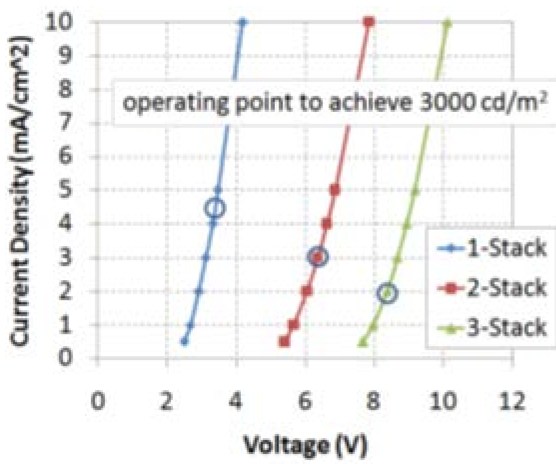


Figure 5.3 Drive Voltage Required for Luminance of 3000 cd/m²

Source: Larry Sadwick, InnoSys and Jeff Spindler, OLEDWorks, DOE SSL R&D Workshop, Long Beach, CA, February 2017 [128]

Data on the OLEDWorks FL300 panel, which has a six-stage structure with an emissive area of 105 cm^2, provides insight into the dependence of luminance on current and voltage. Figure 5.4(a) shows that the luminous flux varies linearly with current. Output of 10 kilolumens per square meter (klm/m^2) can be attained at a current below 0.12 A. Figure 5.4(b) shows this current can be reached at a drive voltage of 19.2 V, or 3.2 V per stage, giving an electrical efficiency of 70%.

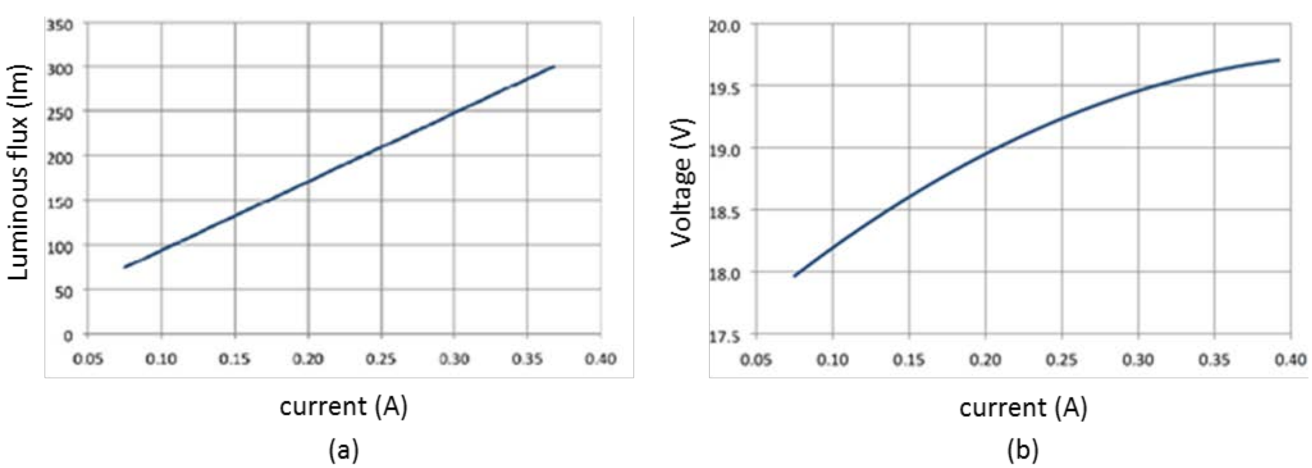


Figure 5.4 Dependence on Current of (a) Luminous Flux, and (b) Drive Voltage

Source: OLEDWorks, Brite 2 FL300 Datasheet, September 2016 [124]

The LG panels reach 3,000 cd/m^2 with drive voltage of 6 V for 2-stack devices and 8.5 V for 3-stack devices, suggesting electrical efficiencies of 75% and 80%, respectively.

Opportunity/Challenge: Increase of drive voltage over the operational lifetime.
One of the issues raised by the PNNL analysis is that the voltage required to drive an OLED panel increases through the operating lifetime. The spec sheet for the Brite 2 FL300 indicates that the voltage needed to reach maximum luminance may rise from 20.5 V to 25.5 V. Allowance for this effect must be made when designing the driver circuit, but allowing headroom for this voltage climb reduces driver efficiency. The voltage increase also reduces the panel efficacy. If, for example, aging results in a 30% reduction in light output and a 25% increase in voltage, the efficacy will fall by 44%. Further research is needed to identify the causes of this rise and to mitigate its effect.

Electrical efficiency is reduced by ohmic losses as charge is transported across the panel through the transparent conductor. These effects are less in multi-stacked devices due to the lower current density. The size of the loss can be estimated from the homogeneity of light emitted from the panel. The luminance varies by less than 20% in the Brite 2 FL300 panel. This indicates that the voltage across the stack varies by only 0.3 V or 1.5% and suggests that ohmic losses in the transparent conductor are less than 1% of the input power.

Opportunity/Challenge: Reduction in the potential difference across the stack.
It has become clear that ohmic losses between the electrodes are larger in devices with multiple stacks. More data on these losses would be valuable, particularly with respect to the charge generation layers and any thick layers that are introduced to increase the separation of the emitter layers from the electrodes. The OLED group at the Tokyo University of Technology suggests that the voltage drop across typical charge generation layers is 0.4 V, which could reduce the electrical efficiency by more than 10% [129].

5.1.4 Internal Quantum Efficiency

The IQE of an OLED depends primarily on two factors. The first is the creation of a balanced flow of electrons and holes into the emission layer. The second is the fraction of recombining electron-hole pairs that lead to the production of visible photons. It is difficult to optimize both factors simultaneously when the emissive layer contains a single component, so typically a dopant to produce the photons is combined with a host that controls the charge transport.

By examining the production of photons near threshold, the OLEDWorks (previously Philips) group has concluded that the IQE for red and green phosphorescent emitters can be as high as 95%, whereas that of fluorescent blue is around 30% [130]. The overall IQE is estimated as 74%. The Brite panels are designed to operate at very high luminance of up to 8,300 cd/m2, producing 300 lm at a current of 0.260 A [131]. The increase from 100 lumens to 300 lumens leads to a 10% decrease in efficacy. The required drive voltage increases from 18.8 to 20.3 V, contributing 8% of the loss in efficacy. This confirms that droop is not a major concern in such multi-stacked devices, since the efficiency in converting current into light drops by only 2%. Thus, the IQE at peak brightness appears to be around 70%.

Opportunity/Challenge: Stable blue emitters with high efficiency.
The search for stable, efficient blue emitters continues. While lower energy emitters and hosts provide stabilities of hundreds of thousands to millions of hours and excellent efficiencies, blue emitters and hosts remain a bottleneck to device performance. The high energy needed to create blue photons leads to the formation of excited states with energies comparable to intramolecular bond strengths of the organic materials. These excited states decay by many non-radiative mechanisms, leading to accelerated deterioration of the organic layers as well as reduced efficacy. This problem is not so severe in fluorescence, because the singlet state lifetimes are short; however, in phosphorescent systems the radiative emission from triplet states is much slower, increasing the probability of non-radiative decay and reducing device lifetime. Although many years of research at Universal Display Company (UDC) and other companies has led to improvements in the performance of phosphorescent emitters, the lifetime is not yet sufficient for commercial adoption for either

lighting or displays. Research is still underway in many university laboratories. For example, in one DOE SSL project, the group at Arizona State University has shown that tetradentate Pt complexes like PtON7, PtON1, and PtNON, have high photoluminescence efficiency and a fast radiative decay process, as shown in Figure 5.5. That enables a viable route for stable blue phosphorescent OLEDs [132]. They have achieved EQEs greater than 17%, and lifetime to 50% of initial luminance (LT50) greater than 3,000 hrs @1,000 cd/m^2.

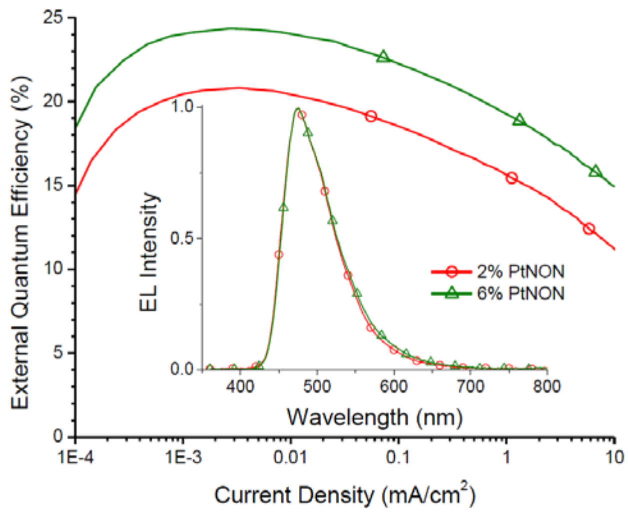


Figure 5.5 External Quantum Efficiency of Platinum Complexes

Source: Jian Li, DOE SSL OLED Stakeholder Meeting, Corning, NY, October 2016 [132]

In another DOE SSL project, at the University of Michigan, the introduction of an "excited state manager" led to 9% EQE and lifetime to 80% of initial luminance (LT80) of 33 hours @1,000 cd/m^2 for a sky blue emitter with CIE (0.16,0.30) [133]. The purpose of the manager dopant is to provide a pathway for exciton decay that spares the organic molecules from degradation. Achieving high luminescence efficiency with such an approach requires careful control of manager doping placement and concentration.

To achieve practical levels of stability, commercial panels rely on fluorescent blue emitters. In particular, sky-blue emitters are used due to their lower excited state energies, compared to deep blues required for displays. Unfortunately, the efficiency of fluorescent emitters is limited to around 25% due to the ratio of singlet to triplet rates. Attempts to harness both singlet and triplet excitons to generate emission of blue photons through fluorescence pathways are underway. In molecules where the triplet energy is close to the singlet energy, thermal upconversion of the triplet can theoretically allow for 100% IQE in TADF. Using TADF, Cynora have achieved 12% EQE at 1,000 cd/m^2 and LT80 of 94 hours from 500 cd/m^2, with CIE (0.17,0.27) [134]. Yagamata University reported studies of pyrimidine-based TADF emitters [135]. A deep-blue emitter exhibited CIE coordinates of (0.16, 0.15), a low turn-on voltage of 3.25 V, a high EQE of 18%, and a high power efficiency of 20 lm/W.

A further extension of the TADF approach has been suggested by the Kyushu University group, in which two dopants are introduced. Exciton formation is accomplished on a TADF dopant and excitons are all transferred to the singlet state of a fluorescent emitter. Proponents predict that device stability and efficiency can be improved over conventional TADF because of reduced triplet energy (due to upconversion), reduced exciton lifetimes, and more efficient transfer processes. Furthermore, this approach can take advantage of available fluorescent emitters and is suitable for display applications as it produces the narrow spectrum of a fluorescent emitter but with greater efficiency. This approach has been termed "hyper-fluorescence" and is being commercialized by Kyulux [136]. As noted in Section 2.5.2, this approach is being pursued by a European team led by Merck in the project HyperOLED.

The National Taiwan University group has achieved record results through using an oriented TADF emitter [137]. The group reports that, "extremely efficient sky-blue organic electroluminescence with external quantum efficiency of ~37% is achieved in a conventional planar device structure, using a highly efficient TADF emitter based on the spiroacridine-triazine hybrid and simultaneously possessing nearly unitary (100%) photoluminescence quantum yield, excellent thermal stability, and strongly horizontally oriented emitting dipoles (with a horizontal dipole ratio of 83%)."

5.1.5 Extraction Efficiency

Extraction efficiency is the ratio of visible photons emitted from the panel to the photons generated in the emissive region. For basic OLED devices on planar glass substrates, only about 20% (17% to 25%) of the generated light is emitted from the panel. This is due to absorption and trapping of photons in the electrodes, transparent substrate, and inner layers resulting from mismatches in the index of refraction along the photon path (i.e., organic materials, anode, substrate, encapsulation layers, and air). The DOE target for light extraction efficiency is 70%, an extraction enhancement of 3x to 3.5x. The extraction efficiency of current products is only 30% to 50%, leaving ample room for improvement and energy efficiency gains.

Two methods to increase extraction efficiency have already been implemented in commercial panels. In early products, a micro-lens array (MLA) was added to the outside surface of the transparent substrate. These arrays are not completely periodic, in order to avoid variations in the color of the light as a function of angle of emission. Such films typically can increase the light extraction efficiency to 32%.

Opportunity/Challenge: Index matched OLED devices.
The refractive index of the materials used in transparent substrates is close to 1.5, while that of the emitter layer is close to 1.75. This means that much of the light does not reach the substrate and cannot be extracted by the MLA. The external film could be more effective if substrates with higher index were used. Unfortunately, no candidates have been identified on which reliable OLEDs can be fabricated at an affordable cost. Nevertheless, the development of a set of materials with a common refractive index would increase the effectiveness of an external MLA and would eliminate Fresnel reflections at internal interfaces.

Opportunity/Challenge: High performance light extraction layers.
The second method that has been incorporated in some commercial products is the insertion of a scattering layer between the transparent electrode and substrate. In the films from the leading supplier, Pixelligent, nanoparticles of zirconium dioxide (ZrO_2) or titanium dioxide (TiO_2) are embedded in a polymer layer [138]. The refractive index of this layer can be graded to reduce Fresnel reflections, and these films lead to extraction enhancement of up to approximately 2.5x. Integrating internal light extraction layers into OLED devices has presented challenges. The extraction film must be stable and compatible with subsequent OLED manufacturing. If polymeric hosts are used, they must be patternable to prevent the ingress of water and oxygen through the extraction layer to the device. Further, the anode deposition and anneal temperatures can be limited and patterning of the anode can be difficult and introduce solvents. In a project supported by DOE, PPG (now Vitro) developed a low-cost online process to embed scatterers into a glass substrate during float glass manufacture. This approach provides a smooth, impermeable glass surface for OLED deposition. However, initial performance results are modest, of around 1.6x extraction enhancement. To reach efficacy projections, high-performance light extraction methods (demonstrating at least 2.5x extraction enhancement) that can be integrated into panels without compromising lifetime and yields are needed.

Opportunity/Challenge: Light extraction enhancement in flexible OLEDs.
The available internal light extraction layers are not consistent with flexible OLEDs. The major challenge is to identify appropriate nanoparticle/host materials and deposition techniques which provide layers that are stable when bending and onto which transparent electrodes and OLEDs can be added. A second concern is patterning of the light extraction layers to prevent the ingress of water and oxygen through the edges.

Opportunity/Challenge: Reduced optical absorption in OLED layers.
The prevalence of multi-stacked OLEDs and the introduction of scattering layers that recirculate many photons within the device has led to increased concern about absorption losses. Each time that a photon is reflected back, either from the scattering layer or the transparent substrate, it must pass across the transparent anode and organic layers twice and then be reflected at the cathode. There are three components of special concern in this regard:

- Transparent anode: indium tin oxide (ITO) is still used in commercial OLEDs. It is extremely difficult to achieve low sheet resistance (less than 10 ohms per unit area, Ω/□) and low optical absorption (less than 5%) simultaneously. In the search for alternative transparent conductors, encouraging results have been obtained in the laboratory for silver nano-wires embedded in a polymer host, but reliable OLEDs deposited on such electrodes have not yet been demonstrated.

- Charge generation layers: Work by a collaboration of Philips (now OLEDWorks), Aixtron and RTW Aachen University has shown that charge generation layers can lead to significant optical absorption, with transmission rates often below 90% [139]. This loss is particularly severe in devices with six organic stacks. The Philips group estimated that the light extraction efficiency drops by 4% in going from 3-stack to 6-stack structures [130].

- Cathode: Imperfect reflection at the cathode can be a major cause of photon absorption. The Philips group demonstrated that the efficacy can be increased substantially by replacing the usual aluminum cathode with a silver cathode. Using the silver cathode, with an internal scattering layer and external foil, it obtained 65% light extraction in a single stack device and 57% extraction with three stacks. Researchers have expressed special concern about the excitation of surface plasmons in the cathode when the emitter layer is very close to the metal electrode. The effect can be reduced by introducing a thick electron transport layer and is of less concern in devices with multiple stacks.

Opportunity/Challenge: Aligned emitting dipoles.
Photons are more likely to escape when they are emitted in a direction close to the normal. This is more likely when the molecular dipoles lie in the plane of the OLED. The development of phosphorescent layers with oriented molecules has been pursued extensively for IR-based emitters at the University of Southern California and for Pt-based emitters at Arizona State U. and Seoul National U. [133] [140] [141]. Figure 5.6 shows that EQE over 35% can be obtained without any extraction enhancement structures.

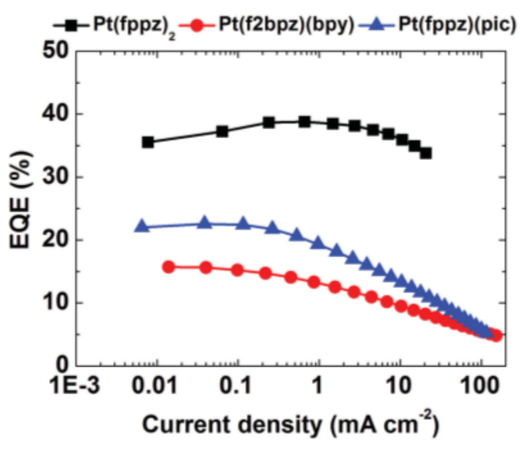


Figure 5.6 External Quantum Efficiency of Phosphorescent OLEDs with Pt-Based Emitters

Source: K.H. Kim et al., Seoul National University, "Crystal Organic Light-Emitting Diodes with Perfectly Oriented Non-Doped Pt-Based Emitting Layer," Advanced Materials, April 2016 [141]

Opportunity/Challenge: Breaking the planar symmetry.
It is difficult to increase the extraction of light from a device in which all the interfaces are planar. The introduction of scattering particles is just one example of many strategies to add three-dimensional (3-D) structures inside the device. Other suggestions have been to introduce grids between the emitting layers and transparent cathodes or internal multi-lens arrays. The latter approach was shown to be very effective in laboratory experiments by Panasonic [142], but they were unable to incorporate the solution in commercial panels.

Researchers have suggested that the planar symmetry can be broken by fabricating OLEDs on corrugated substrates. This is being explored in multiple DOE SSL projects**.** The North Carolina State University group created quasi-random grating structures with 260nm average period and 50nm FWHM, where typical corrugation depth is 90nm. The group observed 87% enhancement in efficacy without any increases in leakage current [143]. The Iowa State University group has reported enhancement factors of up to 2.4 using patterns with depth of 215 to 500nm imprinted in polycarbonate [144]. The major problem with this approach lies in the reliability of OLEDs that are fabricated on corrugated substrates. It may be many years before manufacturers will accept the risk.

A group at the University of Michigan is investigating multiple approaches including: 1) sub-anode gratings – by patterning the substrate beneath ITO with a 300nm blaze; 2) sub-anode grids in top emitting structures – by fabricating a mirror and sub-anode grid on the substrate onto which an OLED and transparent cathode are deposited; and 3) corrugation of cathode surfaces – by patterning the substrate with corrugations using either organic vapor phase deposition-grown organic nanopillars, or imprinted polymer layers on the glass substrate.

5.1.6 Efficacy Breakdown and Goals

Table 5.1 provides estimates of the efficiency factors for two OLED devices, comparing the performance of currently available commercial panels and next generation panel products expected to ship this year. The first column refers to the Brite 2 panel from OLEDWorks, and the second column contains estimates for a panel that will be fabricated on the new line at LG. However, the commissioning of this line may be delayed and the performance parameters may be changed. These data confirm that the color has been improved substantially, but there is a long way to go to optimize device efficiency. Likewise, cost remains a major challenge for OLED product adoption.

Table 5.1 Components of OLED Panel Efficacy

Source	OLEDWorks	LG*
Product	Brite 2	LL056RS1-93P1
Illuminance (lm/m2)	10,000	10,000
LER (lm/W)	302	328
Electrical Efficiency (%)	71	80
IQE (%)	60	62
Extraction Efficiency (%)	49	55
Panel Efficiency (%)	21	27
Panel Efficacy (lm/W)	63	90
CCT (K)	3000	3000
CRI (Ra)	>90	93
CRI (R9)	>70	-
Duv**	-0.0016	0.0005
Lifetime (L70) (hrs)	50,000	40,000

* While the data sheet for this panel is available on the internet, this LG panel has not been commercially released.
** Distance from the blackbody locus in the u-v colorspace.

Figure 5.7 shows OLED loss channels, compares state-of-the-art performance to the program goal, and indicates how much improvement might be possible. The values for 2017 refer to the 6-stack Brite 2 panel, giving an efficacy of 63 lm/W for a current of 85 mA driven at 18.9 V across a panel with a luminous area of 105 cm^2 [124]. The goal corresponds to an LER of 360 lm/W and a panel efficacy of 190 lm/W.

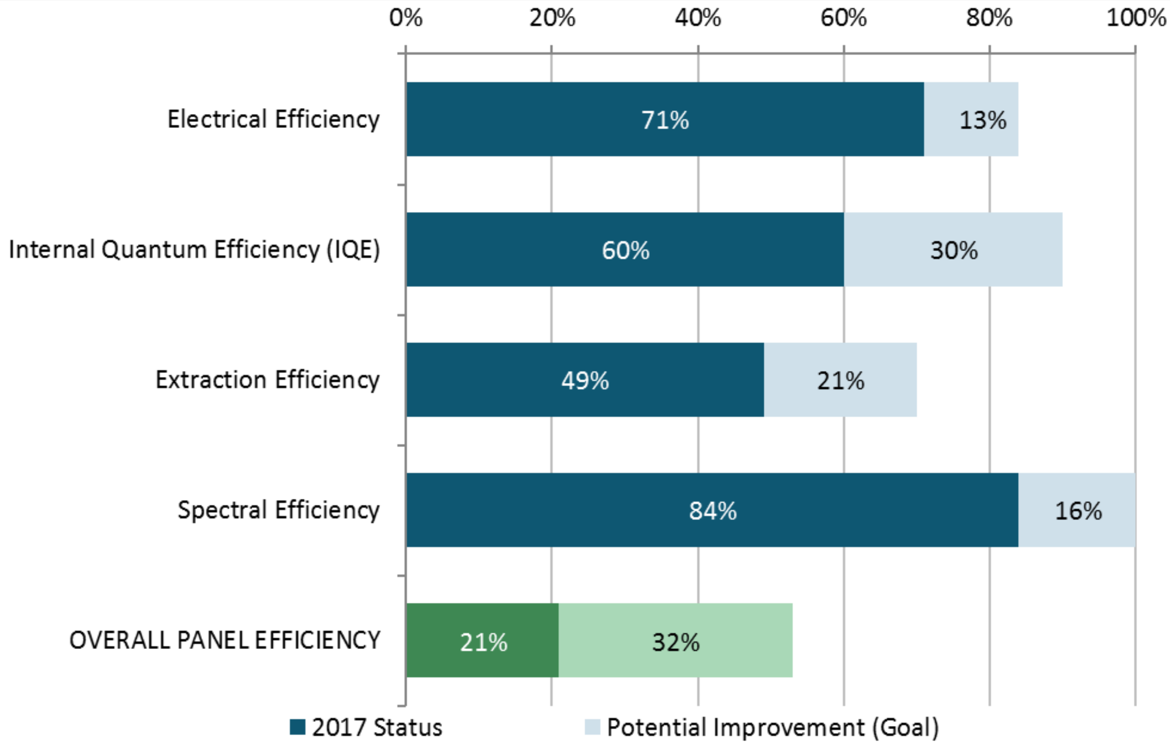


Figure 5.7 OLED Panel Loss Channels and Efficiencies

5.1.7 Panel Color Quality

One of the major reasons for the relatively slow improvement in panel efficacy is that both leading manufacturers have given priority to color quality. The improved representation of red tones is seen in much higher values of R_9. Several recent studies have shown that for low values of CCT, many customers prefer the color point on the CIE (u,v) plot to lie below the blackbody curve. This was achieved in the Brite 2 panel. OLEDWorks provided data using the new TM30-15 metrics, with the fidelity index (R_f) at 86 and the gamut index (R_g) at 100. The color vector graphic shown in Figure 5.8 confirms that all colors are well represented.

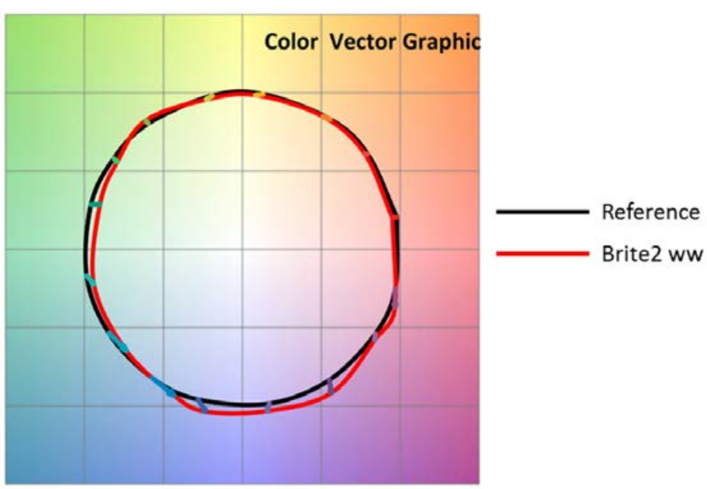


Figure 5.8 Color Vector Graphic for Brite 2 Panel

Source: OLEDWorks, Brite 2 FL300 Datasheet [124]

OLEDWorks and LG have focused their development on warm white panels with CCT at 3000K. Both offer neutral white panels at 4000K, but with an efficacy penalty of 16% to 20%. OLEDWorks also offers an amber light with almost no blue light that is designed for healthcare, senior living centers, public facilities (e.g., prisons), and sleeping areas in residences.

Other colored panels and color tunable panels have been offered by other suppliers, but the low efficacy and high cost of these panels currently exclude them from consideration for general lighting applications.

5.1.8 Form Factor

Although OLED proponents often have shown prototype panels with arbitrary shapes, most commercially available panels are square, rectangular, or circular. OLEDWorks offers three shapes, while the LG catalog offers panels in seven different shapes. Panel shapes are restricted by the few options available for patterning, and only limited progress has been achieved in the development of printing processes in which shapes can be changed easily.

The progress in delivering flexible panels has also been disappointing. Although flexible panels appear prominently in the LG catalog and its promotional material, the availability has been limited and the reliability of these products remains a concern. Fabrication of flexible panels was one of the motivations behind the R2R factory at Konica Minolta, but the line has not yet been brought up to high-volume production.

5.2 OLED Luminaires

To convert an OLED panel to a luminaire, electrical connections and drivers must be added to control the current supplied to the panel, a mechanical housing is provided to support the fragile panel, and thermal management must be considered (although a larger area for heat distribution makes for easier thermal management than in LED luminaires). No external optics are needed if a Lambertian light distribution is appropriate for the application, but beam shaping is a challenge for the future.

5.2.1 OLED Luminaire Efficiency

Many OLED luminaires have been designed such that the only additional efficiency loss outside the panel arises in the driver, which currently causes an efficiency reduction of about 15%. No exterior optics are added, so that the light distribution remains close to Lambertian. However, as with LED fixtures, manufacturers of OLED luminaires may choose to operate their panels under conditions that are different from those used in the spec sheets of the panel suppliers. This section provides examples of commercial OLED light fixtures, assessing the performance of OLED drivers and the light output.

Several luminaires from Acuity have been tested in the DOE CALiPER and Gateway Programs. In a Gateway study of a Trilia™ ceiling fixture installed in the office of Aurora Lighting Design, 120 LG 100 mm x 100 mm panels were driven close to the recommend output of 75 lm per panel, using 11 drivers from OSRAM that were originally designed for inorganic LEDs. The total light output of 8,518 lm was obtained from 189 W with an efficacy of 45 lm/W, compared to the nominal panel efficacy of 55 lm/W, suggesting a luminaire efficiency of 82% [121].

The four luminaires tested in the 2016 CALiPER study are shown in Figure 5.9. The Chalina luminaire uses five of the same LG panels with a measured light output 330 lm from 7.4 W, also giving a luminaire efficacy of 45 lm/W. The evaluators estimated that the driver efficiency was close to 87%. The Aedan wall sconce tested in the same study is available in two versions. The single-panel model produced 65 lm from 2.8 W (equal to 23 lm/W), whereas the dual-panel model gave 130 lm from 4.3 W (equal to 30 lm/W). The driver efficiencies were estimated to be 47% and 58%, demonstrating that driver losses become more serious as the power is reduced. The final luminaire tested in this CALiPER study was the Aerelite desk lamp from OTI Lumionics. This contains a single panel giving 270 lm from 9.6 W with efficacy of 28 lm/W. The driver efficiency was estimated to be 77% [123].

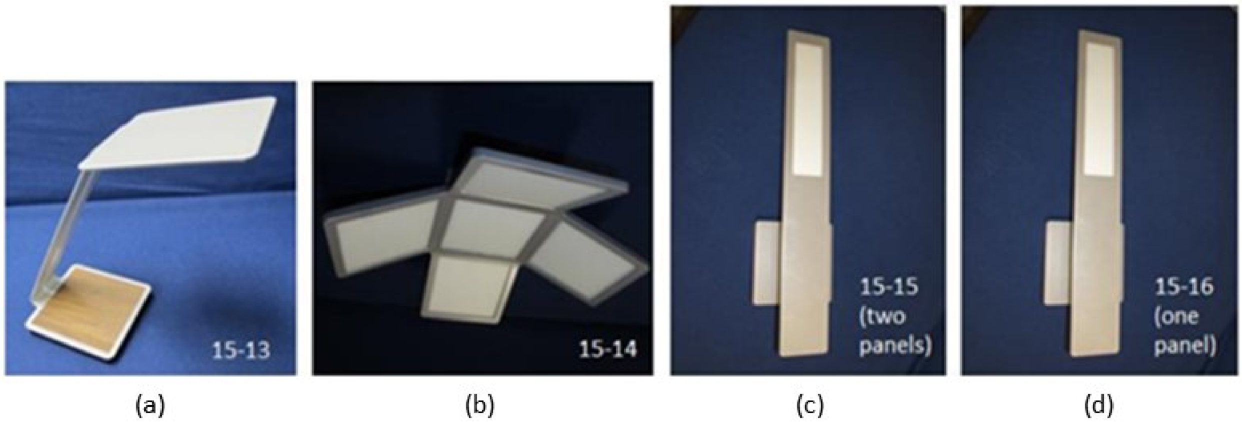


Figure 5.9 OLED Products Tested for the DOE SSL Program's CALiPER Report:
(a) Aerelight Desk Lamp by OTI Lumionics; (b) Chalina Pendant by Acuity Brands; (c) Aedan Double-Panel Wall Sconce by Acuity Brands; (d) Aedan Single-Panel Wall Sconce by Acuity Brands

Source: PNNL, "CALiPER Report 24: Photometric Testing, laboratory Teardowns, and Accelerated Lifetime Testing of OLED Luminaires," September 2016 [123]

The Workrite Ergonomics desk lamp named "Natural" uses an LG Chem panel of 320 mm x 110 mm, and delivers 442 lumens at the maximum brightness setting while drawing 13.8 W, giving an efficacy of 32 lm/W. With its CRI value of 94, 5-year warranty, and online price of $209, the lamp compares well with the equivalent LED lamp from Workrite (Astra 2). The spec sheet from LG Display recommends driving this panel at 4.8 W to produce 250 lm with efficacy of 55 lm/W. The 40% reduction in the efficiency of the luminaire in going to higher output is partly due to overdriving the panel and partly due to losses in the driver.

As part of its OMLED product line, European company Emdedesign has introduced a line of pendants using two to five Brite 1 panels from OLEDWorks. Each of these panels produces up to 300 lm from 7.4 W with a lit area of 102 mm x 102 mm. The maximum recommended is 280 lm at 12 W for the two-panel luminaire and 695 lm at 28 W for the five-panel version. The panels are thus being driven below their peak power, at a level for which the panel efficacy is about 45 lm/W. The efficacy of the luminaires is 23 lm/W for the two-panel luminaire and 25 lm/W for the five-panel luminaire, suggesting a driver efficiency of around 55%.

The "Limit" and "Petal" pendants from Visa Lighting, shown in Figure 5.10, use three of the same Brite 1 panels. The Limit produces 850 lm from 27 W, showing that the panels are being driven closer to their highest power levels. Nevertheless, the efficacy is higher at 32 lm/W, suggesting that the luminaire efficiency is close to 75%. The output of the Petal is only 700 lm from 27 W (26 lm/W), perhaps because some of the light is absorbed in the luminaire, due to its 3-D shape.

Figure 5.10 Limit and Petal Luminaires from Visa Lighting

Source: Visa Lighting product database [145]

OLEDWorks and Acuity Brands have collaborated in a DOE SSL project to develop prototype luminaires based upon newer panels from OLEDWorks. A “Trilia” luminaire was adapted to include 24 prototype panels with efficacy around 72 lm/W, producing 2,240 lm from 38 W, corresponding to luminaire efficacy of 59 lm/W. A single remote driver was used and the luminaire efficiency was more than 80%.

Opportunity/Challenge: OLED-specific drivers.
The use of a single driver for AC-DC conversion and control of the DC voltage does not allow for separate control of the intensity in each panel and can lead to problems when one panel fails. In another DOE SSL project, Acuity Brands tested a 66-panel “Canvis” luminaire in which the AC-DC conversion was performed in a master driver, but DC drivers were added to each panel to allow independent intensity control. The efficiency of the AC-DC converter was 88%, and that of the individual DC drivers was 72% due to the low wattage (0.85 W) delivered to each panel. Although the system was configured with prototype panels from LG with an efficacy of 86 lm/W, the total output of 4870 lm corresponded to a luminaire efficacy of only 55 lm/W [120]. These results indicate that if individual control is to be provided for the light coming from each panel, research is required to increase the efficiency of drivers at low wattage.

Improvements in luminaire design and drivers can help reduce losses. The projections in Table 5.2 assume that the efficiency of OLED drivers will improve along with that of LED drivers, but with a 2-year time lag because OLED-specific drivers are required for optimal operation. Off-the-shelf LED drivers have voltages that do not necessarily correspond to the voltages of the OLED panel or panel aggregates, thus compromising system efficiency. OLEDWorks is now offering specified drivers to complement its panel products to alleviate issues with installation [146]. At the DOE SSL R&D Workshops in 2016 and 2017, the need for the development of such OLED light engines was emphasized. This approach, of designing the stack and drivers in concert, could help to get over electrical efficiency hurdles.

In addition to improvements in luminaire efficacy, the overall utilization efficiency of the OLED luminaire can be affected by the light distribution profile. The broad angular distribution of the light from an OLED can be used to good effect in several ways. The light from ceiling-mounted fixtures or high pendants provides a good balance between illumination of vertical and horizontal surfaces, which is important for viewing faces and wall decorations. If the efficacy can be raised to 100 lm/W or more, OLEDs can then compete on good terms with other sources of ambient light. For task lighting, OLEDs that are placed close to the work surface provide additional illumination without distracting shadows.

In future applications, beam-shaping may be required to focus the light where it is most needed or to avoid glare. It seems unlikely that this will be accomplished within the panel, so exterior optical elements may be needed at the luminaire level. Though some light-shaping optics may be cost effective in high-brightness OLED luminaires, the bare panel will remain sufficient in many applications, which minimizes added costs when going from light source to luminaire.

The anticipated evolution of the efficiency breakdown in a typical luminaire efficiency is shown in Table 5.2. The degradation in projected optical efficiency beyond 2020 represents the optical losses associated with a more directed beam distribution, whereas up until 2020 no external beam distribution is assumed.

Table 5.2 Breakdown of OLED Luminaire Efficiency Projections

Metric	2016	2018	2020	2025	Goal
Panel Efficacy* (lm/W)	60	90	110	150	190
Optical Efficiency of Luminaire	100%	100%	100%	90%**	90%**
Efficiency of Driver	85%	85%	90%	90%	95%
Total Efficiency from Device to Luminaire	85%	85%	90%	81%	86%
Resulting Luminaire Efficacy* (lm/W)	51	76	99	122	162

Source: DOE SSL OLED Stakeholder Meeting, Corning, NY, October 2016 [147]

* Efficacy projections assume CRI >90, CCT 3000K

** Losses representing possible use of beam shaping optics

5.2.2 Luminaire Design

The OLED community is identifying key differentiating features of OLED lighting that are expected to give OLEDs an advantage in the lighting industry, such as glare reduction, conformability, transparency, and thin and lightweight designs. From a product development standpoint, integration of differentiating features is key. Acceleration of luminaire development is anticipated as manufacturers settle on common panel sizes and electrical and mechanical connections. Another path toward simplifying luminaire integration – and thereby accelerating luminaire product development and deployment – is for panel suppliers to develop OLED light engines, which supply the panel or group of panels with an appropriate efficient driving mechanism for luminaire manufacturers to integrate into luminaires. Acuity has made substantial progress in developing architectures for luminaires that can accommodate panels from several manufacturers.

The thin profile of OLED panels enables them to be embedded in appliances, furniture, and architectural features. In 2016, Corning Glass and OLEDWorks organized an OLED lighting design competition and three awards were made. As shown in Figure 5.11, the first went to the Greenlight, by Sadyr Khabukhayev of the Izmir Institute of Technology in Kazakhstan, which demonstrated OLED panels as supplemental lighting in a fixture that acts as a decorative indoor plant holder in addition to a pendant luminaire.

Figure 5.11 Greenlight: Product Design by Sadyr Khabukhayev

Source: Corning, Lighting without a Bulb Contest, 2016 [148]

For some embedded panels, such as in under-cabinet lighting, there is room for traditional drivers and connectors. However, other panels need innovation with respect to mounting schemes, drivers, and connections for power supplies and control. The second design award was given to Matthew Boyko, of Society Creative, for his surface-integrated socket (depicted in Figure 5.12), which could lead to more elegant wall lights.

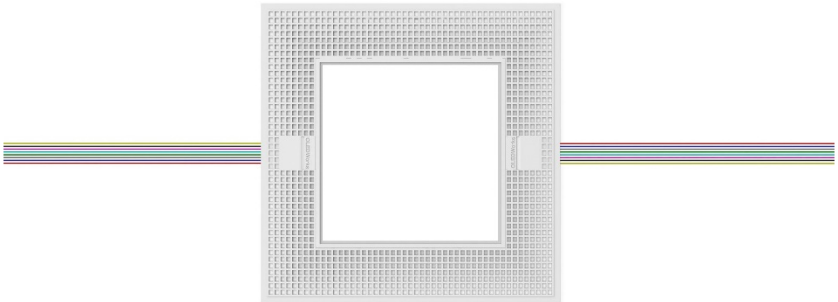


Figure 5.12 Surface Integrated Socket: Product Design by Matthew Boyko

Source: Corning, Lighting without a Bulb Contest, 2016 [148]

The third design award went to Mike Garner of MSG Lighting, for the Hexy OLED luminaire, pictured in Figure 5.13. The Hexy is characterized by multiple planar panels in a visually pleasing 3-D luminaire structure. Many luminaire manufacturers are using this approach as they wait for conformable OLED lighting panels to become commercially available and open a host of new 3-D luminaire design possibilities.

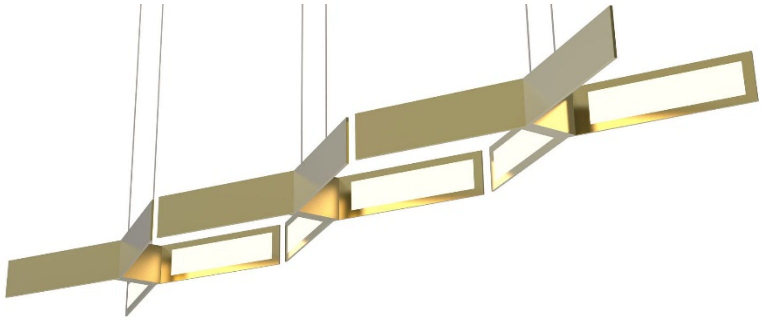


Figure 5.13 Hexy OLED Luminaire: Product Design by Mike Garner

Source: Corning, Lighting without a Bulb Contest, 2016 [148]

Several manufacturers are offering modularity as a feature, including Acuity Brands with its Trilia and Canvis products, and Astel with its Versa family (shown in Figure 5.14). The units are supplied with a variety of mounting options and a driver that supports dimming through digital multiplex (DMX) 512 control.

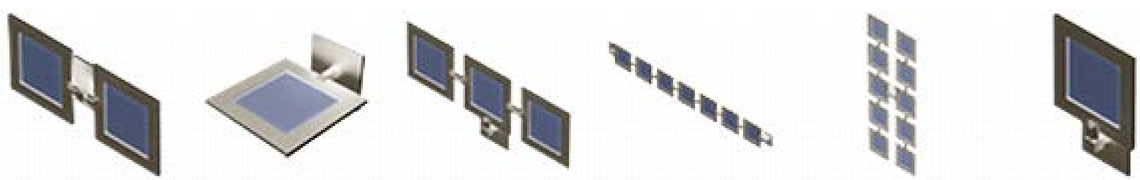


Figure 5.14 Astel Versa Series of Interior OLED Lights

Source: Astel Lighting [149]

Recognizing that LED and OLED sources bring complementary benefits, several luminaire manufacturers have introduced fixtures that combine both technologies. In the Olessence planar pendants from Acuity Brands, shown in Figure 5.15, OLED panels are used to produce direct down lighting with a Lambertian profile. Indirect lighting is provided by LED sources with an injection-molded optical system producing a batwing distribution from the top of the luminaire. Ninety percent of the light is produced by the LEDs, so that the total luminaire efficacy is close to 100 lm/W. The luminaire is available in lengths of 4, 6 or 8 feet, with two 200 mm x 50 mm OLED panels for each linear foot. Both LED and OLED sources are offered with CCT of 3000K, 3500K, or 4000K and CRI greater than 80. Dual-circuit switching is available for independent dimming of direct and indirect light outputs. A wide range of controls is available to enable the inclusion of daylight or occupancy sensors and network connections.

Figure 5.15 Olessence Luminaire that Uses Both OLED and LED Technologies

Source: Acuity Brands, 2016 [150]

OSRAM also has taken a hybrid approach in its prototype automobile rear light, shown in Figure 5.16. OLEDs are used in the tail light and turning indicator, but LEDs are used to provide the brighter light needed to indicate braking or reverse.

Figure 5.16 OSRAM Hybrid OLED-LED Auto Rear Light

Source: OSRAM, OLED-LED Hybrid Rear Combination Light, 2017 [151]

5.2.3 OLED Drivers

Given the broad interest in exploiting the digital nature of SSL, there is growing interest in the circuits and components that control the current supplied to each panel in an OLED luminaire. In most cases, these circuits must first transform the AC mains voltage to DC. Then the panels and connections need to be configured so that the desired DC current can be supplied at the appropriate voltage.

Although the focus in previous reports has been on energy efficiency, there are many other factors that are important in designing a control system.

- **Power factor**: This is the ratio of the real power delivered to the apparent power suggested by the product of the nominal current and voltage. It is governed by the ratio of inductive and resistive loads in the circuit. Recommended values are over 0.95.
- **Total harmonic distortion (THD)**: This is the ratio of the sum of the power in the harmonic modes to that in the fundamental AC frequency. The recommended limit is often 20%, although stricter limits are sometimes desired.
- **Electromagnetic interference**: In the United States, the limits are set by the Federal Communications Commission (FCC).
- **Wiring**: compatibility with regulations, such as those of Underwriter's Laboratory.
- **Flicker**: Most short-term temporal variations in intensity are undesirable. Although simple metrics, such as "flicker percentage" or "flicker index" are often cited, some researchers argue that one needs to study the frequency dependence of intensity variations.
- **Dimming range**: Smooth dimming should be enabled, preferably to below 1% of maximum intensity. Flicker and THD are often exacerbated at low dimming levels, and efficacy can drop substantially.
- **Allowance for aging**: As OLEDs age the luminance of uncompensated panels fades while the voltage drawn increases. The circuit should allow headroom for the increase in voltage, which would be increased further if controls boost the current to maintain the desired luminance level.
- **Independent panel control**: For luminaires with multiple panels, independent control of each panel can add functionality or compensate for undesired differences in the light output from each panel.
- **Failure response**: For almost all driving circuits, failure of one panel changes the current supplied to other panels in the luminaire. Most failures on OLEDs leave panels open.

Until recently, most OLED luminaires used drivers that were originally designed for inorganic LEDs. This can lead to unsatisfactory energy efficiency, especially in single-panel luminaires or fixtures with multiple panels with individual drivers. The problem is illustrated by Figure 5.17, which shows the dependence of a Lumiblade driver on power level [152].

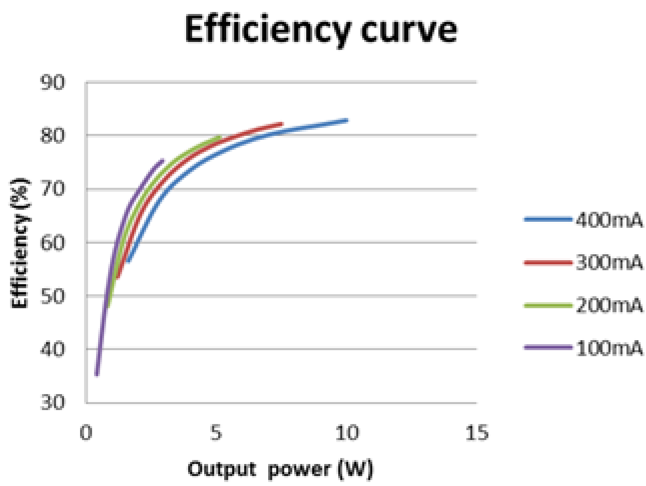
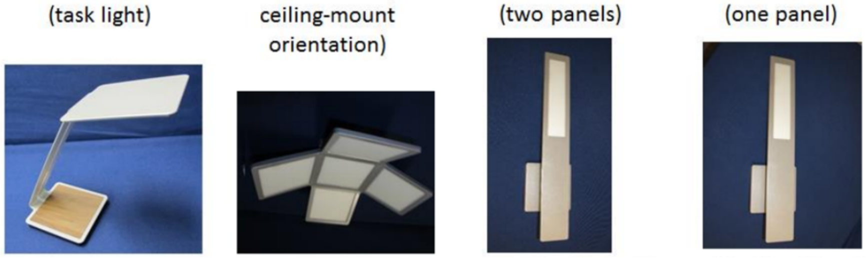


Figure 5.17 Efficiency of the Philips Lumiblade Low-Voltage OLED Driver

Source: OLEDWorks, Philips Lumiblade Specification Sheet, March 2016 [152]

The effect of low power operation is apparent in the measurements made in the 2016 CALiPER study. Figure 5.18 shows that the power factor, THD, and efficacy are unsatisfactory in luminaires with only one or two panels (i.e., test ID 15-13, 15-15, and 15-16).

CALiPER 15-13 (task light) | CALiPER 15-14 (in ceiling-mount orientation) | CALiPER 15-15 (two panels) | CALiPER 15-16 (one panel)



DOE CALiPER Test ID	Initial Output (lm)	Total Input Power (W)	Efficacy (lm/W)	Power Factor	CRI (R_a)	R_9	R_f	R_g	R_f -- Hue bin 1	CCT (K)	D_{uv}	THD-I (%)
15-13	270	9.6	28	0.45	78	-6	78	95	74	2952	0.0010	188.1
15-14 Ceiling	332	7.4	45	0.99	88	21	86	97	83	2946	0.0030	8.6
15-14 Wall	329	7.4	45	0.99	88	20	86	97	83	2940	0.0030	8.6
15-15	130	4.3	30	0.42	88	21	87	97	83	2912	0.0020	189.1
15-16	65	2.8	23	0.40	88	21	87	97	83	2855	0.0030	192.2

Figure 5.18 Colorimetric, Photometric and Electrical Data for Various OLED Products

Source: "CALiPER Report 24: Photometric Testing, laboratory Teardowns, and Accelerated Lifetime Testing of OLED Luminaires," September 2016 [123]

One barrier to the development of drivers that are especially suited for OLEDs has been the lack of standardization in the electrical characteristics of the panels, as summarized in Table 5.3. In addition to standards for panel size, shape, thickness and connection schemes, standards in electrical characteristics can help luminaire manufacturers who are burdened with the task of piecing together various panels and drivers while maintaining reasonable efficacy and retaining flexibility of panel choice for a range of product offerings.

Table 5.3 Operating Voltage and Current for Commercial Panels

OLED Panels	Operating Voltage (V)	Operating Current (mA)
LG N6SA30	6	230
LG N6SA40	8.5	150
OLEDWorks Brite 2 FL300	20	260
OSRAM CDW-031	3.4	186
Kaneka KN-P-P4-BF-30	6.8	210
Lumiotec P11B	9.2	590

Source: Jacky Qui, OTI Lumionics, DOE SSL R&D Workshop, Long Beach, CA, January 2017 [153]

Figure 5.19 shows a control system recommended for multi-panel systems by LED specialists at the 2016 DOE SSL OLED Stakeholder Meeting. The power supply transforms from 120 V AC to 48 V DC, which can be distributed to up to 14 OLED fixtures, each drawing up to 6.6 W, using Class 2 cables and connectors [154]. The 6.6 W could be used to power a single large panel or a string of smaller panels. Control signals are passed internally over separate cables using between 1 and 10 V, or DMX protocols and external links are provided over a Zigbee network [154]. Alternatively, the power and control signals can be combined, perhaps using powerline communication (PLC) or PoE technology [154].

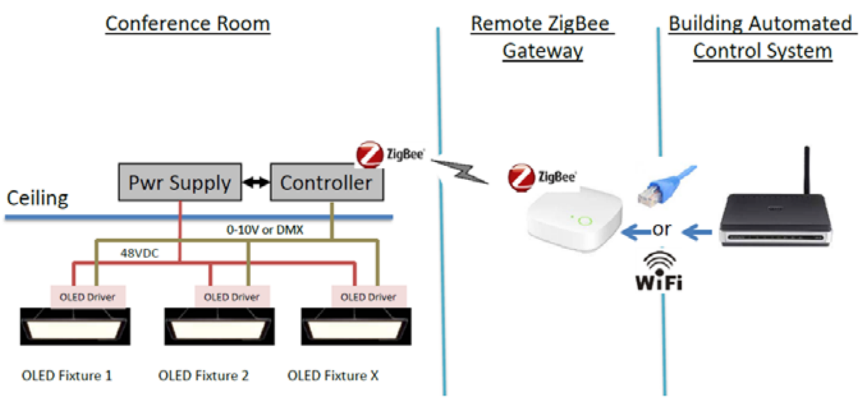


Figure 5.19 Control System for Conference Room Lighting

Source: Mike Fusco, LED Specialists, DOE SSL OLED Stakeholder Meeting, Corning, NY, October 2016 [154]

As noted in Section 5.2.1, Acuity Brands has completed a DOE SSL R&D project to build and test a system to provide individual control over each of the 66 panels in a Canvis luminaire. The configuration is shown in Figure 5.20, with three levels of control. The panels are arranged in six strands, with an intermediate strand controller.

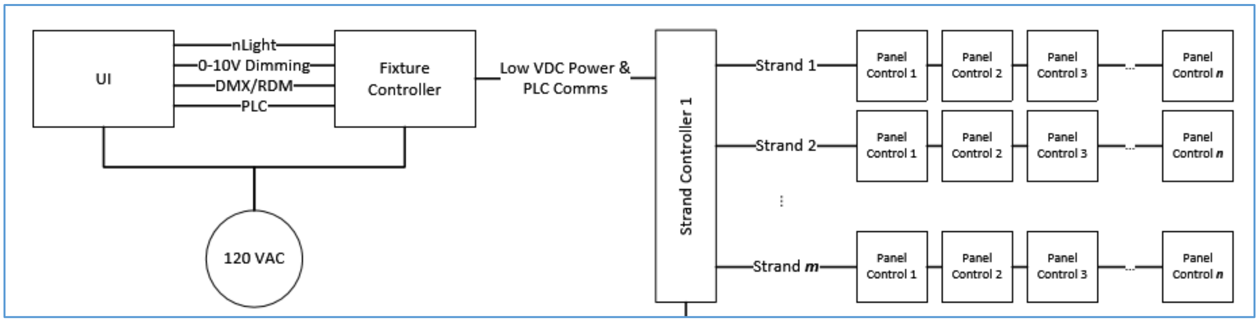


Figure 5.20 System to Provide Control for Individual Panels in an OLED Luminaire

Source: Mike Lu, Acuity Brands Lighting, DOE SSL R&D Workshop, Long Beach, CA, February 2017 [120]

The three components of the driver system are shown in Figure 5.21. The integrated drivers are held on the back surface of the panels using a cassette that provides thermal insulation between the driver and the OLED structure.

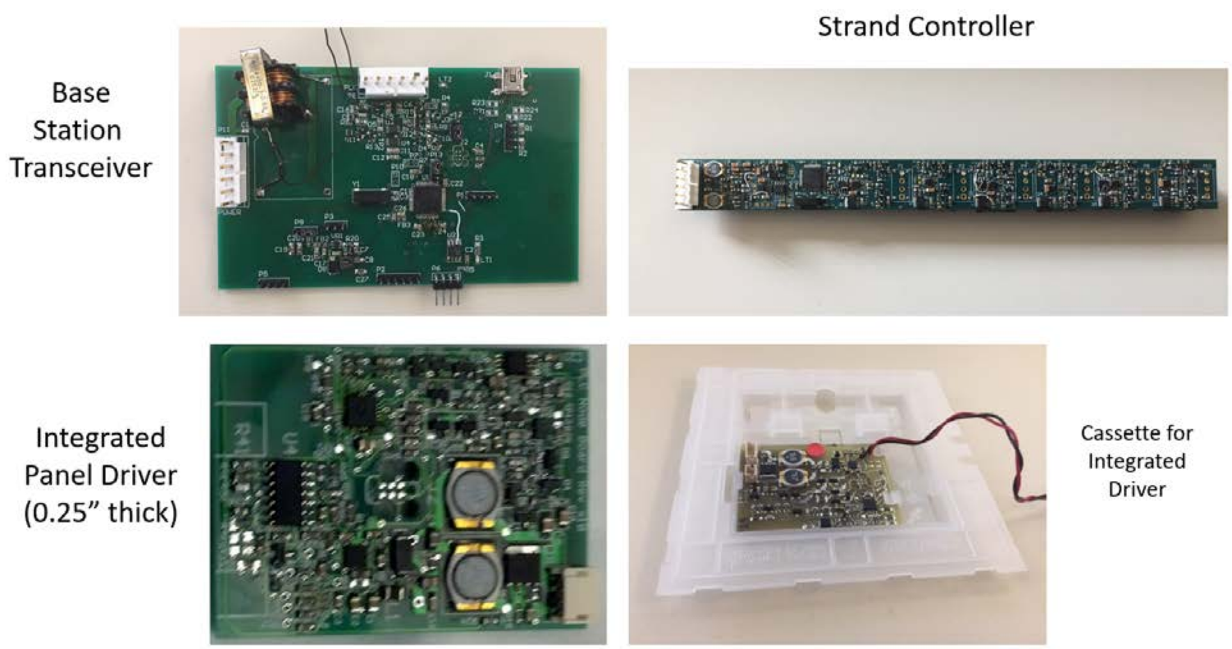


Figure 5.21 Components of the Multi-Panel Driver System with Individual Panel Control

Source: Mike Lu, Acuity Brands Lighting, DOE SSL R&D Workshop, Long Beach, CA, February 2017 [120]

5.2.4 OLED Light Engines

The thin profile of OLED panels can lead to difficulties in mounting and forming electrical connections. Also, luminaire manufacturers may not wish to invest in the evaluation and acquisition of drivers that are matched to the panels. Thus, there is growing interest in the provision of modules or "OLED light engines" through which compatible panels, drivers, and connectors are supplied together.

Figure 5.22 shows the Keuka module from OLEDWorks. The total thickness is 0.6 mm and the socket adds 21 mm to the panel length of 262 mm. Dimming is possible down to 25% of the nominal luminance, which could be as high as 8300 cd/m^2. Samples of these engines were supplied in 2016 and commercial release was scheduled for the first quarter of 2017.

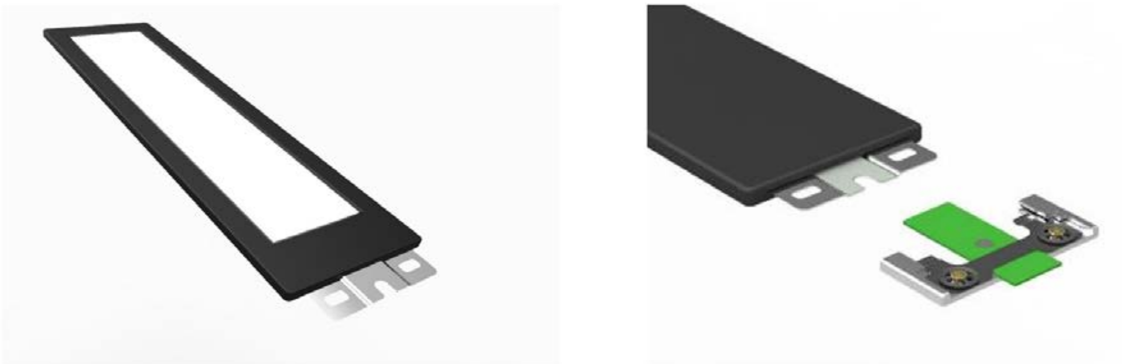


Figure 5.22 Front and Rear View of the Keuka Module

Source: OLEDWorks, Keuka OLED Module Product Sheet, 2016 [155]

5.2.5 OLED Luminaire Reliability

There have been relatively few long-term tests of the reliability of OLED luminaires. A small study of accelerated degradation in four five-panel luminaires was carried out at RTI International with DOE SSL support [156]. The panels were operated inside an oven at 45°C for 4,500 hours with a preset current of 150 mA spread over 81 cm^2 of lit panel area. The remote driver was kept outside the oven.

In one of the luminaires, one panel shorted after 500 hours of operation, and a second after 1,750 hours. There was also a problem in the power supply, but the connection between the driver and panel failures was not established. Other observations that were made during these tests included:

- 13% reduction in luminance, suggesting an L70 value of 10,000 hours at 45°C ambient
- A color shift toward blue with Δu’v’ of approximately 0.004
- 11% flicker at 120Hz

In a second test, one luminaire was operated at 75°C and 75% relative humidity. One of the panels exhibited an open-circuit failure after 750 hours. The panel developed a high impedance (over 4 megaohms) and became transparent.

Luminaire manufacturers are particularly sensitive to early-life failures and have sometimes resorted to burning in each panel before delivery to the customer. But Acuity Brands has reported significant improvement in this respect and has raised its panel failure tolerance level from 1: 1,000 to 1: 10,000.

5.2.6 Specialty Applications

Most of the leading manufacturers of OLED lighting outside the United States have indicated a special interest in automobile applications because they are a high-value application in which a high first cost is less of an issue. However, automobile applications bring formidable environmental challenges, as summarized in Figure 5.23.

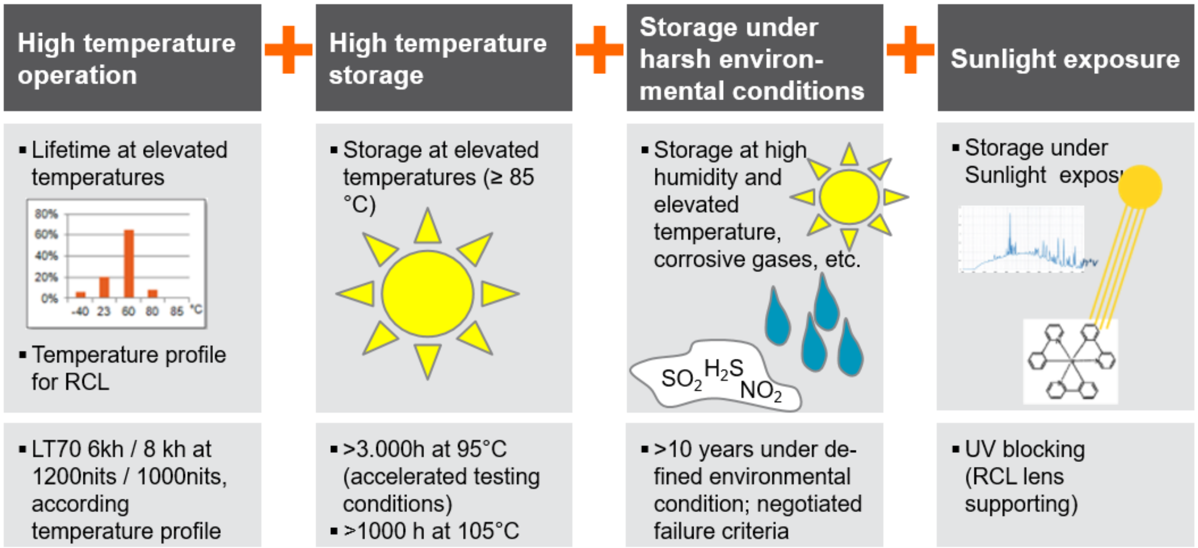


Figure 5.23 Environmental Challenges for Automobile Lighting

Source: Alireza Safaee, OSRAM, DOE SSL R&D Workshop, Long Beach, CA, February 2017 [157]

Much of the focus has been on rear lights. Philipp Rabenau of Audi estimated that on a basis of a surface area of 50 cm^2, the required luminance is 2,000 cd/m^2 for the tail light component, 20,000 cd/m^2 for the brake light, and 25,000 cd/m^2 for the turn indicator light [158]. Additionally, the red color needs to be highly saturated, with CIE (x,y) coordinates close to (0.7, 0.3). The first products were released by Audi and BMW in 2016, but adoption is currently limited to very few models. The slim form factor of OLED panels is also well suited for interior lighting in automobiles and other vehicles. Figure 5.24 shows a van exhibited by Chang's Custom at the Seoul Auto Salon 2016, with OLED panels from LG embedded in the ceiling and sides.

Figure 5.24 LG Display Supplied the OLED Light Panels that Chang's Custom Used to Illuminate the Interior of This Chevy Explorer

Source: LIGHTimes Online, August 2016 [159]

Weight reduction is important in all transportation applications, but particularly in aviation. At the OLEDWorld Summit in 2016, Mark Borus of Zodiac Aerospace estimated the available market for interior OLED lighting in aviation to be $140 million over the next decade [160]. He referred to the prototype demonstration made during a DOE SSL project with UDC and described specific designs for a dome light in the cockpit of the Dassault F5x aircraft.

5.3 OLED Manufacturing Technology Status

The following section focuses on recent progress and major challenges facing OLED manufacturing. The goals of the section are to assess the status of current manufacturing facilities and to identify the remaining challenges.

5.3.1 Current Manufacturing Facilities

OLED manufacturing has evolved from an R&D activity, with test panels being delivered to lighting designers and custom buyers, to pilot production activity, with lines designed for efficient manufacturing. These lines were developed by LG Chem in South Korea, OSRAM and Philips in Germany, First O-Lite in China, Konica Minolta in Japan, and OLEDWorks in the United States. These companies join Blackbody (France) and Lumiotec, Kaneka, and Pioneer (Japan), which have been making panels and selling luminaires for many years. Other companies, such as Panasonic, have delayed entry into commercial production, although they will continue their R&D efforts. Sumitomo Chemical has been pursuing R&D on polymer OLEDs in conjunction with Cambridge Display Technologies, and they showed multi-color panels at several trade shows in 2016, announcing that commercial production for general lighting will begin in 2017 [161].

The difficulty of establishing high-volume markets has led to several corporate reorganizations in the past few years. Philips exited the OLED lighting business and its manufacturing line in Aachen, Germany, was acquired by OLEDWorks [162]. OLEDWorks now produces its main commercial products in Europe and uses its Rochester facility for R&D and prototype panels. LG transferred its OLED lighting business from LG Chem to LG Display, which is constructing a "5th Gen" line using substrates of 1,000 mm x 1,200 mm at its factory in Gumi [163] [164]. OSRAM has continued to focus on establishing the market for automotive lighting and has announced no new manufacturing facilities. In 2013, Mitsubishi Chemical and Pioneer combined their efforts by forming MC-Pioneer OLED Lighting [165]. Further consolidation may follow the announcement in January 2017 that Konica Minolta and Pioneer were planning to merge their OLED lighting businesses in a 50-50 joint venture, with a focus on automotive applications [166]. Their medium-term sales target is 25 billion yen (¥) (approximately US$220 million). Meanwhile the Chinese display company Visionox has formed a new venture, Yeolight, to manufacture and market OLED lighting panels [167].

The new LG line is scheduled to come into production in 2017 with a capacity of 15,000 substrates per month [164]. If no allowance is made for downtime, this corresponds to a processing cycle time (TAKT) of 3 minutes. The nominal target for TAKT is 2 minutes, which would mean that the stated capacity could be achieved with downtime for holidays, maintenance, and line failures. The capital cost of the line has been estimated to be 140 billion Korean Won (KrW), or about US$125 million. Siting this line in Gumi could lead to significant transfer of technology from OLED displays, as LG is investing more than 1 trillion KrW in a line to make flexible OLED displays at the same location [168].

Perhaps the most intriguing feature of 2016 was the apparent absence of commercial products from the R2R line built by Konica Minolta in 2014, which cost about ¥10 billion (US$90 million) [169]. The plant was designed with a capacity of one million panels per month on flexible substrates, but production appears to have been limited to demonstration products. Konica Minolta continues to report on its R&D progress, but has made no public announcements regarding any manufacturing problems.

Most of the current production lines use traditional vapor deposition techniques to form the organic layers on glass substrates sized around 370 mm x 470 mm. Assuming a TAKT of 3 minutes and a yield of 70%, the total capacity of these lines is estimated to be about 100,000 m^2, sufficient to produce 10 million 100 mm x 100 mm panels. Assuming a price of $15 per panel puts estimates of potential global revenues at $150 million; however, sales revenue has been much less than this, suggesting that the available capacity is seriously underutilized.

With notable exceptions, such as LG and Konica Minolta, few manufacturers have the capital and expertise to produce the whole OLED panel. Thus, companies like OLEDWorks and First O-Lite have sought suppliers of integrated substrates, which includes a transparent conductor, light extraction structures, and barrier layers (if plastic foils are used). Although integrated substrates are the subject of intense R&D activities, the current supply is severely limited, due in part to the difficulty of patterning. Sources of integrated substrates from North America or Europe could be of great value to the industry.

Several luminaire manufacturers recently began to manufacture OLED fixtures. In the United States, Visa Lighting and Workrite have followed the precedent set by Acuity Brands, while in Europe, Emdedesign and Neumuller offer a range of OLED luminaires [170] [171] [172] [173]. In Korea, desk lights like those demonstrated by LG at Seoul National University are now being sold, and several niche manufactures offer decorative OLED luminaires. In China, Yeolight has offered desk lamps with LG panels, while it develops its own manufacturing line.

Some OLED lighting manufacturers, such as OTI Lumionics in Canada, First O-Lite in China, and Blackbody in France, are making and marketing their own fixtures [174] [175]. Others, such as OLEDWorks, are developing modules or light engines, in which drivers and connectors are added to the OLED panels to facilitate incorporation in luminaires. LG Display offers its own luminaires and is also supplying furniture manufacturers, such as the Fursys Group in Korea [176].

5.3.2 Cost Reduction

The most critical goal of OLED lighting companies is to reduce cost. The manufacturing cost of OLED panels scales more directly with panel area than with light output. Table 5.4 shows a potential route to meeting a goal of $\$100/m^2$, which may be sufficient to allow significant penetration of the general lighting market.

Table 5.4 Cost Targets for Panels Produced by Traditional Methods

	2016	2018	2020	2025
Substrate Area (m^2)	0.2	1.2	1.2	2.7
Capital Cost ($M)	50	125	125	200
Cycle Time (minutes)	3	2	1	0.5
Capacity (1000 m^2/yr)	17	175	350	2,400
Depreciation ($\$/m^2$)	600	140	70	35
Organic Materials ($\$/m^2$)	150	100	50	15
Inorganic Materials ($\$/m^2$)	200	140	100	30
Labor ($\$/m^2$)	100	25	15	5
Other Fixed Costs ($\$/m^2$)	50	15	10	5
Total (unyielded) ($\$/m^2$)	1,100	420	245	90
Yield of Good Product (%)	70	80	85	90
Total Cost ($\$/m^2$)	1,570	525	290	100

The largest cost component currently is equipment depreciation. One way to reduce the cost per unit area is to increase the size of the glass substrate used with traditional sheet-to-sheet methods. The capital cost of larger tools scales approximately with the linear dimension, while the area of product produced rises with the area of the substrate. Table 5.4 assumes that the substrate size will be 1,800 nm x 1500 mm in 2025. The anticipated size increase has been scaled back compared to previous forecasts due to the difficulty of raising the required capital.

Table 5.4 also assumes that the TAKT can be reduced to 30 seconds. The OLEDWorks line in Aachen was designed with this goal in mind, but the current cycle time is around 2 minutes [177]. An increase in the rate at which each layer can be deposited could thus be a fruitful topic for future research. The most difficult steps include the formation of the active organic layers, the cathode, and the encapsulation layers.

The use of simpler structures could also lead to reduced depreciation costs; however, almost all recent progress in performance has been achieved by increasing the system complexity, and it will be several years before this trend can be reversed. For example, reducing the number of stacks in the OLEDWorks panels from six to three would be a step in this direction.

Greater throughput is one of the potential benefits of R2R processing. Typical web speeds in pilot lines are around 3 m/min with web widths of 300 mm. This would lead to an annual input capacity of 475,000 m^2/yr. This could be sufficient to surpass the output of the new LG sheet-to-sheet line, even with lower substrate utilization and product yield.

The price of active organic materials is also expected to decrease rapidly as volume increases, and this effect has been seen with OLED displays. For example, UDC is the leading supplier of phosphorescent emitter materials; however, their revenues have risen by less than 5% over the past two years, even though the area of OLED panels has more than doubled [178]. This is partly because the costs of manufacturing the materials have been reduced but also because panel manufacturers are using the materials more effectively.

A slower rate of reduction is anticipated in the cost of inorganic materials, since these materials are at a more mature state of development. Finding less expensive alternatives for display glass substrates is proving more difficult than was expected. For example, plastic substrates with effective barriers are currently more expensive than display glass. On the other hand, internal light extraction layers are only just being deployed and should come down in price substantially as volume grows.

The relative contribution of labor costs is already low and should decrease inversely with volume. Lines such as those at OLEDWorks and LG are highly automated and require little supervision.

5.3.3 Printing Methods

Over the past 20 years there has been considerable interest in the development of printing methods for electronic and photonic materials. The use of additive patterning should result in significantly reduced waste of expensive materials. Some have argued that avoiding high-vacuum processing would reduce the capital cost of equipment, but with traditional structures, the presence of very small amounts of water vapor, oxygen, or particulates can be devastating to manufacturing yields and product lifetimes. Therefore, the leading supplier of inkjet tools processes in a nitrogen atmosphere [179]. Additionally, the need for close control of the flow through each nozzle adds to the complexity of the equipment and increases the capital cost.

Simpler methods, such as slot-die coating and gravure, have been adapted for some layers, whereas newer techniques, such as imprint lithography, are being explored to produce light extraction structures.

The inferior performance of solution-processed materials has delayed their adoption in OLED displays and lighting. Although the gap in the efficacy of active organic materials has been reduced, the conductivity of printed conductors remains well below that of bulk metals.

Increased activity in the development of printing tools and soluble materials for OLED displays may be transferred to lighting applications. For example, Kateeva has demonstrated that inkjet printing can be competitive in the deposition of the organic components of encapsulation layers and has made great progress in the deposition of patterned emitter layers.

Most printed layers must be cured after deposition. The traditional thermal curing method requires the inclusion of large ovens and increases the difficulty of reducing TAKT time, as illustrated by the pilot line at the Holst Centre, where the ovens are separated from the deposition chambers to reduce the floor space area of the clean rooms [180]. Photo curing can be accomplished in much shorter times and has been applied to active organic layers, printed grids, and encapsulation materials.

When printing active organic layers, care must be taken to ensure that the deposition of each layer does not damage the underlying material. Inter-layer interactions can be ameliorated by using cross-linked polymers. Reducing the number of layers is a prime goal of solution processing, due to simpler manufacturing and the potential of substantial savings in capital costs. One of its leading proponents, Sumitomo Chemical, has focused on 1-stack structures with only four organic layers [181].

5.3.4 Conformable Panels

Although there is relatively little demand for lights to be continuously flexed or folded, the availability of conformable panels could substantially increase the demand for OLED luminaires, either through the production of 3-D shapes or panels embedded in curved surfaces.

As demonstrated by Corning, bending radii of a few centimeters can be achieved with thin glass, about 100 micrometers (μm) thick [182]. Thin glass can be processed by R2R as well as sheet-to-sheet lines. Even thin glass provides an excellent barrier to water and oxygen, so that the problem of encapsulation is reduced to that of edge sealing. However, such panels are very fragile during manufacture, transport, and installation.

Plastic substrates and covers are more robust, but the materials that are used in displays, such as polyimide and polyethylene-naphthalate, are relatively costly and require expensive barrier layers. The processing temperatures needed for OLED lighting are less than those for the thin film transistor backplanes in OLED displays, so that polyimide may not be necessary.

The requirements for positional accuracy are also more relaxed in the fabrication of OLED lighting panels than for displays, and they can be fulfilled easily in R2R processing. For sheet processing, the plastic substrate is usually attached temporarily to a rigid base during the manufacturing process. The techniques for attaching to and detaching from the temporary substrate that have been developed for OLED displays could be transferred to lighting panels.

Flexibility also constrains the choice of materials for some of the internal layers, such as the light extraction structures. Although tolerance of continual flexing was one of the motives to seek a replacement for ITO as a transparent electrode, thin layers of ITO have been used successfully in conformable panels.

5.3.5 Layer Formation

Deposition of Active Organic Materials

Many factors must be considered when choosing equipment to deposit the organic materials that transport charge between the electrodes and create photons. These include:

- **Deposition times** – For evaporation sources, the deposition rate depends strongly on temperature. Most of the system often operates at temperatures above 300°C, but the substrate should be kept cool. Stability at high temperatures is critical in the choice of organic materials. Deposition rates around 5 nm/s are typical targets.

- **Material use efficiency** – Low utilization levels not only increase the cost of the organic materials, but also necessitate more frequent cleaning. Deposition of organic molecules outside of the substrate (e.g., leading and trailing the substrate onto the walls of the deposition chamber) must be minimized. Typical short-term goals for utilization efficiency are 50% to 70%. Inkjet printing and slot-die coating can achieve much higher levels of material utilization and are clearly advantageous in this respect.

- **Contaminant control** – Studies by UDC have shown that even low levels of water vapor within the deposition chamber can shorten the lifetime of the OLED products. It recommends partial pressures of less than 10^{-8} Pa, which can be attained under ultra-high vacuum conditions or in a nitrogen atmosphere with purification. Particulate control is also critical.

- **Uniformity** – Tight control needs to be maintained over the thickness of the active layers and the doping ratios within emitter layers. Variations of $\pm$3% are typical. With the growing interest in the use of corrugated substrates, conformal deposition is usually desired. However, when the underlying structures contain sharp edges or nanoscale irregularities, some degree of planarization can be important in the first layers, often in the hole injection layer or hole transport layer.

- **Cost** – Although there is little public information about the cost of equipment designed for lighting panels, Display Supply Chain Consultants estimates the total market in 2017 for OLED deposition tools to be $2.2 billion [183]. The anticipated extra production in 2018 is 3 million m^2, suggesting that a capital investment of around $750 is needed to enable each m^2 of annual production [183]. The associated depreciation cost of around $150 (assuming straight-line depreciation over 5 years) would be more than the long-term target for the total panel cost [183]. Thus, it seems essential that less expensive or more productive tools be developed for OLED lighting.

Significant progress has been made in the past few years in the development of evaporation sources that are more suited to lighting applications, e.g., through the DOE SSL funded project at OLEDWorks. Aixtron has obtained excellent results using organic vapor phase deposition, in which the organic molecules are transported from source to substrate in an ultra-pure nitrogen gas atmosphere [184]. Kateeva has brought inkjet printing from the laboratory into high-volume OLED manufacturing, although initial application has been to encapsulation layers [179]. In Japan, JOLED has completed its demonstration that inkjet printing can also be used to print active organic layers with high productivity and reliability, and plans to start construction of its high-volume manufacturing line in 2017 [185].

Light Extraction Structures

In very simple terms, the major goal in the formation of light extraction structures is to break the planar symmetry of OLED panels in such a way that does not make it impossible to deposit effective OLED emitters. As described in Section 5.1.5, this can be accomplished using external films, corrugated substrates, structured electrodes, or additional layers inserted between the substrate and transparent electrode.

There are several providers of external films that can be laminated to the substrate. These films are usually manufactured by positive or negative copying from a master pattern, which could be formed on one of the rolls used in R2R processing. The cost of such films, at around $\$40/m^2$, is large compared to the future cost targets shown in Table 5.4, but is justified by the increase in efficacy. Because such films enhance the light output by up to 80%, the area needed to produce the desired output is reduced by 45%, with savings of about $\$700/m^2$ in 2016.

Although the effectiveness of external films could be enhanced using high-index substrates, most recent efforts have been focused upon internal structures. Pixelligent has shown that scattering layers can lead to enhancements of around 2.5x [186].

Two elements are critical in the design of Pixelligent's films. The first is to be able to control the refractive index, which is achieved with its PixClear technology by embedding ZrO_2 nanocrystals within the film. The surfaces of the nanocrystals are well-passivated by capping agents, which prevent aggregation and offer compatibility in many different solvents, monomers, and polymers. High weight loadings of nanoparticles, which is required to raise the refractive index to better match that of the anode, can be achieved while still maintaining transparency and the low viscosities necessary for solution processing techniques such as inkjet printing and slot-die coating [187]. Pixelligent is also experimenting with graded index layers to reduce Fresnel reflection as light propagates toward a substrate with lower index. The second is the inclusion of larger particles to scatter the light, whose dimensions need to be close to the wavelength of visible light to ensure Mie scattering. Assuring a smooth surface for deposition of the transparent electrode and organic layers is essential.

A few years ago, Panasonic obtained impressive results in an internal scattering layer, which produced a large refractive index contrast by forming a micro-structured high-index layer within an air gap, but was unable to commercialize this approach. There is concern about the inclusion of air within the OLED, and an alternative low-index filler material might be needed. In a new DOE SSL project, MicroContinuum has shown that such structures can be created with pitch less than 1 µm in polycarbonate by R2R printing, as shown in Figure 5.25.

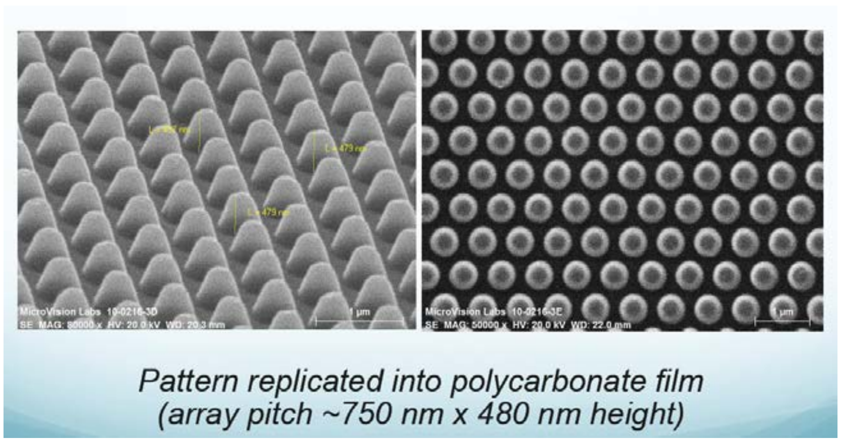


Figure 5.25 OLED Light Extraction Pattern

Source: Dennis Slafer, MicroContinuum, DOE SSL OLED Stakeholder Meeting, Corning NY, October 2016 [188]

A third approach to symmetry breaking is to use corrugated substrates. The group at North Carolina State University has demonstrated two ways to use silica spheres (diameter about 500nm) to form corrugated substrates [143]. One approach is to form a mold of polydimethylsiloxane (PDMS) on top of a closely packed layer of such spheres. The mold is then used to imprint the pattern into a UV-curable resin. The second method is to use the spheres to create a mask for plasma etching of a high-index sapphire substrate.

Electrodes

Two recent developments have reduced activity in development of alternative transparent electrode structures to replace ITO, the use of multi-stack structures and the reduced cost of depositing ITO. The use of multi-stack structures lowers the required current densities, and panels with dimensions up to 100 mm can be manufactured without the need for wire grids to supplement the homogeneous conducting layer. The cost of depositing ITO in high volume has come down in recent years; however, it is still difficult for small OLED manufacturers to obtain patterned ITO substrates and capital costs for in-house ITO deposition are relatively high.

As noted above, silver nano-wires are one of the most attractive ITO alternatives. Although the attention of commercial suppliers has turned to other applications, Sinovia has shown that relatively thick wires can be embedded in polymer layers with a surface that is smooth enough to allow the deposition of long-lived OLED panels [189]. The layers can be deposited by standard solution processing techniques, such as slot-die coating or gravure. Sinovia has demonstrated that its films can be combined with barrier layers from Vitriflex to form flexible integrated substrates [190]. Sinovia already has achieved water vapor transmission rates below 10^{-5} g/m^2/day and sheet resistance of less than 5 Ω/□. The remaining challenge is to improve light extraction. The silver wires provide some haze, but other scattering particles or focusing structures may be needed to meet DOE targets.

Cathode deposition may present a barrier to significant reduction in process cycle times. The preferred technique of evaporation is relatively slow, but does not damage the underlying organic layers. Sputtering can be performed more quickly, but puts greater strain upon the fragile organics. The replacement of Al cathodes by silver or a structure that is less susceptible to surface plasmon excitation may also necessitate a change in fabrication technique.

Barrier Layers

The demand for flexible OLED displays has led to huge investment in equipment to manufacture multi-layer barriers for plastic substrates and covers. Substantial orders for tools capable of handling very large substrates have been received by Applied Material, for plasma-enhanced chemical vapor deposition (PECVD) of the hard, inorganic layers, and by Kateeva, for inkjet printing of the softer organic layers.

For high-volume manufacturers, the productivity of these tools justifies their high capital cost, but alternative techniques may be more appropriate for the smaller substrates and lower volumes of OLED lighting. Atomic layer deposition is being promoted for inorganic layers by European companies such as Beneq, Encapsulix, and Meyer Burger, and by Lotus Applied Technologies in the United States. Vitriflex and Aixtron have developed methods to replace the organic components of multi-layer films by soft layers that can be deposited along with the hard layers. Vitriflex has constructed a R2R physical vapor deposition tool with six deposition zones and a capacity of about one million m^2/yr with a web width of up to 1.4 m [191]. The OptaCap system from Aixtron uses PECVD operating in sheet-to-sheet mode with substrates of width up to 470 mm [184].

Encapsulation

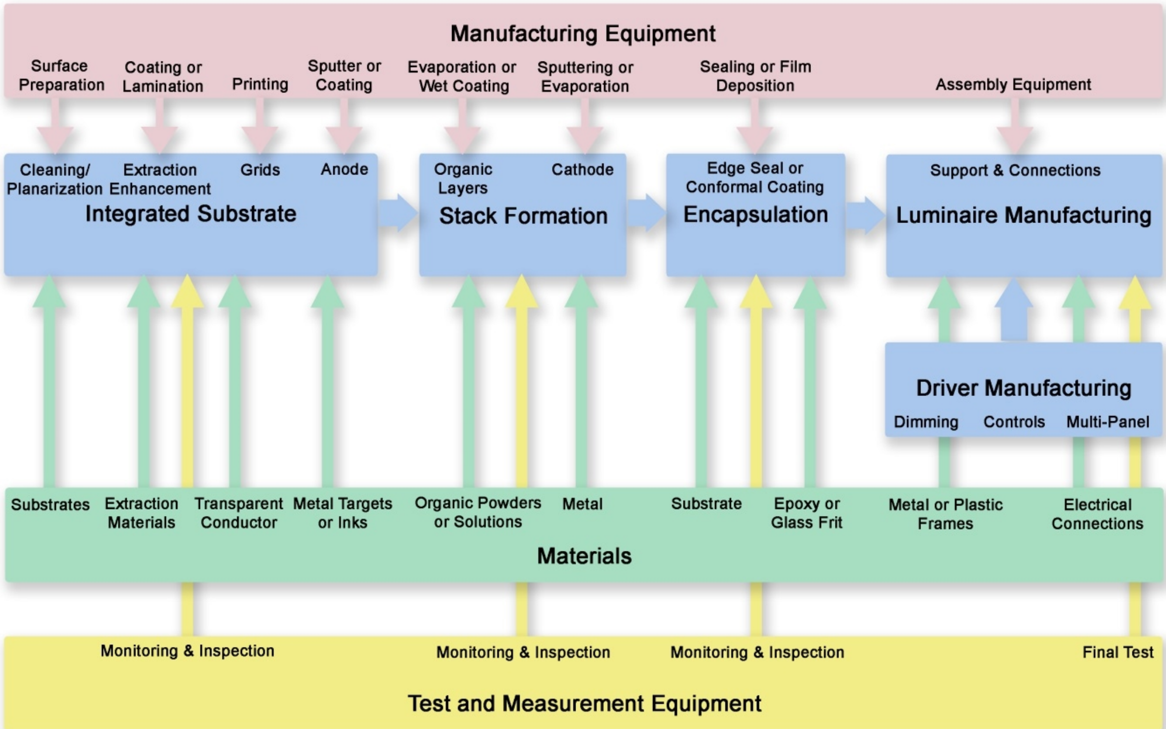
Several encapsulation methods are available that maintain the thin profile and low weight of OLED panels. A sheet of ultra-thin glass or plastic with a multi-layer barrier can be laminated on top of the upper electrode. Care must be taken to prevent the ingress of oxygen and moisture through the edges. Adhesive materials with barrier or absorbing properties are available from several companies, such as Addison Clear Wave, DELO, Henkel, LG Chem, SAES Getters, and 3M. For downward-emitting structures, thin metal can be used as a cover, providing some mechanical stability and thermal distribution, as well as an effective surface barrier. This solution has already been implemented by LG Display.

The edge effects can be minimized by in-situ deposition of a thin film barrier. However, high temperature processes must be avoided to prevent damage to the underlying layers, and patterning is needed to avoid coating the electrical contacts at the edge.

Edge ingress is also a concern whenever relatively thick layers are included in the internal OLED structure. Patterning to isolate such layers from the panel edges can be accomplished during deposition, through inkjet printing, slot-die coating, or gravure. Alternatively, the unwanted material can be removed after deposition through laser ablation.

5.3.6 Supply Chain Outline

Although the number of companies involved in the manufacturing of OLED panels or luminaires is relatively small, they depend on many suppliers of materials, equipment, and process techniques. The roles of the various suppliers are indicated in Figure 5.26. Appendix 6.2.2 contains additional information on companies involved in the OLED supply chain.



Note:

The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow, as indicated by the relevant arrows.

Figure 5.26 OLED-Based SSL Manufacturing Supply Chain

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6 Appendices

6.1 Definitions and Background

Table 6.1 Summary of LED Application-Based Submarkets with Examples of Products in Each [16]

Application	Type	Description	Examples
A-type	Lamp	A-type lamp shapes with a medium-screw base.	
Decorative	Lamp and Luminaire	Bullet, candle, flare, globe, and any other decorative lamp shapes, as well as integrated chandelier, single head pendant, wall sconce, lantern, and cove luminaire	
Directional	Lamp and Luminaire	Reflector (R), bulged reflector (BR), and parabolic reflector (PAR) lamps, as well as track heads and integrated track luminaires.	
Small Directional	Lamp	Multifaceted reflector (MR) lamps.	
Downlighting	Retrofit Kit and Luminaire	Downlight retrofit kits and integrated downlight luminaires.	
Linear Fixture	Lamp, Retrofit Kit and Luminaire	Lamp replacements for T12, T8 and T5 fluorescent lamps, as well as retrofit kits and luminaires replacing traditional fluorescent fixtures (i.e. troffers, linear pendants, strip, wrap around, and undercabinet).	
Low/High Bay	Lamp and Luminaire	High wattage lamp replacements as well as low and high bay integrated fixtures.	
Indoor Other	No Distinction	Lamps with uncommon base types (i.e. festoon, mini bi-pin, etc.), luminaires designed for portable, specialty and emergency applications (white), and rope/tape lights.	
Parking (Lot)	Lamp and Luminaire	High wattage lamp replacements as well as luminaires used in parking lot and top deck parking garage illumination.	
Parking (Garage)	Lamp and Luminaire	Replacement lamps and luminaires for attached and stand-alone covered parking garages.	
Streetlights/Roadway	Lamp and Luminaire	Replacement lamps and luminaires installed in street and roadway applications.	
Building Exterior	Lamps and Luminaires	Lamps and luminaires installed in façade, spot, architectural, flood, wall pack, bollard and step/path applications. Not including solar cell products.	
Outdoor Other	No Distinction	Lamps and luminaires used in signage, stadium, billboard (white) and airfield lighting.	

6.2 SSL Supply Chain – Additional Information

6.2.1 LED

LED, lamp, and luminaire manufacturing are global enterprises with a global supply chain. Some geographical production trends can be identified; however, many of the input materials and semiconductor processing tools are produced worldwide. Table 6.2 and Table 6.3 highlight the global nature of SSL manufacturing by listing some of the key companies in each major geographical region involved in the manufacturing of LED-based SSL products and in the supply of equipment and materials to that market. These tables categorize geographical location based on company headquarter location and may not accurately reflect the balance of manufacturing activity.

Table 6.2 The LED Supply Chain: LED Die, LED Package, and Luminaire Manufacturers

Supply Chain	North America	Europe	Asia
Die Manufacturing	• Cree • Lumileds • Bridgelux • Soraa • SemiLEDs • Luminus Devices	• OSRAM Opto Semiconductors • Plessey Semiconductors	• Nichia • Toyoda Gosei • Harvatek • Sharp • MLS Lighting • Sanan Opto • Citizen • OptoTech • Epistar • Everlight • Lumens • Kingbright • Samsung • Lextar • LG Innotek • Seoul • Semiconductor • Elec-Tech Opto • Edison Opto • HC SemiTek
LED Package Manufacturing	• As above • Xicato	As above and: • Optogan	As above and: • Lite-On • Unity Opto • Refond • Nationstar • Shenzhen Jufei • Honglitronic
Luminaire Manufacturing	• GE Lighting • Eaton • Hubbell Lighting • Soraa • Cree Lighting • Acuity Brands • Lighing Science Group • Digital Lumens • Finelite • Feit • Ecosense Lighting • Ecolite LED	• Philips • Zumtobel • Aura Lighting • Dialight • Fagerhult • Optogan	• Panasonic • Toshiba • Sharp • LG • Samsung • Forest Lighting • LEDVance • Kingsun • Zhejiang Yankon • Shenzhen Changfang • Opple Lighting • PAK Corp • Nationstar • NVC Lighting Tech Corp • FSL

Table 6.3 The LED Supply Chain: Equipment and Materials Suppliers

Supply Chain		North America	Europe	Asia
Equipment Suppliers	• Epitaxial growth	• Veeco Instruments	• Aixtron	• Taiyo Nippon Sanso
	• Wafer • processing	• Plasma-Therm • Lam Research • Ultratech • Kurt J. Lesker Co. • JPSA • Temescal • Applied Materials	• Oxford Instruments • EV Group • SUSS MicroTec • Logitech	• Nikon Corp • Canon Inc. • Ushio Inc. • SAMCO
	• LED packaging	• Palomar Tech • Heller • Nordson ASYMTEK	• Besi • Juki	• ASM Pacific Tech • Thinky • TOWA • Disco • Kulicke & Soffa
	• Luminaire • assembly	• Speedline Tech • Conveyor Tech	• ASM Siplace • Assembleon	• Panasonic • Fuji Machines • Nutek
	• Test and • inspection	• KLA-Tencor • Cascade Microtech • Orb Optronix • Vektrex • Ocean Optics • Lighting Sciences Inc. • Gamma Scientific • Radiant Zemax • SphereOptics • Daitron • Optest • Nanometrics • Chroma • Rudolph Tech • Labsphere	• Laytec • Bede • Bruker • Instrument Systems • Cameca • SUSS MicroTec • Ismeca	• Quatek • Fittech Co • QMC • Everfine • Shibuya • Panasonic • Fujikom

Table 6.3 (continued)

Supply Chain		North America	Europe	Asia
Materials Suppliers	**Substrates**	• Rubicon • Silian • Cree • Kyma	• Monocrystal • Ammono • St. Gobain • EpiGaN • SiCrystal	• Kyocera • LG Siltron • Crystalwise Tech • Air Water Inc. • Ningxia ProCrystal • Namiki • Mitsubishi Chem Corp • Hitachi Cable
	Chemical reagents	• SAFC Hitech • Dow Electronic Materials • Air Products • SAES Pure Gas • Pall Corporation	• AkzoNobel • Linde Industrial Gases • Air Liquide	• Showa Denko KK • Matheson Tri Gas
	Packaging	• Bergquist Company • Cambridge America • CofanUSA • Indium Corp. • DuPont • Alpha	• Heraeus	• Chin-Poon • Gia Tzoong • Tong Hsing • Ecocera • Leatec • Polytronics Tech • Univacco Tech • Taiflex • Kyocera • Viking Tech • Zhuhai Totking • Denka
	Phosphors/ Down-converters	• Intematix • Philips Lumileds (internal) • GE (internal) • PhosphorTech • QD Vision • Nanosys • Pacific Light Tech	• Merck • Osram Opto Semiconductors (internal)	• Nichia (internal) • Mitsubishi Chemical Corp • Shin-Etsu • Denka
	Encapsulation	• Dow Corning • Nusil • SiVance • Momentive Performance Materials	• Wacker Chemie • (LUMISIL)	• Shin-Etsu

6.2.2 OLED

The global extent of the OLED supply chain can be assessed from Table 6.4 and Table 6.5. However, these lists are incomplete, and some of these companies are still at the development stage and may not yet have commercial offerings.

Table 6.4 The OLED Supply Chain: Global Equipment and Materials Suppliers

	Supply Chain	North America	Europe	Asia
Equipment Suppliers	**Vapor deposition**	• Kurt Lesker • Trovato Mfg	• Aixtron • VG Scienta • Von Ardenne	• AMS • Canon Tokki • Choshu • GJM • Hitachi Zosen • Jusung • SFA • SNU Precision • Sunic Systems • ULVAC • YAS
	Coaters, printers, and patterners	• Dimatix • NovaCentrix • nTact • Sono-Tek • Xenon Corp	• 4Jet Technologies • Ceradrop • Coatema • Manz • Mbraun • Meyer Burger	• Dai Nippon Screen • Screen Holdings • Seiko Electron • Sung Am Machinery • Tazmo • Tokyo Electron • ULVAC
	Encapsulation	• Applied Materials • Coherent • Kateeva • Lotus • Veeco	• Aixtron • Beneq • Encapsulix • Kurdex	• AsiaTree • Avaco • Canon Tokki • FujiFilm • HB Industries • Jusung • Shimadzu • ULVAC • Wonic IPD • YAS
	Test and inspection	• Colnatec • Radiant Zemax	• Laytec • Instrument Systems • SEMPA • Schenk Vision • VG Scienta • Vinci Tech	• Chroma ATE • Hitachi High-Tech • Kisco Uniglaobe • KMAC • Konica Monolta • Micro Inspection • Micronics
Materials Suppliers	**Substrates**	• Alcoa • DuPont-Teijin • Pilkington • Corning • PPG	• ArcelorMittal • St. Gobain • Schott Glass	• Asahi Glass • LG Chem • Nippon Electric Glass • SKC Kolon • Ube
	Extraction materials	• 3M • Pixelligent • Luminit	• Covestro	• Kimoto Tech • Toppan Printing
	Active organic materials	• DuPont • PPG • R-Display • UDC	• BASF • Cynora • Merck • Novaled • Ossila • Sensient	• Aglaia • Doosan • Dow Electro-Materials • Duksan Hi-Metal • eRay Opto • Jilin Optical • Kyulux • LG Chem • Lumtech • Mitsubishi Chem • Mitsui Chemical • Nissan Chemical • RuiYuan • Samsung SDI • Sumitomo Chemical • Sun Fine Chemical

Supply Chain		North America	Europe	Asia
				• Hodogaya • Idemitsu Kosan • Nippon Steel Sumikin • Wan Hsiang OLED
	Conductors	• Cambrios • Chasm • DuPont • ElectronInks • Intrinsiq Materials • Micro-continuum • Sinovia	• Agfa • Genes'Ink • Heraeus • Inkron • SEFAR AG	• DNP • Nagase • OLED Materials Solutions
	Encapsulation	• DuPont • 3M • Vitriflex	• DELO • Henkel • SAES Getters • Sud-Chemie • Tesa	• Dynic • Fujifilm • Futaba • Jindal • LG Chem • Konica Minolta • Samsung SDI • Tera Barrier

Table 6.5 The OLED Supply Chain: Global Panel and Luminaire Producers

Supply Chain	North America	Europe	Asia		
Panels	• OLEDWorks	• Astron-Fiamm • OSRAM Opto	• Ason • First O-Lite • Kaneka • Konica Minolta • LG Display	• Lumiotec • MC Pioneer • NeoView Kolon • Showa Denko	• Sumitomo Chemical • Visionox • WiseChip • Yeolight
Luminaires	• Acuity • Alkilu • Birot • Eureka Lighting • OTI Lumionics • Ledra Brands • Visa • Workrite	• Architonic • Blackbody • Emdedesign • Lighting Technologies • Modular Lighting • Neumuller • Regiolux • RP-Technik • ToRed	• Feelux • First O-Lite • Fursis Ilroom	• Morikawa • Synqroa • Verbatim	• Wooree

The key cost drivers for each major element of the OLED supply chain are summarized in Table 6.6.

Table 6.6 The OLED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers
Equipment Suppliers	Sealing	• Seal integrity • Process time
	Evaporators	• Deposition rate • Materials utilization • Capital cost
	Wet Coaters	• Drying time • Patterning
	Luminaire Assembly	• Modularization • Automation
	Test and Inspection	• Throughput • Accuracy
Materials Suppliers	Substrates	• Material selection • Surface condition
	Organic Stack	• Sales volume • Efficacy • Lifetime
	Encapsulation	• Increased sales volume • Elimination of desiccants
	Electrodes	• Material selection • Patterning
	Extraction Structures	• Processing yield • Performance
Panel Manufacturing		• Yield • Throughput • Capital • Testing
Luminaire Manufacturing		• Panel price • Labor • Modularization • Testing

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6.3 DOE Program Status

6.3.1 Funding Levels

DOE received $20.5 million from Congress for SSL R&D in FY 2017, which began in October 2016. These levels are somewhat smaller than congressional appropriations from previous years, as seen in Figure 6.1. In FY 2009, an additional, one-time funding of $50 million was provided through the American Recovery and Reinvestment Act of 2009, to be used to accelerate the SSL R&D Program and jump-start the manufacturing R&D initiative.

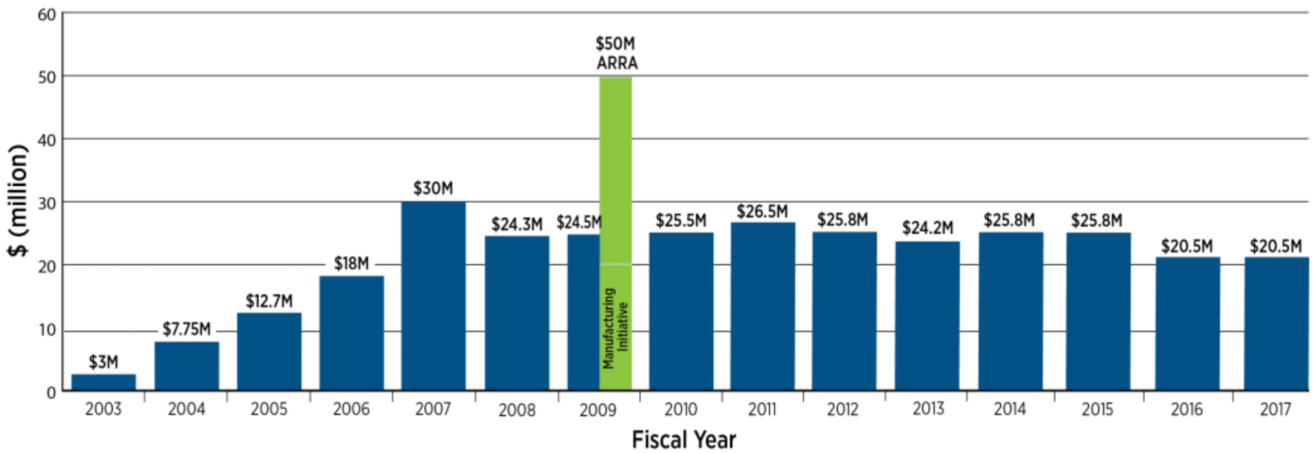

Figure 6.1 Funding Allocations for SSL, FY 2003 to 2016

Source: James Brodrick, DOE SSL R&D Workshop, Raleigh, NC, January 2016 [192]

6.3.2 Current SSL Portfolio

The active DOE SSL R&D Portfolio,[x] as of March 2017, is provided in Table 6.7. The portfolio includes 35 projects that address LED and OLED advancements across the application spectrum. Projects balance long-term and short-term activities, as well as large and small business, national laboratory, and university participation. The portfolio totals some $33.8 million in government and industry investment.

Figure 6.2 provides a graphical breakdown of the funding for the current SSL project portfolio as of March 2017. DOE is providing $27.3 million for the projects, and the remaining $6.5 million is cost-shared by project awardees. Of the 35 active projects in the SSL R&D portfolio, 23 focus on LED and 12 focus on OLED technology.

[x] For the full list of all current and previous DOE SSL funded projects see: https://energy.gov/eere/ssl/downloads/solid-state-lighting-project-portfolio

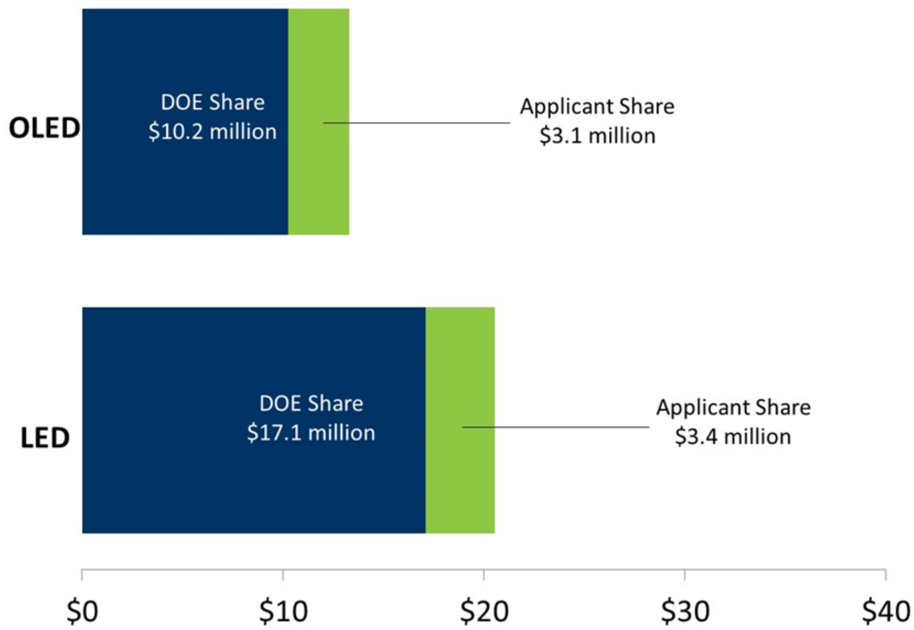

Figure 6.2 Funding of SSL R&D Project Portfolio by Funder, March 2017

DOE supports SSL R&D in partnership with industry, small business, national laboratories, and academia. Figure 6.3 provides the approximate level of R&D funding contained in the current SSL portfolio among the four general groups of SSL R&D partners.

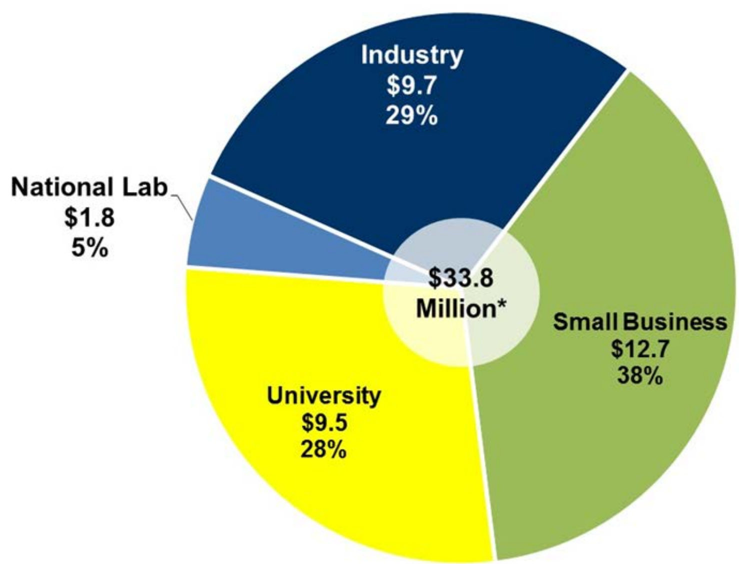

Figure 6.3 DOE SSL Total Portfolio Summary by Recipient Group, March 2017

Table 6.7 SSL R&D Portfolio: Current Research Projects, Q1 2017

	Research Organization	Project Title
LED	Carnegie Mellon University	Novel Transparent Phosphor Conversion Matrix with High Thermal Conductivity for Next Generation Phosphor-Converted LED-based Solid State Lighting
	Cree	Materials and Designs for High-Efficacy LED Light Engines
	University of California, Santa Barbara	Identification and Mitigation of Droop Mechanism in GaN-Based LEDs
	Eaton Corporation	Print-Based Manufacturing of Integrated, Low-Cost, High-Performance SSL Luminaires
	Los Alamos National Laboratory	Next Generation 'Giant' Quantum Dots: Performance Engineered for Lighting
	Philips Research North America	Innovative Office Lighting System with Integrated Spectrally Adaptive Control
	Research Triangle Institute	Luminaires for Advanced Lighting in Education
	Research Triangle Institute	System Reliability Model for SSL Luminaires
	Momentive Performance Materials Quartz, Inc.	Next-Generation LED Package Architectures Enabled by Thermally Conductive Transparent Encapsulants
	Philips Research North America	Innovative Patient Room Lighting System with Integrated Spectrally Adaptive Control
	Lumileds	Improved InGaN LED System Efficacy and Cost via Droop Reduction
	Vadient Optics*	Alternative Interconnect Manufacturing – Printed SSL Optics
	SC Solutions*	Real-Time Learning Temperature Control for Increased Throughput in LED Manufacturing
	UbiQD*	Non-radiative Recombination Pathways in Non-carcinogenic Quantum Dot Composites
	Lumisyn*	High Performance Colloidal Nanocrystals
	PhosphorTech*	Hybrid Down-Converting Structures for Solid State Lighting
	Innosys*	Lowering Barriers to Intelligent SSL Adoption through a Combination of a Next Generation Installation/configuration Software Platform and a Novel Luminaire
	Lucent Optics*	Ultra-Thin Flexible LED Lighting Panel
	Lumisyn*	LED Downconverter Phosphor Chips Containing Nanocrystals
	PhosphorTech*	Plasmonic-enhanced High Light Extraction Phosphor Sheets for Solid State Lighting
OLED	Arizona State University	High-Efficiency and Stable White OLED Using a Single Emitter
	University of California, Los Angeles	The Approach to Low-Cost High-Efficiency OLED Lighting
	University of Michigan	Stable, High Efficiency White Electrophosphorescent Organic Light Emitting Didoes by Reduced Molecular Dissociation
	OLEDWorks, LLC	High-Performance OLED Panel and Luminaire
	OLEDWorks, LLC	Innovative, High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting
	Sinovia Technologies	Integrated Plastic Substrates for OLED Lighting
	Pixelligent Technologies, LLC	Advanced Light Extraction Structure for OLED Lighting
	PPG Industries	Manufacturing Process for OLED Integrated Substrate
	Princeton University	ITO-free White OLEDs on Flexible Substrates with Enhanced Light Outcoupling
	Acuity Brands Lighting	OLED Luminaire with Panel Integrated Drivers and Advanced Controls
	OLEDWorks*	Development of high-efficiency white OLEDs using TADF emitters

* Small Business Innovation Research projects.

6.3.3 Patents

As of January 2017, 118 SSL patents have been awarded to research projects funded by DOE. Since December 2000, when DOE began funding SSL research projects, 274 patent applications have been submitted, including those from large businesses (89), small businesses (99), universities (74), and national laboratories (12). These patents are listed on the DOE website at: https://energy.gov/sites/prod/files/2017/01/f34/patents_factsheet_jan2017.pdf.

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