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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

2018 Solid-State Lighting R&D Opportunities

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Disclaimer

DOE BTO SSL Program, "*2018 Solid-State Lighting R&D Opportunities*," edited by James Brodrick, Ph.D.

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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
ALD	atomic-layer deposition
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
BTO	Building Technologies Office
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-mixedLED
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/internal quantum 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

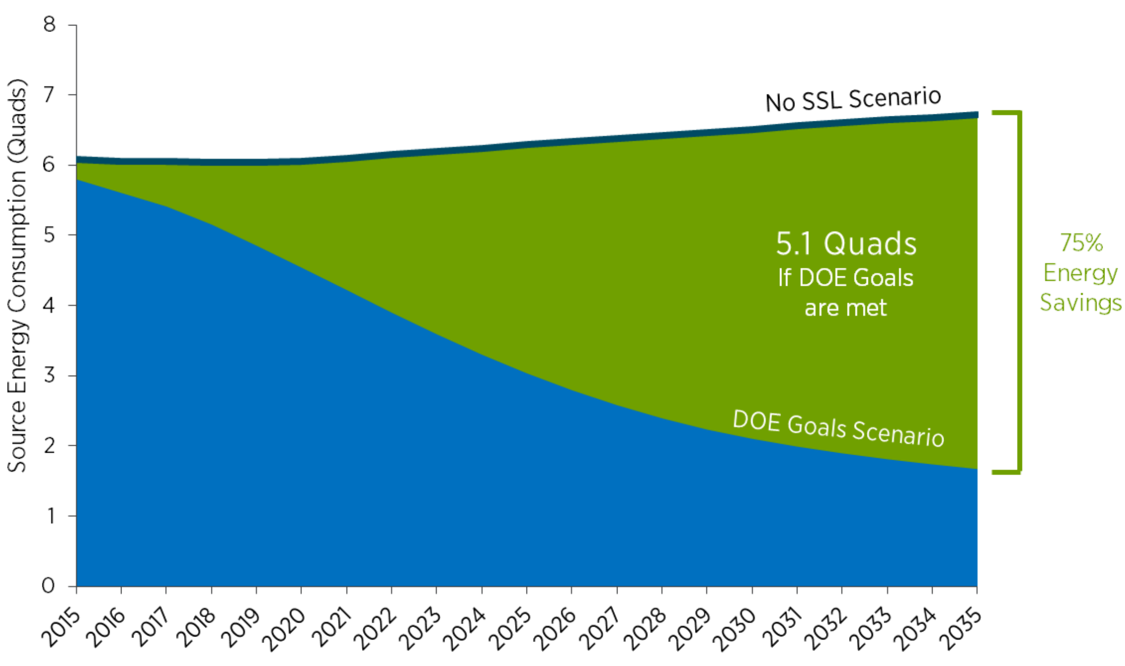
NGLIA	Next Generation Lighting Industry Alliance
NIST	National Institute of Standards and Technology
nm	nanometer
OLED	organic light emitting diode
OVPD	organic vapor phase deposition
PAR	parabolic aluminized reflector
PCB	printed circuit board
PCE	power conversion efficiency
PCS	peelable-clean surface
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
R_9	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
R&D	research and development
SEMLA	sub-electrode microlens array approach
SiC	silicone carbide
SPP	surface plasmon polariton
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 aluminum garnet
ZESCO	Zambia Electricity Supply Corporation
ZrO_2	zirconium dioxide
μm	micrometer
$\Delta u'v'$	magnitude of color shift in the CIE 1976 chromaticity diagram (u', v')
Ω/□	resistivity per unit area

1 Executive Summary

Solid-state lighting (SSL), particularly light emitting diode (LED) based SSL, is on course to become the dominant technology across all lighting applications. The luminous efficacy, as measured in lumens per Watt (lm/W) of SSL continues to advance toward the practical limit of 255 lm/W for phosphor converted LED architectures and the ultimate theoretical limit of 325 lm/W for direct emitting architectures. These advancements are the result of numerous and ongoing breakthroughs in fundamental, early stage R&D that have been applied across the SSL value chain. This document provides further detail on these advancements and priority R&D topics suggested by members of the U.S. lighting science R&D community who collaborate with the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), within the Office of Energy Efficiency and Renewable Energy, on its SSL Program.

High efficacy and low costs result in efficient and cost-effective lighting that is rapidly being adopted and saving substantial amounts of energy. In addition, unlike previous energy saving lighting technologies, LED lighting does not require compromises in performance. LED lighting can be engineered to have almost any spectrum that can provide good color quality. It is fundamentally dimmable, both instantaneously and continuously. Finally, the small source size enables improved optical control. These performance features, coupled with the high efficacy and low cost of LED lighting, enable a rare trifecta for energy efficiency technologies – high efficiency, low cost, and improved performance – which has resulted in rapid adoption and massive energy savings. These features and benefits can also be achieved while reducing the environmental impacts of lighting (beyond benefits from reduced energy generation) in terms of reduced materials toxicity and ecological impacts.



So far, the benefits resulting from the transition to SSL have accrued through replacement of conventional lighting products to more efficient SSL products for the same basic lighting job – illumination and visibility based on the photopic eye response. However, the new capabilities of SSL technology, coupled with new understanding in lighting science, open up possibilities to further reduce lighting energy consumption, improve lighting performance in new ways, and reduce negative impacts of earlier lighting technologies.

Beyond improvements in efficiency or efficacy offered by SSL technology, further energy savings can be achieved through improved optical control, spectral tailoring, and more precise control of intensity. However, a new framework for modeling and evaluating trade-offs between these factors, as well as source efficiency, needs to be developed. Spectral engineering enables improved lighting performance by offering the ability to tailor light for very specific features such as color gamut, discrimination, and replication. Improved optical control could enable reduced glare and more precise delivery of light. Controlling the intensity also enables lighting to achieve the desired levels by application, and to adapt dynamically in response to changes in the outside environment or human needs.

Recent research and an improved understanding of lighting science has shown that there are considerations beyond basic illuminance and color qualities (such as color rendering index (CRI) or correlated color temperature (CCT)). Light that is intense and has a higher blue content affects alertness and melatonin secretion in humans leading to significant health implications. Lighting designers will need to consider these effects as well as photopic eye response when specifying new lighting installations. Lighting product developers will need clear guidance in terms of intensity and spectrum to develop lighting products that are both efficient and supportive of health or well-being compared to legacy lighting installations. This rare combination of energy saving and well-being benefits is offered solely by SSL technology.

The bundle of new discoveries, impacts, and potential benefits of SSL stem largely from advancements in LED efficiency. Improvements to efficiency reduce costs and size while enabling new form factors, improved optical performance, and new lighting applications. Ongoing research and development (R&D) in SSL materials and device efficiency is therefore necessary to meet projected energy savings targets and to also maximize downstream energy savings through improved lighting application efficiency. Future improvements in efficiency for new lighting applications must ensure well-being and productivity are not compromised, and even improved where possible.

Finally, given the fast pace of SSL development and improvement, it is critical that manufacturing approaches keep pace by improving throughput, increasing flexibility, reducing materials usage, and generally advancing manufacturing speed and efficiency. In addition, within the U.S., the vast range of lighting product types and application requirements means that increasingly, products will be customized and produced ‘on-demand’. To support this trend, new flexible manufacturing approaches are necessary. In particular, developing additive manufacturing techniques to maximize the range of products while simultaneously minimizing stored component inventory could have a large impact. Additive manufacturing techniques could be deployed across the manufacturing value chain, from wafer level processing techniques to light fixture creation.

Another technology group within the SSL family is organic LED (OLED). OLED products have the potential to offer unique benefits complementary to LED lighting. However, significant technology barriers remain for OLED lighting, with progress lagging behind LED performance and cost. OLED efficacy greatly lags LED efficacy at approximately 90 lm/W with a target of 190 lm/W; however, there may be application-specific advantages. OLED lighting technology needs ongoing R&D to translate lab scale efficiency and performance advancements to commercially practical approaches. In particular, efficiency can be improved at the material, device, and light extraction levels. Additionally, these advancements in efficiency would have a direct impact on cost and reliability.

OLED lighting offers an intriguing performance and production counter-point to LED lighting. By its very nature, OLED lighting is diffuse, meaning it can be placed very close to the occupant or object being lit. Every other lighting technology, including LEDs, requires optical diffusion to protect occupants from glare from the bright light source. Now, many LED lighting products use waveguide optics to achieve a flat profile, while OLED products such as those shown in Figure 1-2, inherently provide diffuse lighting without the need for additional optics. While OLED lighting offers these unique lighting prospects, OLED lighting does not yet readily work with pre-existing, ubiquitous lighting form factors.

Figure 1-1. OLED Panel

Source: Digital Trends, September 2018 [1]

In terms of production, OLEDs require nanometer scale control of organic material deposition thickness over very large areas (square meters) at high speed. This level of production control is challenging and requires the development of new manufacturing technologies that are compatible with the most efficient OLED materials and device approaches. In addition, OLED devices and materials must be protected from environmental incursions of oxygen and moisture that can disrupt the finely tuned material and device performance. Furthermore, these technology and manufacturing challenges must be achieved while meeting consumer demands for cost, performance, and reliability. If these barriers are overcome, significant benefits to lighting applications could be achieved in terms of energy savings and human comfort and overall well-being. Any advances in OLED lighting would also aid the development of a broad range of similar applications including photovoltaics, displays, advanced fenestration, and beyond – with the potential for significant additional cross-cutting energy savings.

This document discusses R&D topics necessary to make advancements in the areas described above. The specific research topics listed are the result of BTO experts in consultation with stakeholders from academia, national laboratories, and industry who work with BTO's SSL Program. DOE will make the final determination of R&D topics for possible funding. BTO's SSL Program continues to set aggressive performance and cost targets for LED and OLED lighting technology and provide early stage R&D funding and research activities in support of reaching these targets.

The current critical R&D challenges identified by stakeholders during the Roundtable and Workshop discussions are listed below. Further description of the specific R&D topics with supporting metrics is given in Section 3.

LED-Based Lighting R&D

- **Light Emitting Diode Devices and Materials** – Push LED emitters across the visible spectrum that demonstrate advancements in peak efficiency and stable efficiency at high current drive and temperature operating conditions. Also, development of fundamental models to predict LED device performance across a range of materials, device structures, and synthesis techniques.

- **Advanced Emitter Device Architectures** – Explore the use of advanced emitter device architectures with state-of-art-emitter materials to improve the extraction of white photons from a device package, as measured by overall package power conversion efficiency (lm/W), and the ability to deliver white photons to a target, which generally improves with luminous emittance (lm/mm^2).

- **Quantum Dot Optical Down-Converters** – Research to advance understanding in high efficiency, on-chip quantum dot (QD) down converters to match or exceed performance of conventional on-chip phosphor materials at a range of emission wavelengths.

- **Advanced LED Lighting Concepts** – Develop fully optimized color-mixed direct LED lighting product concepts that demonstrate efficiency advancements or lighting products with advancements in lighting application efficiency.

- **LED Power and Functional Electronics** – Develop advanced prototype power delivery concepts for luminaires with high efficiency across the operating range, high reliability, and minimal size and weight.

- **Additive Fabrication Technologies for Lighting** – Develop high volume additive manufacturing technologies for any portion of the LED lighting manufacturing value chain that reduce part count and are cost effective.

OLED-Based Lighting R&D

- **Stable, Efficient White Devices** – Develop novel materials and structures that can help create a highly efficient, stable white OLED device.

- **Advanced Fabrication Technology for OLEDs** – Develop novel approaches and advancements in materials deposition, device fabrication, or encapsulation of OLED panels that lead to significant reduction in processing costs without degrading performance.

- **Light Extraction and Utilization** – Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and advancing state-of-the-art performance of OLED panels.

- **OLED Prototype Lighting Platforms** – Develop OLED lighting platforms that achieve the performance and design goals of OLED lighting technology and demonstrate clear differentiation from existing products.

Cross-Cutting Lighting R&D (LED and OLED)

- **Understanding Human Physiological Impacts of Light to Improve Efficiency–** Research to understand and define physiologically optimized lighting for the general population based on objective physiological responses to light and/or large-scale collection and review of subjective responses for the purpose of optimizing lighting efficiency.

- **Understanding Lighting Application Efficiency –** Develop a general framework, mathematical model, and computer simulation approach to characterize lighting application efficiency for any lighting application in terms of the four primary aspects of lighting application efficiency: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity efficacy.

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2 Introduction

The administration of President Trump calls for investment in "next-generation energy technologies to efficiently convert them into useful energy services (e.g., light, heat, mobility, power, etc.)" [2]. The U.S. Department of Energy (DOE) Building Technologies Office's (BTO) Solid-State Lighting (SSL) Program is playing a critical role in advancing this agenda by investing in SSL R&D. The Administration also calls for "early-stage, innovative technologies that show promise in harnessing American energy resources safely and efficiently" [2]. SSL technology is a prime example of how energy can be converted into a useful service, namely lighting. SSL has demonstrated clear advancements in efficiency over incumbent lighting technologies, resulting in significant energy savings. SSL still has room to become even more efficient and has the potential to improve safety by providing light that reduces the physiological impacts we currently experience with legacy sources. SSL has the potential to harness American energy resources to provide light safely and efficiently.

American Energy Dominance

"Fueling America's greatness requires access to domestic sources of clean, affordable, and reliable energy. Unleashing these abundant energy resources will require investment in next-generation energy technologies to *efficiently convert them into useful energy services (e.g., light*, heat, mobility, power, etc.). Agencies should invest in *early-stage, innovative technologies* that show promise in harnessing American energy resources *safely and efficiently*. Federally funded energy R&D should continue to reflect an increased reliance on the private sector to fund later-stage research, development, and commercialization of energy technologies. Agencies should invest in user facilities that can improve collaboration with industry and academia and achieve advancements across the full spectrum of discovery, from incremental improvements to game changing breakthroughs."

FY 2020 Administration Research and Development Budget Priorities, July 31, 2018

Mick Mulvaney, OMB, Michael Kratsios, OSTP

The BTO 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 BTO SSL Program has developed a comprehensive R&D strategy to support advancements in SSL technology and maximize energy savings. The specific goal of the R&D Program is: ***By 2030, 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 BTO SSL Program supports foundational R&D topics with benefits that apply across the value chain and such R&D that is not typically undertaken within the lighting industry. BTO-supported R&D advances the understanding of underlying physical phenomena, explores new technical and fabrication approaches, reduces the development risk with new technologies, and/or develops understanding of application requirements that improve lighting effectiveness, while simultaneously improving efficiency.

This document, BTO's ***2018 SSL R&D Opportunities,*** is updated annually and provides analysis, context, and direction for ongoing R&D activities to advance SSL technology and increase energy savings. Research areas in this document come from DOE BTO experts with input from members of the lighting science R&D community at National Laboratories and academia as well as large and small businesses. The inputs are collected at the BTO SSL Roundtable meetings, the OLED stakeholder meetings, and the annual BTO SSL R&D Workshop.

3 Research Topics

To reach the full potential of solid-state lighting (SSL), further research is necessary. Despite rapid progress, there are still significant advancements in performance and scientific understanding that can be made. In terms of U.S. energy savings from SSL, 90% of the potential remains untapped.[1] Advancements in SSL technology have highlighted gaps in understanding at not only the material-device level, but also at the lighting science level. Research in these areas will enable the next level of performance advancements for SSL. At the materials and device level, ongoing innovation and breakthroughs in materials, devices, advanced fabrication processes, and integration are needed to realize the full potential of the technology. In addition, at the lighting science level, the SSL technology platform raises new questions as to the effectiveness of the delivery and control of lighting, as well as the effectiveness of lighting for engaging both visual responses and non-visual physiological responses.

The suggested R&D topics described in this document are inputs given by members of the U.S. lighting science R&D community who collaborate with the BTO SSL R&D Program. These stakeholders include academic, National Laboratory, and industry researchers who provide feedback and inputs to the BTO SSL Program. These topics do not represent forward looking directions by the BTO SSL Program, but rather stakeholder suggestions as to the most critical areas for advancement of SSL technologies now. Further analysis and discussion of the suggested R&D topics is provided in the subsequent sections of this document.

3.1 Process and Discussion

The BTO SSL Program has responded to the SSL opportunity by providing direction and coordination of multiple R&D efforts intended to advance the technology and to promote the ultimate energy savings offered by the technology.[2] The BTO SSL Program seeks to fund research that offers innovative advancements such as unique materials or device structures, next generation integration concepts, or develops a new understanding of the underlying technology and lighting science to provide safe and efficient lighting.

3.1.1 Goals and Projections

This section describes expectations for progress toward BTO SSL efficiency goals over time based on performance to date. The projections are based on best-in-class performance, normalized to particular operating conditions to track progress.[3] These advancements translate to improved performance industry wide and promote domestic leadership in this technology.

Efficiency and Efficacy Projections for LEDs

Figure 3-1 panel (a) uses a logistic fit to project efficacy over time for cool white and warm white phosphor converted LED packages and color mixed LED packages. An upper limit of 250 lm/W is assumed for phosphor converted LED packages and an upper limit of 325 lm/W is assumed for color mixed packages.[4] Panel (b) of Figure 3-1 shows projections for power conversion efficiency of blue (440-460 nm), green (530-550 nm), amber (570-590 nm), and near red (610-620 nm) direct emitting LEDs, again with a logistic fit for projected performance, and with an upper limit of 90% power conversion efficiency. Table 3-1 shows historical and projected LED package efficacy for warm white and cool white phosphor converted-LEDs (PC-LEDs), and color mixed LEDs (cm-LEDs). The assumed operating conditions for qualified data points may not correspond to practice, particularly with respect to the increasing use of lower drive currents to minimize current droop. Nevertheless, using a standard current (or power density) at a fixed operating temperature and

1 DOE Solid-State Lighting Program, "Adoption of Light-Emitting Diodes in Common Lighting Applications," Prepared by Navigant Consulting Inc., July 2017. https://www.energy.gov/sites/prod/files/2017/08/f35/led-adoption-jul2017_0.pdf

2 For more information on the DOE SSL Program see: https://energy.gov/eere/ssl/about-solid-state-lighting-program

3 In practice, by adjusting the operating conditions at the luminaire level, LED performance can be improved or degraded from the normalized operating conditions used for these projections.

4 Updated from analysis in DOE Solid-State Lighting Program, "2016 R&D Plan," Prepared by Navigant Consulting Inc., June 2016. https://www.energy.gov/sites/prod/files/2018/09/f56/ssl_rd-plan_jun2016.pdf.

selecting devices within limited ranges of CCT and CRI allow researchers to evaluate developments in emitter efficiency (including the reduction of current and thermal droop) and down-converter performance.

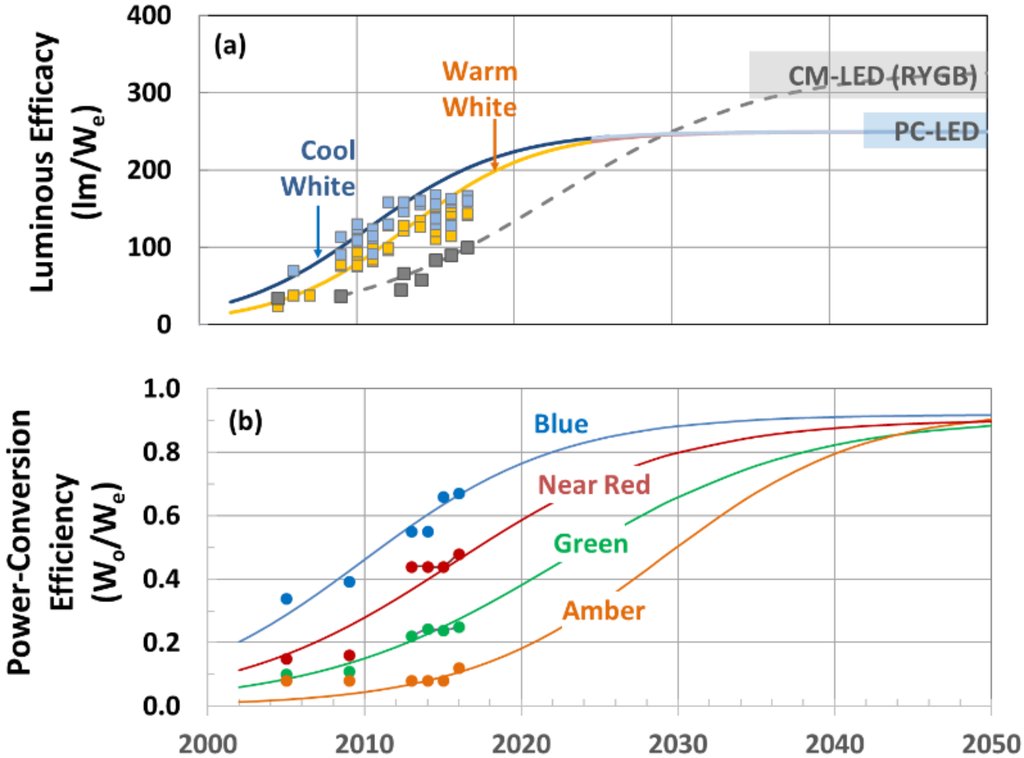

Figure 3-1. Efficacies and Efficiencies Over Time of White and Colored LED Packages

All curves are logistic fits using various assumptions for long-term future performance and historical experimental data. The data are from qualified products at the representative operating conditions of 25°C and 35 A/cm² input current density. They will differ from some commercial products, particularly those that operate at lower drive current densities to minimize current droop.

The upper panel (a) are the luminous efficacies of warm white (3000 K) and cool white (5700 K) phosphor-converted LEDs and hypothetical color-mixed LEDs (CM-LEDs) with a CCT of 3000-4000 K. Luminous efficacies have the typical units of photopic lumens of light (lm) created per input electrical Watt (W_e) of wall-plug power. Year 2017 commercial products reach approximately 180 lm/W for cool white PC-LEDs and approximately 160 lm/W for warm white PC-LEDs. These values correspond to raw electrical-to-optical power-conversion efficiencies of approximately 0.5 W_o/W_e.

The lower panel (b) are the power-conversion efficiencies of direct-emitting LEDs at the various colors (blue, green, amber, and near-red) necessary for CM-LED white light of highest source luminous efficacy and high color rendering quality. Approximate future potential power-conversion efficiencies are depicted as a saturation at 90% for all colors beginning in the years 2035–2040. The historical power conversion efficiencies of these sources were combined and appropriately weighted to give the CM-LED LEDs and conversion efficiencies depicted in the upper panel (a).

Table 3-1. Phosphor-Converted and Color Mixed LED Package Historical and Targeted Efficacy

Metric	Type	2016	2017	2025	2035	Final Goal
LED Package Efficacy (lm/W)	PC Cool White	160	167	241	249	250
	PC Warm White	140	153	237	249	250
	Color Mixed	90	100	196	288	325

Figure 3-1 and Table 3-1 track pc-LED package progress, as that is the mainstream package architecture used in SSL products. Alternative approaches, such as a hybrid combination of a red LED and a phosphor-converted LED, could meet the asymptote more quickly than pc-LEDs due to the availability of narrow linewidth red LED sources.

Efficacy Projections for OLEDs

OLED efficacy has been improving, but not at the desired pace. Though material and device technology has been demonstrated in the laboratory for achieving OLED panels of much greater than 100 lm/W, low light extraction efficiency remains a key technical challenge. Integrating light extraction technology without disrupting the yield and stability of devices has presented a major challenge. Figure 3-2 and Table 3-2 project OLED panel efficacy based on past performance and anticipated progress. The dashed curve presents BTO OLED panel efficacy goals put forth in 2014, whereas the solid curve shows projections based on performance to date. It was realized during the intervening three years that many of the techniques used to raise the efficacy of laboratory devices could not be implemented quickly in commercial products manufactured in high volume. Even though panels with efficacy of 90 lm/W were listed in product catalogs in 2017, they were available only in small quantities.

The changes in these forecasts reflect strategic decisions made by the industry around 2015 to prioritize color quality over efficacy. Increased lifetime and reliability were also prioritized over efficacy. Having met goals with respect to color quality and lifetime, researchers are once again focusing on efficacy with a goal of 190 lm/W. Increased light extraction will be key to success in this endeavor. While significantly lower than the LED efficacy goal of 325 lm/W, OLEDs may be able to offer application specific advantages requiring less light production overall, and therefore lower energy use, for specific use cases.

Data on OLED panels remain rather sparse and show a lot of variation, so there is considerable uncertainty in the projected curve. There is also a significant difference in the efficacy of rigid and flexible panels. Qualified points were defined as those for panels with a minimum area of 50 cm^2, CRI greater than or equal to 80, and CCT between 2580 K and 3710 K. The average of qualified data for each year was used to fit the projection curve.

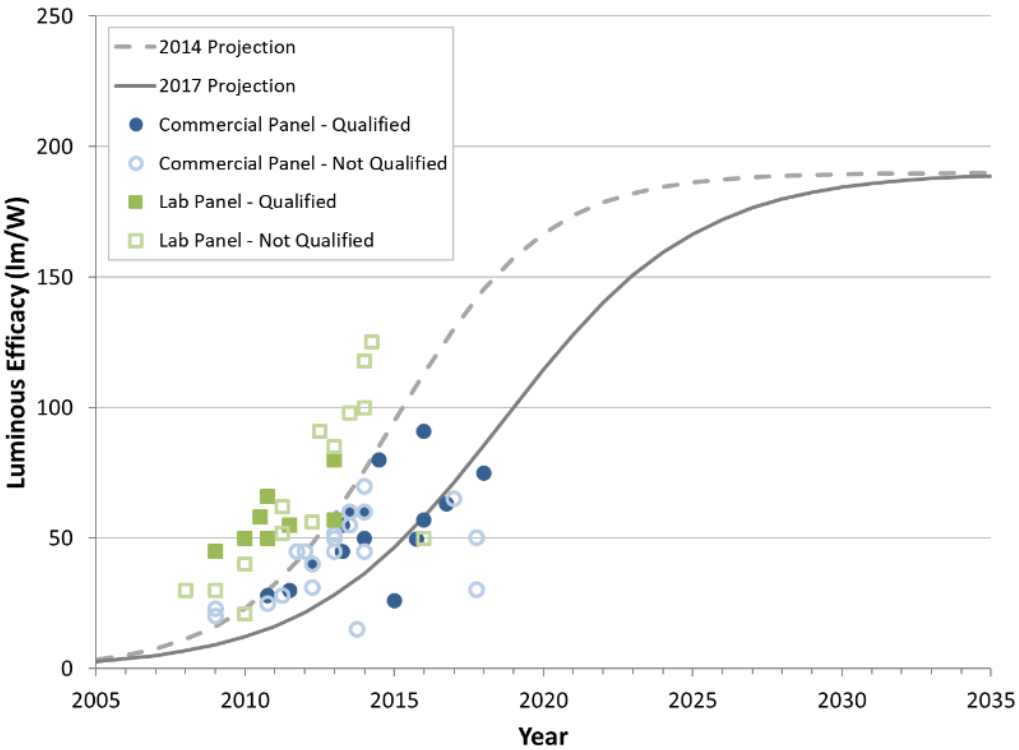

Figure 3-2. White-Light OLED Panel Efficacy Projections

Table 3.2 summarizes a path toward achieving an efficacy of 190 lm/W with low rates of lumen depreciation.

Table 3-2. OLED Panel Historical and Targeted Efficacy

Metric	2016	2017	2025	2035	Goal
Panel efficacy (lm/W)*	60	90	160	180	190

* Projections assume CRI > 80, CCT = 2580K- 3710K.

Achieving efficiency gains and lumen depreciation goals will not alone be sufficient to make meaningful advancements for OLED lighting. The films must also be consistently manufacturable in large areas at low cost, which may limit material choices and stack configurations. Improvements to the stability of OLED luminaires must also be realized. OLEDs are sensitive to oxygen, moisture, and other pollutants in the operating environment. Thus, extensive encapsulation of the OLED panel is required, particularly on flexible substrates. In addition, oxygen, moisture, and other contaminants can become embedded into the OLED in the fabrication process, reducing the panel lifetime.

With respect to reliability, the current specifications on lumen depreciation, L70 at 40,000 to 100,000 hours at 3000 cd/m^2, seem sufficient for almost all applications. The emphasis needs to change to reducing the probability of catastrophic failure, unacceptable color shift, or voltage increases within the anticipated lifetime of the light.

3.2 LED Research Needs

Specific task tables in subsequent LED research sections reference color or descriptive terms for color temperature. Table 3-3 shows these ranges for various color wavelengths and explains the meaning of color temperature.

The milestones provided in the tasks described below represent the minimal descriptions for progress. They provide initial and interim targets for quantitative evaluation of progress. All these tasks will require some additional system-level performance description and, most likely, additional metrics specific to the proposed approach. Researchers in these areas are expected to possess and communicate a detailed, system-level understanding of the role of the described research. Where appropriate, researchers should further define and describe metrics and milestones that are necessary to demonstrate progress in the research topic.

Table 3-3. Assumptions for Wavelength and Color as Used in the Task Descriptions

Color	Dominant Wavelength or CCT	CRI
Blue	440-460 nm	N/A
Green	530-550 nm	N/A
Amber	570-590 nm	N/A
Near Red	610-620 nm	N/A
Warm White	3000 K	≥ 80
Cool White	5700 K	≥ 70

3.2.1 LED Research Tasks

Table 3-4. Emitter Materials

Light Emitting Diode Devices and Materials			
Description: Develop new or improved emitter materials with an advanced fundamental understanding of materials-synthesis-performance relationships for light emitting diodes. Research includes theoretical analysis, analysis of historical results, experimental results, and deep characterization in a closely structured experiment designed to yield more definitive scientific understanding. Project results should enable some of the following: • Guidance for improving red, amber, and green LED performance. • General understanding and model for prediction of LED performance in different materials systems. • Fundamental understanding of current density and thermal droop that can enable improved mitigation approaches. • Modeling that can help project device performance from materials properties of new emitter material systems. Work on novel LED materials should demonstrate a path toward meeting 2025 performance targets. All research should be on highest caliber materials and devices to yield clearest possible results. Results should be impactful for the application of energy saving solid-state lighting by defining a path to achievement of ultimate BTO SSL performance targets described in table below.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
EQE (peak value)	80% (Blue) 44% (Green) 63% (Near Red*) 18% (Amber*)	88% (Blue) 60% (Green) 69% (Near Red) 33% (Amber)	93% (Blue) 75% (Green) 80% (Near Red) 60% (Amber)
PCE† - $35 A/cm^2$, 25^oC	67% (Blue) 27% (Green) 50% (Near Red*) 16% (Amber*)	84% (Blue) 50% (Green) 70% (Near Red) 30% (Amber)	90% (Blue) 75% (Green) 85% (Near Red) 70% (Amber)
PCE† - $100 A/cm^2$, 85^oC	54% (Blue) 13% (Green) 18% (Near Red*) 7% (Amber*)	65% (Blue) 30% (Green) 45% (Near Red) 19% (Amber)	83% (Blue) 60% (Green) 70% (Near Red) 55% (Amber)

* The status of red and amber emitters is based on commercial AlInGaP LEDs. However, there is the possibility of developing InGaN or other material system-based LEDs that emit at these wavelengths. LEDs in novel materials systems would currently have lower performance levels but may represent the path to simultaneously meeting all the ultimate performance targets. Research on novel emitter materials is not expected to meet shorter term performance targets but should demonstrate a clear path to meeting all 2025 performance targets.

† Optical power out divided by electrical power in for the LED package.

Table 3-5. Advanced Emitter Device Architectures

Advanced Emitter Device Architectures			
Description: Explore the use of advanced emitter device architectures with state-of-art-emitter materials to improve existing trade-offs between (a) the extraction of white photons from a device package, as measured by overall package power conversion efficiency (lm/W), and (b) the ability to deliver white photons to a target, which generally improves with luminous emittance (lm/mm^2). An example of such a trade-off is droop, in which power conversion efficiency decreases but luminous emittance increases as input current density is increased. Architectures could include the use of tunnel junctions, photonic crystals, photonic metamaterials, stimulated emission, and/or laser devices. Of interest are both increased luminous emittance without sacrificing power conversion efficiency, or increased power conversion efficiency without sacrificing luminous emittance, to improve overall lighting system efficiency. Trade-offs between device power conversion efficiency and luminous emittance (or optical distribution) should be discussed by the applicant. Device architecture advancements would be demonstrated on blue (or possibly violet) emitters but approaches are encouraged to demonstrate advancements in white emitting architectures as well. Proposed device architectures should enable a meaningful energy impact.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
PCE† - $35A/cm^2$, 25^oC	67% (Blue) [156 lm/W (Warm White)]	84% (Blue) [237 lm/W (Warm White)]	90% (Blue) [249 lm/W (Warm White)]
Luminance and optical distribution for application efficiency	310 lm/mm^2, Lambertian distribution	500 lm/mm^2, optimized optical distribution pattern	800 lm/mm^2, optimized optical distribution pattern

Table 3-6. Understanding Quantum Dot Optical Down-Converters

Understanding Quantum Dot Optical Down-Converters			
Description: Research to advance understanding in high efficiency, on-chip quantum dot (QD) down converters to match or exceed performance of conventional on-chip phosphor materials. Research should explore QD architectures, degradation mechanisms, synthesis techniques, and/or functionalization approaches and demonstrate advancements in on-chip LED performance at multiple emission wavelengths relevant to high efficiency solid state lighting. Research should seek to provide a path to a set of performance parameters that make QDs competitive with conventional phosphors for application in general illumination. Alternatively, research could identify fundamental limitations for QD application in LED lighting applications. Research in quantum dots that do not contain heavy metals or scarce materials is encouraged. Metrics below describe the status of state-of-the-art phosphors used for LED lighting to provide targets for QD performance.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
Quantum yield (QY) at 150°C across the visible spectrum and at 1 W/mm2	88% (Green) 81% (Red)	91% (Green) 88% (Red)	99% (Green) 95% (Red)
Spectral FWHM	110 nm (Green) 75 nm (Red)	70 nm (Green) 30 nm (Red)	30 nm (at all wavelengths)
On-chip reliability: Color shift Depreciation Failure	Δu'v' < 0.007 at 6,000 hours	Δu'v' < 0.002 over life	Δu'v' < 0.002 over life

Table 3-7. Advanced LED Lighting Concepts

Advanced LED Lighting Concepts			
Description: Applicants can pursue one of the following two approaches. 1. Develop fully optimized color-mixed direct LED (without phosphor conversion) modules or luminaires that demonstrate advancements in efficiency and efficacy over previous color-mixed solutions, tracking color-mixed performance shown in Figure 3-1. 2. Develop lighting system architectures that take advantage of the unique properties of LEDs to demonstrate improved lighting application efficiency, including advanced lighting values (e.g., human physiological benefits as demonstrated by spectrum and intensity levels appropriate for engaging these responses). Concepts that demonstrate improvements to lighting application efficiency should address all of the lighting application efficiency metrics described below.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
Color mixed luminaire efficiency, efficacy, and performance across operational range (depends on application – user may define metrics for specific use case)	100 lm/W (3000-4000 K, 80 CRI, ANSI Quadrangle)	150 lm/W (WW and CW)	250 lm/W (WW and CW)
Lighting application efficiency (depends on application – user may define metrics for specific use cases)	Luminaire efficiency: 150 lm/W	Luminaire efficiency: 180 lm/W	Luminaire efficiency: 225 lm/W
	Task optical delivery efficiency: depends on application	Task optical delivery efficiency: applicant discuss and describe improvement	Task optical delivery efficiency: applicant discuss and describe improvement
	Spectral efficiency: depends on application	Spectral efficiency: 90%	Spectral efficiency: 95%
	Intensity control: none or remote at dimmer switch	Intensity control: active and automatic	Intensity control: active and automatic

* Spectral efficiency refers to the overlap of the emitted spectrum with the spectrum appropriate to the activity or desired visual or non-visual response.

Table 3-8. LED Power and Functional Electronics

LED Power and Functional Electronics			
Description: Develop advanced prototype power delivery concepts for luminaires with high efficiency, high reliability, and minimal size and weight. Approaches should explore use of new components, devices, materials, circuits, and system designs to provide improved performance. The integration of wide bandgap components into the driver is encouraged. Additional advancements could include systems with multiple control channels, full dimmability, and maximum efficiency at extended operating ranges. Size and weight advancements should demonstrate an advancement beyond existing power/weight or power/volume relationships. Row 3 below provides a target for 100W power supplies. Work on different power levels (higher or lower) should provide similar targets.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
Power supply efficiency	88%	93% at full power 90% in dimmed state	95% at all operating conditions
Power supply reliability	Applicant estimated lamp/luminaire survival factor (various methods used)	95% survival rate with a 90% confidence level across reported case temperature curve	99% survival rate with a 90% confidence level across reported case temperature curve
Size-volume-form factor: Lumens (or watts) per volume (or mass)	100 W Driver: 650 g 475 cm^3	100 W Driver: 300 g 275 cm^3	150 W Driver: 200 g 175 cm^3

Table 3-9. Additive Fabrication Technologies for Lighting

Additive Fabrication Technologies for Lighting
Description: Develop high volume additive manufacturing technologies for any portion of the LED lighting manufacturing value chain. Approaches should be cost effective and reduce part count in the manufacturing process and be applicable to mass production, not just prototype development. Development of printable materials with properties specific to lighting applications is of interest for additive manufacturing approaches (optical, electronic or thermal properties). Specific portions of processes that are of interest for additive manufacturing advancements include: • Wafer scale packaging, including down-converter and encapsulant deposition. • Power supply component and module manufacturing. • Rapid creation of tooling for optics, heat sink or housing manufacturing. • Flexible production of lighting products. Additive manufacturing techniques apply to many different aspects of the supply chain and manufacturing processes. The proposed approaches will need to detail the baseline performance metrics and the improvements in performance metrics that can be obtained. Researchers should demonstrate thorough knowledge of the portion of the manufacturing value chain they are working in and should provide quantitative metrics, status, and targets for their research.

3.3 OLED Research Needs

Specific critical research tasks were suggested by members of the lighting science R&D community who work with the BTO SSL Program. The limited number of R&D tasks reflects the practical reality that BTO must leverage research funding for early stage research activities to achieve the most meaningful advancements possible.

The OLED tasks identified based on stakeholder suggestions are outlined below. The milestones provided in the tasks described below represent the minimal descriptions for progress. They provide initial and interim targets for quantitative evaluation of progress. All these tasks will require some additional system-level performance description and, most likely, additional metrics specific to the proposed approach. Researchers in these areas are expected to possess and communicate a detailed, system-level understanding of the role of the described research. Where appropriate, researchers should further define and describe metrics and milestones that are necessary to demonstrate progress in the research topic.

3.3.1 OLED Research Tasks

Table 3-10. Stable, Efficient White Devices

Stable, Efficient White Devices			
Description: Develop novel materials and structures that can help create a highly efficient, stable white device. The device should have desirable color qualities, long lifetime, and high efficiency, even at high brightness. The approach may include development of highly efficient blue emitter materials and hosts or, may comprise a device architecture leading to longer lifetime, such as graded doping approaches or tandem structures with improved charge generation layers to maximize internal quantum efficiency (IQE). Materials/structures should be demonstrated in OLED devices that are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate high stability, while maintaining or improving other applicable metrics.			
Metrics	**2017 Status**	**Interim 2025 Target**	**2035 Targets**
Internal Quantum Efficiency	62%	80%	85%
Voltage per stack @ 10,000 lm/m^2	2.83 V	2.75 V	2.7 V
Stability	L70: 40,000 hours at 10,000 lm/m^2 L70 Catastrophic failure rates Color shift	L70: 50,000 Hours at 10,000 lm/m^2	L70: 50,000 Hours at 10,000 lm/m^2

Table 3-11. Advanced Fabrication Technology for OLEDs

Advanced Fabrication Technology for OLEDs			
Description: Novel approaches and advancements in materials deposition, device fabrication, or encapsulation of OLED panels that lead to significant reduction in processing costs without unacceptably degrading performance. The techniques must enable high yields of products that meet BTO SSL performance targets and contribute to meeting ultimate OLED cost targets. Proposals could involve additive, maskless patterning techniques, roll-to-roll handling, high speed deposition of organic materials or barriers, but are not necessarily limited to these topics.			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
Yield	60-85%	95%	98%
OLED panel production cost	\$100/klm	\$20/klm	\$10/klm

Table 3-12. Light Extraction and Utilization

Light Extraction and Utilization			
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state-of-the-art performance of OLED panels. Applicants should consider how their approach integrates and operates in state-of-the-art structures and should include modeling or quantitative analysis that supports the proposed method. Solutions should define a path for low-cost, scalable, and high yield manufacturing. The proposed approach can also explore light-shaping techniques that can be integrated with the proposed light extraction technology to attain increased utilization efficiency of the generated light. Such methods should allow some control of the angular distribution of intensity but minimize the variation of color with angle.			
Metrics	**2017 Status**	**Interim 2025 Target**	**2035 Target**
Extraction efficiency (EQE/IQE)	55%	60%	75%
Color variation with angle (Δu'v')	< ±0.003	< ±0.002	< ±0.002
Light delivery efficiency	Lambertian	20% improvement of optical delivery efficiency	50% improvement of optical delivery efficiency

Table 3-13. OLED Prototype Lighting Platforms

OLED Prototype Lighting Platforms				
Description: Develop OLED lighting platforms that achieve the performance and design goals of OLED lighting technology and demonstrate clear differentiation from existing products. The designs should embody major advances in form factor and/or light distribution, while offering high performance and adaptability. The panels, mechanical supports, drivers and power supplies should be consistent with innovative form factors. Advanced custom power supplies should efficiently convert line power to acceptable input power for the OLED source(s) and maintain their performance over the life of the device. Innovations may include but are not limited to: unique form factor (thin, flexible); beam control; spectral tunability; modularity; automated control of intensity and color in aging. Proposals should provide quantitative targets for distinctive performance.				
	Metrics	**2017 Status**	**Interim 2025 Target**	**2035 Target**
Light engine	Power supply efficiency	50-80%	90%	95% at all operating conditions
	Driver form factor	Typical driver box	Thin to match design of luminaire	Unobtrusive power supply integration
	Light engine efficacy	N/A	135 lm/W	165 lm/W
Luminaire	Efficacy	20-50 lm/W	120 lm/W	150 lm/W

3.4 Cross-Cutting Lighting R&D (LED and OLED)

Specific critical R&D tasks were suggested by members of the lighting science R&D community. The limited number of R&D tasks reflects the practical reality that BTO must leverage research funding for early stage research activities to achieve the most meaningful advancements possible. The topic of understanding physiological impacts of light was consistently prioritized by the BTO SSL Program stakeholders as critical to advance solid-state lighting and to secure its energy-saving potential. Uncertainty around physiological responses to light can slow adoption of energy-saving SSL, and uncertain effectiveness of visual and non-visual physiological responses to light can reduce the efficacy of the lighting system. Improved understanding of this topic will encourage engineering and technology advancements. A more detailed discussion of this topic is found in Section 4.

The milestones provided in the tasks described below represent the minimal descriptions for progress. They provide initial and interim targets for quantitative evaluation of progress. All these tasks will require some additional system-level performance description and, most likely, additional metrics specific to the proposed approach. Researchers in these areas are expected to possess and communicate a detailed, system-level understanding of the role of the described research. Where appropriate, researchers should further define and describe metrics and milestones that are necessary to demonstrate progress in the research topic.

Table 3-14. Understanding Human Physiological Impacts of Light

<table>
<tr><th colspan="4">Understanding Human Physiological Impacts of Light</th></tr>
<tr><td colspan="4">Description: Research to understand and define physiologically optimized lighting for the general population based on objective physiological responses to light or large-scale collection or review of subjective responses. Specific aspects to understand could be optimum and threshold intensity, duration, and spectrum for light during the day and pre-sleep. Specific R&D could be performed on sub-populations that could inform guidance for the general population. R&D efforts should advance lab-scale studies to more naturalistic studies that can guide development and implementation of lighting for positive physiological responses.</td></tr>
<tr><th>Metrics</th><th>2017 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Human physiological impacts</td><td>Lab studies in unrealistic lighted environments; or subjective response with limited participants</td><td>Understand lighting thresholds in realistic settings for physiological responses across all types of lighting applications to maximize efficiency and safety</td><td>Broad implementation of efficient lighting that reduces or eliminates negative physiological impacts of lighting</td></tr>
</table>

Table 3-15. Understanding Lighting Application Efficiency

Understanding Lighting Application Efficiency			
Description: Develop a general framework, mathematical model, and computer simulation approach to characterize lighting application efficiency for any lighting application in terms of the four primary aspects of lighting application efficiency: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity efficacy. Light source efficiency describes the efficiency of the lighting product in generating light from input electrical watts. Optical delivery efficiency describes how efficiently light is delivered for all of the various 'jobs' of the lighting. Spectral efficiency defines the overlap of the ultimate spectrum that reaches the task or eye with an optimum spectrum for the activity or intent of the lighting, e.g. visual acuity, color rendition, engagement of physiological responses, etc. Intensity efficacy describes the difference between the intensity of the provided light and the optimum intensity for the specific intent of the light. Optical delivery, spectral efficiency, and intensity efficacy may have temporal dependency as occupant positioning and activities in a space change over time. The proposed R&D and resulting models should be validated with lighting mock-ups with optimized light placements and optical distributions and then measured. Project status and metrics for progress for this R&D task should be supplied by researchers in this topic. The near term objective for this R&D task is to develop a working framework and vocabulary to characterize *Lighting Application Efficiency* in any lighting application. The framework should allow accurate computer modeling of *Lighting Application Efficiency* and this should be validated in the research against real lighting situations. In addition, the research should provide initial characterization of *Light Source Efficiency* (this should be readily available), *Efficiency of lighting delivery to receptor* (typically the eye), *Spectral efficiency,* and *Intensity effectiveness.*			
Metrics	**2017 Status**	**Interim 2025 Targets**	**2035 Targets**
Lighting Application Efficiency framework and model	No comprehensive framework or model	Application agnostic model that can be used to optimize total *Lighting Application Efficiency*	Ubiquitous use of *Lighting Application Efficiency* modeling for building, room, lighting layout, and product design

4 Directions in Lighting Science

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. 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, long lifetimes 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, as the technology has developed, it has become clear that the impacts of SSL will go far beyond energy savings alone. SSL 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. In particular, the emergence of SSL has enabled key lighting science discoveries that reveal many new and essential connections between lighting exposure and biological impacts. These links further indicate that existing performance parameters, metrics, design norms and guidance are insufficient for describing how lighting should be specified for an application. R&D into lighting science is necessary to ensure that SSL continues to drive energy savings, since the growing use of color tuning, controls and complex sensor networks could result in an increase in energy consumption without targeted research. The following sections explore many of the key directions in lighting science for SSL.

For the past 15 years, progress in SSL has been measured in lumens per watt (lm/W). This framework describes the productive aspect of lighting, the lumen, in the numerator and consumption aspect of producing light – the input electrical power required – in the denominator. Though this metric is easy to use, additional information is required to ensure that the lumens are effective for the intended lighting application. Typically, additional color quality metrics, including color rendering index (CRI) and correlated color temperature (CCT), are also provided to aid in the selection of an application-appropriate lighting product.

While the lumen measures the amount of light generated, it is dependent on the human response to light represented by the action spectrum of the photopic eye response curve. As shown in Figure 4-1, the eye is more sensitive to light in the green spectral regions, so those photons get weighted higher than photons in the deep red or violet spectral regions. Lumens are then calculated from the convolution of the emitted spectrum from a light source and the photopic eye response curve. Therefore, light emission that falls outside of the photopic eye response curve shown below in Figure 4-1 is weighted less and does not contribute as strongly to perceived lumens.

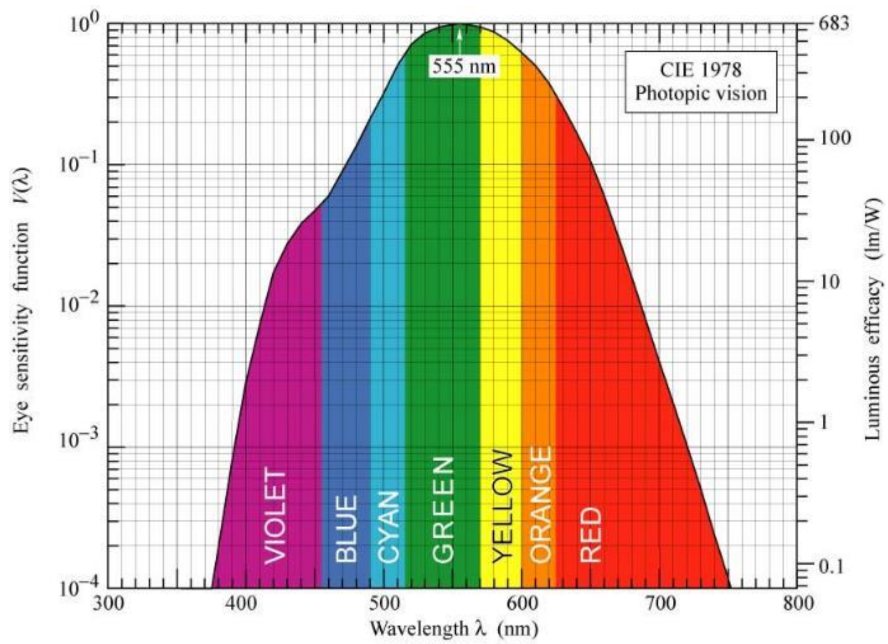

Figure 4-1. Human Eye Sensitivity Function CIE 1978 Photopic Vision

Source: LEDs Magazine, Radiometric and Photometric Terms [3]

This lumen framework represents the foundation of the commonplace efficacy metric, as measured by lm/W, which has been effective in creating efficient SSL solutions and driving performance improvements to date. However, the improvements in LED technology have brought new levels of controllability and functionality, which leaves the metric lm/W unable to fully describe the efficiency, effectiveness, and value of LEDs in many lighting applications. Two examples where the lm/W metric falls short are human non-visual physiological responses to light and horticultural lighting. As discussed further in Section 4.2, both of these applications use different wavelengths of light to impact physiological activity, also known as action spectra, to define the effectiveness of lighting.

In new and pre-existing lighting applications, the effectiveness of lighting may not be solely described in terms of lumens. New action spectra will be used to describe other aspects of lighting effectiveness beyond human visibility. With the new levels of spectral control offered by SSL, the overlap of emitted light with new action spectrum can be optimized. In addition, characterizing lighting systems only in terms of emitted lumens does not account for downstream elements of the lighting system that can greatly affect efficiency. SSL technologies offer precise control of the intensity and direction of emitted light. This control can enable more efficient delivery of just the right amount of light to the right place at the right time. Taken together, precise spectral, optical, and intensity control enable a new frontier of energy savings that is enabled by the high starting efficiency of the SSL source.

While imperfect to describe the full performance in a light application, the lumen still remains the primary metric for describing lighting service since the primary function of light will be to illuminate the physical space and objects within it. However, developing a more holistic framework for characterizing light that reaches the intended target (whether that target is biological or an inanimate object) for the intended application will be beneficial to demonstrate all of the improved functionality of SSL technology.

4.1 Lighting Application Efficiency – A New Framework and Opportunity for Energy Savings

A new framework for characterizing the effectiveness and efficiency of a lighting system would improve the way we differentiate lighting performance for a given application. The new framework would potentially need to consider the:

- **Spectral efficiency** (described in Section 4.1.1);
- **Light source efficiency** of the luminaire (described in Section 4.1.2);
- **Optical delivery efficiency** (described in Section 4.1.3); and
- **Intensity effectiveness** (described in Section 4.1.4).

Combined, these four elements could be used to describe the overall lighting application efficiency demonstrated with SSL systems. While each has been demonstrated, evaluated, and studied independently with SSL, they largely have not been considered holistically within a common framework. If each component of lighting application efficiency continues to be evaluated in isolation, this will inherently limit their use within industry and represents a missed opportunity for energy savings. A holistic framework would enable the different aspects of lighting application efficiency to be considered and optimized for different applications. This proposed framework, shown in Figure 4-2, would also guide future R&D in lighting application efficiency to target the most impactful aspects of performance for a given application.

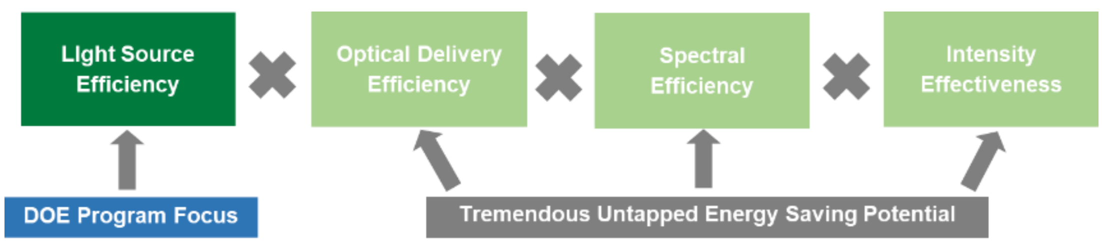

Figure 4-2. Possible Framework for Evaluating Lighting Application Efficiency

The concept of a holistic framework for considering lighting application efficiency is new, particularly when considering the new capabilities of SSL technology. As such, the definitions and framework described here and in the following sections are preliminary.

4.1.1 Spectral Efficiency

Spectral engineering has been a central theme of SSL since its beginning – with significant effort and research towards improving the lighting performance as measured by many of the most common metrics such as lumens, CCT and CRI. In terms of spectral optimization, this is just the beginning, and many applications will benefit from more finely controlled spectra, not only for reducing the energy required for the application, but also for improving occupant well-being and productivity. Spectral efficiency can be defined as the ability of the emitted spectrum to produce the desired response for a given application. Using a tailored spectrum for an application enables maximization of desired wavelengths and the omission or reduction of damaging or unnecessary portions of the spectrum for that task. This concept is still relatively novel for general illumination applications, since fine spectral control has only been made feasible by the recent onset of efficient LED technology. As such, for most lighting applications, the optimum spectrum is not well understood, and significant research will be necessary to develop this understanding.

Spectral efficiency describes how well the spectral power density (SPD) emitted by the lighting product overlaps with the desired action spectrum for the intent of the lighting application. Currently, almost all lighting products are designed for overlap with the photopic eye response action spectrum (which gives rise to the definition of the 'lumen') shown in Figure 4-3. In addition, future lighting systems will need to consider additional action spectrum beyond just the eye response. As research on the physiological responses to light has progressed, action spectra have been developed for physiological responses such as melanopic response, reflective contrast (visibility of colors), color saturation, plant growth response, and animal responses[5], as illustrated in Figure 4-3 below. Future lighting systems must consider different or even multiple action spectra and the ultimate spectral effectiveness of these systems would be characterized by a spectral effectiveness per watt term, similarly to lumens per watt. To develop understanding in physiological responses and the possible benefits from advanced lighting, it is critical to collaborate with a broader set of stakeholders represented by federal agencies, such as NIH, USDA, and more.

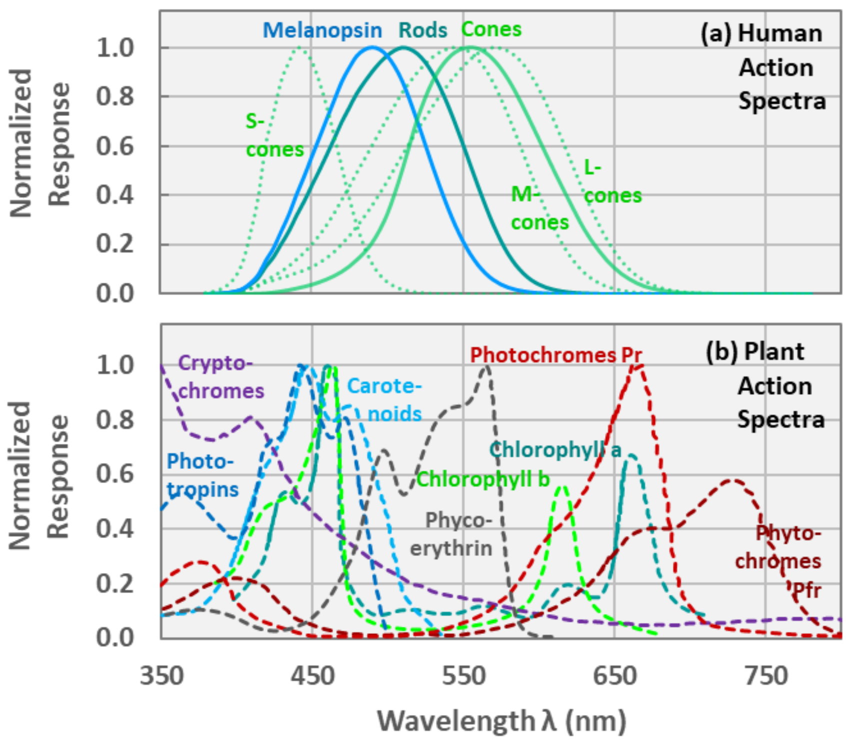

Figure 4-3. Action Spectra for Humans and Plants: (a) Human Action Spectra [4] (b) Plant Action Spectra [5]

4.1.2 Source Efficiency

With the expanded range of possible lighting functions with different action spectra discussed in Section 4.1.1, the properties of the spectrum must be reported precisely. The use of radiometric efficiency and spectral power density will allow the precision of describing the tuned spectra in ways that CCT and CRI never could. These parameters can then be used to determine spectral efficiency for the application – i.e., how well the emitted

5 Animal and plant responses to light are not identified as priority R&D topics by SSL Program stakeholders, but spectral responses for these applications exemplify additional benefits to spectral control offered by solid-state lighting technology.

spectrum overlap with the action spectrum for the given application. In some cases, multiple action spectra and associated metrics of effectiveness may need to be considered for the lighting application.

Currently, an average performing LED lighting product (including power supply) is approximately 42% efficient at converting input electrical power to light, also described as power conversion efficiency (PCE).[6] Discussions for improvements to the source efficiency are covered in detail in Section 5 and Section 6 of this document. With the advancements in the power conversion efficiency of SSL components in recent years, the focus can now include other elements of lighting application efficiency. However, there are still trade-offs between source efficiency and spectral efficiency. For example, high CRI sources have lower source efficiency due to additional phosphor conversion losses. For applications that need a high CRI source, it is appropriate to trade-off efficacy (reduction in spectral overlap with eye response action spectrum) for color quality, although work is ongoing to minimize this trade-off. Designing lights to other action spectrum might involve different trade-offs between source efficiency and spectral efficiency. Similarly, optical delivery efficiency may involve trade-offs between source efficiency and high luminance (see Section 5.4.2), which is typically required for advanced optical control. Finally, in order to achieve optimum light intensity efficiency, it may be necessary to dim the light source, though many integrated lighting products suffer from reduced power supply efficiency as the light is operated at dimmed settings. This is another trade-off that can be considered within the lighting application efficiency framework. Understanding the trade-offs in efficiency losses between source efficiency and the other elements of lighting application efficiency can guide lighting system design and R&D to reduce these trade-offs.

4.1.3 Optical Delivery Efficiency

LED lighting luminaires can be very efficient at producing light with efficacies reaching 200 lm/W. While improving efficacy is important, the effective delivery of the light to the target is another way to improve lighting efficiency. Additional research is needed into optical control of lighting to put more of the light generated to use in the application. The definition of 'useful light' for the application will vary and also needs additional research to define what is "useful." In some cases, it is light on the horizontal work surface, in other cases it is putting light on a specific object and, ultimately, it is delivering light to the eye for both visual and non-visual physiological effects.

While large amounts of lumens are emitted, the proportion of light emitted from luminaires in a room that reaches the eye range is estimated to be 1×10^{-6} to 1×10^{-9} [6].[7] This is highly dependent on the room geometry, lighting layout, occupant orientation, reflectance of surfaces, and more, but these estimates indicate that there is room for practical improvement in optical delivery efficiency without greatly affecting the lighting scheme. Lighting layouts are currently designed to meet even illuminance levels on horizontal surfaces in a room, which inherently does not account for the light levels reaching the vertical orientation of the human eye, nor the illumination required for foveal and peripheral vision. While lighting design choices are complex and consider a variety of additional characteristics such as product cost and aesthetics, it is important to consider the value of having metrics that would more accurately specify the lighting requirements for occupants. However, when considering the pathways to achieving greater optical delivery efficiency, there are significant barriers. For example, retrofit LED lighting products are constrained by performance limitations, luminaire layouts, and optical distributions of traditional lighting technology and are not optimized to effectively provide light that reaches occupants' eyes. In general, lighting products are not designed to precisely deliver the necessary amount and type of light for the intent of the application, and instead are largely focused on replacing legacy lighting systems. Breaking from this paradigm will require advancements in lighting design practices and advanced software tools as well as improved lighting products with controllable optical distribution.

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6 This analysis considers a warm white lighting product (3000K, CRI 80) with an efficacy of 137 lm/W and a luminous efficacy of radiation (LER) of 323 lm/W as described in the 2017 DOE SSL Suggested Research Topics Supplement in Table 4.2. Dividing the actual efficacy of a lighting product by the LER gives the power conversion efficiency for the product.

7 Estimates based on: 1) geometrical analysis of the human field of vision within a typical room, 2) unpublished calculation of measured light received at eye compared to total emitted light in a specific test room.

Simply doubling the optical delivery of light to the eye is a conservative target that will require significant R&D. In particular, research is needed to develop an approach to broadly understand and characterize the status of optical delivery efficiency for all lighting applications for both visual perception of the space and the non-visual biological factors. Once this foundational knowledge is established, effort can turn to the development of software for the optimization of lighting layouts and product optical distributions. In addition to knowing the optimal optical and spectral distribution of the light for various lighting applications, the ability to put the light where it is needed must be improved. Research into new optical control technologies in luminaires systems to improve the efficiency and directionality in primary and secondary optics is required. Some of the various technologies to be investigated include metamaterials, new device structures, and tunable optics. Furthermore, efforts are then needed to inform revised lighting design practices as well as the deployment of new software tools and optical delivery approaches.

4.1.4 Intensity Effectiveness

Conservatively, 50% (or more) of generated light is produced when there is no observer present to see the light, both in buildings and on roadways, leading to wasted light and energy [6]. This inefficient use of light can be improved with better intensity controls. Intensity effectiveness is a term to ensure only the right amount of light is used at a given time (when observers are in the lighted area), and also to help characterize when insufficient light intensity is being provided, impacting the effectiveness of the intent of the light. LED lighting can usher in better intensity effectiveness since it is inherently controllable compared to traditional lighting technologies with its full, instantaneous dimmability. For example, when there is sufficient daylighting or light is not needed, products can be dimmed or turned off to save energy.

Controls and sensors are commercially available and have been deployed to improve intensity effectiveness. However, it is necessary to improve performance, cost, and consumer confidence to increase adoption of controls, and hence, intensity effectiveness. In addition, controls and SSL sources need to be efficient and consume little power in their dimmed and standby- or off-states so that energy savings are not overshadowed.

In terms of lighting science, new guidance needs to be developed for the optimum intensity levels for basic illumination of objects and also for engaging non-visual physiological responses. In addition, it is important that future industry guidance also focus on the color and intensity of light that reaches the eye, not just what is delivered to a surface. Different lighting applications, from roadway to office to industrial, etc. will offer different prospects for understanding the optimum lighting intensity and for engaging controls to get the intensity right. Also, as with the other elements of lighting application efficiency, there may be conflicting demands on the lighting system. Light levels for illumination and performance of tasks may be different than optimum light levels for physiological responses. In a lighted space there may also be different intensity requirements for different population segments. Older eyes require higher illumination levels. Many of these considerations are well known to skilled lighting practitioners, but SSL technology provides new levels of control of the light intensity that were not previously practical. A framework for considering the various intensity requirements and possibilities for active control in a space could guide lighting designers toward the most efficient and practical solutions for optimizing the light intensity levels.

4.2 Visual and Non-Visual 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. It is now clear that light has important effects that can be harnessed for improved health and well-being. 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.

Circadian rhythms are inherently tied to the natural daylight cycle – light enhances wakefulness and darkness promotes sleep. In the natural environment, humans would rise in the morning when the sun comes up and emits high intensity, blue-enriched light. Humans then begin to get tired in the evening when the natural light is blue depleted. With the advent of electric lighting, natural cycles have shifted. Electric lighting not only enables sufficient light to work indoors during the day, it also extends the natural day and provides different lighting signals than the natural environment. Conventional lighting technologies and practices provide relatively low intensity levels during the day compared to daytime sunlight conditions (in most places). On top of this, most indoor lighting has a relatively ‘warm’ color temperature (lower CCT) than natural daylight conditions. In the evening, pre-sleep, there may be too much light with too much blue content, particularly when considering exposure to electronic displays (TVs, tablets, etc.). These electric lighting signals may confuse our natural diurnal rhythms. This basic understanding of these physiological responses to light is new and coincides with the development of SSL technology. SSL technology enables lighting systems that can be designed to engage with human physiological responses; however, clear guidance is needed so that light sources can provide physiologically effective light without compromising efficiency.

4.2.1 R&D Directions for Visual and Non-Visual Responses to Light

The objective of the BTO SSL Program is to reduce energy used for lighting. However, R&D stakeholders have identified the topic of eye-mediated physiological responses to light as critical for the advancement of SSL technology and adoption. It is now clear that existing lighting technologies and solutions may not be optimized for health and well-being. Light levels during the day may be too low with insufficient blue content. And light levels at night, particularly indoors, may be too bright with too much blue content – which counteracts the human lighting needs for natural circadian regulation as described in the previous Section 4.2. Lighting is a ubiquitous part of the built environment and should be designed and deployed first for optimum health and well-being, and second for high efficiency. Therefore, it is critical that physiological responses to light are clearly understood and then efficiently acted upon, in other words, light sources need to first be *effective* and then be *efficient* for illumination and optimum health. The BTO SSL Program is developing agreements to collaborate closely with the National Institutes of Health in this area.

While basic guidance is available, the current knowledge base is limited and much of the underlying physiological responses to light are still unknown or being validated in clinical trials. More R&D is needed to fully understand what lighting inputs produce the different non-visual effects, and how to properly control them in a real-world setting. Continuing fundamental science research is needed to understand and map the physiology responses to lighting. In addition, more research is needed to validate and translate the findings of basic, lab-scale research to realistic lighting use cases. Only then can we begin to guide lighting technology development and lighting design to elicit these physiological responses in an energy efficient manner. In particular, it is important to better understand dose-intensity-color relationships for light and physiological responses in realistic lighting contexts to guide lighting practice. This understanding will guide lighting systems to be effective at engaging physiological responses, which, in turn, will enable lighting manufacturers to develop the most efficient solutions. Some specific directions for research in the topic of physiological responses to light were provided by R&D stakeholders to the BTO SSL Program, listed below:

1. Understanding fundamental non-visual physiological-light interactions, including endocrine responses and other eye-mediated, physiological responses.
2. Understanding dose-intensity-color relationships and physiological threshold levels. At the high end, where more light or more blue-enriched light dosing does not increase alertness or melatonin suppression. At the low end, where light levels are too low to affect melatonin secretion.
3. Understanding synergistic interactions between different colors of light. Does white with blue-enriched content have the same physiological impact as monochromatic blue light with same blue content and how do metamers with different spectral content but the same color point affect physiological responses?
4. Develop best practices for measuring the physiological responses of occupants in a realistic lighting context.
5. Develop a process to determine when published scientific evidence is sufficient to define the physiological response to light in realistic lighting context and consensus is reached to begin to develop lighting guidelines based on the evidence.

As research findings are published there needs to be a robust mechanism for evaluating the findings, and if corroborated, transitioning the findings to standards bodies who can provide guidelines and best practices to the lighting industry. There should also be a means to identify and question lighting product claims that are not supported by academia and scientific evidence as shown in the published research results.

4.2.2 Understanding Relationship Between Energy Savings and Wellness Implications

As stated above, effectiveness of lighting systems for illumination and health must be the primary consideration, and then efficiency. SSL offers improvements to lighting performance and human health and well-being, while also enabling substantial energy savings. Recent R&D into physiological responses to light is providing guidance as to how lighting systems can be optimized for human health and well-being, though additional R&D is required to understand the energy consumption implications for possible new lighting guidelines.

Early guidance suggests that higher light levels, particularly in the morning (but also possibly throughout the day) will have an alerting effect on humans and improve melatonin function at the end of the day. However, it is important to recognize that higher light levels will require increased energy consumption. Research is still ongoing and has not yet generated guidance as to how high the light levels need to be, how long they need to be high, and how much blue content in the light is necessary. More R&D is needed to understand the relationships between timing, duration, intensity, and color of light, as well as the threshold where positive effects saturate. This understanding would enable lighting solutions that maximize both effectiveness and efficiency for daytime lighting environments.

In some lit spaces, researchers are investigating the benefits of lighting that can be tuned from higher blue content white during the day, to lower blue content light in the evening. This dynamic controllable light would provide a signal to our body throughout the day and is thought to improve circadian regulation and appropriate melatonin secretion. However, this approach affects energy consumption because tunable lighting products are generally not as efficient as static non-tunable lights. Tunable products consume more energy because they require multiple types of LED sources that may not be operated at their peak operating range. Therefore, the resulting white light from multiple color mixed LED sources is often less efficient than static non-tunable white LED sources that employ white LEDs. These systems could also have increased optical losses due to the mixing of different color LED sources. And, multi-channel power supplies are necessary to control the different color LED sources, which could result in non-optimized operating conditions. The technical efficiency reductions in tunable lighting products are not fundamental to LED technology, but they do present significant engineering challenges for the lighting product design. These considerations for high efficiency operation of the LED sources and power supplies at a broader range of operating conditions have greatly influenced the priority R&D tasks described in Section 5.

The current understanding of how lighting can be optimized for health is limited, and therefore we do not yet know the full extent of the lighting energy consumption impacts. However, it is clear that increased R&D investigating the physiological responses in common lighting applications, in conjunction with R&D in the engineered color-tunable lighting systems, will enable the development of products that can most effectively and efficiently provide lighting for human health and well-being.

4.3 Connected Lighting

The replacement of the lighting infrastructure with LED products offers the potential for future connected lighting systems (CLS) that could become a platform that enables greater energy savings, lighting effectiveness for new lighting applications, and high-value data collection in buildings and cities. For example, as lighting systems become more connected, it is anticipated that they will increasingly offer the ability to optimize resources and processes, deliver health and productivity gains, and yield new revenue streams. Further, it is likely that these capabilities will offer benefits that match or exceed the value of the energy savings they deliver. The value of services made possible by data from networked SSL systems might partly or fully offset the incremental costs of sensors, network interfaces, and other additional components. Systems made up of connected lighting devices could become data collection platforms that enable even greater lighting and non-lighting energy savings in buildings and cities, and much more.

4.3.1 Energy Savings and Other Valued Features

As SSL technology matures, maximizing the energy savings from connected SSL systems will become increasingly dependent on successful integration into the built environment. Lighting controls have 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 [7].

The ability of connected lighting to collect and exchange useful data, and possibly even serve as a backbone of the fast-emerging Internet of Things (IoT), offers the potential to enable a wide array of services, benefits, and revenue streams that enhance the value of lighting systems and bring that improvement to building systems that have long operated in isolation. Connected lighting systems can help building owners to understand how a space is being utilized by its occupants and to deploy adaptive lighting strategies that increase lighting energy efficiency. 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, 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.

In addition to a range of occupancy and daylight sensors, other types of sensors could be installed, including those to measure carbon dioxide, imaging, vibration, sound, and barometric pressure — resulting in such "smart city" features as air quality monitoring, weather warnings, theft detection, guidance to available parking spaces, and transit optimization. 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 these assets, particularly when there are failures.

If connected lighting products have the capability to self-measure and report energy use, utilities could offer incentives to customers based on actual savings instead of estimated savings. 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, more-accurate energy-savings validation for service-based business models; and self-characterization of available (i.e., marketable) "building energy services."

SSL is already being used as a platform for indoor positioning in retail and other heavy-traffic buildings, by using Bluetooth® and/or visible light communication to provide personalized location-based services for occupants via mobile devices. Retailers use the luminaires to transmit to shoppers location-specific data such as discount coupons or where in the store to find products. 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. Connected lighting is also being considered as a promising new source of broadband communication called Li-Fi, which modulates light to transmit data. Additionally, connected lighting is being combined with spectral tuning in a variety of settings, with the goal of engaging physiological responses to improve mood, productivity, and health.

4.3.2 Lighting Controls 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. CLS will need to operate within the larger environment of building energy management technologies. The challenge is agreeing on common platforms and protocols, among lighting products and within the larger IoT landscape, 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. Interoperability is considered to be the pivotal enabler of and catalyst for IoT deployment and, thus, CLS adoption and associated energy savings [8] [9]. 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 proprietary technologies or their own version of industry standards. The benefit of interoperability is that it enables different devices, applications, networks, and systems to work together and exchange data. For users, it reduces the risk of device or manufacturer obsolescence, as well as the risk of having limited hardware, software, data, and service choices. It also improves system performance by facilitating multi-vendor systems, reducing the cost of incremental enhancement, enabling greater data exchange, and encouraging service-based architecture.

Interoperability requires industry to agree on common platforms and protocols that enable the transfer of usable data between lighting devices, other systems, and the cloud. 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 among commercially available connected lighting systems.

4.3.3 Connected Lighting Test Bed

The BTO SSL Program is working closely with industry to identify and collaboratively address the technology development needs of connected lighting systems. Central to the BTO efforts is a connected lighting test bed (CLTB), designed and operated by Pacific Northwest National Laboratory (PNNL) to characterize the capabilities of 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 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.

The CLTB is being used to investigate several areas and capabilities of connected lighting systems including interoperability, energy reporting studies, and cybersecurity testing. A recent study focused on interoperability as realized by the use of application programming interfaces (APIs) in several connected lighting systems and characterized the extent of interoperability that they provide [10]. The APIs provided by current market-available CLS vendors can be utilized to facilitate some interoperability between lighting systems which enables lighting-system owners and operators to implement a basic level of multi-vendor integration and remote configuration and management services, as well as some adaptive lighting strategies. However, in many instances, API inconsistency and immaturity unnecessarily increase the effort required to implement these services and strategies and reduce the value and performance that they deliver. API developers should explore and attempt to implement common approaches to naming and organizing resources, as well as common information and data models – which are key to both minimizing the effort required to integrate heterogeneous systems and enabling functional, high-value use-cases.

4.3.4 Security

As more devices are becoming part of a connected world, the benefits come with security risks. This has been demonstrated by a few publicized cases in which firewalls have been breached by hacking into lighting products [11]. 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 [11]. 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. 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 several data consumers and controllers, while still maintaining privacy of data where 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.

DOE is collaborating with Underwriters Laboratory (UL) and other Industrial Internet Consortium (IIC) members of a Security Claims Evaluation Testbed on their efforts to develop test methods for cybersecurity vulnerabilities. Evaluation of a recently completed V0 test method is under way in the DOE CLTB using a test setup that currently comprises a cybersecurity gateway, two commercially available cybersecurity software services, and a Kali Linux system. When one or more test methods are deemed sufficient, DOE will conduct studies to evaluate the cybersecurity vulnerabilities in connected lighting, and perhaps the effectiveness of strategies and technologies for addressing them.

5 Directions in LED Science

LED lighting technology has improved dramatically over the past decade to achieve among the highest efficiencies of available white light sources. Improvements in manufacturing has 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 necessary to ensure even more energy savings. LED lighting efficiency and other features, such as color quality, light distribution, form factor, and architectural integration, have room for further advancements. 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 identified in Section 3.2. The key challenges currently facing LED technology also represent some of the greatest opportunities for performance gains. 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.

5.1 White LED Technology

Two common architectures for generating white light will be the focus for the discussion in the following sections; the phosphor-converted (pc) LED based on a blue LED pumping yellow and red wavelength optical down-converters (typically phosphors) to produce white light; and the color-mixed LED (cm-LED) approach using primary colors that compose a red, green, blue, and amber (RGBA) LED combined to produce white light. These are illustrated below in Figure 5-1, with the corresponding optical spectral distributions of these white LED architectures shown in Figure 5-2.

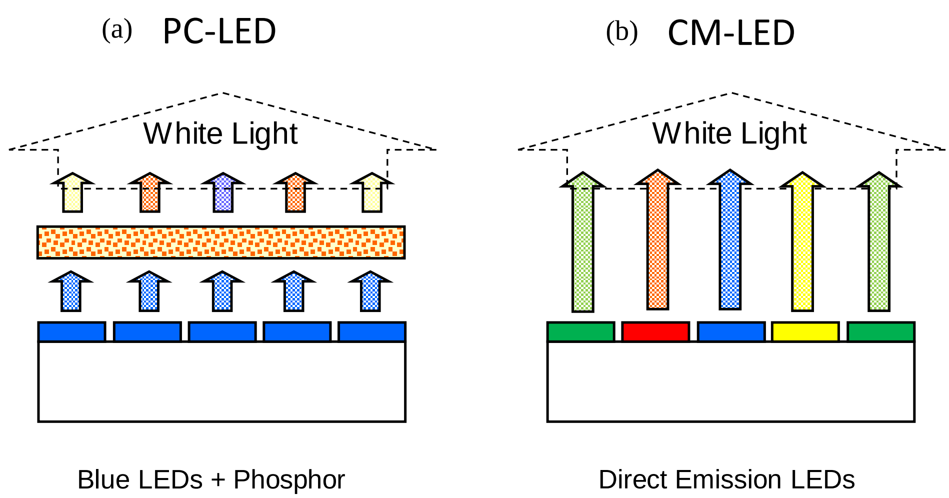

Figure 5-1. Schematic of Two Main White LED Architectures

Note: (a) the phosphor-converted (PC) LED using blue LEDs to pump yellow and red down-converters; (b) the color-mixed (CM) LED using direct emission LEDs to provide the different colors to mix to white.

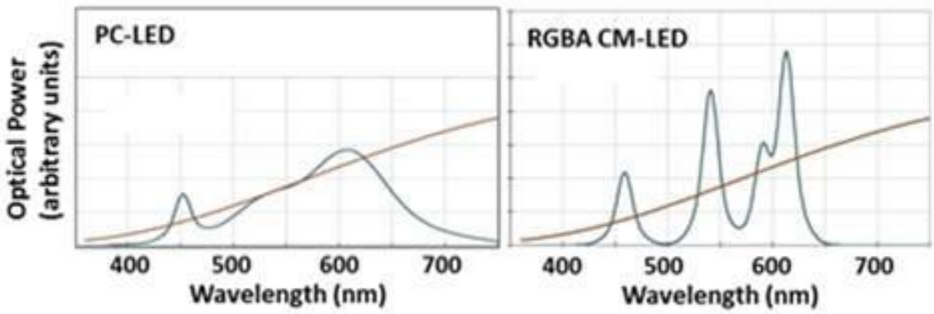

Figure 5-2. Typical Simulated Spectral Power Density for White-Light LED Package Architectures

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.

The pc-LED architecture is by far the dominant white light architecture. It has three major advantages: simplicity (only one LED type), temperature robustness (the InGaN blue LED and YAG phosphor down-converters 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 5-3 shows a history of the luminous efficacy of pc-LEDs since the BTO SSL Program began and the progress that has been made. It is important to note that the assumed operating conditions for qualified data points may not correspond to practice, particularly with respect to the increasing use of lower drive currents to minimize current density droop. Nevertheless, using a standard current (or power density, as measured in Amps per centimeter squared, or A/cm^2) at a fixed operating temperature and selecting devices within limited ranges of CCT and CRI allows researchers to evaluate developments in emitter efficiency (including the reduction of current density and thermal droop) and down-converter performance.[8]

Using these assumed operating conditions, in just 10 years, luminous efficacies have increased by a factor of more than three, from less than 50 lm/W to approximately 165 lm/W. The principal reason has been improvement in blue LED efficiency, although progress has also been made in phosphors (efficiency and wavelength match to the human eye response) and package (optical scattering/absorption) efficiency. Despite these improvements, there is significant remaining potential for improved efficacy. As illustrated by the saturation values of the blue and yellow curves in Figure 5-3, luminous efficacies of approximately 255 lm/W are believed to be practically possible for pc-LEDs.

For the color-mixed architectures an upper limit of 325 lm/W is considered achievable with technology advancements discussed in this chapter. While the performance potential is high, today's efficacies are much lower than the pc-LED approach due to the inefficient green and amber direct emission LEDs. Panel (b) of Figure 5-3 shows projections for power conversion efficiency of blue (440-460 nanometers, or nm), green (530-550 nm), amber (570-590 nm), and near red (610-620 nm) direct emitting LEDs, again with a logistic fit for projected performance, and with an upper limit of 90% power conversion efficiency.

In addition, Table 5-1 shows historical and projected LED package efficacy for warm white and cool white phosphor-converted and color mixed LEDs.

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8 For additional details regarding the specific operating conditions by which LED products are evaluated, see the notes described within Figure 5-3.

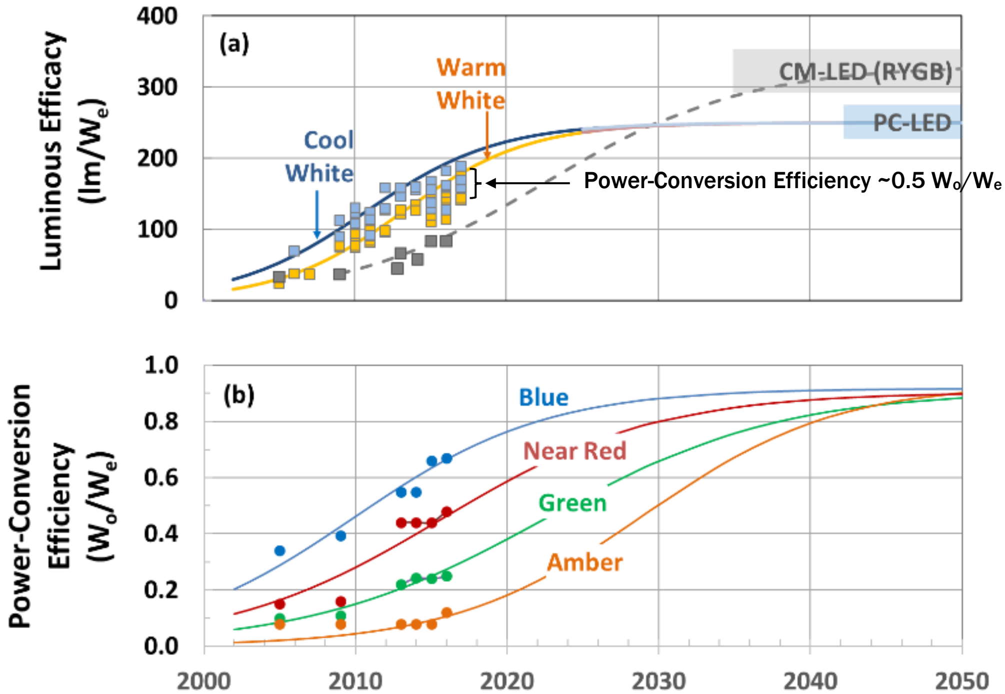


Figure 5-3. Efficacies and Efficiencies Over Time of White and Colored LED Packages

Note: All curves are logistic fits using various assumptions for long-term future performance and historical experimental data. The data are from qualified products at the representative operating conditions of 25°C and 35 A/cm² input current density. They will differ from some commercial products, particularly those that operate at lower drive current densities to minimize current droop.

- *The upper panel (a) are the luminous efficacies of warm white (3000 K) and cool white (5700 K) phosphor-converted LEDs and hypothetical color-mixed LEDs (CM-LEDs) with a CCT of 3000-4000 K. Luminous efficacies have the typical units of photopic lumens of light (lm) created per input electrical Watt (W_e) of wall-plug power. Year 2017 commercial products reach approximately 180 lm/W for cool white PC-LEDs and approximately 160 lm/W for warm white PC-LEDs. These values correspond to raw electrical-to-optical power-conversion efficiencies of approximately 0.5 W_o/W_e.*
- *The lower panel (b) are the power-conversion efficiencies of direct-emitting LEDs at the various colors (blue, green, amber, and near-red) necessary for CM-LED white light of highest source luminous efficacy and high color rendering quality. Approximate future potential power-conversion efficiencies are depicted as a saturation at 90% for all colors beginning in the years 2035–2040. The historical power conversion efficiencies of these sources were combined and appropriately weighted to give the CM-LED LEDs and conversion efficiencies depicted in the upper panel (a).*

Table 5-1. Phosphor-Converted and Color Mixed LED Package Historical and Targeted Efficacy

Metric	Type	2016	2017	2025	2035	Goal
LED Package Efficacy (lm/W)	Cool White	160	172	241	249	250
	Warm White	140	156	237	249	250
	Color Mixed	90	100	196	288	330

5.2 Advanced Material Discovery and Engineering Exploration for LED Development

As discussed in the previous Section 5.1, the past 10 years have seen remarkable progress in LED luminous efficacy, however LED technology still has significant room for improvement. While the pc-LED architecture has seen the most rapid improvements, cm-LED architectures continue to be the architectures with the most potential for efficacy. The BTO SSL Program goal for the white pc-LED is 250 lm/W, while for the white cm-LED is 325 lm/W, which means there is a possibility for another 30% improvement after the phosphor converted approach reaches its maximum efficacy.

However, progress towards improving the efficiency of cm-LED architectures requires improving efficiency in the green-amber-red spectral regions, where there has been limited development. Possible solutions could arise through use of current LED materials such as InGaN and AlInGaP, or through the development of new LED materials. With this uncertainty in mind, two potential research directions are: advanced material discovery or, advancements within the currently used LED materials systems.

Advanced material discovery is necessary to accelerate the rate at which new potentially viable materials are detected. This process involves the evaluation of large numbers of material combinations through the use of powerful computational techniques. Given the near incomprehensive volume of possible materials, supercomputing enables researchers to apply techniques such as machine learning to problems in materials discovery. Further R&D is needed to determine how advanced material discovery techniques could be tailored to identify materials with potential for mitigating or by-passing the efficiency losses (both current density and thermally driven) from the green-amber-red gap. This could potentially be done by defining and screening for an irreducible set of properties, such as a material synthesis and electroluminescence efficiency within the desired spectral region.

While advanced material discovery has the potential to identify suitable material compositions, engineering exploration is then needed to test them in the laboratory and within the cm-LED architecture. For example, several materials have currently been identified with potential for mitigating or by-passing the efficiency losses from the green to red spectral regions – these include GaNP, BInGaN, ultrathin and/or ordered InGaN, and perovskites. Engineering exploration of all identified materials would be significantly time intensive, therefore efforts must be concentrated on the most promising materials systems. These select few need to be tested using high caliber synthesis, materials and characterization techniques, linking results to SSL performance goals. In addition, learnings from the engineering exploration process need to feed back into the advanced material discovery to provide additional guidance that will improve the identification process.

These two research directions are inherently cyclical, with advanced material discovery translating into insights into how best undergo engineering exploration. The engineering exploration then provides feedback that can be used to better tailor the techniques and screening process for advanced material discovery. Combined these methods have the potential to solve the green-amber-near-red gap among other SSL material challenges.

5.3 Understanding Droop in LEDs

How “hard” an LED is driven has a very important implication for SSL – reducing cost. If luminous efficacy (lm/W) can be maintained, the “harder” an LED is driven (in terms of input power per unit chip area), the more lumens are output per unit chip area. Since chip costs scale approximately as chip area, more lumens are then produced per unit chip cost. This has historically been the principal motivation for eliminating or reducing blue LED efficiency droop: the maintenance of high luminous efficacy as LEDs are driven harder, which enables more lumens per LED cost.

However, as chip costs have decreased they have also become a smaller fraction of overall LED package cost. Thus, the magnitude of cost impact of eliminating droop has declined. Nonetheless, eliminating efficiency droop still offers significant benefit, particularly when accounting for overall LED system-level costs, which can be reduced if boards, heat sinks, optics, etc., can be made physically smaller per lumen of light output.

5.3.1 Blue LEDs

The efficiency of blue LEDs has improved enormously over the past decade. Leading research has demonstrated blue LEDs that exceed 80% external quantum efficiency (EQE), but only at relatively low current densities. LED efficiency is still limited at high current density due to a phenomenon known as efficiency droop or current density droop. Operation at higher current densities is desirable to maximize the light emitted from the chip, thereby lowering the cost per lumen of LED lighting products.

There are different physical mechanisms that impact efficiency at different current densities, as indicated in Figure 5-4. At low current densities, the number of defects in the material has a significant impact on efficiency, where Shockley-Read-Hall (SRH) nonradiative recombination dominates. At higher current density operation, Auger recombination dominates, which 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 in the active region (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 within the LED structure [12].

The amount of Auger recombination is controlled by the Auger constant in each quantum well (QW) of the LED active region and the carrier density in each QW, so it is important to have uniform current injection into each QW. The LED epitaxial design can be changed to increase the carrier transport to get uniform injection into each quantum well, as illustrated in Figure 5-4. The problem is that the improved heterostructure leading to uniform carrier injection into the active region, leads to growth conditions that increase the SRH nonradiative recombination. While progress has been made in this area through funded R&D projects, further research in InGaN epitaxial growth is required to continue balance the material quality with the improved heterostructure design for carrier transport [13].

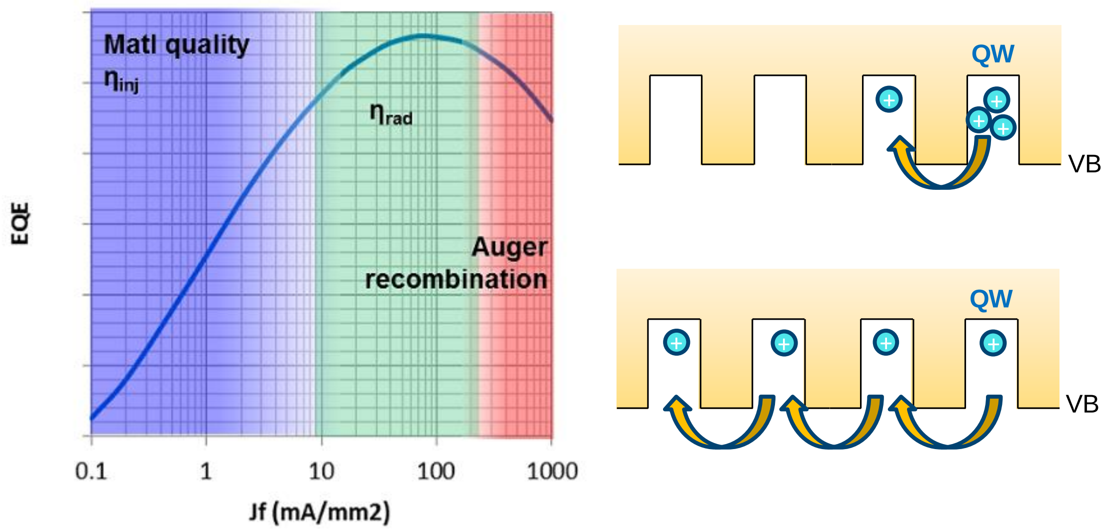


Figure 5-4. Blue LED EQE vs. Current Density and Schematic of LED Quantum Well Valence Band [14]

Note: Blue LED external quantum efficiency as a function of current density (left); the shaded regions indicate the dominant recombination modes. Schematic of the quantum well valence band of an LED showing carriers piling up in the p-side QW (top right) and showing uniform hole injection (bottom left).

5.3.2 Green LEDs

Although the InGaN alloy can theoretically cover the whole visible spectrum, its quantum efficiency drops rapidly above 500 nm as emission shifts from blue to green. Considering the long wavelength side of the visible spectrum, the AlGaInP materials system can provide high-performance red LEDs though the efficiency drops steeply in the amber region [15]. This phenomenon is known as the 'green gap' and is illustrated in Figure 5-5. The low efficiency of green LED is particularly critical, since ultra-efficient white LEDs based on color mixing require a green LED emitter with wavelength around 540 nm — right near the center of the 'green gap.'

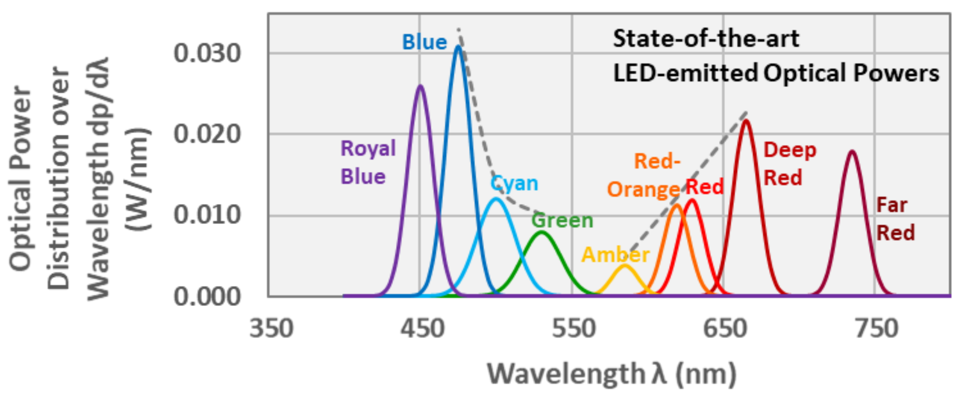


Figure 5-5. Spectral Power Densities of State-of-the-Art Commercial LEDs vs. Wavelength

Notes: 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. Data is for operation at 85 °C and has been "stylized" into Gaussian spectral distributions using efficiencies, center wavelengths and spectral linewidths from the Lumileds Luxeon C Color Line Datasheet DS144 (2018 02 19).

The source of the efficiency drop in the AlGaInP materials system is due to the transition from a direct bandgap to an indirect bandgap in the amber/green spectral region. For InGaN, the materials are less efficient in the green due to the combined effects of high indium compositions (materials challenges), polarization fields (less electron hole wavefunction overlap), and greater Auger recombination. The current density droop problem for green LEDs is even more severe than for blue LEDs. Figure 5-6 shows a schematic of the carrier distribution in a blue LED active region and a green LED active region. The carrier distribution in the green LED active region is poor due to larger energy barriers slowing vertical transport in active region. The increased barriers to carrier transport also result in lower electrical efficiency as compared to blue LEDs due to higher forward voltage relative to its photon energy [14].

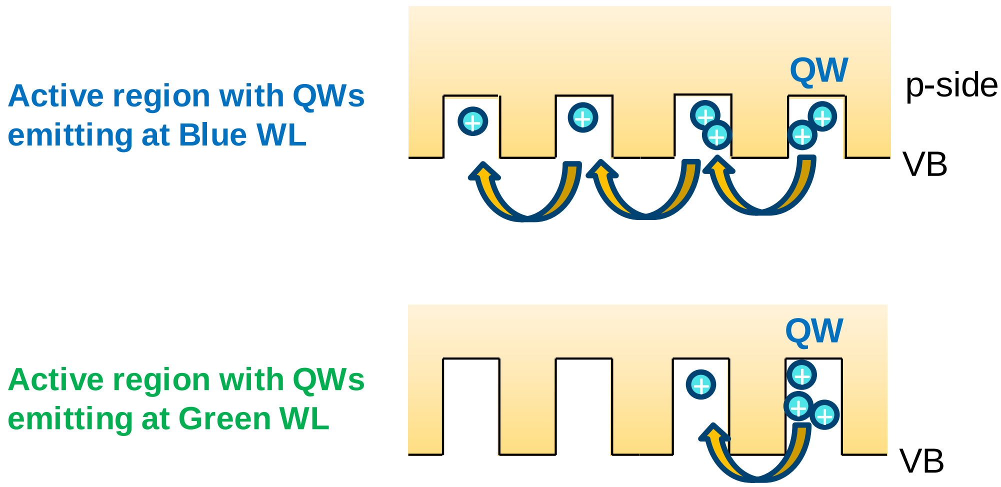


Figure 5-6. Schematic of the LED Quantum Well Valence Band [14]

Notes: Schematic of the quantum well valence band of an LED showing carrier distribution in today's state-of-the-art blue LED QW active region (top) and the carriers piling up in the p-side QW for a green LED active region (top right) and showing uniform hole injection (bottom).

To address the current density droop in green LEDs, more R&D on improving carrier transport between QWs is critical, even more so in green than blue LEDs. However, the biggest challenge is that most LED heterostructure changes that improve carrier transport hurt the material quality — again this is exacerbated for green LEDs relative to blue. Fundamental research in droop mitigation strategies should benefit both blue and green LEDs, though the challenges are magnified in the green spectral region.

5.3.3 Thermal Droop

Thermal droop in LEDs is simply the reduction of the optical power when the temperature is increased, which limits the efficiency of LEDs beyond that attributed to current density droop. Thermal droop is important in commercial devices since the temperature increases at the typical operating conditions in LED luminaires. Some commercial white LEDs are rated for operating up to 150°C, though devices running at 150°C can lose up to 25% of optical power, compared with room-temperature operation. The light output decline is more severe for the AlGaInP materials system where the optical power can drop 70% at 150°C. Figure 5-7 shows some typically thermal droop behavior for various color LEDs.

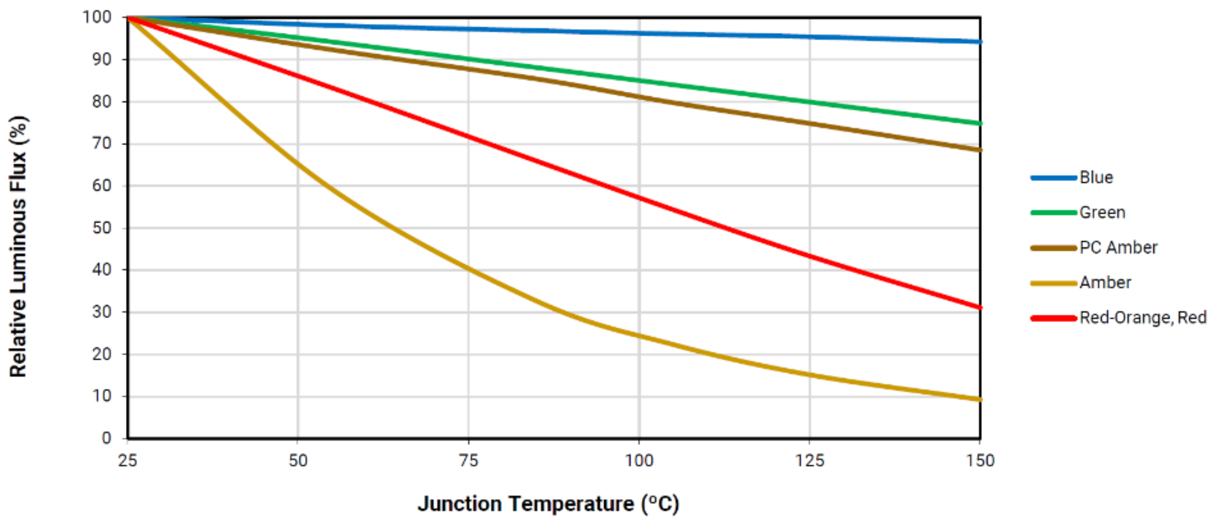


Figure 5-7. LED Efficiency as Function of Junction Temperature [16]

Note: LED efficiency declines as junction temperature increases. AlGaInP and AlGaAs LEDs experience the greatest drop.

Thermal droop occurs because of temperature-dependent semiconductor properties that cause non-radiative recombination and carrier loss. Researchers have been looking for the origin of thermal droop in InGaN LEDs. Work done by researchers at the University of California Santa Barbara show that when blue LEDs are operated at elevated temperatures, they demonstrate an increase in electrons lost via carrier leakage and/or overshoot. This increase of leakage and/or overshoot coincides with the onset of the decrease in light output at ~75°C, a temperature range at which LEDs are commonly operated. These results are consistent with the expected onset of the thermal droop that has been widely reported in scientific literature [17]. New InGaN LED heterostructure designs are needed that can minimize the carrier overshoot at elevated temperatures while maintaining the materials quality and high efficiency.

Thermal droop in AlGaInP LEDs is much greater than in InGaN LEDs. This is due to the materials properties in the semiconductor system. AlGaInP has small band offsets which can lead to significant carrier overflow with increasing temperature, especially for the shorter wavelengths such as amber. Research into new strain engineering approaches for epitaxial growth of the active region is a promising approach for improving the carrier confinement and reducing carrier overflow.

5.4 Advanced LED Architectures

Advanced LED device architectures have the ability to improve efficiency or improve the device's operating ranges. These can lead to improvements in current density droop or provide desirable device performance, such as high luminance, that is not achieved with conventional LEDs.

5.4.1 Droop Mitigation

There are several approaches to reducing or mitigating the impact of droop. One approach is to redesign LED active regions to minimize carrier density within them, as discussed in the previous Section 5.3. This reduces droop; however manufacturers have discovered that it is very difficult to maintain LED material quality with these low-droop designs.

There are also device architecture approaches to mitigating droop – such as using a laser diode (LD) to mitigate droop. In LDs, droop is eliminated when lasing occurs since all excess carriers are consumed by stimulated emission, thus reducing the availability of carriers for the non-radiative Auger recombination processes. This can allow for high flux density and higher wall-plug efficiencies than LEDs at very high current density operation. LDs have clamped charge carrier density, so droop does not exponentially increase at higher operating current, however, with lasers there is also a tradeoff between peak efficiency and droop reduction. Researchers are working on both the peak efficiency of lasers and ways to integrate them into practical lighting products.

As seen in Figure 5-8, an interesting insight involved the so-called “valley of droop” – the region of current density which is high enough that significant LED droop occurs, but low enough that laser diodes do not yet lase. Up until recently, it was thought that current densities associated with the valley of droop were optimal: if LEDs could be driven that “hard” while circumventing droop their photons would be less expensive; if lasers could be driven that “soft” while still lasing resistive losses would be lower and their efficiencies higher.

While the current densities associated with the valley of droop would still be desirable, two trends make it economical to consider on both sides of the valley of droop. First, because the cost of the chip, particularly the cost of the epitaxy, continues to decrease, larger chips driven at lower current density might soon be more economical. Thus, it is of interest to continue to increase peak efficiencies for low current density operation.

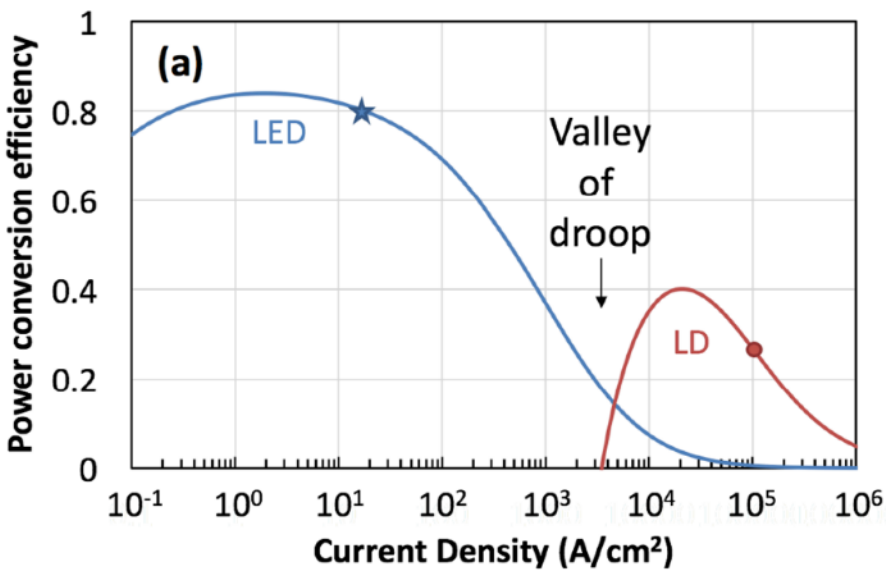


Figure 5-8. PCE Vs. Current Density for a State-of-The-Art LED and LD Emitting at Violet Wavelengths [18]

Notes: Plot of power conversion efficiency (PCE) vs. current density for a state-of-the-art LED and LD emitting at violet wavelengths highlighting the ‘valley of droop’ cross-over between source types.

Second, directional light is becoming increasingly important because it improves photon utilization efficiency. There is a premium placed on small, low etendue sources that can be spatially focused and directed. This is the province of high current densities: blue laser diodes beyond the valley of droop, and blue LEDs driven as far into the valley of droop as possible. Further R&D for laser lighting includes increasing the wall plug efficiency (WPE) of the LD from the current 30-40% range to 60% (LED level).

Finally, new architectures are being explored that could enable the effective straddling of the valley of droop simultaneously in a single structure: stacked tunnel-junction (TJ) series connected LEDs. Essentially, it would create multiple LEDs in series, which would increase voltage while keeping current low. This would enable higher light output from an area of LED material, while keeping the applied current — and resulting droop — low, as illustrated in Figure 5-9.

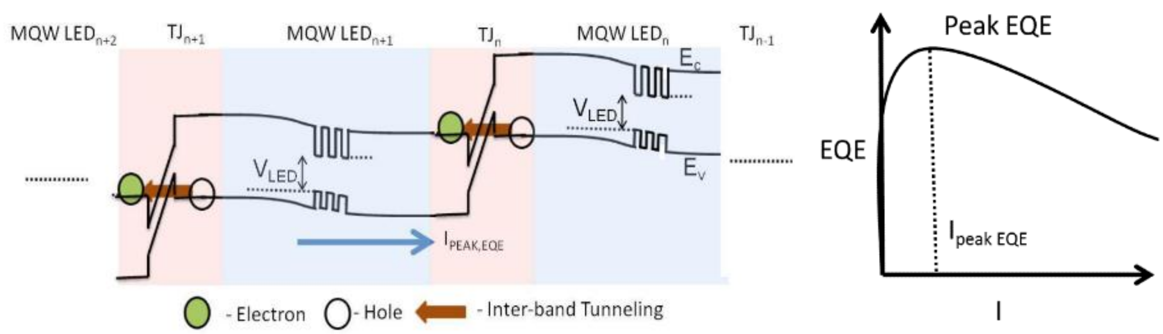


Figure 5-9. Schematic Band Diagram of a Stacked Active Region LED with Tunnel Junctions (left); the External Quantum Efficiency at the Peak LED Operating Current (right) [19]

While research into TJs has increased in recent years, several challenges remain. The increased voltage drop that results from the increased stack voltage can be an issue in TJs and needs to be reduced. Additionally, there are issues associated with activating the p-type dopant in buried active regions grown by metal-organic chemical vapor deposition (MOCVD) and absorption when using InGaN TJs. Moreover, developing growth processes for growing high-quality TJs is required to keep defect densities low and minimize negative impacts of subsequent LED junctions. Alternatively, growth processes such as molecular beam epitaxy (MBE) can be used to overcome some of the growth and activation challenges facing MOCVD (though the added cost of a second growth technique must be overcome).

5.4.2 High Luminance

While improving the efficiency of emitted light from an LED has been a big focus in the LED industry, how that light is delivered to the lighting application is equally as important. Some lighting applications, such as spot lighting, require a very narrow beam of light to illuminate the desired object. If the light is not focused in a tight beam, a significant amount of light generated from the source is not useful, thus lowering the optical delivery efficiency of the luminaire system.

The directionality of the light source also plays a big role in the efficacy of a light source. The 'harder' you can drive a light source, the more light you can generate out of a given area, thus increasing the luminance emittance. Luminance emittance is the luminous flux per unit area emitted from a surface expressed in units of lm/mm^2. When you can increase the lumen emittance, optical source size for a given lumen output can decrease. The smaller the optical source size, the smaller the illuminated area can be for a given size of package/luminaire optics. Equivalently, the smaller the package/luminaire optics can be for a given size of the illuminated area. Thus, in directional illumination, where the spatial profile of the illumination area is tailored, driving LEDs harder to achieve a smaller source size becomes more important.

However, just as efficiency droop causes the trade-off between cost and performance, as discussed in Section 5.3, it also causes a trade-off between luminous efficacy and luminous emittance. Figure 5-10 compares several representative state-of-the-art 2017 commercial white light packages and shows the wide span in efficacy and luminous emittance. As input current density increases, luminous efficacy decreases while luminous emittances increase. At the extreme top left is a mid-power white LED package driven at 0.7 A/cm^2 (shown in dark green text), while at the middle right is a high-power white LED package driven at 35 A/cm^2 (blue text). Also shown at the extreme bottom right is an estimated point for a laser diode (LD) white light package (bright green text).

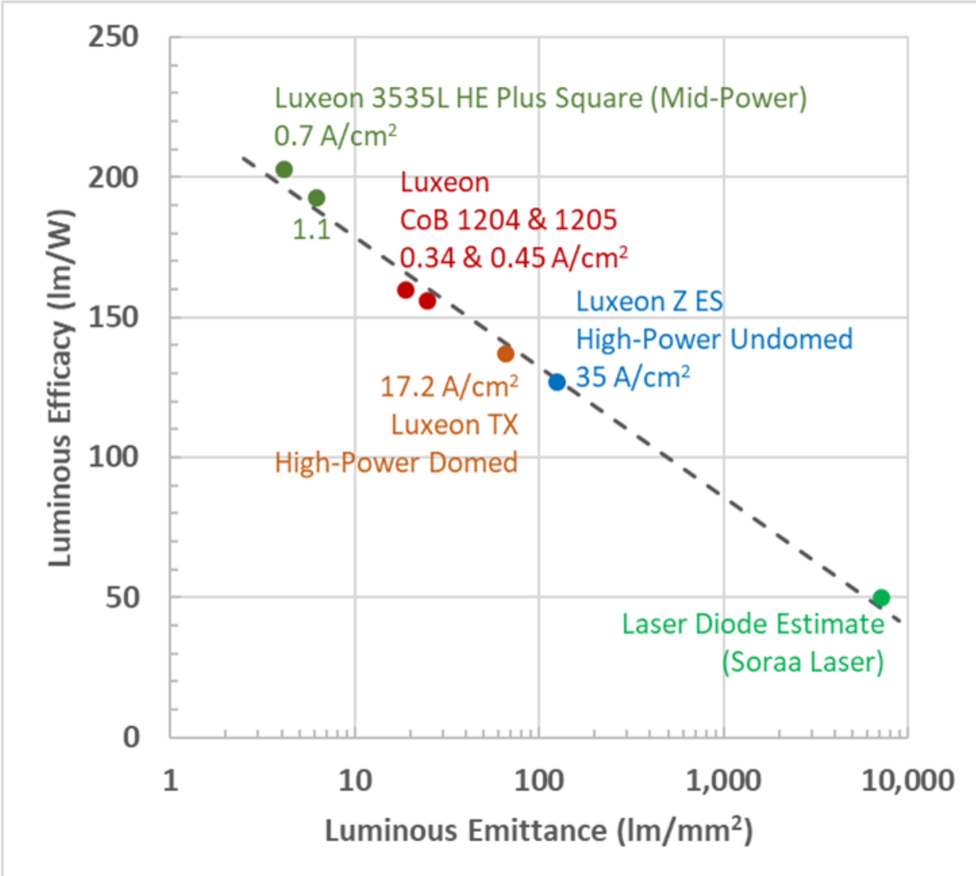


Figure 5-10. Luminous Efficacy vs. Luminous Emittances for State-of-the-Art Commercial White LEDs

Note: The dashed line is an empirical fit using the Equation given in the text.

A log-linear fit to the data points gives the empirical equation:

$$\eta \;=\; 225\,\frac{\mathrm{lm}}{W} - 46.4 \text{ x } \log_{10}\left[\frac{MV}{1\,\frac{lm}{mm^2}}\right]$$

This above shown equation can be thought of as defining the current trade-off between luminous efficacy, η, and luminous emittance, MV. Additional research is needed that focuses on materials and device architectures that go beyond the current state-of-the-art to enable both high luminous efficacy and luminous emittance – as demonstrated by the upper right quadrant in Figure 5-10. Research areas include further reductions in LED efficiency droop, down-converter materials improvement to provide high efficiency and stability at higher luminance, packaging materials improvement to prevent degradation at higher optical flux densities and temperatures, and optical design for angular uniformity of color.

5.5 Optical Down-Converters

State-of-the-art LED lamps and luminaires are predominantly based on phosphor-converted LEDs (pc-LEDs). The phosphors used in these pc-LEDs result in an emission with broad linewidths, which in turn limits their overall spectral efficiency or luminous efficacy of radiation (LER). The broad linewidth is particularly significant for the red spectral region since the broad emission results in a larger portion of the overall light distribution to be emitted in regions of the visible spectrum where the human eye is less sensitive. This portion becomes larger as the CRI increases, because a higher CRI puts more stringent demands on the amount of light emitted in the red wavelength range at the edge of the visible spectrum. However, because pc-LEDs emit a larger portion of their light in those regions, lamps or luminaires made with 90 CRI pc-LEDs have lower efficacy than those made with 80 CRI pc-LEDs due to this spectral inefficiency. This efficacy gap must be minimized to stimulate greater adoption of 90 CRI, pc-LEDs for lighting.

5.5.1 Narrow-Band Phosphors

Typical nitride or oxynitride red LED phosphors have a wide emission linewidth near 100 nm full width at half maximum (FWHM). This causes a significant spillover of light into the deeper red wavelength range, where the human eye is less sensitive, and is a significant contributor to the spectral inefficiency of current pc-LED white light. Figure 5-11 illustrates this behavior by comparing a white LED using a 110 nm FWHM broadband red phosphor with a CCT of 3000K, a CRI ≥90, and an R_9>50 to a white LED (with similar color qualities) using a red phosphor with bandwidth of 30 nm. A 22% improvement in spectral efficiency is gained by replacing the red broadband phosphor, which reduces the wasted emission in the deep red and infrared (IR) wavelength ranges (beyond 650 nm) [20].

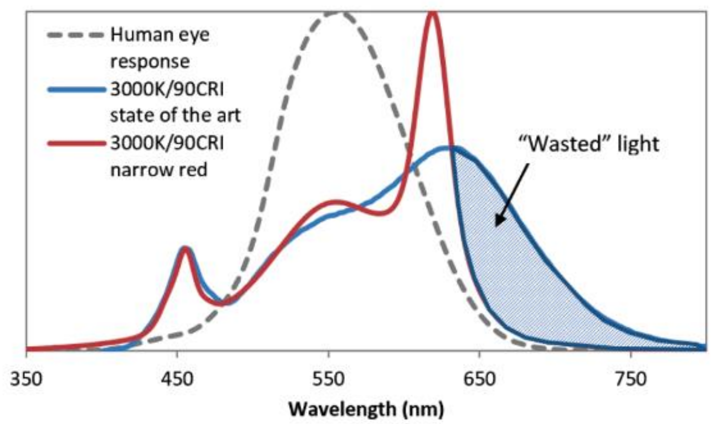


Figure 5-11. Spectrum Comparison of 90 CRI PC-LED, 90 CRI Conventional Red Phosphor LED, and Human Eye Response [20]

There have been recent developments in the field of narrow red down-converters. GE continues to release lighting products that feature its narrow red phosphor, "KSF," under their "Tri-Gain" brand [21].[9] These lights exhibit excellent color quality and high efficacy due to the narrow red emission spectrum of the phosphor. While this phosphor was demonstrated several years back, materials refinements have continually improved its long term behavior. Such improvements include a smaller color shift in LED packages and stronger lumen maintenance stability under high blue flux densities, as seen in Figure 5-12 [21]. 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 [20].[10]

9 KSF, or $K_2SiF_6:Mn^{4+}$, is a potassium fluorosilicate phosphor.

10 SLA, or $Sr[LiAl_3N_4]:Eu^{2+}$, is a nitridoaluminate compound.

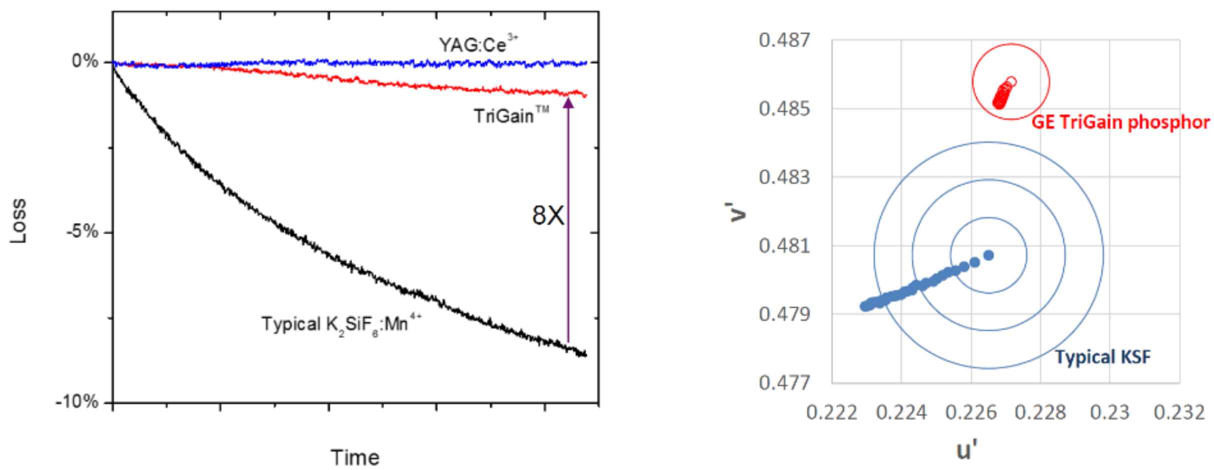


Figure 5-12. Light Loss of Phosphors in LED Packages under High Blue Flux Densities (left) and Color Shift under Stressed Operating Conditions (right) [21]

While significant improvements have been made to narrow-band red phosphors over the past several years, opportunities still exist to improve material synthesis and composition to result in fewer materials defects and to allow for higher activator manganese (Mn) concentrations, which can reduce the amount of phosphor materials needed on the LED. These additional improvements would lead to lower phosphor volumes at the same color point currently in a comparable LED. Further reliability improvements are also desirable to run at higher operating fluxes and temperatures.

5.5.2 Quantum Dot Down-Converters

Quantum dots (QDs) have long been targeted for use as down-converters in LEDs due to their combination of two unique emission characteristics: tunability of wavelength and narrow emission linewidths. These quantum-confined semiconducting nanocrystals are made of inorganic semiconductor material and commonly "grown" using colloidal synthetic chemistry, with electron and hole confinement, that results in unique optical properties. Colloidal QDs feature a tunable band gap that can span the entire visible spectrum with nanometer scale resolution by adjusting the particle size and a narrow FWHM owing to the direct transition from the band gap edge. Until now, QDs have not gained much traction as a drop-in solution into the LED package because the LED operating temperature and blue flux intensities result in strong thermal quenching and fast photo-degradation. R&D progress in this area has been made, though, with Lumileds' commercialization of a mid-power LED package using red QD down-converters (combined with phosphors) this year [22] [15].

As with narrow-band phosphors described in Section 5.5.1, the use of QDs as down-converters can provide improved spectral efficiency gains by reducing the wasted light emission in the deep red and IR portions of the spectrum. Red QDs used in combination with a conventional phosphor material can improve LED conversion efficiency by 5% to 15% over commercial pc-LEDs between CCTs of 2700 Kelvin (K) to 5000 K [23]. Lumileds LEDs with the on-chip application of QDs can operate where the QD temperature exceeds 100°C and the blue flux intensity reaches 0.2 W/mm^2 in mid-power packages. These achievements in QDs demonstrate the essential reliability requirements for use in commercial applications [24].

However, the current high-performance QDs commercialized in LEDs contain a small amount of cadmium (Cd). The use of Cd in electronic devices is regulated by the European Union (EU) under the Restriction of Hazardous Substances (RoHS) Directive; Cd use is limited to 100 parts per million (ppm) in the smallest homogeneous component of an electronic device containing the metal. For on-chip LED usage, the smallest homogeneous component is the down-conversion layer consisting of the QDs, other phosphors, and the silicone binder that is deposited inside the LED package. The exact concentration of Cd depends on multiple factors, such as the LED package design and the final color point, but it has been estimated to range between 150 and 500 ppm [25].

While Cd-containing QDs provide the best performance to date, there is still the need to evaluate alternative Cd-free QDs due to the regulatory requirements on Cd use. The most advanced Cd-free QD technology is currently InP-based QDs; however, currently the FWHM of the emission and environmental stability is not to the level of their Cd-containing counterparts. The FWHM has improved the past few years and is now approximately 40 nm for green and 50 nm for red, nearing the BTO target of 30 nm FWHM [26]. The progress in the last few years has come from better materials design, but stability is still a large hurdle that requires further research and development. Other potential QD systems (that do not contain Cd and will be ROHS compliant) are perovskites and CuSeS QDs, which are still in the early stages of development and require more work to assess the performance levels and stability.

Beyond creating QDs with the required performance properties and reliability behavior for incorporation in LED packages, the ability to manufacture large-scale batches of QD material is critical for use in SSL. One significant hurdle in QD synthesis is controlling the size of the actual QDs. Slight diameter changes will result in wavelength changes in the down-converter, as illustrated in Figure 5-13. When the ensemble of QDs with slightly varying diameters is applied in an LED package, the emission FWHM can broaden. New synthesis techniques can help improve the layer-by-layer synthesis, which is difficult to consistently control.

One effort to potentially significantly improve the scalable synthesis of high-performance QDs employs a convergent (rather than linear) approach that uses a single-step heterostructure synthesis. This creates graded alloy QD architectures using tunable reaction kinetics of a set of precursors. Reliably dictating QD size, concentration, and monodispersity requires well-controlled precursor conversion. Research is underway to prove out the synthesis reproducibility, QD performance, and reliability using new colloidal synthesis.

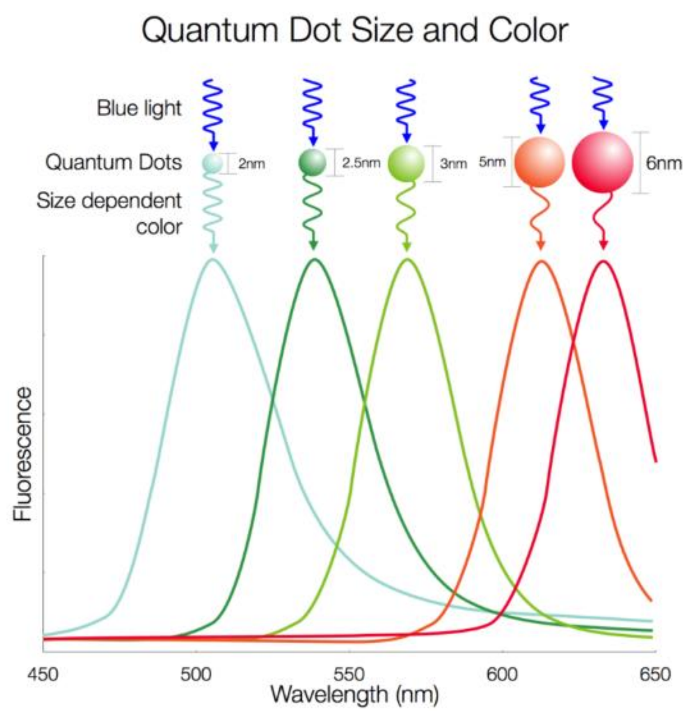


Figure 5-13. Emission Wavelength of CdSe QDs as a Function of Dot Diameter [26]

QDs for on-chip LED application have made remarkable advancements over the past few years. CdSe-based QDs have been released in an initial LED package product this year, demonstrating their commercial viability [22]. While the progress has been promising, more research and development work is required to advance understanding in high-efficiency, on-chip QD down-converters to match or exceed performance of conventional on-chip phosphor materials. In addition, further development of QDs that do not contain heavy metals (such as Cd or Pb) or scarce materials is needed for the changing regulatory requirements on these materials.

5.6 Additive Fabrication Technologies for Lighting

Over the past few years, additive manufacturing has been a growing area of interest for SSL product prototyping and manufacturing. Additive manufacturing is a fabrication process where a 3D object is created by computer-controlled deposition of material (in a layer by layer approach) based on a computer-aided design (CAD) model. 3D printing is one common example of additive manufacturing. It can be more efficient than traditional "subtractive" manufacturing approaches, such as milling, grinding, and polishing, which involve removing material to achieve the desired form, either for the product directly or for making molds and tooling.

Some of the key benefits of additive manufacturing include:

- Complex shapes can be made that are not possible with traditional manufacturing;
- Opportunities to use mixed material types in the same package;
- Lower energy intensity by eliminating production steps, using substantially less material, and producing lighter products;
- Minimized initial equipment investment cost – i.e., no tooling is required, offering flexibility of shapes and reduced inventory with the same equipment;
- Easier to iterate product variations or functional form-and-fit processes and testing; and
- On-demand manufacturing capabilities for projects with shorter lead times.

Additive manufacturing applies to many different aspects of the SSL supply chain and manufacturing processes. Some of these areas include:

- Wafer scale packaging, including down-converter and encapsulant deposition;
- Power supply component and module manufacturing;
- Rapid creation of tooling for optics, heat sink, or housing manufacturing; and
- Flexible production of optics or lighting fixtures.

The primary use of additive manufacturing in SSL has been for rapid prototyping on new product design concepts. 3D printing enables the design of custom fixtures with improved visual appeal, better functionality, and reduced fixture costs. The Philips Lighting (now Signify[11]) Telecaster Program has been developing additive manufacturing for numerous styles of light fixtures, including 3D-printed decorative pendants, track spots, downlights, and large high bay fixtures. Figure 5-14 shows three examples of 3D-printed light fixtures.

[11] As of May 16, 2018, Philips Lighting is now referred to as Signify. Additional information on the announcement of the name change can be found at: https://www.signify.com/en-us/about/news/press-releases/2018/20180516-philips-lighting-is-now-signify.

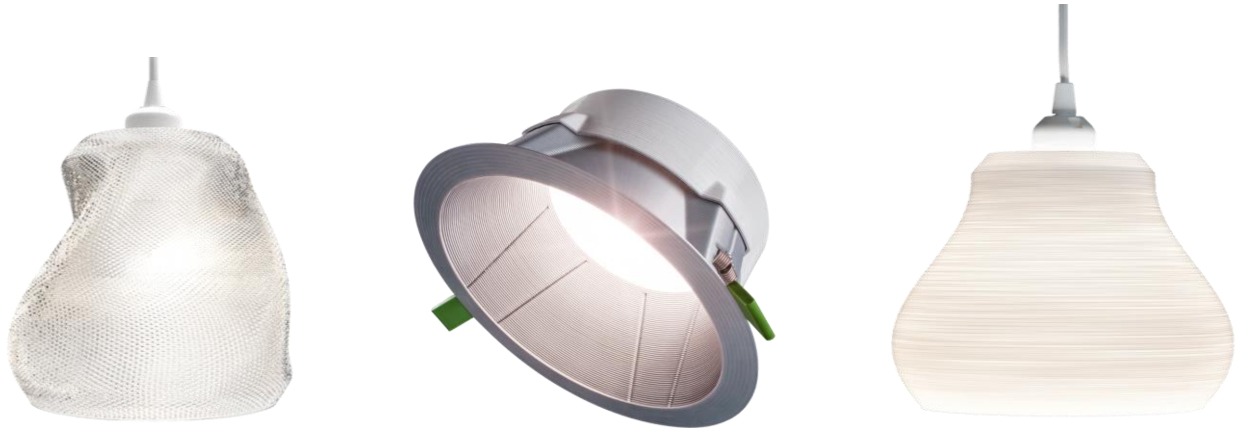


Figure 5-14. Images of 3D-Printed Lighting Fixtures [27]

Beyond the use of additive manufacturing to make luminaire housings, this technique has been used to create the functional components of luminaires, such as optics. These optical structures are made from a UV-curable polymer ink and cured by UV lamps in the print head upon each pass of printed droplets, as illustrated in Figure 5-15. This method allows geometric and free form shapes to provide the desired optical control features, while it simultaneously eliminates the expense of molds and tooling and enables just-in-time manufacturing.

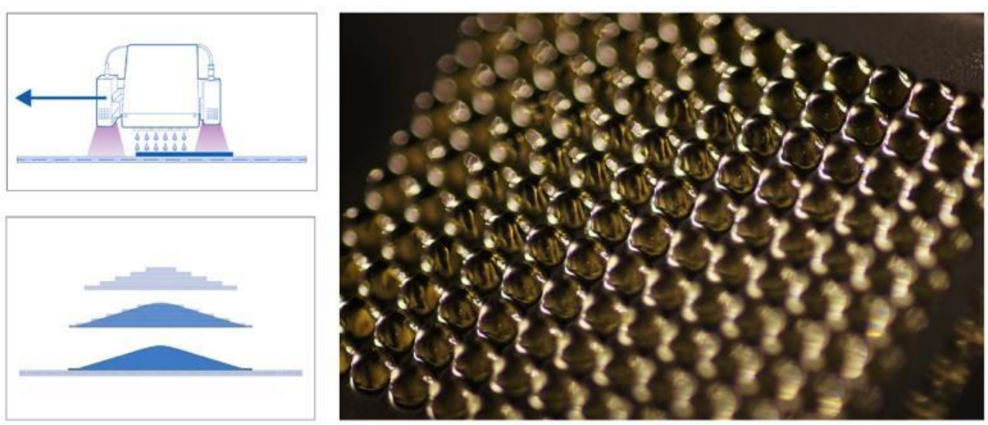


Figure 5-15. Deposition of Droplets by UV Print Head onto Substrate Material (left-top). Droplets of Polymer Are Allowed to "Flow" under Surface Tension before Curing with UV Light, giving Smooth Surfaces Needed for Optics (left-bottom). Array of Micro-Optic Lenses (right). [28]

One of the biggest challenges with implementing 3D printing further into the SSL value chain is the development of printable materials with properties specific to lighting applications – optical, electronic, and thermal properties. In this space the manufacturing advancements achieved by EERE's Advanced Manufacturing Office can be leveraged; however, application-specific manufacturing R&D is necessary. For example, there are challenges achieving the appropriate thermal conductivity of a heat sink using a polymer-based ink with conductive fillers. While these materials can be used to print a heatsink, the thermal conductivity falls short of the performance seen with aluminum heatsinks. Studies have been carried out printing electrical traces for printed circuit boards (PCBs), and while they can be printed, the resistivity of the traces are higher than copper [29]. While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, more research and development is required to develop printable materials with the sufficient properties to replace existing manufacturing approaches in electrical, thermal, and optical components.

Another area of interest for additive manufacturing in the SSL value chain is to create tooling using 3D printing. The lead time for tooling for molding or stamping processes often takes 10-12 weeks to be created. 3D printing has the potential to reduce the lead time significantly and create tooling in 2-4 weeks. This allows for a shorter product development cycle and quicker pilot line development, and the concept has been used to prove out the 3D printing of cars. The use of additive manufacturing in creating tooling has the potential to create efficiency gains with SSL product manufacturing.

5.7 Advanced LED Lighting Concepts

Developing lighting system architectures that take advantage of the unique properties of LEDs can maximize the vast potential of LED lighting over traditional lighting sources. LED lighting provides features such as high energy efficiency to color quality, compact and unique shapes, and other non-energy benefits (e.g., physiological responses to light). Improved lighting application efficiency (discussed in Section 4.1) can help further luminaire performance levels and provide advanced lighting values (e.g., human physiological benefits as demonstrated by spectrum and intensity levels appropriate for engaging these responses). Concepts that demonstrate improvements to lighting application efficiency should be a focus of future research and development.

Color-tunable LED luminaires provide the ability for spectral and intensity tuning, which realizes some value-added features available from LED lighting for applications such as hospital lighting to horticulture. These color-tunable lighting systems, also referred to as RGB, RGBA, spectrally-tunable, or color-changing, usually have three or more different LED primaries that can be individually varied in light output power to create a mixture of light that is white or a saturated hue. The individual LEDs used in a full-color-tuning mixture can be direct emission narrow-band LEDs (producing a narrow range of blue or red, for example), or they can be monochromatic with phosphor coatings that produce a slightly wider spread of color (e.g., a “mint” green LED is a phosphor-coated blue). Usually the different monochromatic LED colors include red, green, and blue (i.e., RGB, the primary colors of light), but these can be augmented with amber (A) or other monochromatic colors. The minimum number of LED colors is three for full-color tuning, though four-, five-, and seven-color systems are also on the architectural lighting market, and some sophisticated color systems use additional unique colors of individual LEDs.

One unique advantage of this type of color-tuning is the ability to move the color point off the blackbody locus or, in other words, to move beyond different CCTs of white light toward light with a distinct color. For example, such a product could provide 4000 K light in an office during the day and then tune to a different color for a purple-themed party in the evening. This makes full-color-tunable products well-suited for theater, theme park, and restaurant applications. Another advantage of full-color tuning is the ability to match the chromaticity of any other light source. Controlling the colors of individual LEDs introduces the option of tuning the spectrum to enhance colors for retail applications – for example, a lighting display can be tuned to make a floral arrangement appear rich and full in color.

The four-color RYGB cm-LED architecture, in which all colors are generated by direct LEDs, can significantly improve efficacy since it will remove the fundamental Stokes losses associated with down-conversion by phosphors or QDs. As indicated by the dashed grey line in Figure 5-3, ultimate upper potential of a four-color RYGB cm-LED can be on the order of 325 lm/W, limited only by the anticipated 80% to 90% efficiencies of the actual LEDs and for the losses when mixing the pure source colors to create white light. At present, the low external quantum efficiency of green/amber LEDs lower the overall system efficacy of a color-mixed system compared to a white pc-LED system. As discussed earlier, the green and amber LED efficiency must be increased to achieve the combined potential of maximized high efficacy and full color control.

With the addition of color-tunable luminaires to the market, color mixing has become a growing challenge. New color mixing optical schemes (e.g., refractive + lighting guiding optics) are needed in luminaires to help provide low-profile optics and efficient mixing optics and to reduce the cost compared to the traditional volume mixing chambers in today's luminaires. The development of efficient optical elements should be considered to improve the efficacy of color mixing.

In addition to more complexity in color mixing, more complexity is required in the control strategies for fully color tunable LED luminaires. This wide variability of full-color-tuning requires a user interface that is more complicated than a simple slide dimmer. These tunable luminaires usually require full, undimmed power to be delivered to the LED drivers in the luminaire, typically delivered using standard building voltage (such as 120V, 277V) using conventional hard-wiring techniques. They generally require separate instructions for the intensity of each color of LED in the optical mix (such as warm white, cool white, red, green, blue, amber, etc., depending on the product design), with instructions for dimmed level and color sent over separate wires or through wireless signals from the user interface to the driver, or from the user interface to the black-box device that processes control signals and converts them to driver instructions. A control protocol such as DMX or DALI can address that the luminaire must be powered separately from the intensity and color control signals. DMX was originally created for the theatre industry, but today DMX is also widely used for dynamic lighting since it is fast – changes in intensity and color can be made virtually instantly.

While these color control strategies are available today, there is a need to reduce the complexity with new driver architectures. Reducing the LED drive output channels from individual to combined control can be one such improvement. Another area where there is room for improvement is how to implement the color mixing logic. Moving the color mixing science and the LED output control to an on-board LED channel management has promise to reduce this complexity [30]. More research and development are needed to create very efficient compact multichannel drivers for color tunable systems.

5.8 LED Power and Functional Electronics

The LED driver is a critical component to the LED luminaire since it powers the LEDs. The driver accepts input power of various types, including conventional alternating current (AC) line power, as well as direct current (DC) power from DC micro-grids or Power over Ethernet (PoE). From there the driver outputs voltages and currents compatible with the LED packages, over single or multiple channels, and may incorporate control functions such as dimmability and color-temperature tuning. The two key aspects of the driver are its reliability and performance, where performance can include efficiency, flicker, surge rating, enhanced lighting functionality, non-lighting multi-functionality, as well as size, weight, and power level (SWaP).

5.8.1 Driver Performance

The key performance metrics of drivers focus on their ability to transform power appropriately and efficiently, while protecting downstream components from power surges and poor incoming power quality. These performance metrics for LED drivers include efficiency (both full power and dimmed), dimming level, absence of flicker, surge protection, size, weight, accommodation of multiple channels and alternative input power.

On/off/dim capability is important as lighting becomes connected and adaptive to user needs and preferences. These functions need to be performed at high driver efficiencies, a challenge in today's drivers where efficiency drops in the dimmed state. Absence of flicker is important for any light source but can be challenging due to a lack of standard definitions for basic quantities such as percent flicker and flicker index. This is further complicated in part because of new types of flicker such as CCT flicker in color tunable lighting systems. Accommodating multiple channels is important for color tuning and/or driving multiple LEDs and LED strings. The ability to utilize alternative input power includes inputs such as DC micro-grids or PoE, which will prove vital for multifunctionality. PoE is a fast-evolving area, as IEEE PoE standards are updated to enable lighting applications by providing higher maximum power per port and per device.

Another overarching feature is the size, weight and power of the driver. In virtually all use cases, a compact driver form factor is better; however, in some use cases it is essential to the functionality of the luminaire. In general, making luminaires smaller would enable greater flexibility and density of luminaire placement, which in turn would enable lighting architects to more freely control lighting scenes and provide denser spatial coverage of sensors. Thus, an important challenge to be addressed is continuing improvement in SWaP, even while sustaining the performance metrics outlined above. A big challenge is maintaining high efficiency and small, light drivers over a large operating power range. Integration of wide-bandgap semiconductors components into the driver have the potential to address a number of these performance metrics and is a potential R&D path. Gallium nitride (GaN) or silicon carbide (SiC) wide-bandgap semiconductors with higher breakdown voltages and greater robustness against power surges may enable two-stage drivers to be reduced to one stage. Furthermore, wide-bandgap semiconductors enable higher switching speeds for voltage transformation. All of these benefits have the potential for size reduction and efficiency improvements.

Although SiC is currently ahead, both SiC and GaN are much less mature than Si, so costs are relatively high. Further research is needed to develop consistency, improve reliability, and to reduce cost of SiC and GaN-based components. One of the advantages of GaN power electronics is that it is able to draw on the considerable existing knowledge and manufacturing base established by InGaN/GaN-based LED lighting. Because of this, it would be coming full circle for LED lighting to in turn benefit from the incorporation of GaN into LED drivers. Indeed, because they share the same materials platform, a long-term opportunity could be integration of GaN power electronics with InGaN/GaN LEDs. Such monolithic integration brings challenges: potential incompatibilities in some of their epitaxial growth and fabrication processes, as well as an inability to bin and match electronic and optoelectronic characteristics after separate fabrication. But such monumental integration also brings opportunities: the pixelated light source discussed above might be most elegantly realized with GaN-based display drivers integrated underneath pixelated LED light sources.

5.8.2 Reliability

Typically, the driver is the first component of a luminaire to fail. By and large, this is because LEDs are so intrinsically reliable that drivers are the resulting weakest link. Driver reliability in some cases is not even as robust as it was for earlier generations of traditional lighting, such as a copper-wound ballast system used for high-intensity discharge (HID) lighting in industrial spaces. This is because power surges and other electrical events that cause abnormalities in power quality can damage LED lighting components more so than traditional lighting systems. While this is not a problem unique to lighting, as more fragile components are introduced into the SSL system, protecting LED luminaires from poor power quality becomes more important. Current surge protection systems are built around larger events, meaning that several smaller events or transitions can get though surge protection systems and these load transitions cause field failures when the power quality is poor.

Driver reliability is an area that presents a significant opportunity for improvement, including fundamental reliability limitations of many of the subcomponents of the driver, such as electrolytic and film capacitors, and to do so in a manner consistent with the ongoing trend to higher performance discussed in the previous Section 5.8.1. Another goal would be to develop a greater degree of power conditioning, especially as fragile components are introduced into the SSL system due to the need for improved performance, particularly those involved in multi-functionality. Currently, most current surge protection systems are designed to block larger events, but not smaller events, which can accumulate over time and eventually cause damage to downstream components.

A closely related challenge is to develop predictive driver reliability models and metrics. Current metrics, such as mean time between failures (MBTF) for individual components, are considered inadequate. Therefore, developing additional metrics to define failure, and ways to predict them would be beneficial to the SSL industry. Metrics to describe performance features such as driver efficiency, maximum temperature rise over ambient and how these change over time are also desirable. Coupled with such models and metrics would be standard highly accelerated reliability testing protocols that can return results quickly, within a matter of weeks.

Further research is needed to improve driver temperature performance, surge rating, reliability and cost. Solid-state component integration into the driver should be explored as a more robust alternative since solid-state drivers can simplify the part count and reduce failures. It would also improve the surge rating and reduce the driver size. Moving GaN or SiC-based power electronics has the potential to improve the efficiency and reliability, though today these solid-state components are still very costly and further research is required in the electronics industry to improve the defect count and reduce cost. Establishing the reliability for GaN and SiC components and the impact on driver reliability is an important opportunity.

5.8.3 Enhanced Functionality of Drivers

Enhanced lighting functionality will be a vital driver feature for future deployment of connected lighting with advanced capabilities and will enable programmable control of that functionality. Real-time control of light placement is an important such enhanced functionality. For example, optical beam shaping through digitally controllable liquid-crystal lenses could enable significant improvement in the use efficiency of light, by tailoring, in real-time, the lighting field of view to the user field of view. In another example, pixilated beams could enable not only similar improvements in use efficiency of light, but also enable augmented reality that highlights salient features of a user’s environment or provides other information to the user. Taken to its logical limit, augmented reality would be a form of illumination and display convergence, which would require drivers with video-display-like driver capability.

Finally, with the advent of connected lighting, lighting fixtures may well become the most ubiquitous grid-connected end-point in the Internet of Things, with opportunity for many desirable new functionalities to be embedded into the fixture. In the short term, separate drivers may be used for these new functionalities. However, in the long term, there may be opportunity for integrated drivers that drive both the LED as well as these new components. One new functionality is communication via Li-Fi, with its need for high-speed modulation, interoperability, and end-to-end security requirements. Another new potential functionality is sensors for monitoring all aspects of the environment including sound, light, temperature, chemicals, motion, human presence, perhaps even LIDAR-based 3D mapping. The complexity of these offerings becomes enormous as each has its own requirements for interoperability and end-to-end security.

6 Directions in OLED Science

OLED technology is steadily improving with commercial products now available that reach performance goals of high efficacy, long lumen maintenance lifetime, and good color quality. OLED lighting configured in a commercial office setting is shown in Figure 6-1.

Figure 6-1. Acuity OLED Luminaires in Office Space

Source: PNNL, "OLED Lighting Products: Capabilities, Challenges, Potential," May 2016 [31] Photos courtesy of Aurora Lighting Design

Further, bendable panels have been commercialized. US-based OLED panel manufacturer, OLEDWorks has made great strides over the past year with the announcement of their Brite 3 panel family. At standard luminance of 3,000 cd/m^2, the warm white (3000K) panels demonstrate 85 lm/W and L70 of 100,000 hours. This represents an impressive 35% increase in efficacy over previous generation Brite 2 panels which demonstrate 63 lm/W, along with a substantial doubling of lifetime (L70). Color quality of panels remains impressive for the Brite 3 products, which offer CRI >90 and R_9 >50. Progress towards flexible panels has also been made with the introduction of a uniaxially bendable panel, the Brite 3 Curve, also called the BendOLED. This product is made using Corning's ultrathin Willow glass as a substrate. The bendable panels do not yet incorporate internal light extraction technology, so the efficacy of these is limited to around 56 lm/W. The Brite 3 panel family is projected to ship in 2018, with rigid panels available in Q3 and bendable panels in Q4. All Brite 3 family products are offered in a neutral (4000K) or warm (3000K) white light color, have a six-stack tandem OLED architecture, and are designed for high brightness (7000 – 8500 cd/m^2) operation. The neutral white panels have a lower efficacy (61 lm/W for rigid panels and 44 lm/W for flexible panels) though have a greater R_9 >75 [32].

LG Display has focused on production improvements rather than on furthering their panel performance. In 2017, their catalog promised warm white (3000K) 3-stack rigid panels that would deliver 90 lm/W with CRI of 93. However, availability of these high efficacy panels was reportedly quite limited. LG has completed their new line located at Gumi in Korea, and production of a Luflex family of panels is underway. The Luflex series comprises panels with a range of shapes (circular, square, rectangular) and sizes as large as 30 cm x 30 cm. Their catalog offers rigid panels in a warm (3000K) or neutral (4000K) color temperature and CRI >90. As with the Brite 3 family products, the neutral white panels are less efficacious, offering 52 lm/W (rigid) as compared with warm white products that reach 72 lm/W (rigid). Flexible panels are offered with warm white emission only and have power efficacy of 50 lm/W. Advertised panel lifetime is adequate, with L70 at 3,000 cd/m^2 of 40,000 hours for warm white and 30,000 hours for neutral white CCT [33].

While LG Display and OLEDWorks move forward with OLED panel technology and production, Japan's Lumiotec has been acquired by V-Technology and has halted production of OLED panels in order to focus on performance and production improvements [34]. Lumiotec has a range of panel products with high brightness (up to 4,600 cd/m^2), CCTs of 3000K, 4000K, and 5000K, and efficacies of 30–45 lm/W. Sales of panels will continue while supplies last.

OSRAM has announced that they are exiting the OLED lighting business. In 2016, OSRAM shifted focus from general illumination applications to making OLEDs for automotive applications. Since then, they have become a lead supplier for Audi and BMW, which have begun incorporating OLEDs in taillights and interior lighting. While they will continue to supply OLEDs to the automotive industry through 2020, they do not plan further R&D efforts in OLED lighting.

China's First-O-Lite claims some of the largest panels (37cm x 47cm) with efficacy >65 lm/W on their second-generation OLED lighting production line. These panels reportedly have a lifetime L70 of >20,000 hours at 3,000 cd/m^2 [35].

As some panel makers push forward and others pull back, the overall performance of OLEDs continues to improve. Table 6-1 provides a breakdown of OLED panel and luminaire efficiency projections. With excellent color quality, lifetimes of up to 100,000 hours, and efficacies approaching 100 lm/W, OLEDs specifications are more competitive. Though costs have rapidly declined, significant reductions are needed to realize their market potential. This section first touches on panel and luminaire efficacy projects and then describes key R&D challenges in OLED lighting that affect the cost and performance of OLEDs. These include: 1) performance materials for stable, efficient devices; 2) light extraction; 3) advanced fabrication technology; and 4) lighting platforms. State-of-the-art methods and new technology directions will be highlighted and targets for future performance increases are suggested.

Table 6-1. OLED Historical and Targeted Luminaire Efficiency

Metric	2016	2018	2020	2025	Goal
Panel Efficacy[1] (lm/W)	60	85	110	150	190
Optical Efficiency of Luminaire	100%	100%	100%	90%[2]	90%[2]
Efficiency of Driver	85%	85%	90%	90%	95%
Total Efficiency from Device to Luminaire	85%	85%	90%	81%	86%
Resulting Luminaire Efficacy[1] (lm/W)	51	72	99	122	162

Notes:
1. Efficacy projections assume CRI >90, CCT 3000K
2. Losses representing possible use of beam shaping optics

6.1 Stable, Efficient White Organic Emitters

OLEDs have significant potential to realize energy savings through its application to large-area solid state lighting sources. However, OLED costs and performance (e.g., device efficiency and longevity) need improvements to stimulate adoption. While phosphorescent red and green emitter systems are available that meet lifetime and efficiency demands, blue emitter materials and hosts have presented an ongoing challenge. 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 since 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

Corporation (UDC) and other companies have led to improvements in the performance of phosphorescent emitters, current lifetime performance is not yet sufficient for commercial adoption for either lighting or displays. To achieve practical levels of stability, commercial panels rely on fluorescent blue emitters. Unfortunately, the efficiency of fluorescent emitters is limited to around 25% due to the ratio of singlet (25%) to triplet (75%) states while phosphorescent emitters can achieve nearly 100% internal quantum efficiency (IQE).

OLED display manufacturers are struggling with blue emitters and hosts as well and are investing heavily in materials development. There are some differences in their materials requirements, such as the need for deep-blue in displays, while sky-blue is adequate for general lighting. Additionally, general lighting applications tend to have longer lifetime requirements than needed for displays. However, technical advancements and materials development can likely be cross-leveraged between OLED display and general lighting. The near-term focus (i.e., 5-10 years) for lighting is focused on small molecule materials deposited by vapor phase deposition, which provide the best performance.[12] Roll-to-roll (R2R) deposition is still of interest for OLEDs, but vapor-phase deposition of the emissive layers can be incorporated into R2R lines. Both display and lighting applications require low-cost materials. Though materials utilization efficiency continues to improve, cost roadmaps demand materials prices to drop as well.

To improve the stability and efficiency of devices while also reducing costs, various alternative materials approaches are being explored. Thermally activated delayed fluorescence (TADF) has gained the most ground in recent years. This technology attempts to harness both singlet and triplet excitons to generate highly efficient *and* stable emission of blue photons through fluorescence pathways. In molecules where the triplet energy is close to the singlet energy, thermal upconversion of the triplet to singlet states can theoretically allow for 100% IQE, shown in Figure 6-2. Cynora has developed sky blue (CIE = 0.37) TADF materials with an EQE of 22% and a lifetime (L50) at 1000 (cd/m^2) of greater than 1500 hours [36] [37]. They have also reported a deep blue (CIE = 0.14) emitter with an EQE of 20% and a lifetime (L97) at 700 (cd/m^2) of 20 hours. Samsung and LG have invested $25M into Cynora for the development of alternative TADF emitters, which are to be in mass production by 2020.

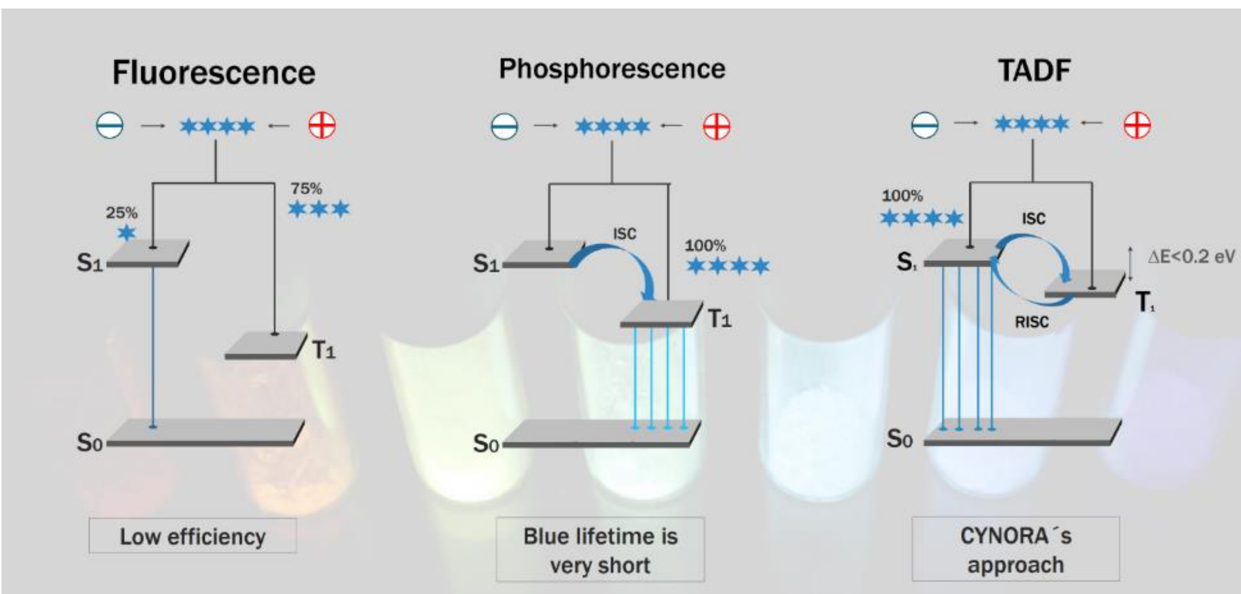


Figure 6-2. Cynora's Illustration of TADF as Compared with Fluorescent and Phosphorescent Approaches [36]

12 There was a push for development of solution-deposited materials for cost reductions in the past few years, but such efforts are now concentrated on display applications, which have different performance requirements and structures that are more suitable for printing.

There is ongoing interest in TADF materials development. In Korea, Material Science, who currently supplies electron transport layer (ETL) and hole transport layer (HTL) materials to OLED manufacturers, has developed blue TADF emitters and hosts for Samsung and LG Display commercial OLED production. The National Taiwan University group has achieved record results through using an oriented TADF emitter. They reached an EQE of ~37% for a sky-blue organic electroluminescence in a conventional planar device structure. A highly efficient TADF emitter was used based on the spiroacridine-triazine hybrid and simultaneously possessed nearly unitary (100%) photoluminescence quantum yield, excellent thermal stability, and strongly horizontally-oriented emitting dipoles (with a horizontal dipole ratio of 83%) [38].

A further extension of the TADF approach has been suggested by the Kyushu University group in which two dopants are introduced: a TADF dopant and a fluorescent dopant. Exciton formation is accomplished on the TADF dopant, and excitons are all transferred to the singlet state of the fluorescent emitter, as displayed in Figure 6-3. Proponents of this approach 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 [39].

Though Kyulux’s initial objective is to develop commercial red, green, and yellow emitter/host systems, they have reported high performance hyperfluorescent blues as well. Recent achievements include blue (470 nm wavelength) with lifetimes (L95) at 750 cd/m^2 of 100 hours and an EQE of 26 - 22% at 1000 cd/m^2. Japan-based chemical producer Nagase has invested $4.6 million in Kyulux. Kyulux’s hyperfluorescence yellow is employed in Wisechip’s flexible passive matrix OLED (PMOLED) displays allowing the display to reduce the power consumption by ~50% compared to a regular fluorescent PMOLED. These panels are expected to be in mass production by the end of 2018 [40]. Hyperfluorescent technology is also being researched by a European team (led by Merck) called the HyperOLED project, as well as by Georgia Tech in a project funded by the BTO SSL R&D Program.

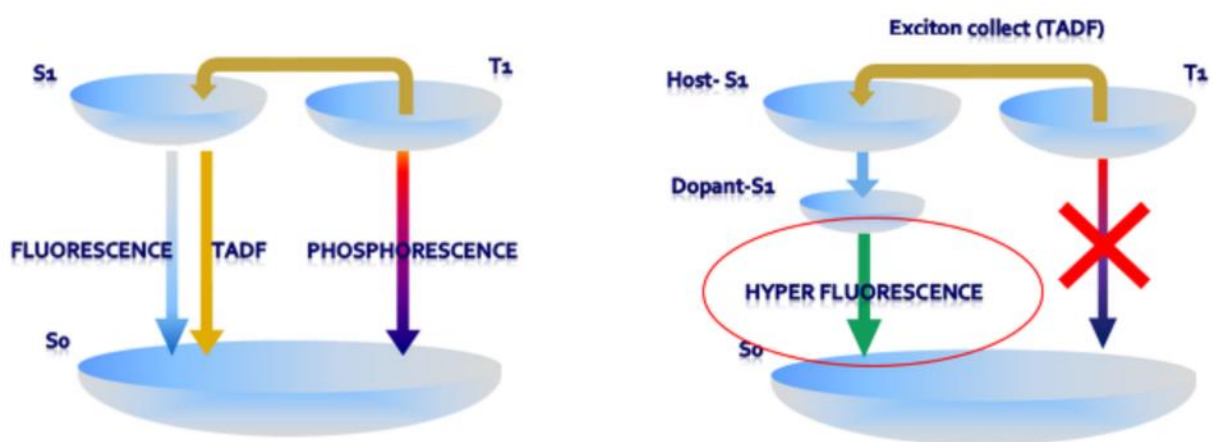


Figure 6-3. Comparison of the Mechanisms of TADF and Hyperfluorescence [41]

While they provide an alternative to phosphorescent materials, TADF approaches suffer similar lifetime limitations due to the high energies involved and the similar order of magnitude of the excited state lifetimes. When excited states are long-lived, there is a higher density of long-lived triplet excitons, which increases opportunities for annihilation. In blue-emitting compounds, the energy dissipated by these exciton-quenching reactions can be large enough to initiate molecular dissociation of the emissive material layer (EML). Degradation of the host molecules in the emitting layer is as much of a concern as the stability of the emitter molecule. New hosts for blue emitter systems are needed that have appropriate energy levels, charge transport properties, and stability.

It is common to use emitters (phosphorescent, fluorescent, TADF) in small (<20%) doping concentrations in a host matrix to prevent aggregation quenching. However, researchers are beginning to explore ambipolar TADF compounds that can operate as "neat" emitter layers – composed entirely of the TADF compound [42]. Efforts are underway at both the University of Southern California (USC) and Georgia Tech to explore this opportunity as a portion of their BTO-funded research. Similarly, TADF molecules can be used as hosts for phosphorescent emitters to achieve long-lived devices. In this case, the triplet excitons of the host (which are typically unstable) are rapidly transferred to the phosphorescent dopant [43].

A hybrid fluorescent/phosphorescent approach is being explored to achieve white OLEDs at USC. In a BTO-funded project led by Mark Thompson, the EML host transfers singlets to the blue fluorescent and triplets to the red/green phosphorescent dopants. In this type of system, high stability and efficiency might be achieved by harvesting the singlets and triplets independently.

In the search for new materials, the use of computational modeling has proven to be a valuable tool to help down-select classes of materials to explore. Researchers at Merck, Harvard University in collaboration with Kyulux, USC, and others are using such tools to predict molecular properties.

Other methods to improve materials performance and stability involve the modification of deposition techniques. While processing conditions of organics for PV have been studied in detail, there is a paucity of reported studies for OLED materials. Recently, TU Dresden and Universitat Autònoma de Barcelona have presented research into the effects of deposition temperature on OLED materials properties. They found that by evaporating the organic materials at the appropriate deposition rate and substrate temperature, they could achieve ultra-stable glasses. Glasses evaporated at substrate temperatures around 85% of the glass transition temperature and low growth rates (generally below 5 A/s) enhance the density – thus, the stability – of the glass. Using four different phosphorescent emitters, over 15% increases in efficiency and operational stability were achieved. Enhancements for TADF materials are expected to be even more impactful [44].

Panel failure can also occur due to the formation and growth of defects in the emitter layers or on the electrodes. Experiments at Penn State University, funded by the BTO SSL Program, have shown that these defects can arise from contaminants among the organic materials and have suggested ways to mitigate the growth of small defects into catastrophic shorts. The BTO goal is to reduce the number of such abrupt failures to less than 1 in 10,000.

6.2 Light Extraction

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% of the generated light is emitted from the panel. This is largely due to absorption, which is amplified by trapping of photons in the electrodes, transparent substrates, and inner layers resulting from mismatches in the index of refraction along the photon path from the emissive region to the outside of the device. In devices in which the cathode is proximal to the emitting region, significant energy can also be lost through the excitation of surface plasmon modes.

Extracting light from substrate modes can be accomplished by the use of external microlens arrays or scattering films laminated to the transparent OLED substrate. This yields an extraction enhancement of around 1.5–1.6x, bringing the EQE of the device up to around 30 - 35%. To extract light typically lost to waveguided modes in the anode and organic stack, internal light extraction layers can be placed between the substrate and anode. This is a much greater challenge, considering that the additional layers threaten to complicate manufacture and interfere with the OLED device. By incorporating both internal and external light extraction technologies in devices, panel manufacturers can achieve as much as 2.2x extraction enhancement factors, and EQEs >40%. Advancements in light extraction, together with refining the stack and utilizing more reflective cathodes (where silver replaces aluminum), have led to lighting panel efficacies of 85–90 lm/W.

While this represents considerable performance enhancement as compared to previous generation devices, the BTO target for light extraction efficiency is 75%, which corresponds to an extraction enhancement of >3.5x.

The extraction efficiency of current products is only 30 to 50%, leaving ample room for improvement and energy efficiency gains. Many approaches are being explored, including: 1) scattering layers; 2) functionalized substrates (e.g. with internal grids, lenses, gratings, corrugations) to break planar symmetry and direct light out of the device; 3) corrugated substrates to reduce surface plasmon modes; 4) tailoring the refractive index; 5) orientation of the emitter dipole; and 6) optimization of the OLED stack. It is important to note that there is still significant variation in panel manufacturer's stack structure, deposition techniques, and value proposition. Because of this, there is likewise significant variation in the applicability of various light extraction techniques as they depend on the OLED architecture, scale-up potential, and cost.

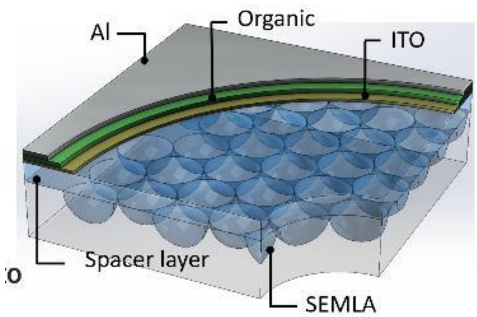
6.2.1 Scattering Layers

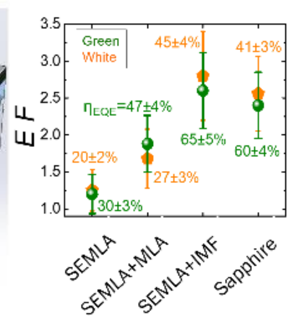
Some commercial products have incorporated scattering layers between the transparent electrode and substrate. In films from a leading supplier, Pixelligent, nanoparticles of ZrO_2 are utilized to achieve a high index polymer matrix which also contains larger TiO_2 particles as scatterers. The density of ZrO_2 particles can be tailored to achieve a graded refractive index of this layer to reduce Fresnel reflections. Using this graded index scattering approach, extraction enhancement of up to approximately 2.5x has been reported.

Concerns with this approach are centered around the introduction of additional layers and materials to the device. Any internal 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. Furthermore, the anode deposition and anneal temperatures can be limited and patterning of the anode can be difficult and introduce solvents. High performance light extraction methods (demonstrating at least 2.5 times extraction enhancement) that can be integrated into panels, without compromising lifetime and yield, are needed.

6.2.2 Functionalized Substrates

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 anodes or to use internal multi-lens arrays. The latter approach was shown to be very effective in laboratory experiments by Panasonic, but they were unable to incorporate their solution in commercial panels [45]. Researchers at the University of Michigan explored a similar concept wherein the multi-lens array is embedded in the substrate. With this sub-electrode microlens array approach (SEMLA), up to 70% EQE was achieved with green OLED devices. This high efficiency was observed using an index matching fluid and large hemispherical lens to extract as much light as possible from the substrate modes. Using the SEMLA with external microlens arrays, EQE of around 47% for green and 27% for white OLEDs was observed, as shown in Figure 6-4 [46].





(a) (b)

Figure 6-4. University of Michigan Sub-electrode Microlens Array Approach: (a) Device Architecture; (b) Light Extraction Enhancement Factor [46]

6.2.3 Corrugated Substrates

Many researchers have suggested the use of corrugated substrates which effectively disrupts the coupling of light to surface plasmon polariton (SPP) modes. This is being explored in multiple BTO SSL Program funded projects**.** The North Carolina State University group created quasi-random grating structures with 260 nm average period and 50 nm FWHM, where typical corrugation depth is 90nm. They observed 87% enhancement in efficacy without any increases in leakage current [47]. The Iowa State University group have reported enhancement factors of up to 2.4 using patterns with depth of 215 to 500 nm imprinted in polycarbonate [48]. The major problem with this approach lies in the reliability of OLEDs that are fabricated on corrugated substrates. Corrugated substrates have been associated with electrical shorts and could contribute to local high-field-induced degradation. It may be many years before manufacturers will accept the risk.

6.2.4 Refractive Index

The refractive index of the materials currently 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 microlens array (MLA). The external film could be much 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. Thus, some groups are exploring altering the index of refraction of the organic stack materials (Professor Giebink Group at Penn State) or looking at graded index layers between the anode and substrate (Pixelligent).

6.2.5 Orientation of Emitter Dipoles

The escape of photons is more likely 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 University and Seoul National University [49] [50] [51]. Figure 6-5 shows that EQE over 35% can be obtained without any extraction enhancement structures [51].

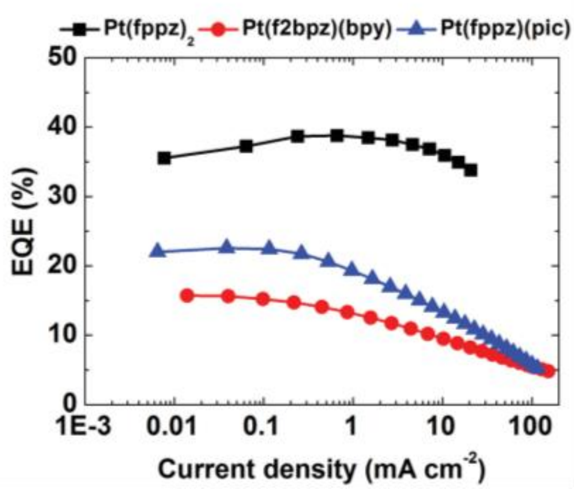


Figure 6-5. External Quantum Efficiency of Phosphorescent OLEDs with Pt-Based Emitters [51]

Recently, researchers demonstrated OLEDs with as high as 56% EQE using molecular orientation and external scattering films tailored for forward-intensive scattering [52]. By tuning characteristics of the bulk scattering layer – such as asymmetry parameter, scattering efficiency and scatterance – the team was able to improve the effectiveness of the external scattering film. Further, their simulations show that EQE_{max} increases significantly with horizontal dipole orientation, even when an external scattering layer is employed. EQE_{max} of an OLED with perfectly oriented dipoles can reach 63%, while it is limited to 45% for isotropic orientation. Experimental results using Ir(dmppy-ph)2tmd emitters with dipole orientation ($\Theta = 0.865$) in combination with SiO_2 or TiO_2 scattering films showed EQEs greater than 50% and as high as 56%.

In order to achieve molecular orientation of the emitter molecules, the shape of the molecule plays a large role. Also, some studies have shown how the molecular orientation of different organic semiconductor molecules can be tuned by changing the deposition temperature [53] [54] . In general, lower deposition temperatures lead to more horizontal alignment.

6.2.6 Stack Optimization

Optimizing device stack structure works to minimize coupling of emission to loss modes. In addition to cavity tuning, attention is paid to layer thicknesses and device architecture. For example, the spacing of the emissive region from the cathode material affects the formation of surface plasmon modes. Thus, multi-stacked tandem devices, and devices with thick ETLs will have lower losses to SPP modes. Layer thickness and materials properties are also important to realize 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: the transparent indium tin oxide (ITO) anode, charge generation layers, and the cathode.

- **Transparent anode:** ITO is still used in commercial OLEDs. It is extremely difficult to achieve low sheet resistance (less than 10 Ω/sq) 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 in a collaboration between OLEDWorks, Aixtron and RTW Aachen University has shown that charge generation layers can lead to significant optical absorption, with transmission rates often below 90% [55]. This loss is particularly severe in devices with six organic stacks where it is estimated that the light extraction efficiency drops by 4% in going from 3-stack to 6-stack structures [56].

- **Cathode:** Imperfect reflection at the cathode can be a major cause of photon absorption. The OLEDWorks 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, they obtained 65% light extraction in a single stack device and 57% extraction with 3 stacks. Many authors 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.

6.2.7 Light Extraction Enhancement in Flexible OLEDs

Currently available internal light extraction layers are not consistent with flexible OLEDs. The major challenge is to identify appropriate nano-particle or host materials and deposition techniques which provide layers that are stable under 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. OLEDWorks and LG Display both offer flexible OLED panels with external light extraction having efficacy of around 50 lm/W and lifetimes of 40,000 to 50,000 hours at 3000 cd/m^2. OLEDWorks' BendOLED is fabricated on Corning's ultrathin Willow Glass whereas LG Display switched to production on polymer substrates due to issues with breakage of glass.

Figure 6-6. OLEDWorks Brite 3 Curve, BendOLED on Corning Willow Glass [57]

6.3 Advanced Fabrication Technology for OLEDs

The two major challenges with respect to the manufacture of OLED panels are to reduce cost and to enable the production of lightweight, ultra-thin conformable panels that will lead to luminaires with distinctive form factors.

In order to enable high-volume sales in competition with LED luminaires, the manufacturing cost of OLED lighting panels needs to be reduced to about $100/m^2. This will allow luminaires to be sold in the range of $200/m^2 to $500/m^2. A path to meeting the target using traditional fabrication techniques was included in the 2017 Suggested Research Topics Supplement and is shown below in Table 6-2.

Table 6-2. Current Status and 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

6.3.1 Depreciation Costs

Depreciation charges depend mainly on the cost of the production facility and the throughput of good products. The estimates given for 2016 in Table 6-2 were consistent with lines in production in 2016 and 2017. The only new facility available in 2018 is the factory operated by LG Display in Gumi. With a substrate size of 1.1 m x

1.25 m and a design throughput of 15,000 sheets per month, the capacity of this facility could exceed that assumed for 2018 in Table 6-2. However, production is being scaled up gradually and no commercial sales had been announced as of mid-August 2018. The throughput achieved in the previous LG line was only 4,000 sheets per month.

It has often been suggested that roll-to-roll (R2R) processing will facilitate the reduction of cycle time. However, cycle times of around 90 seconds are commonly achieved in the display industry by sheet-to-sheet processing. In the short-term, the barriers to greater throughput are in the time taken for individual processes, such as the deposition of organic materials and encapsulation.

In order to reach the long-term SSL cost targets, without the investment of the large capital sums required for substrates as large as those now used in the display industry, it seems essential that the cycle time for the fabrication of OLED lighting panels be reduced to well under one minute. 30 seconds remains a suitable target for any new R&D projects.

6.3.2 Deposition of Organics

Reducing the time taken for deposition of the organic layers to less than 60 seconds is challenging. The traditional approach to faster deposition within thermal evaporation is to increase the temperature in the source. Stability of the organics at high temperature is one issue, as is thermal management within the deposition chamber, especially for plastic substrates. The adoption of Organic Vapor Phase Deposition (OVPD) or nozzle jet printing could lead to faster deposition at lower temperatures, but these techniques have not yet been deployed commercially.

Defect control remains a substantial problem and is restricting the size of available panels. Recent evidence from BTO-supported research at Pennsylvania State University has shown that contamination can occur during deposition and that build-up of organic materials on the walls of the chamber must be avoided.

Data from the OLED display industry shows that the cost of organic materials may provide an obstacle to reaching cost targets for OLED lighting. The structure of the organic layers used by LG Display in panels for OLED TVs is similar to that used for lighting. Display Supply Chain Consultants (DSCC) has reported that the total cost of the materials is $130/m^2, with 40% attributed to the emissive layers and 60% to the transport and charge generation layers. DSCC forecasts that the cost will decrease by only about 25% over the next four years. Reducing the waste of organics is thus critical to achievement of the cost targets in Table 6-2.

6.3.3 Substrates and Encapsulation

DSCC estimates that the average cost of the glass used as substrates in rigid OLED displays is about $18/m^2. The cost of flexible substrates is much greater, at over $60/m^2, mainly due to the need to sustain high temperatures during formation of the active-matrix backplane. The development of less expensive substrates for OLED lighting has achieved only limited success and further R&D is needed, especially for conformable panels. Although toleration of very high temperatures is not required, the surface qualities of most inexpensive plastic substrates are insufficient for OLED fabrication. The development by DuPont-Teijin of PET with a peelable-clean surface (PCS) provides a promising new substrate that is being tested in Europe in the Lyteus project. The addition of a SiN barrier deposited by plasma-enhanced chemical vapor deposition (PECVD) is giving good protection against ingress of H_2O and O_2. The use of ultra-thin glass in conformable panels avoids the need for a barrier, but the cost may be too high for most lighting applications.

Substantial progress has been made in techniques for encapsulation of OLED displays, using hybrid multi-layer films. The organic layers are deposited by ink-jet printing (IJP) in a nitrogen atmosphere and the inorganic layers by PECVD of atomic-layer deposition (ALD). However, the equipment needed for these processes is extremely expensive, adding about $250/m^2 to the depreciation cost. Less costly approaches to encapsulation are needed for lighting applications. As a short-term solution, a thin layer of metal can be used as a cover for bottom-emitting panels. This also helps with thermal management.

Edge patterning is also critical for OLED panels. The presence of layers of organic material means that H_2O and O_2 can also enter through the edges of the panel, leading to early device failure. One approach is to use printing techniques, such as IJP or slot-die coating, to ensure that no organic materials are deposited near the edge. Alternatively, laser ablation can be used to remove the organics after deposition. Care must be taken not to damage the fragile OLED materials that remain and to avoid contamination due to the debris.

6.3.4 Transparent Conductors

The OLED industry has long sought a replacement for ITO as a transparent conductor, partly because of its fragility under bending and partly because of fears of price increases due to a potential shortage of indium. Despite many years of research, a commercially viable alternative has not yet emerged. ITO can sustain the limited bending needed for conformable lighting panels and the materials cost has not escalated. The cost and inconvenience of acquiring patterned ITO from external suppliers has been of concern, due to the limited availability of sources within the US. Laboratory experiments, supported by the BTO SSL program and others, have demonstrated that alternatives such as silver nanowires and wire meshes can meet the required performance targets, but a reliable means of fabricating patterned electrodes with a surface smooth enough for OLED deposition has not yet been demonstrated.

One of the problems of using ITO in flexible panels is the relatively poor performance when deposited at low temperatures. Corning has demonstrated that the use of ultra-thin glass allows deposition at up to 350^{o} C, achieving transparency of over 80% with sheet resistance of 12 Ω/sq.

6.3.5 Substrate Handling

Although R2R processing of OLED lighting panels has been studied in several laboratories in Asia and Europe, there has been little activity in the US since the project at the GE Research Center in 2012. Konica Minolta is the only company that has attempted to use R2R in high-volume production. They completed their production facility in 2014 with a designed capacity of 1M panels per month. However, they have never revealed the performance of the panels that can be manufactured in this plant and it is not clear that products have been offered for commercial sales.

Although Konica Minolta has not revealed the reasons for their challenges with this approach, experience on other pilot lines allows identification of the major challenges and assessment of progress. The most useful information has come from the laboratories involved in the European PI-SCALE project, with pilot lines in the Holst Center in Eindhoven and the Fraunhofer Institute in Dresden.

The team at the Holst Center has studied solution processing with both additive and subtractive patterning on plastic and metal foils. For example, they have demonstrated that slot-die coating can be used to produce rectangular patterns. Solvents in the deposited layers are removed by thermal curing, requiring long residence in large ovens. They obtain good thickness control, to within $\pm$5 nm, at web speeds up to 30 m/min. The Holst team has shown that effective hybrid barriers can be formed on PET or PEN substrates at web speeds of 4m/min, combining an organic planarization layer with a hard coat of SiNx deposited by plasma enhanced chemical vapor deposition (PECVD).

The Fraunhofer group uses 14 vacuum deposition tools arranged around a large drum. The drum provides cooling as well as mechanical support for the web, which can be plastic, metal or ultra-thin glass. The system was designed to operate at web speeds of up to 1 m/min, but it was initially limited to 0.2 m/min to prevent overheating of the substrate during metal deposition. To prevent scratching and particulate deposition during web handling, the team strongly recommends that direct contact is limited to one side and that an interleaf layer is inserted if partially processed webs are rolled-up before panel separation. After the OLED layers are deposited, they can be encapsulated by lamination to a pre-prepared barrier film and are then singulated by laser cutting. By this means, small OLEDs have been produced with yields above 80% and efficacies of 20-25 lm/W.

Maintaining quality control during each process step and scaling the web width from the current 300 mm to between 1 and 1.5 m are so challenging that only relatively modest web speeds seem practical. Rates of 2-6 m/min should be adequate to reach realistic throughput targets for the next decade. Several groups have estimated that the potential savings from R2R processing are about 20-30%. If these estimates are accurate, the major cost reductions must come from elsewhere.

6.4 OLED Lighting Platforms

6.4.1 OLED Features

The major advantage of OLED panels is the glare-free surface lighting. Early proponents envisioned OLED wallpaper, OLED ceilings, and OLED curtains. The luminance was kept below 3000 cd/m^2, so that users could approach the light source without shielding their eyes. However, since the cost of OLED panels scales more directly with their size rather than the light output, the cost per lumen can be reduced by increasing the luminance of the panels. In fact, products with luminance of up to 8000 cd/m^2 have been offered. Thus, one of the challenges in luminaire design is to balance luminance considerations and operating life against manufacturing cost.

For luminaires that are installed above head height, glare could be reduced by beam shaping. Achieving light distributions that differ significantly from the typical Lambertian patterns is difficult while retaining the thin panel profile, but it is possible that some of the concepts that are being explored to enhance light extraction could be extended to focus the beam more narrowly.

Another benefit of OLEDs is the direct production of red, green and blue light meaning that, unlike with LEDs, there is no penalty in efficacy for delivering white light at low color temperature. Although dynamic color tuning is possible, in principle, either by horizontal or vertical separation of the RGB sources, achieving this without significant penalty in cost or efficacy has not yet been implemented commercially.

6.4.2 Special Applications

A number of special applications favor the intrinsic features and performance provided by OLEDs. The low weight and thin profiles of OLED panels are especially attractive in transport applications. Much attention has been paid to automobile tail lights, with segmented panels producing red light with luminance of 1000-2000 cd/m^2. Much brighter panels will be needed for adoption in brake lights (up to 20,000 cd/m^2) and direction indicators (up to 50,000 cd/m^2). Additionally, beam shaping may be needed to meet regulatory requirements [58]. The availability of conformable white panels could also have a major impact on interior lighting for automobiles. Although some prototypes have been demonstrated, further progress is needed in cost reduction and assuring long lifetimes.

Weight reduction and form factor are even more important in aircraft and almost all airlines have enthusiastically adopted SSL [59]. Some airlines offer color-tunable lighting systems, which are used to create custom lighting scenes. Airlines may further customize their interiors through feature architecture and accent lighting. As a critical component of airline branding, cabin lighting systems are subject to intense scrutiny, resulting in strict color and luminance requirements. Increased reliability as measured by Mean-Time Between Failure (MTBF) and Mean-Time Between Unscheduled Removal (MTBUR) is desirable to reduce maintenance costs. Many parts are designed for a 20-year service life.

Similar to the automotive and aviation application examples discussed above, OLED lighting products need to continue to seek out new and pre-existing lighting applications that are favorable for the technology and offer meaningful energy impacts. Within the framework of lighting application efficiency, described in Section 4.1, OLEDs may offer improved optical delivery efficiency since they can be located much close to a task surfaces without creating glare, due to their low brightness and slim form factor.

6.4.3 Modules and Light Engines

Manufacturers of OLED panels and drivers have designed light engines (modules) to facilitate the market introduction of OLED luminaires. One of the early examples was the Keuka module from OLEDWorks, which provided a slim mounting frame and connectors for their rigid panels, along with a dimming driver. The availability of OLED modules which include power supply electronics could enable more rapid adoption of OLED lighting technology by simplifying the integration of OLEDs in the ultimate lighting product. The availability of easy-to-use, cost effective, and high-performance OLED modules could also unlock new ideas for OLED lighting products.

6.4.4 Drivers and Power Supplies

Substantial progress has been made in the development of drivers specifically for OLEDs. Dimming drivers offering protection against shorts and open circuits are available with thickness of less than 5 mm. These can be placed between multiple panels in conformable luminaires, but further reduction in size would be valuable. The efficiency of DC-DC conversion is over 90%, but adapting to AC power supplies is still challenging, partly because the required drive voltage can rise significantly during the lifetime of the panel. Cost is also of concern, especially in luminaires providing independent control of multiple panels.

Recent progress in thin-film electronics raises the possibility of introducing an ultra-thin backplane that contains the drivers along with sensor electronics. A prototype OLED lighting system was developed in the European IMOLA project with a thickness of 3 mm, which the researchers believe could be reduced to around 0.3 mm [60].

7 Appendices

7.1 LED Supply Chain

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 manufacturing 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 7-1 represents the current situation for LED-based SSL manufacturing, but it should be recognized that the supply chain is ever-changing and will continue to evolve and mature. For example, a vertically integrated manufacturer might currently handle a number 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 impacted by developments in technology and product design and can also be impacted by product distribution, including geographical or regulatory considerations.

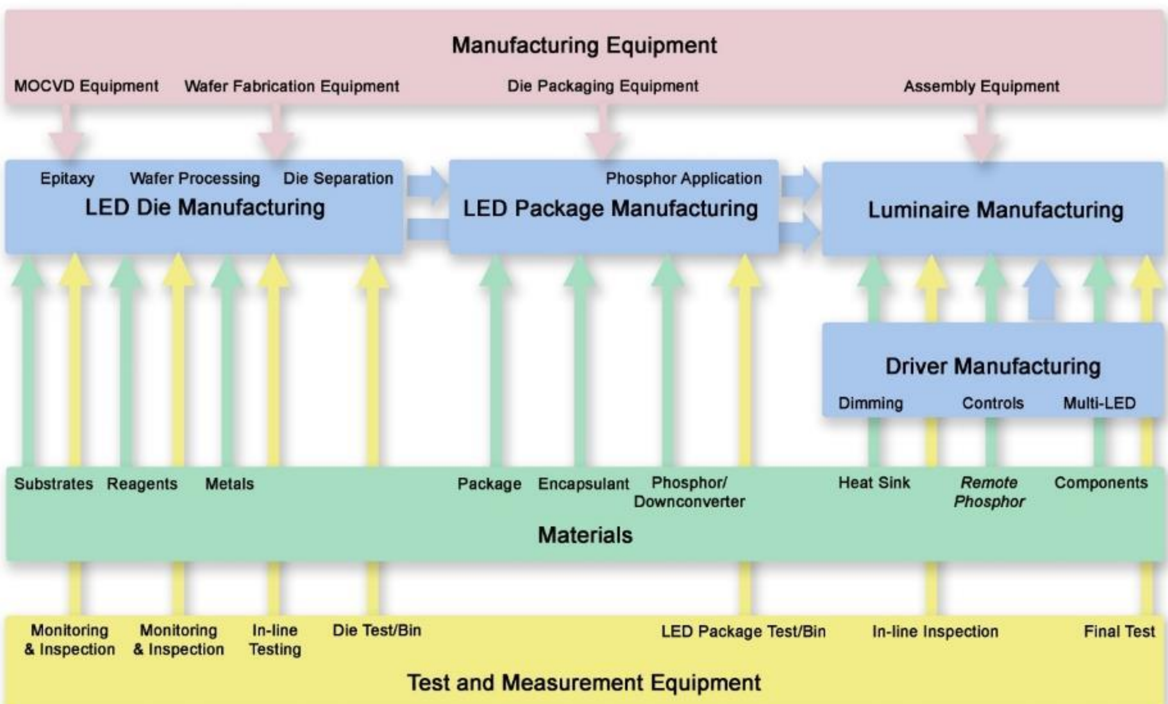


Figure 7-1. LED-Based SSL Manufacturing Supply Chain

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.

The manufacturing process for LED-based luminaires begins with LED die manufacturing, consisting of growth of the LED wafer by metal organic chemical vapor deposition (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.

7.1.1 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 and 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. Such efforts will focus on 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.

There is a growing market demand for integrated light engines comprised of LEDs and the driver. The different integration levels are illustrated in Figure 7-2. 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 the ability to tailor the LED operating conditions, optimize the number of packages employed, and simplify the L2 configuration for lower manufacturing cost while retaining quality and reliability. This translates to reduced system size and/or cost, which is valued by customers.

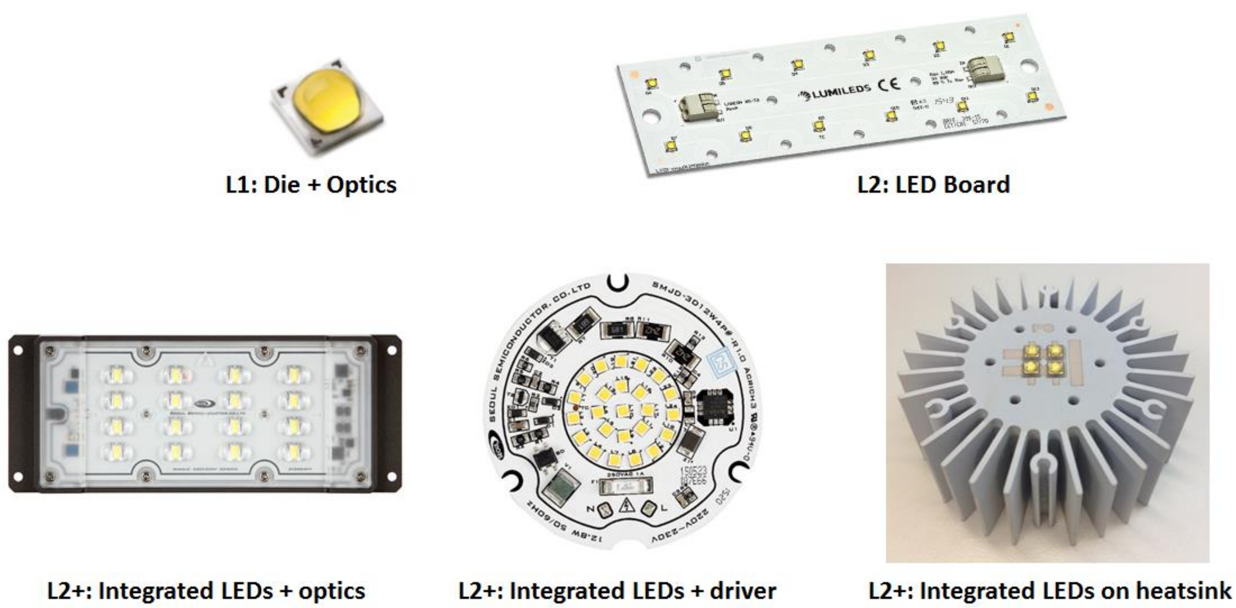


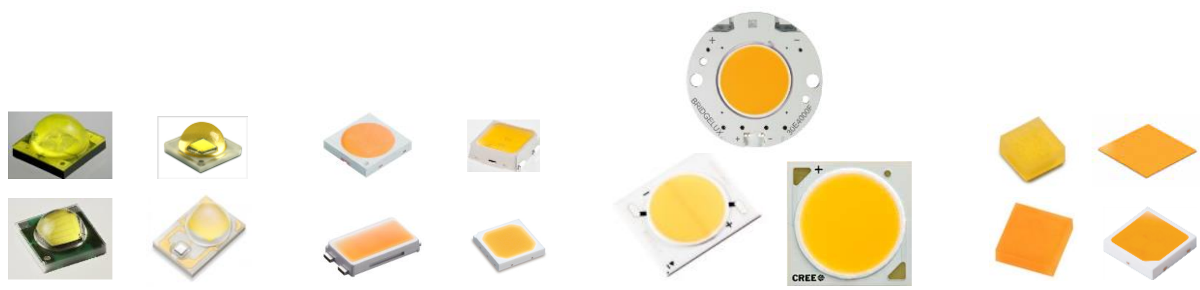
Figure 7-2. Integration Path for LED Components [61] [62] [63] [64] [65]

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 can have as many as 50 different package families, and within each family there are 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 7-3) have emerged:

- 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).
- Mid-power packages (0.1 to 0.5 W) typically used in products requiring omnidirectional emission (e.g., troffers, A-type lamps).
- 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).
- 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.



High-power: ceramic substrates, molded lens | Mid-power: leadframe, polymer package | Chip on Board: metal-core PCB, ceramic PCB | Chip Scale Package: flip-chip with phosphor

Figure 7-3. 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 one mm^2 die, 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 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 for general illumination applications. Mid-power LEDs are low-cost, plastic-molded lead frame packages that typically contain one-to-three small LED die. The die is mounted on a silver (Ag)-coated metal lead frame surrounded by a plastic cavity. The cavity is filled with phosphor mixed in silicone to act as the down-converter and encapsulant. Mid-power LEDs have gained favor over high-power LEDs in a number of applications due to their low cost, which improves the lm/$ for 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 a number of 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 well as the number of manufacturers offering this LED product type. The majority of current CSP products use flip-chip die as a base, onto which the phosphor and encapsulant is applied. 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, either coated on all five sides of the chip or just on the top surface with the side walls containing a white reflective coating.

7.1.2 LED Luminaire Manufacturing

Manufacturing Methods

Manufacturing of 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” 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 leads to earlier lumen degradation and color shift thus affecting the luminaires reliability performance and warranty life. This involves just one tradeoff with the LED source design. Further subsystem design choices such as heatsink, 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 point that different luminaire products bring to market.

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, but instead 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 it is 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, since 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.

7.1.3 OLED Manufacturing

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 7-4.

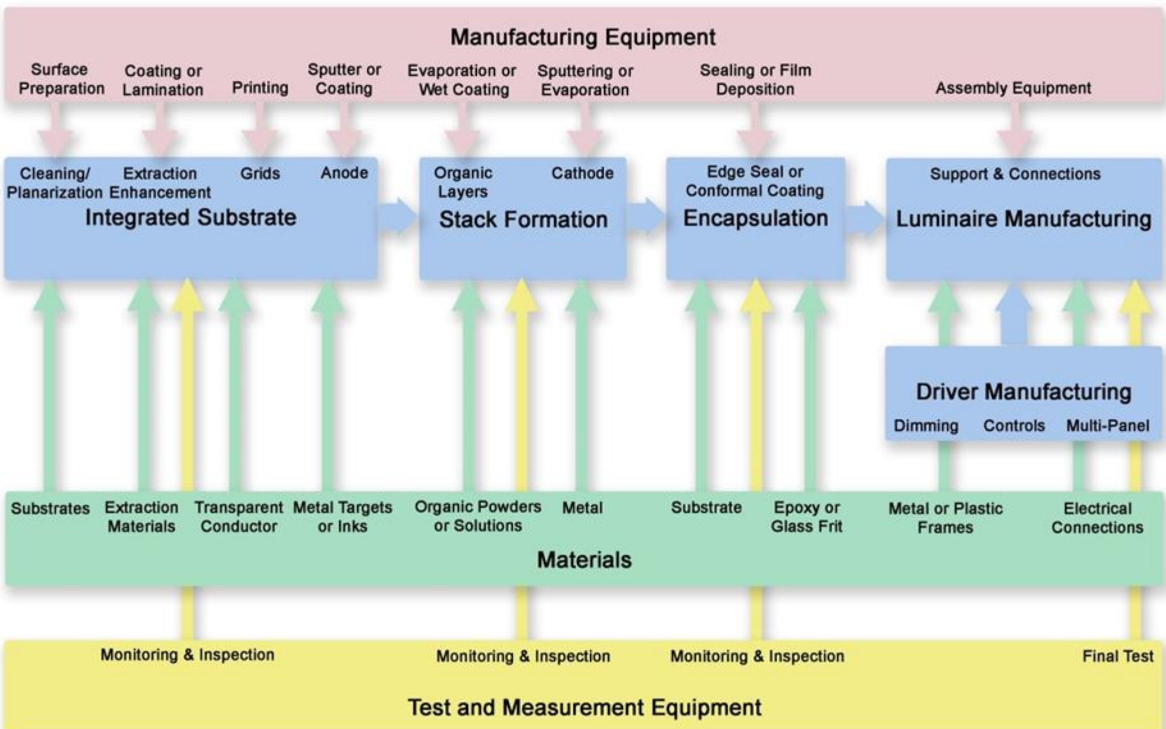


Figure 7-4. OLED-Based SSL Manufacturing Supply Chain

Figure 7-4 provides a general sense of the OLED manufacturing supply chain. However, OLED technology and manufacturing processes need to improve in order for OLED lighting to be commercially viable in terms of performance and cost. While the general manufacturing structure shown above is accurate, many of the detailed processes and materials for OLED lighting are still unknown. Advancements in manufacturing technologies cannot come at the expense of OLED device performance, which is still not quite sufficient. Conversely, higher performance materials and device structures must be compatible with low-cost manufacturing techniques. R&D opportunities for advanced fabrication technologies are described in more detail in Section 6.3.

7.2 BTO Program Status

7.2.1 Current SSL Portfolio

The active BTO SSL R&D Portfolio[13] as of March 2018, is provided in Table 7-1, including SBIR projects which are noted with an asterisk (*). The portfolio includes 24 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 $27.6 million in government and industry investment.

Figure 7-5 provides a graphical breakdown of the funding for the current SSL project portfolio as of March 2018. BTO is providing $23.0 million for the projects, and the remaining $4.6 million is cost-shared by project awardees. Of the 26 active projects in the SSL R&D portfolio, 14 focus on LED and 10 focus on OLED technology.

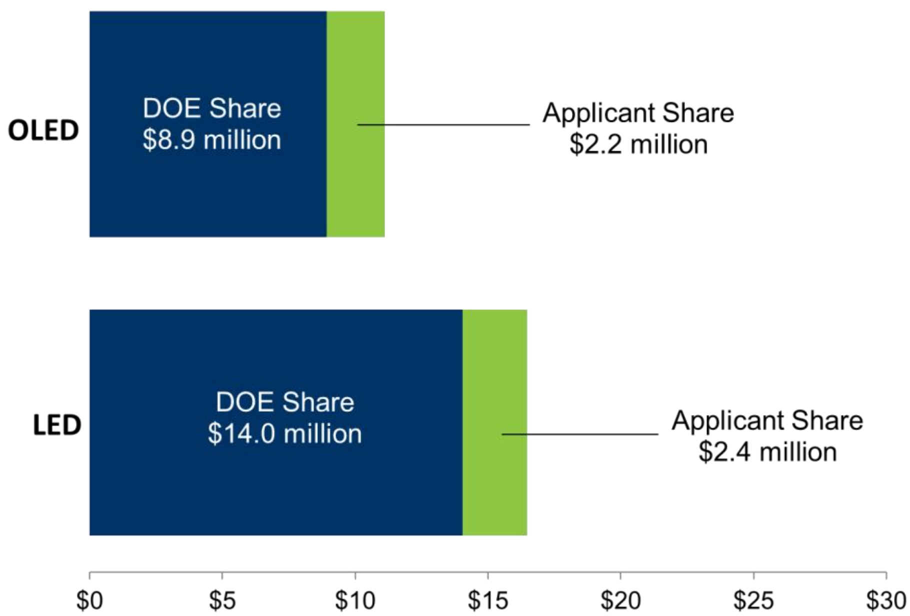


Figure 7-5. Funding of SSL R&D Project Portfolio, March 2018

BTO supports SSL R&D in partnership with industry, small business, national laboratories, and academia. Figure 7-6 provides the approximate level of R&D funding contained in the current SSL portfolio among the four general groups of SSL R&D partners.

[13] 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.

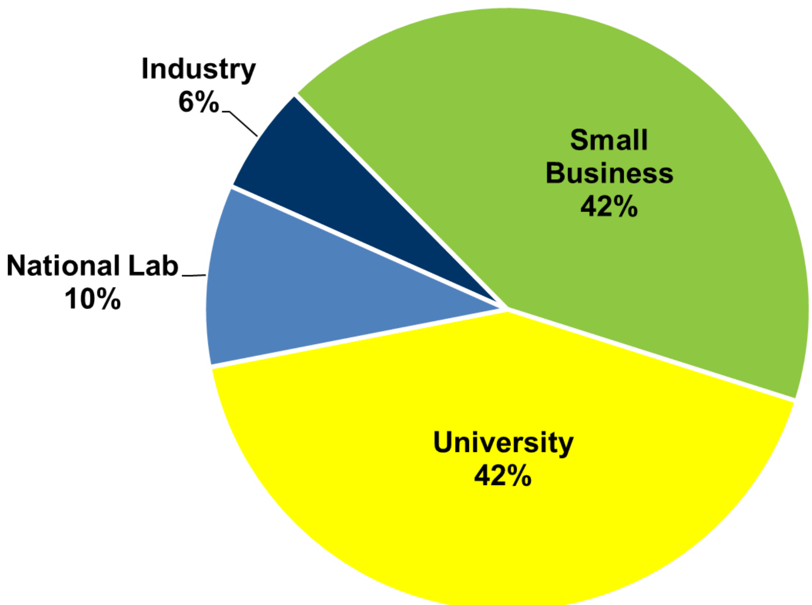


Figure 7-6. BTO SSL Total Portfolio Summary by Recipient Group, October 2018. Total funding is $23.5M.

Table 7-1. SSL R&D Portfolio: Current Research Projects, Q1 2018

	Research Organization	Project Title
LED	Columbia University	Graded Alloy Quantum Dots for Energy Efficient Solid-State Lighting
	EIE Materials (Lumenari, Inc.)	Narrow Emitting Red Phosphors for Improving pcLED Efficacy
	GE Global Research	Highly Integrated Modular LED Luminaire
	Lucent Optics*	Ultra-Thin Flexible LED Lighting Panel
	Lumileds	Improved Radiative Recombination in AlGaInP LEDs
	Lumisyn*	Tunable Nanocrystal Based Phosphors with Reduced Spectral Widths
	Lumisyn*	Nanocrystal-based Phosphors with Enhanced Lifetime Stability
	Lumisyn*	New Class of Encapsulants for Blue LEDs
	PhosphorTech*	Hybrid Down-Converting Structures for SSL
	PhosphorTech*	Plasmonic Enhanced High Light Extraction Phosphor Sheets for SSL
	University of California, San Diego	Novel Lighting Strategies for Circadian and Sleep Health in Shift Work Applications
	University of California, Santa Barbara	High Performance Green LEDs for Solid-State Lighting
	University of California, Santa Barbara	Identification and Mitigation of Droop Mechanism in GaN-Based LEDs
	Virginia Polytechnic Institute and State University	Investigating the Health Impacts of Outdoor Lighting
OLED	Arizona State University	Stable and Efficient White OLEDS Based on a Single Emissive Material
	Georgia Institute of Technology	Stable White OLEDs Enabled by New Materials with Reduced Excited-State Lifetimes
	Iowa State University	Enhanced Light Extraction from Low Cost White OLEDs (WOLEDs) Fabricated on Novel Patterned Substrate
	Luminit*	Light Extraction System for OLED
	North Carolina State University	Low Cost Corrugated Substrates for High Efficiency OLEDs
	OLEDWorks	Mask-Free OLED Fabrication Process for Non-Tunable and Tunable White OLED Panels
	The Pennsylvania State University	Understanding, Predicting, and Mitigating Catastrophic Shorts for Improved OLED Lighting Panel Reliability
	Pixelligent*	Advanced Light Extraction Material for OLED Lighting
	University of Michigan	Eliminating Plasmon Losses in High Efficiency White OLEDs for Lighting Applications
	University of Southern California	Combining Fluorescence and Phosphorescence to Achieve Very Long Lifetime and Efficient White OLEDs
Cross-Cutting	NextEnergy Center	Lighting Technology Energy Solution (LiTES)
	TRC Energy Services	Integrated Solutions for Optimized Performance (ISOP) Packages
	Seventhwave	Integrated controls package for high performance interior retrofit: field testing of packages that include lighting
	Lawrence Berkeley National Laboratory	Getting Beyond Widgets: FlexLab testing of lighting technology packages
	Lawrence Berkeley National Laboratory	Integrated systems packages optimized for real estate life-cycle events: field testing of packages that include lighting
	Lawrence Berkeley National Laboratory	Integrating Autonomous HVAC and Lighting Commissioning with Fault Detection and Diagnostics (FDD) Tools
	Pacific NorthWest National Laboratory	Lighting field testing, modeling, validation, and stakeholder engagement

7.2.2 Patents

As of January 2018, 124 SSL patents have been awarded to research projects funded by DOE. Since December 2000, when DOE began funding SSL research projects, 291 patent applications have been submitted, including those from large businesses (92), small businesses (104), universities (83), and national laboratories (12).

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