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Office of
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RENEWABLE ENERGY

2019 Lighting R&D Opportunities

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List of Acronyms

Abbreviation	Definition
$/klm	U.S. dollars per kilolumen
$/Mlmh	U.S. dollars per megalumen hour
$/MWh	U.S. dollars per megawatt hour
3-D	three-dimensional
A/cm^2	amperes per square centimeter
AC	alternating current
ADB	Adaptive Driving Beam
AlGaN	aluminum gallium nitride
AlInGaN	aluminum indium gallium nitride
AlInGaP	aluminum indium gallium phosphide
AlN	aluminum nitride
ANSI	American National Standards Institute
API	application programming interface
BCH	Boulder Community Health
BEM	building energy management
BTO	Building Technologies Office
BTU	British thermal unit
°C	degrees Celsius
CAD	computer-aided design
CALiPER	Commercially Available LED Product Evaluation and Reporting
CBI	Commercial Building Integration
CCT	correlated color temperature
Cd	cadmium
cd/m^2	candelas per square meter
CEA	controlled environment agriculture
CFL	compact fluorescent lamp
CGL	charge generation layers
CIE	Commission Internationale de l'Eclairage
CLS	connected lighting systems
CLTB	connected lighting test bed
CM-LED	color-mixed LED
COB	chip-on-board
CoL	cost of light
CRI	color rendering index
CSP	chip scale package
CW	cool white
DC	direct current
DLC	DesignLights Consortium
DOE	U.S. Department of Energy
Duv	distance from the blackbody locus in u-v colorspace
EERE	Office of Energy Efficiency and Renewable Energy
EL QDs	electroluminescent quantum dots

EML	emissive material layer
EQE	external quantum efficiency
EU	European Union
FOA	funding opportunity announcement
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
IBHU	Inpatient Behavioral Health Unit
IES	Illuminating Engineering Society
IIC	Industrial Internet Consortium
III-N	III nitride material
III-V	III-V semiconductor material
InGaN	indium gallium nitride
IoT	Internet of things
IQE	internal quantum efficiency
IR	infrared
ITO	indium tin oxide
K	Kelvin
khr	kilohour
L_{70}	duration of lumen maintenance to 70% initial brightness; operational lifetime
LAE	lighting application efficiency
LD	laser diode
LED	light-emitting diode
LER	luminous efficacy of radiation
LES	light-emitting surface
lm/m^2	lumens per square meter
lm/W	lumens per watt
LSRC	LED Systems Reliability Consortium
mAh	milliamp hour
MBE	molecular beam epitaxy
MBTF	mean time between failures
MC-PCB	metal-core printed circuit board
MEMS	micro-electromechanical systems
MLA	microlens array
Mn	manganese
MOCVD	metal organic chemical vapor deposition
MW	megawatt
NGLIA	Next Generation Lighting Industry Alliance
NGLS	Next Generation Lighting Systems
NICU	neonatal intensive care unit
NIST	National Institute of Standards and Technology

nm	nanometer
NPS	U.S. National Park Service
OHSU	Oregon Health Science University
OLED	organic light-emitting diode
OVPD	organic vapor phase deposition
PAR	parabolic aluminized reflector
PCB	printed circuit board
PCE	power conversion efficiency
PC-LED	phosphor-converted LED
PLCC	plastic leaded chip carrier
PNNL	Pacific Northwest National Laboratory
PoE	power over Ethernet
PPER	photosynthetic photon efficacy of radiation
ppm	parts per millions
PPF	photosynthetic photon flux
Pt	platinum
QD	quantum dot
QPL	Qualified Products List
Quad	quadrillion BTU
QW	quantum well
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
RBI	Residential Building Integration
RGB	red, green, and blue
RGBA	red, green, blue, and amber
RoHS	Restriction of Hazardous Substances
RTI	Research Triangle Institute
RYGB	red, yellow, green, and blue
SBIR	Small Business Innovative Research
SEMLA	sub-electrode microlens array approach
SiC	silicon carbide
SPD	spectral power distribution
SPP	surface plasmon polariton
SRH	Shockley-Read-Hall
SSL	solid-state lighting
SWaP	size, weight, and power level
TADF	thermally activated delayed fluorescence
tBTU	trillion British thermal units
THD	total harmonic distortion
TiO_2	titanium dioxide
TJ	tunnel-junction
TWh	terawatt-hours
UGR	unified glare rating

UL	Underwriters Laboratory
UV	ultraviolet
V	volt
VR/AR	virtual-reality/augmented-reality
VTE	vacuum thermal evaporation
W	watt
W/m^2	watts per square meter
W/mK	watts per meter kelvin
W/mm^2	watts per square millimeter
WPE	wall plug efficiency
YAG	yttrium aluminum garnet
ZrO_2	zirconium dioxide
μLED	microLED
μm	micrometer
μ-moles	micromoles
$\Delta u'v'$	magnitude of color shift in the CIE 1976 chromaticity diagram (u', v')
$\Omega/\square$	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 of SSL has surpassed previous lighting technologies and still has significant room to improve, and the price has decreased to the point where it is no longer a barrier to adoption for consumers. The LED technology platform also offers the opportunity to advance beyond legacy form factors, which embody the limitations of the previous lighting technologies; to move past the legacy functionality of providing basic illumination; and to enable energy savings beyond improved source efficiency to encompass more precise delivery of more suitable light at the appropriate time.

The luminous efficacy of SSL, as measured in lumens per watt (lm/W), continues to advance toward the practical limit of 255 lm/W for phosphor-converted LED architectures. LED lighting technology is already saving significant and measurable amounts of energy and, if DOE performance projections are met, will be on track to save about 5 quadrillion British thermal units (quad) per year by 2035. This equates to about $50B in annual energy savings and could account to about a 5% reduction in the total primary energy budget of the United States. The efficacy of LED lighting technology still has considerable room to improve. With greater breakthroughs, particularly for green and amber emitting LEDs, there is the potential to reach the ultimate theoretical limit of 325 lm/W for direct-emitting architectures that combine direct-emitting color LEDs to make white light.

LED lighting can improve the quality of lighting and comfort of building occupants, while simultaneously providing energy savings beyond improved source efficiency. The next generation of energy savings from SSL will come from improving lighting application efficiency (LAE), which characterizes the efficient delivery of light from the light source to the lighted task. LAE can also account for the effectiveness of the light spectrum for the lighting application and the ability to actively control the source to minimize energy consumption when the light is not being used. Improved optical design can allow more efficient delivery of light with the optimum optical distribution. Precise spectral control enables delivery of more suitable light for the application needs and buildings occupants. Instantaneous control over a wide range of intensity provides the ability to deliver the right amount of light on demand. Improvements in LAE can deliver substantial additional energy savings. However, a new LAE framework needs to be developed to understand and quantify these benefits to drive further innovations for energy savings.

LED technologies can enable new lighting functionality beyond basic illumination for vision and visibility. The inherent spectral tunability in SSL provides the potential to improve building occupant well-being and productivity by supporting healthy circadian rhythms. LED lighting can also improve roadway safety by providing more suitable lighting that can enhance visual acuity and discrimination for different roadway situations. The LED lighting platform is also capable of providing outdoor lighting that reduces environmental and ecological impacts, while also increasing safety. In addition, it can also improve the sustainability and resiliency of food production by providing light sources that enable indoor, optimized crop production.

SSL offers the possibility of new form factors that cost less, deliver light more efficiently, use more sustainable materials, and can more easily integrate into buildings. Another technology group within the SSL family is diffuse direct emitters, such as organic LEDs (OLEDs). This low-illuminance lighting has the potential to offer unique benefits complementary to LED lighting since, by its very nature, it is a diffuse light source, meaning it can be placed very close to the occupant or object being lit. Most other lighting technologies, including LEDs, require optical diffusion to protect occupants from glare by a bright light source. However, significant technology barriers remain for OLED lighting, with progress lagging behind LED performance and cost. Current commercial OLED panels provide an efficacy of approximately 90 lm/W. OLED lighting technology needs ongoing research and development (R&D) to translate lab scale efficiency and performance advancements to commercially practical approaches. Other diffuse direct emitter materials, such as electroluminescent quantum dots and perovskites can also provide this low-illuminance lighting and can be compatible with elements of the OLED architecture and manufacturing process.

Unlocking the next wave of advancements in SSL will require numerous and ongoing breakthroughs in fundamental, early stage R&D 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) Lighting R&D Program. The DOE Lighting R&D Program is within the Building Technologies Office (BTO), which is part of the Office of Energy Efficiency and Renewable Energy (EERE).

R&D Opportunities

There are many important R&D opportunities that can advance SSL technology towards DOE's targeted performance levels in 2035. The following sections describe the status of today's SSL technology (Section 3) and the R&D opportunities (Sections 4 and 5) to improve the technology. There are many important R&D opportunities within this technology, as described in this document. Stakeholders and advisors to the DOE Lighting R&D Program have identified the following forward-looking priority R&D Opportunities for near-term R&D funding consideration. More detail on these specific topics can be found in Section 5 of this document.

- **Developing the Lighting Application Efficiency (LAE) Framework:** Understanding relationships between and energy impacts of light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness.
- **LED Research:** Improving basic understanding of LED material-device-synthesis relationships to develop a path to meet DOE LED performance objectives.
- **High Luminance Emitters:** Improving efficiency at high luminance to enhance optical control, including device structures and phosphors.
- **Diffuse Light Source Emitter Materials:** Advancing the efficiency and lifetime of emitter materials and device architectures for low profile, diffuse, and direct emitters, such as OLEDs.
- **Understanding and Advancing Quantum Dot Optical Down-converters:** Improve quantum dot down converters for on-chip LED usage.
- **Diffuse Light Source Optical Efficiency:** Improve light extraction efficiency and optical control for low profile, diffuse direct emitters, such as OLEDs.
- **Advanced LED Light Sources:** Develop LED packages, modules, or lighting products that demonstrate highly advanced performance.
- **Power and Functional Electronics:** Improve power supply efficiency, functionality, and/or form factors.
- **Additive Fabrication Technologies for Lighting:** Develop advanced additive manufacturing technologies for full scale production of lighting products.
- **Understanding and Demonstrating Human Physiological Impacts of Light:** Translate lab-scale human physiological responses to light understanding to practical guidance and understanding of impacts in realistic lighting situations.

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2 Introduction

Over the past fifteen years, lighting technology has seen a monumental shift from vacuum-based conventional lighting technologies, such as incandescent, fluorescent, and high-intensity discharge, to solid-state light-emitting diode (LED) based technologies. This shift has resulted in large-scale, measurable energy savings with all the associated benefits of reducing energy consumption. The move to energy-saving LED lighting technology was enabled by key breakthroughs in LED science and understanding in the late 1990's, recognized with the Nobel Prize in Physics in 2014, as well as consistent, ongoing advancements in LED technology and scientific understanding. The development of LED lighting technology required new manufacturing approaches, supply chain development, and cost of ownership models. During the 2000's, the status of the technology progressed rapidly, and a fully formed supply chain emerged. Over this same decade, further understanding of how light impacts human physiology has occurred. This new understanding, and the control capabilities available with LEDs, necessitates a renewed focus on lighting science. Lighting science must continue to develop improved understanding of non-visual impacts of lighting, lighting application understanding, as well as visual impacts such as glare and color perception in order to provide the ideal lighting while saving energy. Ultimately, understanding these impacts of lighting is necessary to validate technology and to provide efficient and effective lighting.

For the past decade, the focus of the Department of Energy (DOE) Lighting Research and Development (R&D) Program and the industry at large has been on improving the source efficacy of lighting while maintaining a similar level of other lighting performance attributes compared to traditional lighting. LED devices can now achieve efficacy levels of over 200 lumens per watt (lm/W), which represent an electrical to optical power conversion efficiency (PCE) of over 60%. These high efficiency devices can be integrated in lamps and luminaires with minimal loss (~15%) to achieve very efficient, energy-saving lighting products. A full breakdown of LED efficiency and organic LED (OLED) efficiency can be found in Section 3. Continued efficiency advancements of the core LED and OLED lighting technology are the key to enabling low costs and providing the headroom to reap other non-energy benefits and functionalities of the technology discussed below. More efficient LED and OLED sources enable lower-power, smaller-form-factor power supplies and reduced thermal management in luminaires. Reducing size and component count enables more freedom in new lighting form factors and the ability to improved optical control. The small size and high light output of LEDs further increases these benefits, particularly the opportunities for precise optical directionality. Improving the efficiency of all direct emitted colors of LEDs enables increased color control and color tunability, and, ultimately, the achievement of the final DOE efficacy goals.

However, lighting products with high source efficacies are only part of the energy savings story with SSL technology. The recent path of LED lighting technology has shown that there can be significant additional energy savings through improved optical delivery efficiency, optimization of intensity level, and optimization of the spectral power distribution for the function of the light. While often there are performance trade-offs between source efficacy, optical distribution, intensity control, and spectral power distribution, we now have the ability and opportunity to understand the energy savings resulting from optimized holistic lighting performance beyond just improvements to light source efficiency. A new lighting performance framework is necessary for evaluating and characterizing lighting in a specific space for a specific function. This new framework, termed Lighting Application Efficiency (LAE), has been proposed and consists of four major elements: light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. More about the LAE framework can be found in Section 4. It is critical to continue to pursue improved efficiency in SSL emitters, down-converters, and luminaire technology to drive the four pillars of the LAE framework.

In order to fully engage the LAE framework, it is necessary to have a clear understanding of optimal lighting characteristics for the various functions of lighting, including visual performance and non-visual stimuli for building occupants. With SSL technology there is also the opportunity to improve the visual performance of lighting, such as color quality and optical distribution, to ensure that this energy saving technology meets or exceeds the lighting quality of previous lighting technologies. Over the last decade, scientific research has continued to elucidate the human non-visual physiological responses to light, suggesting a need to reassess current lighting practices to address human health and well-being. In addition, a deeper understanding of lighting science that addresses the visual impacts of light such as glare, flicker, and color quality is needed to allow the development of new metrics (if necessary) to effectively address human perception and comfort in the lit environment. Horticultural lighting science, with LED-enabled technology, will also benefit from new research to determine best practices for plant growth. Improved understanding of animal responses to light can enable improved well-being of domesticated animals, as well as minimization of the impacts of light pollution on wildlife. In short, developing a clearer understanding of lighting science, within the context of the new levels of control offered by SSL technology, will support the development of lighting technologies and practices that provide the most efficient, effective and productive light for the application. Without clearer understanding of lighting science, there is the continued risk that efficient SSL sources will be used to provide sub-optimal lighting for the desired lighting function.

2.1 Program Background

The DOE Lighting R&D Program[1] is within the Building Technologies Office (BTO), which is part of the Office of Energy Efficiency and Renewable Energy (EERE). The Lighting R&D Program was created in response to Congressional direction described in Section 912 of the Energy Policy Act of 2005, which directs DOE to perform the following:

> **"Support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light-emitting diodes."**

The Lighting R&D Program has developed a comprehensive R&D strategy to support advancements in SSL technology and maximize energy savings. To achieve these goals, the Program supports R&D in foundational topics with benefits that apply across the value chain and fundamental R&D that is earlier stage than typically undertaken by commercial organizations. BTO-supported lighting R&D advances the understanding of underlying physical phenomena, explores new technical and manufacturing concepts, reduces the development risk with new technologies, and develops the understanding of application requirements that improve lighting effectiveness, while simultaneously improving efficiency.

This document, the 2019 Lighting 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 lighting experts with input from members of the lighting science research community at National Laboratories and academia, as well as large and small businesses. The inputs are collected at the Lighting R&D small group meetings, the OLED stakeholder meetings, and the annual Lighting R&D Workshop.

2.1.1 Mission

The specific goal of the R&D Program is:

> **"By 2035, develop lighting systems that have power conversion efficiency greater than 60%, delivered spectral power distribution optimized for the lighting application, and improved optical delivery efficiency, while also providing optimum light intensity and directionality for the space to reduce energy and increase productivity."**

This updated goal (the facets of which are detailed in the subsections that follow) describes an expansion of previous goals that mostly focused on improving source efficiency, while providing improved lighting

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[1] The DOE Buildings Technology Office Lighting R&D Program has also been previously referred to as the DOE Solid State Lighting R&D Program.

performance as conventional technologies, and leveraging the ongoing cost reductions of LED products in order to enable rapid adoption. Presently, replacement LED lighting products can effectively replace conventional lighting products at a reasonable price and with significantly higher luminous efficacies. Nevertheless, there is still efficiency improvement potential that can yield additional substantial energy savings. With LED and OLED technology platforms, we have learned that the functions of lighting can be achieved much more effectively than was possible with previous lighting technologies. Additional energy savings are not limited to source efficacy improvements, but also can be achieved through optical delivery efficiency, intensity control, and optimized spectrum. Efficiency improvements at the source level enable cost reduction in the lighting product, thereby allowing headroom for new functionality necessary to optimize the lighting in a space.

2.1.1.1 Energy Savings

Based on the rate of LED efficiency advancements to date and analysis of the potential efficiency improvements if DOE performance goals are met, the DOE has developed a projection for energy savings. In order to achieve these efficiency goals and meet energy savings projections, significant advancements must still be made in LED device and materials performance, as well as in luminaire aspects, such as the power supply, thermal handling, and optical control. See Figure 2.1 for the forecasted energy savings associated with SSL adoption and advancement, and see Section 3 for a discussion of the technology advancements to realize these savings.

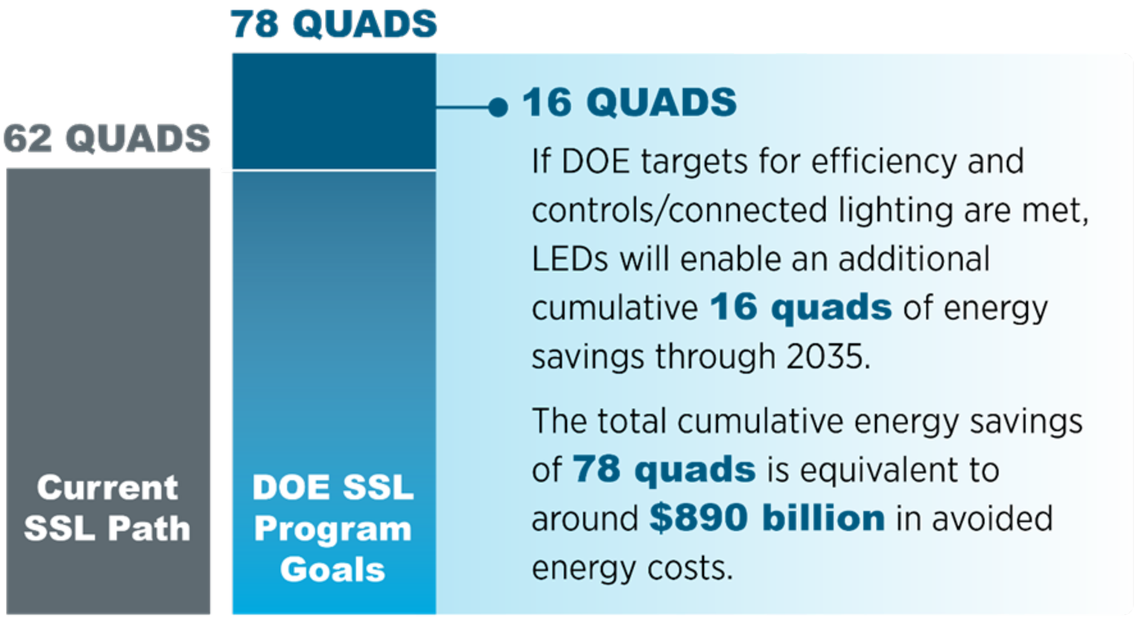

Figure 2.1 U.S. Cumulative Energy Savings Forecast (2017 to 2035). Compared to a hypothetical scenario where LED products never entered the market, these forecasted energy savings result from LED adoption (Current SSL Path) and further improvements in efficiency and connected lighting penetration (DOE SSL Program Goals).

2.1.1.2 Building Occupant Considerations

Previous lighting systems with conventional lighting technologies were designed primarily for vision and visibility using the lowest amount of energy possible. This approach resulted in lighting levels and layouts that provided the minimum light output necessary for basic vision and visibility defined by the type of activities and tasks in the space. New research shows that non-visual light responses should be considered in lighting design to enable optimum health, well-being, and productivity for building occupants. Current understanding suggests that during the day building occupants benefit from light levels and color temperatures resembling daylight. [1] In the evening and prior to sleep, occupants benefit from natural, dark outdoor-like light levels. This shift in approach for lighting designs to account for non-visual light responses is only at the beginning of the process of systematic guidance and codification. Fortunately, these changes in lighting design guidance have developed in parallel with new LED lighting technology, which enables more precisely tuned or tunable lights to achieve light levels and color qualities for optimal occupant health and well-being, while still saving considerable energy.

2.1.1.3 Productivity

Lighting enables different forms of productivity depending on the lighting application. For indoor lighting applications, productivity can be described in terms of worker output or reduction in errors. For roadway lighting, productivity can be expressed in terms of visibility and resulting safety. Improved visibility in specific applications, through optimized color qualities, is a unique feature of LED technology and can enable improved productivity. The spectral power distribution of LEDs can be precisely engineered to increase visible contrast between objects. A particularly important application of improved visibility is in roadway safety. Improvements to roadway lighting, enabled by LED technology can improve roadway safety for pedestrians and drivers. Further advancements in LED technology have the potential to improve object detection distances by providing optimized color qualities of the light and reducing glare through improved optical control not possible with previous technologies. These benefits can be achieved while saving energy and reducing the total amount of necessary light, which can dramatically reduce skyglow and lighting impacts on wildlife.

Most measures of productivity focus on human occupants in a commercial environment. Indeed, improving health and well-being of building occupants will also improve worker productivity. However, solid-state lighting also enables other forms of improved productivity which are not apparent when only the luminous efficacy of the source is considered. For example, LED lighting is now being used in many plant growth and livestock agriculture applications. LED lighting is an enabling technology for vertical farming which has the potential to localize crop production, increase yield per grow area, and dramatically reduce water consumption. LED lighting is also being used in greenhouse crop production and can save significant energy (~40%) compared to conventional high pressure sodium fixtures. Just as LED lighting has the potential to improve human occupant health, animal health and productivity can experience a similar benefit through the provision of optimum light levels with optimal color qualities. [1] LED technology could possibly improve animal behavior (e.g., reduce aggression) and reduce the need for antibiotics and other medicines in the animal growth process, while also saving energy compared to conventional lighting technologies. In plant and animal applications, the long lifetime of LED lighting products also enhances productivity by reducing down-time and maintenance costs to infrastructure.

2.1.1.4 Developing Domestic Scientific Capabilities

The development of SSL has been enabled by a range of breakthroughs in fundamental material science, device physics, and manufacturing technologies over the past 20 years. The advancements in scientific understanding from the development of high performance LEDs and OLEDs products have provided new insight into the underlying physical mechanisms at play within the devices. Ongoing improvements to LED and OLED devices will require continued scientific advancements in the areas of emitter materials and device architectures. In addition, the studies of physiological responses to light for humans, plants, and animals can uncover fundamental molecular, systemic, and behavioral physiological responses to light and advance lighting science understanding. The DOE Lighting R&D Program has fostered the development of U.S. scientific capabilities and expertise through funded R&D projects at universities, national laboratories, and small and large businesses. In addition, the DOE Lighting R&D Program supports domestic scientific capabilities by organizing workshops and meetings that enable scientific information exchange. These meetings include the annual DOE Lighting R&D Workshop and small group topical R&D meetings.

2.1.1.5 Developing Domestic Manufacturing Capabilities

While much of the LED manufacturing process takes place overseas, two companies perform epitaxial growth of LED wafers in the U.S., which is considered the highest value portion of the LED semiconductor fabrication process. Manufacturing and assembly of LED lighting products occurs in the U.S., Mexico, and worldwide. The DOE Lighting R&D Program continually seeks to develop manufacturing technologies that can expand the role of domestic manufacturing within the global supply chain for lighting products. Manufacturing technologies that can enable more efficient manufacturing, use fewer basic parts, and produce a broad variety of lighting products on demand are attractive for domestic manufacturing.

In particular, the DOE Lighting R&D Program has been looking to develop additive manufacturing technologies that can participate in full-scale manufacturing processes. The Program has supported the development of manufacturing processes for placing LED components directly on heat sinks, which removes thermal barriers between the LED and the heat sink and enables deployment of programmable arrays of LED onto a variety of heat sink types. There has also been support of research to develop processes for automated, additive manufacturing of power supply circuit boards that enable a range of power levels that accompany the range of different lighting product types. This enables the manufacturer to stock fewer pre-built power supplies and efficiently build up power supplies as needed.

The general approach is to support technologies that enable rapid, flexible, and reduced part count manufacturing for a broader array of product types. This approach is in alignment with trends in lighting where a broader variety of lighting product types and product qualities are necessary to optimize the benefits of the LED technology platform. The broader range of necessary products makes it difficult to manufacture, transport, stock, and sell such products from overseas in a timely manner.

2.1.2 DOE Lighting R&D Process

The DOE Lighting R&D Program identifies critical R&D priorities through highly informed decision making. The program strives to maximize R&D results from a limited budget. In order to reduce the 'random walk' nature of R&D, the Program works to clearly understand the risks and rewards associated with various R&D topics and approaches. When supporting R&D projects, the Lighting R&D Program goal is to balance the potential rewards against the technical risk.

The annual R&D cycle is shown in Figure 2.2. The DOE Lighting R&D Program stays informed by proactively collecting inputs from expert scientists, product developers, and product deployers. These inputs are gathered from the annual R&D workshop, small group R&D meetings, monitoring of recent R&D findings, and ongoing discussions with a broad range of experts. These inputs are shared through the DOE Lighting R&D sponsored meetings and communication materials and articles. The sharing of these inputs results in accelerated energy savings and R&D advancements. The meetings connect potential collaborators, inform prospective stakeholders, educate down-stream users, and are a credible resource for information on technology concerns. Ultimately, the process serves to accelerate energy savings through informed support of timely R&D and by influencing the broader stakeholder base with these communications. The shared information sets global research and performance expectations and drives lighting performance to fully achievable levels, increasing energy savings and setting new baselines for ongoing R&D.

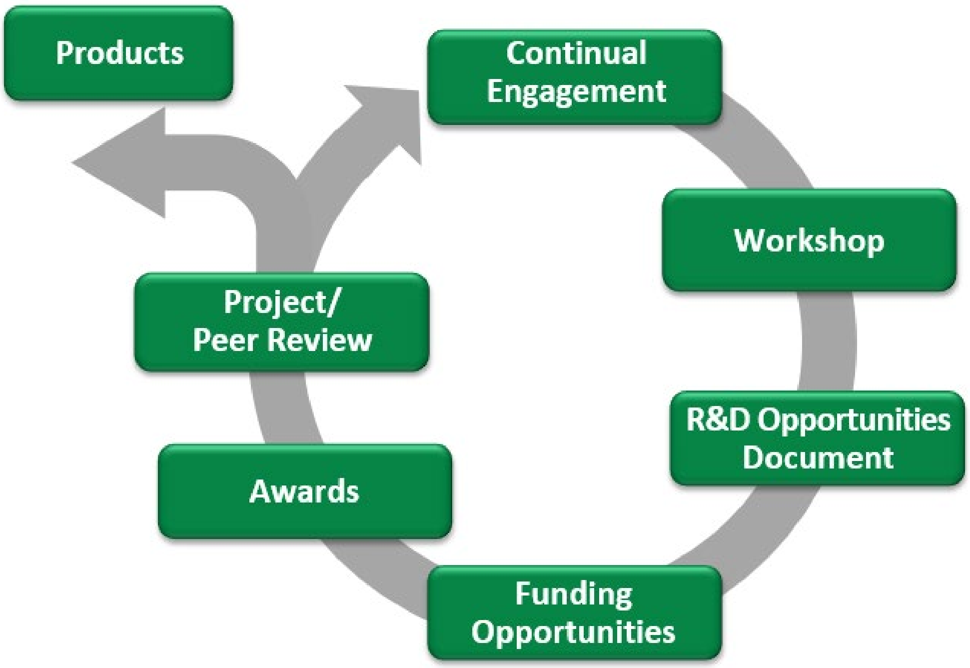

Figure 2.2 Schematic showing the DOE Lighting R&D annual process cycle of collecting inputs and outputs. The Lighting R&D Program works every year to gather current information on the status of energy-saving lighting and the most impactful R&D that can continue to accelerate energy savings and productivity.

2.1.3 Program Activities

The DOE Lighting R&D Program supports a range of R&D activities. The specific mechanisms for supporting R&D are based on the type of R&D, the timeframe for the R&D, and the nature of the entity that can best perform the research.

2.1.3.1 Competitively Funded R&D

The primary mechanism for pursuing scientific, technical, and manufacturing advancements is through competitively funded research and development. The Program defines research priorities and performance targets and, pending appropriations, solicits R&D efforts on these priority tasks to meet the targets. The Program reviews proposals submitted to funding opportunity announcements, makes awards, and proactively manages the resulting projects. Over the last twenty years, the DOE Lighting R&D Program has supported hundreds of R&D projects resulting in the achievements described in Section 2.1.4. A full list of current and previously supported R&D projects can be found in Appendix 6.1.

2.1.3.2 Core Laboratory R&D

In addition to competitively funded R&D projects, the DOE Lighting R&D Program supports research through core Lighting R&D capabilities at Pacific Northwest National Laboratory (PNNL). This work was competitively selected, but it encompasses a broader range of activities that occur over a longer duration. PNNL is researching topics including connected lighting systems and interoperability, color science, translational research to convert research findings or new technologies into the application, daylighting integration, grid enabled lighting, and more. A full description of PNNL activities can be found in Appendix 6.2.

2.1.3.3 Small Business Innovative Research (SBIR)

SBIR projects, funded by DOE Lighting R&D Program and administered by the DOE Office of Science, important research activities. The topics for these annual funding activities are based on priorities identified through the DOE Lighting R&D process. SBIR projects are first selected for a Phase 1 work effort, which is relatively short duration (~9 months) and limited funding (~$150,000), to demonstrate the feasibility of the concept to lighting energy. Phase 1 projects are then eligible to apply for Phase 2 funding to further develop the concept. Phase 2 funding is much greater, and the project duration is longer.[2] Lighting R&D SBIR projects are actively managed by the Lighting R&D team to help researchers and the Program achieve optimal results.

2.1.3.4 Field Validation Capabilities

The DOE Lighting R&D Program also supports R&D activities that are suited to validation of research in actual applications, which is necessary for advancement. The Program supports long-term research in LED and OLED devices, as well as testing of component and product lifetime, reliability, and failure modes. The reliability research includes long term testing of various types of luminaires, accelerated testing of components and luminaires, analysis of luminaire color shift, evaluation of OLED reliability, and evaluation of lighting power supply reliability.[3] The overarching objective of this work is to develop a more holistic representation of luminaire reliability, beyond just LED lumen depreciation, that includes catastrophic failure modes, color shift failure, and other more unusual failure modes. The Program also supports ongoing R&D at the National Institute for Standards and Technology (NIST) where there are projects on color science and LED application.

Another highly successful research mechanism employed by the Lighting R&D Program is the OLED Test Opportunity.[4] Through this opportunity researchers can quickly test the effectiveness and/or compatibility of new OLED materials and structures at a selected test lab. This enables the rapid evaluation of new concepts within the context of state-of-the-art OLED structures. The Lighting R&D Program supports the testing, which is relatively low cost, and has an ongoing, open application process. This R&D model has proven to be highly effective for rapidly testing numerous OLED concepts and greatly increasing the number of research concepts evaluated. As of January 2020, 15 rounds of testing have been completed involving ten different organizations. The testing has covered development work on electron blocking layers; integrated plastic substrates; transparent conductive material as a replacement for indium tin oxide; host materials; hole and electron transport materials; phosphorescent hosts; blue, yellow, and red fluorescent emitters; integrated light extraction substrates with varying haze levels; a fluorine-doped tin oxide coating on soda lime glass; silver nanowire electrodes in combination with light extraction layers; a transparent conductive film for flexible, plastic-based integrated substrates; amber emissive material; and amorphous, composite transport conductive electrodes. This R&D mechanism is an open process, thus there is not a closing date. U.S. R&D institutions can apply at any time to have products tested or be a test facility.

2.1.4 Achievements

The DOE Lighting R&D Program targets early, impactful R&D support. The direction of this support is informed through ongoing communication with researchers, national labs, and business stakeholders. Funded R&D projects have resulted in 316 applied for or awarded patents. 322 funded R&D projects have also directly resulted in the development of 286 distinct lighting products, which encompass materials, production tools, LED packages, and lighting products. This product count does not include next generation or other products indirectly influenced by the supported R&D. The intellectual property, products, and know-how developed through R&D support and through all have resulted in an estimated annual primary energy savings in 2017 of 1,110 trillion British thermal units (tBTU), which equates to over $10B savings in energy costs.[5]

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[2] Further information on the SBIR Program and the specific SBIR lighting topics can be found at https://science.osti.gov/sbir/Funding-Opportunities.

[3] This work is performed by Research Triangle Institute (RTI) through a competitively funded support contract. Current topics for funding span lighting emitting materials, manufacturing technologies, and products for improved lighting application efficiency.

[4] Additional information can be found at https://www.energy.gov/eere/ssl/oled-testing-opportunity.

[5] Additional information on the Lighting R&D Program activities and success can be found at https://www.energy.gov/eere/ssl/program-impacts.

Figure 2.3 Achievements of the DOE Lighting R&D Program. 322 R&D projects have been funded, directly resulting in the development of 316 applied for or awarded patents and 286 SSL products. The installed LED products have resulted in an estimated 1,110 tBTU in annual energy savings (2017), equating to over $10B in energy savings to consumers.

3 SSL Technology: Current Status

Since their introduction on the market, LED products have grown in market adoption each year, highlighting their popularity among consumers and usefulness in achieving energy savings and other application benefits. This section characterizes the SSL market in terms of energy savings realized, current performance levels, and cost-performance trade-offs.

3.1 SSL Energy Savings Potential

In DOE SSL market reports over the past decade,[6] DOE has chronicled the market introduction and rapid adoption of LED lighting. Compared to conventional lighting technologies, tremendous energy savings have been realized by LED replacements. These energy savings are tied primarily to source efficiency improvements over conventional technologies, as current LED lighting products have form factors, light distributions, and light output levels that allow for the direct replacement of existing, lower efficiency conventional lighting products.

The 2018 DOE SSL Forecast Report[7] estimated the installed stock and energy savings associated with LED installations presently and in the future (out to 2035), and these results are summarized in Table 3.1 and Table 3.2. DOE analyzed two scenarios, the Current SSL Path and one based on DOE SSL Program Goals:

- **Current SSL Path Scenario**: The expected future path for LED lamps and luminaires given continuation of current levels of SSL investment and effort from DOE and industry stakeholders.
- **DOE SSL Program Goals Scenario**: The future path for SSL following the DOE SSL Program's goals, representing the ultimate potential of what DOE has determined is technically feasible in the analysis period.

DOE estimated the installed stock penetration in 2017 to be 19%, and in 2035, the penetration was forecasted to reach 84%. LED lighting offered 1.1 quadrillion BTU (quad), or 1,110 tBTU, of energy savings in 2017. If the lighting market continues along the Current SSL Path scenario, a total annual energy savings of 4.8 quads is possible by 2035, of which 12% is made possible by the penetration of connected LED lighting. Compared to the Current SSL Path scenario, the DOE SSL Program Goals scenario offers a different view for the future of LED technology. The primary difference between the two is the resulting energy savings due to penetration of lighting controls, particularly connected versus non-connected LED lighting, and increased LED product efficacy. The increase in connected lighting penetration coupled with the more aggressive projections for LED lamp and luminaire efficacy result in a significant rise in forecasted energy savings for the DOE SSL Program Goals scenario. If the DOE targets are met, LED lighting advancements will enable an additional 1.3 quads in annual energy savings in 2035. Of the total 6.1 quads in annual energy savings in 2035, 16% is made possible by the penetration of connected LED lighting.

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[6] Further information on DOE's market studies can be found at https://www.energy.gov/eere/ssl/market-studies.

[7] The 2018 DOE SSL Forecast Report can be found at https://www.energy.gov/eere/ssl/ssl-forecast-report.

Table 3.1 U.S. LED forecasted stock results for the Current SSL Path Scenario. LED penetration is projected to reach 84% of all lighting installations by 2035.

		2017	2020	2025	2030	2035
Current SSL Path	**LED Installed Stock (million units)**	**1,440**	**2,790**	**5,040**	**6,780**	**7,910**
	Commercial	322	558	964	1,230	1,370
	Residential	1,030	2,060	3,800	5,230	6,210
	Industrial	10	25	56	76	84
	Outdoor	75	146	218	242	256
	LED Installed Stock Penetration (%)	**19%**	**35%**	**60%**	**76%**	**84%**
	Commercial	26%	44%	72%	88%	93%
	Residential	17%	33%	56%	73%	82%
	Industrial	12%	29%	63%	83%	90%
	Outdoor	35%	66%	93%	98%	99%

1. Installed stock for the DOE SSL Program Goals scenario is not provided as there are negligible differences between scenarios. LED installed stock is presented in terms of lighting systems (lamp(s), ballast and fixture are counted as one unit).

Table 3.2 U.S. LED forecasted energy savings by scenario. If the market continues at the current pace, LED products are expected to save 4.8 quads annually in 2035. If DOE goals for efficiency and controls penetration are met, LED products are expected to save 6.1 quads annually in 2035.

		2017	2020	2025	2030	2035
Current SSL Path	**Source Energy Savings (tBTU)**	**1,110**	**1,980**	**3,260**	**4,130**	**4,820**
	Commercial	457	716	1,190	1,570	1,900
	Residential	171	371	719	1,030	1,270
	Industrial	36	94	216	309	372
	Outdoor	444	802	1,130	1,220	1,270
DOE SSL Program Goals	**Source Energy Savings (tBTU)**	**1,140**	**2,310**	**4,160**	**5,380**	**6,130**
	Commercial	468	872	1,670	2,250	2,590
	Residential	171	426	844	1,200	1,460
	Industrial	39	120	291	412	488
	Outdoor	462	896	1,350	1,510	1,580

While SSL performance has already led to meaningful energy savings as shown in the tables above, there is still room for improvement in LED technology performance. The next generation of energy savings from SSL will come from application efficiency, which, at its simplest, characterizes the efficient delivery of light from the light source to the lighted task. If the efficiency of the delivered light is improved, less wasted light will be generated, thus leading to further energy reduction. However, application efficiency can also account for the effectiveness of the light spectrum for the lighting application and the ability to actively control the source to minimize energy consumption when the light is not utilized.

3.2 Lighting Performance

Over the past decade, the efficacy of LED-based lighting products has continued to improve for both indoor and outdoor applications, surpassing incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs), linear fluorescent luminaires, and high-intensity discharge (HID) sources. This improvement in efficacy has allowed LED lighting to penetrate into all lighting applications and continue to grow in percentage of the installed base. Figure 3.1 shows evolution of efficacy over the past decade in LED lighting products. The mean efficacy of a composite of all LED lighting products registered in the LED Lighting Facts database[8] continued to grow each year reaching a mean efficacy of 102 lm/W in 2018.

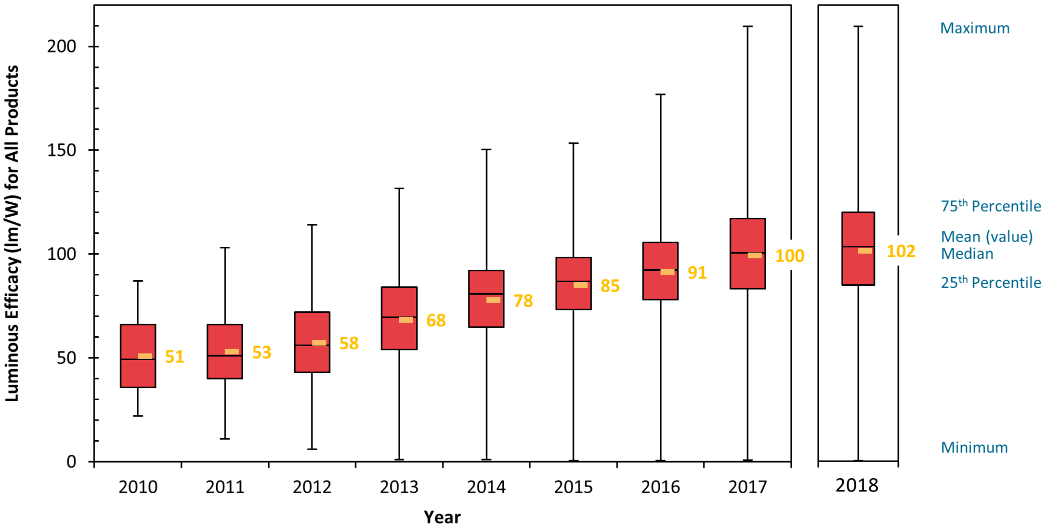

Figure 3.1 Evolution of the annual mean efficacy over the last decade of LED lamps and luminaires listed in the LED Lighting Facts database in June of the charted year. [2] The mean initial efficacy of currently listed products has doubled from 51 lm/W to 102 lm/W between 2010 and 2018. Note: As of December 8, 2017, there were 67,700+ products listed by LED Lighting Facts. There are roughly 50 products of the entire 67,700+ products with efficacy values greater than 177 lm/W. All of these products are industrial luminaires. One has a listed efficacy of 210 lm/W.

While the improvement in LED lighting product luminous efficacy has been impressive, it is only one of the beneficial features of SSL. Lighting attributes, such as spectral (color) quality, optical distribution, intensity level and system reliability can be prioritized along with efficacy to provide the best lighting for the application and the occupants in the space, as illustrated in Figure 3.2. Often, performance trade-offs are required to balance efficacy and these other properties along with cost. Though efficacy has improved over the past decade and cost is low in certain product categories (such as A-lamps), there is still work required in improving spectral quality, optical distribution, and reliability to unlock more of the benefits tied to SSL.

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[8] The DOE LED Lighting Facts® database has been a resource for identifying high-performing LED luminaires since 2010. Receiving data on more than 70,000 products to date, it has been a way for the DOE to assess the progress of the solid-state lighting industry and to help lighting specifiers find high-efficiency, high-quality luminaires. Note: the DOE LED Lighting Facts program ended in June 2018.

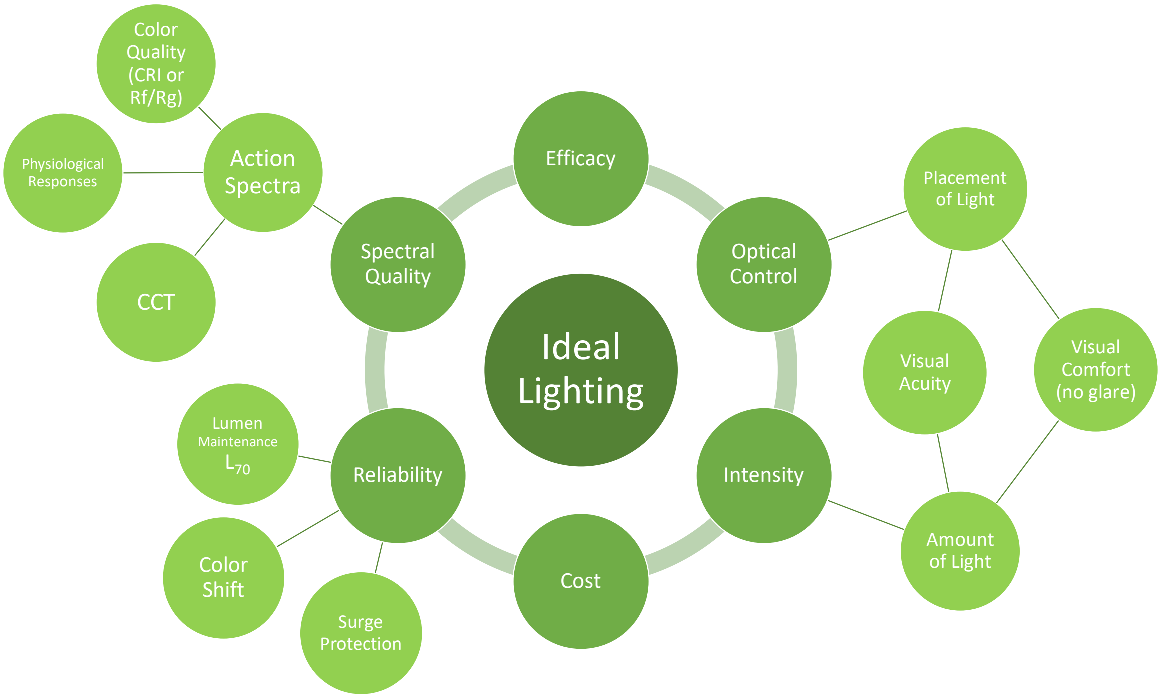

Figure 3.2 A schematic diagram illustrating the key attributes of an ideal lighting solution for an occupant. These attributes move beyond just luminous efficacy and cost to provide the right light at the right time for the application. Improving performance in one of these attributes can often lead to performance trade-offs within other metrics.

The difference in performance between LED lighting products is often a factor of design choices for the product requirements in various lighting applications, which will prioritize performance metrics and attributes in distinct ways. 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 trade-off the manufacturer selected for the end-use case. There are specific cases, such as etendue-limited 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.

Performance and cost trade-offs occur as part of the luminaire design process. For example, a lower cost lamp or luminaire tends to have fewer LED packages that are driven at higher currents to achieve the required lumen output for the application. Reducing the number of LEDs lowers costs, but at the expense of efficacy. The higher LED drive current leads to more efficiency droop in the LED chip and higher temperatures in the package, which leads to earlier lumen degradation and color shift, thereby affecting the luminaire's reliability performance and warranty life. Understanding all the nuanced performance trade-offs and impacts on product design and manufacturing costs will determine what efficacy, correlated color temperature (CCT), color rendering index (CRI), lifetime and cost point different luminaire products bring to market.

High performing LED lighting products in three representative applications were compared for performance attributes. Table 3.3 shows performance metrics for an indoor commercial troffer (2'x4'), an outdoor area light (cobra head fixture), and a lamp product (omnidirectional A19 replacement lamp). The indoor and outdoor luminaire products were selected from the SSL qualification list of Design Lights Consortium (DLC), [9] an

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[9] Information about the DesignLights Consortium and the DLC qualified product list can be found at https://www.designlights.org.

organization that develops product qualification lists to promote high-quality, energy-efficient lighting products in collaboration with utilities and energy-efficiency program members and manufacturers. The lamp product was selected from the Energy Star certified products list, [10] which verifies that products meet strict energy efficiency guidelines set by the U.S. Environmental Protection Agency. The metrics in these three products classes were obtained from the product specification sheets and pricing was obtained from surveying a number of online lighting retailers. These metrics include light output, efficacy, CCT, CRI, L_{70} lifetime, [11] and cost (normalized to US $ per kilolumen of light).

Table 3.3 LED Lighting performance metrics and normalized costs for three representative lighting applications – indoor commercial lighting, outdoor area lighting, and replacement lamps.

Lighting Application	Light Output (lumens)	Efficacy (lm/W)	CCT (Kelvin)	CRI	Lifetime (hours)	Cost ($/kilolumen)
Indoor Troffer (2' x 4')	4000	126	3500	80	50,000	26
Outdoor Area Light (Cobra head)	23,000	127	4000	70	100,000	70
A19 Replacement Lamp	800	81	2700	80	25,000	5

Note: Troffer and area light products selected from DLC qualification list, A-lamp from Energy Star certified products list.

The strengths and corresponding trade-offs for these three lighting application examples in Table 3.3, as well as the ideal light source, are illustrated in Figure 3.3. Five metrics – efficacy, color quality, optical control, L_{70} lifetime and cost – were compared. When comparing lighting attributes for a given product, quality features such as high color rendition, optical control, and longer L_{70} lifetimes most often come at a higher cost. When comparing the products in Figure 3.3 some general trends are observed regarding trade-offs. The A-lamp product is a very cost-effective solution for the quality of light it provides, though it does not provide the optical control of an integrated LED light fixture such as the indoor troffer or the outdoor area light. The A-lamp only fills out three of the five 'spokes' of Figure 3.3, with moderate efficacy, decent color quality and low cost. The reason the cost of the replacement lamp is lower than the other two lighting fixture products is that the lamp is only part of the broader lighting system, whereas the integrated LED luminaires encompass the total integrated system performance of the lighting, and hence have a higher cost per kilolumen of light.

Integrated fixtures generally provide more efficacious solutions and longer lifetimes compared to replacement lamps. Typically, lamps have L_{70} lifetimes between 10,000 – 25,000 hours compared to integrated fixtures (e.g., troffers and outdoor area lights) with lifetimes of 50,000 hours or beyond. Outdoor lighting solutions for street and area lighting require more engineering to create a longer lifetime to reduce the amount of maintenance required in a hard to reach fixture and to provide better optical control to produce the required illumination patterns on the street. The outdoor area lamp from Table 3.3 covers four of the five 'spokes' in Figure 3.3 sufficiently and only concedes in the cost attribute. The additional lifetime and optical distribution requirements over indoor lighting solutions and replacement lamps explain the higher cost per kilolumen of light of those products. The indoor troffer example provides a lower cost solution for high efficacy and color quality with good lifetimes, though the optical control requirements for troffers are not as stringent as outdoor street and area lighting.

These three lighting applications illustrate some of the trade-offs facing the current state of SSL technology. No LED lighting product solution today is without compromise. The value of efficiency, color quality, or lifetime vary for different customers and impact what they are willing to spend for those benefits. With further

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[10] The ENERGY STAR certified product list can be found at https://www.energystar.gov/products/lighting.

[11] A lumen maintenance failure criterion is typically specified as a relative percentage of initial output, most often the point when output has dropped to 70% of the original value, denoted L70.

research and innovation into LED lighting (as highlighted in Section 4), these trade-offs can be reduced further and provide efficient, high quality lighting ideal for the applications at a reasonable cost.

Figure 3.3 Comparison of lighting attribute trade-offs for three representative lighting applications – indoor troffer, outdoor area light, and A-lamp. Each product type is designed to the end application and thus has different strengths of the attributes that lead to performance differences.

Note: For the "Cost" spoke, a higher rating corresponds to a lower initial price.

3.3 LED Performance Breakdown

LED lighting, the most mature of the various SSL technologies, has advanced to the point where it is the best option for most lighting applications. Over the last 15 years, the efficacies of white LED packages have improved from around 25 lm/W to over 200 lm/W. Simultaneously, the costs of LED packages have decreased to the point where LED lighting products can be competitive with conventional lighting products on a first cost basis, while offering significantly lower cost of ownership (initial cost plus electricity cost) during its life cycle. Increasing efficacy and decreasing cost have allowed luminaire manufacturers headroom to provide improved color performance, optical distribution, form factor, and advanced control of the LED lighting products.

3.3.1 LED Package Efficacies: Illumination for Human Visual Acuity

Past, present and projected-future luminous efficacies appropriate for the dominant application of illumination – photopic visual acuity – are given in Figure 3.4(a) and Table 3.4. Here the standard term, luminous efficacy (lm/W), is defined as the ratio between the lumens (lm) associated with a given optical power (the integral of the optical power spectrum po(λ), weighted by the human eye response V(λ), over wavelength) and the electrical source power (pe) used to create the optical power:

$$\text{Luminous Efficacy} = \eta_L = \frac{\int p_o(\lambda)V(\lambda)d\lambda}{p_e}$$

The maximum white light luminous efficacy for a lossless white light source (no loss on conversion from electrical to optical power) with reasonable color rendering quality is ~414 lm/W. [3] As there are no fundamental limits to this efficacy, it seems plausible that practical devices can continue to approach this limit.

The phosphor-converted LED (PC-LED) architecture is by far the dominant white light architecture; the PC-LED architecture uses a blue LED to pump yellow-green and red wavelength optical downconverters (typically phosphors) to produce white light. It has three major advantages: simplicity (only one LED type), temperature robustness (the InGaN blue LED and YAG phosphor downconverters can operate at relatively high temperatures), and color stability (the fractions of red, green, and blue source colors are determined during manufacture by the phosphor optical density and are relatively stable over time). Figure 3.4(a) shows a history of the luminous efficacy of PC-LEDs since the DOE Lighting R&D Program began and the progress that has been made. Over the past decade, luminous efficacies have increased by more than a factor of ~2x, from ~85 lm/W to approximately 185 lm/W at a standard operating current density of 35 A/cm^2. 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 remains more headroom for PC-LED efficacy improvements. As illustrated by the saturation values of the blue and yellow curves in Figure 3.4(a), luminous efficacies of approximately 250 lm/W (which is ~60% of the maximum luminous efficacy of radiation of 414 lm/W) should be practically possible for PC-LEDs.

The color-mixed LED (CM-LED) architecture describes mixing together several monochromatic LEDs, such as red, green, blue, amber (yellow), and cyan to produce white light. For the CM-LED architecture, there are various possibilities to consider: 3-color RGB, 4-color RGBA (or RGBY), and perhaps even 5-color RGBAC. Here, we consider only 4-color RGBA as the best balance between high ultimate luminous efficacy and high color rendering. As indicated by the dashed grey line in Figure 3.4(a) , its ultimate "upper potential" might be on the order of 330 lm/W, limited only by the anticipated 80 to 90% efficiencies of the LEDs themselves and by small losses associated with mixing of their pure source colors to create for white light. The current luminous efficacy of the CM-LED architecture, however, is quite low: about 110 lm/W (an efficiency of ~26%, assuming a maximum luminous efficacy of radiation of 414 lm/W). The main reasons are the inefficient green and amber direct emission LEDs. This can be seen in Figure 3.4(b), which shows historical 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, along with a logistic fit for projected performance assuming an upper limit of 90% power conversion efficiency. Consequently, it not common in most LED lighting but reserved for luminaires used in applications requiring chromaticity tuning. Nonetheless, while the CM-LED architecture currently has lower efficacy performance than the current dominant PC-LED architecture, CM-LED architecture has the potential in future years to leapfrog beyond PC-LED architecture performance.

Table 3.4 Phosphor-converted (PC) and color-mixed (CM) LED package historical and targeted efficacy levels.

Metric	Type	2019	2022	2025	2035	2050
LED Package Efficacy (lm/W)	PC Cool White	184	232	241	249	250
	PC Warm White	168	223	237	249	250
	Color Mixed	114	158	196	288	325

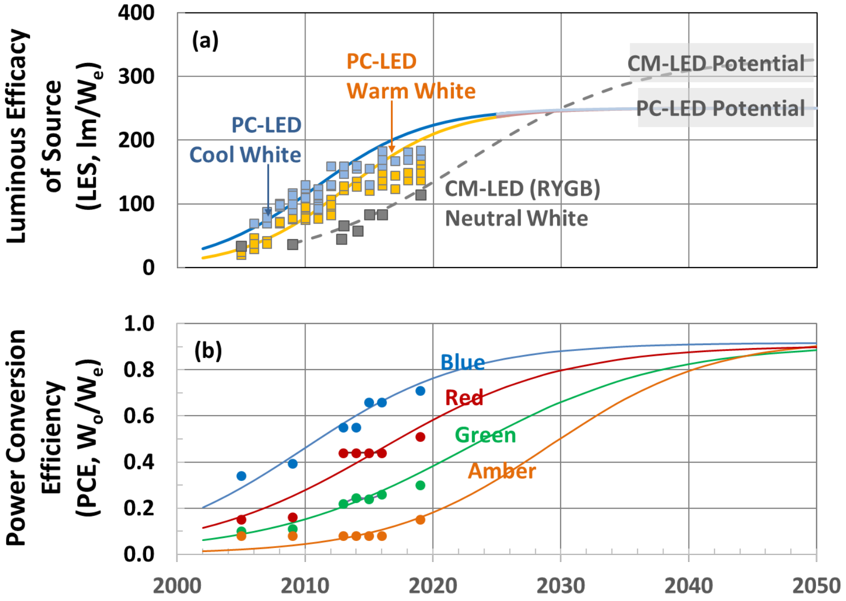

Figure 3.4 Efficacies and efficiencies over time for white and colored commercial LED packages measured at 25 °C and 35 A/cm² input current density. All curves are logistic fits using various assumptions for long-term future performance, and historical experimental data. The data are from qualified products at the representative operating conditions of 25 °C and 35 A/cm² input current density. [4]

Upper panel (a) are the luminous efficacies and conversion efficiencies of warm-white (3000-3500 K) and cool-white (5700 K) phosphor-converted-LEDs (PC-LEDs) and hypothetical color-mixed LEDs (CM-LEDs).

Lower panel (b) are the power-conversion efficiencies of direct-emitting LEDs at the various colors (blue, green, amber, near-red) necessary for CM-LED white light of highest luminous efficacy of source and high color rendering quality. Approximate long-term-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 luminous efficacies of source and conversion efficiencies depicted in upper panel (a).

3.4 LED Luminaire Performance Breakdown

The white light production efficacy of an LED luminaire is limited by the efficacy of the LED package. The other pieces of the luminaire – the power supply and electrical driver on the front end, the mechanical and thermal management structure, and the optical diffusing and/or directing on the back end – contribute additional losses. Various lighting applications have different considerations in optimizing luminaire design and system efficiency. The sub-system (thermal, driver, and optical) efficiencies depend on the design choices for performance levels of the luminaire, as well as the reliability and cost targets. The current status (and future targets) of the sub-system efficiencies associated with the luminaire for a high performance indoor commercial troffer, outdoor area light, and A19 replacement lamp are listed in Table 3.5. The luminous efficacy of a top-bin LED package at room temperature (25°C) is listed for each application, considering the type of package architecture, CCT and CRI requirements of the application. The luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.[12]

Troffers typically use many mid-power packages, which operate at low current densities (< 35 A/cm²) to maintain high efficacy and lower operating temperatures (to improve L_{70} lifetimes). Many A-lamps also use mid-power LED packages, though, due to cost sensitivities, they usually operate fewer LEDs at higher operating temperature to meet the lumen requirements. The trade-off is a loss in thermal efficiency and also a

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[12] Note: Table 3.5 estimates efficiencies for top end products in the lighting applications listed, not average efficiencies.

decrease in L_{70} lifetime. Outdoor area lights and street lights usually require high-power packages to meet the optical distribution requirements (smaller source size) and the longer reliability associated with a package architecture with more thermal and optical design elements built in. In addition, there is suitable room for heat sinks in outdoor area fixtures to remove heat from the packages and extend lifetimes. In contrast, A-lamps have less "real estate" for heat sinking due to required lamp envelope dimensions and optical distribution, thus they are unable to mitigate the heat as efficiently with the higher operating temperatures of the LEDs. This results in a lower thermal efficiency value than a troffer even though the LED package can have the same performance.

As with most of the luminaire and lamp designs considerations, efficiency is traded for lower cost system designs. This is especially true in the LED replacement lamp segment as costs are dropping to commodity levels and achievable efficacies and lifetimes are dropping due to compromises made in the system design. Higher value features (i.e., efficacy, lifetime, color quality, and optical control) require better system engineering, which increases cost. Each of the luminaire sub-systems have room for performance improvements with the goal of reaching 95% efficiency across these sub-systems to meet the DOE efficacy projections 2035. More R&D is required in various technologies to achieve these goals. The technical challenges are highlighted in Section 4.1.2 (Source Efficiency), Section 4.1.5 (Optical Delivery Efficiency), and Section 4.2.3 (Electronics).

Table 3.5 Breakdown of LED luminaire efficiencies for three representative lighting applications – indoor, outdoor, and lamps. The PC-LED package efficacies listed are best in class for the CCT and package type required in the application.

Efficiency Channel	2019			2035
	Troffer	Outdoor Area Light	A-lamp	Goal
LED Package Efficacy (lm/W)	200*	175**	200*	249
Thermal Efficiency Droop (increased T_{op})	93%	90%	86%	95%
Driver Efficiency	88%	92%	84%	95%
Optical Efficiency	92%	87%	88%	95%
Overall Luminaire Efficiency	75%	72%	65%	86%
Luminaire Efficacy† (lm/W)	150	126	130	214

* Top performance mid-power PC-LED packages can reach 200 lm/W at CCTs between 3000-4000 K.
** Top performance high-power PC-LED packages can reach 175 lm/W at 4000 K CCT.
† Luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.
Note: Efficiency estimates are for top performing products in the lighting applications listed, not average efficiencies.

3.4.1 Impact of Performance Variants

The luminaire is the final custom element that tailors how the white light fits into an application, resulting in a wide range of luminaire types. The brightness, size, direction, and beam shape; the aesthetics, shape, size, and cost of the housing and overall luminaire; and the environment with which the luminaire must be compatible and integrate are considerations that lead to a wide proliferation of luminaire types and performance variants. Many of the performance variants that LED luminaire products offer today involve the LED package metrics. Different CCTs, CRIs, lumen levels, and efficacies depend on the LED package design and how they are selected and integrated into the luminaires. These factors create a range of varying efficacy levels that result in a large range of product performance levels and costs. The impacts of these variants are discussed briefly below.

- **CCT**: Achieving higher efficacies has thus far been more challenging for warm white LEDs than for cool white LEDs due to the relative inefficiency of adding red downconverters to the blue LED and yellow-green phosphor. There is a higher energy penalty or Stokes loss associated with converting the high energy blue light to the lower energy red light. In addition, the broader emission linewidth of red phosphors causes a significant spillover of light into the deeper red, where the human eye is less sensitive, and is a sizeable contributor to the spectral inefficiency of current PC-LED white light. Spectral engineering can help reduce the efficiency impact seen by moving to warmer CCTs, as discussed further in Section 4.1.3.
- **Color Rendering**: To satisfy the majority of applications for white light, relatively high color rendering quality (i.e., a "standard" CRI R_a of 80) is desired.[13] However, some sectors of the market increasingly demand even higher color rendering. There is an inverse relationship between luminous efficacy and color rendering. Increasing CRI from 80 to 90 typically decreases the maximum achievable luminous efficacy by approximately 10%. [5] Practical data suggest the drop to be significantly higher in the PC-LED architecture, in the range of 15 to 20 percent, due to deficiencies in the red phosphors. New research in downconverters can help reduce this efficacy penalty and is examined in more detail in Section 4.1.3.
- **Lumen Output**: LED drive current determines the amount of luminous flux generated in the package. Top bin commercial LED packages can achieve luminous efficacies of 200 lm/W, but only by operating at lower current densities (< 35 A/cm^2). This leads to less overall luminous flux generated in the package, and thus results in a higher cost per lumen. Packages driven at a higher current density produce more lumens, however, due to a phenomenon known as current efficiency droop (discussed later further in Section 4.1.3), the efficiency of blue LEDs decreases at the higher current densities, leading to lower white LED efficacies at the higher flux level. To achieve desired lumen output at high efficacies, more LED packages are integrated into the luminaire and operated at lower current densities, which will also increase luminaire costs.

While the LED package selection defines the luminaire product variants described above, other product variants arise with the fixture design. The optical and control system designs also create other product options that impact the luminaire selection for the application. These are summarized below.

- **Optical Control**: Different optical beam patterns are required to meet the needs of different applications. The design of the secondary optics of the light fixture plays the most significant role in optical control, though the selection of the LED package design can help make the optical control of the system easier. For example, selecting a smaller LED source size allows for narrower beam spreads in directional lighting. In outdoor street and area lighting, standard optical distribution types, defined by the Illuminating Engineering Society (IES), describe the shape of the area that is illuminated by the fixture. Different optical lens designs are required of the fixtures to create these defined illumination patterns. Further opportunities for improving optical delivery are discussed in Section 4.1.5.
- **Controls/connectivity**: Luminaires can come with different levels of integrated controls, sensors and connectivity for the functionality required in the space. These can include the integration of sensors to detect occupancy or daylight levels in a building to control lighting operation. Connectivity allows for the collection and exchange of useful data that offer the potential to enable a wide array of services, benefits, and revenue streams, thus enhancing the value of lighting systems. While connectivity is offered for a variety of products today, the challenge becomes the interoperability of these different connected lighting systems, as manufacturers have focused on developing and promoting proprietary

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[13] It is likely that new measures will someday replace or at least augment the standard CRI in ways which depend on the particular illumination application. For example, the Illumination Engineering Society of North America (IES) published TM-30, a new method for evaluating color rending that includes both a "fidelity index" and a "gamut index.

technologies or their own version of industry standards. The challenges and opportunities of connected lighting and integrated controls is further discussed in Section 4.2.5.[14]

3.4.2 Tunable Lighting

Tunable lighting can provide many of the product variants described above in a single system that can be dynamically tuned by the user. The unique features of SSL allow for precise spectral control and color tunability not available with other previous lighting products. SSL products can be designed to emit almost any spectrum of visible light; this ability to dynamically tune the emitted spectrum of the light source can unlock a host of value-added features for SSL beyond energy savings. Tuning a light source between warm, neutral, and cool white is desired in a range of applications – from supporting the circadian system, to changing the mood in a room, to mimicking the changing color from natural light throughout the day indoors. In recent years, LED lamps and luminaires have become widely available with white color tuning (i.e., warm to cool white appearance tuning), as well as those with full color tuning, which includes monochromatic colors such as red, green, and blue.

White tunable LED lamps and luminaries often combine warm white LEDs (usually around 2700 K) and cool white LEDs (usually around 6000 K) to provide a lighting system that enables tuning of chromaticity values along the chromaticity line between chromaticity points of each CCT LED. Adjusting the amount of current delivered to each of the two LED color channels, or 'primaries', will tune the overall luminaire CCT. Since the chromaticity values of the white LED primaries are near the Planckian locus (black body locus), a CCT value can be used to describe a change in the chromaticity value of the luminaire or lamp. This linear CCT tuning in luminaires provides one level of tunability. For white tunable products, adding a third primary to the warm and cool white LEDs allows adjusting the CCT to closely following the black body locus (a nonlinear curve) and fully reproduce the emitted color behavior of incandescent technology. An example of a white tunable LED lighting product that employs linear CCT tuning is compared to a product that follows the nonlinear black body behavior during tuning in Figure 3.5.

Developing white and color tunable luminaire products requires careful consideration of lumen output, efficacy, color quality, and power consumption. There can be a trade-off between efficacy and color performance with tunable products, though this trade-off can be reduced and even minimized with careful engineering, which may require more complex system designs to maintain high efficacy and light quality simultaneously. However, adding the ability to tune color points and the required system complexity to achieve this balance increases the cost of the luminaire.

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[14] The Lighting R&D Program focuses its efforts on lighting specific controls and sensors. The Building Technologies Office also supports R&D on non-lighting controls and sensors, and information on this can be found at https://www.energy.gov/sites/prod/files/2019/04/f61/bto-sc-rdo-041519.pdf.

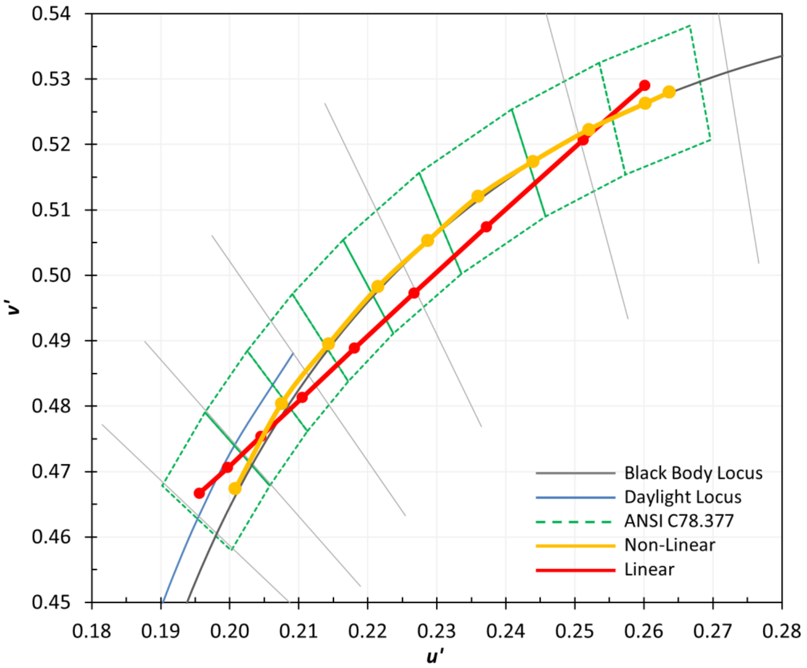

Figure 3.5 CIE 1976 chromaticity diagram showing examples of linear and nonlinear (black body) CCT tuning. The exact curves will vary from product to product, but the key difference is that linear (two-primary) systems can only produce chromaticities that are directly between the two primaries chromaticity points, whereas products with more than two primaries can be used to create light mixes that can follow the black body locus. [6]

3.5 LED and Luminaire Cost Breakdown

Early in the LED lighting revolution, LED package prices tended to dominate the cost breakdown for an LED-based lamp or luminaire; however, rapid price reductions have occurred over the past 5-6 years with the introduction of plastic packaging materials and chip scale packaging (CSP) methods. Current LED packages prices and the cost breakdowns of those packages are considered below.

3.5.1 LED Pricing

Rapid price reductions of LED packages have occurred over the past decade with epitaxy and die fabrication manufacturing process improvements and innovations. The evolution of LED package prices is illustrated in Figure 3.6 for both warm white and cool white high-power and mid-power packages. The steep drop in prices over the past 10 years is associated with the introduction of mid-power LED packages that were originally developed for display backlighting, but these matriculated into general illumination lighting. The mid-power architecture is now the largest volume sector of LED packages for lighting applications.

The price estimates in this section represent typical retail prices for LED packages purchased in quantities of 1,000 for high-power LEDs and 5,000 for mid-power LEDs from major commercial LED package distributors. Each LED manufacturer produces variants of each package design covering a range of CCTs, CRIs, and lumen output levels. Data are selected based on available datasheets and represent devices in the highest flux bins where this is reported (taking the average value within that bin) or typical flux values for the total available distribution. Chosen devices fall within specified ranges of CCT and CRI, as indicated on Figure 3.6. In all cases, the price is expressed in units of U.S. dollars per kilolumen of light ($/klm). The price–efficacy projections from Figure 3.4 and Figure 3.6 are summarized in Table 3.6. The price projections in this table have been adjusted to account for the lower prices associated with mid-power package designs.

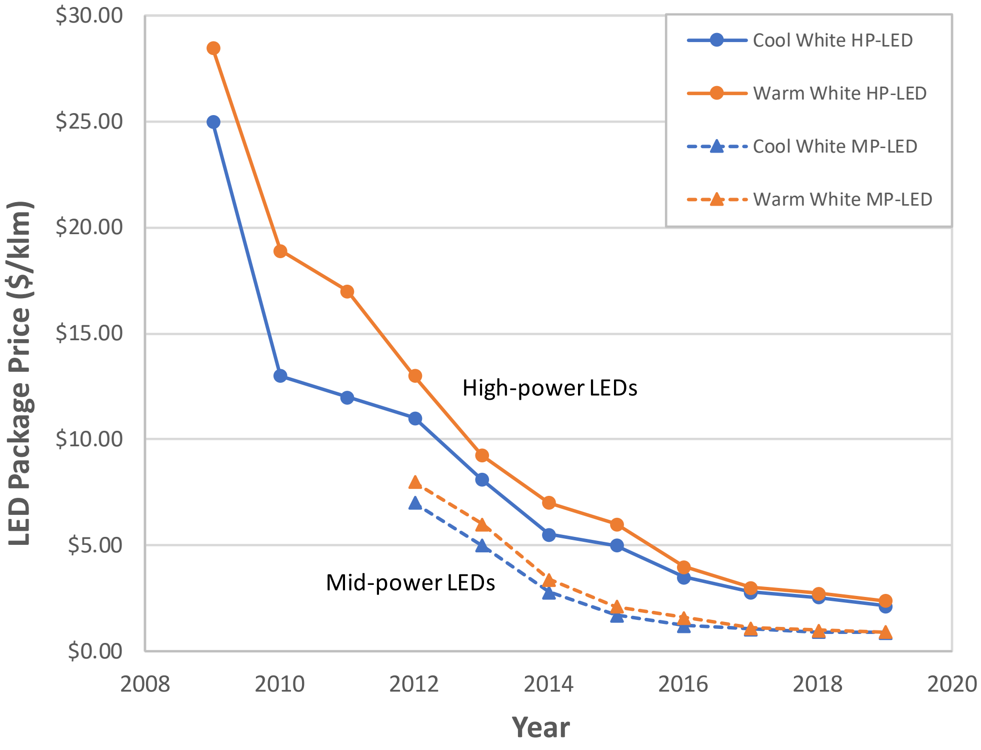

Figure 3.6 Price for high-power and mid-power warm-white and cool-white LED packages over time. The prices have come down rapidly over the past decade with new technology innovation and a more robust supply chain.

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

Table 3.6 Summary of current LED package price and future performance projections. The LED performance projections are taken from Figure 3.4 for LED packages at 35 A/cm2. The price projections, taken from Figure 3.6, represent the lowest prices available with mid-power LEDs.

Metric	2019	2022	2025	2035
Cool White Efficacy (lm/W)	184	232	241	249
Cool White Price ($/klm)	0.88	0.67	0.45	0.30
Warm White Efficacy (lm/W)	168	223	237	249
Warm White Price ($/klm)	0.92	0.70	0.45	0.30

The LED package prices not only depend on the package architecture and color point, but also the efficacy. Mid-power LED packages with efficacies as high as 220 lm/W (cool white) and 200 lm/W (warm white) are available in production in 2019, though most product models tend to have lower efficacies. Prices for these LEDs with very high-end efficacies of 200+ lm/W are nearly 4x of the LEDs in the 130 lm/W efficacy range. The low-end of the price range for the mid-power 3030 style packages is approximately $0.9/klm, but it reaches approximately $3.70/klm at the highest efficacy levels.

High power packages have higher pricing due to the more expensive components to provide high light output and better optical and thermal control. Typically, the mid-power package costs will be 5-10x less than a high-power package (depending on die area), and this is reflected in a similar price differential. Again, as with mid-power LEDs, the efficacy and other performance metrics affect the price of high-power LED packages. High-power LED packages with efficacies as high as 184 lm/W for cool white and 168 lm/W for warm white were readily available in mass production in 2019.[15] Over the past several years, the price difference between warm white and cool white packages has decreased and can be almost negligible for a number of LED packages families.

It is expected that going forward, high-power LED package price erosion will continue, though mid-power package prices may remain more price stable while increasing performance levels at those prices. Market issues (e.g., oversupply), though, could impact these trends leading to further price reductions as more suppliers in China continue to try and grow their market share, resulting in possible price wars. The race to the bottom in pricing has impacted margins, which has led many LED package manufacturers to look towards other applications outside of general lighting, such as automotive and horticulture, to sustain their margins and provide alternate paths to revenue growth.

3.5.2 LED Cost Breakdown

The typical cost breakdowns for high-power and mid-power LED packages are shown in Figure 3.7. The breakdown for the high-power package assumes high-volume manufacturing of 2 mm^2 LED die produced on 150 mm diameter sapphire substrates, which are packaged on ceramic substrates (3.5 mm x 3.5 mm) with a molded lens to produce warm white PC-LED light sources. The breakdown for the mid-power PC-LED package assumes a two die (0.5 mm^2 die) plastic leaded chip carrier (PLCC) 3030 package (3.0 mm x 3.0 mm). As seen in the cost breakdown, the LED die (including epitaxy, wafer processing, and singulation) is the largest cost element accounting for just above half of the package cost. The relative contribution of the packaging costs and phosphor cost is where the mid-power and high-power packages diverge. The high-power package uses more expensive ceramic substrates and hemispherical over-molded lenses compared to the metal lead frame and plastic molded housing with a dispensed encapsulant. The low packaging costs in the mid-power architecture makes the relative contribution of the phosphor cost element rise in percentage of total cost as compared to the high-power package architecture.

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[15] Note: these efficacies for high-power LEDs are listed at a current density of 35 A/cm^2, consistent with Figure 3.4.

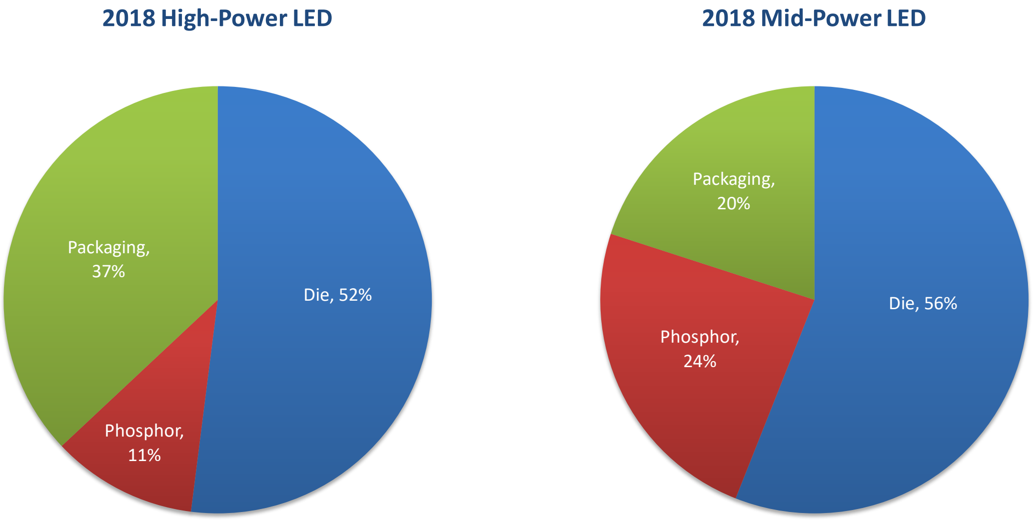

Figure 3.7 Typical cost breakdowns for high-power and mid-power LED packages. The LED die represents the biggest cost contribution of the LED package.

Note: The high-power package assumes a 2 mm² LED die packaged on a ceramic substrate (3.5 mm x 3.5 mm) with a molded silicone lens. The mid-power PC-LED package assumes a two die (0.5 mm² die) plastic leaded chip carrier (PLCC) 3030 package (3 mm x 3 mm).

Source: Inputs from DOE SSL Roundtable and Workshop attendees

Over the past 5 years, the high-power LED package cost has continued to come down as volumes ramped up. During this period, the relative contribution from epitaxy and wafer processing decreased as LED production wafer sizes increased; in addition, the chip design has changed to allow for lower cost manufacturing processes to be employed. These two factors have led to a lower cost percentage associated with the LED die, while the relative contribution from packaging and phosphor has continued to rise.

Mid-power packages have reached prices that are close to the raw materials cost due to the intense competition and oversupply in this market segment since 2014. The small LED die costs have decreased to such low levels that now many of the mid-power packages for lighting contain two die instead of only one die. The LED die cost is a key driving factor in the pricing of mid-power LED packages since the margins in packaging cost elements are minimal.

A third prominent class of LED light sources is chip-on-board (COB) LEDs, which are used in products requiring high lumen output from small optical sources or extremely high-lumen density. COB LEDs 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 often used in downlights, directional lighting, and high/low-bay lighting. Their ease of use in luminaire manufacturing appeals to some smaller luminaire manufacturers who do not have the surface mounting equipment to assemble discrete packages onto MC-PCBs.

The cost breakdown for a COB LED is shown in Figure 3.8. The COB LED breakdown assumes a 20 W class product with a light-emitting surface (LES) size of 12-14 mm on an MC-PCB. One major difference for the COB LEDs compared to the high-power and mid-power LEDs discussed above is the number of die and subsequent assembly costs required to place anywhere from 15-100+ LED die on the array substrate. For this reason, assembly cost and substrate costs have been broken out as separate cost elements instead of including them together as the packaging cost element (as was done for high-power and mid-power LEDs). As can be seen from Figure 3-8, the assembly cost is the most significant element for the COB LED, with LED die cost as the second highest element. As the LES size of the COB LED is increased, the LED die content proportion will increase relative to the COB substrate area.

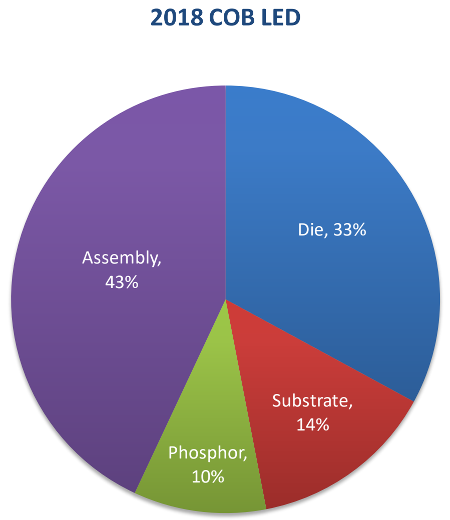

Figure 3.8 Typical cost breakdowns for chip-on-board (COB) LED packages. The assembly cost is a significant contribution of the COB cost due to the large number of chips that need to be attached compared to high-power and mid-power LED packages.

Note: The COB LED breakdown assumes a 20-Watt class product with a light-emitting surface (LES) size of 12-14 mm on a PCB substrate.

Source: Inputs from DOE SSL Roundtable and Workshop attendees

While pricing for LED packages have dropped by substantial amounts this past decade, there is still room for innovation in the area of LED packages. Reducing the cost premiums for the highest efficacy LEDs requires innovation in LED chips, down-converter materials, and package designs, as discussed in Section 4.1.3. Different approaches to cost reduction include technology improvements, new design concepts, and manufacturing innovations. Some key areas include:

- Optimized packages (e.g., simplified designs, lower cost materials, and multi-chips);
- Improved yields in epitaxy and wafer fabrication;
- Chip-scale and wafer-scale packaging; and
- Eliminating current density droop.

3.5.3 LED Luminaire/Lamp Cost Breakdown

As discussed in the sections above, the typical cost breakdown for a lamp or luminaire vary depending on the lighting application and performance metrics of the luminaire. Figure 3.9 shows a comparison of the cost breakdown for an LED troffer, indoor residential downlight, outdoor area lamp, and A19 replacement lamp. This comparison reveals that relative costs for different form factors can vary considerably.

A noticeable trend over the past 5 years is how fast relative LED package cost is dropping in both luminaires and lamps. Early in the development of LED lamps and luminaires, the cost of the LED packages dominated the total product cost, but this is no longer the case due to the lower prices and wide availability of lighting class LED packages. The cost of LED packages has continued to drop, even to commodity levels for some form factors, so future cost reduction must be achieved by focusing more on optimization of the complete system rather than focusing on any specific cost element. For most luminaire products, the dominant subsystem cost has become thermal/mechanical/electrical, which represents the housing, heat sinking elements, electrical connectors, and mechanical fasteners.

Overhead and assembly costs also represent a real cost element and should be included in the cost charts along with the bill of materials. The overhead included in the cost charts refers to manufacturing engineering, product development, documentation, in-line and compliance testing, shipping, and distribution. The retail price will include an additional channel margin of approximately 20% to 30%.

While a straight cost down process is one approach to reducing luminaire cost, system redesigns are a more common way to make greater jumps in cost reduction by changing the amount and type of components in a system. This system redesign approach also affects the relative sub-system cost over time as different design approaches to achieving good optical, electrical, and thermal performance will affect the component costs and therefore their ratios. Manufacturers continue to seek manufacturing approaches that can enable cost reduction without degrading system performance in terms of efficacy, lifetime, color quality, etc.

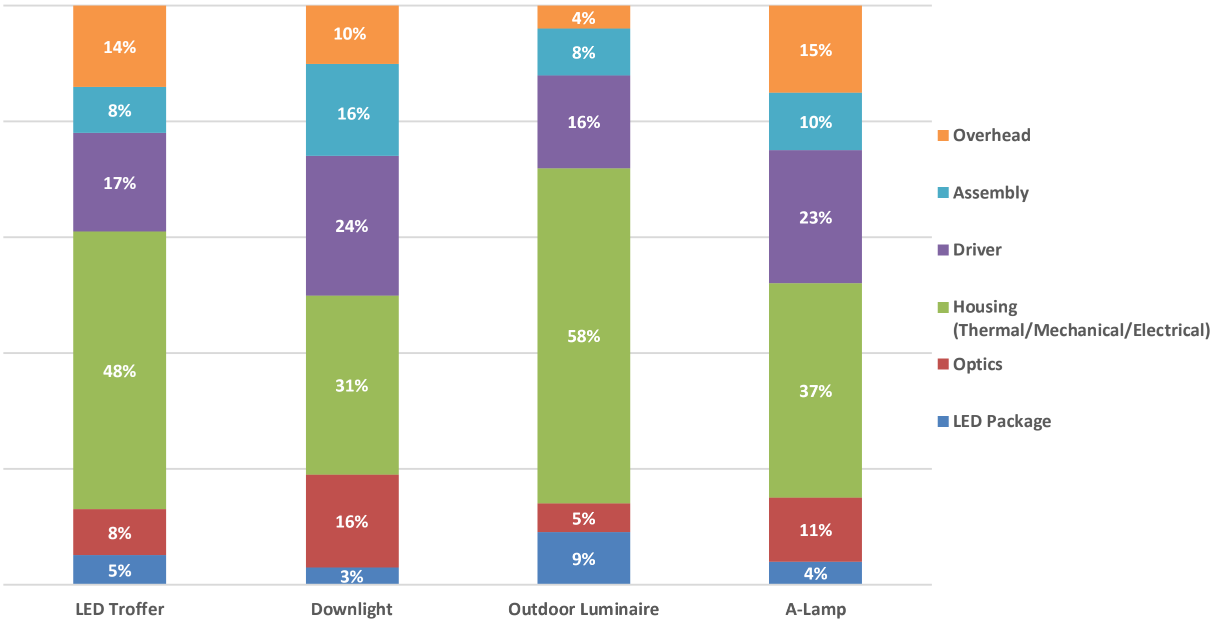

Figure 3.9 Comparison of cost breakdown for different lighting applications in 2019. The categories of LED lighting products include a troffer, a downlight, an outdoor area light, and an A-lamp. Each product has a different balance of cost in the major elements, though housing is the biggest contributor in each product type.

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

Source: DOE SSL Roundtable and Workshop attendees and industrial partners

3.5.4 Historical Cost of Light

In Section 3.3, the performance of past and potential-future SSL technology was outlined with respect to luminous efficacy, ηL. Combined with other quantities such as lamp life and cost, luminous efficacy then determines the cost of light (CoL) in terms of the operating and capital costs of light:

$$CoL = CoL_{ope} + CoL_{cap}. [7]$$

The operating cost of light, $CoL_{ope} = CoE/\eta L$, in units of U.S. dollars per megalumen hour (\$/Mlmh), is the cost of electricity, CoE (in \$/MWh), divided by luminous efficacy, ηL (in lm/W). The capital cost of light, $CoL_{cap} \approx \$\varphi/\tau$, also in units of \$/Mlmh, is approximately the cost to purchase the lamp package per lumen that the lamp package supplies, $\$\varphi$ (in \$/klm), divided by the life of the package, τ (in khr).

Figure 3.10 shows the evolution of these costs for solid-state lighting over the past 15 years. [8] The operating cost of light has decreased by about one order of magnitude, from ~5 \$/Mlmh to ~0.5 \$/Mlmh. The capital cost of light has decreased by about two and a half orders of magnitude, from ~29 \$/Mlmh to ~0.1 \$/Mlmh. The sum of the two, the overall cost of light, has decreased by about one and a half orders of magnitude, from ~34 \$/Mlmh to ~0.6 \$/Mlmh.

To put this in context, Figure 3.10 also shows for reference the costs of light for traditional lighting circa 2001 (and which has not changed much since then). The red, blue and green curves correspond to constant total cost-of-light curves associated with incandescent, fluorescent and high-intensity-discharge lamps. The red, blue and green open circles correspond to particular lamps, sized in area according to their 2001 U.S. market size in lumen-hours of light per year produced by that lamp. The diagonal white line represents the lamp capital to operating cost ratio of 1/6 that characterizes traditional lamps, while the dashed diagonal black line represents a capital to operating cost ratio of 1.

Two pivotal years can be seen in the history of solid-state lighting. First, in 2008, the cost of light for SSL lighting packages decreased below that of incandescent lamps – it thus became economical to switch from incandescent to solid-state lighting. Second, in 2013, the cost of light for solid-state lighting packages decreased below that of fluorescent and HID lamps – it thus became economical to switch from fluorescent and HID to SSL.

This year, 2019, is also pivotal, in a different way. Just as for traditional lighting, for solid-state lighting packages, the capital cost of light has become about a factor of 6 lower than the operating cost of light – the 2019 data point lies very close to the white line in Figure 3.10. In other words, for the function of basic white light, SSL has become, just as traditional lighting was, a true “energy service,” for which the dominant ownership cost is due to consumption of energy. Thus, for future SSL, there is increasing headroom for adding device cost, which adds to the capital cost of lighting, in order to improve functionality. [9] Such functionality (e.g., engineered light in space and spectrum) might in turn enable increased application efficacy – i.e., decreasing light intensity where and when it is less desirable but increasing it where and when it is more desirable, and tailoring spectra for human (and plant) health.

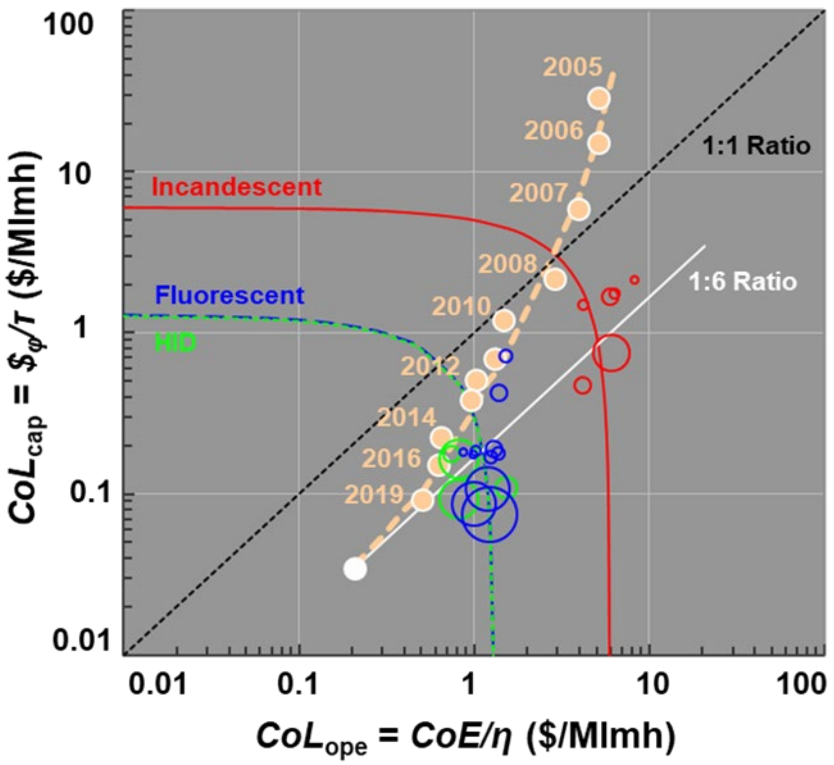

Figure 3.10 Equivalent capital and operating costs of light for various past and potential-future traditional and SSL lighting technologies. [8] Open colored circles represent traditional lamps (red = incandescent, blue = fluorescent, green = HID), drawn so that their areas are proportional to their 2001 U.S. market size in lumen hours per year produced by that lamp. [10] The red, blue, and green lines represent contours of constant market-weighted aggregate ownership costs of light for incandescent, fluorescent, and HID lighting in 2001. Filled tan circles represent past and present SSL (packaged but not yet integrated into Edison-style bulbs). The dashed tan line is intended to guide the eye only. The 2019 data point corresponds to the Lumileds Luxeon 2835 Color Line. The diagonal dashed black line represents a lamp capital to operating cost ratio of 1:1; the diagonal solid white line represents a lamp capital to operating cost ratio of 1:6.

3.6 OLED Lighting Performance

Organic light-emitting diodes (OLEDs) represent an area of SSL technology that can create diffuse light sources with direct emitters that are thin profile and bendable. This technology can produce new form factors and lighting design flexibility not available with today's LEDs or traditional lighting technology, though OLED efficacy performance and costs lag those of LEDs. OLED technology is steadily improving with commercial products now available that reach reasonable performance in efficacy, lumen maintenance lifetime, and color quality. Further, bendable panels have been commercialized; an example of a bendable OLED panel product is shown in Figure 3.11. Other luminescent materials, such as electroluminescent quantum dots (EL QDs), and perovskites can also provide this direct-emitting diffuse lighting that can work within the OLED architecture. Hybrid structures of OLEDs with QDs are another avenue to provide diffuse direct emitter lighting.

Figure 3.11 The LumiCurve Wave bendable OLED panel demonstrates the flexible design possible in OLED technology. [11]

3.6.1 OLED Performance Breakdown

Although an efficacy of over 130 lm/W in warm white OLED panels was demonstrated in 2014, the efficacy of commercially available panels still significantly lags that of inorganic LEDs. Table 3.7 shows the characteristics of warm white rigid and flexible panels with a 3000 K CCT and 90 CRI at brightness levels of 3000 cd/m^2 and 8500 cd/m^2. [11] [12] The improvement in lifetime (L_{70}/B_{50}[16]) from previous generations of OLED panels has mainly come from reduced current density enabled using multiply stacked devices. Such tandem structures reduce the current density, thereby increasing lifetime, but also increase the operating voltage. The spatial and angular variation in color coordinates are 0.002 and 0.005, respectively, and the spatial homogeneity of the light intensity is over 90%.

Table 3.7 Characteristics of a commercial OLED panels in early 2019. The Brite 3 is a flat panel and the LumiCurve is a bendable panel. The performance is shown at two different operating levels. [11] [12]

	Brite 3		LumiCurve	
Thickness (mm)	1.4		0.4	
Weight (gram)	38		15	
Lit area (mm)	102 x 102		221 x 46	
Light output (lm)	100	300	100	300
Voltage (V)	17	18.6	17	18.6
Current (mA)	70	215	95	295
Efficacy (lm/W)	85	75	62	55
L70/B50 (1000 hrs)	100	30	50	10

With high CRI, lifetimes of up to 100,000 hours, and efficacies approaching 100 lm/W, OLED specifications are starting to bridge the gap to become more competitive with LED technology. Though costs have rapidly declined, significant reductions are still needed to realize meaningful market penetration. Figure 3.12 shows the OLED performance and cost advancements since 2014 and future projections for improvements to efficacy, light extraction, lifetimes, and cost. Improvements in efficacy and lifetime were realized this past year

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[16] Typically, manufacturers assign a lifetime rating to a lamp based on the time at which 50% of a large sample is expected to have stopped working, using measurements and predictive models, denoted B50.

and new innovations from further R&D, as discussed in more details in Section 4.1.4 and Section 4.2.6, can help further performance improvements.

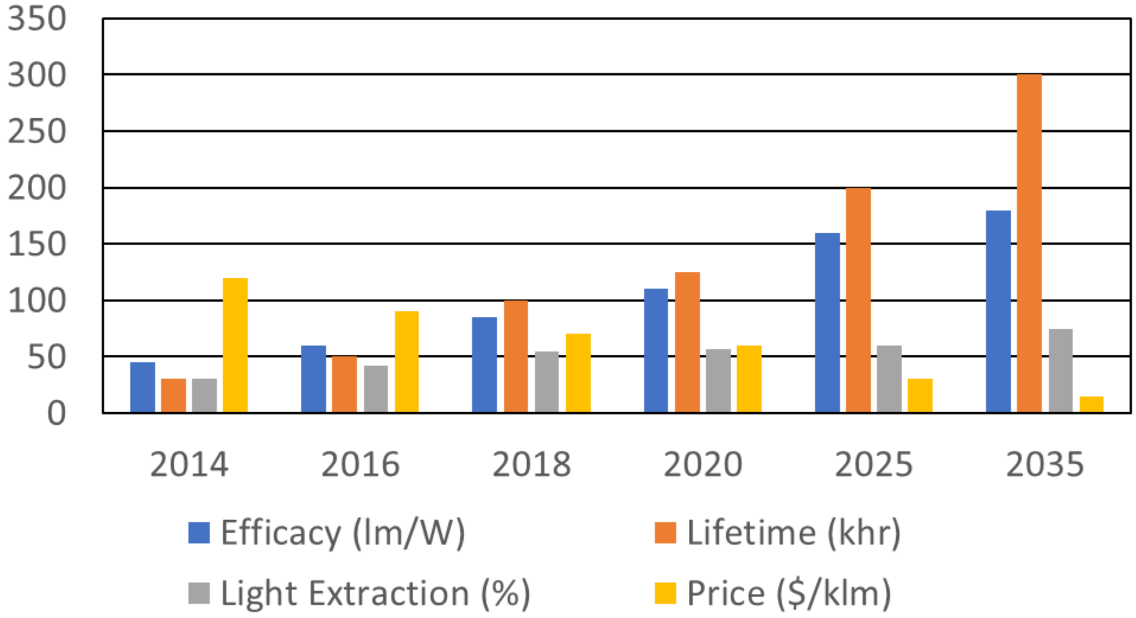

Figure 3.12 Advances and projections in key attribute for OLED panels over time. [13] The OLED efficacy and lifetime continue to increase over time while the cost decreases.

The white light production efficacy of an OLED luminaire can only be as high as the efficacy of the OLED panel. The other pieces of the luminaire – the power supply and electrical driver on the front end and the beam shaping optics on the back end – can only contribute additional losses. Progress in (and future targets for) the various efficiencies associated with these pieces of the luminaire (i.e., the driver efficiency, the optical efficiency) and the luminous efficacy of the OLED panel are indicated in Table 3.8.

Table 3.8 Breakdown of warm-white OLED luminaire efficiency with historical and targeted performance projections.

Metric	2019	2022	2025	2035
Panel Efficacy[1] (lm/W)	85	120	155	180
Optical Efficiency of Luminaire	100%	100%	90%†	90%†
Efficiency of Driver	88%	90%	92%	95%
Total Efficiency from Device to Luminaire	88%	90%	81%	86%
Resulting Luminaire Efficacy* (lm/W)	72	108	128	154

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

OLED luminaire efficiency improvements involve developing the optical control of the light emitted from the OLED panel. The OLED panels produce diffuse light with close to a Lambertian distribution, which is appropriate for many applications where the form factor of OLED lighting is desirable. In these applications, no external optics are added and therefore there are no optical losses in incorporating the panels in commercial luminaires. Though for luminaires that are installed above head height, glare could be reduced by adding beam shaping by the addition of external patterned films. Such films could be added externally or incorporated into internal light extraction enhancement structures. The optical efficiency of the luminaire in Table 3.8 considers the case where beam shaping is required.

OLED driver efficiency is another area that requires research to improve. The small size and low power levels of individual OLED panels create several problems in the design of efficient drivers. The limited availability of custom drivers for these power levels means that electrical losses in the control circuit can be substantial.

The key R&D challenges in OLED lighting that affect the cost and performance of OLEDs include:

1) Performance materials for stable, efficient devices (see Section 4.1.4);
2) Light extraction; (see Section 4.1.4);
3) Advanced fabrication technology; (see Section 4.2.3); and
4) Luminaire design – including optical control and drivers (see Section 4.2.3).

New technology directions to address these key R&D challenges will be discussed in more detail in the sections highlighted in the list above.

3.6.2 OLED Cost Breakdown

The two additional challenges for OLEDs, beyond improving OLED performance, are to reduce cost and to enable the production of lightweight, ultra-thin conformable panels that will lead to luminaires with distinctive form factors. Although the high production volume of OLED displays has led to substantial cost reduction for OLED production, the cost of displays for OLED TV is still around \$800/m^2, which is much higher than the long-term goal for OLED lighting. 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 \$200/m^2. This will allow luminaires to be sold in the range of \$400/m^2 to \$600/m^2. Current costs are much higher, due to the low manufacturing volume, but a path to meeting the target using traditional fabrication techniques is shown below in Table 3.9.

Table 3.9 Current status and cost targets for OLED panels produced by traditional methods.

	2019	2022	2025	2035
Substrate Area (m2)	0.2	0.2	1.2	2.7
Capital Cost ($M)	50	75	200	400
Cycle Time (minutes)	3	1.5	1	0.5
Input Capacity (1000 m2/yr)	25	60	500	2,400
Depreciation ($/m2)	400	250	80	35
Organic Materials ($/m2)	200	150	80	35
Inorganic Materials ($/m2)	600	450	200	100
Labor ($/m2)	100	80	15	5
Other Fixed Costs ($/m2)	50	40	10	5
Total (unyielded) ($/m2)	1,350	970	385	180
Yield of Good Product (%)	70	75	80	90
Total Cost ($/m2)	1,930	1,300	480	200

Notes:

- The cost of materials is separated into the organics in the active layers and inorganics in the substrates, electrodes, and light extraction layers.
- The labor costs for manufacturing, the depreciation of capital equipment, and other fixed costs are added to the materials cost to give the cost of processing each square meter of substrate.
- This cost is then adjusted to allow for the waste area on the substrate and the production of unacceptable panels.

The typical cost breakdown for an OLED panel is provided in Table 3.9 as cost per square meter. This includes the materials (organic for emission layers) and inorganic for the substrates and electrodes. The labor costs for manufacturing, the depreciation of capital equipment, and other fixed costs are added to the materials cost and then multiplied by the product yield to produce the total costs. The cost breakdowns show increases in capital cost and inorganic materials costs over time, which result in significant increases in total cost. Previous estimates likely overestimated potential and timing of cost reductions based on limited actual production data. As OLED technology has matured and production has increased, there is improved accuracy in the manufacturing cost data. If these cost projections can be achieved, then, in 2025, the yielded cost could be $480/m^2. While there is a lot of room to improve labor, depreciation, and overhead costs by having a full, high-yielding factory, significant innovation in fabrication methods will be needed to reach the 2025 targets.

4 Lighting R&D Opportunities

This section describes R&D opportunities for advancing the energy savings and functionality of lighting. Prioritized R&D opportunities will be highlighted and will have further detail provided in Section 5. The opportunities are organized within the framework of lighting application efficiency (LAE) that considers the function of lighting and breaks down the lighting system, including impacts of the lighted space, into source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness. In order to optimize the system energy savings, clear guidance is necessary as to what constitutes the optimum lighting for different lighting functions and different situations. Advancements in lighting science will provide guidance as to optimum light levels, spectral power distributions, and optical distributions for various tasks in various settings. This new guidance may not be different from current guidance, but it is appropriate to update the underlying research within the context of the new levels of control offered by SSL technology. Lighting science is needed to not only understand and guide optimum lighting conditions but also to avoid or minimize negative side effects of lighting such as glare or temporal light artifacts. Precise modeling is also necessary to understand the impacts of the space on the light as it is supplied from the luminaire and travels to the ultimate receptor (typically a human eye). Modeling can enable optimization of the various factors of lighting application efficiency according to understood trade-offs between color quality and source efficiency, for example, or optical control and source efficiency as another example. Light source efficiency is still an active R&D opportunity since there must be good efficiency to enable good efficacy or effectiveness of the light for its function per power input.

4.1 Lighting Application Efficiency

Lighting application efficiency is the new frontier in improving the next generation of energy savings from SSL projected in the DOE SSL Program Goals Scenario shown in Section 2.1. Lighting application efficiency, at its simplest, characterizes the efficient delivery of light from the light source to the lighted task. However, application efficiency can also consider the effectiveness of the light spectrum for the lighting application, and the ability to actively control the source to minimize energy consumption when the light is not being used. 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 consider the:

- Light source efficiency of the luminaire;
- Optical delivery efficiency;
- Spectral efficiency; and
- Intensity effectiveness.

Combined, these four elements could be used to describe the overall lighting application efficiency of SSL systems. While each of these performance aspects has been demonstrated, evaluated, or studied independently with SSL, they largely have not been considered holistically within a common framework. Most SSL R&D effort to date has focused on improving light source efficiency. Improvements to light source efficiency also directly enable the ability to improve optical performance, color quality, and intensity control. However, there are still trade-offs between light source efficiency, optical delivery efficiency, spectral efficiency, and delivered optical intensity. When each component of lighting application efficiency is evaluated in isolation, this limits their use and understanding within industry and represents a missed opportunity for energy savings, because holistic optimization of all LAE factors can yield energy savings beyond just improvements to light source efficiency. A holistic framework would enable the different aspects of lighting application efficiency to be considered and co-optimized for different applications. This proposed framework, shown in Figure 4.1, would also guide future R&D in lighting application efficiency to target the most impactful aspects of performance for a given application. In order to factor the energy efficiency impacts beyond improvements to luminous efficacy, and to consider lighting functions beyond vision (non-visual responses to light), all of these aspects of lighting application efficiency must be addressed.

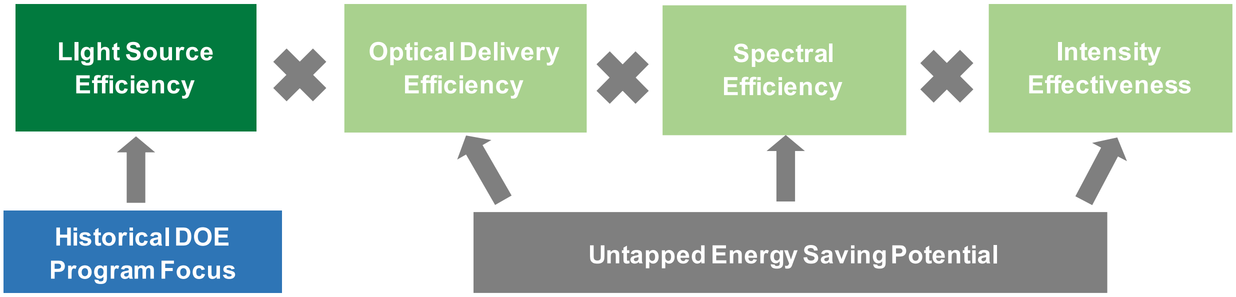

Figure 4.1 Proposed Lighting Application Efficiency (LAE) framework. Each of the four major efficiency elements are multiplied to provide the overall lighting application efficiency.

Currently, light source efficiency, at the luminaire level, is around 50% of what could be possible as shown with the luminaire losses in Table 3-5 and an ultimate CM-LED performance objective of 314 lm/W. The level depends greatly on many factors including lighting product form factor, color quality, optical distribution, and more. There are not validated estimates for optical delivery efficiency, spectral efficiency, and intensity effectiveness, but based on initial estimates only about one in a million photons emitted from an electric light source reach the eye. [14] For spectrum designed to meet basic color quality requirements, previous DOE (2015 MYPP) analyses show that the luminous efficacy of radiation (LER) for phosphor-converted LEDs could be improved from about 330 lm/W to 387 lm/W with a more optimized spectral power distribution. Optimizing this LER requires decreasing the spectral width of red downconverter materials. The LER equivalent can be calculated for any response spectrum and trade off against the performance of different practical emitters. This demonstrates the potential to improve spectral efficiency and the relationship between spectral efficiency and light source efficiency.

Often, surfaces are overlit in a space which would indicate a waste of light and contribute to occupant discomfort with glare, or areas are underlit indicating reduced productivity or functionality resulting from the light. This is the consideration of intensity effectiveness – to provide the right amount of light. Intensity effectiveness and optical delivery efficiency are related factors, and both are impacted by the optical distribution of the light and the geometry and finishes in a space. Ultimately all of the factors, or sub-efficiencies, of LAE are interdependent and full optimization for specific spaces will require a sophisticated modeling approach.

4.1.1 LAE framework R&D

In order to develop the LAE framework, significant R&D is necessary. To begin, a more substantive approach is necessary that quantifies the relationships between the different LAE sub-efficiencies. For example, existing modeling software could be used and modified to understand how changes in the optical distribution efficiency and spectral power distribution of a light source in a space affect the delivered light level and color qualities at a specific target area. This modeled, delivered light could then be compared against an optimum light level, light directionality, and color quality for a given task. Such a model could also be used to work backwards; starting with an optimum lighting condition in a target area, the model could develop co-optimized lighting product qualities (light output level, optical distribution, and color quality) and layouts and finishes for the lighted space. With this optimized understanding, informed decisions and trade-offs could then be made between different aspects of the lighting source performance, as well as design aspects of the space.

The framework and model would need to be validated in lighting mock-ups that measure the light in an area of a space and compare it against the modeled results, which could result in improvements to the model. Once the model is validated, it could be used for advanced lighting and space design. In addition to this modeling capability, a better understanding of the optimum light for different lighting functions is necessary. The optimum lighting definitions need to include new understanding of non-visual aspects of light, as well as more refined understanding of lighting optima based on updated lighting research that considers the advanced capabilities of the SSL platform. Developing the LAE understanding, framework, and associated modeling capabilities is an R&D opportunity described in Table 5.2 in Section 5.

4.1.2 Source Efficiency

LED lighting technology has improved dramatically over the past decade, and improvements in manufacturing enabled LED products to achieve a low cost enough to develop products in all general illumination applications. Despite this progress, further improvements are possible and necessary to ensure further energy savings. LED luminous efficacy 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 enable further LED prevalence, resulting in the greatest possible energy savings for the nation. OLED source efficiency has also improved dramatically over the past decade, offering a baseline and platform for low luminance light sources that are promising for larger area, lower luminance, and low glare lighting solutions that could have benefits in terms of optical delivery efficiency within the LAE framework.

The following sections explore the current status, performance improvement opportunities, and challenges for LED and OLED technologies. The key challenges currently facing these technologies also represent some of the greatest opportunities for performance gains.

4.1.3 LED Source Efficiency

This section covers efficiency contributions of both the LED package, which creates the white light, and the LED luminaire, which houses the LED package and provides the appropriate interface between the electrical supply, mechanical integration, thermal handling, and optical distribution.

4.1.3.1 Materials and Devices

Two common architectures for generating white light will be the focus for the discussion in the following sections: the PC-LED based on a blue LED pumping yellow and red wavelength optical down-converters (typically phosphors) to produce white light and the 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 4.2, with the corresponding optical spectral distributions of these white LED architectures shown in Figure 4.3.

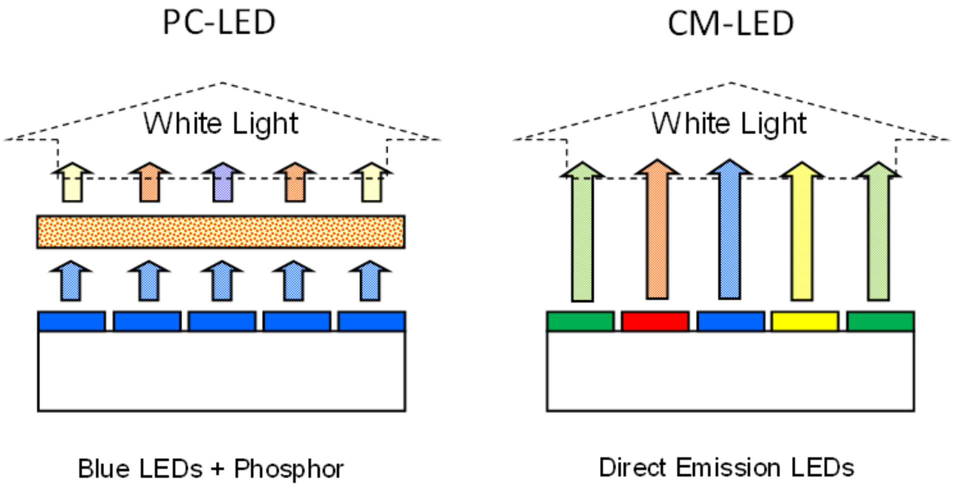

Figure 4.2 Schematic of two main white LED architectures. (a) The phosphor-converted (PC) LED uses blue LEDs to pump yellow and red down-converters; (b) the color-mixed (CM) LED uses different color direct emission LEDs and mixes the colored light to create white emission.

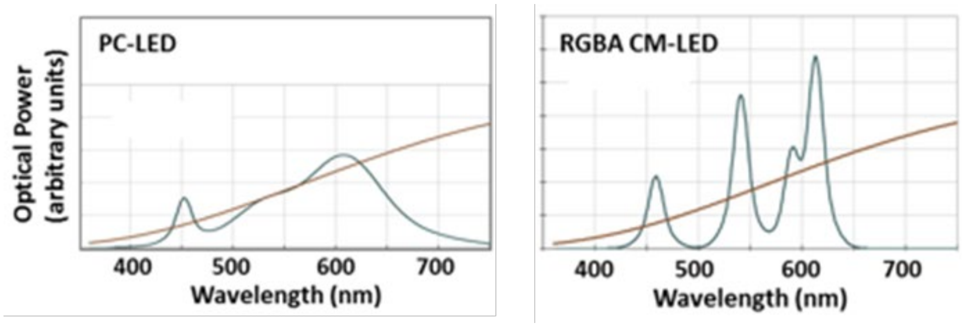

Figure 4.3 Typical simulated spectral power density for white-light LED package architectures. In both the PC-LED and CM-LED, the peak wavelengths and relative intensities are those which maximize LER for a 3000 K CCT (warm white), a "standard" CRI Ra of 80 and a CRI associated with the ninth, deep-red Munsell color sample R9 >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 3000 K.

The PC-LED architecture is the dominant white light architecture used for LED lighting today. 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 4.4 shows a history of the luminous efficacy of PC-LEDs since the DOE Lighting R&D Program began and the progress that has been made. It is important to note that the listed operating conditions for qualified data points may not correlate to operating conditions used in all LED lighting products, particularly with the trend of lower drive currents to minimize current density droop and thus maximize luminous efficacy. Nevertheless, using a standard operating 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 technology developments in emitter efficiency (including the reduction of current density and thermal droop) and down-converter performance.[17]

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 wavelengths to maximize spectral efficiency) and package efficiency (optical scattering/absorption). 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 4.4, luminous efficacies of approximately 255 lm/W at the prescribed operating conditions 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 greater breakthroughs in the 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 (known as the 'green gap'). Panel (b) of Figure 4.4 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.

In addition, Table 4.1 shows historical and projected LED package efficacy for warm white and cool white phosphor-converted and color mixed LEDs.

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[17] For additional details regarding the specific operating conditions by which LED products are evaluated, see the notes described within Figure 4.3.

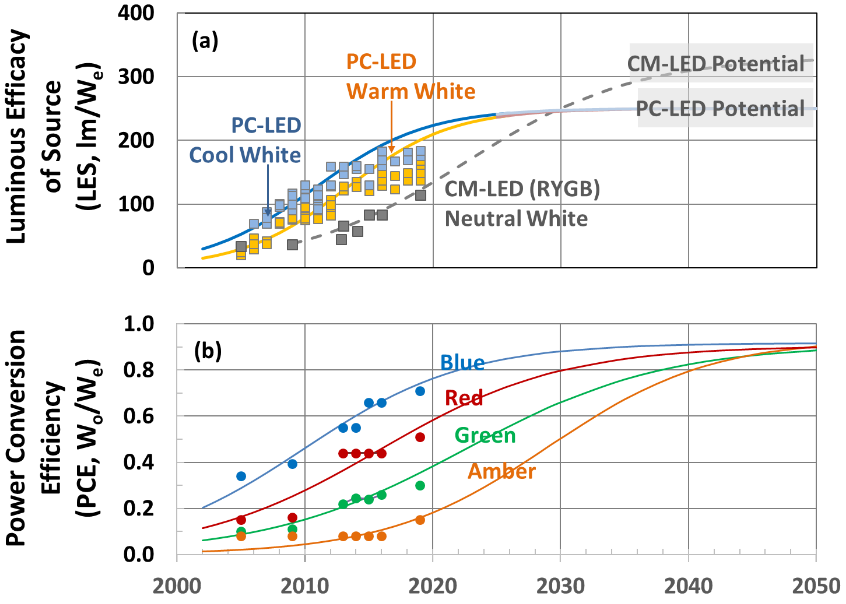

Figure 4.4 Efficacies and efficiencies over time of white and colored LED packages.

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 (3000-3500 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 (We) 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 Wo/We.

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 4.1 Phosphor-Converted and Color-Mixed LED package historical and targeted efficacy.

Metric	Type	2019	2022	2025	2035	Final Goal
LED Package Efficacy (lm/W)	Cool White	184	232	241	249	250
	Warm White	168	223	237	249	250
	Color Mixed	114	158	196	288	325

4.1.3.1.1 Emitters

While LED emitter materials have improved rapidly over the past decade, there are still key technological challenges that are limiting further improvement. As described above, the impact of droop in LEDs limits performance at higher operating currents and temperatures. Additionally, the low efficiency of green and amber direct emission LEDs constrains the performance of color-mixed LED systems. This section will describe the current status of droop and the ‘green gap’ and discuss current approaches to reduce these performance barriers. In addition, the performance of red LEDs will be discussed.

Current Density Droop

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 this has only been achieved 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 area, thereby improving optical performance and/or reducing the cost per lumen of LED lighting products.

There are different physical mechanisms that impact efficiency at different current densities, as indicated in Figure 4.5. 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. [15]

The amount of Auger recombination is controlled by the carrier density in each quantum well (QW) of the LED active region, 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 4.5. The challenge is that the improved heterostructure leading to uniform carrier injection in 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 balancing the material quality with improved heterostructure design for carrier transport to reduce the current density droop further. [16]

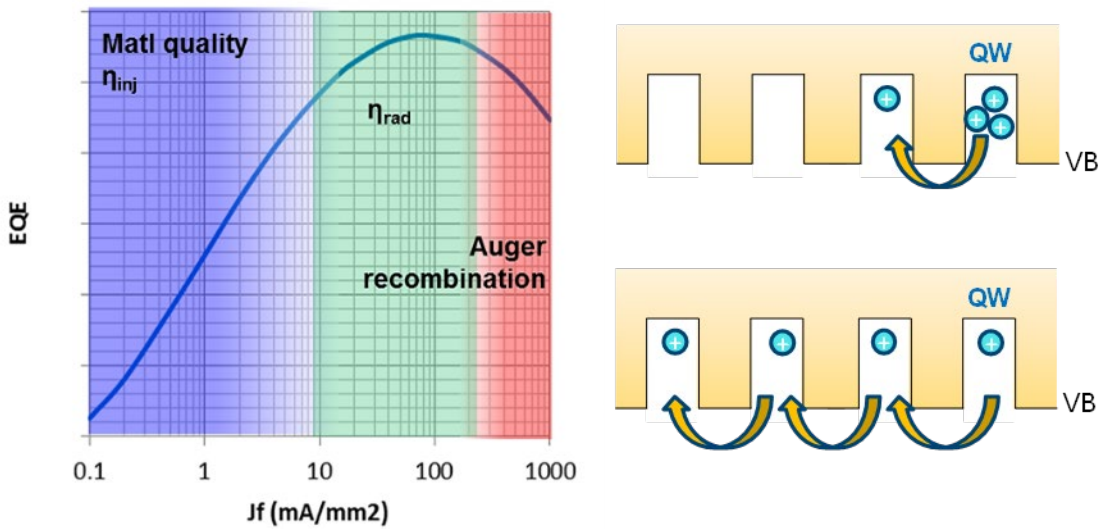

Figure 4.5 Blue LED external quantum efficiency (EQE) vs. current density (left) and schematic of LED quantum well (QW) valence band (right). [17] The shaded regions of the graph indicate the dominant carrier recombination modes. The schematic of the QW valence band shows the carriers piling up in the p-side QW (top right) and showing uniform hole injection (bottom left).

Green Gap

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. [18] This phenomenon is known as the 'green gap' and is illustrated in Figure 4.6. The low efficiency of green LED is particularly critical, since ultra-efficient white LEDs based on color mixing require a green LED emitter with a wavelength around 540 nm – near the center of the 'green gap.'

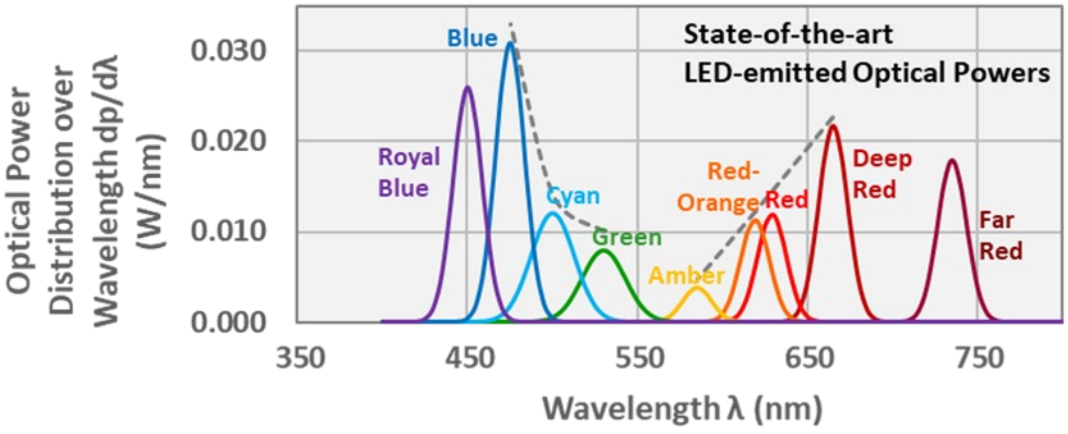

Figure 4.6 Spectral power densities of state-of-the-art commercial LEDs vs. wavelength. The dashed lines are guides to the eye, illustrating the "green gap": the decrease in efficiency from the blue to the green-yellow and from the red to the green-

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 (material quality 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 4.7 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 the 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. [17]

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 hurdle 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.

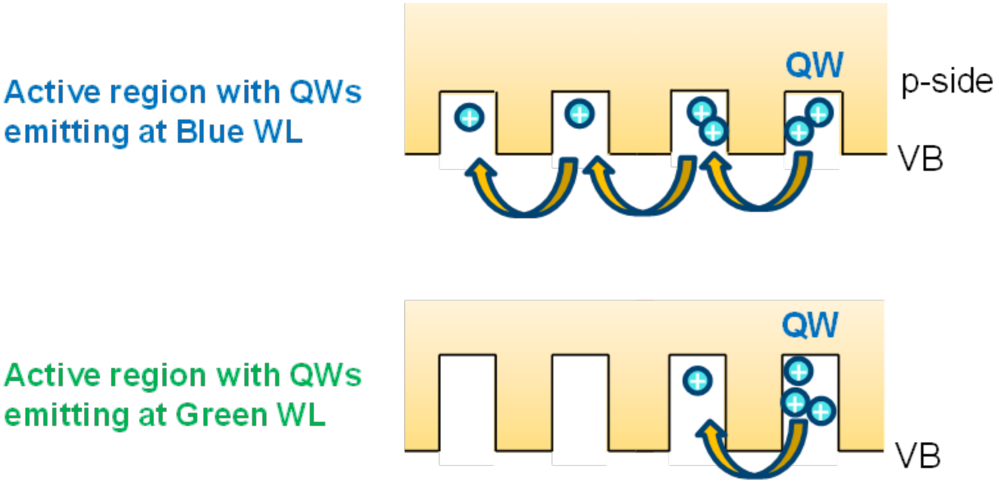

Figure 4.7 Schematic of the LED quantum well valence band in a blue LED (top) and a green LED (bottom). [17] Notes: Schematic of the quantum well valence band of an LED showing carrier distribution in today's state-of-the-art blue LED QW active region (top) and the carriers piling up in the p-side QW for a green LED active region (top right) and showing uniform hole injection (bottom).

Advances in Red LEDs

While there has been much emphasis in improving the green gap performance of LEDs, good progress has been made in improving the efficiency in red LEDs. Horticultural applications require improvements in the deeper red regions, both at 660 nm (commonly referred to as 'deep red') and between 700-800 nm (called 'far red') to seed germination and vegetative growth. The growing demand for horticultural lighting and the importance of the red spectrum for the growth of plants has led to renewed efforts in improving the efficiency of red LEDs. The increase in power conversion efficiency (also called wall plug efficiency) for AlGaInP LEDs as a function of emission wavelength over the past few years is shown in Figure 4.8. At wavelengths above 600 nm, the PCE for red LEDs at a current density of 45 A/cm2 has improved between 10-20% since 2015, with the largest gains coming at the longer wavelengths.

The PCE improvements in AlGaInP red LEDS came from improvements in the LED materials and device design. Multiple facets of the LED performance were addressed to achieve these new wall plug efficiencies. Improvements in the epitaxy included optimizing the materials growth to reduce absorption and improve the current spreading with the heterostructure design. The device design optimization required improvements in the texturing and micro-prism pattern design to improve light extraction. In addition, improvements in the n-contacts and the metal and dielectric mirror contacts on the p-side led to device performance improvements. These red LED improvements are illustrated in Figure 4.9.

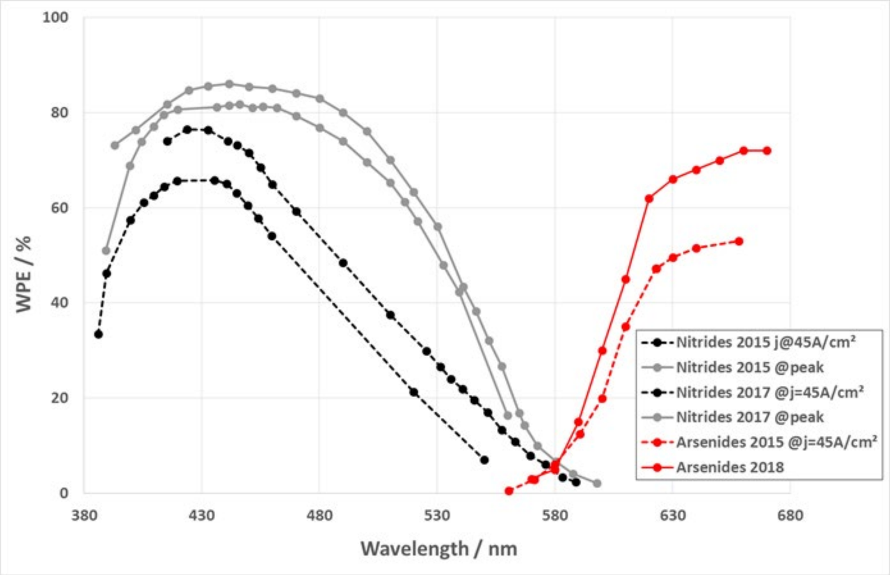

Figure 4.8 Progress in wall plug efficiency (WPE) of LEDs as a function of wavelength. [19] The red points show the improvement in wall plug (power conversion) efficiency at a current density of 45 A/cm² for AlGaInP (arsenides) LEDs from 2015 to 2018. The wall plug efficiency improvements for InGaN (nitrides) LEDs are shown between 2015 and 2017 for peak operation (gray points) and 45 A/cm² current density (black points).

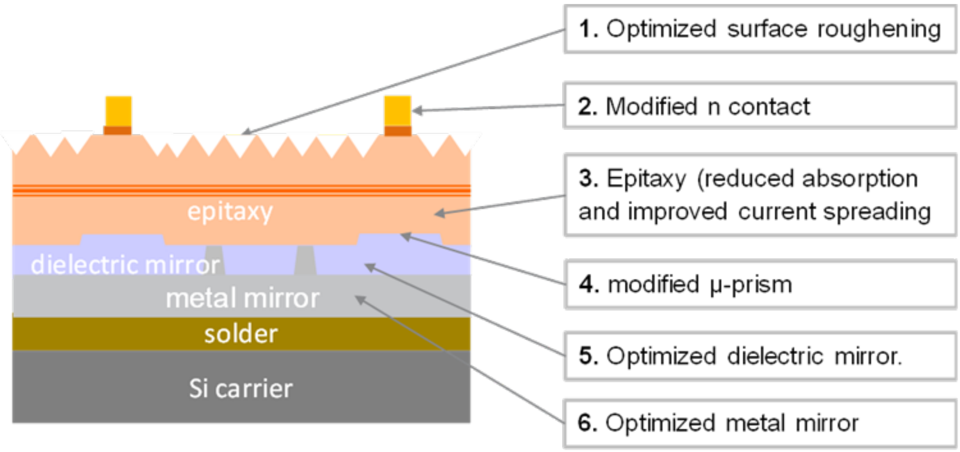

Figure 4.9 Schematic of red LED device and the improved aspects of the chip leading to improved wall plug (power conversion) efficiency. [19]

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 4.10 shows some typically thermal droop behavior for various color LEDs.

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 one university 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. [20] New InGaN LED heterostructure designs are needed that can minimize the carrier overshoot at elevated temperatures while maintaining material quality and high efficiency.

Thermal droop in AlGaInP LEDs is much greater than in InGaN LEDs. This is due to the material 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.

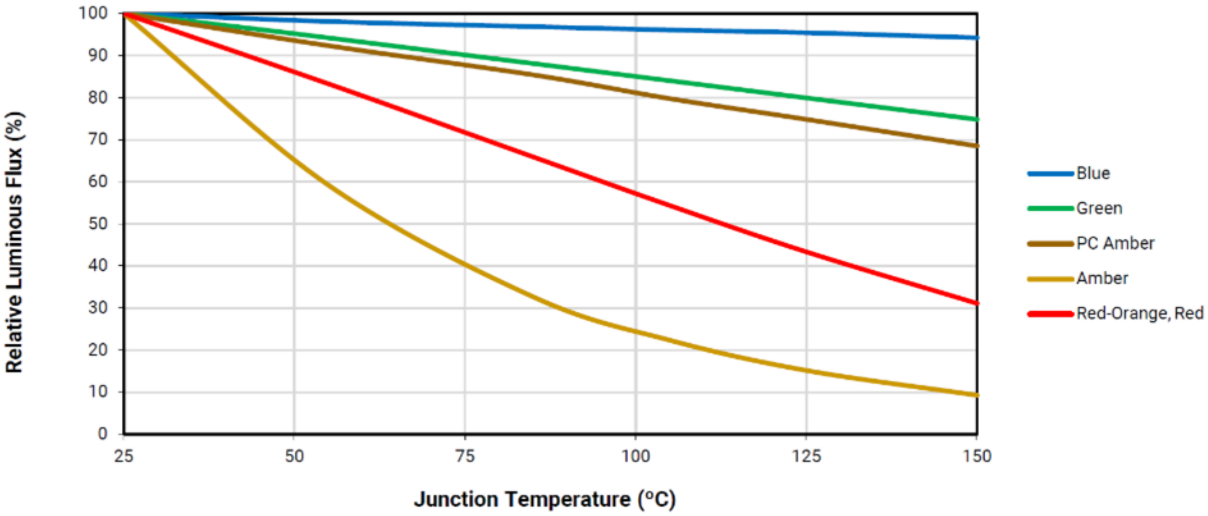

Figure 4.10 LED efficiency as function of junction temperature. [21] The thermal droop is seen as the LED efficiency declines as junction temperature increases. AlGaInP and AlGaAs LEDs experience the greatest thermal droop.

4.1.3.1.2 Wavelength Downconversion

State-of-the-art LED lamps and luminaires are predominantly based on phosphor-converted LEDs. The phosphors used in these PC-LEDs result in an emission with broad linewidths, which in turn limits their overall spectral efficiency or 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 achieve optimal energy savings of 90 CRI, PC-LEDs for lighting.

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 4.11 illustrates this behavior by comparing a white LED using a 110 nm FWHM broadband red phosphor with a CCT of 3000 K, a CRI ≥90, and an R9>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). [22]

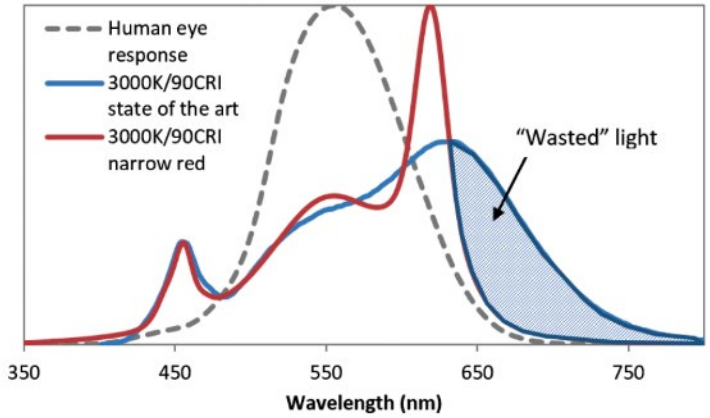

Figure 4.11 Spectrum comparison of a 90 CRI PC-LED with conventional phosphors (blue), a 90 CRI PC-LED with a narrow-band red phosphor (red), and the human eye response curve (dashed). [22] A narrow-band red down-converter will improve the spectral efficiency by reducing the wasted emission in the deep red and infrared portion of the spectrum.

There have been recent developments in the field of narrow red down-converters. One manufacturer continues to release lighting products that feature its narrow red phosphor, "KSF."[18] [23] 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 4.12. [23] Similarly, another manufacturer has commercialized mid-power LED packages that use its "SLA" phosphor to provide narrow red emission and enable good color quality and high efficacy.[19] [22]

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

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

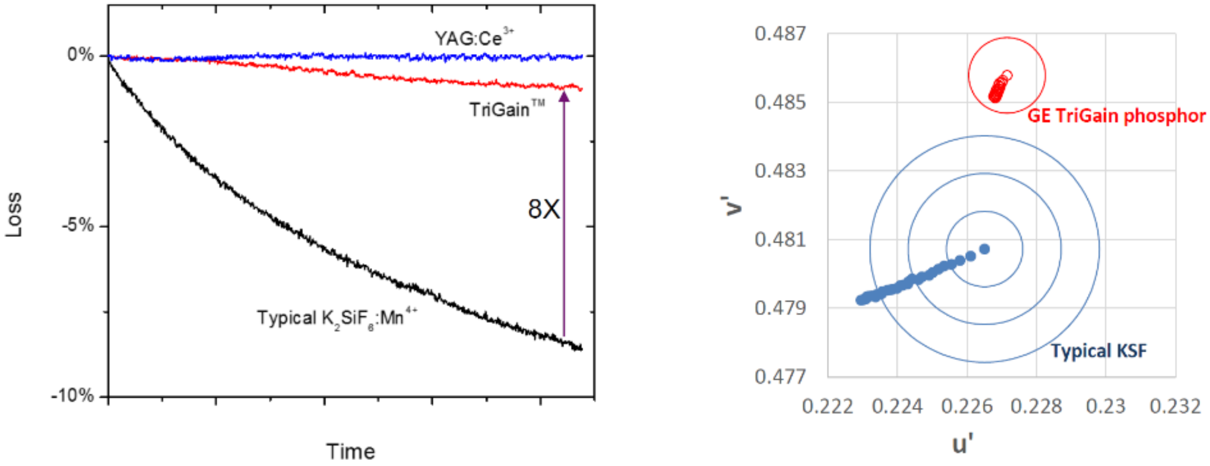


Figure 4.12 Light loss of phosphors in LED packages under high blue flux densities (left) and color shift under stressed operating conditions (right). [23] The TriGain KSF narrow-band red phosphor has shown improved stability under blue flux densities over the past several years of the earlier KSF phosphors, which will lead to better white LED stability.

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 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 operate at higher fluxes and temperatures.

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 progress to commercialize a mid-power LED package using red QD down-converters (combined with phosphors). [24]

As with narrow-band phosphors described above, 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. [25] 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. [26]

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 less than 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. [27] This ROHS limit on Cd does not allow for enough QD material to be applied on the LED chip to generate a sufficient red spectral peak needed for warm white light emission. Therefore, the QD LED products on the market today require that the QDs be blended with red and yellow phosphors to provide the required spectral peak content for warm white LEDs.

While Cd-containing QDs provide the best performance to date, there is still the need to develop alternative Cd-free QDs due to the regulatory requirements on Cd use. The most advanced Cd-free QD technology is currently InP-based QDs, which is the dominant QD system for display applications. Currently the FWHM of the emission and environmental stability of InP QDs 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. [28] 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 Cd-free QD systems include 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 4.13. 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. [29]

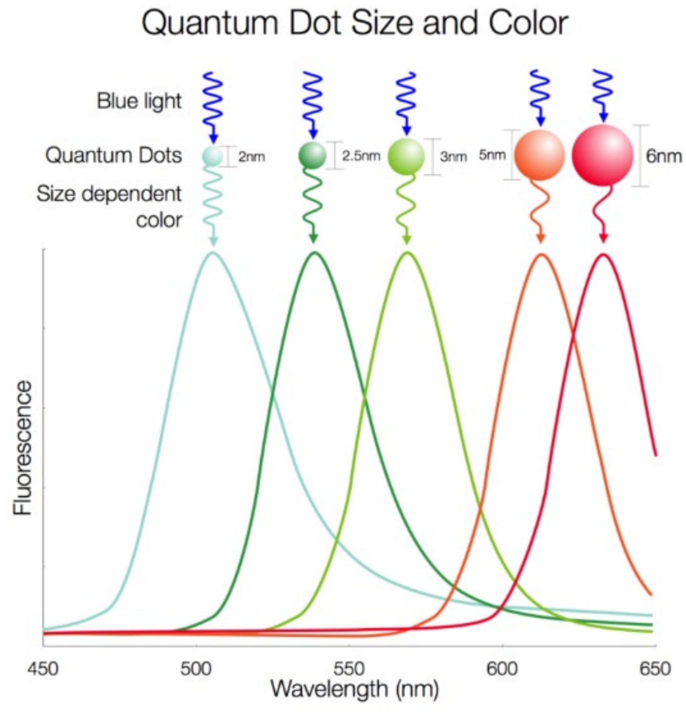
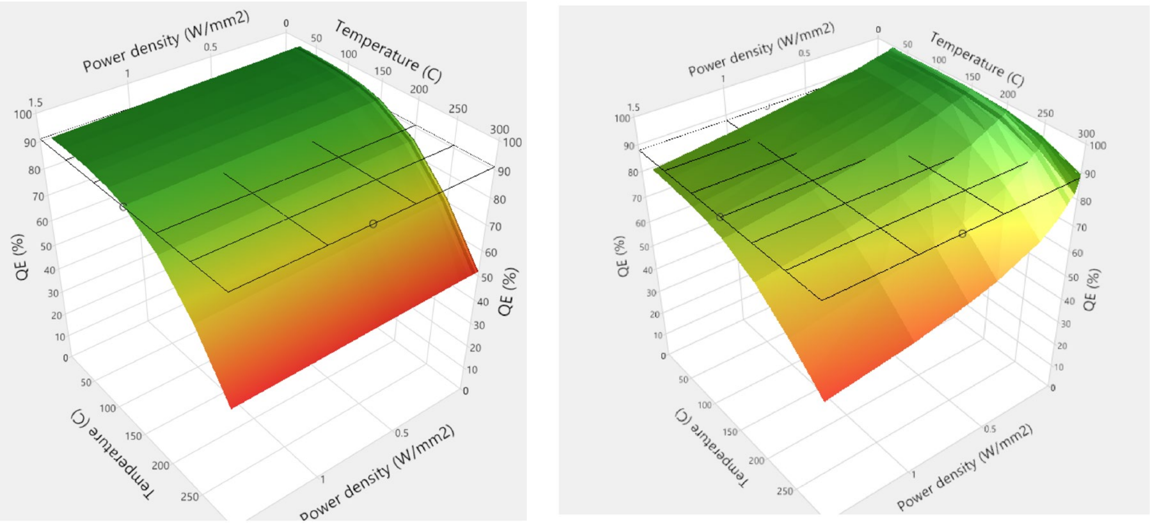


Figure 4.13 Emission wavelength of CdSe QDs as a function of dot diameter. [28] As the diameter increases, the emission wavelength of the QD increases.

QDs for on-chip LED application have made remarkable advancements over the past few years. CdSe-based QD technology has progressed to the level of commercial viability in LED package products with improved stability behavior. [24] 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.

4.1.3.1.3 High Luminance Down Converter Materials

Some lighting applications require a considerable amount of light delivered by a small illumination form factor, such as spot lighting, which can be important for improved optical delivery efficiency. These high luminance applications require more extreme optical flux densities hitting down-converters, which often results in performance and stability problems. Improved materials properties are required to allow phosphors and QDs to withstand these flux densities and the heat resulting from the down-conversion process (Stokes loss). Currently, phosphors are considered the most promising materials for high luminance applications, since QDs still struggle at the conventional high-power LED current densities of 1 optical watt/mm^2. The photothermal stability for the typical YAG:Ce broadband yellow phosphor is quite suitable for the broad range of high luminance LED architectures. The photoquenching is minimal in YAG and most of the efficiency droop is due to thermal quenching. [30] The photothermal stability of garnet-based phosphors is shown in Figure 4.14 and is compared to that of the typical nitride red phosphor implemented for warm white LEDs. The red phosphors suffer more photothermal instability, which limits high luminance warm white LED performance.



Typical Garnet Phosphor

Typical Nitride Phosphor

Figure 4.14 The quantum efficiency of a typical garnet phosphor (left) and nitride phosphor (right) are shown as a function of temperature and optical power density. This figure shows the quantum efficiency as a surface with a mesh is added as a guide at the DOE 2025 target QEs for phosphor materials. The garnet phosphors are relatively insensitive to photoquenching but are impacted by thermal quenching at high temperatures. On the other hand, nitride phosphors are impacted by both photo and thermal quenching which impacts performance at high luminance operating conditions (high optical power density and temperature).

Engineering the phosphor formulation can help address the photothermal quenching, though in some cases it leads to trade-offs with other materials properties. Photosaturation may be minimized by lowering the activator concentration, as seen in the (Ba,Sr)2Si_5N_8:Eu (BSSN) phosphor. [31] Using a lower Eu concentration improves the efficiency, but the overall amount of the material in the LED package will increase, thus raising the product cost. The band structure of the host lattice is also critical for engineering photothermal quenching. If the excited state is too close to the conduction band, it will show stronger thermal quenching, resulting in a lower quantum efficiency. [32]

As SSL sources for high luminance lighting moves to even higher optical power densities, such as with laser lighting, the photothermal degradation of the down-converters becomes more severe. YAG phosphors can be combined with blue InGaN lasers to create cool white light that is currently being used in applications such as automobile headlamps or architectural lighting. The red phosphor material performance limits the ability to use extremely high luminance laser lighting to create warm white light for these applications. R&D into new host materials for red phosphors is important to realize high luminance warm white sources.

4.1.3.2 Chips and Packages

4.1.3.2.1 Advanced LED Architectures for Droop Mitigation

Advanced LED device architectures have the ability to improve efficiency or improve the device 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.

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 previously in this section. This reduces droop; however, manufacturers have discovered that it is 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. With LDs, droop is eliminated when lasing occurs; 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 high current density operation. LDs have clamped charge carrier density, so droop does not exponentially increase at higher operating currents; however, with lasers there is also a trade-off between peak efficiency, thermal losses at high currents, and droop reduction. Researchers are working on both the efficiency of lasers and ways to integrate them into a broad range of practical lighting products.

As seen in Figure 4.15, an interesting insight involves the “valley of droop” – this is the region of current density which is high enough that significant LED droop occurs, but it is low enough that laser diodes do not yet lase. 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; and if lasers could be driven that “soft” while still lasing, resistive losses would be lower and their efficiencies higher.

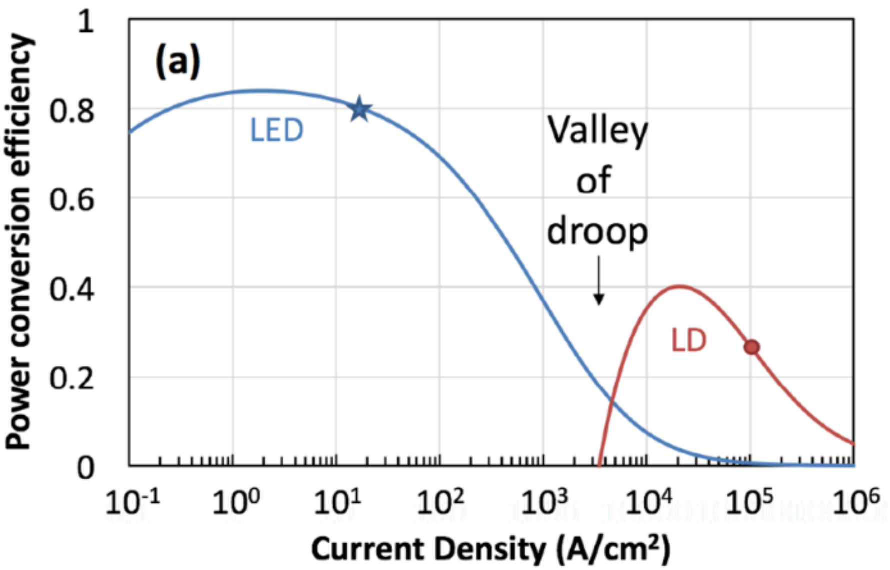


Figure 4.15 Power conversion efficiency vs. current density for a state-of-the-art LED and laser diode (LD) emitting at violet wavelengths. [33] This plot highlights the 'valley of droop' cross-over between the two light source types.

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 are becoming more economical. Thus, it is of interest to continue to increase peak efficiencies for low current density operation. 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 power conversion efficiency of the LD from the current 30-40% range to 60-70% (i.e., 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 4.16.

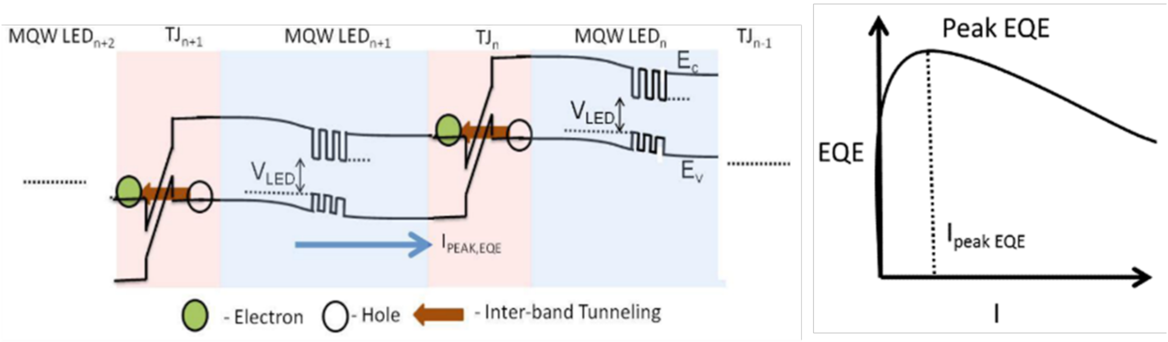


Figure 4.16 Schematic band diagram of a stacked active region LED with tunnel junctions (left) illustrating the tunneling effect of carriers. The external quantum efficiency at the peak LED operating current shows the tunnel junction LED operating at the peak EQE range while generating more light from the multiple stacked active regions. (right) [34]

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 is a remaining hurdle to overcome.

4.1.3.2.2 High Luminance

While improving the efficiency of emitted light from an LED has been a strong 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 significant role in the efficacy of a light source. The ‘harder’ a light source is driven, 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 the lumen emittance increases, the 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, package/luminaire optics can be smaller given the presumably smaller size of the illuminated area. Therefore, 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 previously, it also causes a trade-off between luminous efficacy and luminous emittance. Figure 4.17 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 LD white light package (bright green text).

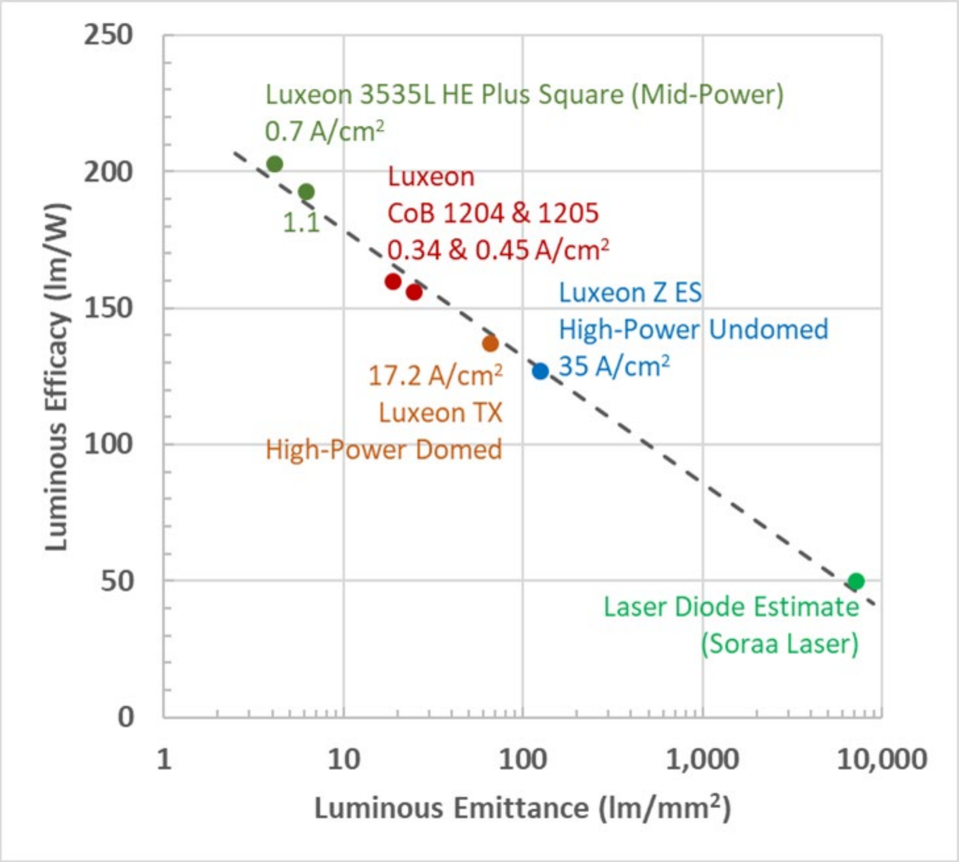


Figure 4.17 Luminous efficacy vs. luminous emittances for state-of-the-art commercial white LEDs. There is a performance trade-off between luminous efficacy and luminous emittance in today's LEDs.

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:

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

This equation shown above 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 4.17. Research directions 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.

4.1.3.2.3 LED Size Effects

Micro-LEDs have been an area of great interest and innovation for displays using a much higher pixel density to achieve high resolution, wide color gamut, high dynamic range (contrast), long lifetimes, and lower power consumption. In addition, micro-LEDs have provoked interest in automobile lighting to create an illumination and display feature that can serve as conventional vehicle lighting and also communicate messages to those around the vehicle, which is especially important in autonomous vehicles. While the market interest is strong, there are several technical challenges that must be overcome to commercialize micro-LED technology.

Advances in the placement processes is an area of research with a variety of approaches being pursued, including mass parallel transfer and rapid pick and place schemes. In addition to developing a placement process to move large number of die, the LED supply chain also must innovate to provide high performing micro-LED die for the application requirements.

Micro-LEDs are generally described as having a size of 50 µm or less. The challenges that occur when moving to these small dimensions is that the EQE of LEDs can drop rapidly with chip size. As the LED device becomes smaller, the perimeter to area ratio becomes larger. The issue with having more perimeter is the sidewall damage that can occur during device formation can lead to nonradiative recombination. With smaller devices, the carriers can have sufficient surface recombination velocity to reach the edges more readily, which leads to more SRH nonradiative recombination that decreases the LED's EQE. The effect is more dramatic in the AlGaInP materials systems since it has a higher surface recombination velocity and also a higher minority carrier diffusion length than the InGaN materials systems. [35] [36] In addition, as the size of the LEDs becomes smaller, the current density increases, which can result in higher current density droop. The impact of the LED device size on EQE in InGaN does differ between research groups. More research is needed to identify the differences in observed EQE scaling behavior as a function of micro-LED size.

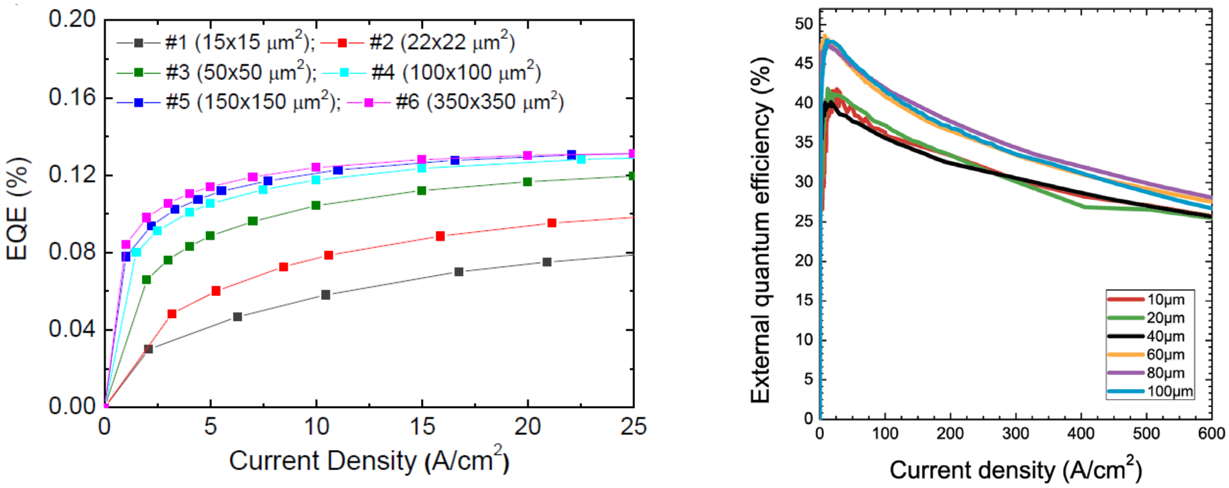


Figure 4.18 External quantum efficiency (EQE) curves for six different sizes of AlGaInP LEDs (left) and six different sizes of InGaN LEDs (right) as a function of current density. [35] [36] As the LED size is reduced, the EQE drops due to the ease of carriers reaching the LED sidewalls resulting int nonradiative recombination.

The other challenge with small die is that the conventional manufacturing and die measurement techniques cannot be performed in the same manner. Typically in die manufacturing, each LED is measured for electrical and optical characteristics, binned, and then transferred onto a sorted die sheet specific to a particular performance bin. When moving to die that are smaller than the typical bond pad size on conventional small LED die, the conventional LED testing and binning approach is no longer viable. Until industry can solve the issues with die placement processes and outgoing micro-LED testing and die carrier form factor, mini-LEDs have instead filled the gap for display applications. Mini-LEDs are typically 100-200 µm in size and fall in the size range between conventional small LED die for packages and micro-LEDs. The benefit of mini-LED die is that they utilize the existing supply chain in terms of die manufacturing, testing, and binning, but they provide a better pixel density than using LED packages for backlighting. Mini-LEDs are leveraging new modified pick and place equipment designs that can place the LEDs more accurately and rapidly than conventional pick and place tools used in LED packaging today. Many leading display companies have shown demonstrations of mini-LED displays this year at the Consumer Electronics Show with improved performance in resolution, color gamut and dynamic range.

4.1.3.2.4 Advanced Package Materials

The performance of PC-LEDs depends not only on the LED chip, but also on the rest of the packaging materials. The properties of the encapsulant impact the resulting thermal and optical properties of the LED package. The low thermal conductivity of current silicone encapsulants (~ 0.2 W/mK) can lead to heating of phosphor particles and rapid degradation of conversion efficiency when the LED is driven under high current conditions. The Stokes losses from the conversion of blue to white light result in 20% to 30% of the absorbed pump energy to be lost as heat. The resulting heat from the phosphor particle reduces its efficiency if it cannot be conducted away by the surrounding encapsulant. Increasing the thermal conductivity of the encapsulant to 1 W/mK can lower the phosphor layer temperature by 50°C or more, which can lead to phosphor efficiency improvements of 10% or more during standard operating conductions of the LED package, as seen in Figure 4.19.

Increasing the refractive index of LED encapsulants can also improve the light extraction out of the package, thereby leading to higher efficiencies. The higher the refractive index, the more light that can be coupled from the chip. Methods to increase the refractive index involve adding more phenyl end groups to the silicone molecular backbone (phenyl-based chemistry) compared to the methyl-based silicones. The methyl silicones used in blue LED packages have a refractive index of 1.4; phenyl silicones commonly used in white PC-LED packages have a refractive index of 1.55. There is a practical limit to adding phenyl end groups; when too much phenyl content is added, the stability of the silicone decreases under LED optical flux densities and temperatures, essentially creating an upper limit at the 1.55 refractive index available today. [37] Adding high refractive index nano-fillers such as titania or zirconia have potential, though their integration into the polymer chains is critical for performance and is still an area of intense research.

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

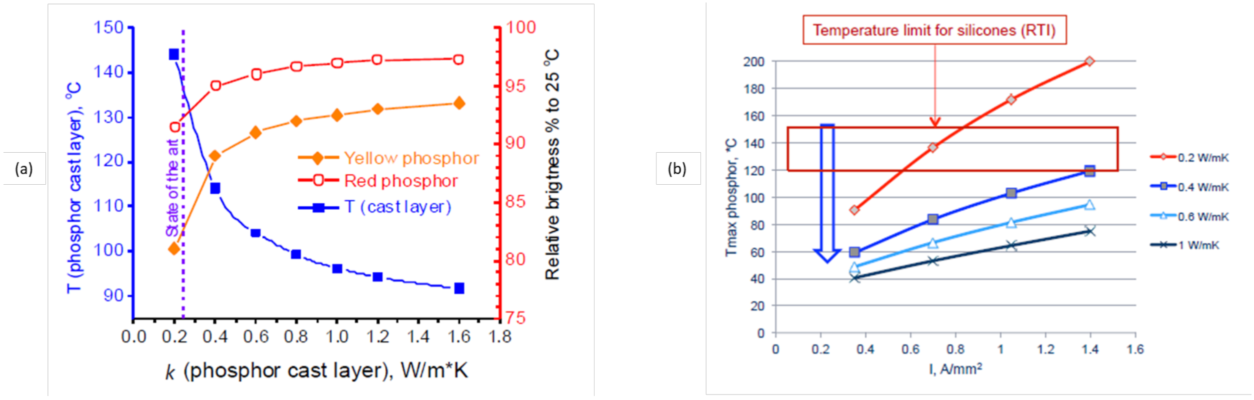


Figure 4.19 The temperature of the phosphor layer as a function of thermal conductivity and the impact to the relative brightness of LED phosphors and (b) the temperature of the phosphor layer decreases with increasing thermal conductivity of the encapsulant. [38]

4.1.4 OLED Source Efficiency

OLED lighting represents an opportunity for low luminance, diffuse, thin, large area lighting that can be placed to occupant and close to the illuminated area, which can have benefits in optical delivery efficiency. As discussed in Section 3, OLEDs continue to improve in luminous efficacy and offer commercial promise.

OLEDs also offer the possibility of being compatible with low cost roll to roll or printed manufacturing approaches. Other technologies can be employed for low luminance lighting. Edge coupled LED lighting products are on the market that can be thin and diffuse with good efficacy. These products do suffer from additional optical losses and may ultimately be limited in thickness compared to OLEDs. There are also other possible emitter materials that could work within the OLED device architecture, such as electroluminescent quantum dots or perovskite materials. However, these materials will need to clearly demonstrate the possibility of catching up to and surpassing all aspects of OLED performance.

4.1.4.1 OLED Materials

With OLEDs, light is created within the organic layers by the formation of excitons through electron-hole recombination and emission of radiation. The keys to efficient light production are to ensure that the energy from both singlet and triplet excitons leads to photon emission and that the flow of electrons and holes to the recombination region is balanced.

OLEDs with state-of-the-art phosphorescent emitters can be very efficient. Internal quantum efficiency levels approaching 100% have been demonstrated. However, the stability of phosphorescent blue emitters is insufficient for commercial panels. Fluorescent emitters are more stable, but these lead to radiation only from singlet excitations, so that well over 50% of the energy is lost. Attempts are underway to harness the triplet energy through thermally activated delayed fluorescence (TADF), as described in the following discussion.

To improve the stability and efficiency of devices while also reducing costs, various alternative materials approaches are being explored. Emitters exhibiting TADF have gained the most ground in recent years. This technology attempts to harness both singlet and triplet excitons to generate highly efficient and stable emission through fluorescence pathways. In molecules where the triplet energy is close to the singlet energy, thermal upconversion of the triplets to singlet states can theoretically allow for 100% IQE, as shown in Figure 4.20. Researchers have developed sky blue (CIE = 0.37) TADF materials with an EQE of 22% and a lifetime (L50) at 1000 (cd/m2) of greater than 1500 hours. [39] [40] They have also reported a deep blue (CIE = 0.14) emitter with an EQE of 20% and a lifetime (L97) at 700 (cd/m2) of 20 hours.

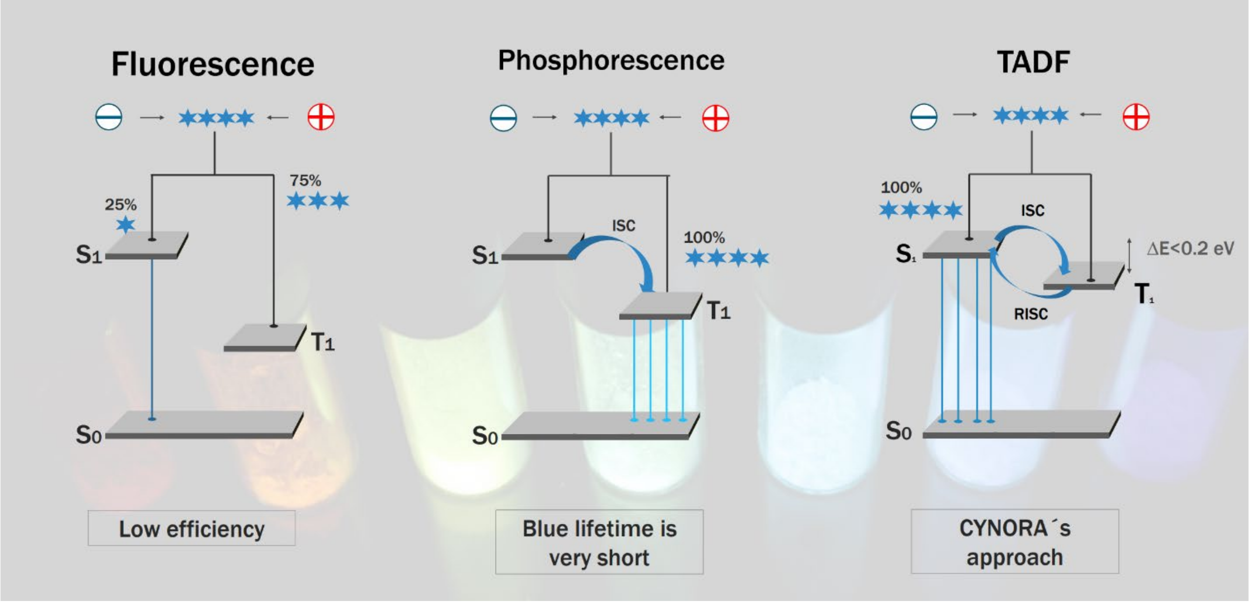


Figure 4.20 Illustration of TADF as compared with fluorescent and phosphorescent approaches. [41] Figure shows different OLED light emission mechanisms. Fluorescent emission is stable but inefficient. Phosphorescence allows for both singlet and triplet emission and can approach 100% IQE. Thermally activated delayed fluorescence enables upconversion of triplet excitons to singlet excitons and can theoretically reach 100% IQE.

A further extension of the TADF approach has been suggested 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 4.21. 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."

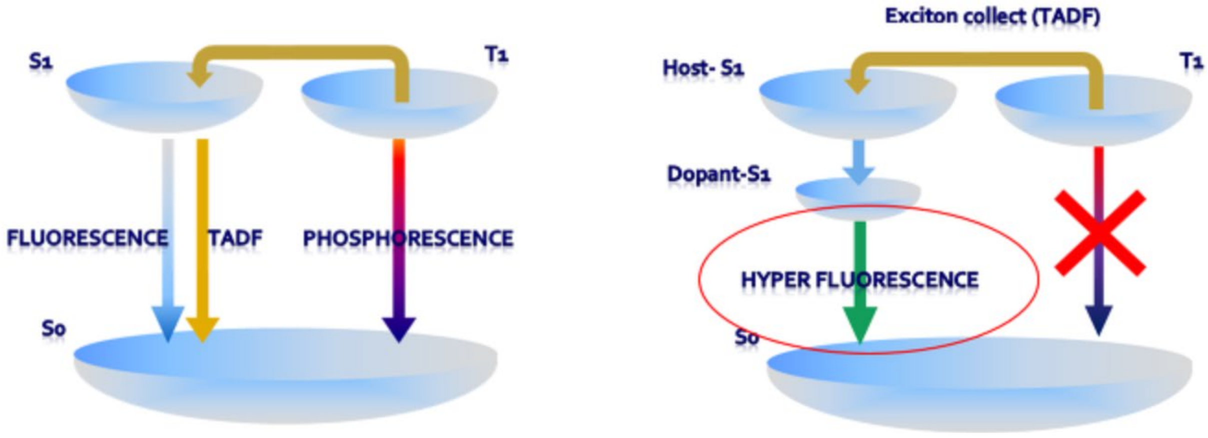


Figure 4.21 Comparison of the mechanisms of TADF and hyperfluorescence. [42] Through the use of TADF and fluorescent dopants, triplet excitons are formed but transfer to the singlet state of the fluorescent emitter and recombine more rapidly. The left portion of the figure shows typical TADF recombination mechanisms. The right portion of the figure shows the TADF recombination mechanisms where transfer efficiency is improved and recombination lifetime is reduced, resulting in increased singlet recombination.

The initial objective of hyperfluorescence was to develop commercial red, green and yellow emitter/host systems, but blue hyperfluorescent results have been reported as well. Recent achievements include blue (470 nm wavelength) with lifetimes (L95) at 1000 cd/m^2 of 200 hours and an EQE of 22% at 1000 cd/m^2. Hyperfluorescent technology is also being researched by European and Asian research groups and through a DOE Lighting R&D funded project. [39] [40] The DOE project has published findings related to: the impact of dimerization and aggregation on TADF device color purity; kinetic modeling of transient photoluminescence from TADF; and enhancement of optical and electrical performance of TADF by dilution in an inert host.

While they provide a high efficiency 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 increase 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). To overcome lifetime issues in these molecules, emitters must be designed to have short radiative emission lifetimes. Researchers have developed new copper-based TADF OLED emitter compounds that emit throughout the visible spectrum, demonstrate PL yield approaching unity, and have lifetimes around 1 microsecond. [43] Another approach to longer lived devices is to use TADF molecules 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.

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. There are several efforts to improve host materials as well as develop higher performance stacks through better transport materials.

While efficiency and stability improvements are necessary to reach the performance milestones for OLED lighting, progress towards cost metrics can be achieved through reducing the cost of materials or manufacture of OLED active layers. One approach is to simplify the OLED device architecture, minimizing the number of dopants, layers, processing time, etc. 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. [44] Efforts are underway under another DOE-supported project to explore this opportunity. [45] Recent results for yellow-green devices showed a maximum EQE of 21% and power efficacy of 79 lm/W at 10 cd/m2. Similarly, a single layer, green-yellow TADF device was made using a diboron-based TADF material which exhibited low operating voltage (2.9V @ 10,000 nits), high EQE (19% @ 500 nits) and lifetime of 1,880 hours (L50 for 1,000 nits). [46]

In another DOE Lighting R&D project, researchers are working to develop white light from single emissive dopants. Through intricate design, the team uses novel blue emitter materials that, when in proximity of each other, interact to form excimer emission in the orange spectrum. With optimum doping concentrations, the emission ratio of monomer (blue) to excimer (orange) can be tailored to achieve white light. [47] Yet another approach to decrease manufacturing cost and complexity is to use OLEDs with thick layers of hybrid perovskite materials. The thick (~2000nm), current-spreading perovskite layers help to smooth substrate defects and prevent shorting through layers. [48] [49]

4.1.4.2 Light Extraction

Light 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 the 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. Electroluminescent quantum dots or perovskite materials will likely employ a similar architecture as OLED devices, using similar organic charge injection, transparent conductor, and substrate materials, so light extraction limitations are expected to be similar.

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 with EQEs >40%. Advancements in light extraction, together with refining the stack, minimizing absorption, 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 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 40%, leaving ample room for improvement and energy efficiency gains. Many approaches are being explored, including: 1) internal 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 to enhance light outcoupling and minimize absorption and losses to surface plasmons. 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.

4.1.4.2.1 Scattering Layers

Some commercial products have incorporated scattering layers between the transparent electrode and substrate. There are materials for light extraction films which comprise nanoparticles of ZrO_2 to achieve a high index polymer matrix and larger TiO_2 particles which act 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.

A key issue with this approach is the introduction of additional layers and materials to the device. Any internal extraction films must be stable and compatible with subsequent OLED manufacturing. If polymeric hosts are used, steps such as patterning must be taken to prevent the ingress of water and oxygen through the extraction layer to the device and thorough drying procedures must be completed to drive out any moisture or solvents. Furthermore, low temperature tolerance of polymer layers can limit the anode deposition and anneal temperatures and complicate patterning of the anode. High performance light extraction methods (allowing devices with EQE of 60% or more) that can be integrated into panels, without compromising lifetime and yield, are needed.

Researchers have shown EQE >50% using only external scattering. While there are certainly limits to extraction enhancement with external only approaches, the team was able to develop a comprehensive and analytical methodology to predict structures to maximize efficiency and then realize these features in SiO2 scattering films. Orange emitting prototypes yielded EQE of 56% and 221 lm/W power efficacy.

4.1.4.2.2 Functionalized Substrates

It is difficult to increase the light output of a device in which all of 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, but they were unable to incorporate their solution in commercial panels. Other researchers 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. Another approach is to use RIE (easy, scalable, lith-free and still control topography) to get controllable nanostructures with directional randomness and directional order. [50]

4.1.4.2.3 Corrugated Substrates

Many researchers have suggested the use of corrugated substrates, which effectively disrupt the coupling of light to surface plasmon polariton (SPP) modes. This is being explored in multiple BTO Lighting R&D Program funded projects. A research 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. [51] Another research group has reported enhancement factors of up to 2.4 using patterns with depth of 215 to 500 nm imprinted in polycarbonate. [52] 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 highfield-induced degradation. The risk associated with this approach may cause manufacturers to delay its utilization by several years.

4.1.4.2.4 Refractive Index Engineering

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 or looking at graded index layers between the anode and substrate.

4.1.4.2.5 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 various research groups. [53] [54] [55] Figure 4.22 below shows that EQE over 35% can be obtained without any extraction enhancement structures.

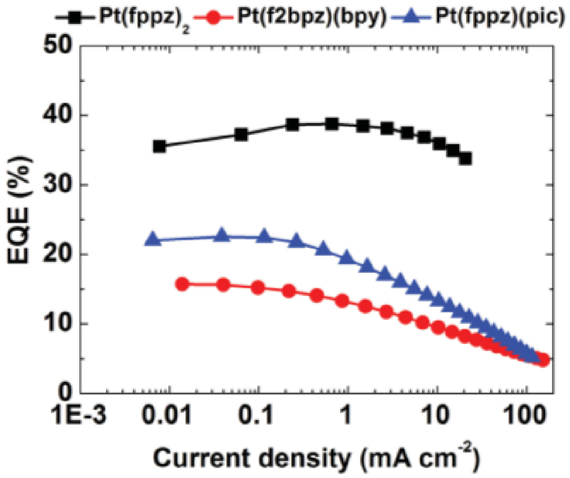


Figure 4.22 External quantum efficiency of phosphorescent OLEDs with Pt-based emitters. [55] Data in black is EQE for emitters with in–plane oriented molecular dipoles. All EQE data is measured without the use of any light extraction enhancement structures. Blue and red data points show typical EQE for random oriented emitter molecules.

Recently, researchers demonstrated OLEDs with as high as 56% EQE using molecular orientation and external scattering films tailored for forward-intensive scattering. [56] 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 maximum EQE increases significantly with horizontal dipole orientation, even when an external scattering layer is employed. Maximum EQE 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 SiO2 or TiO2 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. [57] [58] In general, lower deposition temperatures lead to more horizontal alignment.

4.1.4.2.6 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 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.

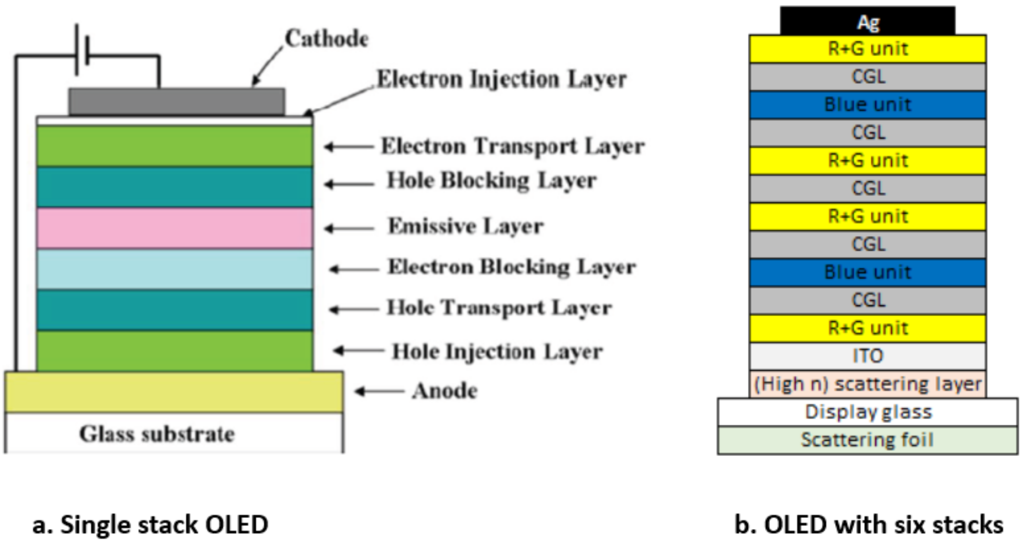
- Transparent anode: ITO is still used in commercial OLEDs. It is extremely difficult to achieve low sheet resistance (less than 10 Ω/sq) and low optical absorption (less than 5%) simultaneously. In the search for alternative transparent conductors, encouraging results have been obtained in the laboratory for silver nano-wires embedded in a polymer host, but reliable OLEDs deposited on such electrodes have not yet been demonstrated.
- Charge generation layers: Research has shown that charge generation layers can lead to significant optical absorption, with transmission rates often below 90%. [59] 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. [60]
- Cathode: Imperfect reflection at the cathode can be a major cause of photon absorption. It has been 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 researchers have expressed special concern about the excitation of surface plasmons in the cathode when the emitter layer is very close to the metal electrode. The effect can be reduced by introducing a thick electron transport layer and is of less concern in devices with multiple stacks.

4.1.4.2.7 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. Two major manufacturers 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/m2. One is fabricated on Corning's ultrathin Willow Glass, while the other is produced on polymer substrates due to issues with breakage of glass.

4.1.4.3 OLED Devices

Figure 4.23(a) shows a single stack structure for an OLED in which seven organic layers are deposited between the two electrodes. Most of the layers are designed to ensure that holes and electrons are injected efficiently and reach the emission layer but are not transmitted to the opposite electrode.



a. Single stack OLED **b. OLED with six stacks**

Figure 4.23 Layer structures of single stack and multiple stack OLEDs. Structure 'a' shows a simple single OLED stack without inclusion of light extraction enhancement features. [61] Structure 'b' shows an OLED structure with six emitter layers and the use of an internal light scattering layer and an external scattering foil to improve light extraction efficiency. [60]

Figure 4.23(b) shows a panel structure where each of the six emitter units could contain most of the layers shown in the single stack unit. The charge generation layers (CGL) contain a p-doped region and an n-doped region, so that the total number of layers can be as many as 40.

In the six-stack OLEDs, up to six photons can be created from each electron-hole pair injected from the main electrodes. The reduction in current density leads to less internal damage and more than a ten-fold decrease in the rate of lumen depreciation. Separating the emission of high-energy blue photons from that of red and green means that the average drive voltage per photon is also reduced.

Clearly, the more complex structure increases the manufacturing cost of the OLED and also increases the amount of photon absorption. The development of long-lived structures with only two or three stacks is a topic for future R&D.

In the panel shown in Figure 4.23(b), the aluminum cathode has been replaced by silver, primarily to enhance light reflection. ITO remains as the anode, despite many years of R&D to find an alternative with lower sheet resistance that is more pliable. Several groups have demonstrated encouraging results using silver nanowires (AgNW) and Ag grids, but these have not yet been implemented in commercial panels, primarily due to shorting concerns. Even with ITO, the surface needs to be very smooth and short reduction layers may be needed to mitigate against roughness. In addition, light extraction enhancement layers are often introduced between the anode and the transparent substrate. Figure 4.23(b) shows a layer with light scattering particles, but other forms have been proposed.

4.1.4.3.1 Encapsulation

The active organic layers must be protected against the ingress of water, from the top, bottom and edges. An inexpensive effective surface barrier for plastic substrates had proved elusive, so that the ultra-thin glass is now preferred for conformable panels. The top surface can be protected by the combination of an in-situ deposited layer and a laminated film, as shown in Figure 4.24. The edges must be sealed so that no O_2 or H_2O can enter into any active organic or polymer layer.

Figure 4.24 Encapsulation structures for conformable OLED panels. [62] Figure shows a conformable OLED structure that uses ultra-thin glass and a backside protective film that enables both conformability and protection from the ingress of water into the OLED device structure.

4.1.4.3.2 Bottom Emitters vs Top Emitters

Although the light is emitted through a transparent cathode and the top surface in most OLED displays, bottom emission has been preferred in lighting panels. Upward emission in displays avoids absorption by the transistors, capacitors, and conduction lines in the active matrix backplane. Some researchers have explored the use of top emission for lighting, but no substantial advantage has yet been seen.

4.1.5 Optical Delivery Efficiency

As has been discussed earlier, the key historical advances in LED-based solid-state lighting have been related to improving source efficiency, particularly the materials and device/package advances underlying that improved source efficiency. On the horizon, however, are parallel advances that will enable improving LAE – our ability not just to produce light efficiently, but to use light most efficaciously for the application at hand. Using light most efficaciously, in turn, will benefit from two advances. The first – the emerging science of visual and physiological responses (to inform the "when, where, and what" of light deployment) – is discussed in Section 4.2.7. The second – the ability to engineer and, in some instances control in real-time, intensity distributions in space, time, and spectrum – is discussed in Sections 4.1.5, 4.1.6, and 4.1.7.

Figure 4.25 Streetlighting LED retrofit showing reduced over-illumination and eliminated upward illumination. [63] The image shows how LED roadway lighting can achieve a more uniform optical distribution, improved color quality, and elimination of upward emitted light.

Light intensity distributions that can be engineered in space, spectrum, and time, if necessary, would reduce the over-illumination and under-illumination of spaces and spectral regions. [64] Such engineered light could thus simultaneously reduce energy use and improve application efficacy. [65] This could apply to current mainstream lighting applications – general indoor and outdoor illumination for humans to “see by” (visual imaging) – as well as newer lighting applications growing rapidly in importance. [1]

Optical delivery efficiency can be improved in two ways. First, improved luminance and resulting optical control can be designed into a static or configurable lighting product that is installed in a space. The product would be installed to achieve precise optical performance for a given task or set of tasks. Improvements in LED device level luminance enable much improved optical control, particularly compared with conventional technologies. The other approach is to use actively, optically controllable lights to continuously deliver light to the targeted areas in a space. It is expected that the LAE framework will provide guidance as to which approach is most suitable for which specific lighting situations. The following discussion will cover some of the latest approaches for active optical control of lighting.

4.1.5.1 Single Beams

For single-beam approaches, the idea is to steer and shape a single beam, and thus to selectively illuminate sub-spaces within a space. For steering light, the most common approach is use of mechanically swivelable (physically non-stationary) luminaires (e.g., track lighting). More recently, making use of the small source size (etendue) of LEDs, steering has been accomplished much more compactly using mechanical movement of internal (hidden) secondary optics in physically stationary luminaires with little or no beam occlusion at any steering angle. [66]

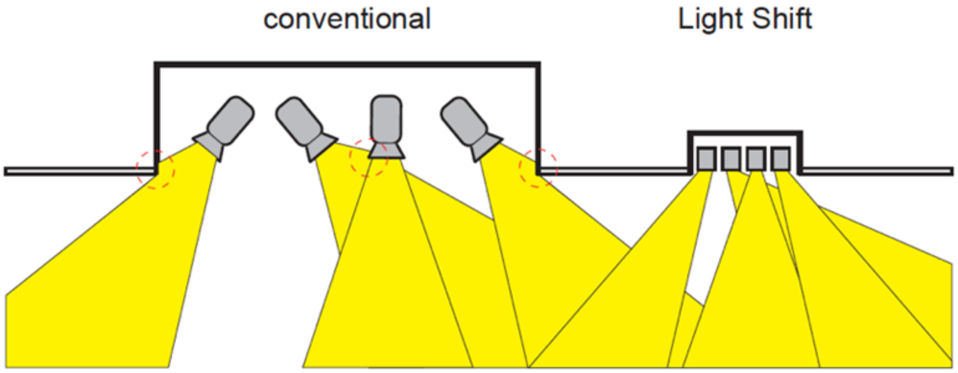


Figure 4.26 Cartoon illustration of a matrix of single beams, steered using (left) conventional technologies versus (right) advanced and physically stationary “light shift” technologies. [66] The image on the right shows how steerable LED lights can have much smaller volume while effectively covering the lighted area.

For shaping and steering light, new technologies based on liquid crystal electro-optics have also been demonstrated. [67] Laterally varying voltages applied to a glass/liquid-crystal/glass sandwich create laterally varying orientations of liquid crystal molecules, and laterally varying indices of refraction. The result is the effective functionality of beam-expanding/beam-focusing lenses and beam-steering prisms.

Note that, in conjunction with the steering and shaping of beams, source etendue is critical. The smaller the optical source size, the smaller the illuminated area can be for a given size of package/luminaire optics; equivalently, smaller the package/luminaire optics can then be attained for a given size of the illuminated area. For a given lumen output, smaller optical source sizes thus mean driving LEDs harder to increase luminous emittance (in lm/mm^2). Typically, driving LEDs harder results in a lower source efficiency or luminous efficacy, so there is a trade-off between efficacy and luminous emittance, and hence optical control. Figure 4.17 above shows this efficacy trade-off versus luminous emittance for a number of state-of-the-art 2017 commercial white light packages.

A research direction associated with this trade-off is developing new materials and device architectures that fall to the right of this current trade-off, and that thus go beyond the current state-of-the-art. Doing so might involve further reductions in efficiency droop, but it might also involve improvements to the absolute luminous efficacies and optical delivery efficiencies of LEDs and LED packages. Importantly, these improvements could be offset by higher light application (or use) efficiency.

4.1.5.2 Pixelated LEDs

For pixelated LEDs, the approach is to make use of multiple beams, each originating from a different LED "pixel" element and focused and steered slightly differently. By selectively turning pixels on and off, or by changing their relative lumen outputs, light can effectively be distributed in space with display-like control. The pixelation can be at "macro" or "micro" levels.

Figure 4.27 Macro-pixelated white LED light source: Omnipoint by Osram. The Osram Omnipoint was an early example of a multipixel light source where individual pixels can be controlled to 'steer' the beam to highlight specific regions of the lighted area.

At a macro level, multiple discrete LED or LED packages ("macro-pixels") are independently placed in a fixture or on a PC board, independently focused and directed, and independently controlled. An early demonstration of this was Osram's OmniPoint product in which 61 individually-controllable LEDs were mounted in a fixture. [68] The granular control enabled the fixture to independently tailor the intensity of 61 zones of light through a smartphone application – e.g., accenting one sub-space and dimming other sub-spaces in a space, or creating moveable and arbitrarily shaped (circular, elliptical) beams. More recent demonstrations have been in automotive headlights, where arrays of 100-200 (e.g., 6x24) discrete LED pixels provide both vertical and horizontal segmentation for "Adaptive Driving Beam" (ADB) control. [69] Such ADB headlights enable much increased light intensities projected onto road and road-boundary zones, along with de-glaring (selective darkening) of illumination into the visual field of oncoming traffic.

At a micro level, a single large LED can be pixelated into an array of "micro-LEDs" (μLEDs), each with an area on the order of 50x50 μm2 or less. The closely spaced micro-LEDs – each emitting directional light – can be directly addressable via integrated CMOS switches, resulting in a highly pixelated directly imageable source. [70] In the short run, these might be configured into high-resolution but small RGB direct-view displays for virtual-reality/augmented-reality (VR/AR). [71] In the medium run, these might be configured into white-light projection systems for automotive headlights with much higher resolution than that possible with the macro-pixilated approach. In the long run, these might be configured into high-resolution RGB projection displays which project wall-sized images intended to be viewed either directly (as images) or indirectly (as secondary sources of light). This longer run scenario has significant implications for energy consumption: as displays occupy an increasingly large fraction of wall spaces, their share of building energy consumption is also likely to continue to increase.

4.1.5.3 Laser Rastering

The extremely small etendue of laser-based sources make it possible to engineer more extreme light distributions in space than are possible with LED-based sources. Current technology (e.g., a flashlight based on laser white light) can deliver 250 lumens to an area as small as ~3m in diameter at a distance of ~100m. [72] In terms of non-active lighting control, this means that more light can be delivered on target at further distances to spotlight an object with the minimum amount of total light.

When combined with a MEMS (micro-electromechanical system) deflection mirror, which rasters blue laser light over a luminescent converter or phosphor, highly localized bright spots of white light can be created and then imaged and projected out into a space. By rastering fast enough while modulating the laser power, an arbitrary high-resolution luminance distribution can be tailored in real-time into the space, such as an automotive headlight ADB on a road. [73] In other words, although this is a single-beam approach, because of the small etendue of the laser, it can functionally accomplish that of a pixilated LED approach.

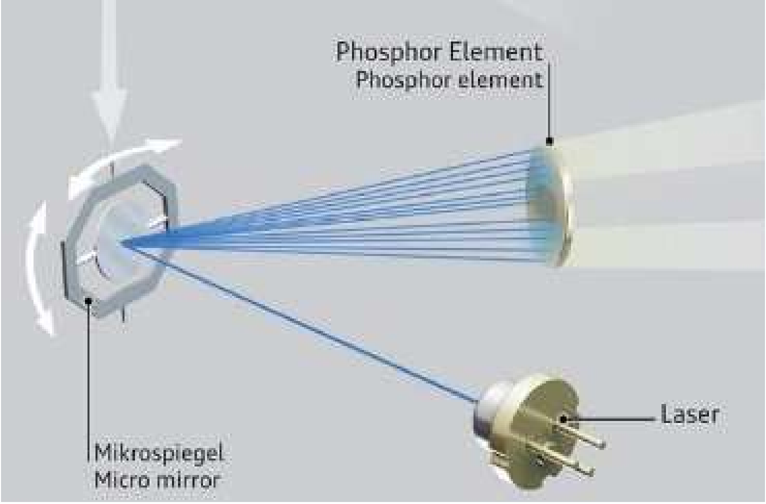


Figure 4.28 Schematic of a laser rastered white-light system with its major components: a blue laser diode; 2D MEMs mirror and a phosphor element. [69] By rastering the mirror the optical distribution of the light exiting the phosphor element can be controlled.

4.1.6 Spectral Efficiency

SSL technology offers the new capability of precise control of the spectral power distribution (SPD). The SPD can be tailored for various applications and, in some products, can be actively controllable. This ability to tailor or actively control the spectrum from lighting products enables the ability to deliver SPD that are engineered to engage specific human visual, non-visual, plant physiological, or even semiconductor detector (i.e., HD camera) responses, or a combination of such responses.

As part of the basic LAE framework, spectral efficiency is loosely defined as the spectral effectiveness of the delivered SPD compared to an optimum spectrum for the function of the light. For example, for basic vision an optimum spectrum can be determined for prescribed color fidelity (TM-30 Rf or CRI) and CCT that maximizes the LER. The delivered SPD could be quantitatively compared against this optimum. There could be trade-offs between spectral efficiency and source efficiency based on the efficiency of the emitters at different emission wavelengths. In this example, color fidelity, chromaticity coordinates, LER, or luminous efficacy can be optimized. Within the LAE framework it is important to recognize that the spectrum delivered to the ultimate receiver (typically the human eye) is not necessarily the same as the spectrum of the light that is emitted from a light source. When the light is emitted from a light source it can be affected by transmissions though materials, such as a lamp shade or fog for an outdoor situation, or by reflections off of surfaces in a space that can preferentially reflect some colors based on the colors on the surfaces. These effects are part of the holistic lighting system that the LAE framework will be designed to capture.

The delivered spectrum from a light source can also be optimized or co-optimized for different response spectra than the basic human photopic eye response. The delivered spectrum can be optimized to deliver, or not deliver, light that overlaps with the human melanopic response function, which is described in following sections. For this lighting function it may be desirable to provide blue-rich white light to provide a strong melanopic signal to the occupants of a space. To achieve this function there will be a different optimum spectrum than for basic vision. In other words, the delivered spectrum would be optimized against the melanopic response spectrum rather the photopic eye response spectrum. In most lighting applications, visual and non-visual responses to light will need to be co-optimized. While understanding of the melanopic non-visual responses to light are still evolving, there is an understood melanopic response spectrum that delivered light can be characterized against. However, understanding optimum timing and intensity levels for light to evoke melanopic responses is still evolving.

For any lighting application, delivered optimum spectrum and intensity of the light are not independent factors. For example, to achieve a desired melanopic physiological response, light can be enriched with blue or intensity can be increased. Further understanding is necessary to optimize light spectrum and intensity for maximizing or minimizing non-visual physiological responses, according to the time of day and needs of the occupant. In particular, research is necessary to better understand light levels with respect to spectral content that are too low to evoke a melanopic response or are high enough that the melanopic response is saturated in realistic lighting situations.

There are trade-offs between efficiency and various emission wavelengths or colors that is generally referred to as the ‘green gap’. These efficiency-color trade-offs can affect the optimal SPD for achieving the function of a light with respect to energy consumption of the light. As described in the example above, the typical function that is considered with lighting is visual function based on the photopic eye response. Even within this function there can be trade-offs between total light output, color quality, and energy consumption. As more lighting functions are considered with different response spectra, then additional and different trade-offs must be considered.

In order to accommodate different response spectra in the same space at different times or in different situations, there are now spectrally tunable light sources. These sources can be either white tunable or color-tunable. [74]

4.1.6.1 White Tuning

The most basic form of spectral engineering is white tuning: the shifting of the white light CCT from warm-white (usually around 2700 K) to cool-white (usually 5000-6500 K). There are two general approaches to white tuning: linear or non-linear (see Figure 3.5).

In the linear approach to white tuning, two PC-LEDs are controlled: one warm-white and one cool-white. By individually raising and lowering the output of the two LED “primaries,” white colors between the two color points can be created along the straight line that connects them on a chromaticity diagram. Note, though, that since the blackbody line is curved, admixtures of two colors of white cannot track exactly along the blackbody and, the wider the range of CCTs, the greater the maximum deviation from the blackbody.

In the nonlinear approach to white tuning, three or more LED primaries are used. Such products can track the nonlinear curve of the blackbody and will not appear off-color (green or pink) compared to a reference light source whose chromaticity falls right on the blackbody curve.

Both types of white tuning – linear or nonlinear – allow for tailoring the color temperature for a number of reasons: aesthetics, psychological mood, and possible alerting effects. In one important class of white tuning, “dim to warm,” the idea is to mimic the decrease in CCT of incandescent or halogen lamps from warm (2700-3000 K) to candlelight-color warm (~1800 K) when they are dimmed.

4.1.6.2 Color Tuning

Some products can tune their output SPD by adjusting different color LEDs within the lighting product. These products, also referred to as RGB, RGBA, RGBW, or color changing, usually have three or four different LED primaries that can be individually varied in output to create a mixture of light that is white, a tint of white, a hue, or a saturated hue. The individual LEDs used in a full-color-tuning mixture can be narrower-band direct-emitting LEDs (producing a narrow range of blue or red, for example), broader band but still monochromatic phosphor-converted LEDs (e.g., a "mint" green LED is a phosphor-coated blue), and/or phosphor-converted white LEDs (W). Usually the different monochromatic LED colors include red, green, and blue (RGB, the primary colors of light), but these can be augmented with amber (A), other monochromatic colors, and/or one or more white PC LEDs (W).

4.1.6.3 Spectral Tuning

The minimum number of LED colors is three for full-color tuning in the traditional CIE color space. However, the three-primary color space is an extremely simplified representation of a spectral distribution of light. Light with very different spectral power densities can be represented by the same color point in the CIE color space (i.e., they can be metamers) but have very different effects on how colored objects will be rendered, as well as their effects on human and plant physiological responses. Indeed, it is the SPD that is the definitive signature of light, and the ability to replicate SPDs at will is the ultimate form of spectral engineering.

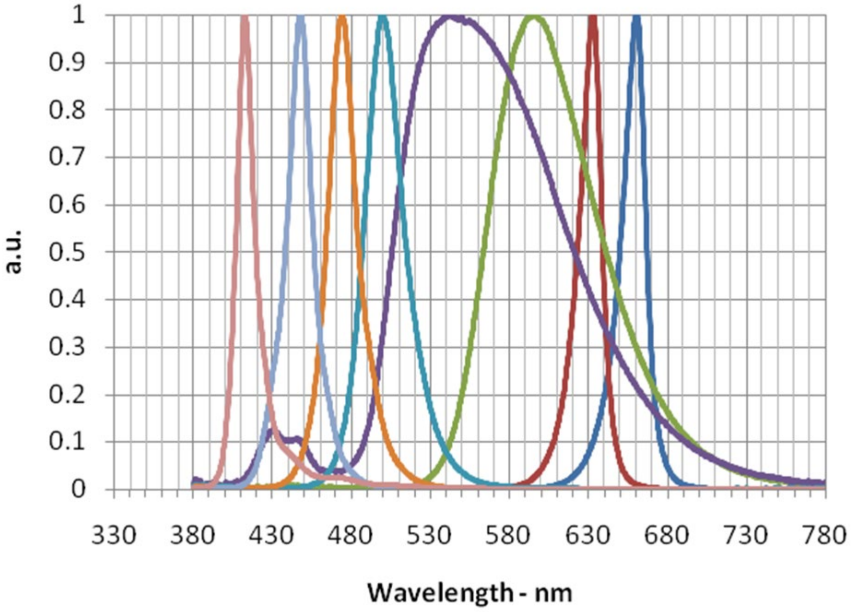


Figure 4.29 Illustration of spectral-power-density "building blocks" available from a state-of-the-art eight-color spectral-power-density-tunable system. [75]

Thus, it has also been of interest to move beyond simple three-color, to five-or-more-color systems. Such systems have generally been at the luminaire, not package (light-engine) level. Moreover, color mixing at the luminaire level can be non-trivial and lead to efficiency losses, but such systems can give exquisite control over spectral power density. An eight-channel 415-660 nm multispectral luminaire can tailor light spectra throughout most of the human visual range, while a sixteen-channel 395-735 nm light replicator can tailor light spectra over an even broader wavelength range with smaller wavelength steps for a wide range of human, fauna, and flora applications. [75]

4.1.7 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. [65] This inefficient use of light must be improved to provide better light application efficiency. Intensity effectiveness is a term to describe using only the right amount of light at the right time (when observers are in the lighted area), and also to characterize when insufficient light intensity is being provided to the application. SSL 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; though, further performance and cost improvements could continue to increase consumer confidence and controls utilization (thus, improving 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 focuses 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 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.

4.1.7.1 Glare

Having the right intensity level is important since excessive brightness and brightness contrast can produce glare and lead to visual discomfort. Optical control to manage light distribution is an important part of providing light to the application without impacting the comfort of the occupants. One of the challenges with LEDs is the very high intensity provided from a small light source. The luminance of an individual LED can easily exceed 1,000,000 cd/m^2 compared to that of a T5 fluorescent lamp with a luminance of 25,000 to 30,000 cd/m^2. [76] The challenge for LED lighting is taking the high luminance of many LED sources and providing a uniform luminance that is visually pleasant for the occupant.

Current discomfort glare metrics such as the unified glare rating (UGR) still face challenges with LED sources due to the way it calculated. Average luminance over luminaire aperture is most commonly used for luminaire luminance, though it can be highly inaccurate when considering luminaires with visible arrays of LEDs (non-uniform luminance across the luminaire aperture. This calculation can misstate the area and the luminance. Other challenges include how UGR handles the assumptions of the viewer's line of sight. It assumes that the observer does not look up past the horizontal field of view and is not impacted by overhead glare. In addition, the glare metric does not consider how the spectral power distribution can affect the discomfort glare response.

There is the need for more research to develop a physiological understanding of how we perceive discomfort glare to create better metrics to describe the acceptable properties of luminaire. There has been some research to replace the current phenomenological models to glare with physiological based models. Researchers are investigating receptive field (of the eye's photoreceptors) models to link the neural response to a luminance map, which is a determining factor for the visual discomfort sensation. [77] Further work in this area can lead to physiological-based glare metrics that may have improved success in describing glare thresholds for an application.

New classes of LED lighting products have begun to address the luminance uniformity of the luminaire aperture by using edge lit optical waveguides to distribute the light more uniformly from the high intensity LED sources. These include flat panel indoor lighting products as well as outdoor area lights as shown in Figure 4.30.

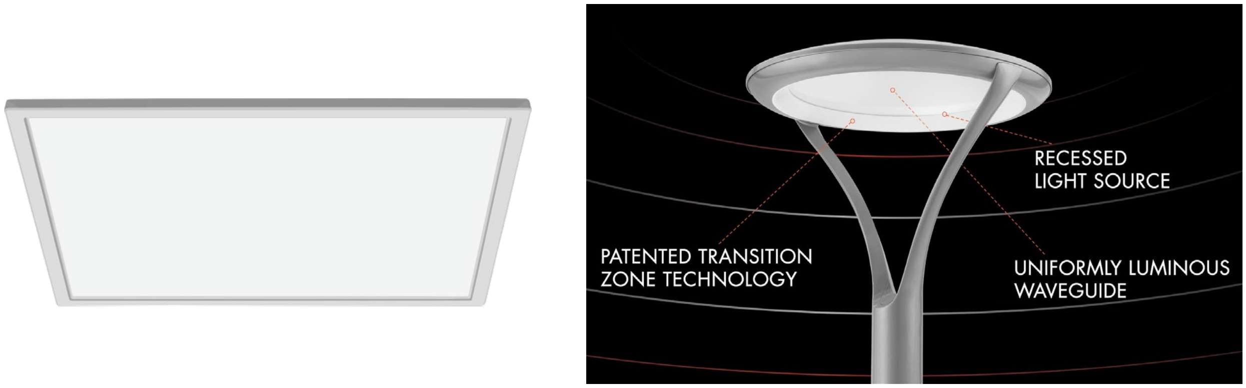


Figure 4.30 Images of a 2' x 2 LED flat panel luminaire (left) and outdoor area light (right) that are designed for low glare. [78] [79]

OLED lighting products, on the other hand, inherently have the advantage of producing soft light that does not need to be hidden from the eye. To minimize the risk of glare, luminance levels have been traditionally limited to around 3000 cd/m^2. Brighter panels can be used in some applications and some panels are designed to provide up to 8500 cd/m^2. [12] Dimming capability is then essential so that users can tune to the most comfortable level.

The light distribution from all commercial OLED panels is close to Lambertian. This is good in that it prevents the formation of sharp shadows, but it also increases the possibility of glare. Cavity tuning can be used to modify the distribution of monochromatic light and one research group has demonstrated a dual stack structure in which the beam shape can be adjusted dynamically. [80] Research into control of the beam shape for white light is still needed and is a natural extension of the work on light extraction.

4.2 Supporting Science and Technology

The proposed LAE framework provides a basis for characterizing the entire lighting system which includes the light source and influence of the lit space on the ultimate delivery of the light to the receptor. The concept of the LAE framework is that it is both application and detector (or spectral response) agnostic. There are several R&D topics that can be explored that will support advancement of the LAE framework as well as lighting in general. Advancements in lighting science will provide guidance as to optimum light levels, spectral power distributions, and optical distributions. Research in aspects of the light source will improve trade-offs between optical performance, light intensity control, spectral power distribution, and efficiency. Research in improved power supply and control of lighting products improves efficiency, enables active spectral control, and can even enable new form factors for improved light delivery in a space.

4.2.1 Computational Modeling

A key pillar of the lighting application efficiency framework will be the ability to predict light levels, light directionality, and spectral power distribution for any area in a lighted space based on the geometry of the space, the surface finishes and features within the space, and the lighting product performance (i.e., SPD and optical distribution, and layout of the light sources). This modeling capability would enable optimization of these factors, including the lighting product specifications, to enable optimization of the light qualities at a given area of plane within the lit space. Computational models exist that can predict the SPD and intensity within a lit space based on room geometry, surface finishes, and lighting product performance. Computational modeling such as this should be used to validate the LAE concept and framework and optimize the lighting system to achieve optimal lighting in a space for any lighting application. Work to further develop computational modeling for lighting design that includes spectral effects and room geometry and surface finishes should be an integral part of R&D to develop the concept of lighting application efficiency.

4.2.2 Building integration

Despite advancements in lighting technology, lighting is still installed and connected into buildings as it has been for decades. LED and OLED lighting technology offer new form factors and building integration approaches that are not constrained by limitations of the previous technologies. Building integration of lighting consists of:

- **Architectural integration**: how the lighting product is mechanically attached and integrates with the building structure;
- **Daylight integration**: how the lighting integrates with daily and seasonal daylight from windows;
- **Electrical integration**: how the lighting product is powered;
- **Controls integration**: how the lighting product is controlled, typically through a light switch; and
- **Optical integration**: how the light emitted from the lighting product is distributed through the lighted space.

Within the framework of the lighting application efficiency it may be desirable to provide different ranges of lumen outputs from lighting products with a broader range of optical distributions and such products could be architecturally integrated in ways that no longer require holes in the ceiling and extra depth above the ceiling. In many buildings, lighting systems currently interact with building energy management (BEM) systems that provide computerized control over lighting operations, which can include the functionality to be grid-connected and eventually enable grid-responsive lighting. Lighting systems should also integrate with natural light provided by windows to provide optimum light levels. There are advantages to low voltage DC electrical integration, which removes the need to convert the electrical input from alternating current (AC) to direct current (DC) in individual luminaires (see the following section for more details). For control of lighting products, there are numerous new approaches described in Section 4.2.5. As capabilities are added to lighting products, such as spectral or optical tunability or sensor capabilities, additional channels of control and communication will be necessary. Wireless control is, perhaps, the most obvious means of control. However, resiliency, simplicity, and robustness will need to be considered. Lighting is fundamental for safety and productivity and should not ‘crash’ or malfunction when there are problems with a router, WiFi signal, hub, sensor, or communications with a sensor. Optical integration of light in a space can also be considered, modeled, and executed in new ways with the SSL technology platform. The lighted space functions as an extension of the luminaire and impacts the light emitted from a luminaire as it is delivered to the ultimate receptor or receptors. With SSL, the concept of the built space as an extension of the luminaire, affecting optical delivery and even delivered spectrum, can be taken to the next level for optimization of the delivered light.

4.2.3 Electronics: Power, Functional, Control, Communication, Sensor

The power supply is a critical component to the luminaire since it powers the LEDs or OLEDs. The driver accepts input power of various types, including conventional AC line power, as well as 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).

4.2.3.1 LED 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, which is a challenge in today's drivers where efficiency drops in the dimmed state. Absence of flicker is important for any light source, but it can be challenging due to a lack of standard definitions for basic flicker quantities, such as percent flicker and flicker index. This is further complicated, in part, because of new types of flicker in current devices, 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 semiconductor 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 can 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 can lead to size reduction and efficiency improvements, as illustrated in the 220 W LED driver example in Figure 4.31. [81]

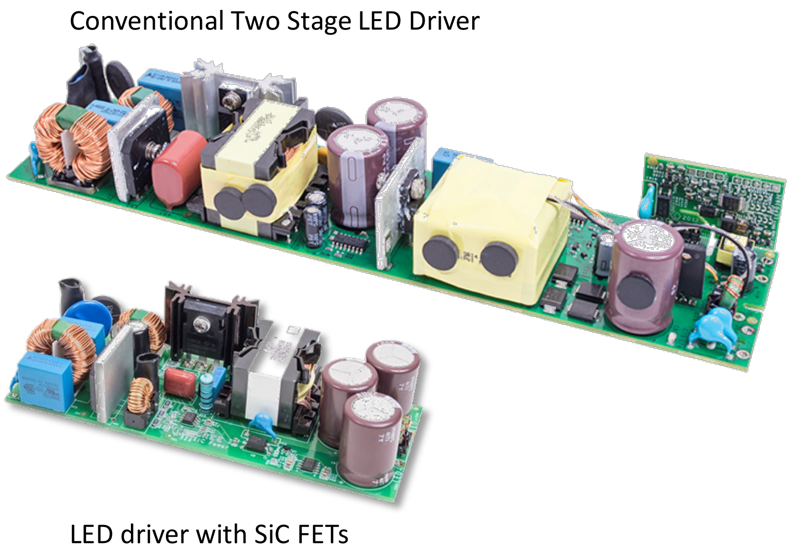


Figure 4.31 Comparison of a 220 W LED driver with and without wideband gap components. The two-stage conventional LED driver employing silicon MOSFETs (top) is about 40% bigger than an equivalent unit based on 900-V SiC MOSFETs (bottom). The driver with SiC MOSFETs has a higher peak efficiency. [81]

A two-stage conventional LED driver employing silicon MOSFETs is compared to an equivalent unit based on 900-V SiC MOSFETs (single stage driver). The superior performance of SiC semiconductors enables the implementation of a simple and cost-effective single-stage topology that delivers the performance of a two-stage topology. The key performance parameters of these two drivers are compared in Table 4.2. The SiC-based driver delivers > 50% volume/weight reductions with a higher peak efficiency of 94.4% and lower cost than the conventional driver with silicon components.

Table 4.2 Driver performance parameters for a conventional two-stage driver with silicon MOSFETs and a single stage driver with SiC MOSFETs. The driver with SiC components provides smaller size, higher efficiency and a lower cost. [81]

220 W LED Driver	650V Si Based Two-Stage	900V SiC Based Single-Stage
Input voltage Range	120-277V AC	120-277V AC
Output Voltage Range	150-210V DC	150-210V DC
Max Output Current	1.45 A	1.45 A
Peak Efficiency	93.50%	94.40%
Input THD	< 20%	< 20%
Output Current Ripple	>0.95	>0.95
Output Current Ripple	±5 %	±10 %
Size	220×52×30 mm	140×50×30 mm
Weight	2.7 lbs / 1.3 kg	1.1 lbs / 0.5 kg
Relative cost	1	0.85

Integration of wide bandgap semiconductors can be used to extend the power and/or efficiency of single-stage topologies, leading to a simplified and lower cost approach, as illustrated in Figure 4.32. Typically, single-stage driver approaches are best suited for cost-driven solutions, such as residential lighting, whereas two-stage approaches are best suited for performance-driven solutions, such as commercial lighting. The ability to move to single stage topologies reduces complexity and part count, and therefore cost. The clear division on the most cost-effective way of implementing LED drivers is set, in good part, by the semiconductor performance. Newer wide bandgap SiC or GaN devices (lower voltage and lower power) will extend the benefits, demonstrated at high powers 200W to 75 W LED drivers.

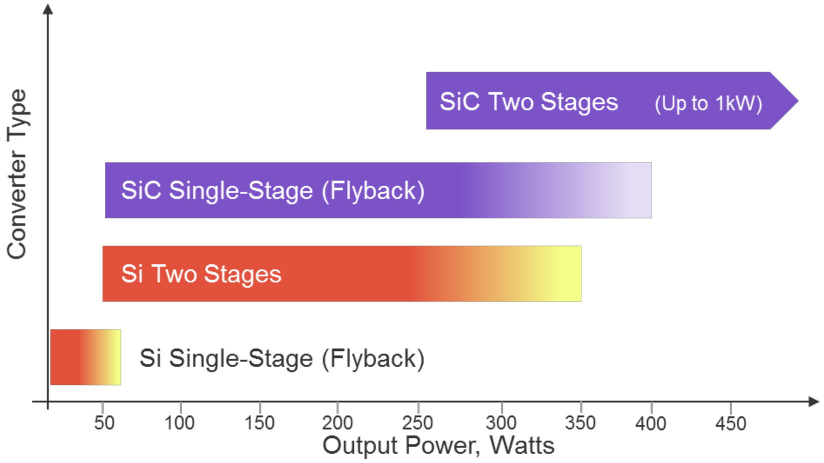


Figure 4.32 LED driver topologies based on semiconductor component types illustrated as a function of power output. [81]

Although SiC is currently more advanced, 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 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.

4.2.3.2 OLED Driver Performance

OLEDs have many of the same power supply considerations as LEDs, but there are also important differences. The small size and low power levels of individual OLED panels create several problems in the design of efficient drivers. Panels with areas around 100 cm^2 draw 5W or less. The limited availability of custom drivers means that electrical losses in the control circuit can be substantial. However, drivers specifically designed for OLEDs limit losses to around 8% when powered by a 24V DC source, [82] with about 15% losses due to AC/DC conversion from a mains supply.[20] Further R&D is needed to reduce the total losses to less than 10%. For luminaires with more than one panel, connecting these in series with a single driver can lead to higher efficiency, due to the increase in voltage, but providing independent control over each panel without adding significant cost for the whole fixture remains a difficult challenge. Preliminary studies were carried out in a DOE SSL project, [83] but more research is needed.

Efforts are underway to reduce the thickness of OLED drivers so that they can be included in fixtures with a slim profile. One driver developed through a collaboration has dimensions of 38 mm x 24 mm x 3.8 mm, and perhaps the ultimate goal is a thin-film driver that matches the form of the OLEDs and similar to those that are being introduced in flat-panel displays.

In 2017, one manufacturer introduced an interesting series of products based upon a square panel in which the lit area has dimensions of 80 mm x80 mm and the frame adds an extra 5 mm on each edge. The version with a CCT of 3000 K and CRI of 93 produces 60 lm from 1.7 W at an efficacy of 37 lm/W. A dimming drive circuit and connector can be attached to the back of the panel such that the thickness of the complete module is only 5 mm. However, the output drops to 57 lm and the DC power input increases to 2.5 W. Ten of these modules are used in the wall light shown in Figure 4.33. The input is now 60 W of AC power (100-240 Hz), so that the overall efficacy drops to below 10 lm/W. While efficacy is poor, this design shows a path toward elegant and effective power supply integration with OLEDs, if the efficiency can be improved.

Figure 4.33 OLED module and LUCE wall light.

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[20] AC/DC conversion losses are estimated based on a comparison of efficacies from product data provided by Acuity Brands and OLEDWorks.

4.2.3.3 Driver Reliability

Typically, the driver is the first component of a luminaire to fail. Predominantly, 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 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 through 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 shown previously in Table 3.5. 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.

4.2.3.4 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 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, pixelated 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 3-D mapping. The complexity of these offerings becomes enormous as each has its own requirements for interoperability and end-to-end security.

4.2.4 Advanced Manufacturing Technologies

As the technology for lighting has changed, there have necessarily been modifications in how lighting products are manufactured. Many of the technologies discussed in this document have required new manufacturing technologies to be developed. With SSL, there is still an opportunity to rethink how products and components are manufactured across the value chain and to embed sustainable manufacturing processes and materials in the manufacturing processes. New and improved manufacturing processes and technologies can improve lighting product quality, reduce cost, and enable a wider variety of form factors and features. New manufacturing technologies can also influence where, when, and how products are manufactured, possibly enabling more localized production.

4.2.4.1 Additive Manufacturing

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 3-D object is created by computer-controlled deposition of material (in a layer by layer approach) based on a computer-aided design (CAD) model. 3-D 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.

Additive manufacturing offers flexibility of shapes and designs and allows for reduced inventory levels while leveraging the same equipment. It allows for complex shapes that are not possible with traditional manufacturing, easier product variations, and on-demand manufacturing capabilities for projects with shorter lead times. In addition, reduced costs can be realized with a lower equipment investment, since no tooling is required, and with a lower energy intensity that comes with eliminating production steps, using substantially less material, and producing lighter products.

Additive manufacturing can impact the LED lighting supply chain in multiple areas including fixture housings, secondary optics and even electronic components and modules. For the most part, the primary use of additive manufacturing in SSL has been for rapid prototyping on new design concepts to iterate product variations or functional form-and-fit processes and testing. Recently, lighting fixtures manufactured with 3-D printing have become commercially available, as shown in Figure 4.34. 3-D printing enables the design of custom fixtures with improved visual appeal from unique designs and reduced costs.

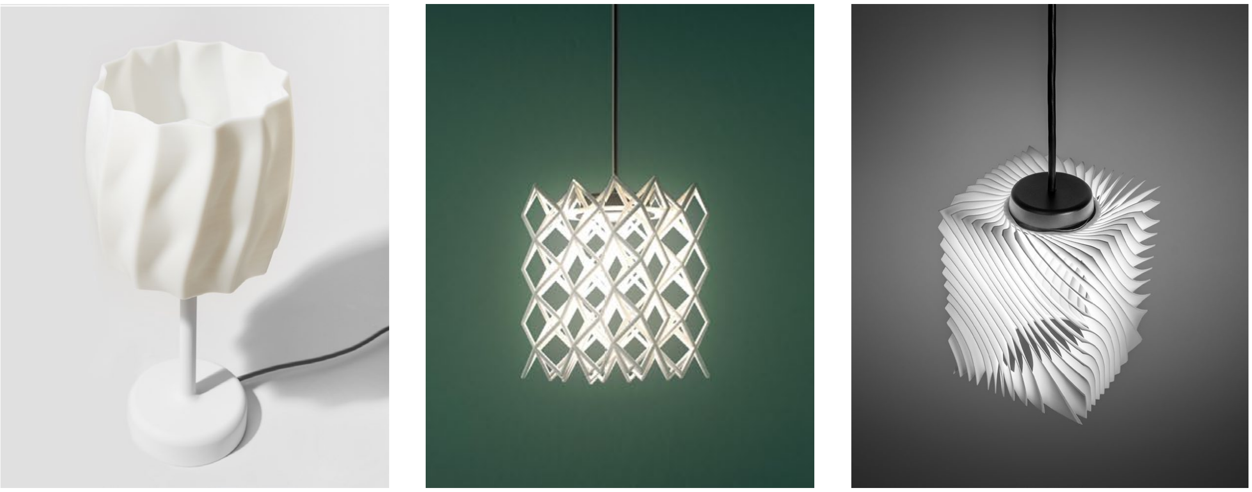

Figure 4.34 Images of 3-D-printed lighting fixtures. [84] [85] Custom optical distribution features of decorative luminaires can be achieved through additive manufacturing approaches that would not otherwise be practical or possible to achieve.

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 4.35. 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 on demand manufacturing.

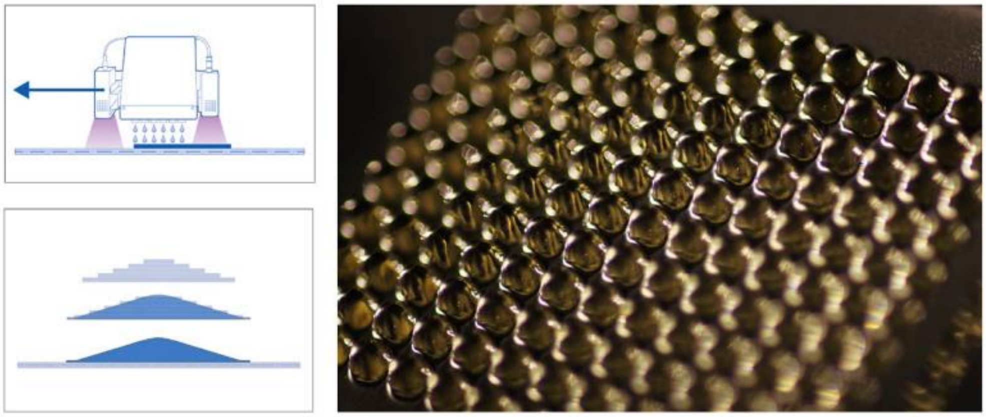

Figure 4.35 Deposition of droplets by UV print head onto substrate material (left-top). Droplets of polymer are allowed to “Flow” under surface tension before curing with UV light, giving smooth surfaces needed for optics (left-bottom). Array of micro-optic lenses (right). [86]

Another additive manufacturing technique being explored in LED luminaires is developing direct chip-to-system solder-attach geometry that will enable LED electrical integration into systems for improved performance at a simultaneously reduced fabrication cost. One manufacturer has focused on replacing the metal-core printed circuit board and thermal interface material with a printed circuit on the luminaire system (metal) to reduce the thermal interfaces, thus improving thermal resistance. [87] Adding an integrated driver circuit facilitates full automation of electronics component assembly, and this significantly reduces material costs. Fully printed, integrated circuitry with LED, driver, sensors, and antennas was demonstrated in the project shown in Figure 4.36.

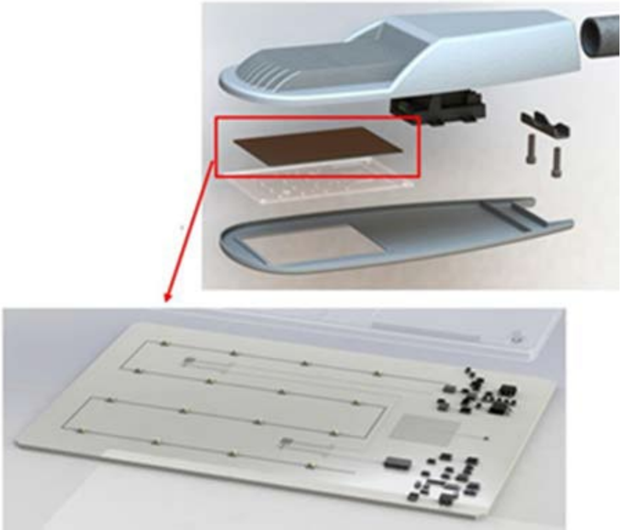

Figure 4.36 Images of integrated roadway luminaires with fully printed, integrated circuitry with LED, driver, sensors, and antennas. [88]

One of the biggest challenges with implementing 3-D printing further into the SSL value chain is the development of printable materials with properties specific to lighting applications – optical, electronic, and thermal properties. For example, there are challenges in 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 heat sink, the thermal conductivity falls short of the performance seen with aluminum heat sinks. 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. [89] 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 3-D printing. The lead time for tooling for molding or stamping processes often takes 10-12 weeks to be created. 3-D 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 3-D printing of cars. The use of additive manufacturing in creating tooling has the potential to create efficiency gains with SSL product manufacturing.

4.2.4.2 Advanced Manufacturing Techniques for OLEDs

The current OLED manufacturing process is illustrated in Figure 4.37. The organic materials have traditionally been deposited through vacuum thermal evaporation (VTE), which is a batch process. In order to increase the deposition rates and improve manufacturing throughput, the temperature in the evaporation chamber should be increased, thus decreasing the stability of the fragile organic molecules. Higher deposition rates can be achieved with less stress on the organic molecules by using an organic vapor phase deposition (OVPD) in which an inert carrier gas is used to transport facilitate the transfer of the organic molecules from the evaporation source to the substrate.

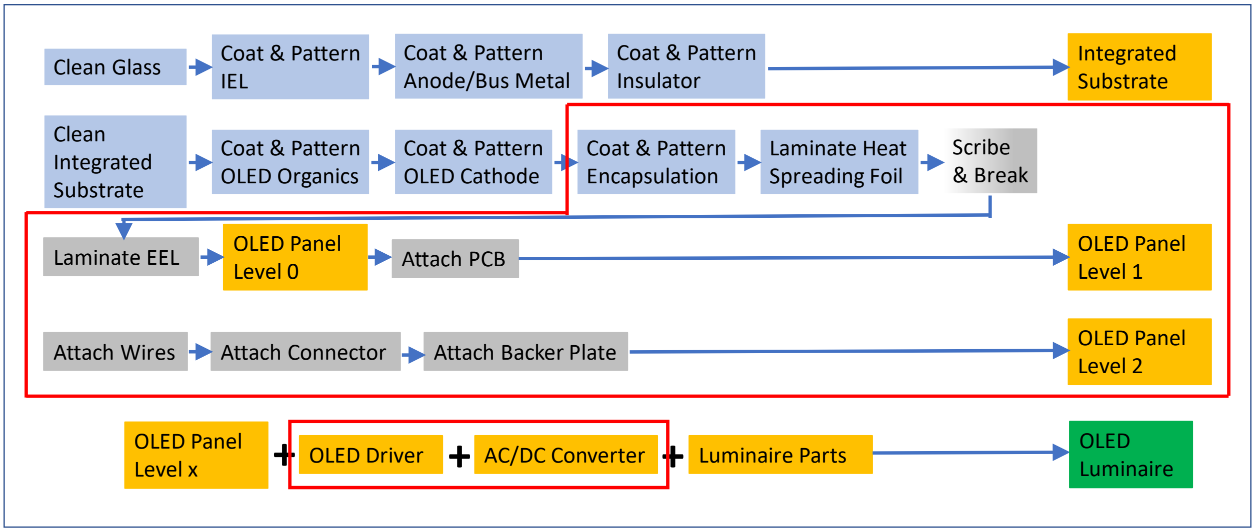

Figure 4.37 Current manufacturing process flow for OLED luminaires. [13]

While there is room for innovation in the batch manufacturing process for OLEDs, roll-to-roll (R2R) processing is an attractive additive manufacturing technique that can shorten production times and reduce costs for OLEDs relative to the conventional manufacturing process. This is perhaps the most cost-effective way to reduce handling times. In 2014, one manufacturer completed a R2R fabrication line to produce flexible lighting panels in high volume, based on attractive prototypes from its R&D laboratories. However, it has not yet been able to produce commercial products in high volume from the line, suggesting that R2R technology was not mature at that time.

One researcher has estimated that an R2R line producing 720,000 m^2 per year could be constructed at a cost of €250M and would lead to a 15% reduction in costs when compared to a sheet-to-sheet line with similar capacity. This capacity could be achieved with a web of with 1 m running at ~3 m/minute. Another researcher has estimated the potential savings as ~30%. Although these required web speeds can easily be met using available rolling and unrolling equipment, executing and synchronizing each of the many processing steps with cycle times under 1 minute presents several major challenges, for example in deposition of the organic materials and in encapsulation.

Printing techniques are often used in conjunction with R2R substrate handling and have been explored by several laboratories in OLED fabrication. Ink drying is often the rate limiting process and has required extremely large ovens in some implementations. It is not clear whether this step could be accelerated substantially by photonic curing at affordable cost. The quality of the OLEDs produced in most of these trials has been disappointing. To bring together the best aspects of each manufacturing process, speeds of R2R with materials quality from vacuum processes, a research institute has demonstrated that vacuum processes such as VTE can be carried out within R2R manufacturing.

Previous R&D by some OLED researchers and past experiences have made it clear that further R&D is needed before large scale R2R manufacturing of OLED lighting is attempted. The issues that must be addressed include:

- Defect control – prevention of particulate deposition and scratching of surface;
- Materials quality of organic films deposited at high speeds;
- Thermal management during processing – limited temperature rise in thin substrates;
- Mask handling or mask-free patterning;
- Removal of residual water from plastic substrates; and
- Singulation – cutting of glass substrates without edge damage.

4.2.5 Connected Lighting

4.2.5.1 Connectivity

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. 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.

4.2.5.2 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. [90]

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 improvement to building systems that have long operated in isolation. Connected lighting systems can help building owners understand how a space is being utilized by its occupants and 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, and 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 that deliver further energy savings (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). Connected street lights can 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 a 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.

4.2.5.3 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 an important facilitator for IoT implementation and increasing CLS installations, which would result in further energy savings. [91] [92] 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 SIG, 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. At present, these efforts are either too incomplete or immature to support lighting applications sufficiently and are not adopted by a significant number of lighting manufacturers. There is currently little native interoperability among commercially available connected lighting systems, so today's interoperability between CLS offered by different vendors is facilitated primarily through application programming interfaces (APIs).

As more LED lighting systems are being installed in buildings and municipalities, it is important to future-proof these systems to be able to work with lighting controls, or the potential for further energy savings will be lost as building owners will be slower to replace their conventional LED luminaires with new CLS. The potential connected location or 'node' may be lost for up to 10 years. For example, mesh topology is scalable and there is not a single point of failure with the mesh as there can be with a gateway approach. This allows for self-healing, and adding/removing devices can be done without disruption or reprogramming. Some proprietary systems are implementing a mesh network which has these benefits of the topology, and while interoperability may be lacking, the potential for improvement is being explored. In general, an open ecosystem with native interoperability is important for the full promise of CLS to be realized.

4.2.5.4 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. [93] 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. The potential vulnerabilities of IoT devices require that manufacturers integrate security into their product and software development lifecycle right from the start. In addition, IT departments need to be part of the discussion of integrating the CLS into buildings to ensure they can manage the connectivity and security of these systems.

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 ensure 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.

One benefit of the Qualified Bluetooth Mesh standard is that security is mandatory and built into the standard, even for the commissioning process. There are three types of security keys; first, the network key allowing a lighting node to join and send messages to the network; second, an application key so that a user can only control the lightings and not have access to other building systems such as HVAC; third, the device key that can remove a node from the network and refresh the network and application keys for the remaining nodes (this prevents the discarded node to be a point of attack). [94]

4.2.5.5 Connected Lighting Test Bed

The DOE Lighting R&D Program is working closely with industry to identify and collaboratively address the technology development needs of connected lighting systems. Central to the DOE efforts is a connected lighting test bed (CLTB), designed and operated by 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 they relate 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 facilitated by the use of APIs in several connected lighting systems and characterized the extent of interoperability that they provide. [95] 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. Further studies are ongoing to explore the ability of multiple streetlight central management systems to retrieve asset information from various make and model luminaires, and the ability to incorporate streetlight occupancy sensor data into the configured control strategies for one or more luminaires.

The establishment of specified test methods that target known vulnerabilities, either by design or via machine learning techniques, can be an important risk management layer for CLS. Standardized testing and certification for device cybersecurity is in its infancy, and DOE technical support can assist in the development of those standards to make them appropriate in scale and complexity for the lighting industry. DOE is collaborating with Underwriters Laboratory (UL) on their efforts to develop a standardized test method for cybersecurity vulnerabilities by evaluating draft methods in the CLTB and sharing results with Industrial Internet Consortium (IIC) partners. When one or more test methods are deemed sufficient, DOE will conduct studies to evaluate the cybersecurity vulnerabilities in connected lighting and the effectiveness of strategies to address them.

4.2.6 Reliability

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

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

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

4.2.6.1 LED Lumen Maintenance

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

The useful life of an LED package is often cited as the point in time where the luminous flux output has declined to 70% of its starting value, or L70. For products with lifetimes of many years or even decades, failures may be very slow to appear under normal operation. In 2008, the IES published IES LM-80, an approved method for measuring the lumen maintenance of solid-state (LED) light sources, arrays, and modules. [96] The LM-80-08 procedure required measurements of lumen output and chromaticity for a representative sample of products to be taken at least every 1,000 hours, for a minimum of 6,000 hours.

Many researchers have put much effort into devising a way to project the time at which L70 will be reached for an LED package in a luminaire, and IES has documented a forecasting procedure, IES TM-21, [97] which uses the LM-80 test data for the lumen maintenance projections (a minimum of 6,000 hours of test data is required). The LM-80 data (luminous flux vs. test hours) for the LEDs tested is averaged and an exponential curve fit is applied to the data; the results of the curve fit are used to calculate a lumen maintenance lifetime projection. This technical memorandum stipulates that any projection may not exceed a set multiple (depending on sample size statistics) of the actual hours of LM-80 testing data taken, which helps avoid exaggerated claims.

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

The impact of LED package design and materials of construction on performance, color quality, lumen maintenance and color shift have been investigated for a variety of LED packages. Different LED package platforms (detailed in Section 4.1) have different intrinsic characteristics based on materials of construction and manufacturing processes. At high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate, leading to lumen depreciation and color shift. More information on package degradation mechanisms and their impact can be found in LSRC's published paper, *LED Luminaire Reliability: Impact of Color Shift*.[21] [98]

4.2.6.2 LED Chromaticity Maintenance

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

The importance of chromaticity stability varies by application, and it may be more detrimental than lumen depreciation for some applications. For example, a high degree of chromaticity stability is crucial for light sources in a museum or retail store, but less important for street lighting. Chromaticity stability of the lamps and luminaires is important where multiple lamps or luminaires are being used to wash a wall, or where objects are being evaluated based on color, such as in a hospital or factory.

The color of light can be represented using chromaticity coordinates to describe its hue and saturation. A pair of chromaticity coordinates corresponds to a unique color of light; two sources with the same chromaticity coordinates should theoretically appear the same. Chromaticity diagrams representing the different color space have been developed and standardized by the Commission Internationale de l'Eclairage (CIE). The most commonly used chromaticity diagrams are the CIE 1931 chromaticity diagram using (x, y) coordinates to

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

specify chromaticity, and the CIE 1976 chromaticity diagram using (u', v') coordinates. To date, the industry generally quantifies chromaticity shift using Δu'v', which describes the magnitude of chromaticity shift, but does not capture the direction of the shift. (The actual chromaticity coordinates u' and v' are required to know the direction of the chromaticity shift.) The point at which a chromaticity shift becomes noticeable and results in parametric failure will depend on the lighting application. If the chromaticity change occurs slowly over a long period (e.g., 25,000 hours), it may not be objectionable in the case where the light sources shift by the same magnitude and in the same direction (but this is unlikely in practice).

There are no official standards limiting the amount of acceptable chromaticity shift in LED lighting products, but different certifications have established requirements. For example, to qualify for the ENERGY STAR label, 9 out of 10 samples of an LED lamp or luminaire must have a measured chromaticity shift (Δu'v') less than 0.007 over the first 6,000 hours of operation. Chromaticity shift requirements are not currently included in the technical requirements for DLC's SSL Qualified Products List (QPL), though will be added in the Version 5.0 technical requirements for future QPLs. For applications that require high chromaticity stability today, a specification may be established on a project-by-project basis. Beyond the lack of agreement on acceptable levels of chromaticity shift, there is no standard methodology for projecting future chromaticity maintenance using standard test procedures as there is for projecting LED package lumen maintenance. Furthermore, there are no established methods for accelerated testing, leaving each manufacturer to develop its own testing methodologies and predictive modeling approaches. A consensus methodology for predicting chromaticity shift will be a challenge as different materials of construction and manufacturing processes can affect the results; however, an IES committee is working to come to accord on this pressing issue (TM-35).

Chromaticity stability can vary based on LED lamp or luminaire product design with several factors affecting the resulting performance. Ambient air temperature, drive current, and the design of the lamp or luminaire's thermal management system can influence the junction temperature of the LED, which in turn, can affect its output characteristics. Aging-induced changes in the emitter, phosphor, encapsulant materials, and plastic resin can also affect chromaticity point stability in LEDs. Emitters can exhibit decreases in radiant flux over time; phosphors can experience decreases in quantum efficiency or shifts in emission spectrum due to oxidation; encapsulants can exhibit cracking, oxidation and yellowing, or changes in index of refraction; and resins can discolor and absorb photons, as illustrated in Figure 4.38. Higher temperatures will accelerate these degradation mechanisms leading to greater color shift, though the magnitude of the color shift as a function of temperature will vary with packaging materials and manufacturing processes. As with lumen maintenance behavior, if the LEDs are operated at low drive currents and lower than normal operating temperatures, these materials changes leading to chromaticity shift will be very slow to develop, if they occur at all.

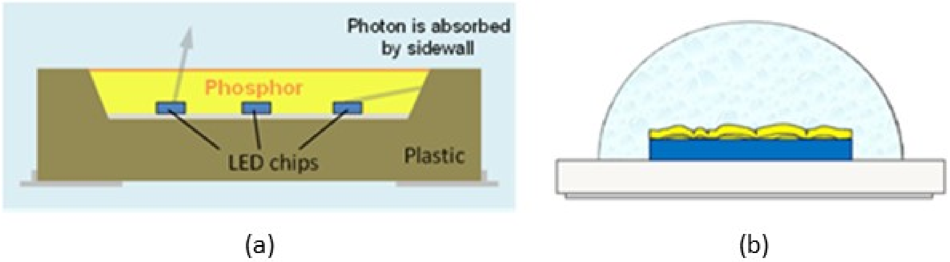
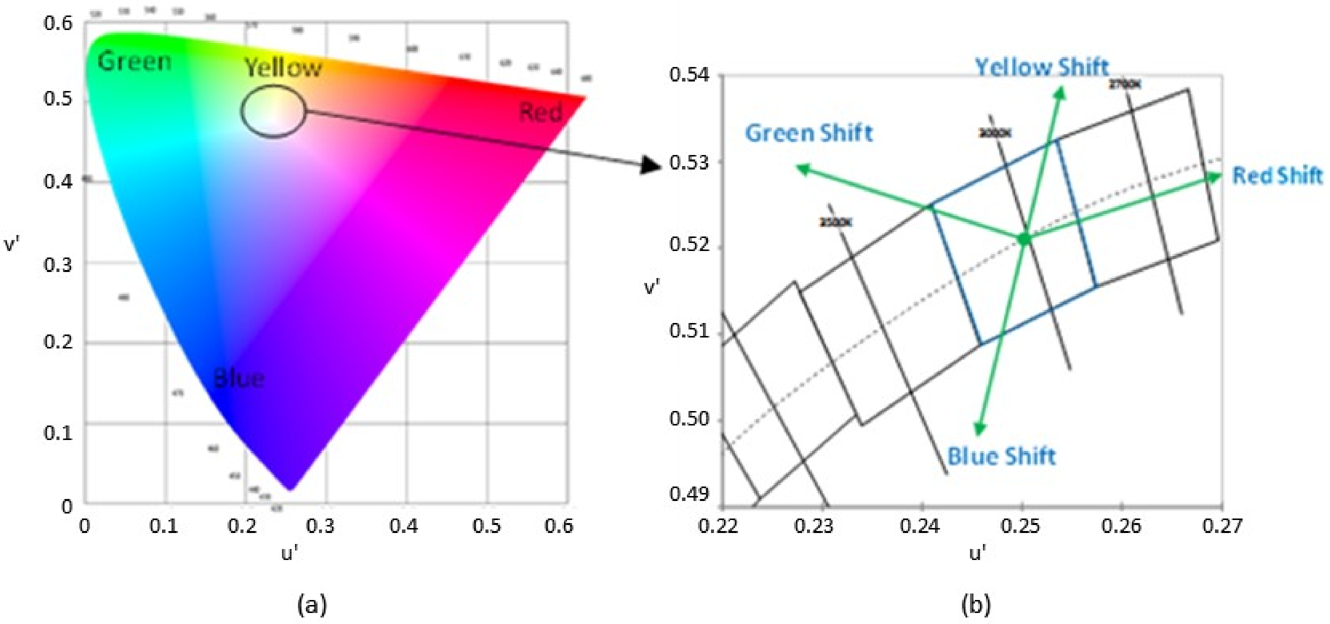


Figure 4.38 LED package schematics showing cases of color shifting:
(a) sidewall discoloration in a mid-power package that absorbs long-path length blue photons resulting in an overall blue chromaticity shift, and (b) phosphor delamination in a high-power package leading to a yellow shift due to the longer path-length through the phosphor when it delaminates. [99]

The resulting direction of chromaticity shift depends on the dominant degradation mechanisms occurring in the package, which in turn depends on the package's materials and methods of construction. The chromaticity shifts can be toward the yellow, blue, green, or red colors using the CIE 1976 chromaticity diagram as illustrated in

Figure 4.39. Different package platforms have shown distinct differences in the chromaticity shift signatures. Four main chromaticity-shift modes were identified and caused by changes in the LED packaging materials, including the behavior of the LED chip, the phosphor and silicone binder, as well as the plastic molding used as in the package body. More details on the color shift mechanism can be found in the DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) report titled "Chromaticity Shift Modes of LED PAR 38 Lamps Operated in Steady-State Conditions.[22]" [100]



(a) (b)

Figure 4.39 The 1976 CIE chromaticity diagram (u', v') detailing color shifts: (a) The white chromaticity region (denoted by the black circle) and the common directions of chromaticity shift in LED packages. (b) Zoomed in image of the white chromaticity bins (black circle). [101]

4.2.6.3 LED Luminaire Reliability

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

Further research has shown that electronic or driver failures, solder joint failures, or degradation of optical components can often occur long before LED package lumen depreciation results in failure. More information about observed system level failures can be found in LSRC's *LED Luminaire Lifetime: Recommendations for Testing and Reporting*[23]. [102]

LED luminaire failures can be parametric (lumen depreciation or chromaticity shift) or catastrophic (no light output). Both types of failure modes need to be considered when life testing LED systems. Continuous testing

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

[23] LSRC's report titled "LED Luminaire Lifetime: Recommendations for Testing and Reporting" can be found at: https://www.energy.gov/sites/prod/files/2015/01/f19/led_luminaire_lifetime_guide_sept2014.pdf

often leads to the emergence of parametric failure, though catastrophic failures can occur when the testing includes on-off cycling due to thermal expansion, which can lead to strain and breakage in different components or solder joints. [103] A study on LED A-lamps showed that lamps under life testing performed with on-off cycling showed a shorter time to failure relative to continuous life testing. In addition, many lamps failed catastrophically before L70 values were reached – in this case due to solder joint failures and driver electronics failures. [104] The way A-lamps will perform in the field also will strongly depend on the application, whether they are in a downlight fixture or table lamp, but more complete life testing protocols would help identify potential sources of catastrophic failure that may lead lower lifetimes than projected L_{70}.

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

4.2.6.4 Tunable Luminaire Reliability

The reliability of tunable luminaires brings additional sets of reliability challenges compared to single LED primary luminaires. These tunable systems still experience to lumen depreciation, chromaticity shift and catastrophic failures, but now there are more components to consider: multi-channel driver, multiple LED primaries, color mixing optics, and sensors. As with single LED primary systems, catastrophic failures can still occur but there are more components to worry about. As discussed in Section 3.4.2, tunable LED luminaire systems use two or more primaries to create various white chromaticity points, thus resulting in systems that can operate over a large range of possible light output conditions. Lumen depreciation is still an issue for the different individual LED primaries, but now with multiple LED primaries, lumen depreciation can also cause color degradation if the different primaries (colors) depreciate at different rates. If you change chromaticity, other parameters such as flux, efficacy, power factor, and color rendering all can change – some more than others. For any particular parameter, if the chromaticity is changed, then the parameter variation will be described by some surface. For example, as seen in Figure 4.40, flux will have a maximum at some color and fall off elsewhere. If there are more than 3 primaries, there will be multiple surfaces per parameter. For instance, if you have the ability to change color saturation, then the surface will change for each value of saturation.

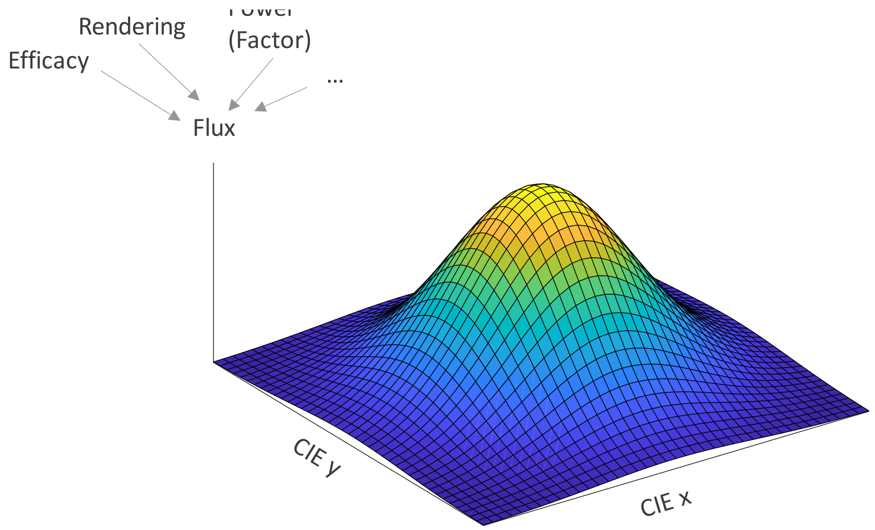

Figure 4.40 A surface showing the flux as a function of chromaticity point (CIE x and y parameters) for a tunable lighting system with three primaries. Multiple surfaces are possible if more than one parameter can be controlled simultaneously. [105]

With such a large set of operating ranges to adjust to the variety of chromaticity points and lighting output levels (including dimming), predicting the lumen and chromaticity depreciation can be very complex. As discussed above, different operating levels can result in different temperature and degradation rates in the LED packages. The operating history for the tunable luminaire in one installation may be different for another application and hence makes predicting the system lifetime, including chromaticity maintenance, much more difficult than conventional, single primary LED luminaires.

The starting point to gaining an understanding of tunable luminaire system reliability involves characterizing tunable luminaire products over a large range of possible light output conditions. Organizations have approached the testing challenge of tunable LED lamps and luminaires differently, depending on the purpose of the test data. Energy Star's Specification for Luminaires Version 2.2 requires that all tests and evaluations be performed at the least efficient white light setting included in this specification. [106] Additionally, watts, lumens, chromaticity, and CRI shall be tested and reported for the default and most energy consumptive white light settings as applicable (if different from least efficient white light setting).

PNNL published a report titled *Photometric Testing of White-Tunable LED Luminaires*[24] through the DOE CALiPER program, which evaluates emerging SSL products by producing objective data that quantify SSL technology performance for understanding the current issues facing SSL deployment. [107] The focus of this CALiPER study was to understand the amount of testing required to properly characterize a white tunable product. White tunable luminaires were tested at dozens of points covering the range of CCT tuning and dimming levels, though the focus of this study was on full-intensity measurements, which were typically at 11 color set points covering a range of CCTs. The results of the study revealed substantial variation in input power, lumen output, efficacy, and D_{uv} (distance from the black body locus) over the color-tuning range for many of the products. Such a variation would not be captured with only a few test points. The study concluded that testing will likely require at least five to seven measurement points to provide a reasonable characterization.

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[24] DOE's CALiPER report titled "Photometric Testing of White-Tunable LED Luminaires" can be found at: https://www.energy.gov/sites/prod/files/2018/09/f55/caliper_23_white-tunable-led-luminaires_0.pdf

Dim-to-warm lamps and luminaires are another class of tunable lighting, though they differ from white tunable LED luminaires by incorporating an architecture to automatically change the CCT to a warmer value as the intensity of the light is dimmed, imitating the behavior of incandescent lamps. Dim-to-warm LED lighting requires at least two different LED primaries, but usually only one control signal (single channel) that adjusts both chromaticity and intensity simultaneously according to the preprogrammed logic set by the manufacturer. White dim-to-warm LED lamps are not as flexible in the CCT tuning range as white tunable luminaires, but the simplicity of achieving this chromaticity change upon dimming is attractive for application areas such as restaurants, hotel lobbies and guestrooms, ballrooms, theaters, and residential spaces. The LSRC has published a report titled *Dim-to-Warm LED Lighting: Initial Benchmarks* where a methodology was developed to evaluate different architectures and dimming behavior for performance characteristics across the dimming range. [25] [108] The results in this study show that testing only at full power does not provide full performance information. Efficacy, flicker, and power factor all change at different dimming levels, and these parameters can fall out of range of some performance standards or specifications upon dimming.

These characterization studies are a good start to assess the various performance levels at a variety of operating conditions for tunable luminaires. IES is working on developing standardized testing protocols for white tunable luminaires which will help gather a more consistent suite of data for study. Further work is required to develop reliability models to understand the cause of system failures with a large variety of operating conditions.

4.2.6.5 OLED Lighting Reliability

Although the rate of lumen depreciation in OLED panels has decreased substantially through product improvements, stress tests of early OLED luminaires revealed deficiencies in encapsulation, leading to black spots and other defects. [109] In other cases, premature failures occurred through shorting in early usage. At the research level, significant progress has been made in understanding the growth of defects that lead to shorting and catastrophic failure. [110] The research has shown that most of the critical defects come from particulates in the organic layer rather than from the ITO electrode. These findings led to the development of a new device architecture that has achieved a substantial reduction in the number of early failures of OLED panels.

Recent accelerated-aging tests conducted by the Research Triangle Institute (RTI) have shown that considerable progress has taken place during the past three years in some panels. [111] Studies under ambient humidity were performed at room temperature (25^{o}C) and at elevated temperatures of 35^{o}C and 45^{o}C. The most stressful test was carried out with a 1-hr power on and 1-hr power off cycle at a constant temperature of 65°C and relative humidity of 90%. Although the studies on the most recent panels are still in progress, valuable data have already been obtained on lumen maintenance, voltage rise, and color shifts. No catastrophic failures have been seen in the panels to date, although driver failure has occurred under the high-humidity conditions.

The lumen depreciation observed for warm-white panels over 7,000 hours of operation is shown in Figure 4.41. The data shown in the left-hand frame show that the rate of lumen decay rises significantly in the high-temperature, high-humidity conditions, perhaps due to enhanced ingress of water. The right-hand frame shows the decay of the three-color OLED emitter layers at 45^{o}C, as deduced from the evolving spectrum of the emitted light. The impact of differential aging can also be seen in the changes in the color coordinates (u',v'), as shown in Figure 4.42. The shift is seen mainly in v', showing a shift to yellow.

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[25] The LSRC report titled "Dim-to-Warm LED Lighting: Initial Benchmarks" can be found at: https://www.nglia.org/documents/LSRC_Dim-to-Warm_Paper_final_073019r.pdf

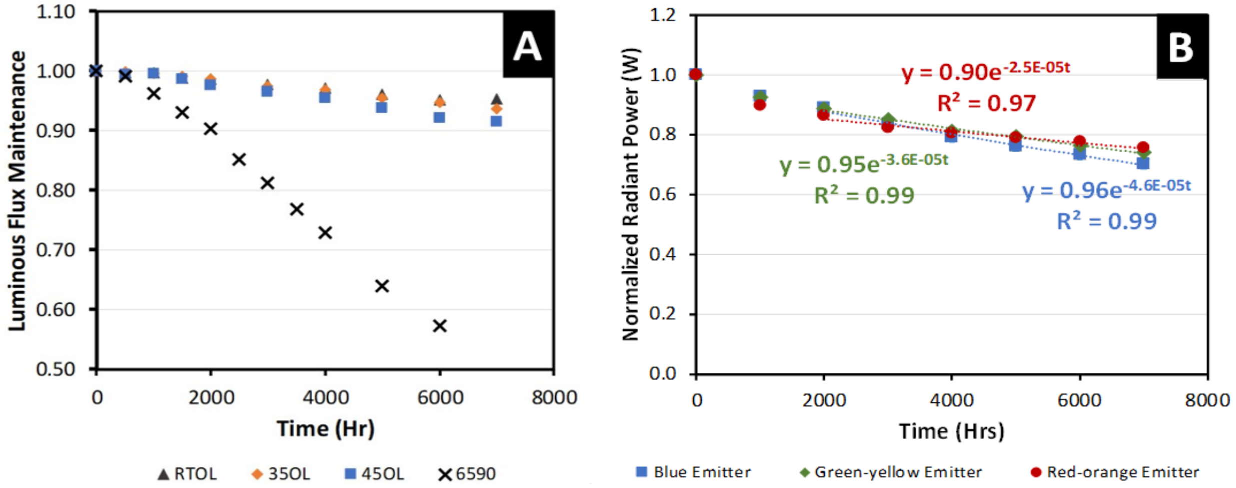

Figure 4.41 Lumen depreciation for warm white Brite-3 panels: A) at different operating conditions with respect to temperature and humidity, B) results for the three-color OLED emitter layers at 45oC operating conditions. [111]

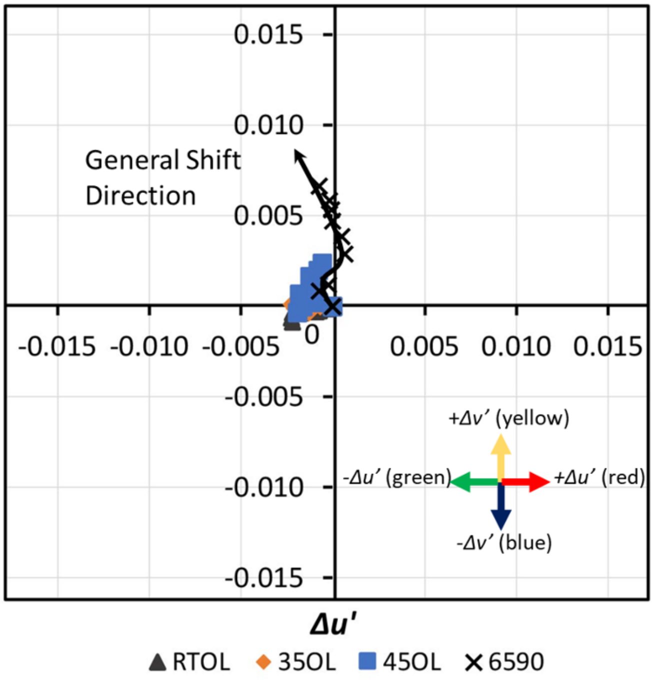

Figure 4.42 Shifts in the CIE color coordinates (u’,v’) with aging for the Brite-3 panels for different operating conditions with respect to temperature and humidity. [111]

Another concern that was confirmed in these stress tests is the rise of voltage and power needed to maintain the desired current and light output. Even under normal room conditions, these rose by ~8% for the warm-white panels. These results in this study were obtained while operating the panel at the maximum luminance (8,500 cd/m^2). In practice, many users run their luminaires at lower output levels and will experience slower aging impacts, though these results help point to the improvements required in OLED devices to reach higher light output luminaires. [111]

4.2.7 Lighting Science

Advancements in lighting science will provide guidance as to optimum light levels, spectral power distributions, and optical distributions for various tasks in various settings. This new guidance may not be different from current guidance, but it is appropriate to update the underlying research within the context of the new levels of control offered by SSL technology. We need lighting science to not only understand and guide optimum lighting conditions but also to avoid or minimize negative side effects of lighting such as glare or temporal light artifacts.

4.2.7.1 Human Vision

Within the vision function of lighting, light spectra have historically been optimized to maximize the luminous efficacy while also achieving adequate or desired general color qualities as described by the metrics of CCT and CRI R_a or, more recently, IES TM-30 R_f and R_g. The new ability to tailor the spectrum of LED technology enables more customized optimization for specific visual functions, such as color discrimination, color discernment, or color contrast. An example of LEDs engineered for color discernment of specific objects is depicted in Figure 4.43 below. The LED packages are spectrally engineered to provide color peaks in the desirable attributes of the illuminated objects and have reduced color of the less desirable aspects of the objects. A more general understanding can be gained by considering that the reflectance spectra of the objects were considered in the design of the LED spectrum to maximize or minimize reflectance of certain portions of the spectrum.

Nichia’s Data

Figure 4.43 LED packages spectrally engineered to highlight different color aspects of certain products or targets. [112] The color balance of the LED package can be engineered to highlight (or minimize) reflectances of features within the illuminated product. The same concept could be applied to medical applications where color balances could enable discernment of certain maladies.

This approach can be extended to any visual application where discernment of different color objects or different colors within an object are important. To support the LAE framework, lighting science related to human vision can provide guidance as to ideal intensity levels, directionality, and spectrum for a given activity. While this guidance does exist, it was mostly developed when there were few tools and limited computational means to determine optimal lighting conditions, and there were even fewer products for delivering optimum light. With the SSL platform, very precise lighting can be delivered to a defined target and new lighting science can guide understanding of exactly what precise light (and level of precision) is necessary for various lighting activities.

The control offered by SSL in terms of spectrum and optical control (including active control), as well as new understanding of non-visual responses to light, necessitate improved understanding of glare. Also, SSL technology that is static, dimmable, and color tunable brings up new questions about temporal light artifacts or flicker.

In order to deliver precisely optimized light, glare needs a better understanding through updated quantifiable metrics. There are a vast number of lighting installations, both indoor and outdoor, where a large portion of light from the source reaches the eye directly. This light is not illuminating an object and, in fact, makes objects more difficult to view. This light is unnecessary and detrimental to the function of installed lighting products. So, in many lighting situations, glare-causing portions of light can be eliminated, thus improving the lighting function and saving energy. For certain, higher risk activities, such as driving at night, glare can reduce safety for both drivers and pedestrians.

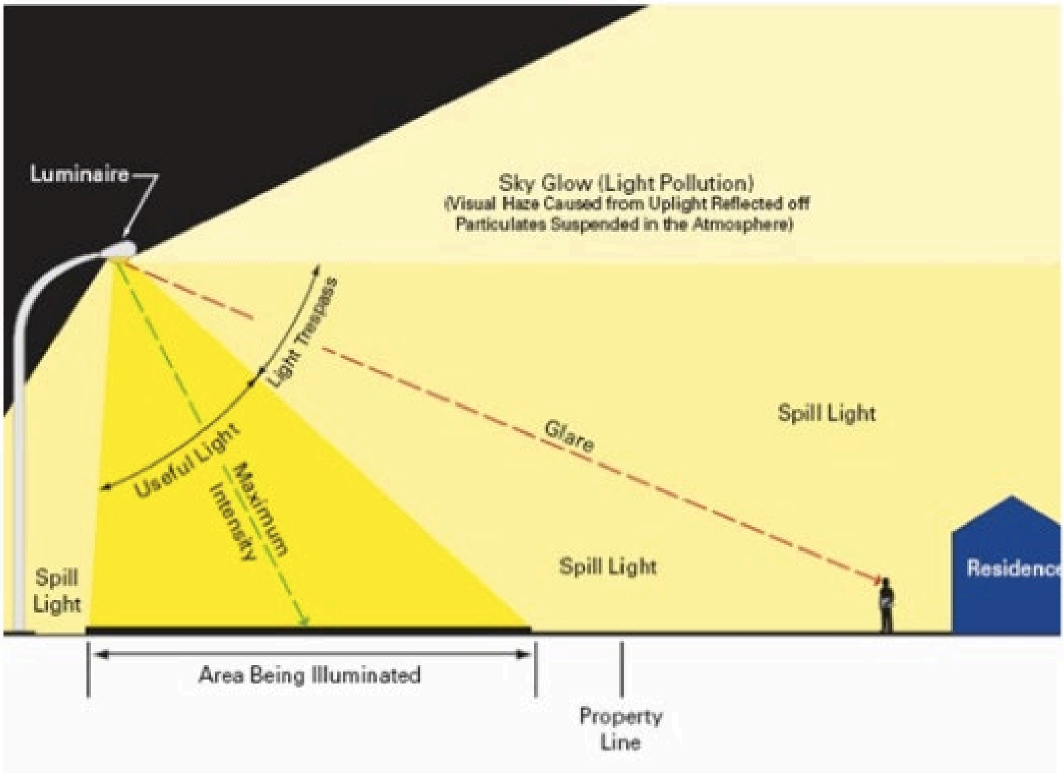

Figure 4.44 Typical streetlight showing a small portion of useful light and significant light pollution and glare, which reduces the functionality of the light. LED technology can be much more precisely engineered to minimize detrimental light emissions. [113]

For roadway lighting safety there is also initial evidence that the spectrum of roadway lights has a significant impact on detection distance of objects in and around the road. In Figure 4.45, LED lighting with a CCT of 4100 K has a significantly longer mean detection distance compared to HPS or warmer color temperature LED lighting. This translates to increased response time for a driver. More research of this type can provide additional guidance as to optimum SPD, intensity, and optical distribution that will minimize glare and maximum detection distances for various roadway settings.

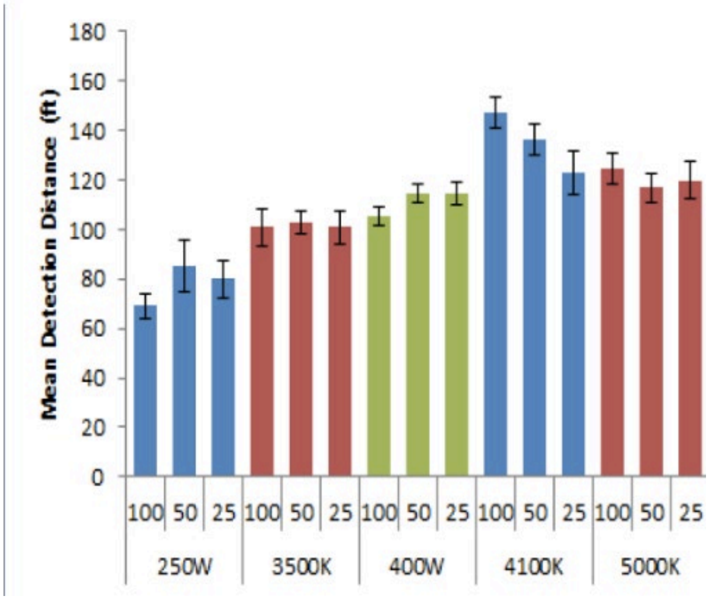

Figure 4.45 Initial research showing increased detection distance for 4100 K white LED roadway lights compared to HPS and warmer spectra LED lighting. [114] Increased detection distance should result in increased stopping distance or improved safety.

The examples described above are just two examples of the need for improved lighting science guidance to enable the full benefit of the SSL technology platform. Clear understanding of lighting science enables improved lighting performance, and clear lighting guidance enables product developers to achieve the guidance using the lowest possible amount of energy. So improved lighting science understanding will enable both improved lighting performance (in terms of productivity, health, and safety) as well as reductions in energy consumption while achieving these benefits.

4.2.7.2 Non-visual Physiological Responses

General illumination enables humans to see via their primary optical tract, furthering productivity indoors and/or at night when sunlight is unavailable. We now know that there is also a second pathway between the eye and the brain that supports light regulation of circadian, behavioral, and endocrine responses and ultimately has a significant impact on human health and productivity (see Figure 4.46). The discovery and delineation of this second optical pathway is relatively recent and there is ongoing research that is refining the understanding of these physiological impacts of light.

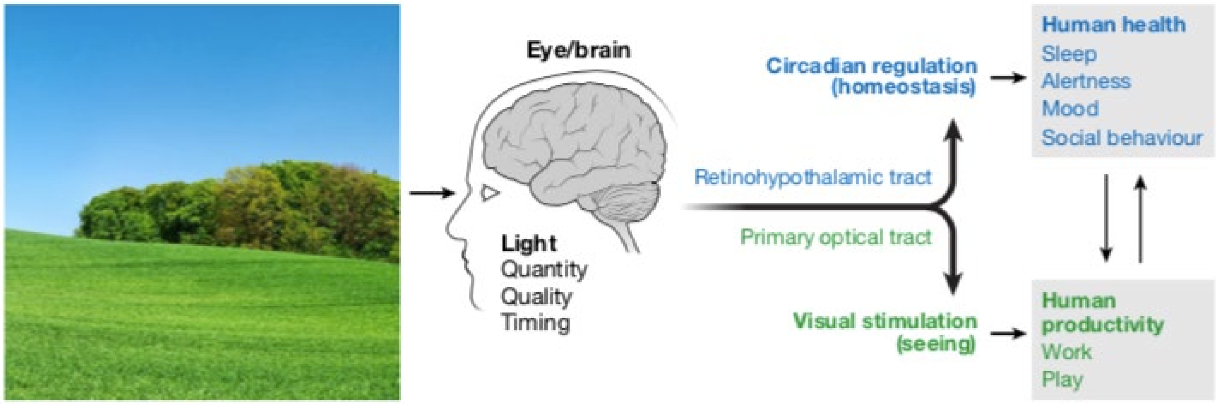

Figure 4.46 The two photoreceptor pathways between the human eye and the brain. [1] Light detected by the eye enables visual stimulation (vision) and also circadian regulation which affects human health by affecting sleep, alertness, mood, and social behavior.

Scientists have only recently been able to delineate the photoreceptive input to the circadian and neuroendocrine systems and have identified 446–477 nm as the most potent region for acute melatonin suppression in healthy human subjects, as seen in the action spectra curve below (Figure 4.47). However, further understanding is necessary to understand and optimize light spectrum and intensity for optimizing non-visual physiological responses in realistic lighting settings. In particular, research is necessary to better understand light levels, with respect to spectral content, that are too low to evoke a melanopic response or are high enough that the melanopic response is saturated in realistic lighting situations. This understanding needs to be developed while considering that there can be a wide range of physiological responsiveness to light from different individuals. Identifying the range of individual responsiveness is an additional challenge for interpreting research results and developing lighting guidance. There are also factors of timing, individual light history, duration of the light stimuli, and individual physiological differences that can impact the effectiveness of the light stimuli for achieving the desired physiological responses. The impact of these factors needs to be understood for real world settings, so research findings can be translated into practical, beneficial implementation.

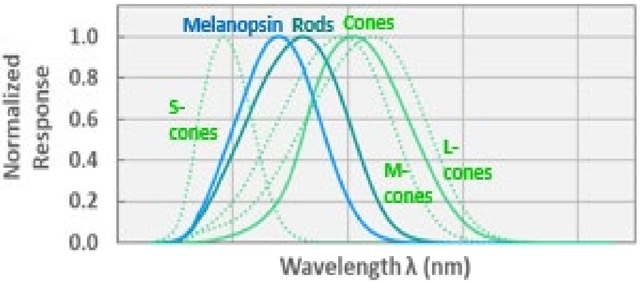

Figure 4.47 Action spectra for humans. [115]

In addition to controlling for mediating factors in the research, many physiological studies have also focused on sub-populations, such as nightshift workers, or populations of subjects that have particular maladies or sensitivities to light. This research can be informative for the development of lighting guidance for the broader population of healthy day-workers; however, the findings must be appropriately translated for more general guidance. Night-shift studies, in particular, represent an unusual situation where light, work, and wake cycles are greatly offset from natural daily rhythms. For those working on a night-shift, the objective is to maintain alertness while minimizing circadian disruption, if possible, while for healthy day workers the alerting impacts of light and healthy circadian entrainment are in alignment. This will be the case for the vast majority of lighting deployments and, as such, should be the focus of research and implementation to achieve maximum health, productivity, and energy savings benefits. Even a marginal health impact for the vast day-working, healthy population that lives and works under electric lighting would result in enormous health and productivity benefits. Validating and quantifying these benefits, locally and globally, will be an important aspect of this research.

Ongoing translational research is necessary to translate lab-scale and sub-population level research into general guidance for lighting practice. To be as clear as possible, translational research should consider changes in lighting conditions in realistic lighting settings that result in a measurable change in physiological responses for a meaningful number of subjects/occupants in the space. The measured physiological responses should be objective and cover as many occupants as possible. This is challenging research since there are numerous lighting applications, settings, functions of light, and variations in occupants that can complicate the research, so significant efforts will be necessary. Clear lighting guidance, with respect to non-visual human physiological responses, will enable improved occupant health and lighting manufacturers to develop products with clear performance targets that can be achieved with maximum efficiency.

Specific research directions to help elucidate the physiological responses to light and aid translation into real world installations include:

- Low light intensity and high light intensity response thresholds;
- Spectrum-intensity relationships for achieving responses;
- Individual variations in physiological responses due to individual phenotype or individual mediating factors including, photohistory, optical factors such as age and pupil responses, behavior, and/or specific sensitivities;
- Understanding and validation of levels of objective physiological impacts in realistic lighting environments; and
- Relating objective physiological impacts to benefits in health and productivity for various lighting situations.

All research should be performed with the objective of providing clear guidance for lighting deployment to achieve physiological benefits. Research on sub-populations or specialized lighting situations is supported as long as the findings can be applied to more general lighting situations for healthy occupants on standard, day-working schedules that have the greatest health, productivity, and energy savings impacts.

4.2.7.3 Horticulture

Indoor horticulture, also known as controlled environment agriculture (CEA) is a relatively new application for LED lighting. In this application, plants are the primary receiver of the light emitted from a fixture[26] and plants have multiple receptors with unique response spectra as shown in Figure 4.48 below.

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[26] The term ‘light’ implies a human visual response to the radiation which is not the case for plant reception. However, light is a useful term for describing the emission from a fixture that is received by both humans and plants.

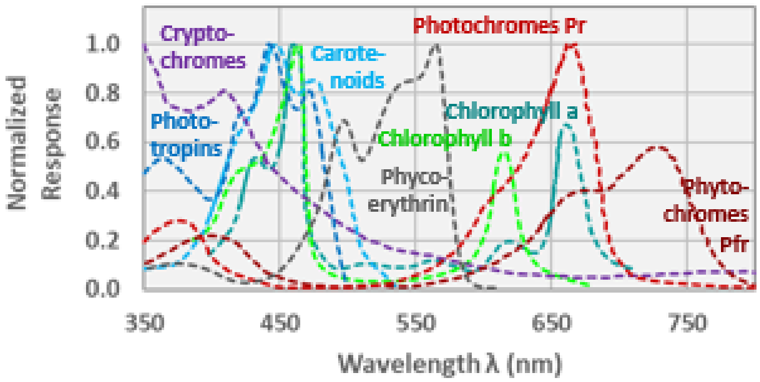

Figure 4.48 Plant action spectra associated with the primary classes of photosensitive molecules in plants. [1]

These receptors play a role in both plant growth and development, and the light from a fixture can be optimized to preferentially overlap with the different receptors. However, because the receptors span wavelengths from 400-700 nm (and likely beyond), plant responsivity to light is weighted equally across the spectrum between 400 and 700 nm. In addition, since plant responses are driven by photon reception, characterization of light for plant responses is in terms of photons rather than optical power or lumens as it is with human lighting. The analogous lumen-based metrics and accepted plant metrics are provided in Table 4.3 below. As more granular understanding of plant spectral needs is understood, then more specific plant response spectra may result, and light fixtures can be engineered to optimize that plant response. However, just as illumination for humans must accommodate multiple functions of light, horticultural lighting must be suitable for multiple plant responses, and it can be helpful to enable close inspection of plants by humans (or possibly machine vision inspection of plants) for pathogens, nutritional deficiencies, or other problems.

Horticultural lights use a measure called photosynthetic efficacy (µmol/J): the ratio between the photosynthetic photon flux (PPF, µ-moles/second) and the electrical source power (pe) used to create that photosynthetic photon flux:

$$\text{Photosynthetic Efficacy} = \frac{PPF}{p_e}.$$

The photosynthetic flux is the molar flux of photons within the plant absorption spectrum (typically taken to be wavelengths between 400 and 700 nm):

$$\text{PPF} = \frac{1}{N_A}\int_{400}^{700}\frac{p_o(\lambda)}{hc/\lambda}\,d\lambda,$$

where NA is Avogadro's number, c is the speed of light, h is Planck's constant, and hc/λ is the energy of a photon at wavelength λ. Note that there is no wavelength-dependent weighting of photon efficacy, though one could imagine someday including such a weighting as our understanding of plant responses to light becomes more sophisticated. [143]

Table 4.3 General illumination and horticultural metrics.

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

Horticultural lighting products can now readily achieve 2.4 – 2.5 µmol/J efficacy at output levels corresponding to 1000 W high pressure sodium lights (HPS), and some have claimed greater than 3 µmol/J efficacy. These efficacy levels are in alignment with LED performance projections shown in Figure 4.49 below and consider typical luminaire fixture losses. Earlier products tended to use a blue + red spectrum to capitalize on spectral benefits suggested by photosynthesis response peaks and the availability of efficient LEDs at these wavelengths. More recent products are tending toward the use of white or white + red LEDs since recent research suggests that green photons are valuable for photosynthesis, are important for pest and pathogen inspection and detection by workers in the grow area, and are lower cost.

Historical and projected future LED horticultural efficacy levels can be derived from the LED performance projections found in Figure 4.49. As with other LED projections in this document, the efficacy levels can be increased by running the LEDs at a reduced current density, and they can be decreased by increasing the current density.

Two photosynthetic efficacy curves are shown in Figure 4.49. The curve in blue is associated with conventional PC-LED white light. Since LED packages that have been optimized for humans are being used in some horticulture applications, we have also assumed here an LED package with a color rendering index of 80 – even though plants, of course, are not sensitive to color rendering, but humans working in the area will be. The trend for horticultural efficacy is similar to that for humans: a steady increase this past decade by also more than a factor of ~2x, from ~1 to ~2.4 µmol/J, driven similarly by the increasing efficiencies of the blue LED, phosphor, and package. There is a projected future saturation at ~3.1 µmol/J, similarly limited by phosphor conversion efficiency losses, not including Stokes losses.

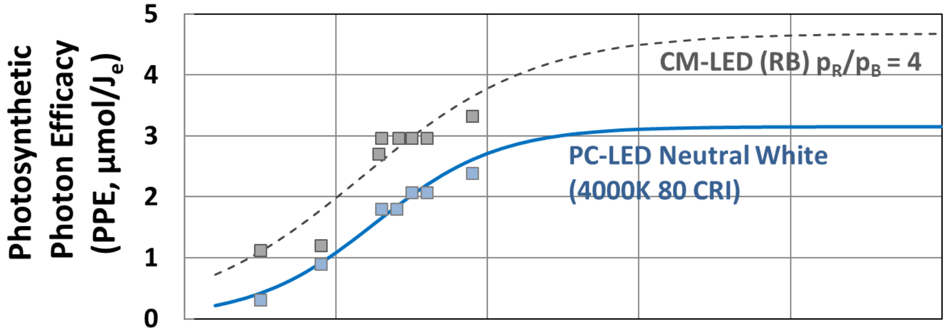

Figure 4.49 LED photosynthetic photon efficacy measured at 25°C and 35 A/cm2 input current density. PPE for a typical PC-LED architecture with a neutral white color temperature, and for a hypothetical CM-LED architecture containing only red and blue LEDs with an optical power ratio of 4:1. The points and lines represent the photosynthetic efficacies of source assuming the same historical (points) and projected (lines) efficiencies of the underlying LED technologies. [4]

The curve in blue is associated with a CM-LED architecture. Here, a 2-color RB in a ~4:1 power ratio is considered, as this is a common configuration. The PPE for this color combination is higher than the phosphor-converted white LED. This difference persists out to the future, where long-term target efficiencies for red and blue LEDs would result in PPE of 3.1 and 4.7 µmol/J for the PC-LED and CM-LED architectures, respectively. Many horticultural lights now use a phosphor-converted white LED + red spectrum, which would have PPE levels between the two curves in Figure 4.49. Of course, there are considerations beyond pure PPE. Light spectrum will affect plant growth and development and the role of green light is being researched. [116] Figure 4.49 describes LED package performance. When these LED packages are integrated into a light fixture there will be efficacy losses, similar to those described in Table 3.5. Thus, fixtures can be expected to achieve about 80-85% of the LED PPE, keeping in mind that the LED package PPE may be higher than what is shown in Figure 4.49 if LEDs are operated at reduced current density.

4.2.7.4 Animal Responses to Light

Just as plants and humans have particular physiological responses to light, animals have their own physiological and behavioral responses to light as well. A significant amount of animal production occurs in controlled environments that require electric lighting and these responses can be engaged to make animal production healthier and more productive. In these environments, lights can be engineered in terms of spectrum and intensity to provide naturalistic signals to support healthy circadian rhythms; the spectrum can also be tailored to improve health, improve productivity, and even reduce aggressive behaviors. This is a newer value proposition for lighting, but it is one that is synergistic with developments in lighting for human health and well-being and controlled environment horticultural lighting.

Light at night also impacts wild animals. Roadway lighting, signage, and light spillage from buildings at night can all have negative impacts on local wildlife. The light spectrum from some of these night lights can be adjusted to minimize negative impacts on wildlife. However, the function of the light must be considered as the primary consideration, particularly when it comes to lighting for roadway safety. Fortunately, for roadway lighting, LED technology offers the possibility of reducing the total amount of light while maintaining sufficient light for roadway safety through the use of more precise optical control (optical delivery efficiency), reducing light levels through the use of dimming controls when the light is not necessary (intensity effectiveness), and providing optimum spectrum for safety and then minimized ecological impacts.

4.3 New Frontiers in Light

The DOE Lighting R&D Program has focused on saving energy through the development of more efficient light sources for general illumination. The development of LED and OLED lighting technology platforms enables energy savings through more efficient sources and also through better control of the generated and delivered light. There are also new opportunities for improved lighting effectiveness and productivity, as described in the previous discussions. These new opportunities in lighting effectiveness and productivity require consideration of a broader range of applications beyond general illumination that offer energy savings and productivity possibilities (e.g., horticultural lighting or lighting for animal production). Related technologies that similarly use LEDs and OLEDs, such as information displays, can also be considered for energy savings and productivity benefits. The DOE Lighting R&D Program is developing a framework for evaluating the energy savings and productivity benefits for these new frontiers in R&D and comparing the prospects against potential for energy savings and productivity benefits within general illumination. The results of these evaluations will inform future R&D directions for the DOE Lighting R&D Program. The particular evaluation criteria that will be considered are:

- Current total energy consumptions in the application;
- Future total energy consumption;
- Prospects for technology enabled efficiency improvements;
- R&D impacts of DOE R&D support;
- Productivity and other non-energy benefits associated with application; and
- Technology overlap with general illumination technologies

5 Priority R&D Opportunities

Descriptions of specific R&D opportunities are provided below. Some descriptions of research reference color or descriptive terms for color temperature. Table 5.1 shows these ranges for various color wavelengths and explains the meaning of color temperature.

The metrics 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.

Color	Dominant Wavelength or CCT	CRI
Blue	440-460 nm	N/A
Green	530-550 nm	N/A
Amber (Yellow)	570-590 nm	N/A
Near Red (Orange)	610-620 nm	N/A
Red	650-670 nm	N/A
Warm White	3000 K	≥ 80
Cool White	5700 K	≥ 70

Table 5.1 Assumptions for wavelength and color as used in the task descriptions.

Lighting Application Efficiency Framework			
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 and quantification of *Light Source Efficiency* (this should be readily available), *Efficiency of lighting delivery to receptor* (typically the eye), *Spectral efficiency,* and *Intensity effectiveness.* The proposed framework and model should result in predictable characterization of Lighting Application Efficiency for any lighting application and enable modeling tools to optimize lighting application efficiency for any application in any space.			
Metrics	**2019 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

Table 5.2 LAE Framework R&D Opportunities

Light-Emitting Diode Research

Description: Develop new or improved emitter materials with an advanced fundamental understanding of materials-device-synthesis relationships and resulting performance 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:

- Improvements or guidance for improving red, amber, and green LED performance.
- Improved understanding and models for prediction of LED performance in different materials systems.
- Fundamental understanding of non-radiative recombination mechanisms, including non-radiative defects and impurities, current density droop, and thermal droop, that can enable improved mitigation approaches.
- Modeling that can help predict device performance from materials properties of new emitter material systems.

Work on novel LED materials should be structured to achieve definitive understanding on some aspect of LED science. All research should be on highest caliber materials and devices to yield clearest possible results. Results should ultimately 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	2019 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† - 35A/cm^2, 25^{o}C	71% (Blue) 30% (Green) 51% (Near Red*) 16% (Amber*)	84% (Blue) 50% (Green) 70% (Near Red) 30% (Amber)	90% (Blue) 75% (Green) 85% (Near Red) 70% (Amber)
PCE† - 100A/cm^2, 85^{o}C	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)

Table 5.3 LED R&D Opportunities

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* 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>
<tr><th colspan="4">High Luminance Emitter Device Architectures</th></tr>
<tr><td colspan="4">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) or luminance (cd) through increased collimation of the light output. 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. This topic includes research on phosphor materials and matrices suitable for high luminance operation that can also achieve suitable color quality.</td></tr>
<tr><th>Metrics</th><th>2019 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>PCE† - 35A/cm^2, 25^{o}C</td><td>71% (Blue)
[168 lm/W (Warm White)]</td><td>84% (Blue)
[237 lm/W (Warm White)]</td><td>90% (Blue)
[249 lm/W (Warm White)]</td></tr>
<tr><td>Luminance and optical distribution for application efficiency</td><td>310 lm/mm^2, Lambertian distribution</td><td>500 lm/mm^2, optimized optical distribution pattern</td><td>800 lm/mm^2, optimized optical distribution pattern</td></tr>
</table>

Table 5.4 High Luminance Emitters R&D Opportunities

<table>
<tr><th colspan="4">Diffuse Light Source Emitter Materials</th></tr>
<tr><td colspan="4">**Description:** Develop or advance materials and structures that can improve the performance of low profile, diffuse lighting concepts that leverage the OLED technology platform. Advancements to the state of the art of OLED platform could be in the emitter materials, the device architecture, or system reliability. Approaches should demonstrate a path to achieving efficient, low profile, diffuse lighting performance with good color quality and lifetime. Alternative emitter concepts, such as electroluminescent quantum dots or perovskites, that leverage the OLED platform will be considered as well, but they must demonstrate a path to equal and then surpass all aspects of OLED device performance.</td></tr>
<tr><th>Metrics</th><th>2019 Status</th><th>Interim 2025 Target</th><th>2035 Targets</th></tr>
<tr><td>Internal Quantum Efficiency (white emitter)</td><td>62%</td><td>80%</td><td>85%</td></tr>
<tr><td>Voltage per stack @ 10,000 lm/m^2</td><td>2.83 V</td><td>2.75 V</td><td>2.7 V</td></tr>
<tr><td>Stability</td><td>L70: 40,000 hours at 10,000 lm/m^2 L70 Catastrophic failure rates
Color shift</td><td>L70: 50,000 Hours at 10,000 lm/m^2</td><td>L70: 50,000 Hours at 10,000 lm/m^2</td></tr>
</table>

Table 5.5 Low luminance Emitters R&D Opportunities

<table>
<tr><th colspan="4">Advancing Quantum Dot Technology</th></tr>
<tr><td colspan="4">Description: Research to advance understanding of on-chip quantum dot (QD) down converters to match or exceed performance of conventional on-chip phosphor materials. Research should explore materials 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 performance levels that make new materials competitive with conventional phosphors for application in general illumination. Research in down-converters that do not contain heavy metals or scarce materials is strongly encouraged. Metrics below describe the status of state-of-the-art phosphors used for LED lighting to provide targets for down converter performance.</td></tr>
<tr><th>Metrics</th><th>2019 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Quantum Dots
Quantum yield (QY) at 150°C across the visible spectrum and at 1 W/mm2</td><td>88% (Green)
81% (Red)</td><td>91% (Green)
88% (Red)</td><td>99% (Green)
95% (Red)</td></tr>
<tr><td>Quantum Dots
Spectral FWHM</td><td>110 nm (Green)
75 nm (Red)</td><td>70 nm (Green)
30 nm (Red)</td><td>30 nm
(at all wavelengths)</td></tr>
<tr><td>Quantum Dots
On-chip reliability:
Color shift, Depreciation, Failure</td><td>$\Delta u'v' < 0.007$
at 6,000 hours</td><td>$\Delta u'v' < 0.002$
over life</td><td>$\Delta u'v' < 0.002$
over life</td></tr>
</table>

Table 5.6 Down Converters R&D Opportunities

Diffuse Light Source Optical Efficiency			
Description: Develop or advance optical efficiency and optical control approaches to improve the performance of low profile, diffuse lighting concepts. Proposed concepts can apply to the OLED technology platform to improve light extraction efficiency while also enabling control over the optical distribution.			
Metrics	2019 Status	Interim 2025 Target	2035 Targets
Diffuse direct emitter - Light Extraction Efficiency	55%	60%	75%

Table 5.7 Diffuse Light Source Optical Efficiency R&D Opportunities

Advanced Lighting Concepts

Description: Develop component or full lighting product concepts that demonstrate new or advanced lighting features, including very high efficacy, color tunability with high efficiency, or improvements to other aspects of lighting application efficiency. Improvements can be to the LED chip, package, module, or integrated lighting product. Concepts could also demonstrate favorable form factors for improved LAE, lighting performance, ease of installation, or building integration or could demonstrate the use of new, more sustainable materials or reduced materials in the lighting product. R&D concepts should describe advancements in terms of quantitative improvements to one or more aspects of lighting application efficiency-

Metrics	2019 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)	114 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: limited to remote at dimmer switch	Intensity control: active and automatic	Intensity control: active and automatic

Table 5.8 Advanced Lighting Concepts R&D Opportunities

* 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>
<tr><th colspan="4">Power and Functional Electronics</th></tr>
<tr><td colspan="4">Description: Develop advanced prototype LED or OLED 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 for suitable applications. 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 or provide for new form factors that enable advanced lighting concepts. Work on different power levels (higher or lower) should provide similar status levels and targets.</td></tr>
<tr><th>Metrics</th><th>2019 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Power supply efficiency, multi-channel</td><td>88%</td><td>93% at full power
90% in dimmed state</td><td>95% at all operating conditions</td></tr>
<tr><td>Power supply reliability</td><td>Applicant estimated lamp/luminaire survival factor (various methods used)</td><td>95% survival rate with a 90% confidence level across reported case temperature curve</td><td>99% survival rate with a 90% confidence level across reported case temperature curve</td></tr>
<tr><td>Size-volume-form factor: Lumens (or watts) per volume (or mass)</td><td>100 W Driver:
650 g
475 cm^3</td><td>100 W Driver:
300 g
275 cm^3</td><td>150 W Driver:
200 g
175 cm^3</td></tr>
</table>

Table 5.9 Power and Functional Electronics R&D Opportunities

Additive Fabrication Technologies for Lighting

Description: Develop high volume additive manufacturing technologies for any portion of the 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.
- Roll to roll production of planar, diffuse lighting products
- Printable lights

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. Manufacturing technologies and advancements should not come at the expense of efficiency or performance.

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.

Metrics	2019 Status	Interim 2025 Targets	2035 Targets
Additive manufacturing (metrics vary by application and use case)	Materials utilization: depends on application	Materials utilization: applicant discuss and describe improvement	Materials utilization: applicant discuss and describe improvement
	Manufacturing cost reduction: depends on application	Manufacturing cost reduction: applicant discuss and describe improvement	Manufacturing cost reduction: applicant discuss and describe improvement

Table 5.10 Additive Manufacturing R&D Opportunities

<table>
<tr><th colspan="4">Understanding and Demonstrating 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, day working 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. Translational R&D should provide convincing validation of the physiological impacts and resulting benefits of lighting that engages human non-visual responses.</td></tr>
<tr><th>Metrics</th><th>2019 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 5.11 Physiological Impacts of Light R&D Opportunities

6 Appendices

6.1 Currently Funded Projects

Table 6.1 SSL R&D Portfolio: Current Research Projects, September 30, 2019

	Research Organization	Project Title
LED	Columbia University	Environmentally Robust Quantum Dot Downconverters for Highly Efficiency Solid State Lighting
	Eaton Corporation	Additively Manufactured Solid-State Luminaire
	EIE Materials, Inc. (dba Lumenari, Inc.)	Narrow Emitting Red Phosphors for Improving PC-LED Efficacy
	Glint*	Antireflective Materials for High-Efficiency Lighting
	Hazen Research, Inc.*	Low-cost Flexible Transparent Electrodes Based on Ag–ZTOF (Zn–Sn–O–F) Amorphous Composites through Inkjet Printing
	Innosys*	Novel Materials for Flexible Solid-State Lighting
	Lucent Optics, Inc.*	Ultra-Thin Flexible LED Lighting Panel (Phase II)
	Lumileds, LLC	High-Luminance LED Platform for Improved Efficacy in Directional Lighting
	Lumileds, LLC	Improved Radiative Recombination in AlGaInP LEDs
	Lumisyn, LLC*	New Class of Encapsulants for Blue LEDs
	Lumisyn, LLC*	Tunable Nanocrystal-based Phosphors with Reduced Spectral Widths
	National Renewable Energy Laboratory	AlInP-based LEDs for Efficient Red and Amber Emission
	Ohio State University	High Efficiency InGaN LEDs Emitting in Green, Amber, and Beyond
	Pacific Northwest National Laboratory	Characterization of Connected Lighting Systems Potential to Provide Grid Services
	PhosphorTech Corporation*	Stable Perovskite Core-shell Nanocrystals as Down-Converting Phosphors for Solid State Lighting
	PhosphorTech Corporation*	Hybrid Down-Converting Structures for Solid State Lighting
	Sandia National Laboratories	Tunneling-Enabled High-Efficiency High-Power Multi Junction LEDs
	Tetramer Technologies, LLC*	Transparent Conductive Anodes for Solid-State Lighting
	University of California-Santa Barbara	High Performance Green LEDs for Solid State Lighting
	Virginia Polytechnic Institute and State University	Adaptive Lighting for Streets and Residential Areas
	Virginia Polytechnic Institute and State University	Investigating the Health Impacts of Outdoor Lighting
OLED	Arizona State University	Improved Light Extraction by Engineering Molecular Properties of Square Planar Phosphorescent Emissive Materials
	Atom*	Scalable Ultrahigh Conductive Transparent Single-Walled Carbon Nanotube Films for High-Efficiency OLED Lighting
	Electroninks Inc.*	High Performance Substrate Embedded Microgrids for High Efficiency, Flexible Organic Light Emitting Diodes
	Electroninks Inc.*	Microfluidic Printing of High Performance Microgrids for High Efficiency, Flexible Organic Light Emitting Diodes
	Georgia Institute of Technology	Stable White Organic Light-Emitting Diodes Enabled by New Materials with Reduced Excited-State Lifetimes
	InnoSense, LLC*	Nanomaterials-Enabled Transparent Conductive Film
	Iowa State University	Enhanced Light Outcoupling from OLEDs Fabricated on Novel Low-Cost Patterned Plastic Substrates of Varying Periodicity
	LED Specialists Inc.	High Efficiency OLED Light Engine
	North Carolina State University	Manufacturable Corrugated Substrates for High Efficiency OLEDs

OLEDWorks, LLC	Mask-Free OLED Fabrication Process for Non-Tunable and Tunable White OLED Panels
OLEDWorks, LLC*	Printed Anodes and Internal Extraction Layers on Flexible Glass to Create Cost Effective High Efficacy Bendable OLED Lighting Panels
OLEDWorks, LLC*	High Efficacy Bendable OLED with Cost-Effective Internal Light Extraction and Transparent Anode Layers
OLEDWorks, LLC*	Commercialization of an Ultra-Thin, Bendable, High Efficacy OLED Light Engine (Phase I: Ultra-thin, Curved, High Efficacy OLED Light Engine)
Pennsylvania State University	Low Refractive Index OLEDs for Practical High Efficiency Outcoupling
Pennsylvania State University	Understanding, Predicting, and Mitigating Catastrophic Shorts for Improved OLED Lighting Panel Reliability
Pixelligent Technologies LLC*	Improved Light Extraction for a 130 lm/W OLED Lighting Panel
Pixelligent Technologies LLC*	Advanced Light Extraction Material for OLED Lighting
R-Display & Lighting*	Novel Blue Phosphorescent Emitter Materials for OLED Lighting
Solution Deposition Systems, Inc.*	Dual Function OLED Transparent Electrode and Light Extraction Layer
University of Michigan	From Deposition to Encapsulation: Roll-to-Roll Manufacturing of Organic Light Emitting Devices for Lighting
University of Michigan	Eliminating Plasmon Losses in High Efficiency White Organic Light Emitting Devices for Lighting Applications
University of Southern California	Combining Fluorescence and Phosphorescence to Achieve Very Long Lifetime and Efficient White OLEDs

*** Small Business Innovation Research projects.**

6.2 Core Lighting R&D Activities

The remaining work described in this appendix is conducted at DOE's core laboratory for lighting R&D, a capability that Pacific Northwest National Laboratory (PNNL) provides to the DOE Lighting R&D program. PNNL carries out research in lighting science and technology topics supporting energy efficiency, quality of the built environment, and technology advancement. All activities are linked to improvement in lighting application efficiency (LAE): delivery of the appropriate light intensity and spectrum to the right place at the right time, as energy-efficiently as possible. PNNL's research approaches the challenges of maximizing LAE from multiple angles, from visual science experiments gauging human perceptions and preference, to spectral modeling depicting light stimulus at occupants' eyes, to evaluating connected lighting systems' ability to adapt lighting to the application. PNNL employs several mutually-informative and reinforcing research approaches to provide insights into emerging capabilities and challenges in solid-state lighting technology: simulations and modeling, laboratory-based experiments, test bed evaluations, and field validation.

6.2.1 Stakeholder Interaction

Collaboration is a foundational principle of PNNL's approach to lighting science and technology research, in line with DOE's mandate to improve energy security, economic prosperity, and technology advancement. The roles of the DOE Lighting R&D Program in setting research goals and the technology roadmap, leveraging research investment, convening the lighting industry and research communities, and conducting objective technology evaluations is well-recognized and highly-valued by the lighting industry and research community, and has been documented and evaluated in two reports by the National Academies of Science (National Academies Press 2013 and 2017). Every aspect of PNNL's scope of work involves collaboration with external entities, primarily industry, universities and other research organizations, voluntary standards bodies, and government at federal, regional, state, and local levels. Partnerships range from short-term, project-based collaborations to long-term research and standards development roles. Collaborations primarily take the following forms:

- Standards bodies and industry consortia: PNNL team members chair or serve as members of key committees developing test methods, metrics, recommended practices, and standards (many following the ANSI accreditation process), including IES, CIE, NEMA, IEEE, and ASHRAE.

- Research collaborations with universities, university-based institutes, and individual researchers: these may be sub-contracts issued by PNNL to a researcher or institution to support a specific study or study element, or non-contractual research collaborations leading to co-authorship of journal publications and other materials.
- Field research project teams: these partnerships revolve around lighting installations in buildings, facilities, municipalities, or other properties. They typically involve a non-binding letter agreement or memorandum of understanding stating the roles of PNNL and other parties involved in the project, such as facility owner/operator, lighting designer/specifier, architect, manufacturer, manufacturer's representative, and in some cases, electric utility or energy efficiency sponsor.
    - In the case of the Next Generation Lighting Systems (NGLS) installations, PNNL issues sub-contracts to the host organizations for site support services.
    - Data-sharing agreements: an increasingly important aspect of field research in realistic settings and with early adopters of connected lighting systems is data sharing, which may take the form of direct or secondary access to lighting system data, and/or de-identified required reporting data collected by facilities such as school systems, hospitals, and long-term care facilities.
- Lighting product and system evaluations in PNNL labs or test beds: lighting and auxiliary equipment may be purchased through normal market channels or donated or loaned by technology developers and manufacturers. The latter arrangements often involve a bailment agreement specifying the duration and terms of the equipment loan for research purposes. In some cases, a non-disclosure agreement is also required, particularly for pre-commercial systems and components.

Collaboration partners are identified through industry committee and consortia involvement, open calls for participation, annual DOE SSL R&D workshops and working group meetings, annual peer review, conference participation, and project follow-on actions. The process of selecting partners involves:

- Opportunity assessment including:
    - Quality of research, project design, technology, systems, and products
    - Timing, logistics, and schedule fit
    - Partner commitment, capacity, and capabilities
    - Alignment with DOE/PNNL research objectives
- Specified technical requirements, for participation in:
    - Next Generation Lighting Systems
    - Connected Lighting Test Bed
    - Other lighting product or system testing/evaluation

6.2.2 Research Topics

PNNL is currently engaged in an approved three-year scope of work for the period October 1, 2018 – September 30, 2021, organized into five high-level topics:

1. Emerging Lighting Science - addresses human physiological (visual and non-visual) responses to light, with the objective to optimize energy efficiency, lighting quality, and human physiological benefits
2. Application Specific Lighting – addresses outdoor and CEA lighting, with the objective to optimize energy efficiency, outdoor lighting visibility and safety, outdoor night environment, and CEA productivity
3. Connected Lighting Systems – addresses emerging capabilities of CLS related to energy, data, and resilience, with the objective to enable data-driven energy and lighting performance management and value-added features
4. Next Generation Lighting Systems – addresses CLS performance attributes that must be evaluated in realistic settings, especially configuration complexity and integrated sensor performance, with the objective to significantly decrease complexity, configuration time, installation cost, and performance problems

5. Lighting and Grid – characterization of the potential for CLS to provide electric grid services, including definition of CLS characteristics, and integrating CLS performance attributes into a grid services co-simulation model to evaluate the potential

Additional detail on each topic area is described below.

6.2.3 Emerging Lighting Science

Emerging science on the effect of light on human physiology, both visual and non-visual, has challenged some of the assumptions that drove early generations of SSL. In the visual realm, trade-offs between luminous efficacy and lighting quality provide challenges for future generations of SSL. New developments in color science have led to new metrics, requiring new engineering developments. Glare is a visual response that also requires new metrics and new engineering approaches with SSL. Emerging evidence from the medical research community has linked lighting to non-visual physiological responses, such as circadian entrainment and acute alerting effects. These non-visual responses have spectral sensitivities that differ from those used to define the lumen, so that luminous efficacy and metrics related to lighting energy efficiency may be less relevant in the future. The science indicates that addressing non-visual needs may mean a need for more optical radiation and thus more energy use by electric lighting systems. Consequently, the energy use for these lighting uses is expected to be more than what might initially be assumed using lumen-based analyses for traditional applications that are based solely on task performance. PNNL’s scope of research seeks to ensure that future generations of SSL can address both energy efficiency and human physiological goals. Specific research topics include:

- Informing next generation SSL systems through research on visual phenomena including color rendition, glare, flicker, uniformity perception, and brightness perception; recent publication topics include:
  - Evaluating Tradeoffs Between Energy Efficiency and Color Rendition (August 2019, *OSA Continuum*)
  - Spectral Characteristics Influencing the Metameric Uncertainty Index (June 2019, *Proceedings of the 29th CIE Session*)
  - Experimental validation of color rendition specification criteria based on ANSI/IES TM-30-18 (June 2019, *Lighting Research & Technology*)
  - Analysis of Color Rendition Specification Criteria (March 2019, *Light-Emitting Devices, Materials, and Applications*)
  - A Vector Field Color Rendition Model for Characterizing Color Shifts and Metameric Mismatch (February 2019, LEUKOS)
  - Perceived colour fidelity under LEDs with similar R_f but different R_a. (January 2019, *Lighting Research & Technology*)
  - Comparing Measures of Gamut Area (November 2018, *LEUKOS*)
  - Characterizing Photometric Flicker: Handheld Meters (November 2018, DOE)

- Informing next generation SSL systems through research on non-visual phenomena including circadian entrainment and acute alerting effects:
- **Circadian Metric Modeling.** In partnership with design company CIRCA DIES and environmental analysis tool developer Solemma, DOE is working to understand how well available software tools model light spectrum and intensity within the built environment. These tools will then be used to understand how designing for circadian metrics affects lighting energy consumption in multiple space types. Explorations of visual and non-visual physiological effects in realistic settings to evaluate the validity of principles found in controlled laboratory studies when applied to complex environments. Specific subjects include:
  - **University of Kentucky’s Neonatal Intensive Care Unit (NICU)**. The University of Kentucky is the focus of a partnership with DOE, HGA Architects and Engineers, Pivotal Lighting, and Lutron to understand NICU occupant response to older lighting systems versus

  - a new SSL system with controls and automatic color temperature changes during the day. DOE is leading the analysis of light measurements, user surveys, and control data.
  - **Boulder Community Health (BCH) Inpatient Behavioral Health Unit (IBHU)**. Similar to the NICU evaluation, DOE has joined forces with BCH and design specialists Boulder Associates to study responses by IBHU staff and patients to an old fluorescent lighting system versus a new advanced SSL system with controls and automatic color temperature change during the day. Researchers are collecting light measurements, nurse surveys, and patient sleep and behavior data for analysis by PNNL.
  - **Georgia Tech SimTigrate Patient Room Study.** DOE is helping to understand responses of nurses and patients to traditional, contemporary, and future patient room lighting. The study involves a controlled experiment using the Philips patient room lighting system that was developed in part with DOE Lighting R&D Program funding and installed in the university's SimTigrate Lab. PNNL is overseeing experimental design and analysis and co-authoring resulting papers for peer-reviewed journal submittal.
  - **ACC Care Center in Sacramento, California.** In collaboration with ACC Care Center, Brown University, and the Center for Design for an Aging Society, DOE is helping to understand occupant response to a new advanced SSL hallway lighting system that changes in color temperature and intensity over a 24-hour cycle. The study will examine whether these lighting changes affect physiological, cognitive, behavioral, and psychological well-being of the aging occupant population. PNNL is assisting with experimental design and lighting measurements.
  - **Mild Cognitive Impairment Empowerment Program – Emory University in Atlanta**. In collaboration with Emory's Brain Health Center and Georgia Tech's SimTigrate Design Lab, DOE is part of this new program combining research, clinical care, and caregiver support to empower patients.
  - **Tunable White Lighting for Elders – Oregon Health Science University (OHSU) and Portland VA Hospital.** DOE is partnering with OHSU and VA medical and healthcare researchers to better understand response to tunable lighting in the homes of senior citizens. This research team was recently awarded partial funding from the OHSU Hartford Center for Research & Practice program.

6.2.4 Application-Specific Lighting

In several applications where the use of lighting is expected to grow rapidly over the next decade, and where legacy lighting systems are inefficient, human visual response is not the primary concern. Instead, plant and animal responses to optical radiation are the primary concern, and these responses frequently have very different spectral sensitivities than human vision. SSL systems that have been optimized for maximum luminous efficacy may not serve these emerging applications in the most energy efficient manner. In horticulture and agriculture applications, the amount of light needed for maximum benefit is likely to exceed the amount of light typically needed for human visual tasks. Consequently, the energy use intensity for these applications is expected to be more than that for traditional applications that are centered on human vision. Furthermore, demands to minimize the impact of exterior lighting on the night sky and wildlife in sensitive outdoor environments have put pressure of current SSL systems. A lack of standardization in performance metrics and measurement methods inhibits the implementation of new, optimized solutions for these lighting applications. This research will enable future SSL systems to be optimized to minimize energy use while maximizing the desired benefits in these applications. Specific research topics include:

- Optimizing SSL systems for exterior applications, considering the most energy efficient means of mitigating potential adverse biological effects of light, including validation of available sky glow models with real-world data
  - Lighting and Power Upgrade Recommendations for U.S. National Park Service (NPS) Caribbean Units (May 2019). Developed in the wake of 2017 hurricane damage to NPS properties in the Caribbean, the report is the culmination of collaborative efforts among scientists, park managers, and engineers at PNNL, Seattle City Light, and the NPS Natural

    - Sounds and Night Sky Division. The report provides guidance to NPS units in upgrading damaged properties in the inter-related areas of outdoor lighting, resilience, protecting the night skies and other natural environmental aspects of the properties, and electrical supply systems.
    - PNNL partnered with the Adler Planetarium and the City of Chicago to begin a new project designed to document the changes to the light that reaches the night sky, as a result of converting street lighting from HPS to energy-efficient LED. The project will employ multiple measuring techniques, both ground and sky-based, to quantify uplight as the city converts to LED lighting.
- Optimizing SSL systems for CEA lighting applications, including evaluation of horticultural lighting metrics and system performance attributes

6.2.5 Connected Lighting Systems

Connected lighting systems comprise an emerging class of lighting infrastructure that does more than just light spaces. Through the incorporation of distributed intelligence, one or more network interfaces and application-specific sensors, CLS become data collection platforms that enable a wide range of valuable new capabilities. While application-specific CLS with access to the right data have the potential to be significantly more energy-efficient than their historical counterparts, their cost is unlikely to be justified by energy savings alone. This task area defines technical research in six areas that are key to enabling the energy savings potential of CLS: energy reporting accuracy, system-level energy performance, interoperability and system integration, key new features, cybersecurity vulnerability, and electrical immunity. The majority of the proposed work is carried out in the Connected Lighting Test Bed (CLTB) established by PNNL in Portland, OR, and focused on examining and revealing common challenges and limitations as well as potential value-added opportunities emerging from CLS technologies. In addition, PNNL collaborates with system developers, integrators, and early adopters of CLS to define technology studies, share data from real-world installations, and leverage research results towards stimulating and contributing to technology evolution and developing guidance for key industry stakeholder groups. Specific research topics include:

- ***Energy reporting accuracy*** of available CLS, including development of voluntary industry standard test methods and performance classifications. Studies focus on lighting applications that are poised to have a significant market impact, driven by high user demand and the emergence of a significant number of competing solutions targeting a significant application (e.g., street lighting).
- ***System energy performance*** of available CLS, utilizing and further developing PNNL-developed device-level and system-level test methods to characterize the energy performance of connected devices and/or systems, and compare those results with self-reported data, if available. Studies focus on lighting applications that a) utilize technology that is new or currently foreign to the lighting industry, and therefore prone to misunderstanding or misrepresentation, b) have functionality that goes beyond lighting in ways that may significantly affect energy performance, c) utilize different system architectures or core technologies that are known or expected to have different energy performance and/or d) are poised to have a significant market impact.
- ***Interoperability*** of available CLS, including educating lighting stakeholders on the benefits of interoperability, and contributing to the development and promotion of greater CLS interoperability and system integration. Studies focus on evaluating the effort required to integrate available CLS using APIs or other approaches, and/or evaluating and comparing the level of interoperability that can be achieved by available integration approaches or technologies. Evaluation results and experience will be leveraged towards accelerating the development of appropriate common industry consortia approaches or technologies (e.g., API requirements, information models).
- Ability of CLS to deliver significant non-energy benefits, enabled by ***key new features***. Studies focus on exploring how benefits vary by application and use-case and characterizing sensors that facilitate those use-cases. In both instances, it is likely that interoperability between CLS and other systems will be required. Use-cases selected are driven by engagement with real-world users who are either planning or deploying CLS and pursuing integrations that require interoperability to realize specific high-value use-cases.

- ***Cybersecurity*** vulnerabilities in available CLS, working towards the development of a test method suitable for executing studies. Studies focus on characterizing the range of performance available in the market.
- ***Electrical immunity***, evaluating the performance of available CLS when integrated into electric grid systems with known issues (e.g., due to aging infrastructure, or outdoor infrastructure subject to environmental events) or when integrated with application-specific modifications or extensions to traditional electric grid systems, with a focus on understanding whether CLS are compatible (i.e., can operate as intended) with the targeted grid system.

6.2.6 Next Generation Lighting Systems

The goal of NGLS is to understand and address the configuration complexity of CLS through a structured observation and evaluation process in real buildings. The program creates hands-on research environments using early stage CLS, installed by licensed electrical contractors, and evaluated by expert lighting professionals who specify and design lighting systems for the application under study. While CLS are evolving at a rapid pace, they are currently in the early stages of their development, and many challenges stand in the way of the full realization of their potential energy saving and functional benefits. Configuration complexity, which has long made lighting controls difficult to install and set up correctly, can lead to user frustration and less than full utilization of system capabilities. NGLS seeks to identify and address configuration complexity in the early stages of development to improve the chances that CLS will deliver exceptional energy efficiency and lighting services in the built environment. Specific research topics include:

- Evaluation of 12-16 CLS installed in classrooms at Parsons School of Design, The New School in New York City, including assessment of configuration complexity during installation and commissioning; daylight sensing functionality; and user interface and wall controls.
- Evaluation of 6 outdoor CLS installed in parking lots on the campus of the Virginia Tech Transportation Institute, including assessment of configuration complexity during installation and commissioning, and performance of occupancy sensors and system level impacts of presence detection functionality.

6.2.7 Lighting and the Grid

CLS incorporating SSL technology have the potential to provide a broad range of electric grid services, including those that rely on fast response, for which many other building end-uses (e.g., heating, ventilating, and air conditioning) are not well suited. SSL power draw can be quickly modulated by varying light output, spectrum, and distribution, thereby providing grid services at time frames of hours (e.g., for energy services) to seconds or less (e.g., for frequency regulation). Further, CLS can monitor energy use and space conditions that affect occupant satisfaction and share historical and projected data for coordination and optimization with other building equipment. However, the ability of CLS to deliver potential grid services while simultaneously delivering sufficient lighting service and occupant satisfaction has not yet been proven or quantified. This project will evaluate and advance the ability of CLS to provide grid services through modeling and simulation, laboratory testing, and field testing. Project results will be disseminated via targeted mechanisms to technology developers, building owners and operators, system integrators, industry standards organizations, and other researchers.

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