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2022 Solid-State Lighting R&D Opportunities

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Disclaimer

Comments

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List of Acronyms

Abbreviation	Definition
$/klm	U.S. dollars per kilolumen of light
(Sr, Ca) AlSiN3:Eu	europium-doped oxy-nitride phosphors
ABS	acrylonitrile butadiene styrene
AC	alternating current
ACGIH	American Conference of Industrial Hygienists
ADB	adaptive driving beam
AI	artificial intelligence
Al	aluminum
ALFA	adaptive lighting for alertness
ANSI	American National Standards Institute
API	application programming interface
AR/VR	Augmented Reality or Virtual Reality
a-Si	amorphous silicon
BESS	battery energy storage system
BTO	U.S. Department of Energy Building Technologies Office
CAD	computer-aided design
CBECS	Commercial Buildings Energy Consumption Survey
CCT	correlated color temperature
Cd	cadmium
CDC-NIOSH	Center for Disease Control National Institute for Occupational Safety and Health
CEA	controlled environment agriculture
CIE	International Commission on Illumination
CLS	connected lighting systems
CM-LED	color-mixed LED
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
COB	chip-on-board
CRI	color rendering index
CSP	chip scale packaging
DC	direct current
DFM	designs for manufacturing
DHS	Department of Homeland Security
DIN	Deutsches Institut für Normung
DLC	Design Lights Consortium
DOD	Department of Defense
DRAM	distributed recycling and additive manufacturing
DVRPC	Delaware Valley Regional Planning Commission
EBL	electron blocking layer
EEL	external extraction layer
EERE	Energy Efficiency and Renewable Energy Office
EIA	Energy Information Administration
EIL	electron injection layer

ELQDs	electroluminescent quantum dot materials
EML	emission layer
EPA	Environmental Protection Agency
EQE	external quantum efficiency
ETL	electron transport layer
EU	European Union
Eu	europium
EUI	energy use intensity
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FOA	funding opportunity announcement
FWHM	full width at half maximum
GaN	gallium nitride
GDP	gross domestic product
GUV	germicidal ultraviolet
HBL	hole blocking layer
HF	hyper-fluorescence
Hg	mercury
HIL	hole injection layer
HPS	high pressure sodium lights
HTL	hole transport layer
HVAC	heating, ventilation, and air conditioning
IALD	International Association of Lighting Designers
IEA	International Energy Agency
IEL	internal extraction layer
IES	Illuminating Engineering Society
IGZO	indium gallium zinc oxide
IoT	Internet of Things
ipRGCs	intrinsically photosensitive retinal ganglion cells
IQE	internal quantum efficiency
IR	infrared
ITO	indium tin oxide
IUVA	International Ultraviolet Association
LAE	lighting application efficiency
LCA	life cycle assessment
LCD	liquid crystal display
LD	laser diode
LED	light emitting diode
LER	luminous efficacy of radiation
LES	light-emitting surface
LESA	Lighting Enabled Systems and Applications
LiDAR	light detection and ranging
lm	lumens
lm/W	lumens per watt
LMPV	low pressure mercury vapor lamps

LPIG	Light-Physiology Interest Group
LSRC	LED System Reliability Consortium
LSTL	Lighting Science and Technology Laboratory
LTPS	low temperature polycrystalline silicon
MC-PCB	metal-core printed circuit board
m-EDI	melanopic equivalent daylight illuminance
MELs	miscellaneous electric loads
MEP	mechanical-electrical-plumbing
MES	manufacturing execution systems
MMT	million metric tons
Mn	manganese
MOCVD	metal-organic chemical vapor deposition
MOU	memorandum of understanding
MTBF	mean time between failures
NASA	National Aeronautics and Space Administration
NGLIA	Next Generation Industry Lighting Alliance
NGLS	next generation lighting system
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMSC	non-melanoma skin cancer
PC	polycarbonate
PCB	printed circuit board
PC-LED	phosphor-converted LED
PLCC	plastic leaded chip carrier
PoE	power over ethernet
PPE	photosynthetic photon efficacy
ppm	parts per million
PSPS	public safety power shutoffs
PTFE	polytetrafluoroethylene
PV	photovoltaic
QE	quantum efficiency
QW	quantum well
RFI	request for information
RGBA	red, green, blue, and amber
RHT	retinohypothalamic tract
RoHS	Restriction of Hazardous Substances
RTI	Research Triangle Institute
SAG	selective area growth
SBIR	Small Business Innovative Research
SiC	silicon carbide
SPC	statistical process control
SPD	spectral power distribution
SRH	Shockley-Read-Hall
SSL	solid-state lighting
STEM	science, technology, engineering, and mathematics

SWaP	size, weight, and power level
TADF	thermally activated delayed fluorescence
TJ	tunnel junction
TOF	time of flight
TWh	terawatt-hours
USB	universal serial bus
USDA	U.S. Department of Agriculture
UVC	ultraviolet C-band
VTTI	Virginia Tech Transportation Institute
WHO	World Health Organization
YAG:Ce	cerium-doped yttrium aluminum garnet

Executive Summary

Light emitting diode (LED) based solid-state lighting (SSL) is one of the predominant general illumination technologies. LED lighting offers very significant savings compared to almost all conventional lighting technologies and has further room for improved efficiency. It also offers compelling new features that can further energy savings and improve the functionality and value of lighting.

Ongoing research in LED lighting technology supports multiple priorities for the U.S. public interest. LED lighting has led to products that demonstrate considerable, measurable energy savings through improvements to light source efficiency. These energy savings result in dramatic reductions to the emission of greenhouse gases through reduction in the electricity required to power lighting. The ubiquity of lighting means that even modest improvements to average efficiency and energy consumption aggregate to meaningful savings nationally and worldwide. Efficient LED lighting also reduces energy generation and accelerates the transition to a decarbonized power grid in support of grid-interactive, net-zero, and zero-energy buildings. LED lighting is also generally robust and reliable, supporting a resilient building infrastructure. Furthermore, LED lighting enables new lighting form factors which can support new building design, new opportunities for both saving energy and decarbonizing the built environment, as well as efficient and cost effective construction techniques. Crucially, LED lighting offers significant savings on energy bills, as well as greater lighting quality and productivity.

As a technology that has emerged within the last two decades, LED lighting has required new manufacturing techniques and a new global supply chain. The techniques and production of lighting products are still maturing. This opens the possibility of fostering domestic manufacturing capabilities for some parts of the lighting supply chain. Among the barriers to rapid deployment of highly-efficient, grid-interactive connected lighting, one of the largest is a mismatch in required skills throughout the new lighting-related workforce. LED lighting still requires knowledge of general lighting practices, but now also requires understanding network communications, building systems, new features enabled by LED technology, power grid behavior, and even new application understanding such as human health impacts, horticultural optimization, and animal responses to light. The changes along the lighting value chain from manufacturing to installation and maintenance mirror the changing needs of the lighting workforce, which requires new skills and new ways to acquire them.

Data and analysis also reveal disparities for product availability and access to high-quality lighting, both in retail and in public spaces, that have strong energy justice considerations. Separately, there are persistent challenges to improving diversity, equity, and inclusion in the lighting community and industry. Addressing both energy justice and inclusion among lighting professionals is vital, not only for realizing the inherent potential of historically disadvantaged communities, but also to increasing the deployment of energy efficient lighting and addressing the key challenges to adoption of solid-state lighting today.

LED lighting currently saves approximately 185 terawatt-hours (TWh) of site energy per year compared to conventional lighting technologies, and with continued advancements and adoption, has the potential to save over 500 TWh of site energy per year by 2035. The advancements necessary to achieve this level of energy savings include further improvements to light source efficiency, more effective control of light intensity to ensure suitable light levels, and lighting control that turns off lights that are not needed. Additional energy savings can be achieved by improving optical delivery efficiency, which means putting light only where it is useful. Analyses have shown that only a small fraction of light—well under 1%—generated by luminaires reaches an occupant's eye. If the proportion of generated light that supports a visual function and reaches an observer is doubled then there could be dramatic additional energy savings in addition to gains through source efficiency and intensity control.

Lighting energy savings and productivity enabled by lighting are inextricably linked. Electric lighting performs a critical function, enabling human visual function to perform activities that could otherwise not be done. LED lighting has demonstrated the capability to improve the visual function by providing high color quality, crucial for adoption, and tailored for specific end uses. LED lighting can also provide improved optical distribution and can be instantaneously dimmed and turned on and off. LED technology can improve the basic job of lighting – enabling visual function – while also saving significant amounts of energy.

We now know that lighting unavoidably affects human health and well-being beyond basic visual function. Lighting provides signals to the human endocrine system that can support or disrupt healthy circadian rhythms with broad implications for health and well-being. These considerations are now becoming part of the design process for lighting, but there is still much more to understand in terms of the underlying physiology and the application of lighting to support health.

Unlocking the next wave of advancements in SSL will require further breakthroughs in fundamental, early stage R&D across the SSL value chain, as well as better understanding of barriers to deployment for technologies with the highest decarbonization potential. This document provides detail on these advancements and the R&D necessary to make breakthroughs.

In the two years since the previous DOE *Solid-State Lighting R&D Opportunities* report was issued, there are several R&D themes that continue. As of the writing of this report in August 2021, the most notable achievements, and the resulting changes, are in the following areas:

- Lighting application efficiency: Recognizing the significant gains realized in source efficiency of LEDs, and also improved understanding of other paths that can save energy, a more holistic vision for energy and emissions efficiency is now an explicit focus across much of the portfolio.
- Lighting science: Due to significant new results about lighting, heath, and human factors, this document has increased emphasis on lighting science in general, particularly related to lighting application efficiency, that reflects research findings and changes to technology and products.
- Changing product needs: Thanks in part to previous engagement with the lighting community, there are increased calls for the Program to work on germicidal UV lighting and displays, and these topics will be considered where they converge with the Program’s technical direction and resource availability.
- Integration and validation: In response to new understanding of barriers to adoption for advanced lighting, there is now greater emphasis on R&D that addresses challenges related to deployment.

R&D Opportunities

Priority SSL R&D opportunities are listed below. There are numerous additional R&D topics that are important (as well as non-R&D SSL topics, including those regarding deployment and usage) but the following list describes topics that are believed to have highest impact in support of DOE SSL R&D objectives of energy savings and improved building occupant health and productivity. The current status of lighting performance and practice is described in Section 2 of this document and detailed in further technology discussions in Sections 3 and 4.

Lighting Platform Technology R&D Priorities: This suggested research supports scientific, technological, integration, and manufacturing understanding and advancements of the LED technology platform that enable energy savings and support occupant health and productivity. The specific priority Platform Technology R&D topics and their goals are listed below:

- **LED Material and Device Science:** Research and develop new or improved emitter materials or device structures. Improve the fundamental understanding of material-device-synthesis relationships and resulting performance for LEDs.

- **Down Converter Technology:** Explore and develop high efficiency wavelength down conversion materials to use with LEDs.

- **Diffuse Light Source Materials and Devices:** Develop materials and device structures that improve the performance of low profile, diffuse lighting concepts with OLED materials or that leverage the OLED technology platform.

- **Optical Delivery and Control:** Research and develop approaches to improve optical delivery control and efficiency for white light at the chip, package, and/or luminaire level.

- **Power and Functional Electronics:** Improve power supply efficiency, functionality, and/or form factors.

- **Advanced Lighting Concepts:** Develop high efficiency LED packages, modules, or lighting products that demonstrate advanced performance, features, or energy savings through improved lighting application efficiency.

- **Manufacturing Technologies for Lighting:** These R&D Priorities are described in the Manufacturing Status and Opportunities document.

Lighting Science R&D Priorities: These priorities support research and understanding of fundamental lighting science to guide effective implementation of LED light source technology.

- **Lighting Application Efficiency (LAE) Framework:** Develop a general framework and computational model to characterize LAE which balances light source efficiency, optical delivery efficiency, spectral efficiency, and intensity efficacy for specific lighting applications. Quantify the energy savings benefits resulting from improved LAE practice.

- **Human Physiological Impacts of Light:** Research to understand and define physiologically supportive lighting for general population and in specific settings. Assess energy impacts, and screen for health impacts, in both long-term and acute parameters for well-being.

Lighting Integration and Validation: This research supports field research to transition new lighting technology and understanding to practice and quantify the benefits.

- **Translating Lighting Research Findings to Practice:** Transition new lighting technology capabilities and lighting science understanding to broad-scale practice to achieve the objectives of the DOE SSL Program, specifically lighting energy savings and occupant health and productivity. Quantify the benefits.

Connected Lighting with Integrated Controls and Grid-interactive Capabilities: While lighting systems exist with the capability of sensing occupancy and light levels, communicating with building and grid systems, and responding via intensity and spectral changes, various barriers to adoption remain. The following research will aid deployment of connected lighting systems:

- **Simplicity and Resiliency:** Research to make connected lighting systems simpler to install, commission, and operate (e.g., user interface), as well as research into how these systems can be made more resilient.

- **Energy and Non-energy Benefits:** Research to quantify energy and non-energy benefits associated with connectivity and control.

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1 DOE Solid-State Lighting Program

Solid-state lighting (SSL), particularly light-emitting diode (LED) based SSL, is saving significant amounts of energy with clear paths for additional energy savings in the future. The LED technology platform offers the opportunity to advance beyond legacy form factors that embody the limitations of the previous lighting technologies. Beyond providing basic illumination and enabling energy savings through improved source efficiency, the SSL technology platform will encompass more precise delivery of more suitable light at the appropriate time for the application.

Improved energy efficiency, and the resulting energy savings, will come from two main areas of innovation, and enable grid flexibility as well. LED lighting products could soon achieve up to 250 lumens per watt luminous efficacy through further LED performance improvements and advancements to luminaire integration that minimize system losses. The second area of increased energy savings will come from improved application efficiency of LED lighting technology into the built environment. This means improving the optical delivery to satisfy lighting requirements while using less total emitted light from the luminaire. The spectral power distribution (SPD) of light can also be optimized to improve visual performance and non-visual physiological benefits, while simultaneously providing appropriate light levels. With new levels of control available using LED technology, the lighting can also actively deliver just the right intensity of light for the application, thereby eliminating excess light that wastes energy. The broader availability of sensors has also aided in optimizing the intensity of light by reducing light levels when there are no occupants in a room, no pedestrians or vehicles on a roadway, or enabling grid flexibility. These additional energy savings opportunities with LED lighting are not readily apparent when just considering luminous efficacy of a light fixture, but can enable considerable additional energy savings, along with improvements to light source efficiency. If they interface with other building systems in an interoperable manner, sensors and connected controls can also enable energy savings in other building systems, such as heating, ventilation, and air conditioning (HVAC).

With LED technology, the efficiency and energy savings benefits can be achieved while simultaneously improving the performance and function of lighting, the health and safety of occupants, and reducing the negative impacts of light such as light pollution in the environment. In addition, SSL enables new opportunities for integrating lighting into buildings, in terms of physical, electrical, and thermal connections, as well as building communications, that could enable more efficient building methodologies, healthier buildings, and, of course, more carbon- and energy-efficient buildings.

1.1 Program Background

The Department of Energy Solid-State Lighting Program is within the Building Technologies Office (BTO), which is part of the Office of Energy Efficiency and Renewable Energy (EERE). The SSL 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."***

Over the last two decades, the DOE SSL Program has developed a comprehensive R&D strategy to support advancements in lighting technology and maximize energy savings. To achieve this goal, the Program supports R&D in foundational topics, with benefits that apply across the value chain, and supports fundamental R&D that is earlier stage or of a broader scope than typically undertaken by commercial organizations. This R&D advances the understanding of underlying physical phenomena, explores new technical and manufacturing concepts, and develops the understanding of application requirements that improve lighting effectiveness, while reducing development risk with new technologies. More information about the Program can be found on the SSL Program's About webpage.[1] This report, the *2022 Solid-State Lighting R&D Opportunities* document, provides performance status and targets, analysis, context, and direction for ongoing R&D activities to advance SSL technology and increase energy savings. The suggested research topics come from inputs 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 small group meetings, the annual SSL R&D Workshop, through project management, and other channels.

1.1.1 Program Mission and outcomes

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 and application to reduce energy and optimize health and productivity."***

This goal describes improving source efficiency with the additional objectives of saving energy from better delivery of light, while recognizing that lighting has important impacts on human activity in terms of work productivity related to the visual function of lighting, health and well-being related to non-visual physiological impacts of lighting, and safety related to lighting. In addition, reducing counter-productive aspects of lighting in terms of visual performance (glare), health (flicker, sleep health, etc.), connected controls that can enable load flexibility, and better understanding of other impacts can and has led to increased benefits enabled by new LED lighting technologies.

1.2 DOE SSL Program Processes

The DOE SSL Program strives to maximize R&D results and resulting impacts from a limited budget to advance and influence the technology and practice of lighting. The Program identifies critical R&D priorities through highly informed decision making. In order to reduce the 'random walk' nature of R&D, the Program works to clearly understand the risks and rewards associated with various research topics and approaches, grounded by input from participants in technologies, markets, and policy. The SSL Program goal is to balance the potential rewards against the technical risk and to balance near term and long term impacts of R&D with the supported R&D projects.

The annual DOE SSL Program cycle is shown in Figure 1.1. The SSL Program stays informed by collecting inputs from expert scientists, product developers and manufacturers, and product specifiers and users. These inputs are gathered from the annual SSL R&D Workshop, small group R&D meetings, monitoring of recent R&D findings, and ongoing discussions with a broad range of stakeholders. The inputs are shared through sponsored meetings, the Program website, emails to stakeholders, reports, and presentations at industry conferences. The sharing of these inputs results in acceleration of R&D advancements that, when commercialized, result in energy savings for our nation. DOE meetings connect potential collaborators, inform prospective stakeholders, educate down-stream users, and are a credible resource for information on SSL technology benefits and concerns. Ultimately, the process serves to accelerate energy and carbon 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.

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[1] https://www.energy.gov/eere/ssl/about-lighting-rd-program

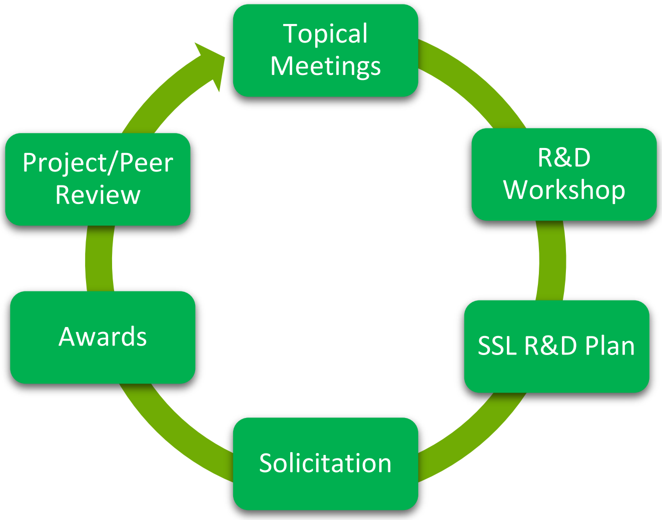

Figure 1.1 Schematic showing the DOE SSL R&D annual process cycle of collecting inputs and outputs. The SSL Program works every year to gather current information on the status of energy-saving lighting and the most impactful R&D that can continue to accelerate energy savings and productivity.

In 2020, the SSL Program leveraged another avenue for input via a request for information (RFI). This RFI was released seeking suggestions for priority research topics that could provide the largest advancements and impacts for carbon savings and energy-efficient lighting.

1.2.1 Engagement

The DOE SSL Program actively engages with numerous groups and agencies to communicate findings, understand needs, and exchange ideas. These relationships and the sharing of information accelerate adoption of energy saving lighting technology and support development of new technology and understanding for lighting products and systems. The DOE SSL Program has the following formal partners to support development and adoption of LED lighting technology:

- Next Generation Industry Lighting Alliance (NGLIA)
- Illuminating Engineering Society (IES)
- International Association of Lighting Designers (IALD)

These partners provide inputs to guide DOE SSL R&D activities, collaborate with DOE on meetings and workshops, help to reduce barriers to adoption, and generally amplify the impacts of the DOE SSL Program activities. The NGLIA was explicitly created as a lighting industry group to foster the relationship between the DOE and the lighting industry and to support DOE SSL R&D activities.[2]

Since electric lighting is a ubiquitous element of our built environments there are also numerous federal agencies that are interested in various aspects of lighting. Among these federal government agencies, the DOE SSL Program has an explicit memorandum of agreement with the National Institutes of Health (NIH) since they have an active interest in sleep health and have funded research in lighting impacts on sleep.

The DOE SSL Program also actively collaborates and communicates with researchers at the U.S. Department of Agriculture (USDA), National Aeronautics and Space Administration (NASA), Department of Defense (DOD), NIH, Center for Disease Control National Institute for Occupational Safety and Health (CDC-

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[2] The specific memorandum of agreement can be found at this link – https://www.nglia.org/pdfs/MOA-NGLIA-and-DOE.pdf.

NIOSH), National Park Service, Fish and Wildlife Service, Federal Communications Commission (FCC), Federal Aviation Administration (FAA), and Department of Homeland Security (DHS) to provide inputs and cross pollinate among the different research and missions that are advanced with LED lighting technology.

The DOE SSL Program currently supports two working groups that meet on a regular basis to develop and improve understanding of critical topics. These groups are the LED System Reliability Consortium (LSRC) and the Light-Physiology Interest Group (LPIG). As a new light source technology, LED lighting reliability requires new understanding and predictive techniques and these techniques need to be communicated to stakeholders and consumers. LSRC members include LED and lighting manufacturers and reliability scientists. The LPIG members include light and health physiological researchers, LED and lighting manufacturers, and representatives from interested government agencies (NIH, FAA, NASA, DOD).

1.3 Range of Program Activities

The DOE SSL Program supports R&D in identified priority research topics through multiple funding mechanisms as will be highlighted in this section.

1.3.1 Funding Opportunity Announcements

The primary R&D funding mechanism is an annual funding opportunity announcement (FOA). Domestic universities, companies, national laboratories, and other research institutions submit proposals to address R&D priorities identified in the FOA, drawn from the R&D priorities identified in this document and previous versions of this document.

Included within FOA R&D mechanisms are competitively awarded R&D projects performed at DOE National Laboratories. In some years there are explicit Lab Call FOAs where only DOE National Laboratories are eligible to apply and in other years the labs are eligible to participate in the annual FOA. National Lab researchers also support industry-led R&D projects as sub-contractors, providing characterization, synthesis, and modeling support to advancements on state-of-the-art LED devices and materials. Pacific Northwest National Laboratory (PNNL), Sandia National Laboratory, Oak Ridge National Laboratory, Los Alamos National Laboratory, Brookhaven National Laboratory, Argonne National Laboratory, Lawrence Berkeley National Laboratory, and the National Renewable Energy Laboratory have all participated in DOE SSL Program funded research. Current projects at DOE National Labs are included with the list of ongoing FOA projects in the Appendix (Section 5.1).

The DOE SSL Program also supports R&D through the Small Business Innovation Research (SBIR) awards. In the first phase of a project, the feasibility of a concept should be demonstrated. Then the performer can apply for a second phase with greater funding and effort to further develop and commercialize the concept. Only the most successful projects from Phase I are chosen for Phase II. SSL R&D topics for SBIR funding that align with the SBIR project structure are pulled from this document. A list of ongoing SBIR projects in provided in the Appendix (Section 5.1.2).

1.3.2 Pacific Northwest National Laboratory

In addition to competitively funded R&D projects, the DOE SSL Program supports research through core SSL R&D capabilities at PNNL including lighting science, engineering, design, and application expertise and facilities. Previously, PNNL was also competitively selected to deliver research on the potential for connected lighting systems to provide electric grid services, and on simulation and design tools for better integration of daylight and electric light in buildings. The PNNL team leverages its lighting expertise to obtain deeper understanding of a variety of topics including data-driven lighting systems, system interoperability, vision science, light and human health, daylight and electric light integration, and the potential role of lighting systems in a more stable, reliable electric grid. PNNL also leads research to validate and quantify energy savings and non-energy benefits (health, safety, productivity) in LED installations. PNNL conducts research on connected lighting devices and system testing in the Lighting Science and Technology Laboratory (LSTL) in Portland, Oregon, as well as simulation-based research, and extensive field research in real facilities nationwide.

PNNL conducts experimental research on visual functions to better understand human psychophysical responses to light, including perception of color, flicker, glare, and luminance uniformity. These studies typically require a range of measuring equipment along with uniquely designed rooms and one-of-a-kind apparatus available in the LSTL. Additionally, extensive testing of lighting system devices for reliability, accuracy, and cyber-security occurs in the LSTL using commercially available lighting products. All of these activities support the development of lighting recommendations, test methods, and metrics.

Outside of the laboratory, PNNL has collaborative research relationships with on-going field projects across the United States in a variety of facilities where advanced lighting systems are installed. These field projects are leveraged to better understand occupant responses to lighting systems, the configuration complexity of lighting systems, grid services, maintenance and operations, and energy reporting, along with other opportunities for energy optimization. PNNL is also focused on improving the accuracy and integration of dynamic electric and daylighting simulations, which are critical for improving the design of lighting systems to meet occupant visual and non-visual needs. PNNL works closely with the lighting industry across all research efforts, providing input to industry consensus standards, creating model specifications, and seeking additional opportunities to increase industry engagement and recognition through prizes, challenges, and competitions. A full list of PNNL activities can be found in the Appendix (Section 5.1.4).

Figure 1.2 The LSTL at Pacific Northwest National Laboratory in Portland, Oregon.

1.3.3 Other R&D Mechanisms

The SSL Program supports R&D through other funding mechanisms. The OLED Testing Opportunity is a small effort offered by the SSL Program that enables OLED technology developers to test their innovations within a standard OLED device structure to ensure compatibility and clearly demonstrate performance advancements. This testing mechanism enables rapid feedback on developments of individual aspects or portions of the OLED device structure. The OLED testing opportunity has been in operation since 2013. As of 2020, there have been 17 rounds of testing involving 11 different research organizations. OLED substrates, organic transport materials, transparent conductors, organic emitters, and light extraction approaches have been tested on a standard device structure.[3]

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[3] https://www.energy.gov/eere/ssl/oled-testing-opportunity

The DOE SSL Program also directly supports R&D through an interagency agreement with the National Institute of Standards and Technology (NIST). This research covers the topics of lighting science and metrology. As LED technology has emerged, it has been critical to understand necessary changes and improvements to lighting product characterization. Lighting research at NIST has been leveraged with funding from the Department of Commerce and other non-DOE partners, and it has enabled standard characterization practices to keep abreast of LED technology developments.

Similarly, the SSL Program supports ongoing research on LED system reliability at Research Triangle Institute (RTI). RTI researches various LED specific failure mechanisms such as output depreciation, color shift, and catastrophic failure to support development of a holistic understanding of LED lighting and OLED lighting product reliability.

1.3.4 Prizes

The SSL Program also fosters advancements in LED lighting technology through product development competitions or 'prizes'. The first competition was the L-Prize®, first introduced in 2010. This competition stimulated the development of an early LED product designed to replace a conventional 60W incandescent lamp with equivalent lighting specifications and greatly improved luminous efficacy. In 2011, Philips was awarded the prize for development of an LED lamp that met all of the prize requirements for performance and reliability. This product demonstrated the capability of LED technology to surpass lighting performance of conventional technologies with greatly reduced power consumption and increased lifetimes. Figure 1.3 shows how Philips' LED lamp offerings evolved from their L-Prize winning lamp.

Figure 1.3 Philips' LED lamp offerings based on technology development for the L-Prize. [1]

In 2019, the DOE SSL Program offered a prize for the sustainable manufacturing of LED luminaires. The prize was awarded to Brad Koerner of Koerner Design for the bamboo LED pendant design. The design incorporated bio-derived and biodegradable, low toxicity, and sustainable materials, and was operated with a centralized DC power supply to reduce power conversion losses and simplified connection with renewable energy sources.[4] Figure 1.4 shows an illustration of this concept.

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[4] https://www.energy.gov/index.php/eere/buildings/articles/energy-department-announces-winner-sustainable-manufacturing-luminaires

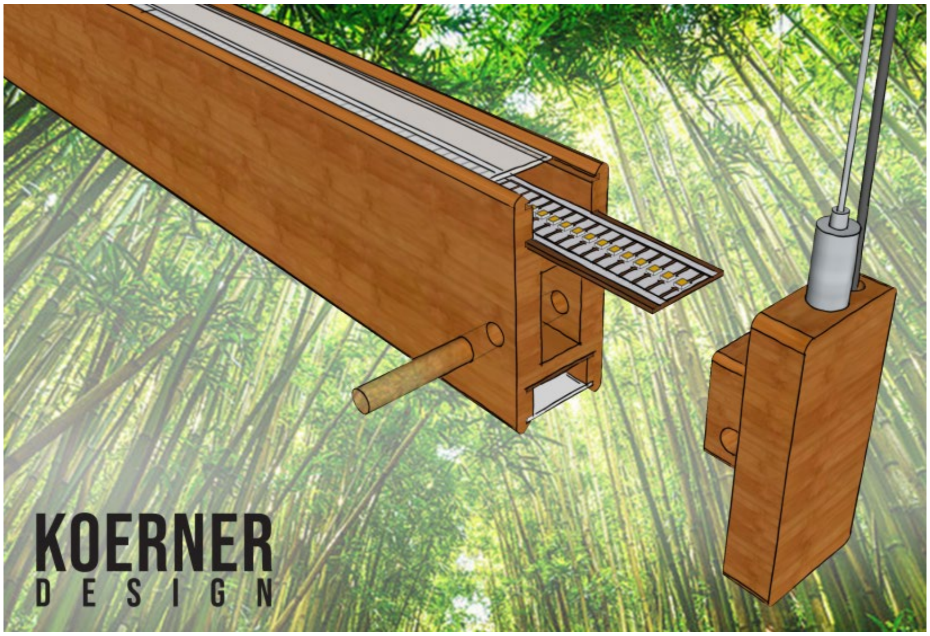

Figure 1.4 Brad Koerner's award-winning design for a sustainable LED luminaire.

In May 2021, a new L-Prize competition was announced by U.S. Secretary of Energy Jennifer M. Granholm. The new L-Prize competition features three phases of competition and teaming opportunities for U.S.-based applicants, as illustrated in Figure 1.5. Phase 1 is a lighting Concept phase with up to 10 winners of $20,000 each. Phase 2 is a Prototype phase with up to 3 winners splitting a prize pool of $2 million. Phase 3 is the Manufacturing and Installation phase with up to 2 winners splitting a $10 million prize pool. Applicants can apply to any or all of the phases.[5]

Figure 1.5 The timing and prize pool of DOE's recently announced L-Prize competition.

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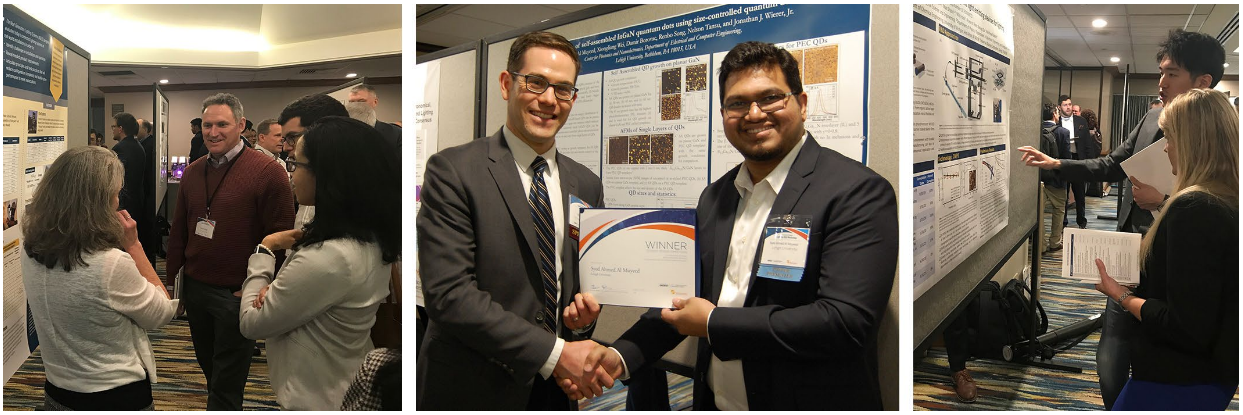
[5] https://www.energy.gov/eere/ssl/l-prize-competition

The SSL Program also honors student R&D in lighting technology every year at the annual DOE SSL R&D Workshop through a student poster competition, shown in Figure 1.6. Undergraduate and graduate students can submit their research to the DOE in advance of the workshop and winners are selected to present their research at the Workshop alongside funded DOE R&D researchers.



"Talking about [my] work helped solidify future directions and also helped me establish contacts with people in industry, a few of which pioneered the work I was presenting." – Clayton Cozzan, past winner

"I enjoyed the opportunity to talk with a variety of people about my research. Posters are a great way to meet people at a conference, and I think it was a great way to help us students meet people from industry, including people I probably wouldn't have approached otherwise." – Stacy Kowz, past winner

Figure 1.6 Student pictures and testimonials from the DOE SSL R&D Workshop.

1.3.5 Analyses

To guide and support R&D efforts, the SSL Program continuously performs and publishes analyses on all aspects of lighting technology. These analyses enable a deeper understanding of the most energy impactful research areas. Recent analyses and reports include:

- LED Manufacturing Supply Chain[6]
- SSL Manufacturing Status and Opportunities Document (coming soon)
- Adoption of Light-Emitting Diodes in Common Lighting Applications[7]
- Energy Savings Potential of SSL in Agricultural Applications[8]
- Energy Savings Forecast of Solid-State Lighting in General Illumination Applications[9]
- A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions[10]

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[6] https://www.energy.gov/sites/default/files/2021-05/ssl-2020-led-mfg-supply-chain-mar21.pdf

[7] https://www.energy.gov/sites/prod/files/2020/09/f78/ssl-led-adoption-aug2020.pdf

[8] https://www.energy.gov/sites/prod/files/2020/07/f76/ssl-agriculture-jun2020.pdf

[9] https://www.energy.gov/sites/prod/files/2019/12/f69/2019_ssl-energy-savings-forecast.pdf

[10] https://www.tandfonline.com/doi/full/10.1080/15502724.2021.1872383

PNNL also provides analyses in support of the DOE SSL Program. Some examples include:

- Metadata Schemas and Ontologies for Building Energy Applications: A Critical Review and Use Case Analysis[11]
- Energy Impact of Human Health and Wellness Lighting Recommendations for Office and Classroom Applications[12]
- Evaluating Tradeoffs Between Energy Efficiency and Color Rendition[13]
- Energy Saving Opportunity from Advanced LED Lighting Research[14]

RTI provides technical reports and analyses related to reliability of lighting products. Some examples include:

- Dim-to-Warm LED Lighting: Stress Testing Results for Select Products[15]
- Dim-to-Warm LED Lighting: Initial Benchmarks[16]
- LED Luminaire Reliability: Impact of Color Shift[17]

1.4 Achievements & Impacts

Beyond these direct impacts of energy efficient lighting, the pursuit of advanced lighting technology has resulted in the development of numerous patents, improvements to scientific understanding, and the development of new manufacturing technologies. As part of the built infrastructure, energy-efficient LED lighting can be an enabling technology in support of net-zero energy buildings, grid-interactive buildings, resilient buildings, and built environments that support occupant health and well-being. The following sections describe energy and R&D achievements associated with SSL as well as near-term likely impacts enabled by this technology.

1.4.1 DOE SSL Program Achievements

According to the DOE SSL Program market adoption model, LED lighting technology saved 185 terawatt-hours (TWh) of site energy in 2020 versus legacy lighting technologies. Based on recent U.S. averages for U.S. power utilities, these savings entail 79 million metric tons (MMT) of avoided carbon dioxide (CO_2) emissions per year, or 131 MMT of carbon dioxide equivalents (CO_2e).[18] Using DOE's lighting market model, we infer that LED lighting technology saved consumers $20 billion in electricity costs in 2020.

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[11] https://www.mdpi.com/1996-1073/14/7/2024

[12] https://www.sciencedirect.com/science/article/pii/S0378778820306514

[13] https://www.osapublishing.org/osac/fulltext.cfm?uri=osac-2-8-2308&id=416133

[14] https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-29342.pdf

[15] https://www.energy.gov/eere/ssl/downloads/dim-warm-led-lighting-stress-testing-results-select-products

[16] https://www.nglia.org/documents/LSRC_Dim-to-Warm_Paper_final_073019r.pdf

[17] https://www.energy.gov/sites/default/files/2019/10/f67/lsrc_colorshift_apr2017.pdf

[18] This document uses MMT of avoided CO_2 for consistency and comparability with other DOE analyses. Prior DOE SSL Program reports calculated avoided CO_2e using the U.S. Environmental Protection Agency's *Greenhouse Gas Equivalencies Calculator*. However, the EPA's calculator does not forward project the conversion ratio of carbon emissions to electricity consumption. In this report, carbon savings are calculated using the U.S. EIA's Annual Energy Outlook 2021. Using the EIA's AEO report for avoided CO_2 calculations allows forward projection of carbon savings from energy efficient lighting by accounting for future changes in the ratio of carbon emissions to electricity consumption (the AEO's projections account for expected changes in the grid-mix). Note that the ratio of carbon emissions to electricity consumption is projected to decrease over time based on EIA's AEO analysis.
The AEO data tables can be found at https://www.eia.gov/outlooks/aeo/tables_ref.php. For projected CO_2 savings from LED lighting, see Table 2.2.

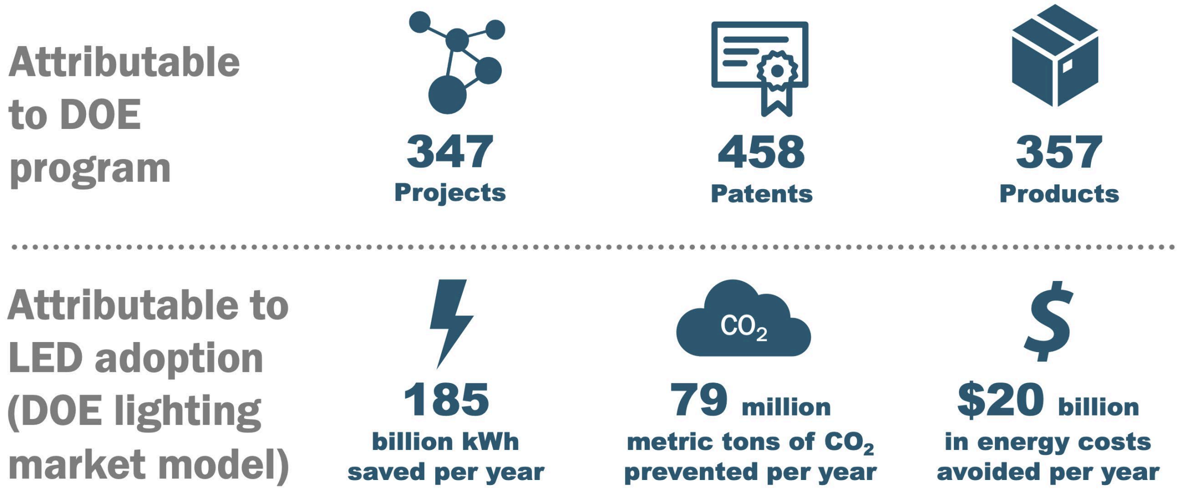

Figure 1.7 Facts and figures regarding the impact of the DOE's SSL Program for 2020. [2] Annual energy saved per year is calculated from the DOE Lighting Market Model for the year 2020. Carbon savings numbers correspond to carbon dioxide from energy combustion in million metric tons and are calculated using energy-to-carbon data from the U.S. Energy Information Agency (EIA) Annual Energy Outlook (AEO) 2021.

Since its inception, the DOE SSL Program has funded 347 R&D projects to advance the technology and reduce the cost of energy-saving solid-state lighting. These projects have produced 458 patents and have also directly resulted in 357 specific products within the energy efficient lighting supply chain with countless follow-on products.[19] The products developed include LED components, lighting products, materials used within the LED or luminaire, OLED components, optics and power supplies within the luminaire, and manufacturing tools that enable better and more effective production of lighting products.

1.5 Energy, Climate, and Environmental Impacts

In addition to direct substantial energy savings, LED technology also enables substantial additional environmental benefits compared to previous lighting technologies.

Climate Impact: Reducing the amount of energy consumed by lighting has already had measurable reduction on energy consumption in the United States, with a direct benefit of reducing emissions of pollution (carbon and other emissions from power generation). The energy savings already enabled by, and projected from, more efficient lighting has been calculated as a 79 million metric tons (MMT) reduction in CO_2 annually. By 2035, 196 MMT of CO_2emissions savings could be achieved annually if the SSL Program goals are met.

Grid Flexibility: LED lighting is inherently dimmable and instant on/off. Intelligent lighting systems can be configured with controls systems to respond to transactive control signals to instantaneously reduce grid load.

Zero Energy Buildings: The very high efficiency of LED lighting also directly supports the development of zero energy (and other ultra-high performing) buildings. Ongoing advancements to lighting efficiency not only reduce the consumption of energy, but when combined with other distributed resources they can provide grid services, as well as energy storage to support zero energy building objectives. The gains in lighting efficiency have value beyond simple payback in a conventional grid attached lighting system.

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[19] U.S. DOE SSL program Impacts. https://www.energy.gov/eere/ssl/program-impacts

DC Grid Operation: LED lighting technology is fundamentally a direct current (DC) driven light source, which can enable more efficient integration with renewable energy sources (which are typically DC sources). This avoids the need to generate DC power, invert it to AC, and then convert the AC back to DC to power the lighting. LED lighting technology is aligned with the use of simple DC micro-grids powered by renewable energy and backed up by energy storage. LED lighting can also be grid-interactive to participate in demand response programs.

Beyond the clear and compelling benefits of improved light source efficiency and associated reduction in required electricity and detrimental impacts of electricity generation on the environment, LED lighting offers additional environmental benefits.

Reduced Light Pollution: LED lighting offers direct benefits for reducing the environmental impacts of light pollution. LED technology enables improved optical control, which allows roadways to be lit to achieve recommended illuminance levels with less total light and less off-target light that contributes to skyglow, light trespass, and unintended wildlife responses to light. Outdoor LED lighting can also be controlled to dim or turn off when unnecessary to help reduce light pollution and ecological impacts. LED lighting can have tailored color to reduce specific wildlife impacts, though this must be considered alongside potential impacts to visual function for the intended function of the light, e.g. roadway or pedestrian safety. Staff from PNNL contributed to the development of a new IES Technical Memorandum, IES TM-37, the Description, Measurement, and Estimation of Skyglow. This Technical Memorandum allows for the standard characterization of skyglow and understanding of the lighting practices that contribute most to skyglow.[20]

Lifecycle Impacts: The longer operational lifetime of LED lighting technology enables a reduction in the amount of material that must be replaced as lighting products reach the end of their life. In addition, the materials chosen for LED lighting products can be sustainably developed with low embedded energy. LED components are comprised of relatively benign materials with a reduced reliance on scarce or otherwise critical materials, compared to previous lighting technologies. For example, it is estimated that a compact fluorescent lamp uses 0.18 mg of europium (Eu), a rare earth material, while LED lamps can use as little as 0.008 mg – approximately 95% less. [3]

Reduction of Toxic Materials: In particular, LEDs do not require the use of mercury (Hg), which is a common component in conventional fluorescent and high-intensity discharge (HID) lamps. Considered by the World Health Organization (WHO) as one of the top ten chemicals of concern, mercury poses a threat to human health. Broken or discarded fluorescent bulbs release this toxic substance, mainly into the air through landfills, where it can then contaminate the food chain. The U.S. Environmental Protection Agency (EPA) estimates that over 4000 kg of mercury was used in lamps sold in the United States in 2018, representing 16% of that used in all manufactured products. [4] Proper recycling is required by most states for commercial facilities, but overall recovery rates are low. Globally, only about 10% of the mercury in discharge lamps is recovered. The amount of mercury used in lighting has been reduced substantially, due to technical improvements in discharge lamps and more and more by their replacement by LED lighting. The remaining installed U.S. base of about 4 billion discharge lamps and luminaires contain about 15,000 kg of mercury. LED lighting technology is also contributing to the reduction of mercury emissions through the reduction in the use of coal and other fossil fuels in the generation of electricity. Coal burning power plants have been the largest source of mercury emission in the United States, releasing 10,000 kg in 2017, with about 1500 kg attributable to electricity generation for lighting. Transitioning to LED lighting technology reduces mercury emissions from power generation and mercury contained within fluorescent lighting products.

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[20] https://store.ies.org/product/tm-37-21-description-measurement-and-estimation-of-sky-glow/

In 2013, the United States signed the Minamata Convention, which prohibited the manufacture, import and export of mercury-containing products after 2020. However, exemptions were granted for fluorescent and discharge lamps since viable alternatives were not available. These exemptions are being reconsidered in light of increasing performance and availability of LEDs.

1.6 Manufacturing and Jobs

LED lighting requires different manufacturing processes than previous lighting technologies. These changes to lighting-related manufacturing offer the possibility that portions of the lighting manufacturing supply chain can be encouraged and fostered within the United States, particularly as new manufacturing methods and technologies are developed. One notable opportunity for the lighting supply chain is the development of additive manufacturing technologies, which can automate, simplify, and streamline the production of lighting products. Within the entire lighting production value chain there are opportunities for domestic manufacturers to expand their range of production and increase the proportion of U.S. made content within lighting products. The lighting technology, manufacturing technology, and lighting science understanding continue to evolve and create new opportunities to establish lighting manufacturing practices and facilities within North America, including the United States. [5]

As LED lighting continues to improve and become the primary lighting technology, all jobs in the lighting industry will have a role in creating the U.S. clean energy economy. The transformation in lighting technology, including changes with controls and building integration, require lighting professionals to develop new expertise and understanding so that lighting applications can be fully optimized. This will require new sources of trained lighting professionals who understand LED lighting technology, the latest lighting practices, and the new and broader impacts of lighting. There continues to be a dearth of young lighting professionals due to limited vocational, undergraduate, and graduate programs dedicated to advanced lighting. This situation will become more dire as the existing lighting workforce retires.

1.7 Science – Scientific Discoveries and Application Understanding

The introduction and adoption of LED lighting has been enabled by profound scientific discoveries and has led to further advancements in optoelectronic materials science. Adoption of LED lighting highlighted limitations in lighting science and is enabling new understanding, applications, and benefits with lighting. As science advances and new discoveries are made, our understanding of lighting and its effects on human health and productivity will continue to improve.

1.7.1 Optoelectronic Materials Science

The advancement of LED lighting has been enabled by profound discoveries in materials science and semiconductor physics, particularly the invention of the blue LED. [6] As LED technology has improved, the knowledge developed on underlying semiconductor physical mechanisms has enabled new understanding in materials science and optoelectronics that spans into a broad array of cross-cutting applications, including optical communications, UV radiation generation for germicidal and other application areas, photovoltaics, displays, and power electronics. To make the next leap in LED performance, new scientific understanding will need to be developed.

OLEDs have also ushered in a new level of understanding for organic optoelectronic materials. There have been breakthroughs and advancements in organic emitter materials, charge transport layers, light extraction, encapsulation, and deposition for organic semiconductor optoelectronic materials. The organic electronic platform, enabled by OLED lighting research, can potentially be used with electroluminescent quantum dot emitters, organic photovoltaics, displays, and numerous other energy related applications.

1.7.2 Lighting Science

Beyond new understanding in materials and device science, LED lighting technology is enabling a revolution in understanding how best to use electric lighting. Previous lighting technologies had fundamental performance limitations that hindered research efforts and the motivation to understand lighting at a deeper physiological level since there was not a practical technology that could act on such advanced understanding. Now, LED technology can provide an almost infinite range of spectra with good efficiency, at a broad range of intensity, luminance, and optical distribution with a range of practical mechanical form factors. The current challenge is to perform the lighting science research that provides the guidance as to how best to use these capabilities. This guidance and understanding can be improved for human visual function, the core function of lighting, but also for non-visual human physiological responses to light that can greatly affect health and well-being.

Based on the discovery of non-visual photo-receptors within the human eye, intrinsically photosensitive retinal ganglion cells (ipRGCs), and subsequent research, it is now clearly understood that existing lighting practices can negatively impact human health and well-being. Indoor lighting may provide a weak signal to the ipRGCs which regulate melatonin secretion and therefore may result in less sleep time and poorer sleep quality, as well as numerous other downstream and related health impacts. While the understanding of the impacts of light on health are still being elucidated, it is imperative that updated lighting practices include this new and developing understanding. Even if the benefits of improved lighting on health may be individually modest, considered nationwide or globally these impacts will be large scale and contribute to a healthier world. Clear guidance on healthy lighting practices will allow for the most efficient achievement of these objectives.

There is also the opportunity to improve understanding of physiological responses to light by animals and plants. LED technology has advanced the benefits for indoor growth of plants, often leading to reduced needs for transportation over long distances and substantial reduction in the use of water. Optimized electric lighting can improve health and productivity of domesticated animals while under electric light, and the impacts on wildlife at night can be minimized. Understanding physiological and behavioral responses to light for humans, animals, and plants opens windows to understanding and connecting molecular responses across all species. The understanding and practice of physiological responses to light requires a robust feedback loop that connects scientists, product developers, lighting practitioners, and lighting practice standards groups, such as the IES and the International Commission on Illumination (CIE). Input from the user community is also essential in each application area.

2 Lighting Energy and Technology Status

Since their market introduction, LED products have grown in adoption each year, highlighting their acceptance 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. Additionally, the status of integrating lighting into buildings, the productivity from lighting, and how to effectively improve the energy and carbon efficiency for application driven designs will be discussed. Finally, the cross-cutting applications that use light beyond general illumination will be briefly described.

2.1 SSL Energy Savings Potential

Over the past decade DOE SSL market reports have chronicled the market introduction and rapid adoption of LED lighting.[21] [7] Compared to conventional lighting technologies, tremendous energy savings have been realized by LED lighting technology. 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 2019 DOE SSL Forecast Report estimated the installed stock and energy savings associated with LED lighting installations presently and in the future (to 2035), with results summarized in Table 2.1 and Table 2.2.[22] [2]

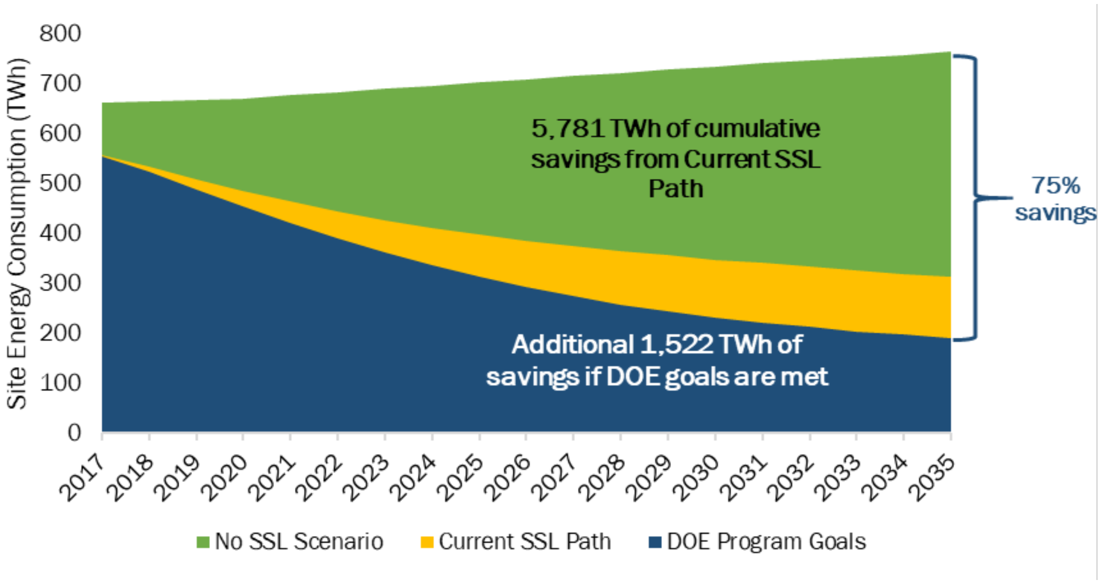

Figure 2.1 DOE SSL Program Goal Scenario Energy Savings Forecast, 2017-2035. The Current SSL Path scenario is projected to save 5,781 TWh of site energy from 2017 to 2035, with an additional 1,522 TWh of savings if DOE goals are met.[23]

DOE SSL Forecast analyzed two scenarios, the Current SSL Path for adoption and performance and one based on aggressive DOE SSL Program Goals:

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

[22] https://www.energy.gov/eere/ssl/ssl-forecast-report.

[23] Current SSL Path energy savings are calculated relative to a hypothetical No SSL scenario which assumes LED technology never entered the lighting market. The additional 1,522 TWh of savings are calculated relative to the Current SSL Path scenario.

- **Current LED Path Scenario**: The expected future path for LED lamps and luminaires with expected levels of SSL investment and effort from industry stakeholders and continued adoption of LED products.
- **DOE LED Program Goals Scenario**: The future path for SSL following the DOE SSL Program goals, representing the ultimate potential of what DOE has determined is technically feasible in the analysis period which included increased connected lighting adoption and technology efficacy improvements.

In the Current SSL Path Scenario, DOE's Lighting Market Model estimated the projected installed stock penetration in 2020 to be 35%.[24] By 2035, the penetration is forecasted to reach 84%. LED lighting provided an estimated 185 TWh of site energy savings in 2020. Energy savings for LEDs are calculated relative to a 'No SSL' baseline, a hypothetical scenario that assumes LED technology never entered the lighting market. If the lighting market continues along the Current SSL Path scenario, a total annual site energy savings of 450 TWh is possible by 2035, of which 12% is made possible by the adoption of LED lighting controls. These energy savings equate to an estimated CO_2 savings of 79 MMT in 2020 and 154 MMT in 2035.[25] In 2020, total CO_2 emissions due to lighting in the United States was estimated to be approximately 208 MMT. If LED technology never entered the lighting market, the annual CO_2 emissions for 2020 would have been 287 MMT.

Table 2.1 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.

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

Compared to the Current SSL Path scenario, the DOE SSL Program Goals scenario offers a more aggressive view for the future of LED technology. The primary difference between the two is the resulting energy savings due to increased LED lighting product efficiency and increased adoption and use of lighting controls. The increase in lighting controls 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 122 TWh in annual site energy savings in 2035 (relative to the Current SSL Path) for a total annual site energy savings of 572 TWh (relative to No SSL scenario), equivalent to savings of 196 MMT of CO_2. Of the total 572 TWh in annual site energy savings in 2035, 16% is made possible by the penetration of connected LED lighting. Cumulative

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[24] For more information on the Lighting Market Model, please see: https://www.energy.gov/eere/ssl/ssl-forecast-report

[25] This document uses MMT of avoided CO_2 for consistency and comparability with other DOE analyses. Prior DOE SSL Program reports calculated avoided CO_2e using the U.S. Environmental Protection Agency's *Greenhouse Gas Equivalencies Calculator*. However, the EPA's calculator does not forward project the conversion ratio of carbon emissions to electricity consumption. In this report, carbon savings are calculated using data tables 2 and 18 from the U.S. EIA's Annual Energy Outlook 2021 which show around 0.03-0.04 MMT carbon emissions per TBtu of electric power consumed in the U.S. The conversion factor for site energy in TWh to source energy in TBtu is about 10.713 TBtu/TWh. Using the EIA's AEO report for avoided CO_2 calculations allows forward projection of carbon savings from energy efficient lighting by accounting for future changes in the ratio of carbon emissions to electricity consumption (the AEO's projections account for expected changes in the grid-mix). Note that the ratio of carbon emissions to electricity consumption is projected to decrease over time based on EIA's AEO analysis. The AEO data tables can be found at https://www.eia.gov/outlooks/aeo/tables_ref.php

from 2017 to 2035, if DOE meets the SSL Program goals, this will lead to an additional 1,541 TWh of site energy savings from the Current SSL Path and a total site energy savings of 6,176 TWh compared to the No SSL Scenario (see Figure 2.1). While the current LED path will enable massive electricity savings, the further electricity and carbon savings enabled by achievement of DOE SSL Program goals continue to justify R&D to achieve the maximum benefit offered by LED lighting technology. The over-arching Program goals used for this analysis assume that LED lighting controls adoption accelerates and LED efficacy goals are met, as described in the 2019 DOE SSL R&D Opportunities document, which projects that average LED lamp/luminaire efficacy reaches 209 lm/W in 2035.[26]

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[26] https://www.energy.gov/sites/default/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf

Table 2.2 U.S. LED forecasted energy and carbon savings by scenario. If the market continues at the current pace, LED products are expected to save 450 TWh of energy and 154 MMT of carbon annually in 2035. If DOE goals for efficiency and controls penetration are met, LED products can save 572 TWh of energy and 196 MMT of carbon annually in 2035.

		2020	2025	2030	2035
Current SSL Path	**Site Energy Savings (TWh)[1]**	**185**	**304**	**386**	**450**
	Commercial	67	111	147	177
	Residential	35	67	96	119
	Industrial	9	20	29	35
	Outdoor	75	105	114	119
	Carbon Savings (MMT)[2]	**79**	**112**	**139**	**154**
	Commercial	29	41	53	61
	Residential	15	25	35	41
	Industrial	4	7	10	12
	Outdoor	32	39	41	41
	Cost Savings ($)[3]	**$20.0B**	**$32.5B**	**$41.2B**	**$47.9B**
	Commercial	$7.1B	$11.7B	$15.4B	$18.5B
	Residential	$4.2B	$8.3B	$12.0B	$14.8B
	Industrial	$0.6B	$1.4B	$1.9B	$2.3B
	Outdoor	$8.0B	$11.1B	$12.0B	$12.3B
DOE SSL Program Goals	**Site Energy Savings (TWh)**	**216**	**388**	**502**	**572**
	Commercial	81	156	210	242
	Residential	40	79	112	136
	Industrial	11	27	39	46
	Outdoor	84	126	141	148
	Carbon Savings (MMT)	**92**	**143**	**182**	**196**
	Commercial	35	57	76	83
	Residential	17	29	41	47
	Industrial	5	10	14	16
	Outdoor	36	46	51	50
	Cost Savings ($)	**$23.3B**	**$41.3B**	**$53.3B**	**$60.6B**
	Commercial	$8.7B	$16.5B	$22.0B	$25.2B
	Residential	$4.9B	$9.7B	$14.0B	$17.0B
	Industrial	$0.8B	$1.8B	$2.6B	$3.0B
	Outdoor	$8.9B	$13.3B	$14.8B	$15.4B

1. Energy savings shown here are calculated relative to the baseline No SSL scenario, a hypothetical scenario that assumes LED technology never entered the lighting market, to show estimated energy savings from LEDs.

2. Carbon savings are for carbon dioxide from energy combustion in million metric tons. This document uses MMT of avoided CO_2 for consistency and comparability with other DOE analyses. Prior DOE SSL Program reports calculated avoided CO_2e using the U.S. Environmental Protection Agency's *Greenhouse Gas Equivalencies Calculator*. However, the EPA's calculator does not forward project the conversion ratio of carbon emissions to electricity consumption. In this report, carbon savings are calculated using data tables 2 and 18 from the U.S. EIA's Annual Energy Outlook 2021 which show around 0.03-0.04 MMT carbon emissions per TBtu of electric power consumed in the U.S. The conversion factor for site energy in TWh to source energy in TBtu is about 10.713 TBtu/TWh. Using the EIA's AEO report for avoided CO_2 calculations allows forward projection of carbon savings from energy efficient lighting by accounting for future changes in the ratio of carbon emissions to electricity consumption (the AEO's projections account for expected changes in the grid-mix). Note that the ratio of carbon emissions to electricity consumption is projected to decrease over time based on EIA's AEO analysis.

3. Cost savings are calculated using data table 8 from U.S. EIA's Annual Energy Outlook 2021 which show the national average electricity prices by sector for 2020 to 2035. All values are in 2020 U.S. dollars.

While SSL performance has already led to meaningful energy savings, as seen in the tables above, there is still room for improvement in LED lighting technology performance. The next generation of energy savings will come from improved LED source efficiency as well as lighting application efficiency (which characterizes the delivery of optimal 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. 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 necessary.

2.2 Lighting Performance Status

Over the past decade, the efficacy of LED-based lighting products has continued to improve for both indoor and outdoor applications, surpassing all other lighting source technologies. This improvement in luminous efficacy, along with ongoing cost reductions, has allowed LED lighting to penetrate into all lighting applications and continue to grow in percentage of the installed base. As an example, Figure 2.2 shows evolution of efficacy over the past decade in A19 LED lamps and LED troffers.

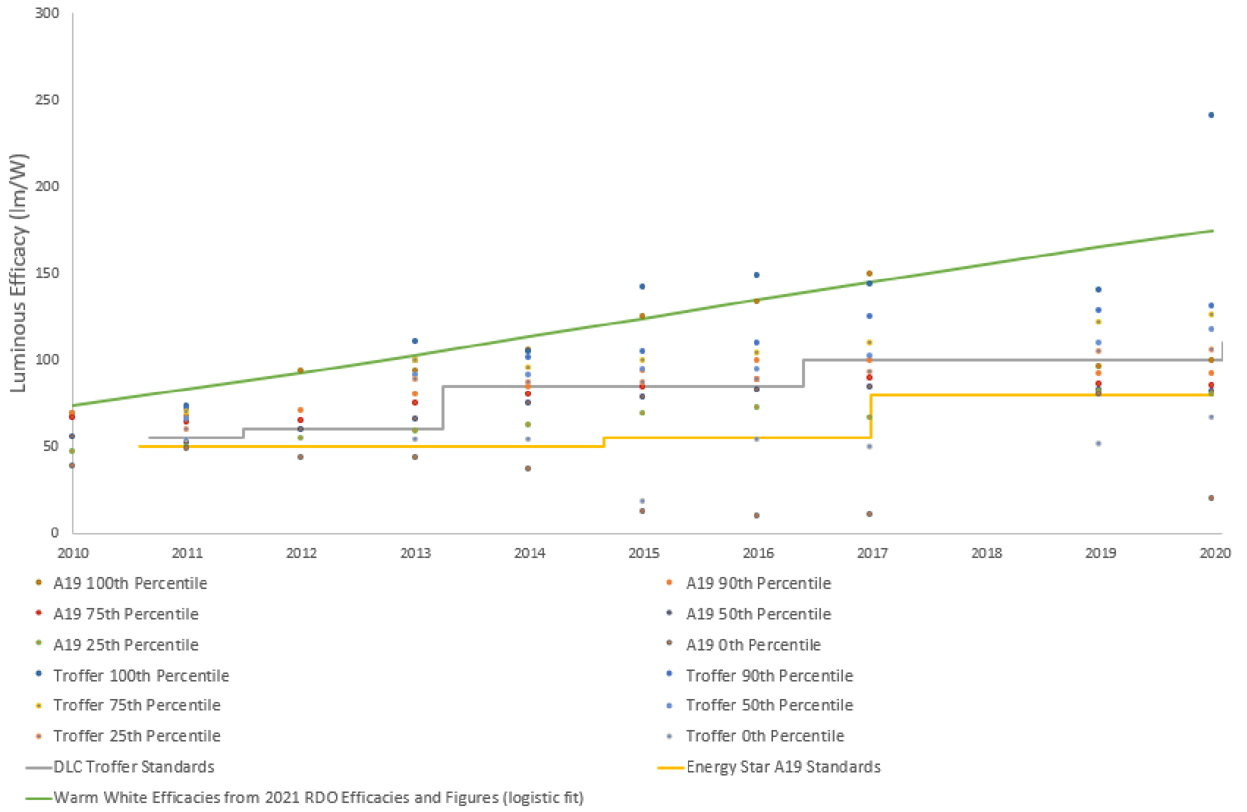

Figure 2.2 Evolution of the 90th percentile efficacy over the last decade of LED lamps and luminaires listed in based on web-scraped LED data across lighting distributors in the United States. [8] The increases in standards over the same period are also shown. The 90th percentile initial efficacy of currently listed A19 products has increased from 69 lm/W to 92 lm/W. The 90th percentile initial efficacy of currently listed Troffer products has increased from 72 lm/W to 131 lm/W.

While the improvement in LED lighting luminous efficacy has been impressive, it is only one of the many beneficial features of SSL. Lighting attributes, such as spectral (color) quality, optical distribution, intensity control, 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 2.3. Often, performance trade-offs are required to balance the attributes of ideal lighting, such as efficacy and many other properties along with cost. Though efficacy has improved over the past decade and cost is low in most product categories (such as A-lamps), there is still work required to simultaneously improve efficiency, spectral quality, optical distribution, and reliability to unlock more of the benefits tied to SSL. In addition, there is significant room for improvement to reduce existing performance and cost trade-offs and get closer to achieving ideal lighting performance for the given application.

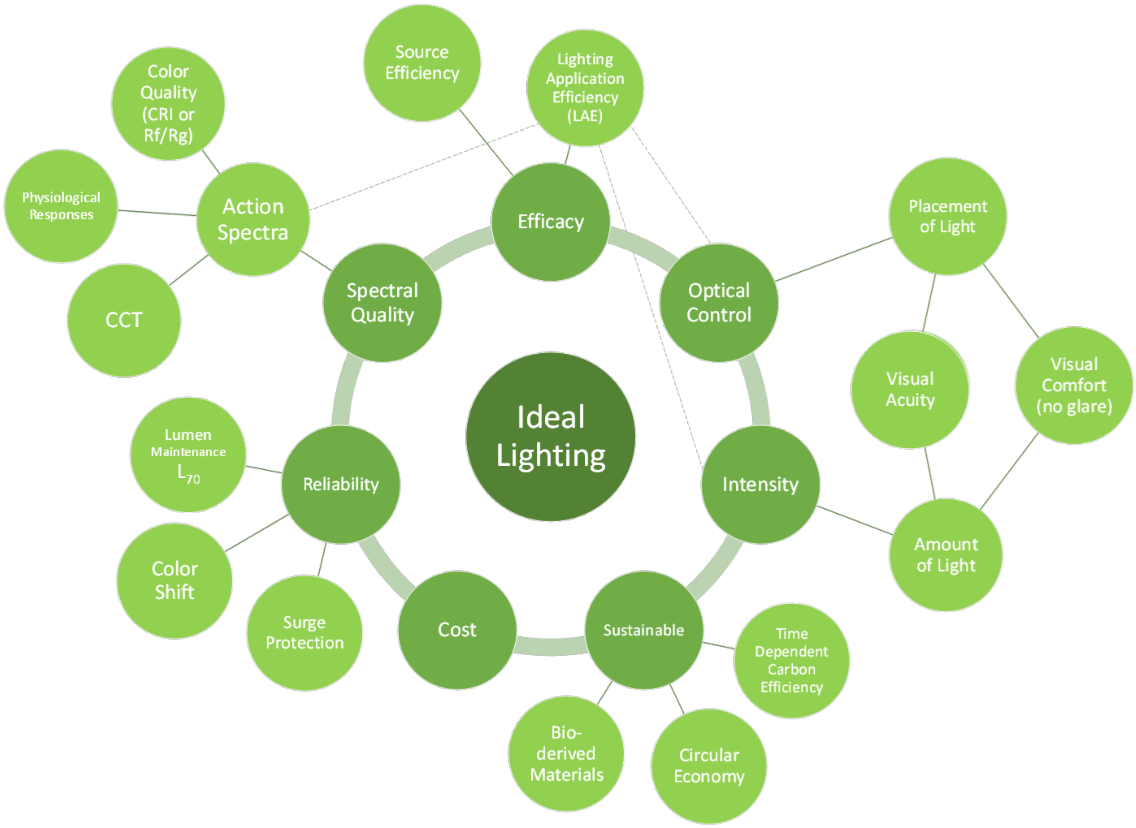

Figure 2.3 A schematic diagram illustrating the key attributes of an ideal lighting solution for an occupant. These attributes move beyond just luminous efficacy and cost to provide the right light at the right time for the application. Improving performance in one of these attributes can often lead to performance trade-offs within other metrics.

The performance difference between LED lighting products is often a factor of the design choices for the 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 based on price pressures of particular market segments. 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 luminous 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 fidelity, 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 2.3 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), an 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.[27] The lamp product was selected from the Energy Star certified products list, which verifies that products meet strict energy efficiency guidelines set by the U.S. Environmental Protection Agency.[28] 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, color rendering index (CRI), L_{70} lifetime, and cost (normalized to US $ per kilolumen of light).[29]

Table 2.3 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 2.3, as well as the ideal light source, are illustrated in Figure 2.4. 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 fidelity, optical control, and longer L_{70} lifetimes most often come at a higher cost. When comparing the products in Figure 2.4 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 2.4, with moderate efficacy, acceptable 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 2.3 covers four of the five 'spokes' in Figure 2.4 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. As elsewhere, every LED lighting product solution today entails trade-offs. The value of energy and carbon efficiency, color quality, or lifetime vary for different customers and impact what they are willing to spend for

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

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

[29] 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.

those benefits. With further research and innovation into LED lighting (as highlighted in Section 3.2), these trade-offs can be reduced further and provide efficient, high quality lighting ideal for the applications at a reasonable cost.

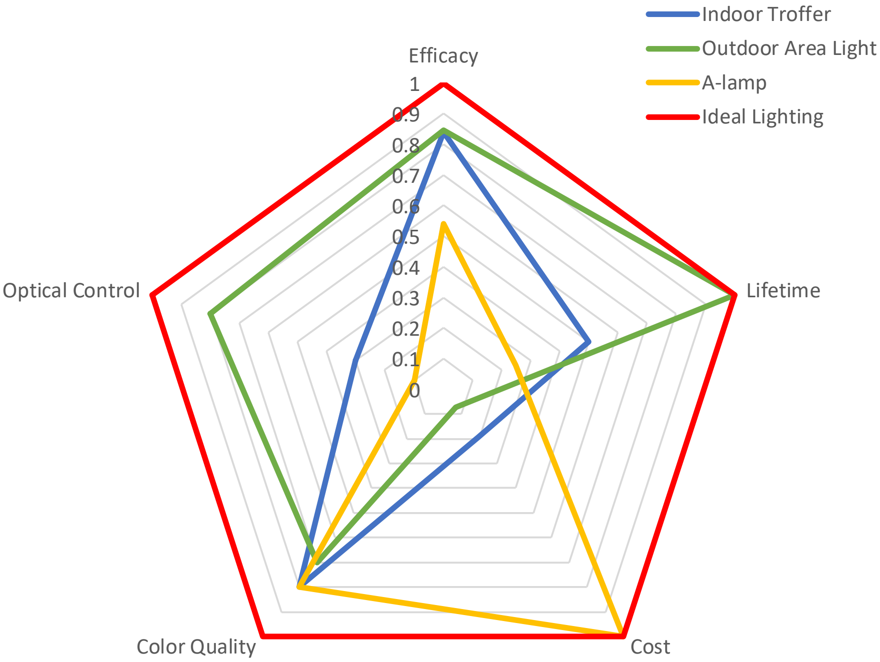

Figure 2.4 Comparison of lighting attribute trade-offs for three representative lighting applications – indoor troffer, outdoor area light, and A-lamp. Each product type is designed to the end application and thus has different strengths of the attributes that lead to performance differences.

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

2.3 LED Efficiency and Cost

The efficiency and performance of LED lighting has continued to improve over the past fifteen years to the point where it is the best option for almost all lighting applications. During this time, the luminous efficacies of white LED packages have improved from around 35 lm/W to well over 200 lm/W. Simultaneously, the costs of LED packages have decreased to the point where LED lighting products are 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. Although LED luminous efficacy has increased tremendously over the past decade, further increases to LED efficacy create the efficiency headroom for luminaire manufacturers to provide improved features such as better color quality, varying spectral power distributions, changing optical distributions, new form factors, and advanced control of the LED lighting products, all while still driving further energy savings.

2.3.1 Efficiency status and breakdown

Historically, progress in SSL has been measured in terms of luminous efficacy expressed in lumens per watt (lm/W). The lumen measures the amount of light generated weighted by its relative perception by the human eye. The relative perception of light with different wavelengths is defined by the action spectrum of the photopic eye response curve. The standard term, luminous efficacy (lm/W), is used to describe how well a light source produces light for photopic visual acuity and is defined as the ratio between the lumens (lm) associated with a given optical power (the integral of the optical power spectrum $p_o(\lambda)$, weighted by the human eye response $V(\lambda)$, over wavelength) and the electrical source power (p_e) 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. [9] LED technology has demonstrated ongoing advancement toward this limit and there are not known fundamental limitations on further advancements; however, DOE analyses include practical limits for LED and luminaire performance. A presentation of historical and projected LED package efficacy for warm white and cool white phosphor-converted and color-mixed LEDs is given in Figure 2.5(a) and summarized in Table 2.4. The analysis assumes operating conditions for qualified data points (35 A/cm^2 and 25^{o}C). These conditions may not correspond to typical LED operating conditions, particularly with respect to the use of lower drive currents to minimize current density droop. Nevertheless, using a standard current (or power density) at a fixed operating temperature and selecting devices within limited ranges of CCT and CRI allows researchers to evaluate technical developments in emitter efficiency (including the reduction of current and thermal droop) and down-converter performance against a consistent baseline.

The phosphor-converted LED (PC-LED) architecture is, by far, the dominant white light LED architecture. It uses a blue LED to pump yellow-green and red wavelength optical downconverters (typically phosphors) to produce white light. The PC-LED 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 2.5 (a) shows a history of the luminous efficacy of PC-LEDs since the DOE SSL Program began and the progress that has been made. Over the past decade, luminous efficacies have increased by more than doubled, 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, headroom remains for further PC-LED luminous efficacy improvements. As illustrated by the saturation of the blue and yellow curves Figure 2.5(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. This analysis considers a 4-color RGBA, since it is a suitable balance between high ultimate luminous efficacy and high color rendering. As indicated by the dashed grey line in Figure 2.5(a), its ultimate "upper potential" might be on the order of 330 lm/W, limited only by the anticipated 80 to 90% external quantum efficiencies of the LEDs (demonstrated now by existing blue and violet LEDs) themselves and by small losses associated with mixing of their pure source colors to create white light. The current luminous efficacy of the CM-LED architecture, however, is quite low: about 138 lm/W (a power conversion efficiency of ~33%, 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 2.5(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, the color-mixed approach is not common in most LED lighting but reserved for luminaires used in applications requiring color 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 2.4 PC- and CM-LED package historical and targeted efficacy levels.

Metric	Type	2020	2025	2030	2035	2050
LED Package Efficacy (lm/W)	PC Cool White	185	228	246	249	250
	PC Warm White	165	210	231	241	250
	Color Mixed	138	204	245	281	336

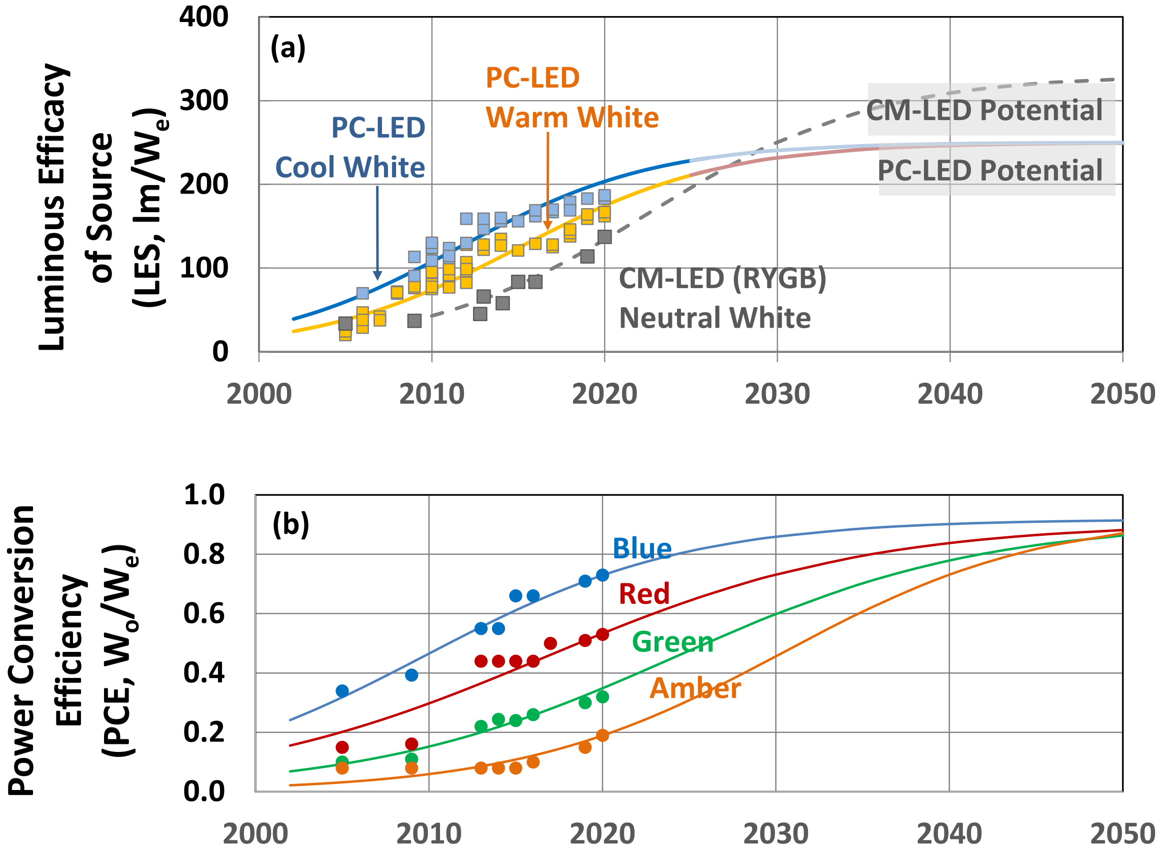

Figure 2.5 Efficacies and efficiencies over time for white and colored commercial LED packages measured at 25°C and 35 A/cm^2 input current density. All curves are logistic fits using various assumptions for long-term future performance, and historical experimental data. The data are from qualified products at the representative operating conditions of 25°C and 35 A/cm^2 input current density.

Upper panel (a) are the luminous efficacies and conversion efficiencies of warm-white (3000-3500 K) and cool-white (5700 K) PC-LEDs and hypothetical 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 2040-2045. 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).

2.3.2 LED Luminaire Performance Breakdown

The upper limit for luminous efficacy of an LED luminaire is set 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 – induce losses to the starting LED performance. Various lighting applications have different considerations in optimizing luminaire design and system efficiency. The subsystem (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 subsystem efficiencies associated with the luminaire for a high performance indoor commercial troffer, outdoor area light, and A19 replacement lamp are listed in Table 2.5. 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 from the best demonstrated subsystem efficiency for those lighting product categories. Note, the calculated efficiency values in Table 2.5 estimate efficiencies that are achievable if the best subsystem designs are integrated into the product. Most lamps and luminaires have market factors that play a role in the cost versus performance trade-offs, so typical products do not meet these high end performance values.

Table 2.5 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. The best in class subsystem efficiencies are calculated to estimate the top end luminaire luminous efficacy achievable with current technology. Note: this does not represent typical product performance levels where the upper limit of performance is defined by LEDs driven at lower current densities.

Efficiency Channel	2020			2050
	Troffer	Outdoor Area Light	A-lamp	Goal
LED Package Efficacy (lm/W)	210*	185**	210*	250
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)	158	133	133	214

* Top performance mid-power PC-LED packages can reach 210 lm/W at CCTs between 3000-4000 K.

** Top performance high-power PC-LED packages can reach 185 lm/W at 4000 K CCT.

† Luminaire efficacy is obtained by multiplying the package efficacy by the overall luminaire efficiency.

Troffers typically use many mid-power packages, which operate at low current densities (< 35 A/cm^2) 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 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 effectively 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 system cost. This is especially true in the LED replacement lamp segment as costs are dropping to commodity levels and achievable luminous 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 and have understood trade-offs with cost. Improving LED efficiency can create more headroom for overall luminaire losses but each of the luminaire subsystems still have room for performance improvements with the goal of reaching 95% efficiency across these subsystems to meet the DOE luminous efficacy projections for 2035. Continued R&D is required in various technologies to achieve these targets and to reduce the cost-performance trade-offs. The technical challenges are highlighted in Section 3.2.1 (Source Efficiency), Section 3.2.3 (Optical Delivery Efficiency), and Section 3.2.6.1 (Electronics).

2.3.3 Impact of Performance Variants

Though the luminous efficacy metric is easy to use, additional information is required to ensure that the delivered lumens are effective for the intended lighting application. Typically, additional color metrics, including color fidelity and CCT, are also provided to aid in the selection of an application-appropriate lighting product, and have implications for efficacy performance. For many segments, luminaires are the final customized products that tailor 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.

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 3.2.

Color Fidelity: 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.[30] 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%. [10] 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 3.2.1.3. In addition, new benefits from spectral engineering of LED sources are emerging. LED technology is unique among lighting technologies in that an almost infinite range of spectral power distributions (SPDs) can be produced. Light sources with SPDs engineered to highlight specific colors or features in the products being illuminated are now available. Additionally, lighting products with full spectrum sources, similar to the spectral content of sunlight, are also now being offered. These engineered colors will have various trade-offs with efficiency depending on the specific SPD that is engineered.

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[30] 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 (IES) published TM-30, a new method for evaluating color rending that includes both a “fidelity index” and a “gamut index.

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 further in Section 3.2), 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 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 3.2.3.

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 technologies or their own version of industry standards. The challenges and opportunities of connected lighting and integrated controls are discussed in Section 2.4.2.[31]

2.3.3.1 Form Factor

Most LED-based lighting products replicate the form factors of previous conventional lamps or luminaire products. This enables easy replacement into existing fixtures, ceiling spaces, and light poles and provides a sense of comfort for consumers who may be skeptical of new form factors. However, forcing LED lighting technology into legacy form factors limits performance and increases cost of the lighting products. For example, with the common A19 lamp form factor, the screw-in Edison socket does not provide a thermal path to dissipate heat from the LEDs, and the required optical distribution is difficult for LEDs to match and frequently is not optimum for the lighting application. Developing new luminaire form factors can maximize LED lighting performance while reducing cost and delivering appropriate light levels. While there are some form factors embracing the unique features of LEDs, the majority of products resemble legacy form factors and building integration schemes. This reimagining of form factors can also lead to improved designs for manufacturing (DFM) in terms of assembly complexity and ease of automation. [11] Novel form factor products will require rethinking of existing lighting systems and possible redesign of how lighting is mechanically, electrically, and informationally integrated into buildings. The use of DC micro-grids in buildings, along with new form factors and lighting layouts, can help reduce the power supply conversion losses today and allow more efficient use of renewable energy sources such as photovoltaics.

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[31] The SSL Program focuses its efforts on lighting specific controls and sensors. The Building Technologies Office also supports R&D on a broader array of controls and sensors for building energy management. Information on this can be found at https://www.nrel.gov/docs/fy20osti/75601.pdf.

2.3.4 LED and Luminaire Pricing and 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 6-7 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.

2.3.4.1 LED Package Platforms

The diverse set of LED packages available in the marketplace today is designed to tackle an array of different lighting applications. Because of the various LED package families available, there is a wide set of materials and methods of construction used to create these light sources. The various LED packages can be grouped into 4 major platforms, as illustrated in Figure 2.6:

- High-power ceramic-based LEDs (1-5 W) consist of an LED die mounted onto a ceramic substrate with phosphor-silicone composite on top of the die and a molded silicone hemispherical lens. These are typically used for applications that require high power and high reliability or small source sizes such as directional lamps.

- Mid-power polymer-based LEDs (0.2-1 W) contain one or two small die mounted onto a metal lead frame embedded in a polymer cavity and filled with a phosphor containing encapsulant. These LED packages evolved from the plastic leaded chip carrier type of electronic packages. They are primarily used in omni-directional applications.

- COBs (10-80 W) vary largely in size and power level. They contain many small LED die mounted to a metal core printed circuit board (PCB) or ceramic substrate, which are then coated with a phosphor containing encapsulant. These are used when high luminance is required from small source size or high lumen density is needed.

- Chip scale packages (1-3 W), also referred to as package-free LEDs, consist of a flip-chip LED die coated with phosphor to create a "white chip". Some styles contain white reflective sidewalls around the die to create a top side emitter. Since the package has a similar footprint to the LED die itself, they can be closely packed together in LED arrays with compact overall source size.

High-power: ceramic substrates, molded lens

Mid-power: leadframe, polymer package

Chip on Board: metal-core PCB, ceramic PCB

Chip Scale Package: flip-chip with phosphor

Figure 2.6 Representative examples of LED packages from the four main platforms, including (from left) high-power ceramic-based LEDs, mid-power polymer-based LEDs, CSP LED packages, and COB LEDs.

2.3.4.2 LED Pricing

Rapid price reductions of LED packages have occurred over the past decade with manufacturing process improvements and innovations in epitaxy and die fabrication. The evolution of LED package prices is illustrated in Figure 2.7 for both warm white and cool white high-power and mid-power packages. The steep drop in prices over the past ten years is associated with the introduction of mid-power LED packages that were originally developed for display backlighting but graduated into general illumination lighting usage. 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 is 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 2.9. In all cases, the price is expressed in units of U.S. dollars per kilolumen of light ($/klm) at nominal drive conditions. The price–efficacy projections from Figure 2.5 and Figure 2.7are summarized in Table 2.6. The price projections in this table have been adjusted to account for the lower prices associated with mid-power package designs.

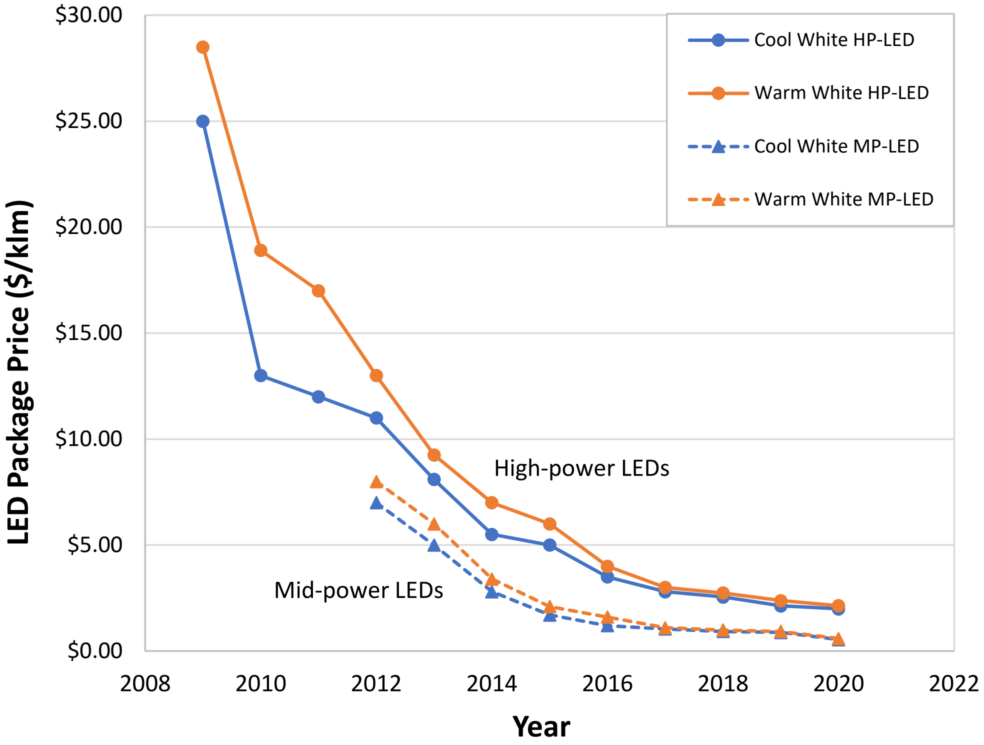

Figure 2.7 Price for high-power and mid-power warm-white and cool-white LED packages over time. The prices have come down rapidly over the past decade with new technology innovation and a more robust supply chain.

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

Table 2.6 Summary of current LED package price and future performance projections. The LED performance projections are taken from Figure 2.5 for LED packages at 35 A/cm^2. The price projections, taken from Figure 2.7, represent the lowest prices available with mid-power LEDs.

Metric	2020	2025	2030	2035
Cool White Efficacy (lm/W)	185	228	246	249
Cool White Price ($/klm)	0.54	0.48	0.41	0.30
Warm White Efficacy (lm/W)	165	210	231	241
Warm White Price ($/klm)	0.59	0.52	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 240 lm/W (cool white) and 210 lm/W (warm white) are available in production in 2020, though most product models tend to have lower efficacies. Prices for these LEDs with very high-end efficacies of 200+ lm/W are nearly 400% more than the price of LEDs in the 130 lm/W efficacy range. The low-end of the price range for the mid-power 3030 style packages is approximately $0.6/klm, but it reaches approximately $4.00/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 185 lm/W for cool white and 165 lm/W for warm white were readily available in mass production in 2020.[32] 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 high-power LED package price erosion will continue, though mid-power package prices may remain more stable while increasing performance levels are offered at those prices. Market issues (e.g., oversupply), though, could impact these trends leading to further price reductions as more suppliers in Asia compete for 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.

2.3.4.3 LED Cost Breakdown

For SSL manufacturing, reducing the cost of the final product involves an understanding of the source of costs at each key stage in the manufacturing process, and requires careful attention to the design of the product and of the manufacturing process. A more detailed cost analysis is available in the DOE SSL Program's Manufacturing Status and Opportunities document. [11] The typical cost breakdowns for high-power and mid-power LED packages are shown in Figure 2.8. 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 then 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

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[32] Note: these efficacies for high-power LEDs are listed at a current density of 35 A/cm^2, consistent with Figure 2.5.

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.

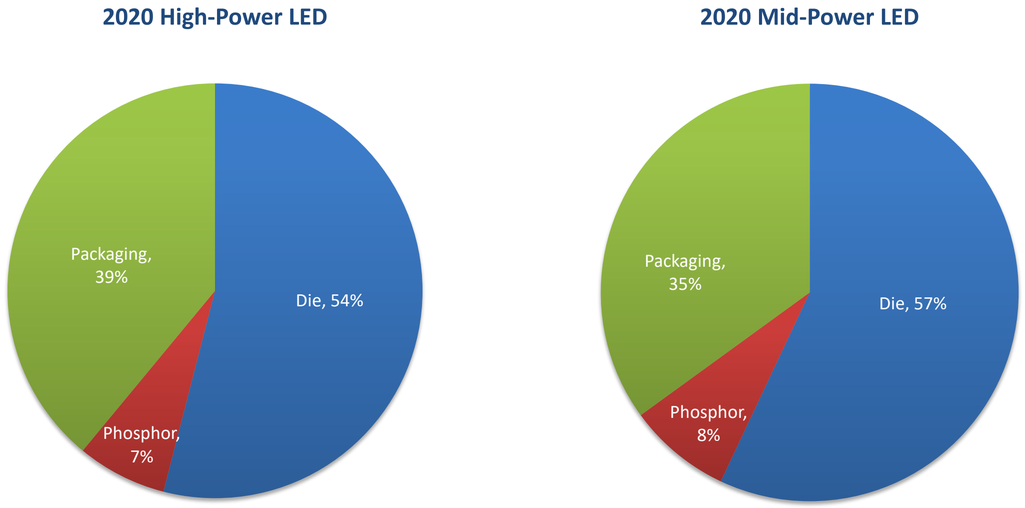

Figure 2.8 Typical cost breakdowns for high-power and mid-power LED packages. The LED die represents the biggest cost contribution of the LED package.

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 6-7 years, the high-power LED package cost has continued to drop as volumes have ramped up. The overall reduction in cost during this period is due to general reductions in materials costs, simplified chip designs, and a continuing erosion of gross margins. 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. The leverage of increasing wafer size on cost is not too surprising since the final product is a packaged die and there are many thousands of such die on each wafer (e.g., around 15,000 1 mm^2 die on a 150 mm diameter substrate). The costs associated with die-level activities are not reduced in the same way as wafer level processes, so manufacturers will need to address die-level packaging process and material costs or perform more of the packaging activities at a wafer level in order to realize further cost reductions

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 die cost and package cost are much lower for the mid-power package and the relative phosphor contribution is similar to that in high-power packages. 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. While the die and phosphor costs are decreasing in these platforms, they still retain a very important role in the resulting LED package performance.

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 that 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 2.9. 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 substrate. 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 2.9, 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.

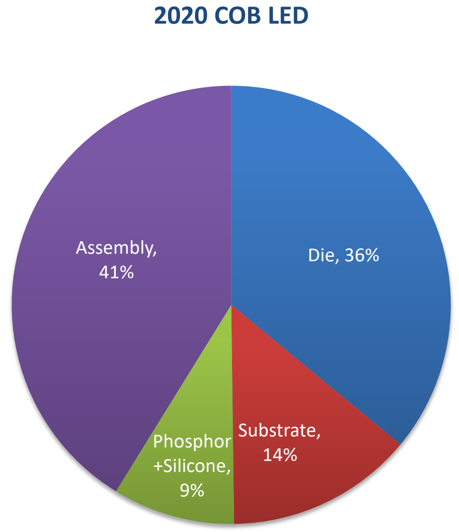

Figure 2.9 Typical cost breakdowns for COB LED packages. The assembly cost is a significant contribution of the COB cost due to the large number of chips that need to be attached compared to high-power and mid-power LED packages.

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

Source: Inputs from DOE SSL Roundtable and Workshop attendees

While pricing for LED packages has 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 3.2. 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 upstream process control (yields); [33]
- Improved equipment throughput (processing, testing, and inspection);
- Increased automation; and
- Chip-scale and wafer-scale packaging.

2.3.4.4 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 2.10 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 6-7 years is how fast relative LED package cost is dropping in both luminaires and lamps; it has fallen dramatically from around 33% of the cost of a 6" downlight in 2014 to 3% in 2020, as shown in Figure 2.11. 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%.

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[33] Wafer-level costs such as substrates, epitaxial growth, and wafer processing, comprise a smaller percentage of the final device cost, but improvements here can have a significant impact on packaging costs and device performance.

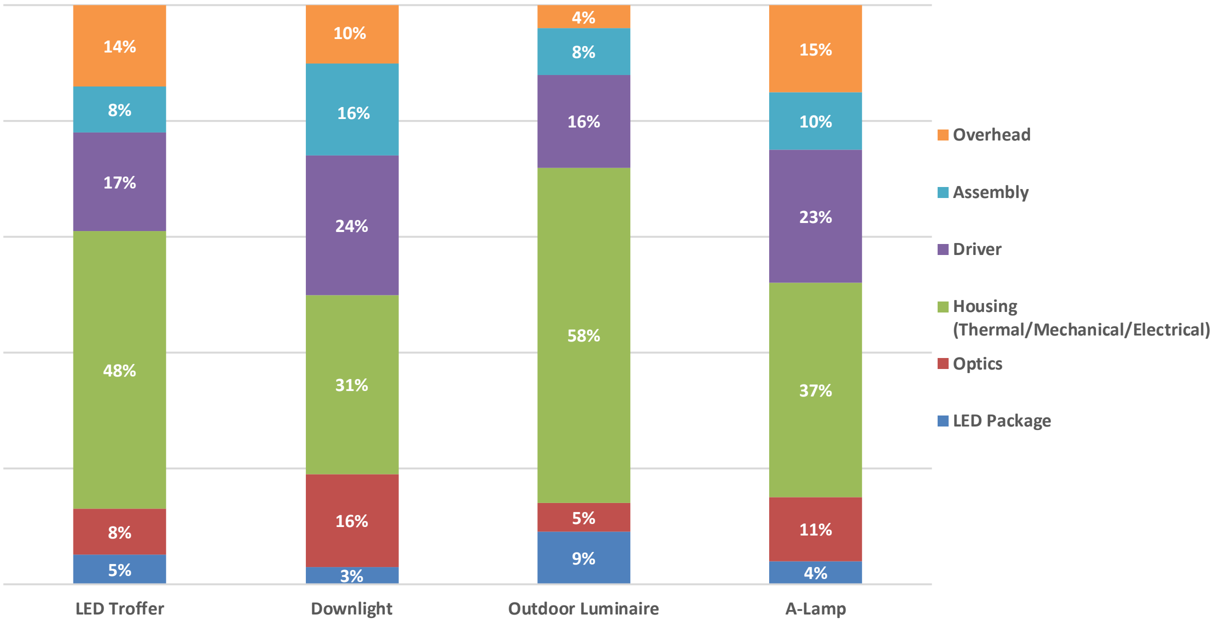

Figure 2.10 Comparison of cost breakdown for different lighting applications in 2019. The categories of LED lighting products include a troffer, a downlight, an outdoor area light, and an A-lamp. Each product has a different balance of cost in the major elements, though housing is the biggest contributor 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

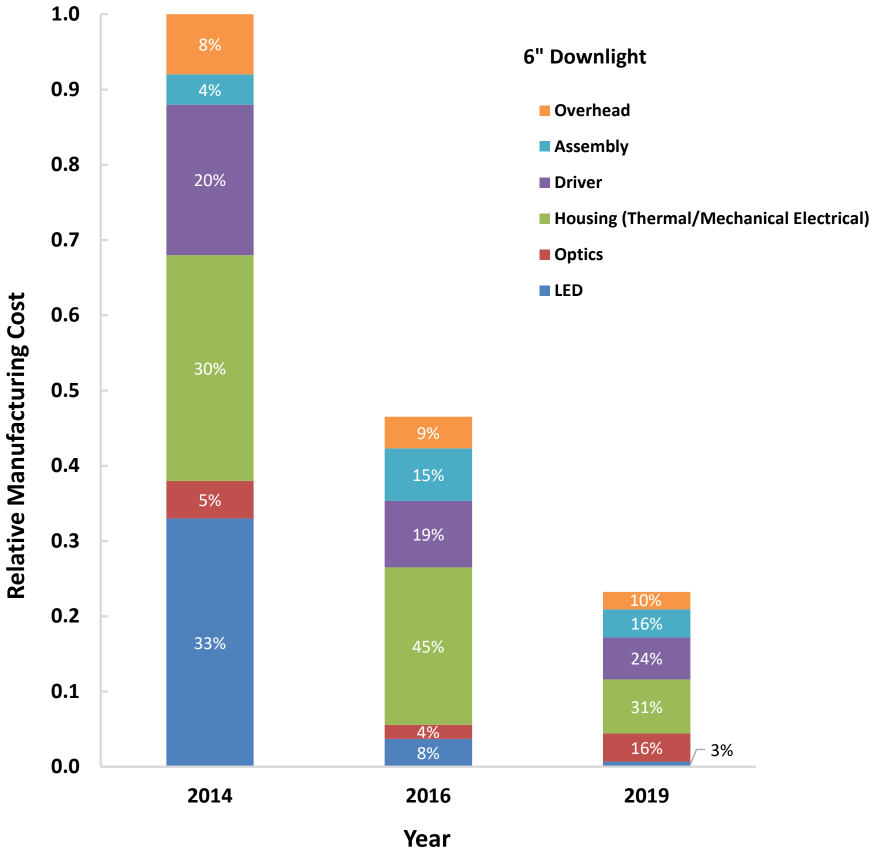

Figure 2.11 Comparison of cost breakdown for a 6” downlight from 2014 to 2019. The relative cost of the LEDs has dropped dramatically while other elements such as the driver retained similar relative cost breakdown even as cost has gone down.

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

While a straight cost reduction 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.

2.3.5 Diffuse Light Sources

In all general illumination lighting applications, the intent of the light is to reflect off an object into the sight of an observer. To economically achieve this effect, traditionally the bright lamp must be shielded from direct view by the addition of a lamp shade or diffuser or placed at such site or distance where it is not within a typical line of sight. This situation remains true with the introduction of LEDs, due to their small size and intense brightness providing significantly higher luminance than the previous traditional light sources. One solution to reduce glare and provide a more comfortable lighting experience is to spread the light source over a larger surface area. Thin, lightweight diffuse lights can be made using OLEDs or waveguides lit by an array of LEDs placed at the edge or behind the waveguide. These thin panels can be planar, for attachment to ceilings or walls, or can be conformable, for use in pendants (Figure 2.12) or embedded in furniture or appliances.

Figure 2.12 Example of white OLED panels integrated into a linear light fixture. [12]

2.3.5.1 OLED Panels and Luminaires

OLED light sources have led to a substantial improvement in the image quality and efficiency of flat panel displays. The resulting OLED displays have gained a significant market share in high-performance cell phones and televisions and are beginning to penetrate other display market segments. OLED technology for general lighting, however, is less mature than OLED displays and inorganic LED lighting. While LEDs have become the dominant lighting technology for most applications and now have a mature manufacturing base, OLED lighting technology has struggled to find its niche and value proposition in the general illumination market. OLED technology, with its large area and moderate brightness, can provide an extended, larger area light source that reduces glare and provide soft comfortable light, even when placed close to the observer. This avoids the need to optically manage a high brightness light source to minimize glare, which is the case for LED and all previous light source technologies. Also, the color quality is important in supporting the comfortable feel of the distributed light source. OLED lighting has the potential to complement high brightness LED technology, but must compete with the LED-based diffuse light source solutions.

OLEDWorks is one of very few manufacturers of OLED lighting sources, and their products demonstrate state of the art performance levels for OLED technology. Panels from OLEDWorks have been integrated into lighting fixtures by various vendors. At 3000 K CCT, the rigid panels offer a luminance over 8500 cd/m^2, corresponding to light output of ~25,000 lm/m^2. The efficacy is 75 lm/W at maximum intensity and 85 lm/W at a more typical luminance of 3000 cd/m^2. Some examples of OLED panels are shown in Figure 2.13.

Figure 2.13 A rigid and flexible OLED light, respectively. The flexible light can be bent with a radius of curvature of 10 cm or higher. [13] [14]

A compelling, distinguishing feature of OLED lighting is the availability of very thin and conformable panels, manufactured on glass with a thickness of only 0.1mm, allowing the total panel thickness to be about 0.6mm. Light extraction efficiency can be lower with conformable panels; however, solutions to this problem have been developed and flexible panels with efficacy of 125 lm/W have been demonstrated in the laboratory. [15] The relative performance of LED and OLED flat panels is summarized in Table 2.7. Performance parameters were chosen from characteristic products from leading vendors, but the values may vary significantly between products. Unfortunately, with the limited production volume of OLED lighting, the cost remains high.

Table 2.7 Comparison of the performance parameters of OLED and LED flat panels.

Technology	Efficacy	Color Rendering Index		CCT Range	Operating Lifetime (L_{70})	Thickness	Weight
Unit Type	(lm/W)	(R_a)	(R9)	(K)	(hours)	(mm)	(kg/m^2)
OLED (rigid) [16]	85[1]	>90	>50	3000-4000	100,000[1]	1.4	6.7
OLED (conformable) [17]	62	90	70	3000-4000	50,000	0.6	1.5
LED [18]	Up to 113	Depends on LED choice		3500-5000	60,000	32	11.8

1. The data are for CCT at 3000K and intensity of 9000 lm/m2. The lifetime from 25,000 lm/m2 is 30,000 hours

OLEDs continue to be of interest for energy saving lighting application because they offer an entirely different material and manufacturing approach for light sources which present the opportunity to support new lighting value propositions as the technology matures. Interest in OLED panels for automobile tail-lights is increasing, due to their light weight, optical emission homogeneity, and compatibility with segmentation, which has led to improvements in the performance of red OLEDs. [19] The OLED technology platform also provides a good starting place for the exploration of other diffuse light emitter materials, such as electroluminescent quantum dot materials (ELQDs). As OLED technology continues to mature, it is expected to enable new manufacturing technologies that result in new lighting form factors and value propositions, while diversifying the capabilities, value, and manufacturing supply chain for lighting.

2.4 Lighting-Building Integration status

Lighting systems exist in the context of the built environment and the successful integration of lighting with other building systems can lead to greater energy savings. LED lighting improves building energy and carbon efficiency, building resilience, grid-interactivity, lighting sustainability, and lifecycle. These impacts will be discussed further in this section.

2.4.1 Building Energy and Carbon Efficiency

In the United States, overall energy intensity has generally declined across the entire economy as a result of faster increases in real gross domestic product (GDP) relative to total energy consumption. Additionally, building energy consumption across many economic sectors in the U.S. has experienced significant reductions, in large part due to increased energy efficiency of individual building systems – including lighting. The Energy Information Administration's (EIA) 2021 *Annual Energy Outlook* shows that the U.S. energy intensity in 2020 was approximately half of its amount in 1990. A review of the EIA Commercial Buildings Energy Consumption Survey (CBECS) data shows that in 1992, the energy use intensity (EUI) of electric lighting over all commercial buildings types was 5.0 kWh/SF, while in 2012 that had dropped to 2.5 kWh/SF. [20] [21] The data for the 2018 CBECS survey has not yet been publicly released, but data from EIA suggests that in 2020 155 TWh of electricity was used to light 93 billion square feet of commercial space, giving an EUI of 1.67 kWh/SF. [22]

Overall lighting energy use in commercial buildings has been lowered due to the high efficiency LED lighting installations, though it still represents a significant proportion of overall building energy use. The continuing improvement in LED lighting efficacy and application efficiency is a key part of the current and on-going gains in whole building efficiency. According to the 2021 *Annual Energy Outlook,* lighting systems consume approximately 12.1% of the total energy in commercial buildings. This lighting consumption in buildings is roughly equivalent to that of other individual environmental control systems (refrigeration, space cooling, and ventilation), as shown in Figure 2.14. [23] The combined total of these four building infrastructure subsystems (including lighting), represents approximately half of the electric energy end-use demand in commercial buildings. Therefore, improving lighting system energy efficiency (as well as the efficiency of the other infrastructural environmental control systems) has the potential to substantially reduce whole building energy consumption. For example, integrating the lighting system with the building daylight system through the use of highly efficient fixtures, intelligent controls, and effective daylight control to maximize daylighting (minimizing the need for electric lighting) can be used to minimize building internal heat gains, thus reducing energy demand for cooling. [24]

a)

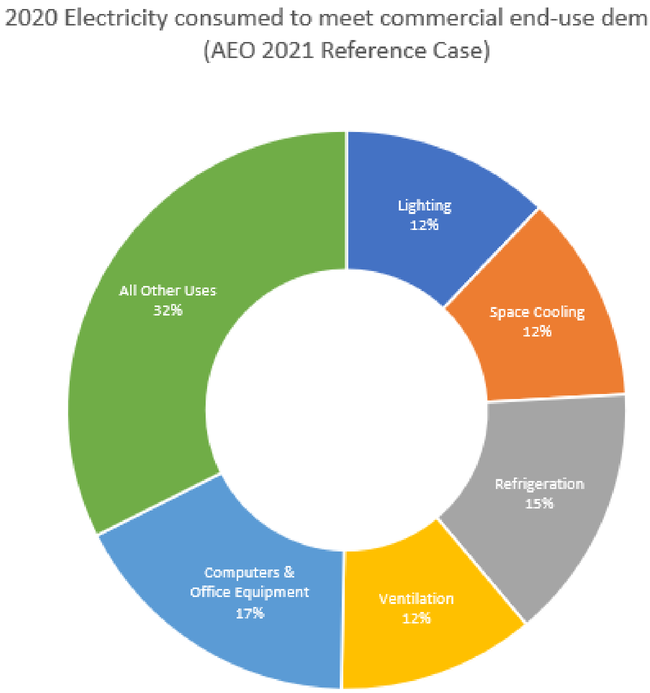

Figure 2.14 2020 Electricity consumed to meet commercial end-use demand, based on the 2021 Annual Energy Outlook reference case. Numbers shown for each category are the percentage of the total end-use demand for the Annual Energy Outlook 2021 reference case. Commercial lighting end-use demand is approximately one eighth of commercial end-use electricity demand.

The "all other uses" category listed in the 2021 *Annual Energy Outlook* consumes over one third of the total energy budget for both commercial and residential buildings. When combined with other plug and appliance loads, the miscellaneous electric loads (MELs) and plug loads make up approximately one half of the electrical end-use demand in both residential and commercial buildings. Within these categories information displays, such as computer monitors, televisions, etc., could benefit from improved LED and OLED technology with higher efficiency, as well as a concerted effort to understand system losses in displays and R&D to address these losses. There is significant overlap between energy efficient lighting technology and display technology and efforts can be leveraged to reduce energy consumption in both applications (as described in Section 2.8.2 and in the Appendix).

Advanced lighting systems can also contribute to improved carbon efficiency through grid responsive lighting systems that engage with distributed energy resources and intermittent grid-scale renewable energy sources. Lighting has the potential to load shed, load modulate and, potentially, load shift with the use of fixture level or building level energy storage strategies. Further improvements to efficiency also reduce the amount of distributed energy resources required for building operation and reduce the amount of energy storage that would be required for load shifting. Further information on the potential for grid-interactive lighting can be found in the Grid-interactive Efficient Buildings Technical Report for Lighting and Electronics.[34]

2.4.2 Lighting System Integration into Buildings

There are many different types of lighting systems that are integrated into buildings, including the typical electric lighting, as well as daylighting systems and connected lighting systems (with lighting controls and communications). LED lighting has led to significant energy savings in buildings, though more energy savings is possible with well-designed integration strategies with other building systems. While further energy benefits (and non-energy benefits) can be realized when these lighting systems are integrated with other building systems, the challenge of complexity in building system design and operation are often experienced. Common challenges with the integration of these types of lighting systems into buildings will be discussed below.

Daylight Integration: Integration of electric lighting and daylighting systems, with careful consideration of building form and orientation, can both reduce lighting energy consumption and improve occupant well-being. [25] When designed together with daylighting system strategies, a substantial reduction in size and overall demand for energy from electric lighting and other building systems can be realized. For example, a well-designed daylighting strategy will reduce the size and energy consumption of the electric lighting system, but will also reduce the size and energy consumption of the HVAC system. [26] Building form and orientation influence exposure to solar energy, which also impacts the energy requirements for providing comfortable conditions (temperature, humidity, and lighting levels) for its occupants. Daylighting integrated with electric lighting systems that are responsive to daylight availability can minimize glare, avoid excess heat gains from solar radiation, and can potentially save 50-80% of electric lighting systems energy. [27] [28] [29] Additionally, correctly specifying lighting system equipment is key to achieving multiple design goals, including comfortable visual and non-visual conditions for occupants with minimized overall construction, operation, and maintenance costs. Oversized systems can exacerbate utility peak demand during extreme weather events, particularly as other systems (primarily cooling) are consuming more energy to maintain comfortable conditions. [30]

Light Delivery and Form Factor: Efficiency of lighting products do not tell the entire story when it comes to lighting energy savings in buildings. The use of less light through improved optical and intensity control can result in further energy savings with more effective lighting systems. The impact of LED lighting system integration into buildings has considerable upside due to new form factors and improved granularity of optical delivery. In addition, there are numerous opportunities for different optical distribution typologies and development of new lighting functions. More fine-grained delivery of light can create better daylight adaptation in urban buildings. Optical distribution properties and lighting functions can be developed for previously unforeseen circumstances in both new and existing construction. Furthermore, new lighting system form factors can potentially result in meeting lighting needs with smaller light fixtures, which can reduce the physical space allocated to electric lighting systems, thereby freeing space for other buildings systems, services or occupant uses.

Connected Lighting Systems: The replacement of the lighting infrastructure with LED lighting products offers the potential for connected lighting systems (CLS) that can enable 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 improve resources and processes, deliver health and productivity gains, and yield new revenue streams. The value of services made possible by data from networked CLS might partly or fully offset the incremental costs of

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[34] https://www.energy.gov/eere/buildings/downloads/grid-interactive-efficient-buildings-technical-report-series-lighting-and

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.

CLS 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.

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.

However, the more capabilities the CLS has, the more complex it is, leading to potential complications and challenges. Building owners are also often reluctant to invest in systems they believe are complex, fearing operational and maintenance issues. First, CLS often use products or need to connect to products from different manufacturers which can lead to interoperability and integration challenges due to lack of standardization in the industry, particularly around communication protocols and configuration methods. Installation can also be a major challenge due to contractor unfamiliarity with the new systems, limitations with available installation materials/tools, use of inconsistent/unfamiliar terminology, and complex commissioning processes required. Complications may also arise from connecting the CLS to the building's energy management system/internet and cybersecurity can be a major concern. Finally, when problems in the system arise, it can be very difficult to troubleshoot and figure out what is wrong with the system. [31]

More R&D is needed to improve CLS, including to: to help develop more standardized user interfaces; improve configuration tools and instructions to be more intuitive; improve troubleshooting capabilities (automated fault detection and diagnostics); develop software workflows that provide simple/automated performance validation and verification; and develop self-commissioning CLS. In addition to R&D, data collection and field validation projects are also needed on CLS, including to: analyze and quantify the benefits of integrations with other building systems; analyze and quantify the value of non-energy benefits of CLS (color tuning and human centric lighting); collect/analyze feedback from facility operators to better understand common problems the systems face; and expand current field validation efforts to include longer-term remote monitoring for more building types/sizes. [31]

Interoperability: Lighting system interoperability is key to enabling benefits such as increased connectivity to other building systems. LED lighting technology enables greater flexibility and opportunity, yet the adoption of lighting control systems continues to lag because of the challenge in realizing the value promised. Interoperability of lighting systems can make it easier to gather and share data across systems. The benefit of data has the potential to drive adoption of connected lighting systems; however, lighting systems continue to be difficult to integrate due to a lack of standardized terminology, application programming interfaces (APIs) that are not formatted in a standardized manner, drivers that do not behave as expected, software updates, along with many other issues difficult to replicate in laboratory settings. In addition, specifications documents need a defined section where an API or interoperability standard appears. Currently there is not adequate guidance, therefore specifications documents are not consistent, which leads to confusion and errors during design, construction, and commissioning. Having a defined Masterspec format for controls would be very helpful, since in the absence of such a definition, design teams rely on inconsistent documentation for oversite of work by design consultants and contractors in the field. Improved interoperability of lighting systems can also benefit the lighting workforce making it easier to keep up with the latest knowledge on one or two lighting protocols, instead of the current situation where the workforce must learn in real-time how to install a specific manufacturers' proprietary control system.

Lighting Data: While the promise and benefits of lighting data was discussed previously, the validation of the value of lighting data continues to be a barrier to adoption. Lighting system data has the potential to deliver improved space utilization, building operational efficiency (e.g., predictive maintenance and asset tracking), well-being of building occupants, emergency response, and user/occupant experience. More pilot projects are needed that demonstrate the value of data, along with guidance related to the privacy and security of the data and the accompanying case studies explaining different scenarios of who ultimately owns the data and how it is shared. The case studies need to show how collected data is converted into actual action and improvement. Data that sits on a server and is not utilized results in wasted energy from collecting and storing the data with no benefit. The potential usefulness of artificial intelligence (AI) and machine learning applied to lighting system data should be explored. Case studies comparing standalone sensor networks to sensors integrated with the lighting system may help to educate the lighting industry and broader building industry regarding the advantages and drawbacks of these approaches. Innovative ideas are needed to keep lighting systems delivering value to building owners.

Deployment Challenges: Installation of lighting integration systems in small- to medium-sized projects are not occurring as frequently as those of large enterprises. Also, these small-to medium projects do not using building management or energy management systems. For this scale of project, when a high-performance design is undertaken, it is necessary to rely on the mechanical-electrical-plumbing (MEP) contractor to properly zone lighting and controls systems, and to ensure those systems are carefully controlled with regard to those zones. At this point in time, due to the absence of a recognized standard for controls, daylight and electric light controls systems are simply being layered on top of each other, rather than being integrated. In order to overcome this absence, making controls work is necessarily part of the building design process, especially as advanced lighting control systems are increasing in complexity. Without a common standard and in the absence of a regular industry design practice, current industry recommendations for control systems have leaned toward separate systems for electric light controls and daylight controls, in order to avoid this complexity. [32]

Furthermore, the cost of control systems can rival the cost of the lighting system hardware upgrade. While there is value in developing rich sensor and controls systems, this added expense and operation and maintenance learning curve may ultimately result in limited, or no, energy savings if not operated as designed. This, in turn, can become a barrier to adoption. What it does do is bring the conversation forward about an integrated approach - being able to downsize a network of systems when everything is looked at together. It also raises an issue that is critical for understanding deep energy efficiency retrofits: sometimes the best solution for the bigger picture of driving down building energy use means that each system, taken in isolation, may not reach its peak efficiency.

Resiliency: Lighting resiliency encompasses the benefits of reduced required energy for buildings and also lighting systems that are immune to network failures, cyber-attacks, operator and installer errors, and failures from adjacent systems. Granular control can enable larger scale system simplicity by allowing the reconfiguration of system elements digitally. This ability to aggregate and disaggregate components over system lifecycles is dependent on controls interoperability and system modularity.

Another aspect of resiliency is for multiple building systems, such as entire buildings. A highly-resilient building will less susceptible to disruption, and more likely to resume its intended functional state, after an event that causes immediate, short term damage from a variety of structural and environmental impacts. Features enabling such resiliency can be designed into a building's electric lighting systems so that for most hours of operation, lighting is provided by daylight to all occupied spaces. More broadly, resiliency can be designed into the electric lighting system such that an electric lighting systems would have connection to local renewable energy sources and energy storage technologies to allow them to operate without the need for connection to a larger electrical grid.

2.4.3 Lighting and the Grid

The building to grid relationship has been the focus of exploration and research with respect to the manner in which energy delivery and energy demand are linked with renewable energy sources, energy storage systems, and building energy consumption patterns.[35] Recent history and experience with grid reliability, in the face of extreme weather and unpredictable events, has shone a spotlight on the building to grid relationship. The prevalence of renewable energy deployments and the federal mandates allowing grid interconnection of those deployments have proliferated, the prototypical one-way grid-to-building connection now has changed. Buildings can respond to increased demand across the grid through manual demand response or automated demand response controls, whereby connected and controllable building systems are tuned to reduce their overall demand on the grid.

A building with an on-site renewable energy deployment can use the energy created on site for consumption on site, using the grid as a source of energy when production is lower than the on-site demand (as a result of seasonal changes in weather or diurnal changes in supply). Alternatively, the building can be an energy sink when the renewable energy source is producing more energy than is needed by the building. The addition of these systems to the suite of choices for creating healthy, safe, and comfortable buildings have created an array of ways for buildings to interact with the grid. [33] This type of grid interaction, unfortunately, can distort local energy supply and demand curves based on occupational patterns and availability of renewable energy resources, as in the California "duck curve" shown in Figure 2.15. Buildings with energy storage deployments, both residential and commercial, could use that storage to flatten the curves associated with the misalignment of demand for energy and supply of energy. Buildings with renewable energy sources, energy storage, and smart and controllable systems (such as lighting systems) could be used to mitigate the harshest effects of excessive demand (brown outs or black outs), while being resilient to loss of grid supplied energy in the event of those harsh effects – including the events like the recent public safety power shutoffs (PSPS).

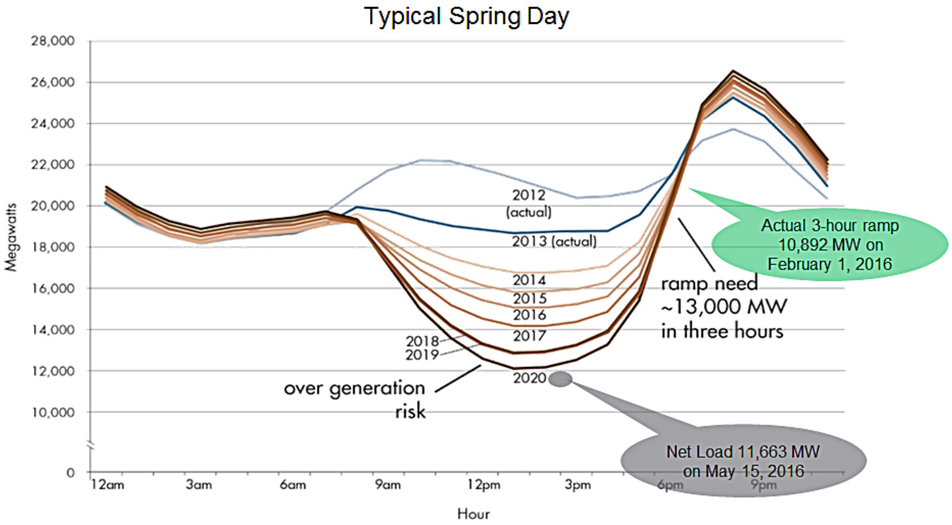

Figure 2.15 California "duck curve" showing the mismatch between electricity demand and renewable energy production, which leads to over generation of energy during the middle of the day and the under generation of energy as demand spikes in the afternoon. [34]

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[35] https://gmlc.doe.gov/resources

2.4.3.1 Grid-Interactive Lighting

Lighting contributes significantly to building total and peak load electricity use and has untapped potential to provide cost-effective grid services through advanced demand-side management strategies. In 2018, lighting loads during peak periods (12-6pm) comprise about 16% and 19% of residential and commercial electricity use.[36] These lighting peak loads also generally coincide with daily peak load hours, as show in Figure 2.16However, lighting is seldom utilized in automated demand response programs in the United States today. Penetration of grid-interactive lighting is low—it was estimated to be used in only 4% of commercial buildings according to the 2012 Commercial Buildings Energy Consumption Survey, while it is essentially nonexistent in the residential sector. [35] A 2018 survey of 155 U.S. utilities found that only eight utilities reported that commercial and industrial customers enrolled in automated demand response utilized lighting, compared to 23 utilities that utilized HVAC. [36] Also, automated demand response for lighting is generally very simple, done today primarily by configuring connected lighting systems to dim light levels in commercial and industrial buildings. Furthermore, lighting is only valuable as a demand response resource when aggregated across the whole building, hence large commercial and industrial buildings are generally the most viable market for grid-responsive lighting. However, smaller commercial or residential buildings can work with demand aggregators to participate in grid service markets.

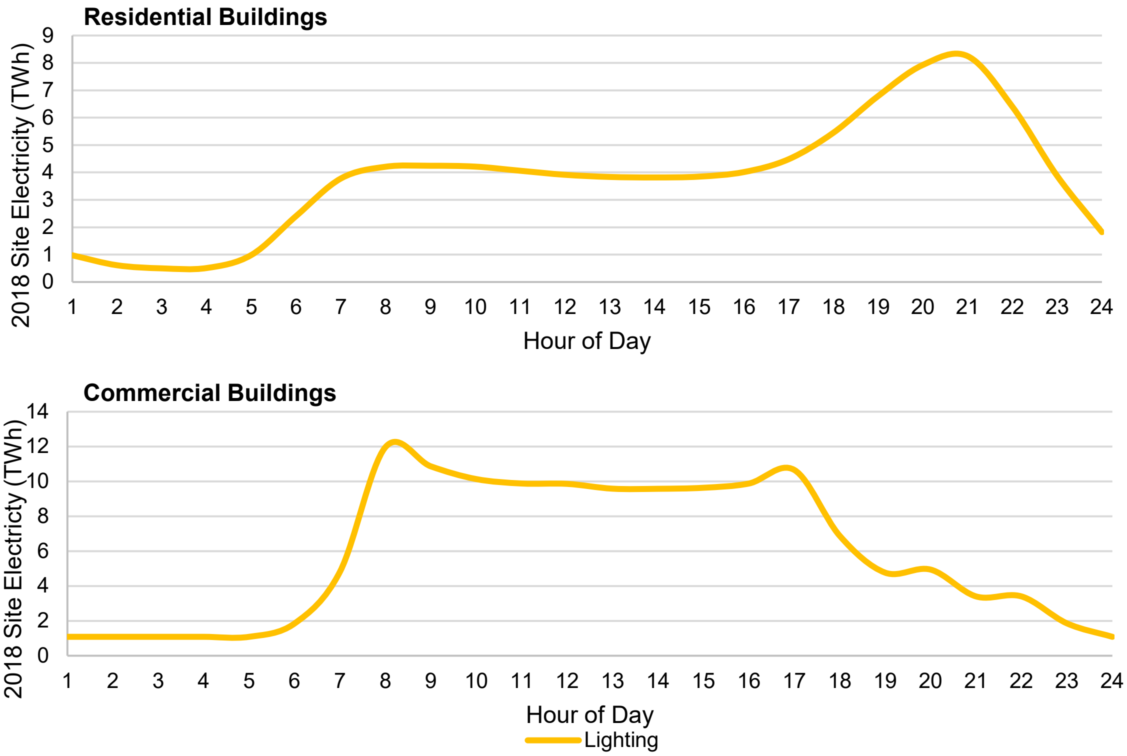

Figure 2.16 Hourly Site Electricity Use for Residential (top) and Commercial (bottom) buildings.

Note: Data are generated using the Scout time-sensitive efficiency valuation framework, which attributes annual baseline energy use estimates from the EIA's 2019 Annual Energy Outlook across all hours of the year using energy load shapes from ResStock (NREL) and the Commercial Prototype Building Models. [37] [38] [39] *Contributions of each end use to total peak period energy use were calculated with Scout using the energy savings from a measure representing 100% energy use reduction for the entire end use for one hour (e.g., 3–4 p.m.) during the peak period. The energy savings from each hour for a given end use were then summed across the peak period.*

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[36] For more information on how these figures were calculated, see the Note associated with Figure 2.16

Connected lighting systems with advanced sensors and controls (utilizing controls and algorithms to automatically modulate lighting levels or potentially other power-consuming lighting features in response to external grid/pricing signals) have potential to provide grid services, among other energy savings benefits. They have the advantage of providing shedding for demand response/building peak demand-side management and total energy savings over traditional SSL lighting technologies. For example, systems with occupancy sensors, daylighting sensors, and automated dimming can optimize lighting use across control zones based on occupant patterns, available daylighting, and learned lighting level preferences/needs, while also reducing energy use (shedding) during peak periods or emergency events. However, the shedding/modulation strategies are restricted to dimming and limited modulation of lighting levels or other power-consuming lighting features because of the necessity of lighting in occupied spaces.

For connected lighting systems, significant barriers exist that limit the potential to provide grid services, including limited dimming levels for lighting load shedding, lack of OpenADR lighting products, traditional focus on HVAC and industrial loads in the automated demand response industry, focus on commercial and industrial sectors for lighting demand response, and market adoption barriers for connected technologies (cybersecurity, interoperability, and high cost).[37] However, as technological advances are made, the potential to provide grid services may increase. In most circumstances today, energy savings at all times is the still the greatest grid benefit a lighting system can provide. More research is needed to better understand and quantify the potential for connected lighting systems to provide grid services beyond efficiency.

Ultimately, lighting is a critical building service with possibly limited opportunity for load shedding from an already efficient source with an optimized control configuration, as implied by the existence of a grid connected system. Lighting systems are using less and less energy to accomplish a critical building function, so while the technical capability to engage lighting systems for grid level load shedding exists, it may not be the most effective technology for these events as there is minimal energy to save and the critical function of the lighting system can be interfered with. In addition, these systems may interfere with building scale resiliency by introducing complexity, system inter-relationships, and external communications with the potential to disrupt operation of the lighting system. While these challenges exist, this technology is still being explored for a role within the grid

Some of the challenges and R&D opportunities for advanced sensors and controls to provide grid services are summarized in Table 2.8 below. For more information on the potential of grid-interactive lighting, see the DOE Grid-interactive Efficient Buildings Technical Report Series: Lighting and Electronics report.[38]

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[37] OpenADR is a smart grid standard that is designed to integrate building systems communication and to automate and streamline demand response processes. For more information, see: https://www.openadr.org/

[38] https://www1.eere.energy.gov/buildings/pdfs/75475.pdf

Table 2.8. Summary of Challenges and R&D Opportunities for Grid-Interactive Lighting

Challenges	R&D Opportunities
Demand Response Protocols and Control Algorithms	• Quantify the demand flexibility potential of lighting manipulations in various building types, designs, activities, and conditions • Determine the optimal communication protocols and control algorithms for maximizing grid services provided (shedding and modulating) and minimizing occupant impact • Novel control algorithms that leverage data and machine learning capabilities to customize strategies • Determine the impact to occupants from lighting systems providing grid services through demand flexibility (productivity, comfort, etc.)
Sensors Integration	• Optimize techniques, design, and methods for embedding sensors directly in lamp/luminaires to enable multiple methods of control • Improve signal-processing techniques to reduce the error margin within the sensing range and increase the task-specific ability of the sensors

2.4.3.2 DC Microgrids

A microgrid is a decentralized network of loads and energy generation units located within specified electrical boundaries. Beyond the conventional electric grid used to power buildings, DC microgrids are gaining further attention due to the increasing use of DC renewable energy sources and DC devices such as LED lighting in buildings. LED lighting systems have the potential to be zero net energy in their operations by creating a lighting system-scaled microgrid that can be powered independent of the building itself, and potentially independent of the utility grid, as illustrated in Figure 2.17. LED lighting system-scaled microgrids can be powered by DC electrical systems, rather than the standard alternating current (AC) systems. In the near term, there is opportunity to better understand the benefits and efficiencies of DC systems that use building mounted and building integrated solar photovoltaics to power the building lighting system, providing an opportunity to reduce losses due to the conversion of DC to AC to DC, along with opportunities to reduce materials such as conduit. The potentials of this change in delivering energy to lighting systems in buildings is made possible by the increased penetration of LED lighting in commercial buildings and the development of native DC technologies for energy systems (solar photovoltaics, batteries, and the component pieces of the building electrical systems that supply energy to and from the grid), thus enabling the development of lighting system specific, building-scale microgrids.

This potential for using DC electrical connections also brings with it the possibility of direct communications between components of the lighting system and other building systems as well. Power over ethernet (POE) and similar connections provide both the electricity to power the lighting, as well as enabling communications in the same connection. This opens the door to better communication and the potential utilization of a lighting system sensor network to create more granular levels of control and an information reservoir for analyzing and improving building energy efficiency beyond lighting systems.

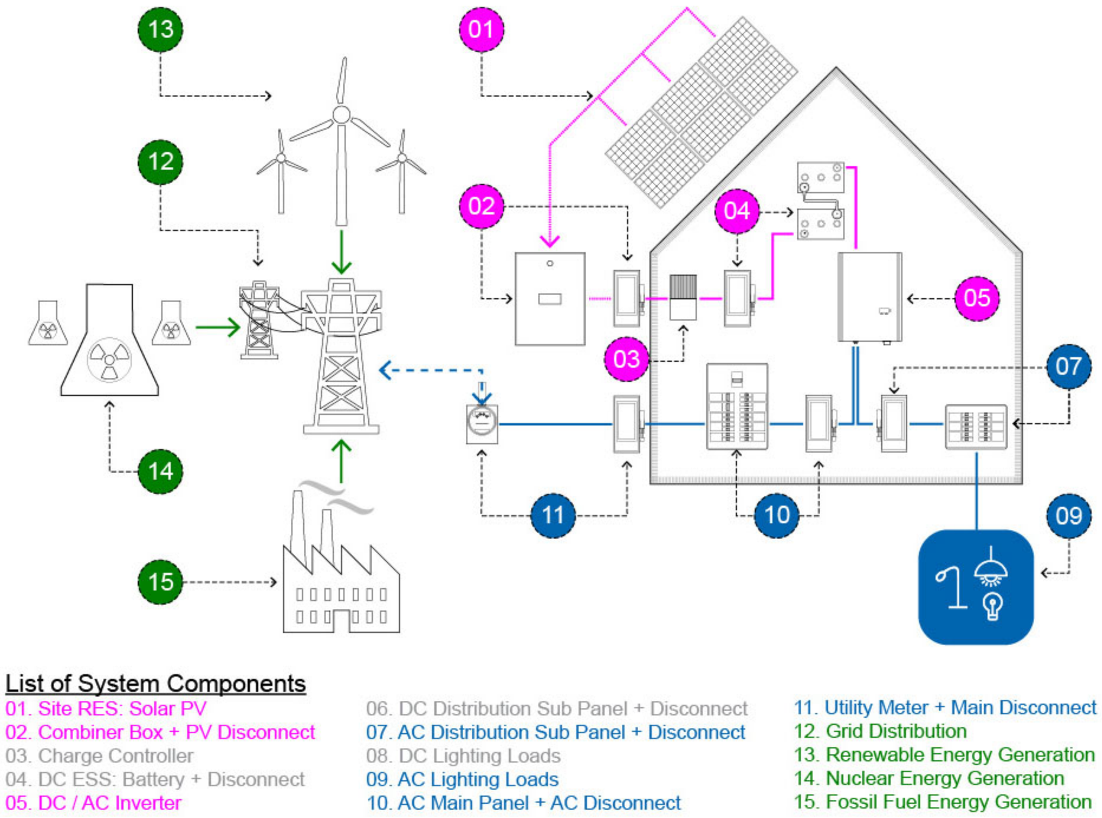

Figure 2.17 Example of a grid-connected, net metered building with solar photovoltaic array for on-site energy generation and lighting loads on a secondary AC Distribution Panel that can be powered through the on-site battery-based energy storage system. This configuration could use the power of on-site energy generation and storage for its back up power supply. The circuit could also be entirely independent of the rest of the building and could be DC with a direct connection to power through a battery and solar photovoltaics. This separate DC circuit could still be connected to the utility grid, however, it would need to have the capacity to convert AC grid power to the DC system power.

2.4.4 Lighting Sustainability and Lifecycle

The examination of the full lifecycle of LED lighting technology broadens sustainability considerations to include the manufacturing and assembly of the luminaires, shipping, operation, and end-of-life recycle and reuse. Life cycle assessments (LCAs) are used to examine environmental impacts. Although the method varies between LCAs, some common impacts include energy consumption, ecotoxicity, landfill use, and ozone depletion. A 2014 review of primarily lamp LCAs published by the International Energy Agency (IEA) 4E Solid State Lighting Annex, noted that 85% of the environmental impact occurs during the operation phase, with efficacy and lifetime being the biggest factors during this phase. [40] The manufacturing and end-of-life phases are the majority of the remaining impact, with shipping only accounting for 1 to 2%. The report also noted that the largest contributors to environmental impact are the heat sink, electronics, and LED packaging.

More recently, an LCA compared a baseline 2011 A19 LED lamp to modern A19 LED lamps, finding that the total mass and metal mass were significantly reduced, though there was an increase in the use of plastic. [41] The research found a 53-64% reduction in hazardous waste to landfills, acknowledging that the lifetime is a critical aspect of the lifecycle. The authors noted that if the LED lamps reach rated life, they will have a reduced environmental impact in all LCA categories compared to incandescent and fluorescent lamps. Another aspect that affects the life cycle is the ability to control the lighting, including dimming, which can further reduce energy associated with operation and also extend lifetime. A summary of the LCA's output is shown below in Figure 2.18.

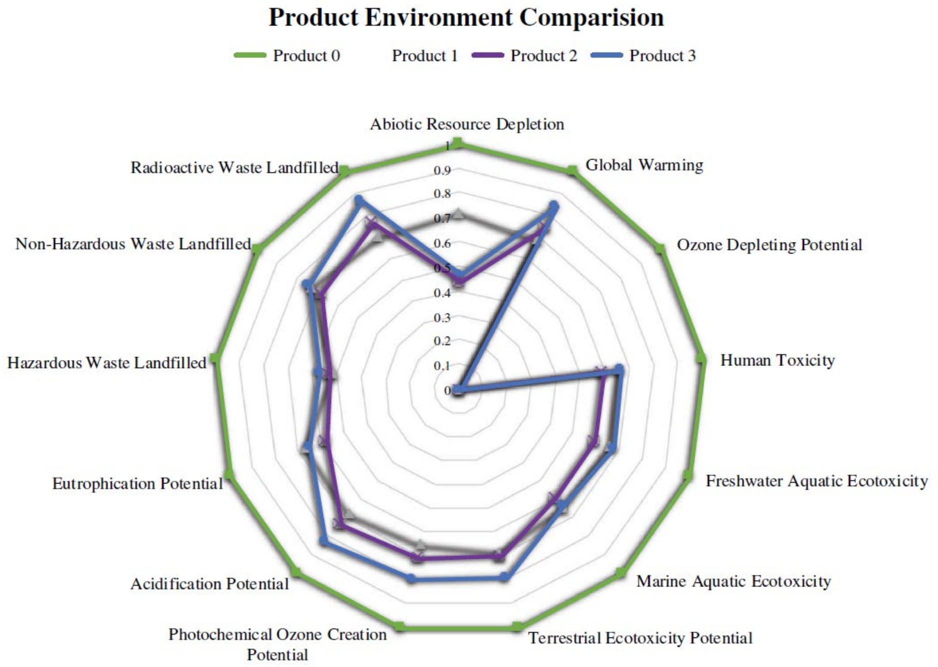

Figure 2.18 A life cycle assessment published in 2020 compared three contemporary LED lamps (products 1–3) with the LED lamp considered by Scholand and Dillon (2012; product 0) as the new benchmark. The scale for each environmental impact category is a percentage of the maximum value for all lamps. [41]

In additional to improvements to source efficacy and lifetime, there is the opportunity to improve the sustainability of lighting manufacturing and assembly while also considering product end-of-life. Reuse of lighting product materials minimizes the use of virgin resources, reduces waste, and has the potential to be economically beneficial. Designing for disassembly at the end-of-life, including PCB disassembly is a growing area of interest. As previously noted, the DOE SSL Program offered a prize for the sustainable manufacturing of LED luminaires. Key components of the award-winning concept by Koerner Design were fast disassembly for circular economy processing and flax-based PCB that could be easily separated and partially composted. There remain important tradeoff considerations during the design process, and the success of end-of-life disassembly depends in part on the ability to align the interests of manufacturers, users, and recyclers.

Other ways to incorporate more sustainable practices include the potential to use recycled material in SSL lamps and luminaires, such as plastics. Modularity of components can extend the life of luminaires by allowing driver or light source replacement while retaining the rest of the luminaire. There may be trade-offs with modularity, such as imperfect matching of replacement components to the luminaire design, but modularity may be appropriate for installations in which luminaires are infrequently replaced. If an integrated product fails, the entire luminaire needs to be replaced, and if a similar product is not found then all the luminaires may need to be replaced depending on the importance of the light color and output characteristics as well as the aesthetic appearance of the luminaire.

There are a variety of methodologies, frameworks and metrics that have been proposed for assessing the sustainability of products developed by researchers and other experts outside of the U.S. lighting industry. [42] One recent research effort supported by the European Union is Repro-light, with the focus on a more sustainable luminaire life-cycle that aligns with the circular economy.[39] The multi-year project resulted in

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[39] https://www.repro-light.eu/

several publications, including product and process design guidance, luminaire prototypes, and market adoption research.

Within LED packages themselves there are minimal scarce or toxic materials. LEDs do not contain mercury and displace mercury containing fluorescent lighting technology. Some rare earth materials are used in limited amounts in the phosphor materials that provide the optical down-conversion in LED packages. Two common phosphors are cerium-doped yttrium aluminum garnet (YAG:Ce), and europium-doped oxy-nitride phosphors [(Sr, Ca) $AlSiN_3$:Eu]. Yttrium is not officially a rare earth metal but is often classified as such, and cerium is a rare earth metal, but one of the more abundant rare earth elements. As described previously, it is estimated that a compact fluorescent lamp uses 0.18 mg of Eu, a rare earth material, while LED lamps can use as little as 0.008 mg – approximately 95% less. [3] Other elements within the LED chip are gallium, indium, and aluminum provided as metal-organic precursors to the LED epitaxial process. Furthermore, there are carrier gases (nitrogen and hydrogen) used in the epitaxial process, as well as magnesium (metal-organic precursor) and silicon (silane gas) dopants. All of these materials are conventional and widely available for the LED production processes and are typically used as part of the broader suite of semiconductor production materials.

Recently, there has been work to develop cadmium and non-cadmium containing quantum dots for use as optical down converters for phosphor-converted LEDs. Quantum dots that contain cadmium (Cd) have better efficiency and lifetime than non-cadmium quantum dots today. However, while quantum dots in LEDs have been commercialized, they are not yet a typical material used in the vast majority of LEDs. Research on perovskite quantum dots, which contain lead, is also growing, though it is exploratory at this stage since the technology remains unproven in performance and stability when combined with LEDs.

In summary, analyses have shown that LED lighting technology provides a demonstrated life cycle improvement over previous lighting technologies and has the potential for further improvements. Most importantly for life cycle benefits, efficiency of LED lighting can still be improved. Also, lighting product form factors, design, materials, and manufacturing methods can be reconsidered in light of the new technology to provide further sustainability advancements and these efforts should be supported. LED packages themselves use fewer and relatively benign materials and use less scarce or toxic materials as previous light source technologies. All aspects of lifecycle and sustainability should continue to be reviewed and optimized to achieve the most benefit as the lighting industry fully transitions to LED lighting technology.

2.5 Public Investment

Investment in maintaining and improving infrastructure is key to human productivity, and often underserved communities bear more of the burden of deteriorated infrastructure. Initial investments in advanced lighting systems often yield energy-savings within a couple of years; however, initial funds for investments are required for the savings to be realized, which is a hurdle in lower-income communities. Partnerships, such as the Delaware Valley Regional Planning Commission (DVRPC), are allowing small communities to come together to achieve the buying power of larger town and cities when purchasing advanced streetlighting systems. Leveraging these types of partnerships allows for pooling of knowledge, legal and financial services, all of which are occurring as part of the DVRPC streetlighting project.

In the design and construction industry, often when a new technology such as an advanced lighting system is considered, the price is even higher because of the additional risk associated with the design, installation and commissioning of a system that is unfamiliar. This circumstance creates economic pressure that increases the hurdles for adoption. On the other end of the spectrum, the development of energy-efficient LED lighting systems that are connected to both renewable energy sources and energy storage systems allows for the addition of low cost lighting solutions to communities that are not connected to a utility grid. This provides remote communities in the U.S. and around the world access to efficient, high-quality light without the cost of creating a utility grid.

2.5.1 Equitable Lighting

There are basic principles that define equitable lighting. At its core, equitable lighting is efficient, quality lighting available to all as well as benevolent darkness. Aged and deteriorated lighting installations cost more to operate and have higher maintenance costs. Older outdoor lighting systems may also have worse lighting performance resulting in reduced roadway and pedestrian safety as well as higher levels of glare and light pollution. All of these factors result in reduced health and safety for the lighted area. In indoor settings, schools for example, aged and deteriorated lighting systems can affect visual function, cognition, and general well-being resulting in reduced scholastic performance. These old systems will also cost more to operate (energy cost) and maintain. New LED lighting systems cost less to operate and can provide a high-quality environment for learning and general health. However, for any lighting setting, suitable lighting systems must be carefully selected and installed. Not all LED lighting products have equivalent quality and resulting benefits. This is another element of equitable lighting.

Some communities, especially marginalized or low-income communities, may not have the expertise or resources to select optimal lighting products. This can result in early failures, reduced energy savings, and poor-quality lighting for the occupants. Furthermore, conditions such as overlighting and light pollution have negative consequences for public health. [43] The adoption of high quality and energy efficient lighting lags behind in marginalized communities due to these barriers (cost and lack of knowledge transfer). Therefore, it is critical that lighting justice is a key part of the strategy for increasing the installed stock of LEDs in markets where they lag the most. Equitable lighting considerations are core to achieving the Program’s long-term objectives.

As noted by the Environmental Protection Agency, environmental justice “will be achieved when everyone enjoys the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.” Quality light plays a critical role in health, learning, and productivity while poor lighting can represent a health and safety hazard. It is part of the mission of the DOE SSL Program to address barriers to adoption for quality lighting products to maximize energy saved. This includes barriers caused by social and environmental injustice that result in inequitable lighting and reduce the benefits—energy, health, and productivity—of good quality lighting systems.

2.5.2 Workforce Training and STEM pipeline

General trends in the lighting industry and the shift to LED lighting technology are creating numerous opportunities for the lighting workforce. The lighting industry is a large and global industry with all nature of job types, from workforce (e.g., manufacturing and installation) to the STEM pipeline (e.g., design, engineering, and research). Prior to the introduction of LED lighting technology, lighting technology development was relatively static with a well-known range of product options with known performance. The introduction of LED lighting technology has disrupted the industry, requiring new technical and practical understanding. In addition, new practical considerations have become necessary with the understanding of non-visual responses to light and other new lighting science understanding highlighted or enabled by LED lighting technology capabilities.

Alongside these industry technical dynamics, the lighting industry struggles to attract new professionals due to limited dedicated vocational and secondary education training programs. These factors create great opportunities for a new generation of lighting professionals to fill the gap and the opportunity to develop tailored educational programs to develop the necessary skills. With LED lighting technology and new appreciation for the energy, environmental, heath, and productivity benefits from lighting, all lighting professionals will be at the forefront of the sustainable energy economy.

Training a new generation of lighting professionals also provides an opportunity for the lighting industry to address issues of diversity. The lighting industry, like many other technology sectors, has lacked diversity in its workforce and the science, technology, engineering, and mathematics (STEM) pipeline. Lighting is a technology that is used in nearly every indoor and outdoor environment, from work to recreation, and has a ubiquitous impact on the everyday lives of all people. Therefore, it is critical that equity and inclusion be top-level objectives in order to foster a more innovative and sustainable industry. [44]

At its core lighting is an endeavor that relies on STEM. The next generation of lighting professionals will require backgrounds in scientific, technical, engineering, and math disciplines to provide and achieve the full benefits offered by the LED technology platform.

2.6 Productivity from Lighting

Due to the diverse benefits and effectiveness that lighting provides, the program uses the term "productivity" to describe them collectively, following standard economic practice. There are two general elements to characterizing human productivity from lighting: the light stimulus and the resulting visual or non-visual physiological response, which enables the productivity. Historically, lighting productivity has been described in terms of a stimulus characterized based on the human eye response in units of lumens (human perceived brightness with respect to the wavelength of light). Typically, color quality metrics are also provided that characterize light stimulus in terms of white hue and color fidelity compared to sunlight or an incandescent light source. Within this paradigm, lighting productivity can also be characterized by the luminous efficacy of the lighting product (lumens per watt). Advancements in luminous efficacy enabled by LED technology have reduced the energy required to light all spaces, including offices, warehouses, educational facilities and many more. While this document lays out opportunities to further decrease the power and energy per lumen output consumed by LEDs, understanding and increasing benefits beyond basic visual function and luminous efficacy also serve to extend the productivity and effectiveness of lighting to achieve maximum lighting benefit per energy input.

Improving task and cognitive performance at work, in academic settings, and other facility types are productivity advancements made possible with LED lighting technology. Health and well-being benefits related to lighting can also be enabled by the spectral options inherent with LED technology. At night, color qualities of LED lighting can produce roadway lighting that can reduce roadway accidents. In the context of horticulture, LEDs can use less energy while increasing yields, desirable textures, and appearance of crops grown under electric lighting by specifically tuning the wavelengths to maximize the plant growth at its different life stages. All of these benefits can be achieved with LED lighting technology while still saving energy compared to conventional lighting technology. None of these various productivity benefits can be represented by luminous efficacy (e.g. in units of lumens per watt). Additional metrics for assessing productivity related to lighting must be developed and used. Improved understanding of lighting productivity benefits for a variety of applications and how to measure the outcomes will enable achieving the maximum benefits with the minimum amount of lighting energy.

2.6.1 Light Stimulus and Physiological Responses

A key advancement in research over the past decade has been in understanding the role of light spectrum, intensity, optical distribution, and timing in physiological responses to light. Further research is needed to better define action spectra and intensity thresholds for any and all of the functions of lighting that relate to energy use, productivity, occupant well-being, and other priorities in the built environment. This is true for visual function, where research has advanced understanding in color perception and color contrast, thereby enabling more effective lighting for certain lighting applications that rely on color discernment (e.g. surgical lighting or retail lighting). This is also true for the non-visual function of light that affects health and well-being. A specific application example is with roadway lighting, where ongoing research is resulting in improved understanding of what constitutes the safest lighting for vehicles and pedestrians around roadways. The understanding of light stimulus must relate to understanding of the visual or non-visual responses to light, and the response should connect to a tangible benefit.

Visual Responses: There have been improvements in characterizing light stimulus for visual function and non-visual physiological responses exemplified by methodologies described in standards such as IES TM-30 and CIE S 026:2018. IES TM-30 provides new characterization metrics that better portray the fidelity and color gamut of lighting.[40] Advanced color metrics for more specific visual functions that describe object contrast and visibility based on the incident light color quality and reflectance spectrum of the viewed objects will benefit inspection and visual function activities, including surgery, defect and product inspection, medical diagnostics, and even retail sales. The LED technology platform enables the development of light sources that can be tailored to maximize visibility and contrast for specific applications, which is exemplified by LEDs designed to maximize specific, desirable reflectances in a retail setting, as seen in Figure 2.19. Further refinements and improved understanding of the light stimulus impacts are likely to occur, and the highly tunable nature of LED lighting is suitable for to meet changing guidance and requirements of light stimulus.

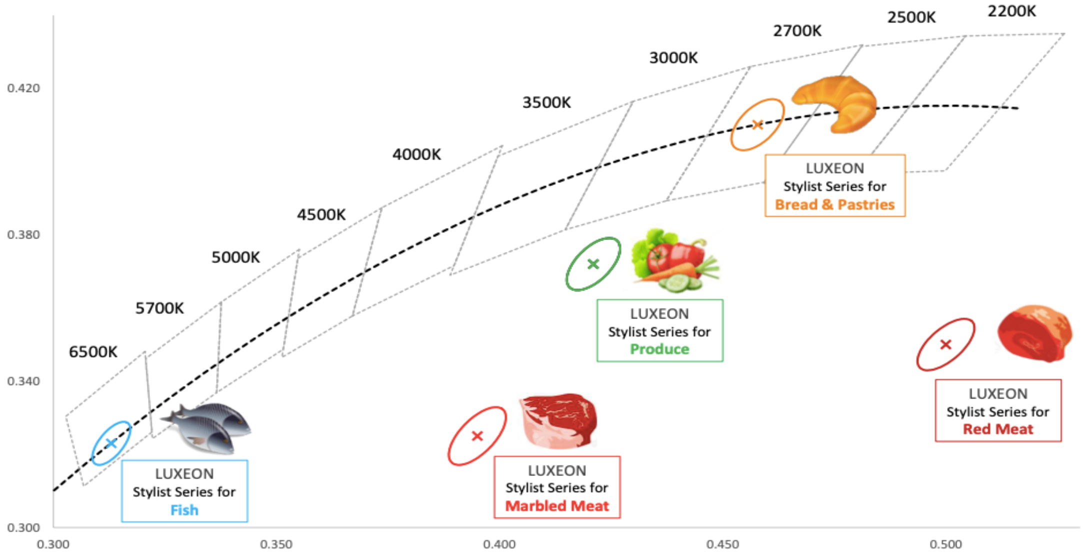

Figure 2.19 LEDs color optimized for viewing of specific retail products such as food type. Off-Planckian color points allow for spectral designs that highlight specific hues. [45]

Non-Visual Responses: Research has shown that light plays a primary role in supporting regulation of human circadian, neurobehavioral, and neuroendocrine responses, which greatly impact human health and productivity. [46] The understanding of non-visual responses to light is relatively new, and the relationship between the stimulus and response is still getting refined. There remain questions about spectrum, intensity, timing, and duration of the light stimulus that provokes the non-visual responses. Additionally, responses to light can be highly individualized and can go beyond physiological responses indicated by alertness measures, melatonin biomarkers, or circadian phase setting. For human health considerations, Melanopic Equivalent Daylight Illuminance (m-EDI) is the circadian metric adopted by the CIE, which issued an international standard, CIE S 026:2018[41] that defines the characterization of light stimulus that induces non-visual physiological responses, typically related to melatonin secretion. Light within the 446-477 nm wavelength range has the most potent effect, so, similar to the eye response function, an action spectrum is used to weight the potency of the light stimulus for the calculation of m-EDI. The initial scientific guidance for light stimulus to evoke healthy physiological responses is a minimum of 250 lux of melanopic EDI at the eye during the day, 10 lux m-EDI pre-sleep, and the sleep environment should be kept as dark as possible. [47] This guidance provides a clear connection between standard characterization of the non-visual light stimulus and beneficial physiological responses described in the scientific literature; however, it is likely that the understanding of non-visual physiological responses and resulting desirable lighting stimulus will continue to evolve and result in new guidance for optimal lighting conditions.

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[40] IES TM-30: https://store.ies.org/product/tm-30-20-ies-method-for-evaluating-light-source-color-rendition/

[41] CIE S 026:2018: CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light | CIE

For both visual function and non-visual human responses to light, the light emitted from the light source is not the same as the light that eventually reaches the eye. Between the time the light leaves the source and reaches the eye, it can (and should) be mediated by reflections from the objects or the structure in the space, which affect spectrum and intensity as light travels to the eye. The lighted environment greatly affects the specific stimulus received at the eye. In addition, posture and behavior will influence the specific amount of light that reaches the eye.

2.6.2 Productivity Benefits from Lighting

The mission of the DOE SSL Program is to reduce lighting energy consumption and increase the productivity enabled by lighting, in other words: increased benefit for reduced input power. To this end, it is important to understand and quantify tangible benefits from lighting improvements. The difficulty in quantifying these benefits is that they can also be influenced by other factors. Two examples highlighting the potential productivity benefits of lighting and the challenges in clearly linking the light stimulus to the physiological response are provided below:

> ***Roadway***: For roadway lighting, researchers are seeking to understand how different lighting spectra and distributions of light in nighttime environments can increase the visibility of objects in the road to improve the safety of drivers and pedestrians. The SPD of LEDs can be engineered to increase visible contrast between objects found in the roadway setting under nighttime visibility conditions. 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 that was not possible with previous technologies. These benefits can be achieved while saving energy and reducing the total amount of emitted light, which can dramatically reduce skyglow and lighting impacts on wildlife.
>
> ***Classrooms***: In the classroom setting, changes to lighting can impact student performance, though the underlying mechanism might not be entirely clear since there are intertwined aspects to student performance that affect the findings. It might not be clear if changes to student performance were due to changes in lighting that affected alertness or cognition or if new lighting provided a cue to students to pay more attention or if teachers or students were otherwise incentivized to perform better due to ongoing observation inherent in the study. This type of research and understanding is important, but ultimately, the light stimulus and performance response relationship encompasses a long chain of events from lighting properties, usage patterns, student and teacher behaviors, mediating factors of the lighted space, specific visual and physiological responses, and translation of those responses to performance metrics over a period of time where there may other factors in student and teachers' lives. This is also true for lighting applications in a health care facility where lighting affects patient outcomes in numerous ways, in office and production environments where lighting affects worker health and productivity, and on the roadway where lighting affects driver and pedestrian safety. It is important to identify opportunities to evaluate the impacts of light with the clearest link between light stimulus and measured response in a realistic environment.

Beyond these examples, there can be potential productivity improvements in other areas such as factories, office buildings, hospitals and more. There is potential that improved lighting for health and well-being can help worker alertness and efficiency in certain settings, while also reducing error rates in other settings (e.g. medical errors in hospitals). Improved health of workers can lead to less missed work time and better morale.

While there is focus on understanding of the various aspects of productivity enabled by lighting, it is equally important to understand the counter-productive aspects of lighting. These can include glare and flicker, which reduce visual function. Also, mis-timed lighting non-visual stimulus can negatively impact human health and well-being, such as receiving bright, blue-rich light pre-sleep or receiving low light levels during the day. Light pollution is also a counter-productive aspect of lighting that leads to skyglow and detrimental impacts on wildlife. For example, turtle hatchlings can become disoriented by anthropogenic light at night which guides them away from the safety of the ocean. Ongoing research to better understand all productive and counter-productive aspects of lighting is needed so that ideal lighting can be achieved with maximum benefit, minimum side effects, and minimized energy consumption.

2.7 Lighting Application Efficiency

LAE describes the effective generation and delivery of optimized light to the user in the right place at the right time. The main tenets of this concept are illustrated in Figure 2.20

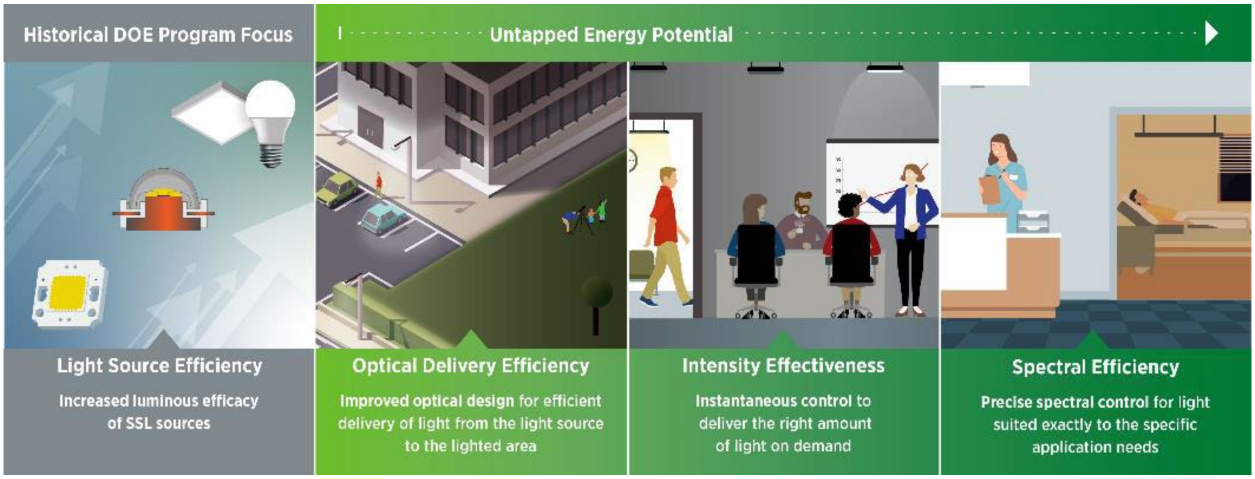

Figure 2.20 There is an untapped potential in energy savings that can be reached beyond improving SSL source efficiency. The first panel shows the historic focus of the DOE SSL Program to reduce energy consumption by improving light source efficiency. The next panel shows how light can be more directed to achieve the lighting function (e.g. night-time parking lot lighting) while saving energy and reducing unnecessary and detrimental light in the environment. The next panel shows how brighter light with a higher blue content is important for visual function and alertness while dimmer higher red content light is important pre-sleep. The last panel shows how intensity can be controlled to optimize light levels for the intended visual function.

Historically, the DOE SSL Program had focused on improving light source efficiency. Light source efficiency is still a priority for SSL R&D, since it directly enables reduced energy use, cost reduction, improved performance, and new features. However, energy savings can also come from other advances like improving optical delivery efficiency to achieve desired lighting functions with a reduced amount of emitted light. At any given time in a space, optimized SPD of light can improve the lighting functions, thereby enabling increased productivity with lighting. In addition, optimizing light intensity for a task can also reduce energy and/or increase productivity since too much light for a lighting function is wasted energy and too little light might decrease the lighting function. These other factors can also save energy, improve lighting effectiveness or productivity, and are not considered within the luminous efficacy metric for the source.

When considering the aspects of LAE, it is important to understand that they are inter-related and time and activity dependent. For example, humans benefit from higher light levels and/or increased blue content in light in the morning but should have reduced light levels pre-sleep. Daylight supplementation during the day may reduce or eliminate the need for electric light during parts of the day. Different activities in a space often require different lighting functions. The time and activity dependency of lighting needs will be an important area for the use of controls and sensors. However, in many spaces, there may be limited benefit to highly dynamic/automated lighting systems where improved static lighting designs and layouts can achieve the benefits of the LAE concept.

All of the aspects of LAE should be considered within the context of the lighted space and the desired functions of the lighting for the occupants. The configuration or layout of the lighted space affects the geometry of optical delivery and intensity, and also affects of the SPD of the light that ultimately reaches the eye or other detector. Consequently, understanding lighting and LAE performance within the context of the space where the lighting is deployed is critical. New lighting design modeling tools can aid in this endeavor with their ability to model illuminance and SPD on various planes within a space, while taking into account furnishing, finishes, light source optical distribution, and light source SPD. This is a considerable opportunity for new lighting technologies that are no longer tethered to performance limitations of previous lighting technologies. Advanced lighting design modeling is a critical requirement to enable the LAE framework, along with improved guidance and lighting metrics to optimize lighting benefits and minimize negative side-effects.

2.7.1 LAE Status

LED lighting technology has demonstrated the ability to achieve target light levels with reduced overall light output. This has been most clearly achieved with roadway lighting, but similar benefits could be achieved for indoor lighting. Indoor and outdoor LED lighting has the capability to reduce light levels when not necessary for the application at a given time. For example, LED roadway lighting can be dimmed or instantaneously turned off and on, which was not possible or practical with previous HID technologies. Additionally, LED lighting has the capability to have SPD designs for specific lighting applications. This can be seen in lighting products with SPD designs for engaging human physiological responses or by LED lighting tailored to specifically highlight the desirable attributes of a retail product in the store.

There is new guidance for integrative lighting from the CIE and new research is ongoing to refine lighting targets to enable improved health and productivity. For example, areas of interest for roadway lighting safety include color discrimination, glare, skyglow, and wildlife impacts. This research can improve lighting guidance and enable lighting design that balances productive (safety) and counter-productive (light pollution impacts) aspects of lighting. It is expected that new understanding and guidance could feed into new modeling capabilities which could predict lighting intensity and SPD on a plane within a space based on the optical distribution and SPD of a light source, as well as, the lighting layout, geometry, finishes, and furnishing within the space. These models could be used to optimize lighting conditions at typical gaze directions and posture for common activities in a space, maximizing the utilized light and minimizing less useful light. These models could also be used to develop optimum lighting products with ideal light distribution and SPD for a space and configure the layout for optimal effectiveness.

Roadway applications have shown that required light levels can be achieved with ~50% less total generated light when using LED technology compared to previous sources. [48] Indoor lighting designs could also be achieved with slight reduction in light levels where light is less necessary in a space to save energy. Initial estimates have predicted that in some indoor environments, only one in a million generated photons reaches an observer. [49] Developing a better understanding of the most effective distribution of light and improving this efficiency to even 1 in 500,000 photons reaching an observer, could represent a massive energy savings. Moreover, dynamic optical distributions could be deployed to actively concentrate light when and where it is needed. Engineered SPDs can be used to improve the function of the light at the task, whether it is color discrimination, color highlighting, or engaging human non-visual physiological responses to light. In order to achieve these benefits, more refined (in terms of specific target area and according to specific lighting function) lighting illuminance targets within a space or room need to be developed to support visual function and occupant well-being at typical work postures and gaze orientations. This will require more advanced predictive lighting design modeling software that can consider spectrum, effects of room finishes, a wider variety of lighting layouts and optical distribution patterns from luminaires, and the range of vertical and horizontal target areas in a room. It would be beneficial if such software could also optimize lighting layouts and optical distributions to maximize LAE for the space and application.

2.7.2 LAE Examples

In this section, lighting applications will be generally analyzed for their LAE prospects. As a framework for LAE evaluation is developed and improved, a more detailed breakdown of the different LAE aspects can be generated to help develop guidance for improved total lighting system performance as described by LAE.

For roadway and outdoor area lighting, LED technology has enabled improved light source efficiency and luminous efficacy. Due to its small source size and resulting improved optical control, LED technology also provides improved optical directionality, which can result in less total light being generated to achieve the required light levels. Additionally, this improved optical control allows LED fixtures to spread the light more evenly on the roadway than previous technologies, which leads to reduced maximum/minimum light ratio and a more targeted delivery of light on the roadway and to adjacent areas. This optical control can also reduce glare from roadway lights. LED lighting can reduce light pollution and light trespass where light at night is undesirable since LED roadway lights can have minimal light off-target and should have no light that is directly emitted upward. Most high-pressure sodium light fixtures have a small (~2%) but meaningful portion of light that is emitted directly upward that provides no benefit to the lighting application and greatly contributes to skyglow.

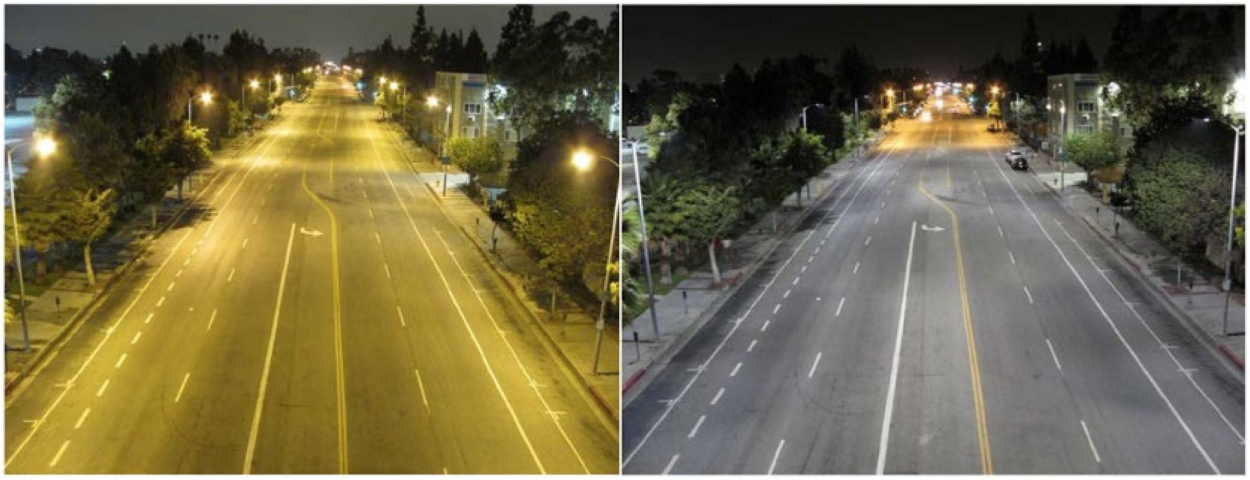

Figure 2.21 LED roadway lighting retrofit of HPS lights. Left image shows upward directed light and intensity non-uniformity on road surface. LED lights on right have potential for adaptive dimming and spectral optimization for safety. [50]

With LED technology, the spectrum of light for roadway can be tailored to improve contrast and roadway visibility, increasing stopping distance and resulting in improved safety, especially at intersections. [51] Spectral tailoring can also be considered for minimizing skyglow and the impacts on local wildlife, but the impact on human safety should be considered the highest priority for roadway lighting. Finally, in terms of intensity control, adaptive roadway and area lighting has the potential to be dimmed when unnecessary. This was not feasible with previous technologies, but intensity control saves energy and reduces environmental impacts of light at night. All of these features for roadway lighting are possible, but not typically considered or deployed. These features may require trade-offs at the light source and balancing of impacts. For example, there is often a trade-off between light source efficiency and optical control. If only luminous efficacy is being considered, then light source efficiency will be prioritized, but if the benefits of improved optical control are considered in terms of total lighting energy and application impacts, such as reduced light pollution, then these factors should be balanced in a holistic framework like LAE. With the example of roadway lighting, energy and environmental impacts can be reduced through optical control and adaptive dimming, which would not be apparent by only considering the luminous efficacy of the light source, and roadway safety can be improved through improved spectrum and reduced glare.

Indoor applications can be considered similarly. The luminous efficacy of office, school, or healthcare setting lighting still has room to improve. In terms of optical delivery efficiency, a higher proportion of light can be directed to task areas where increased light levels improve productivity and reduced in areas where higher light levels are not necessary or provide less contribution to healthy light levels for the occupants. The SPD could be tailored or actively tuned to support the work activity and also support occupant health and well-being. The intensity of the lighting could also be tuned throughout the day, such that it is brighter in the morning and dimmer in the afternoon, in support of healthy circadian cycles. Of course, most indoor lighting should be dimmed or turned off when there are not occupants and be responsive to daylight supplementation so that lights are not on when unnecessary.

In an industrial or warehouse type lighting application, the optical distribution can be tailored for maximum visibility of the products on the shelves. The spectrum and intensity can be optimized for color discrimination and worker health, and there can be aggressive occupancy controls since much of the space is not occupied for much time.

The overarching concept with LAE is that source luminous efficacy is important, but not a sufficient metric for describing energy savings, productivity, and health benefits with lighting. The factors of source efficiency, optical delivery efficiency, spectral efficiency, and intensity optimization may need to be balanced for maximum energy savings and productivity, which requires a clear application specific guidance and an application agnostic framework to evaluate the impacts. More details on these LAE aspects can be found in Section 3.2.8.

2.8 Crosscutting R&D Opportunities for Lighting Technology

The DOE SSL 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 in lighting effectiveness and productivity in a broader range of applications beyond general illumination that offer energy savings and productivity possibilities (e.g., germicidal ultraviolet, horticultural lighting, and 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 SSL Program is developing a framework for evaluating the energy savings and productivity benefits for these new frontiers in lighting 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 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;
- Impacts of DOE R&D support;
- Productivity and other non-energy benefits associated with application;
- Technology overlap with general illumination technologies

2.8.1 Germicidal Ultraviolet

The COVID-19 pandemic has put a spotlight on germicidal ultraviolet (GUV) irradiation for air and surface disinfection. When considering the potential jump in electricity load with increased implementation of GUV in buildings, this area represents a growing opportunity to embed energy saving in luminaire designs and application practices. LED GUV sources and luminaires have low efficiencies and a lot of headroom to improve the application effectiveness with technology improvements. There are a number areas in GUV technology that require further technology advances, including:

- Increasing ultraviolet C-band (UVC) LED source efficiency
- Improvements to GUV luminaire designs for effective delivery
- Enhancing materials reliability with UVC exposure (both inside the GUV fixture and in the room)
- Creating reliable GUV modeling software
- Implement accurate UV source characterization methods and tools.

UVC LEDs are currently less efficient than low pressure mercury vapor and excimer sources, but they have considerable headroom to improve efficiency. While efficiencies are low (~ 2-4% power conversion efficiency at 260 nm) due to difficult materials challenges, the past two decades of learning in GaN-based semiconductors for visible LEDs provides a solid materials foundation to leverage for future innovation. Other important research areas that could lead to significant breakthroughs in technology development and implementation include: a better understanding of the photobiological effectiveness of GUV for a variety of pathogens and application use cases, as well as standards development and design guidelines for implementing GUV in buildings. More details about GUV can be found in the appendix (Section 5.2.1).

2.8.2 Displays

The energy used for powering televisions and displays in buildings has continued to rise with the implementation of more screens with more on time in homes and offices. The combined contribution of televisions, computers, and related electronics has approached similar levels of electricity use as general lighting, and a substantial fraction of that energy is used by the displays. Although the introduction of LEDs has led to a significant efficiency increase in the backlights used to generate the light of the displays, the demand for improved image quality means that more of that light is absorbed internally. In most high-performance displays, only ~ 5-10% of the generated light is transmitted through to the observer, so that the overall efficacy is rarely above 10 lm/W. This is as inefficient as an incandescent light bulb.

The largest opportunity for energy savings is addressing the massive optical losses in displays. In liquid crystal displays (LCD), polarizers lead to the absorption of at least 60% of the light and the color filters (used to separate the colors in the sub pixel) lead to further absorption. The combined effect of these two factors is that a maximum of 12% of the light is transmitted. Each of the other layers in the complex optical structure lead to additional absorption and about 20% of the light can be lost even before the light reached the polarizers. An emissive display architecture can lead to much higher efficiencies by eliminating in the lossy polarizers and color filters present in the LCD approach. There are two primary SSL approaches for producing emissive displays today: OLEDs and micro-LEDs. Each have R&D challenges to improve performances and implement in mass production, but both provide pathways to significantly decrease display power consumption. Smaller OLEDs are already heavily deployed in smartphone displays where efficiency is critical to reduce battery size.

The display industry is heavily investing in R&D and there are a number of areas of technology crossover with lighting technology, which allows for synergistic R&D opportunities between the two applications. For example, both communities are eager to develop more efficient, stable blue OLEDs and improve light extraction efficiency. The ability to reduce the reflected light in the OLED display will allow removing the polarizer layer currently required. Additionally, the demand for higher color gamut has motivated R&D on QDs which has reawakened interest within lighting applications. The development of edge-lit display backlights has also led to performance improvements and substantial cost reduction in waveguides which has enabled their use in general illumination for slim planar ceiling lights as alternatives to troffers. Finally, the growing interest in mini-LEDs and micro-LEDs has stimulated research into LED loss mechanisms and fabrication techniques for a much smaller size scale and may open up opportunities to design SSL fixtures that avoid the glare associated with many current luminaires and enable new forms of building integration. In addition, new functionality such as animation and way finding can be integrated into buildings with mini and micro-LED technology. More details about displays can be found in the appendix (Section 5.2.2).

2.8.3 Horticultural Lighting

Indoor horticulture, also known as controlled environment agriculture (CEA) is a growing application for LED lighting. The increased use of electric lighting in CEA systems has been driven by advancements in horticulture science and LED lighting technology. In addition to driving photosynthesis, light regulates several plant attributes, including flowering, branching, plant height, biomass accumulation, plant immunity and defense, stress tolerance, and phytoceutical production. This can then influence various aspects of plant growth, such as the size of the plant, germination process, flowering, vegetation, and even nutritional value. LED lighting technology offers the unique ability to spectrally tune light sources to engage specific plant light responses. Additionally, LED lighting can be designed with a vast array of light output levels, optical distributions, and controls that were not possible with previous lighting technologies.

The unique controllability of LEDs, along with their high efficiency, can lead to energy savings in tandem with improved plant/crop productivity. More on the energy savings potential can be found in the 2020 report: *Energy Savings Potential of SSL in Agricultural Applications.*[42] The report estimated that if all indoor horticultural lighting was converted to LED technology, annual horticultural lighting consumption would be reduced from 9,591 to 6,307 GWh per year of electricity, a 34% reduction equating to $350 million in saved electricity cost. [52] Improved photosynthetic photon efficacy (PPE) of LED lighting can also be used to improve productivity and yield while keeping energy consumption the same as previous technologies.

There is considerable technology overlap between horticultural and general illumination lighting products. In general, the same LEDs are used, although more direct blue and red LEDs are used for horticulture than in general lighting. The LED packages must be integrated into a lighting fixture and similar fixtures losses are incurred as with general illumination. There are some distinct features with horticultural LED lighting. For example, efficiency is valued more with horticulture than in general illumination. Higher efficiency enables higher light outputs, reduced electricity costs, and more rapid return on investment. Lighting electricity costs are a major expense for indoor growers since lights can be on 12 to 18 hours per day and lighting power density can be very high. Horticulture lighting users are also more sensitive to light output depreciation since plant growth is generally proportional to light output from the fixture (i.e., when light output from a fixture depreciates by 10% there will be 10% less plant growth). For horticulture fixtures, the standard is to report lifetime of the fixture in terms of 10% output depreciation (Q90) rather than 30% depreciation (L70) which is typical in general illumination. More discussion about horticultural lighting can be found in the appendix (Section 5.2.3).

2.8.4 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. The considerations for domesticated animals and wild animals can be very different and will be discussed as two distinct applications.

Domesticated Animals

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 animal 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 in controlled environment horticultural lighting.

LED technology together with improved understanding of animal physiological responses to light could enable improved productivity and animal welfare. LED technology also directly enables significant energy savings. The DOE report *Energy Savings Potential of SSL in Agricultural Applications* showed that 3,667 GWh per year of electricity is used for controlled environment animal production. If the light sources were converted to LED technology 901 GWh per year could be saved equating to $96 million in electricity cost. Animal lighting uses the same basic lighting technology as general illumination for humans, so there is considerable technology crossover. There is also crossover in the understanding of physiological responses to light among animal and humans. Animal models are often used for research to understand the underlying physiological mechanisms of human physiological responses to light.

Wild Animals

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[42] https://www.energy.gov/sites/default/files/2020/07/f76/ssl-agriculture-jun2020.pdf

Light at night also impacts wild animals. Roadway lighting, signage, and light spillage from buildings at night all have negative impacts on local wildlife. The Illuminating Engineering Society and the International Dark-Sky Association as well as the U.S. National Park Service have converged upon a set of best practices for outdoor lighting to reduce skyglow and ecological impacts from lighting. [53] [54]

- Lights should only be installed and used where necessary
- Lights should only be on when necessary
- Lights should be no brighter than necessary
- Lights should have warmer color temperatures

These practices align with the concepts described by the LAE framework. LED technology enables improved optical control so that outdoor lights have little or no upward emission and light is directed to the targeted area. Unlike conventional outdoor HID technology, LED lighting can be instantaneously turned on or off or dimmed, when controls are included in the system. Finally, warmer color temperature spectra can be designed, but their use must be balanced against safety considerations for drivers, which are why the lights have been installed in the first place. With these practices, the impacts of lighting on skyglow and wildlife can be dramatically reduced. Currently, most LED lighting products and installations do not follow these practices, but LED technology has the fundamental capability to fully optimize all of these practices. Migratory birds, hatchling turtles, fish, coastal rodents, marine birds, insects, bats, and numerous other animal species are negatively impacted by anthropogenic light at night. LED technology can reduce overlighting, light emission in unnecessary directions, and enable presence control and time of night dimming which greatly reduces the amount of light in the nighttime environment. Improved understanding of the roadway and other light at night applications will enable improved design standards which in turns allows for products that achieve required performance with reduced counter-productive side effects.

3 R&D Priorities

This section describes priority R&D topics to support the mission of the DOE SSL Program. It begins with an overview of the approach taken by the DOE SSL Program, followed by specific topics and problems of interest. Please note that, although these discussions can include specific discussion of technologies and organizations, these are intended as illustrations and do not entail endorsement.

3.1 R&D Priorities Organization

The DOE SSL Program pursues a multi-faceted approach for accelerating and achieving energy efficient lighting that supports health, productivity, and well-being (illustrated in Figure 3.1). The following discussion of priority R&D topics is organized by three main facets of research:

- **Platform Technology**: *Applied research and development that improves lighting application efficiency through advancements in LED materials, device structures, components, capabilities, lighting product integration, and manufacturing technology improvements. In the process, the intent is to lower barriers to adoption and decrease current performance trade-offs between LED performance attributes, such color, lifetime, manufacturing competitiveness, etc.*

- **Lighting Science**: *Research to understand how best to apply new capabilities enabled by LED lighting for productivity benefits and lighting application efficiency. Despite large impacts from LEDs so far, there are specific submarkets where barriers and opportunities are less well-known. In addition, we seek to understand and quantify benefits from new lighting systems, beyond conventional measures of luminous efficacy.*

- **Integration &Validation**: *Efforts to demonstrate LED performance and related benefits in realistic lighting settings to provide confidence in the technology and understand barriers to adoption of advanced lighting. Moreover, by demonstrating integration of lighting into the building or space and quantifying energy and other benefits, this work can reduce development and deployment risks with future installations.*

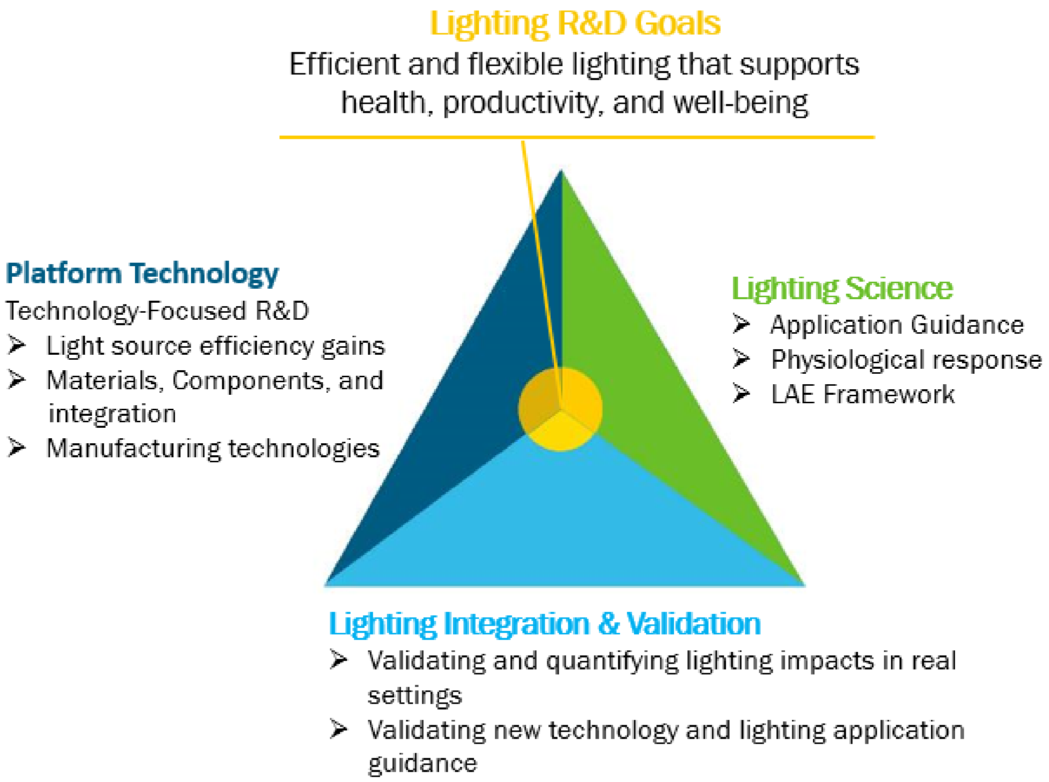


Figure 3.1 A multi-faceted approach by the DOE SSL Program for accelerating and achieving energy efficient lighting that supports health, productivity, and well-being.

3.2 Platform Technology

Platform technology is application focused R&D to develop new materials and devices and integrated lighting products that exhibit improved power conversion efficiency and improved optical performance and control in support of energy savings through reduced power consumption and lighting application efficiency.

3.2.1 LED Sources

LED lighting technology has improved dramatically over the past decade. In addition, improvements to manufacturing of LED lighting products has enabled LED products at low enough cost to deploy 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 adoption, resulting in the greatest possible energy savings for the nation.

3.2.1.1 LED Emitter Materials

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 3.2, with the corresponding optical spectral distributions of these white LED architectures shown in Figure 3.3.

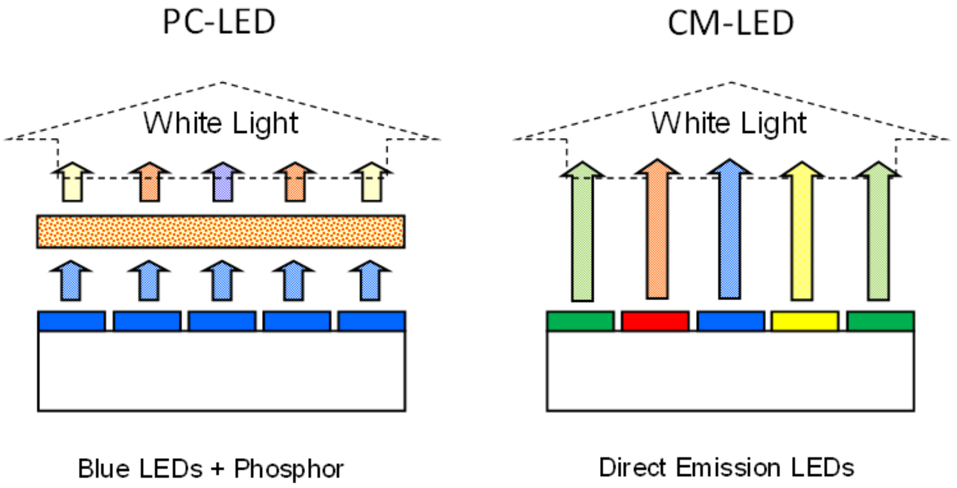


Figure 3.2 Schematic of two main white LED architectures. (a) The PC-LED uses blue LEDs to pump yellow and red down-converters; (b) the CM-LED uses different color direct emission LEDs and mixes the colored light to create white emission.

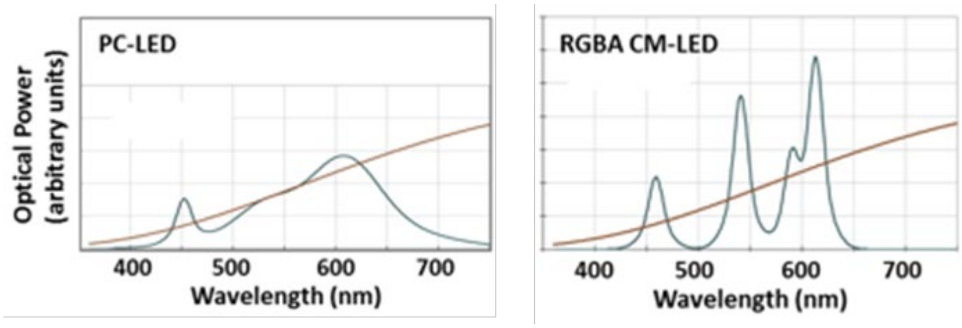


Figure 3.3 Typical simulated spectral power density for white-light LED package architectures. In both the PC-LED and CM-LED, the peak wavelengths and relative intensities are those which maximize LER for a 3000 K CCT (warm white), a "standard" CRI Ra of 80 and a CRI associated with the ninth, deep-red 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 3.4 shows a history of the luminous efficacy of PC-LEDs since the DOE SSL 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 density 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.

Over the past decade, luminous efficacies have more than doubled, 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 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 3.4, luminous efficacies of approximately 250 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 3.4 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 3.1 shows historical and projected LED package efficacy for warm white and cool white phosphor-converted and color mixed LEDs.

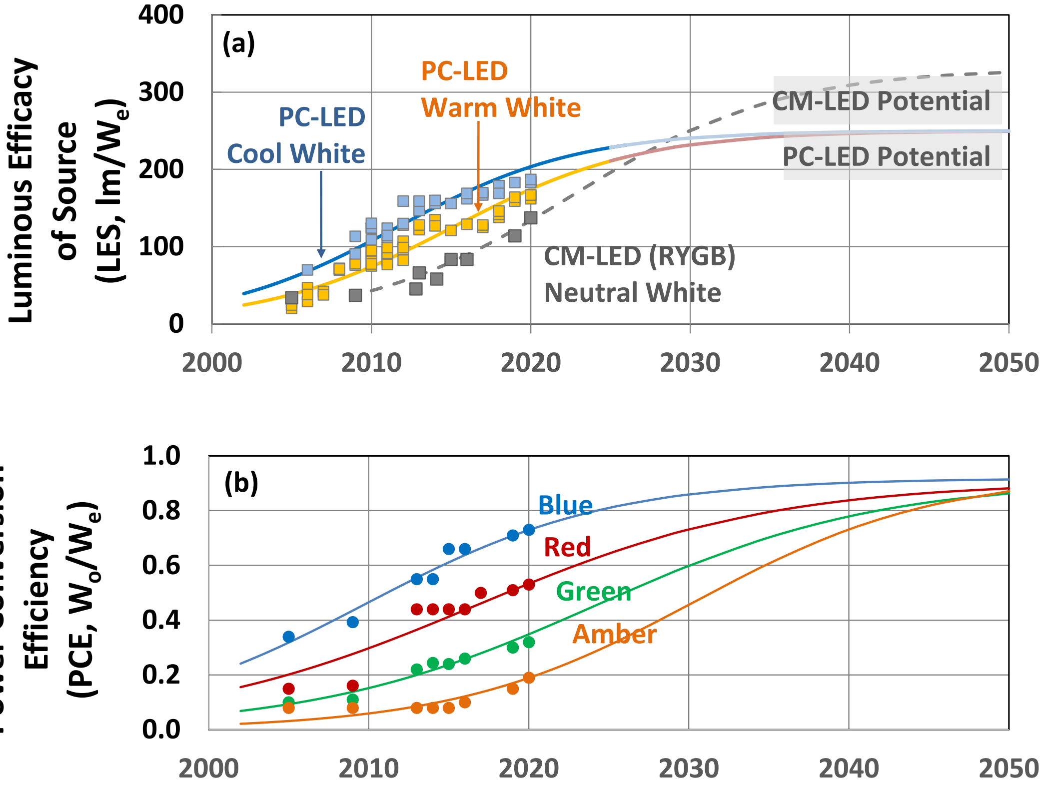


Figure 3.4 Efficacies and efficiencies over time for white and colored commercial LED packages measured at 25°C and 35 A/cm² input current density. All curves are logistic fits using various assumptions for long-term future performance, and historical experimental data. The data are from qualified products at the representative operating conditions of 25°C and 35 A/cm² input current density. *They will differ from some commercial products, particularly those that operate at lower drive current densities to minimize current droop.*

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) *with a CCT of 4000 K. Luminous efficacies have the typical units of photopic lumens of light (lm) created per input electrical watt (W$_e$) of wall-plug power. Year 2020 commercial products reach approximately 185 lm/W for cool white PC-LEDs and approximately 165 lm/W for warm white PC-LEDs.*

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 2040–2045. The historical power conversion efficiencies of these sources were combined and appropriately weighted to give the CM-LED LEDs and conversion efficiencies depicted in the upper panel (a).

Table 3.1 Phosphor-converted (PC) and color-mixed (CM) LED package historical and targeted efficacy levels.

Metric	Type	2020	2025	2030	2035	2050
LED Package Efficacy (lm/W)	PC Cool White	185	228	246	249	250
	PC Warm White	165	210	231	241	250
	Color Mixed	138	204	245	281	336

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 3.5. 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. [55]

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. Additionally, increasing the recombination volume by injecting carriers into more of the QWs reduces the average carrier density, and thus the Auger recombination. The LED epitaxial design can be changed to increase the carrier transport to get uniform injection into each quantum well, as illustrated in Figure 3.5. 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. [56]

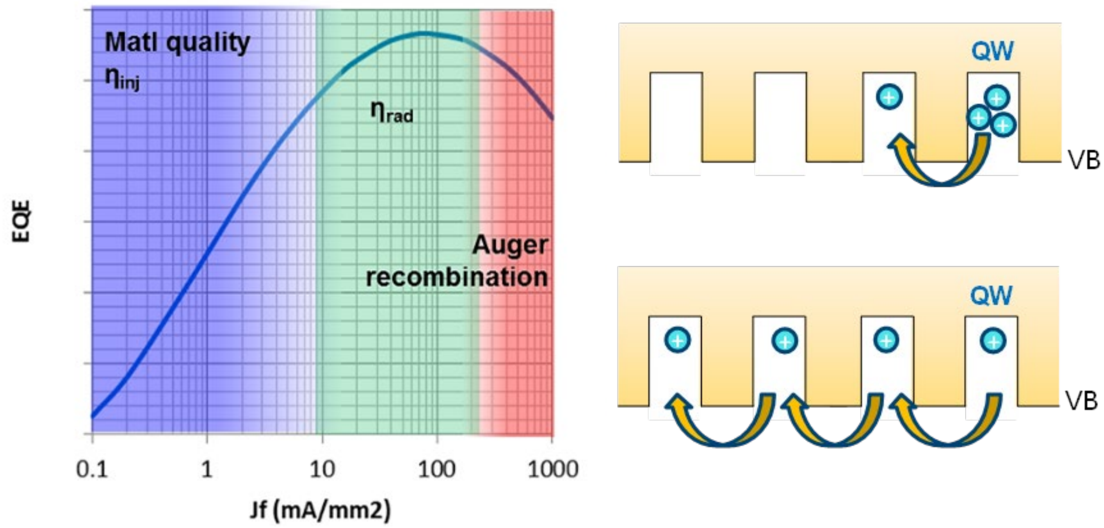


Figure 3.5 Blue LED EQE vs. current density (left) and schematic of LED QW valence band (right). [57] The shaded regions of the graph indicate the dominant carrier recombination modes. The schematic of the QW valence band shows the carriers piling up in the p-side QW (top right) and showing uniform hole injection (bottom left).

Green Gap

Although the InGaN alloy can emit light at wavelengths across the entire visible spectrum, 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. [58] This phenomenon is known as the 'green gap' and is illustrated in Figure 3.6. 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.'

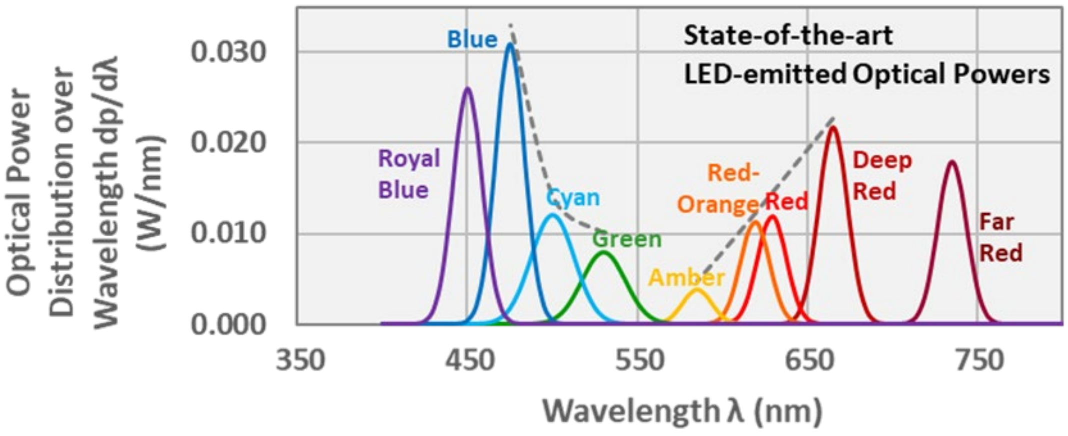


Figure 3.6 Spectral power densities of state-of-the-art commercial LEDs vs. wavelength. The dashed lines are guides to the eye, illustrating the "green gap": the decrease in efficiency from the blue to the green-yellow and from the red to the green-yellow. Data is for operation at 85 °C and has been "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.

There are several factors that contribute to the lower efficiency of InGaN green LEDs compared to InGaN blue LEDs. First, the radiative lifetime increases with increasing indium composition (In %) in the QW because of the reduced electron-hole wafer function overlap from the higher polarization fields at higher In %. The radiative lifetime is on the order of tens of nanoseconds for blue LEDs and hundreds of nanoseconds for green LEDs. [59] The longer radiative lifetime results in higher carrier density in a QW for a given current density and leads to higher Auger recombination, and thus more severe current density droop, as seen in Figure 3.7.

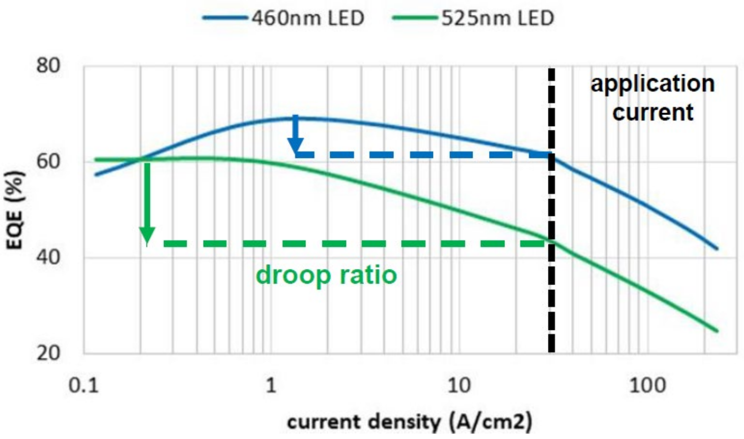


Figure 3.7 External quantum efficiency of blue and green LEDs as a function of current density shows the earlier onset of drop for green LEDs. [59]

Second, the carrier distribution in the green LED active region is poor due to larger polarization induced energy barriers slowing vertical carrier transport in the active region. Figure 3.8 shows a schematic of the carrier distribution in a blue LED active region and a green LED active region. These high energy barriers, as well as large band offsets in the green LEDs, lead to sequential carrier injection in the QWs, which causes a larger excess voltage in green LEDs relative to their blue LED counterparts. For green LEDs structures, the QWs closest to the p-side and n-side have highly unbalanced carrier densities relative to the center QWs leading to different carrier densities and radiative rates within the active region. [60]

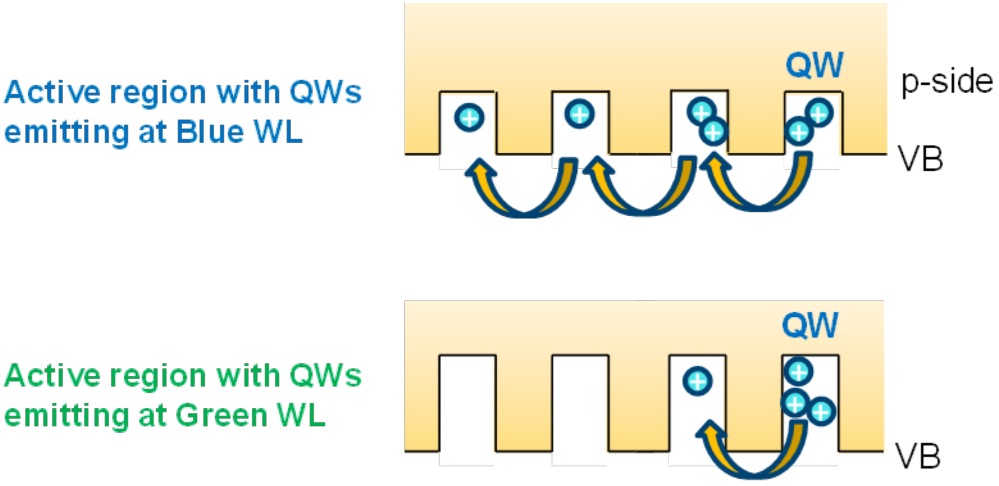


Figure 3.8 Schematic of the LED quantum well valence band in a blue LED (top) and a green LED (bottom). [57]

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).

One concept to improve the carrier injection into the active region of a green LED is to utilize vertical carrier injection through V-pit defects occurring in the InGaN active region. V-shaped pits occur during the InGaN/GaN superlattice layer growth (below the QWs) and are centered on a threading dislocation in the growing film. These angled crystallographic planes in the V-pit allow lower barriers for carrier injection throughout the different quantum wells as illustrated in Figure 3.9(a). When comparing the conventional planar orientation in the heterostructure (away from a V-pit), the electrons and holes are injected from the n- and p-side, respectively. With the V-pit, the holes can inject easily through the angled V-pit sidewalls allowing more uniform hole carrier distribution in all the QWs. This is also illustrated in the valence band schematic in Figure 3.9(b). Carrier injection modeling shows the high hole density at the V-pit sidewalls in Figure 3.9(c). V-defect engineering in green production LEDs has led to much lower forward voltages due to the improved carrier injection. [61] This is a potential pathway for improving excess voltage in longer wavelength amber and red InGaN LEDs, as demonstrated by some research groups. [62]

While V-defect engineering is an interesting path, there are some challenges to overcome. Engineering defects into the LED heterostructures can have impacts on other materials parameters than can lead to a trade-off in performance. The active region layers must be optimized for pit size and density, though the optimum conditions may vary for different active region designs or indium compositions. Additionally, predictive 3D modeling of the V-pit density in the LED heterostructure is challenging since the behavior of one V-pit may not be representative of the whole distribution of V-pits. [59]

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. This will also result in reductions of the excess voltage common with green LEDs. However, the biggest hurdle is that most LED heterostructure changes that improve carrier transport hurt the material quality (point or extended defect generation) – again this tradeoff 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.

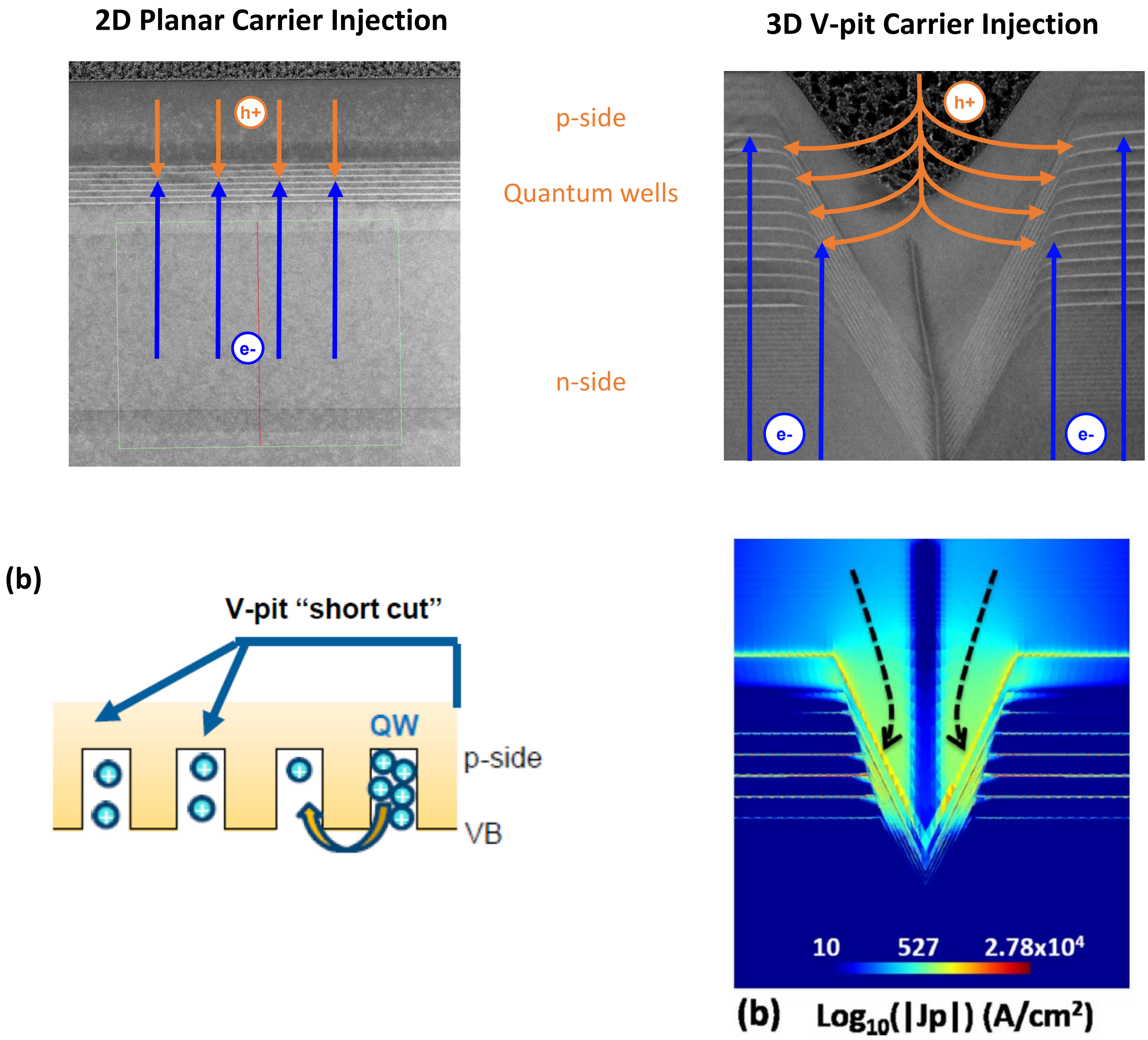


Figure 3.9 (a) Comparison of carrier injection in planar section of the LED active region to that occurring at a V-pit defect. The V-pit defect allows easier hole injection to all the quantum wells than in the planar structure where there are energy barriers from polarization and band offsets. [61] (b) Schematic illustration of the LED valence band and how the V-pit defect hole injection can distribute holes across the active region. [59] (c) Model of the hole current density distribution around a V-pit in the QW active region showing the carrier density is high across the angled sidewalls of the V-pit. [63]

Advances in Amber and Red LEDs

While there has been emphasis in improving the performance of green-emitting LEDs, amber and red LEDs have also made progress. 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 adoption of direct amber LEDs (~580-595 nm) has so far been limited by their lower power conversion efficiency, which is related to the fundamental difficulty in confining carriers to the quantum well at these shorter wavelengths. Many LED manufacturers offer an amber PC-LED where a blue LED is combined with a phosphor to create the yellow emission since it can be more efficient than a direct emission amber LED. While more efficient, the additionally phosphor application process does add more manufacturing steps and cost to the amber PC-LED compared to the direct emission amber LED.

The challenges in the AlGaInP material system include a diminishing internal quantum efficiency at shorter wavelengths due to the lack of current confinement as it approaches the indirect band gap crossover energy (amber region), and the low extraction efficiency due to the higher index of refraction. Lumileds has a funded project from the DOE SSL Program to improve the efficiency of AlInGaP LEDs in the amber to red wavelength range by using strain-engineered cladding layers to enhance carrier confinement. [64] The approach is based on advanced characterization of the atomistic and electronic nature of defects in strained AlInGaP layers, and the subsequent development of epitaxial growth conditions to eliminate these defects. Devices with improved design were fabricated at the end of the second year, resulting in an EQE of 22% in a finished amber LED with 1 mm^2 die size at 350 mA drive current, as seen in Figure 3.10. With further optimization and refinement, the strain engineering approach employed here has a potential to achieve even higher EQE values.

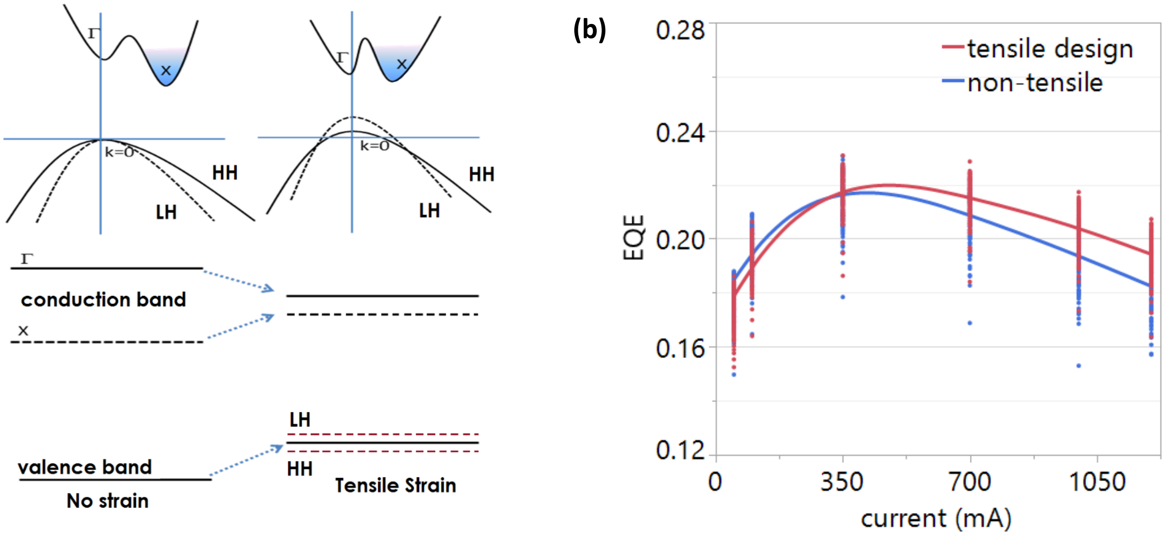


Figure 3.10 (a) Energy band diagrams for AlGaInP LEDs for unstrained active region designs (left) and a tensile-strained barrier active region design (right). The tensile strain impacts the conduction and valence band energy in the indirect band part of AlInGaP alloy by reducing the energy level of the direct band (Γ) and raising the energy level of the indirect band (χ), so more electrons can participate in radiative recombination. (b) Comparison of the EQE for amber AlGaInP LEDs using tensile-strained quantum barriers in the active region (red curve) and the standard non-tensile barrier active region (blue curve). The tensile-strain barriers are used to overcome the limited carrier confinement in lattice-matched AlGaInP in amber wavelength, thus improving the EQE at higher drive currents. [59] [64]

The increase in PCE for AlGaInP LEDs as a function of emission wavelength over the past few years was mainly driven by the need for brighter red LEDs in horticultural lighting. The PCE improvements in AlGaInP red LEDs came from improvements in both the LED materials and the device design. 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 microprism 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 3.11.

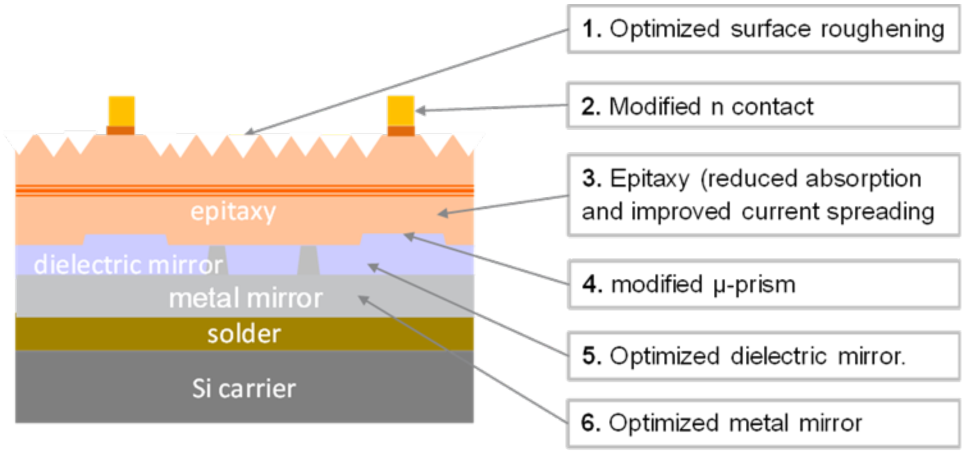


Figure 3.11 Schematic of red LED device and the improved aspects of the chip leading to improved wall plug (power conversion) efficiency. [65]

Progress in red and amber LEDs has been made through improvements in the emitter materials and other device components, but additional approaches are needed to overcome fundamental loss mechanisms that limit device performance at amber wavelengths. There is an opportunity to learn from the adjacent photovoltaic (PV) industry whose III-V multi-junction solar cells have advanced on the foundation of semiconductor materials control (epitaxy, compositional homogeneity, doping, non-radiative recombination centers, access to lattice-mismatched compositions, extended defects, tunnel junctions, and device design). Areas for leveraging semiconductor knowledge and capabilities from PV to improve AlGaInP based red and amber emitters include: developing better material control during epitaxy, understanding loss mechanisms, better close-coupling between epitaxy and characterization, access of desired compositions through lattice-mismatched growth, alternative perspectives on device design, and computational capabilities to understand electronic structure, defects, etc.

AlInP is an alloy that has a higher direct-indirect bandgap crossover energy than AlGaInP, as illustrated in Figure 3.12. AlInP provides an additional energy barrier to electron loss to the indirect conduction band minima in the quantum wells. The challenge with AlInP is that these alloys have a larger lattice constant than the GaAs growth substrate which creates dislocations due to the lattice mismatch. This requires metamorphic growth techniques to accommodate the lattice mismatch. Leaning on the long history of metamorphic growth in PV cells to leverage the know-how needed to improve AlInP active regions can help provide an R&D path forward for amber LED efficiency improvements.

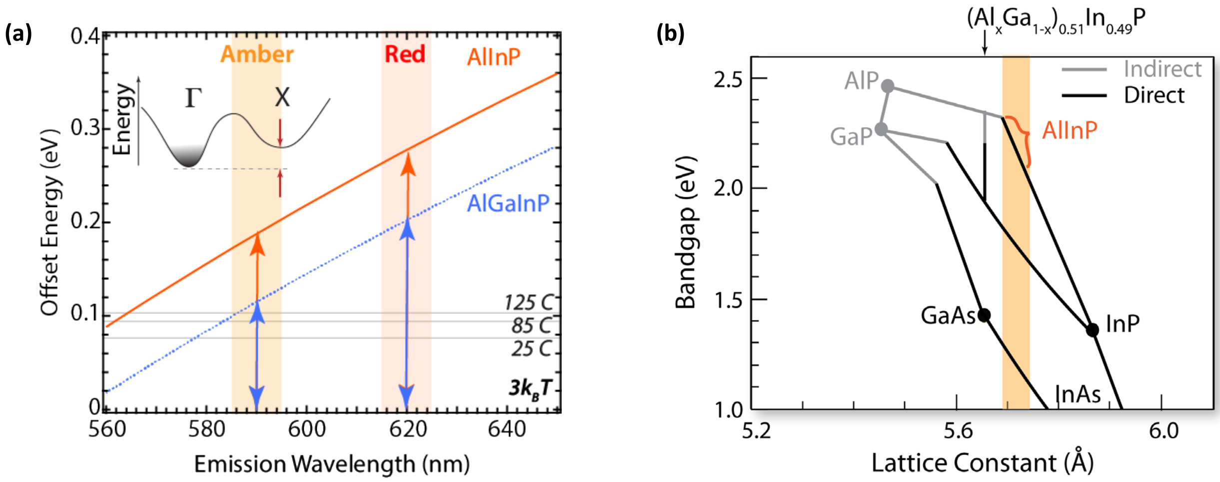


Figure 3.12 (a) Energy band offsets as a function of emission wavelength for the AlGaInP and AlInP emitter systems. AlInP has a higher direct-indirect bandgap crossover energy than AlGaInP. (b) Plot of bandgap versus lattice constant for red and amber emitter materials systems including AlGaInP and AlInP. The AlGaInP alloy can be lattice matched to the GaAs substrate, though metamorphic growth techniques are required for AlInP to manage the strain resulting from the lattice mismatch. [66]

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

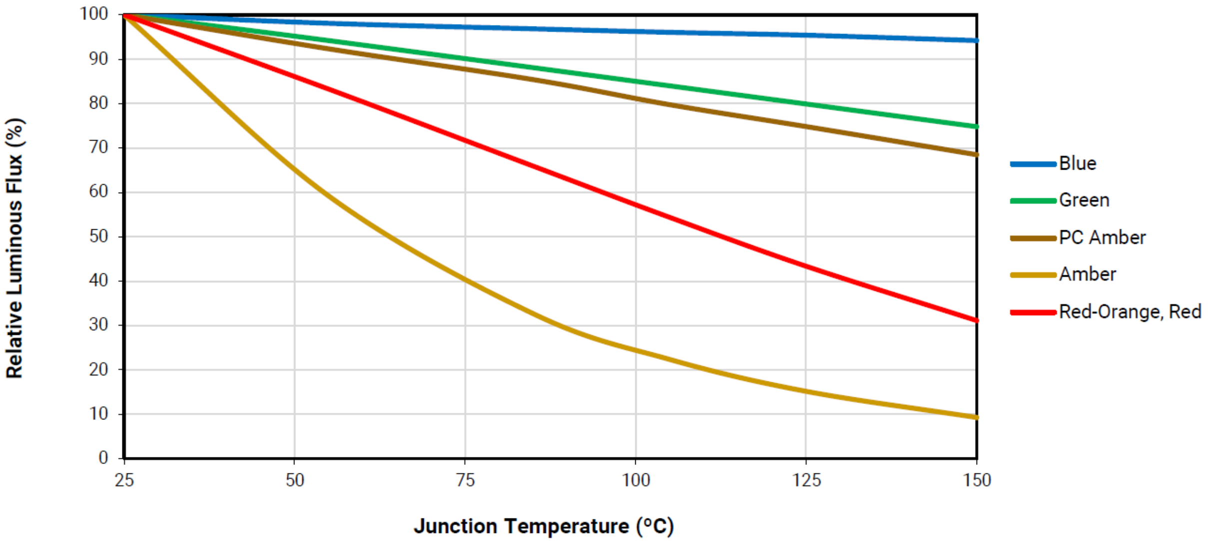


Figure 3.13 LED efficiency as function of junction temperature. [67] The thermal droop is seen as the LED efficiency declines as junction temperature increases. AlGaInP and AlGaAs LEDs experience the greatest thermal droop.

Thermal droop occurs because of temperature-dependent semiconductor properties that cause non-radiative recombination and carrier loss. Researchers have been looking for the origin of thermal droop in InGaN LEDs.

Work done by researchers at the University of California, Santa Barbara show that when blue LEDs are operated at elevated temperatures, they demonstrate an increase in electrons lost via carrier leakage and/or overshoot. This increase of leakage and/or overshoot coincides with the onset of the decrease in light output at ~75°C, a temperature range at which LEDs are commonly operated. These results are consistent with the expected onset of the thermal droop that has been widely reported in scientific literature. [68] 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 in the AlGaInP materials system. AlGaInP has small band offsets, which leads to significant carrier overflow with increasing temperature preventing them from contributing to radiative recombination. This is exacerbated where the aluminum (Al) composition difference between QWs and barriers becomes smaller as the wavelength decreases towards amber, resulting in lower light output and hot/cold factor compared to red LEDs. This effect is illustrated by the drop in internal quantum efficiency (IQE) and hot/cold factor seen in Figure 3.14. Research into new strain engineering approaches for epitaxial growth of the active region (discussed above) is a promising approach for improving the carrier confinement and reducing carrier overflow.

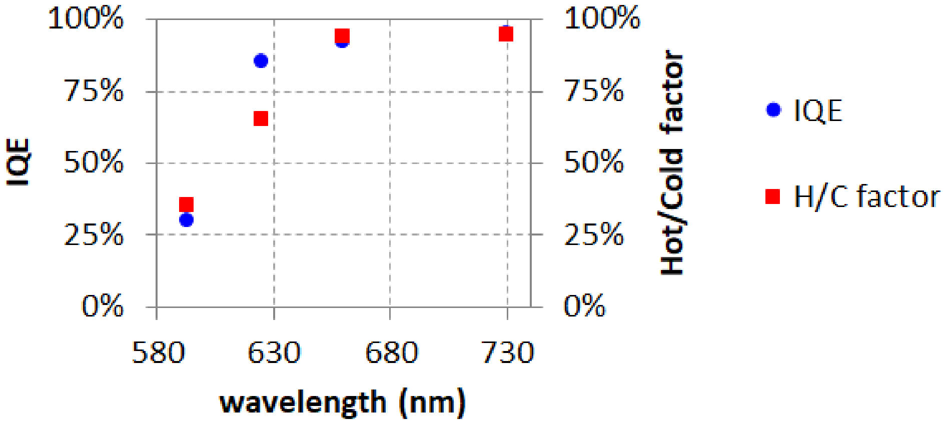


Figure 3.14 The internal quantum efficiency (IQE) and the hot/cold factor of AlGaInP LEDs decreases as the wavelength drops towards the amber region. This is due to the significant carrier overflow with increasing temperature as a result of the smaller band offsets with decreasing wavelength. [59]

Novel Emitter Materials

While potential R&D pathways are recognized for improving LEDs with conventional III-V semiconductor materials, further research into new materials beyond InGaN and AlGaInP may be necessary for additional improvements in the yellow/amber and red wavelengths. There are many less-studied materials that can be integrated with GaN (or AlN). II-IV-nitrides are one family of possibilities being explored; in these materials the group-III elements are substituted with group-II and IV elements. Some advantages over conventional III-nitrides includes the large band offsets allowing new heterostructure designs, expanded opportunities for doping, and novel device designs. New active region engineering approaches use thin layers of $ZnGeN_2$ or $ZnSnN_2$ embedded within an InGaN QW to create a type-II InGaN-$ZnGeN_2$ heterostructure. [69] This band structure leads to a strong confinement of holes in the Zn-IV-N_2 layer allowing a lower In-content InGaN QW to increase the emission wavelength relative to a conventional InGaN QW. The Zn-IV-N2 alloys can be lattice matched to GaN and InGaN as shown in Figure 3.15 (a). Other candidates include the addition of boron into InGaN to reduce the lattice mismatch to GaN, as seen in Figure 3.15(b). Boron does not increase the band gap, still enabling luminescence in the visible region while reducing the lattice. Finally, the introduction of small amounts of antimony (< 1% Sb) into GaN dramatically reduces the band gap, enabling luminescence in the visible while preserving lattice matching. These and other less-studied ternary nitride compounds have suitable bandgaps for visible light emission, and it is possible to grow them via heteroepitaxial integration on GaN.

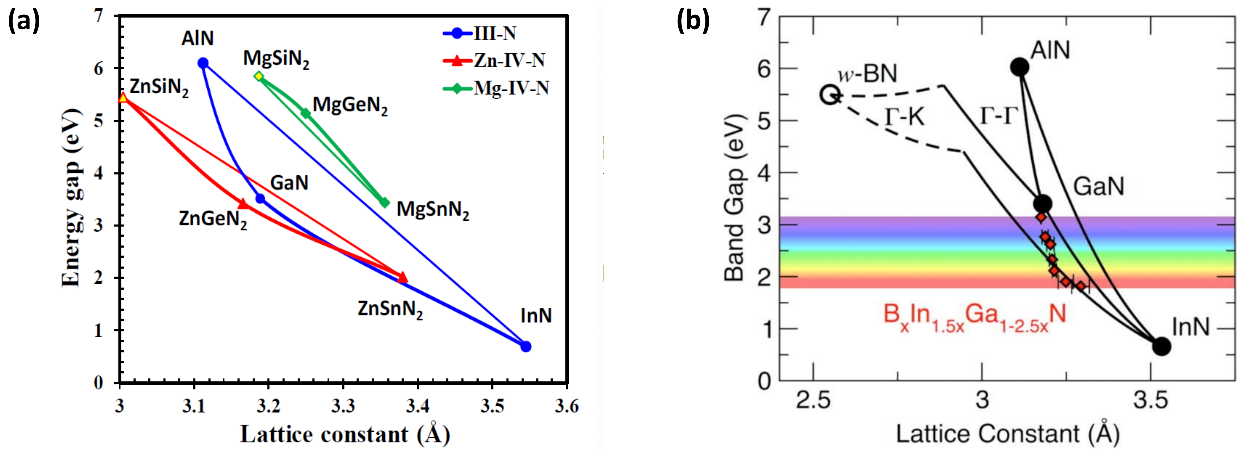


Figure 3.15 The energy band gap as a function of lattice contacts for (a) II-IV-nitride alloys and boron-containing III-nitride alloys. These new alloys can provide new optical and electrical design degrees of freedom while retaining lattice matching to GaN or InGaN, thereby reducing materials strain. [70] [71]

The exploration of new materials, as well as the relationship between modeled performance and experimental results, can enable advancements in understanding and performance of conventional LED materials and devices. Computational materials discovery can be used to identify new materials and their applicability to SSL. Compositions, crystal structure, basic properties, and synthesis methods can be determined computationally. Computational methods can also help identify the performance and application for known compounds. An example of the use of computational materials discovery can be seen in Figure 3.16, where a large stability map of the inorganic ternary metal nitrides was constructed. This map clustered the ternary nitrides into chemical families with distinct stability and metastability, identifying promising new ternary nitride spaces for experimental investigation. [72] Computational approaches still need refinement. Results to date for LED device materials and down-converters have been somewhat disappointing. These approaches need to be coupled with experimental validation. Additionally, materials properties targets need to be refined and better related to target LED device performance.

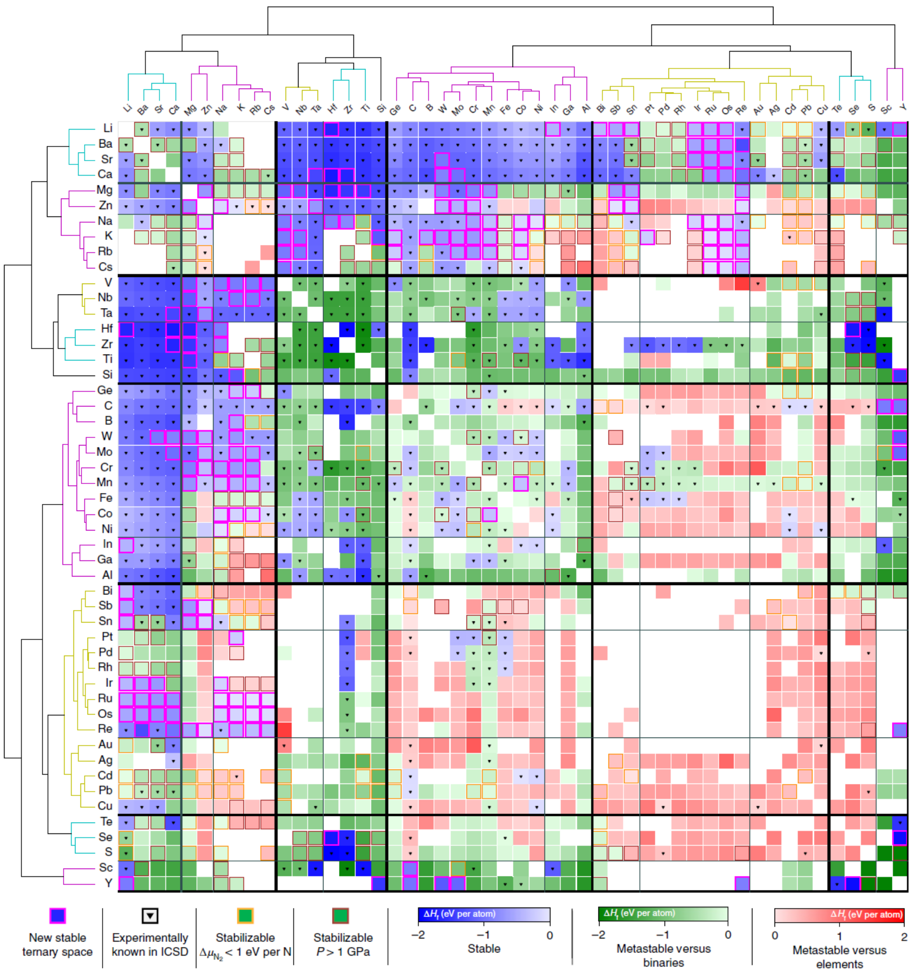


Figure 3.16 Computational materials discovery was used to create a stability map of inorganic ternary metal nitrides and identify promising new ternary nitride compounds. This figure illustrates the potential for new materials through computational approaches, though experimental validation and device testing remains crucial. [72]

Materials criteria can aid in recognizing key factors that distinguish contenders for LED emitters. Identifying properties such as the band gap range, band offsets, alloy and dopant possibilities, and polarization effects are important to realize the potential of the material for device architectures. Another major consideration is determining if the material quality and synthesis possibilities are amenable for bright emission and whether it can be improved or if there are fundamental limits. Once known compounds are classified to have met the criteria required for the applications, then the materials design process begins with the development of composition-gradient thin-film synthesis and fine tuning of properties – often by alloying.

3.2.1.2 LED Device Architectures

New LED device architectures can enable performance improvements tailored for different lighting applications. Several different designs will be discussed to improvement performance including designs to circumvent current density droop and LED devices scaled down to a few microns in size.

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). 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 3.17, 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.

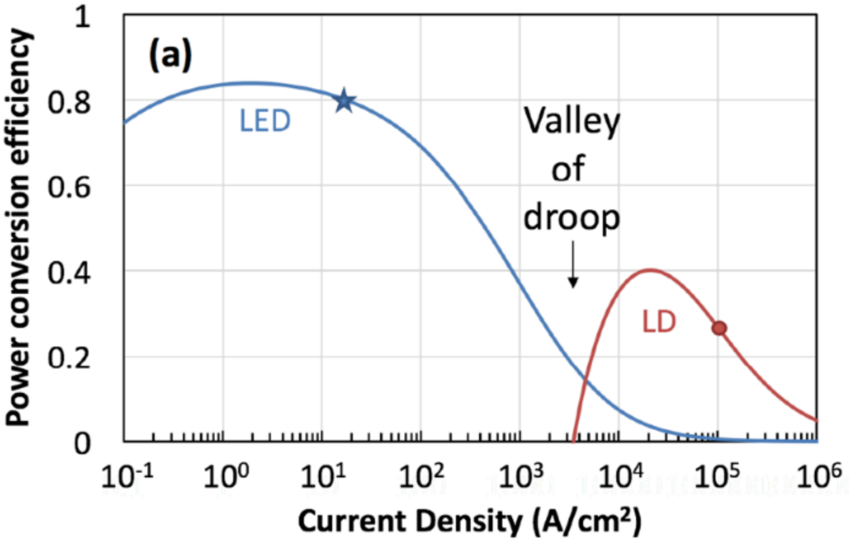


Figure 3.17 Power conversion efficiency vs. current density for a state-of-the-art LED and laser diode (LD) emitting at violet wavelengths. [73] This plot highlights the ‘valley of droop’ cross-over between the two light source types.

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 LED 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 optical utilization efficiency. There is a premium placed on small, low etendue sources that can be tightly focused and directed to the target. 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.

LDs can produce smaller spot sizes and coherent beams of light relative to LEDs. The stimulated emission from the LD is an inherently more efficient radiative recombination process than spontaneous emission. If similarly efficient blue/violet LDs were demonstrated, their photons could very well have lower cost per photon than LED photons, potentially displacing LEDs in many current SSL applications, while possibly enabling new lighting product form factors currently impractical. State of the art blue LDs trail blue LEDs with power conversion efficiencies in the 40-45% range compared to 60-70% for blue LEDs. However, there is no fundamental reason why LDs cannot have as high or higher power-conversion efficiencies than low-luminance LEDs (e.g. GaAs LDs >70% today). Good progress has been made over the past decade in improving performance as evidenced in Figure 3.18, with blue LDs reaching peak PCEs of 45%.

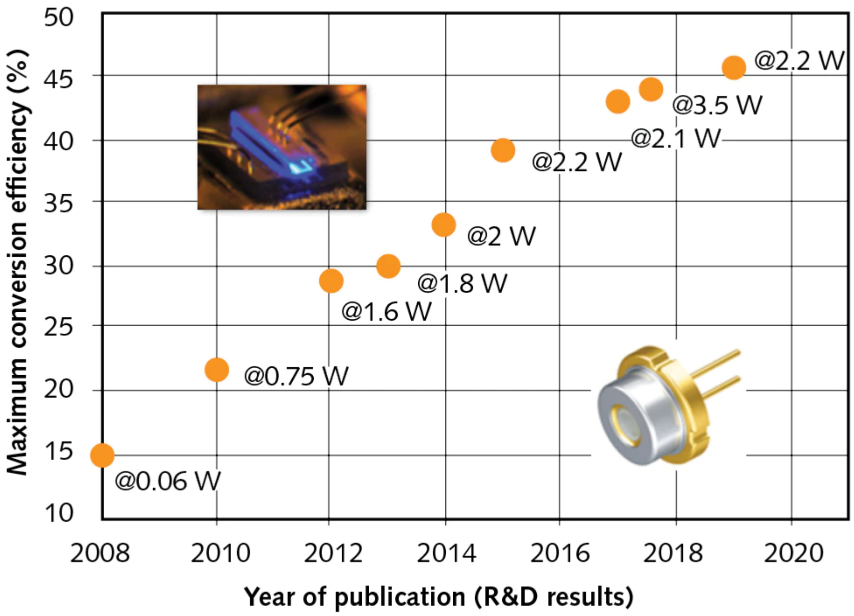


Figure 3.18 The peak (maximum) power conversion efficiency of blue laser diodes over time. The PCE has grown rapidly over the past decade surpassing 45% in 2019. [74]

Traditionally LDs are packaged in TO cans as pictured in Figure 3.18, though that is not compatible with the design of most SSL luminaires since they are designed around surface mount technology used in LED packages. Recently, a surface mount laser-based package with integrated phosphor has been commercialized by SLD Laser (Figure 3.19a). These white illumination-grade packages provide 500 lumens at 6000 K CCT and can produce a very narrow beam of light which can provide improved application efficiency in directional lighting applications. In addition, smaller source size can lead to improved dynamic optical control and enable applications such as entertainment lighting and way finding. A big challenge facing the use of LDs for lighting is breaking the spatial coherency for eye safety. The laser surface mount package utilizes the benefit of the phosphor (needed to convert the blue light to white) scattering the laser emission to break the coherency. The package design concept is illustrated in Figure 3.19(b).

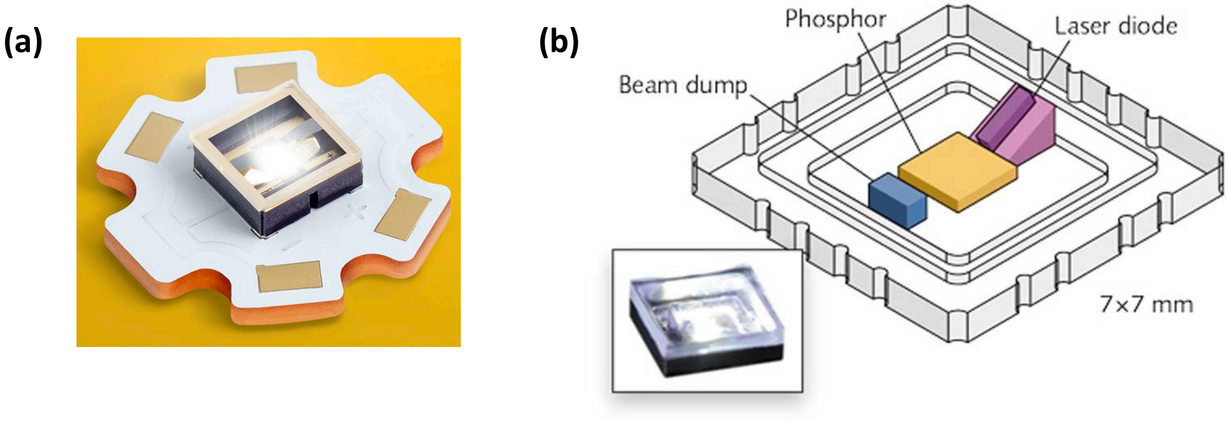


Figure 3.19 (a) Image of a surface mount white laser-based illumination package and (b) a schematic showing the internal configuration of the laser diode and the phosphor. [75] [76]

While laser-based lighting has progressed to developed initial products for lighting applications, more work is needed to broaden the application use of laser lighting. Currently, the phosphor selections that can handle the high intensity blue laser emission is limited to cool white phosphors. The red phosphors cannot handle the blue flux density so warm white CCTs are not available. More work is needed in developing phosphors for high illuminance sources to allow laser lighting (or other LED-based high illuminance sources) to be used for a wider variety of illumination applications, as will be discussed in Section 3.2.1.3.

Another new device architecture that could be effective for straddling of the valley of droop is the tunnel junction (TJ). TJs can be used to improve the current spreading limitations of p-type GaN in LED structures, and also can enable novel device structures like the cascaded multi-junction LEDs to mitigate the impact of current density droop in LEDs by scaling output power at low current densities. TJs can be utilized to enable a series of connected LEDs in one epitaxial structure. Essentially, this cascaded LED structure would create multiple LEDs in series, which would increase voltage while keeping current low. This can allow higher light output from the same area of LED material, while keeping the applied current – and resulting droop – low. Under reverse bias electrons tunnel from valence band on the p-side of the TJ to open states in the conduction band on the n-side of TJ, as illustrated in the band diagram in Figure 3.20(a). Tunneling enables the effective hole injection to the p-side of reverse biased TJ. The use of TJs enables the stacking of multiple LEDs in the same epitaxial device stack seen schematically in Figure 3.20(b).

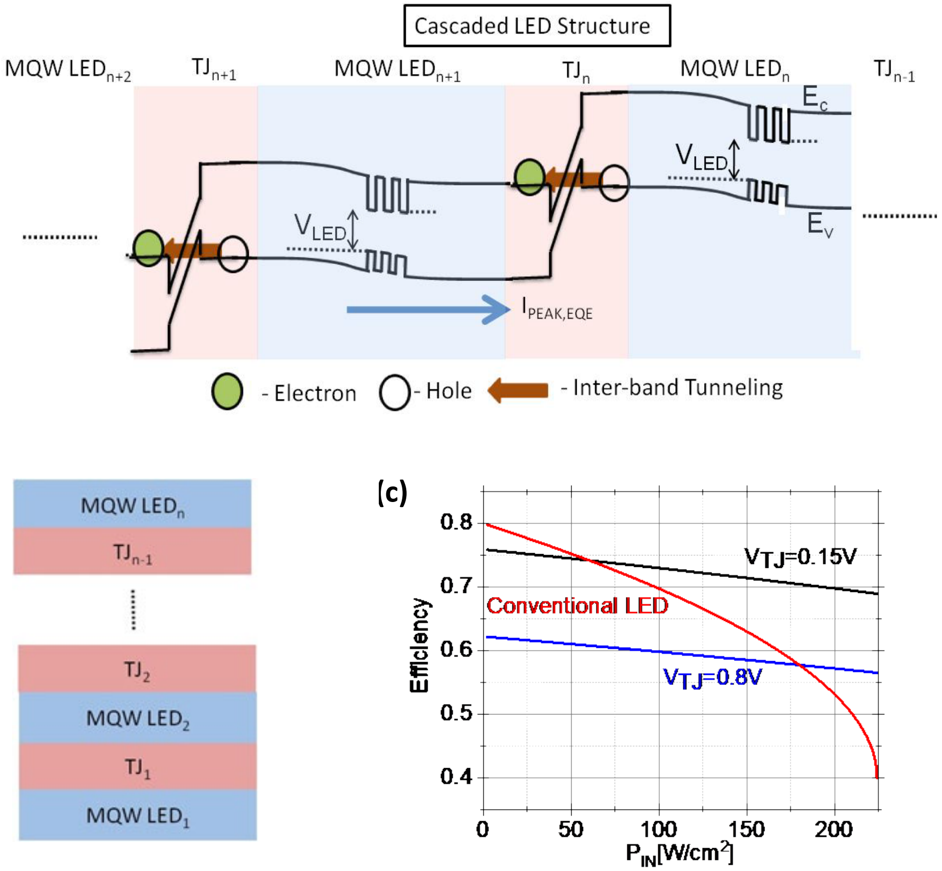


Figure 3.20 (a) Schematic band diagram of a stacked active region LED with tunnel junctions illustrating the tunneling effect of carriers, and (b) illustration of the resulting epitaxial LED structure. (c) The external quantum efficiency of cascaded LEDs can remain high even as the input power to the device increases compared to the conventional LED which droops in efficiency at higher input powers due to Auger recombination. Cascaded LEDs with a TJ voltage penalty of 0.15 V and 0.8 V (black and blue curve, respectively) are compared to a conventional LED (red curve). [77]

Tunnel junctions have been implemented in optoelectronic devices in conventional III-V semiconductors, but they are not yet used in mass production of III-nitride devices to due high excess voltages because of the challenges with p-type doping and activation in metal-organic chemical vapor deposition (MOCVD) grown tunnel junctions. The performance of MOCVD tunnel junctions has improved considerably over the past few years leading to smaller excess voltages of approximately 0.2 V, which make a cascaded multi-junction LED structure more feasible. New innovations in the implementation of tunnel junctions have also been realized, such as selective area growth (SAG) of tunnel junctions in a micro-LED scale device. [78] This has led to more size-independent micro-LED voltages than experienced with traditional contacts or tunnel junctions. The breakthroughs of achieving a low voltage penalty for an all MOCVD-grown tunnel junction provides an opportunity to employ new LED device structures aimed at improving LED efficiency at a broader range of operating conditions.

While research into TJs has led to improved device performance, several challenges remain. The increased voltage drop that results from the increased stack voltage can reduce the efficiency of the devices and limit their applicability. Additionally, there are issues associated with activating the p-type dopant in buried active regions grown by MOCVD and the 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.

Additional LED device concepts can also be considered to improve efficiency and/or luminance. These include the use of LED resonant cavities, photonic crystals, and metasurfaces. More investigation and demonstration into practical considerations for lighting application is required. Much of the existing work on improved optical control/increased luminance is applicable to monochromatic sources which could support direct-emitter color mixed lighting solutions. However, the development of approaches to improve luminance to increase optical control for white LEDs would also be highly valuable. This will be more challenging since solutions must work simultaneously for a range of wavelengths.

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 display applications are currently driving the R&D, these small LED device form factors are being considered for illumination applications for their ability to offer improved directional lighting and new lighting functions using adaptive pixels for wayfinding, emergency lighting, and information display. Critical to implementation in either lighting or displays, the micro-LED performance needs to improve to meet the applications requirements and enable greater energy savings.

Micro-LEDs are generally described as having a size of 50 μm or less. As the LED device dimensions shrink, the LED efficiency decreases in both InGaN and AlGaInP material systems. This effect is driven by the fact that perimeter to area ratio increases, allowing carriers to reach defects at the device sidewalls and recombine nonradiatively. The efficiency falloff with LED size reduction is especially pronounced for AlGaInP material system, where surface recombination velocities are an order of magnitude higher than for InGaN. [79] [80] The EQE of a red AlGaInP LED drops rapidly below a chip size of 70 μm. At 250 μm the red LEDs show an EQE of 35% and drops to about 1% at 35 μm in size. InGaN LEDs also experience an EQE decline as the LED shrinks, though they are not as sensitive to the increasing perimeter to area ratio. A blue InGaN LED drops from nearly 40% EQE at 250 μm to approximately 5% EQE at 4 μm (these LED size effects are illustrated in Figure 3.21). The reduced peak EQE occurs at higher current density with reducing LED size. Improving this EQE at small sizes requires optimized epitaxial structures and device processing. The green gap is negligible for very small pixels as seen in 4 μm LEDs with the blue devices showing 37% EQE and the green devices at 36% (Figure 3.21). InGaN red LEDs do not show the same size dependency behavior of EQE, though the EQE is fairly low at ~ 3% for all sizes from 1 mm down 4 μm.

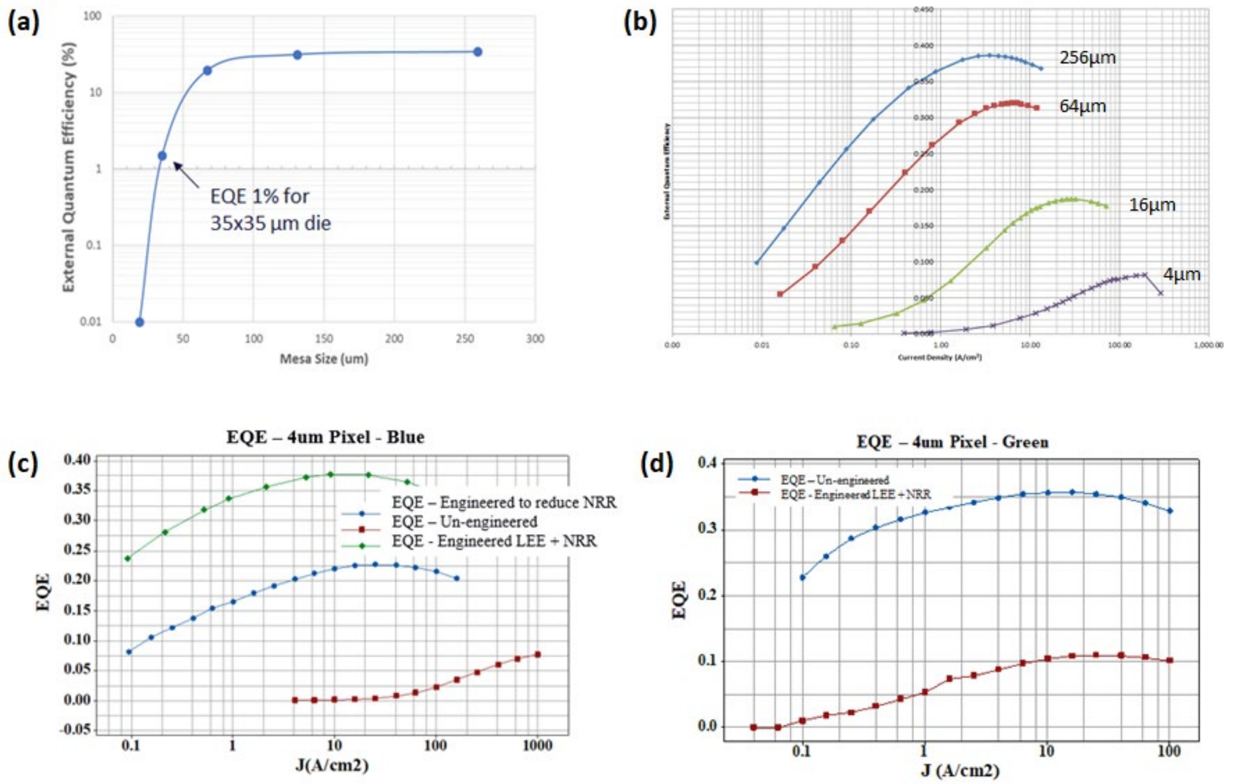


Figure 3.21 (a) External quantum efficiency as a function of LED mesa size for AlGaInP LEDs grown on GaAs. The EQE reduces rapidly below 70µm due to the high surface recombination velocity ushering carriers to nonradiative recombination center at the LED sidewalls. (b) EQE of blue InGaN LEDs as a function of current density for LED sizes ranging from 4 to 256 µm; as the device size shrinks the efficiency drops. The reduced peak EQE occurs at higher current density with reducing LED size. (c) EQE of blue and (d) green 4 um micro-LEDs with optimized epitaxial growth and improved light extraction in the device design leads to peak levels of ~ 37% for both blue and green LEDs. There is not the same green efficiency gap at the micro-scale.

The inefficient performance of both AlGaInP and InGaN has led to a ‘red gap’ in the micro-LED space. Approaches to understand the performance cross-over for red LEDs of different sizes and material systems are needed. In addition, these small devices operate at much higher current densities making current density droop an important consideration in device performance. Further R&D is necessary to understand how much of the decrease is driven by size effects, defects at the sidewalls, and the differences between epi quality in different research teams. IQE improvements for the devices are largely focused on keeping carriers away from defects. Another focus area will be to develop fabrication techniques to reduce sidewall damage during the mesa etching process and surface treatments to passivate the sidewalls and limit nonradiative recombination (Figure 3.22). [81] Other device fabrication improvements such as reflective contacts or surface texturing can be employed to enhance light extraction, and hence EQE performance in micro-LEDs. Technology investment is required to further study and mitigate the efficiency reduction that arises as a consequence of die miniaturization. Advances in device processing, characterization, epitaxial growth should be explored.

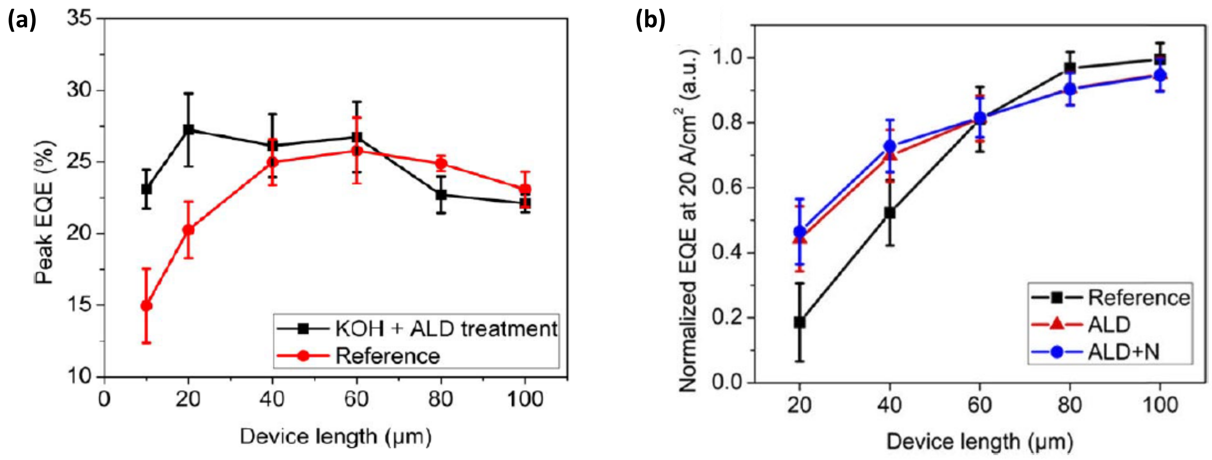
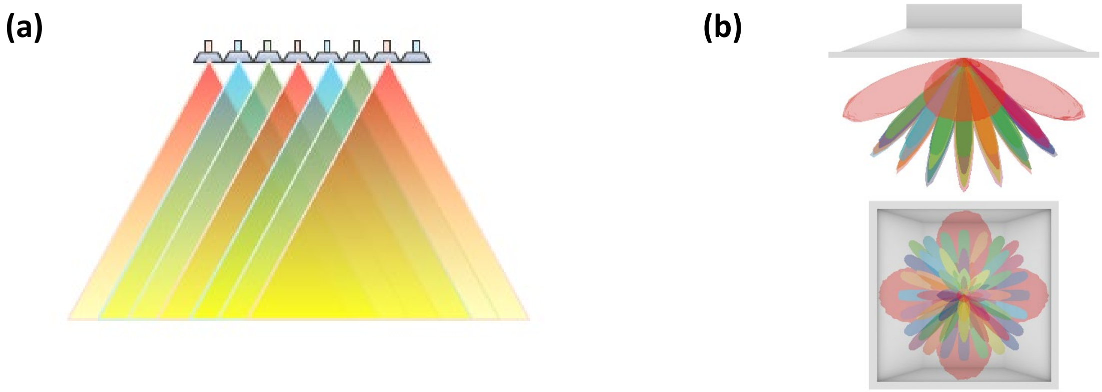


Figure 3.22 LED device sidewall surface treatments using chemical treatment (KOH) and atomic-layer deposition (ALD) coatings help limit the impact of the EQE reduction with device size by passivating sidewall defects to limit nonradiative recombination for (a) InGaN LEDs and (b) AlGaInP LEDs. [81] [82]

The other challenge with micro-LEDs is that the conventional manufacturing and die measurement techniques cannot be performed in the same manner as conventional LED sizes. 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.

Another area of advanced manufacturing involves high density LED assembly. The future use of high-density pixelated LED sources to create advanced lighting designs necessitates new methods to assemble large number of mini and micro-LEDs at speeds and cost levels that can be supported in the lighting industry. The challenge with using these smaller micro-LED die (< 50 μm size) to create small pixel sizes is the conventional manufacturing technologies don't scale effectively – both from the device fabrication side, as well as the die transfer process (at the light engine level). 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. Additionally, manufacturing developments in the display industry should be leveraged for micro-LED lighting in terms of die testing, die transfer, circuit designs, and control schemes.

Until industry can solve the issues with outgoing micro-LED testing and die efficiency reductions, mini-LEDs have instead filled the gap (especially in display applications). Mini-LEDs are typically 100-200 μm in size and fall in the size range between conventional small LED die for lighting 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 conventional LED packages. 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 in the 2020 Consumer Electronics Show (CES) with improved performance in resolution, color gamut, and dynamic range. Lighting companies are looking at implementing mini-LEDs in new lighting schemes as illustrated in -3.23. These new full color pixelated lighting sources can provide high-precision dynamic beam shaping and color projection and will start to create lighting-display fusion by incorporating features such as wayfinding or information display.



-3.23 Illustrations of new lighting schemes (a) and (b) using color tunable pixelated light sources to create different spectral power distributions and optical profiles. [83] [84]

3.2.1.3 LED Package Materials

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 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 lower efficacy of current PC-LED white light. Figure 3.24 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 can be gained by replacing the red broadband phosphor with a narrowband alternative, which reduces the spillover emission in the deep red and infrared (IR) wavelength ranges (beyond 650 nm). [85] The deep red photons have a lower perceived brightness since they lie the visible region where the eye is less sensitive (lower on the photopic eye response curve); thereby the lower luminous contribution of deep red photons reduces the luminous efficacy of the white LED.

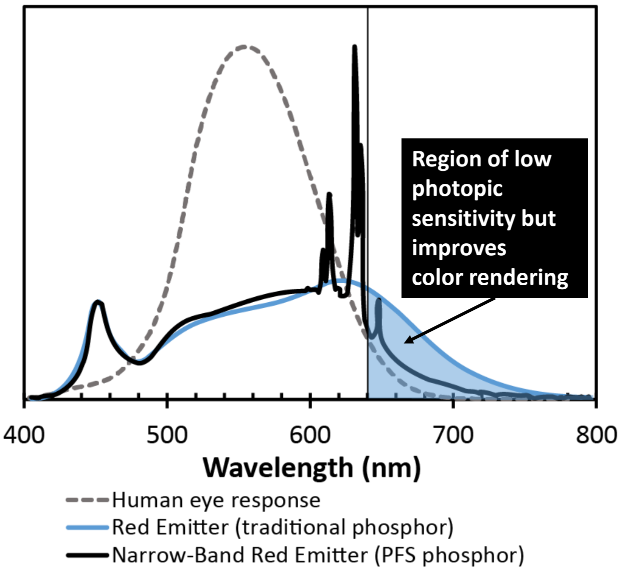


Figure 3.24 Spectrum comparison of a 90 CRI PC-LED with conventional phosphors (blue), a 90 CRI PC-LED with a narrow-band red phosphor (black), and the human eye response curve (dashed). [86] A narrow-band red down-converter will improve the spectral efficiency by reducing the region of low photopic sensitivity in the deep red and infrared portion of the spectrum (though at the expense of color rendering at these long red wavelengths).

Narrow red down-converters (phosphors and quantum dots) have been released in several LED package products to improve the luminous efficacy of high CRI lighting products. These lighting products exhibit a more efficacious solution at improved color quality due to the narrow red emission spectrum of the phosphor. The narrowband red phosphor commonly used is potassium fluorosilicate $K_2SiF_6:Mn^{4+}$ (KSF or PFS). While this phosphor was demonstrated 7-8 years ago, 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 3.25. [87]

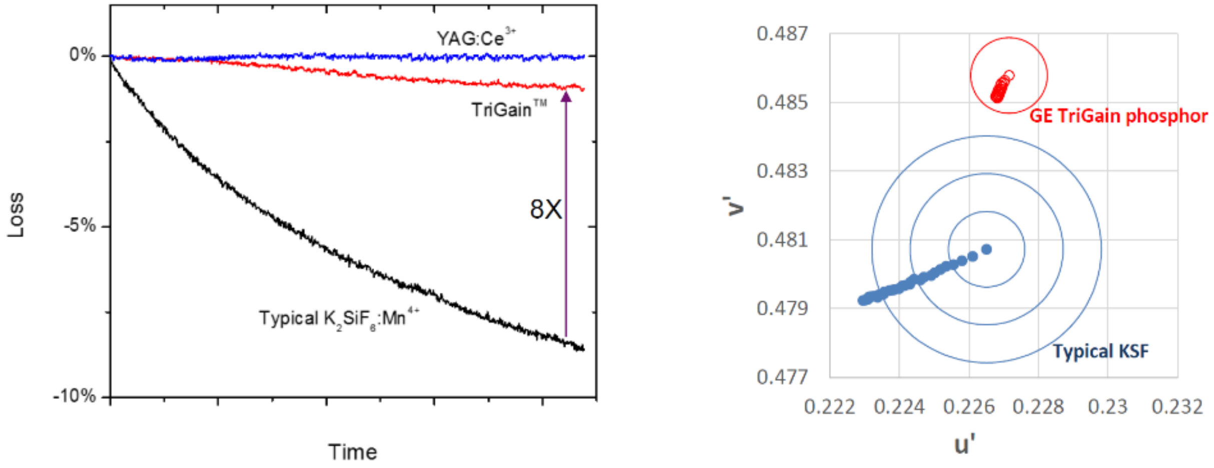


Figure 3.25 Light loss of phosphors in LED packages under high blue flux densities (left) and color shift under stressed operating conditions (right). [87] The TriGain KSF narrow-band red phosphor has shown improved stability under blue flux densities over the past several years of the earlier KSF phosphors, which will lead to better white LED stability.

Innovations in phosphor synthesis and materials processing has led to improved QE in KSF phosphors as seen in Figure 3.26. 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. Impurities can decrease optical property performance much more rapidly than mechanical properties. These impurities may be introduced in one of the reactants, a solvent, or by the equipment used during the manufacturing of the phosphor. It is not uncommon to find that 10 parts per million (ppm) or less of a metal impurity can significantly decrease phosphor brightness. For example, large improvements in phosphor quantum efficiency (QE) may result in shifting from a 99.5% pure precursor to a 99.99% pure precursor. Other areas for materials improvement include the realization of more uniform particle sizes, better controlled morphology, improved chemical and thermal stability, and more consistent excitation characteristics. Further reliability improvements are also desirable to operate at higher fluxes and temperatures.

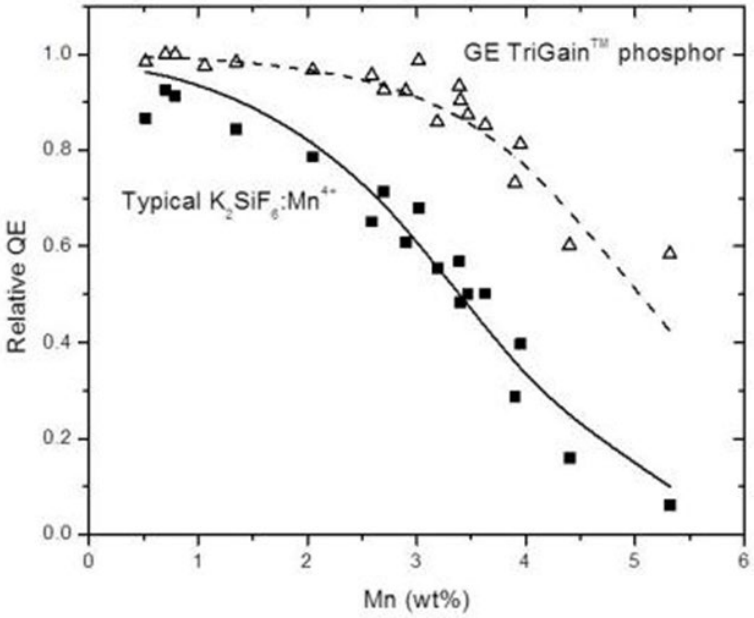


Figure 3.26 Quantum efficiency (QE) improvements can be seen in KSF phosphor from improvements in synthesis and materials processing innovations when comparing improvements by GE in their TriGain KSF phosphor to the typical KSF phosphor. [88]

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 recently, 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). [89]

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 K to 5000 K through reduction of the amount of longer wavelength red light where there is limited eye response (Figure 3.27). [90] Replacing the conventional red phosphor completely a red QD provides a bigger boost of ~ 25% to the luminous efficacy with CRI 90. Figure 3.29 compares the performance characteristics of an LED package with red phosphor, a hybrid QD-phosphor red downconverter, and red QDs, showing the improved efficacy at high color quality. LEDs with on-chip application of down-converter material 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. [91] While QDs can be now implemented in the lower power LED package models, the current environmental stability has limited QD implementation into higher power LED packages. PLQY and reliability are highly dependent on surface layer and barrier coating, encapsulation, and the barrier coating/QD interface. Better barrier layers must be developed to electronically passivate the QD surface, provide moisture barrier, ion-barrier, and pH buffer, in order for QDs to be better utilized in LED packages for lighting applications.

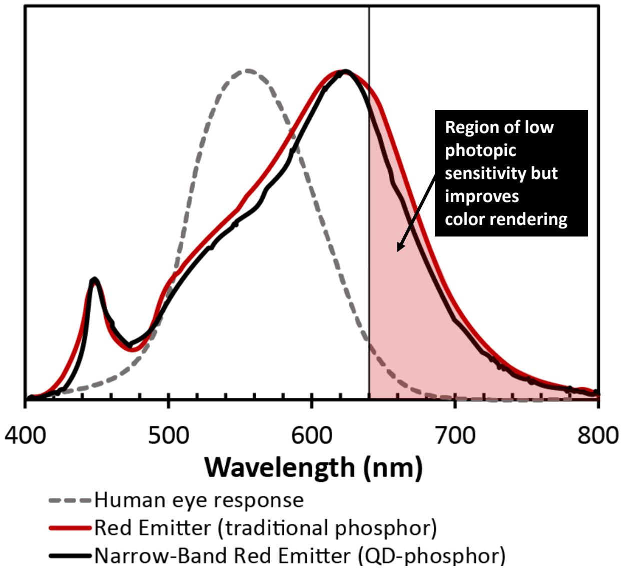


Figure 3.27 Spectrum comparison of a 90 CRI PC-LED with conventional phosphors (red), a 90 CRI PC-LED with a narrow-band red quantum dots (black), and the human eye response curve (dashed). [92] A narrow-band red down-converter will improve the spectral efficiency by reducing the region of low photopic sensitivity in the deep red and infrared portion of the spectrum (though at the expense of color rendering at these long red wavelengths). [86]

	Efficacy (lm/W)	[Cd] (ppm)	LER	CCT (K)	CRI	R9
Phosphor	158	0	298	2983	92	59
QDs	165	90	303	3018	93	56
QDs	**203**	**600**	357	2957	90	50

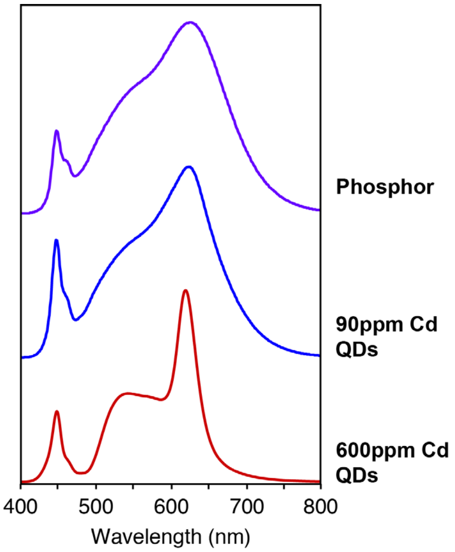


Figure 3.28 Comparison of LED package performance characteristics with red phosphor, a hybrid QD-phosphor red down-converter (90 ppm Cd), and red QDs (600 ppm Cd). The corresponding spectra for these three LED configurations are shown. A 25% efficacy improvement is realized when replacing the red phosphor down-converter with QDs. [93] [94]

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 downconverter, as illustrated in Figure 3.29. 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 that could significantly improve the scalable synthesis of high-performance QDs employs a convergent (rather than linear) approach. It 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. The DOE SSL Program is funding research to prove out the synthesis reproducibility, QD performance, and reliability using new colloidal synthesis. [95]

The current high-performance QDs commercialized in LEDs contain a small amount of 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 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. [96] 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 34 nm for green and 37 nm for red, nearing the DOE target of 30 nm FWHM. [97] 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. The SSL Program is funding R&D to improve performance and stability of InP QDs. [98] [99] Other potential Cd-free QD systems include perovskites, which are still in the early stages of development and require more work to assess the performance levels and stability.

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. [89] 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. Once the performance properties and stability challenges with QDs have been largely met, then development work to scale up QD synthesis for mass production is required. 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.

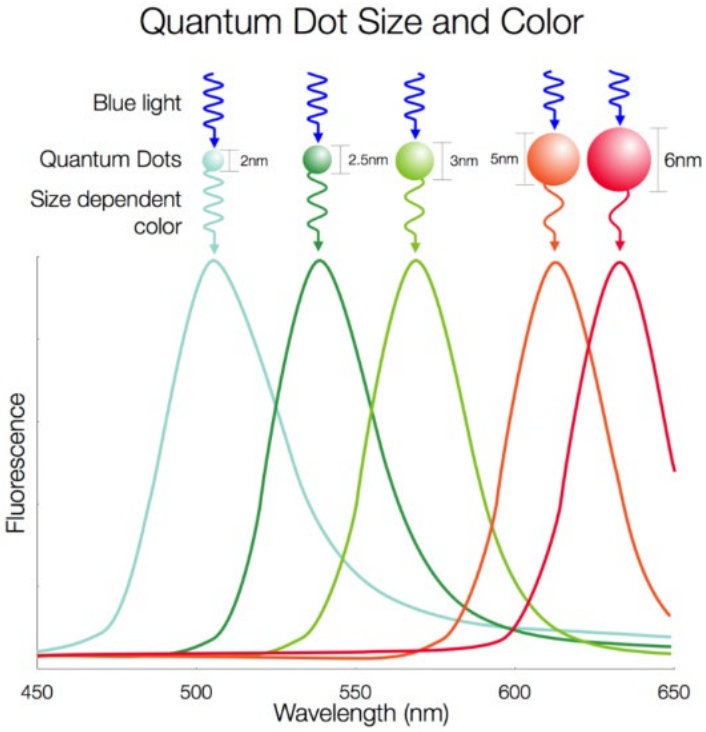
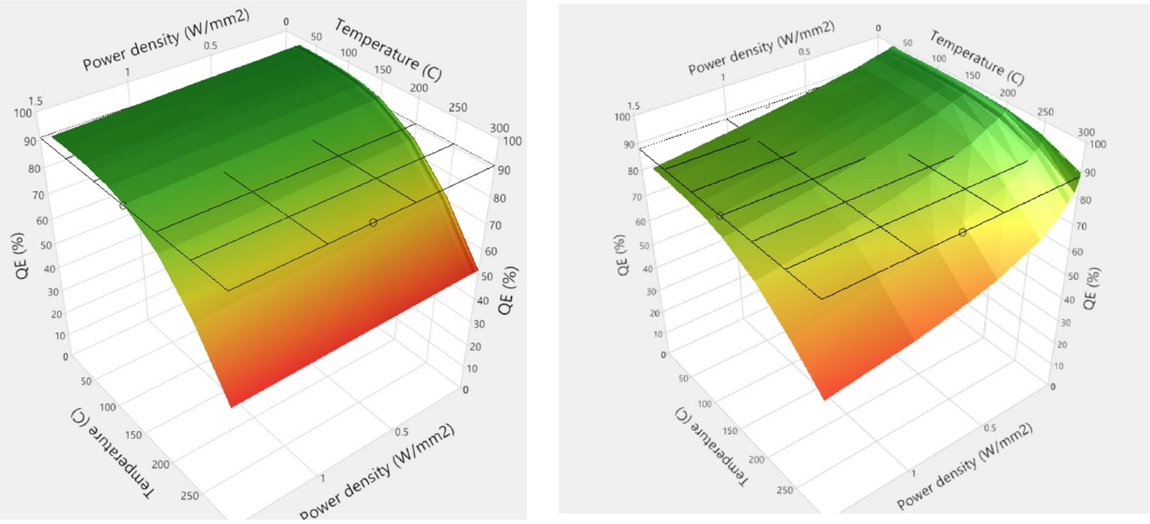


Figure 3.29 Emission wavelength of CdSe QDs as a function of dot diameter. [100] As the diameter increases, the emission wavelength of the QD increases.

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. [101] The photothermal stability of garnet-based phosphors is shown in Figure 3.30 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 3.30 The quantum efficiency of a typical garnet phosphor (left) and nitride phosphor (right) are shown as a function of temperature and optical power density. [101] 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. [102] 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. [103]

As SSL sources for high luminance lighting moves to even higher optical power densities, such as with laser lighting, the photothermal degradation of the downconverters 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.

Phosphor encapsulant materials could also be improved to increase LED efficiency and enable higher temperature and therefore higher flux density/luminance/brightness operation. Existing silicone formulations have exceptional long-term stability considering the extreme temperature and blue photon flux levels they experience. They are also highly transparent, minimizing optical losses. However, increasing the index of refraction of the silicone could enable additional optical efficiency of the LED package and increasing thermal conductivity could enable higher temperature operation for the LED. The DOE SSL Program has funded several R&D projects to pursue these improvements which have demonstrated some success, but it has proven challenging to make advancements in these areas of silicone performance without degrading existing transparency and stability.

3.2.1.4 Novel Source Architectures

Beyond and building off the R&D directions described above, there is an intriguing possibility of radically new LED system architectures that provide further improved efficiency, advanced embedded functionality, and new manufacturing prospects. The concept is functional, integrated LED lighting systems fully fabricated with automated semiconductor production processes. The on-chip LED systems could include arrays of LEDs of different colors to enable color tuning and optical control as well as integrated power conversion, control, and communications electronics fabricated using advanced semiconductor production technologies. This concept builds off of advancements to mini-and micro-LED understanding and manufacturing techniques, advanced silicon semiconductor processing, and new and proliferating optoelectronic applications such as LIDAR. The technical and materials challenges with such a concept are significant. Integration of different color emitters, either direct or phosphor converted is an existing challenge. Integrating power, control, and communication electronics at the chip level is also a significant challenge. This approach would move advanced aspects of luminaire functionality to the LED package or chip level. The benefits of such an approach would be improved manufacturability with highly scalable semiconductor manufacturing processes, customizable functionality that could be produced on-demand, improved system efficiency, and a broader range of lighting fixture form factors and building integration concepts.

3.2.2 OLED Sources

3.2.2.1 OLED Emitters

With OLEDs, light is created within thin organic layers by the formation of excitons through electron-hole recombination and emission of radiation. A typical structure for the stack of organic layers is shown in below in Figure 3.31.

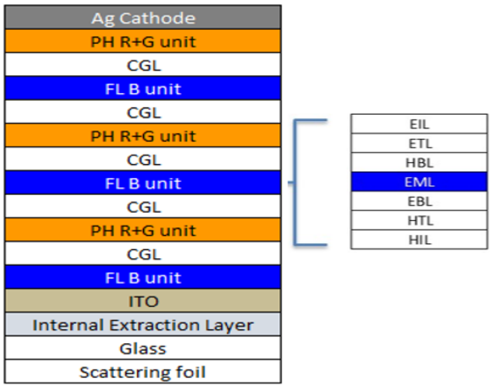


Figure 3.31 A typical structure used in the stack of organic materials for OLED lighting panels with six emitter units labeled PH R+G for phosphorescent red and green or FL B for fluorescent blue, each of which has multiple layers . Charge generation layers (CGL) provide for electron and hole charge transport between the emitter units. At the top of the figure there is a reflective silver cathode and at the bottom a transparent indium tin oxide (ITO) anode. Below the ITO, in the figure, is a light extraction layer to improve light extraction efficiency, glass, and a scattering foil to further improve light extraction efficiency.

Multiple emitter layers are used to reduce the current density needed to achieve the desired light output and extend the operating lifetime.

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. In addition to directly improving blue phosphorescent materials, attempts are underway to harness the triplet energy through thermally activated delayed fluorescence (TADF) and hyper-fluorescence (HF). With TADF, molecules are chosen that have very small energy gap between the singlet and triplet excited states, so that thermal energy is enough to lead to transitions from the triplets to the singlets. In HF, a second fluorescent material is added, so that the energy can be transferred between the two dopants.

The HF approach leads to a narrower blue emission peak and so is favored in display applications. The wider peak in TADF emitters may be acceptable in lighting. However, the lifetime of both forms of blue emitters is still inadequate, at around 250 hours for LT95 from an initial luminance of 1000 cd/m^2. [104] [105] For comparison, the corresponding lifetime of pure fluorescent emitters is around 800 hours. [106]

One approach to greater stability is to reduce the radiative lifetime of triplet excitations to below 1 µs which reduces the opportunity for non-radiative events. Current phosphorescent and TADF emitters emit within 1-10 µs. The University of Southern California OLED chemistry research group has shown that exploitation of inter-ligand charge transfer, rather than metal–ligand charge transfer can reduce emission lifetime to less than 100ns in some Cu, Ag and Au compounds. [107] They believe that new host and transport materials will be needed to exploit this discovery in more stable blue OLED stacks.

One of the loss mechanisms for photons created in thin OLEDs is the excitation of surface plasmons, which are collective oscillations of electrons near the surface of a metal at the interface with a dielectric layer. This typically occurs at the cathode-organic interface shown at the top of Figure 3.31. It has been pointed out that such energy transfer can reduce the lifetime of triplet excitations, but this is only beneficial if this is a radiative recombination lifetime. [108] If the energy can be fed back into photons through the formation of a resonant optical cavity, the overall effect might be to enhance light emission, rather than to reduce it. Although this application of plasmonic effects was initially tested in top-emitting devices for displays, it could perhaps be adapted to down-emitting OLEDs in general lighting.

The relatively broad peak in red OLED emitters leads to the production of infra-red light that provides little benefit in general lighting and reduces the luminous efficacy of radiation of white light devices but does enable good red color quality. A narrower phosphorescent emitter has been developed for automobile lighting, with a FWHM of 43nm and peak near 640nm. [109] A similar red emitter with a peak near 625nm would be beneficial for general illumination applications.

Although the efficiency and stability of green phosphorescent emitters are sufficient for multi-stack OLED devices, longer operation lifetime at high current density is needed to allow a reduction in the number of emission layers and simplify OLED device structures. Universal Display Corporation has developed a new green emitter for automotive applications peaking at 545nm with a FWHM of 71nm, with LT95 of 300,000 hours from 1000 cd/m^2. [110] This luminance can be achieved with a current density of 1.1 mA/cm^2. If the current density is raised to 10 mA/cm^2, the LT95 lifetime falls to 7000 hours.

To optimize the efficiency and stability of OLED emitters, matching the transport layers to the dopant and hosts in the emissive layer is essential. Electron injection layers (EIL) and hole injection layers (HIL) are used to facilitate the emission of charge from the cathode and anode. Electron transport layers (ETL) and hole transport layers (HTL) then ensure a balanced supply of electrons and holes to the emission layers (EML), where they form excitons and then photons. Electron blocking layers (EBL) and hole blocking layers (HBL) are usually added to make sure that the electrons and holes do not traverse the emission layers rather than forming excitons. Controlling the interaction between the various layers is essential. [111]

Charge generation units are required in devices with more than one emission region. These often involve combinations of the materials used in the injection and transport layers. Since the light that is created in the emission layers may have to cross the transport and charge generation layers several times, reduction in photon absorption in those layers is critical.

3.2.2.2 OLED Materials

Conventional organic stacks have an effective refractive index of around 1.7. Light generated by the organic emission layers must pass through the organic-glass optical interface and then the glass-air interface in order to be useful. Only photons that are emitted in a narrow cone around the normal direction can escape directly and even many of these are reflected back into the organic stack. Laterally emitted photons may become waveguided within the organic stack and photons emitted toward the cathode may incur reflectance losses. In planar OLED devices about 80% of the photons generated by the organic emitters are trapped within the device reducing the efficiency of the OLED. Several methods are under investigation to increase the fraction of light that can escape.

Typical approaches to improve light extraction efficiency are to insert a buffer dielectric layer between the silver cathode and the organic stack to reduce plasmonic effects. Internal optical scattering layers can also be used to reduce waveguide of light within the organic stack and redirect light into the extraction cone. Finally, an additional scattering layer can be used on the glass substrate to reduce waveguiding within the glass and redirect light into the glass extraction cone.

A new approach that is being considered is to align the molecules so that the electric dipole is in the plane of the device and more of the photons are emitted in a direction close to the normal. Early experiments with polymer OLEDs showed that the preferred orientation of long polymer chains along the panel surface could lead to an increased proportion of light generated normal to the OLED plane resulting in a higher proportion of light that can escape from the organic stack. Recent experiments have observed similar effects in small molecule phosphorescent emitters. [112] Other studies have shown that control of orientation during film deposition can also have beneficial effects on charge balance. [113]

A more radical approach is aimed to remove the major cause of the problem by lowering the refractive index of the organic stack. Researchers at Pennsylvania State University have observed that electron and hole transport is filamentary, as shown in Figure 3.32. [114]

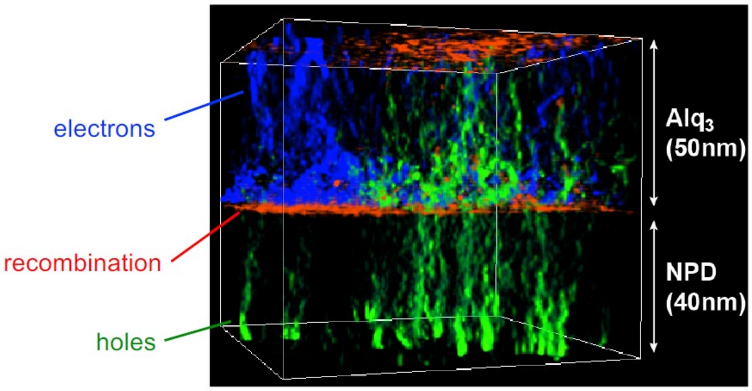


Figure 3.32 Percolative transport of electrons and holes in an OLED stack, involving less than 5% of the molecules [114]

This observation suggests that it may be possible to dilute the transport layers with molecules that reduce the refractive index. The challenge is to do this without disturbing the major function of these layers, which is to supply a balanced supply of charge to the recombination region with minimal drive voltage. Trials at OLEDWorks with an organic stack similar to that used in commercial panels confirm that dilution of the transport layers can indeed increase the amount of emitted light, as shown in Figure 3.33.

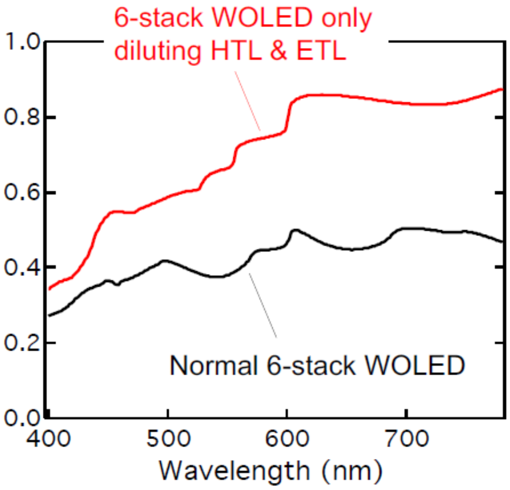


Figure 3.33 Relative light output from a multi-layer stack with diluted hole- and electron-transport layers [114]

The gain in this case is more effective for the red portion of the spectrum than for the blue. This is common for many extraction enhancement procedures.

In many OLED displays, the sub-pixels that produce red, blue, and green light have different stack structures. This means that micro-cavity effects can be used to enhance the emission of each color since micro-cavity designs depend on the wavelength of light emission. There has been considerable debate as to the extent to which microcavity effects can be effective in the production of white light for general illumination which includes a broad range of wavelengths and which requires a consistent color mix at all optical distribution angles. Micro-cavity device structures are engineered for a specific wavelength and different wavelengths would have preferential emission at different angles resulting in different color emission based on the viewing angle of the light which is generally considered undesirable. Experience with light extraction enhancement techniques suggest that it may be fruitful to use cavity effects to favor blue emission and scattering particles to suppress any angular variations.

3.2.2.3 Electroluminescent Quantum Dot Emitters

ELQDs are being considered as an alternative to organic emitter materials. They would have similar brightness and could leverage existing OLED device structure, including charge transport layer understanding and light extraction techniques. Although QDs have recently been used in down-conversion of blue light in displays and LED packages, they were originally proposed as alternative photon sources through electroluminescence. The efficiency in which current can be converted into light has increased substantially in the last decade, as shown in Figure 3.34.

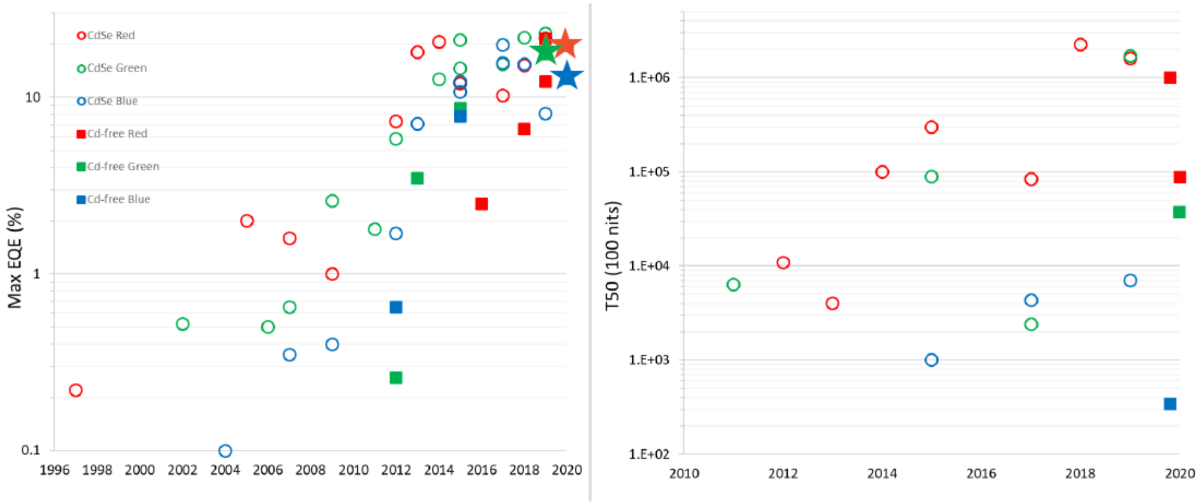


Figure 3.34 Improvements between 1996 and 2019 in the external quantum efficiency and time for the luminance from ELQD devices to decay to 50% from an initial value of 100 cd/m². Results for cadmium- containing materials are shown as open circles and those from cadmium-free materials are shown as solid symbols. Stars indicate most recent results, which are also Cadmium-free. [115]

The best results have been obtained with QDs containing cadmium, which has raised concerns about the environmental impact of using cadmium, considered a toxic heavy metal. Although the amount of cadmium used can be reduced to meet the current ROHS standards, the industry is determined to develop cadmium-free alternatives. The data in Figure 3.34 shows that the gap in EQE has almost disappeared, however there is still a substantial deficiency in the stability of cadmium free quantum dots.

Care must be taken in interpreting data on operational lifetime. Values are often expressed in terms of L50 (T50 in the figure) from 100 cd/m^2. These values need to be reduced by a factor of around 100 to estimate the values of L70 from 1000 cd/m^2, which is commonly used in specification for OLED lighting.

As with OLEDs, stability of blue emitters represents the major challenge. Efficient blue emission has been demonstrated using quantum dots with a ZnSe core, but the peak at 429nm is on the very edge of the visible spectrum. [116] The peak can be moved to ~455nm by doping with tellurium. [117] [118] These devices appear to be much more stable than the CD-free blue material cited in Figure 3.34. [115] Researchers in Korea have reported a value of LT50 of 442 hours from 650 cd/m^2, which scales to over 10,000 hours from 100 cd/m^2. [118] Commercial suppliers in the US have also reported very encouraging results on stability. [115]

One of the potential advantages of using quantum dots rather than OLEDs is that the structures might be simpler and more amenable to printing methods. However, it is still essential to ensure a balanced injection of electrons and holes and to match the emission and transport layers. [119] For example, charge carrier imbalance in ELQDs may arise from large energy barriers to hole injection into the emission layer and relatively faster electron transport rates in inorganic ETLs than in organic HTLs. It is also not clear that ELQDs will enable improvement of light extraction limitations inherent with the planar OLED device structure. OLED emitters are currently much more efficient and mature than ELQD emitters for lighting application. There is the possibility that ELQDs could provide an advancement in certain aspects of performance or cost compared to OLEDs, but any advancements need to be achieved without degrading other aspects of device performance, such as lifetime or color quality.

3.2.2.4 OLED Panel structures

The typical structure of an OLED lighting panel is shown in Figure 3.35. This conformable panel is manufactured on ultra-thin glass, allowing bending with a radius of curvature down to 10 cm.

Figure 3.35 The structure of a conformable OLED lighting panel made on ultra-thin glass. The organic layers are encapsulated to prevent the ingress of water and oxygen while allowing the supply of current through flexible electrical contacts. [120]

OLED Substrates

Alkali-free glass has been the substrate of choice for rigid OLED panels, typically with thickness of 0.7mm. Ultra-thin glass sheets with thickness less than 0.2mm are used in the formation of conformable panels. OLED display panels with greater flexibility have been manufactured on plastic substrates, mainly on clear polyimide. The plastic sheets are attached to a rigid substrate during fabrication and lifted off after processing. The high cost of the polyimide material and of the extra processing steps makes this approach unattractive for lighting applications.

Plastic substrates also require an effective barrier against the permeation of water and oxygen. Although inorganic materials are available with very low intrinsic porosity, the major challenge is to prevent local ingress cause by pinholes or particulate contamination. As described in the MSO, the preferred method is to use multiple layers with alternating hard and soft layers. [11] Hybrid combinations of inorganic and organic materials have been successful in OLED displays but also seem to be too expensive for lighting.

Light Extraction

The traditional approach to solving this problem is to scatter or deflect the light, through external extraction layers (EEL) on the outside of the substrate or internal extraction layers (IEL) between the substrate and the anode.

One of the simpler ways to form an IEL is to insert a polymer layer of refractive index between that of the anode and substrate with embedded scattering particles, as shown in Figure 3.36.

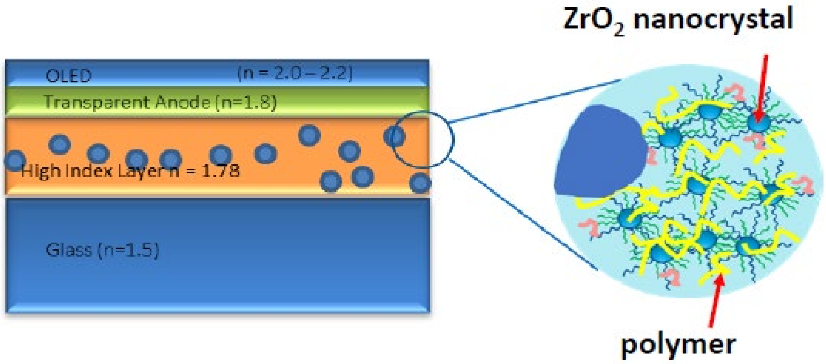
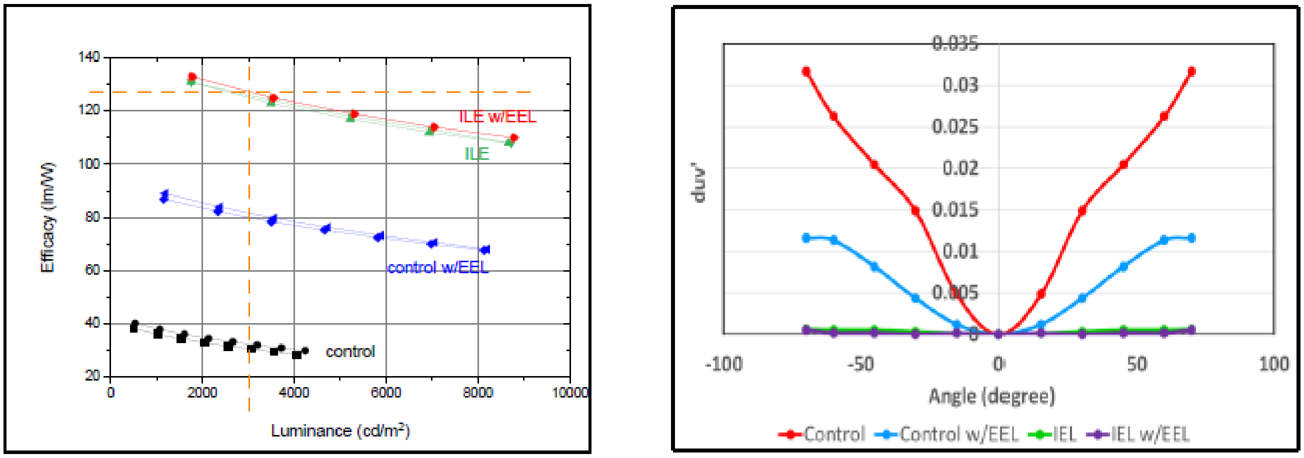


Figure 3.36 Internal light extraction layer with nanocrystals to tailor the refractive index and larger particles to scatter light [121]

Figure 3.37 shows that this method can lead to a substantial increase in panel efficacy and eliminate observable color shifts with the angle of emission.



(a)

(b)

Figure 3.37 Effect of internal scattering layer using index matching and scattering particles: (a) Increase in panel efficiency, (b) Reduction in color shifts with angle of emission as measure from changes in the CIE (u', v') color coordinates [120]

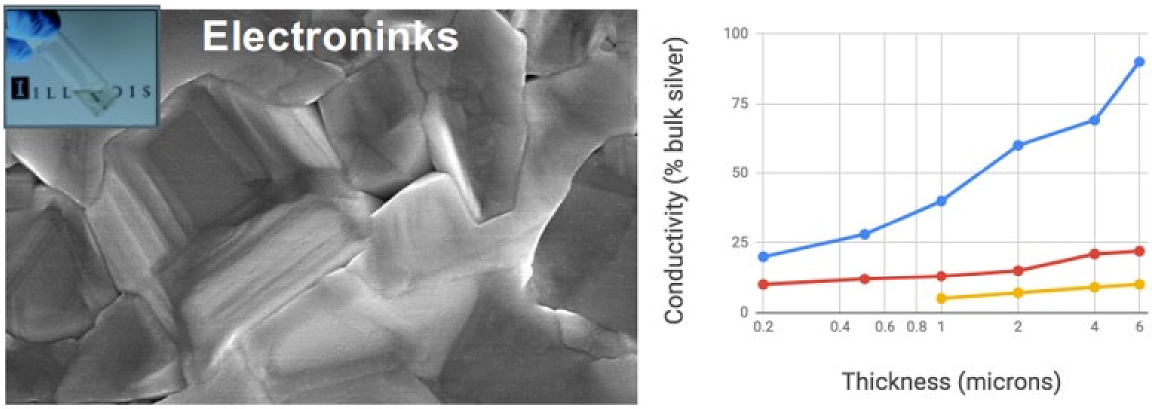
An alternative approach to light extraction layers is to break the planar symmetry by inserting structures that deflect the light towards the normal. These can be micro-lens arrays or corrugated substrates. Encouraging results have been obtained in laboratory experiments, but none have yet been deployed in commercial production. [122] [123] [124]The structure and fabrication of these layers is described in more detail in the MSO.

Electrodes

Despite many years of research into alternative transparent conductors. indium tin oxide (ITO) is still preferred anode for OLEDs and is adequate for small panels on glass. However, the quality of ITO films is dependent on the temperature at which it is deposited and degrades significantly if formed on plastic substrates. Many laboratory experiments have shown that silver nanowires can be deposited by printing at low temperature and give results as good as the best ITO, with sheet resistance below 10 Ω/square and optical transmittance over 80%. [125] [126] However, concern about roughness has inhibited adoption in commercial OLED panels and a smoothing layer may be necessary to avoid shorting.

Lower sheet resistance will be needed for larger panels or for OLEDs with fewer emission layers requiring higher current densities. Much lower sheet resistance can be attained by using metal grids supplemented by sheets of ITO, PEDOT or Ag nanowires. [127] This approach was used in early OLED products by LG Chemical and Osram. Recent experiments have shown that it can be accomplished in corrugated substrates. [128]

The simplest way to form a wire grid is to deposit a uniform layer of solid metal and remove the unwanted material by photolithography and plasma etching. This means that most of the material needs to be recycled. Printing the mesh directly would seem to be a better approach, but the conductivity of most links is much less than that of solid metals. However, particle-less inks are now available that enable conductivity close to that of bulk metal, as shown in Figure 3.38. [129] [130] Several examples of grids with sheet resistance <1 ohm/square and over 90% transmission have been reported.



(a) (b)

Figure 3.38 Particle free inks: (a) micro-structure; (b) comparison of conductivity of different forms of metal inks particle-free ink nanoparticle ink flake paste [128]

The most important characteristics of the cathode are its work function and its reflectivity. OLEDWorks has recently introduced silver cathodes to replace the tradition aluminum. As shown in Figure 3.39, the reflectance of Ag is higher than that of Al over most of the visible spectrum, but not at wavelengths less than 500nm.

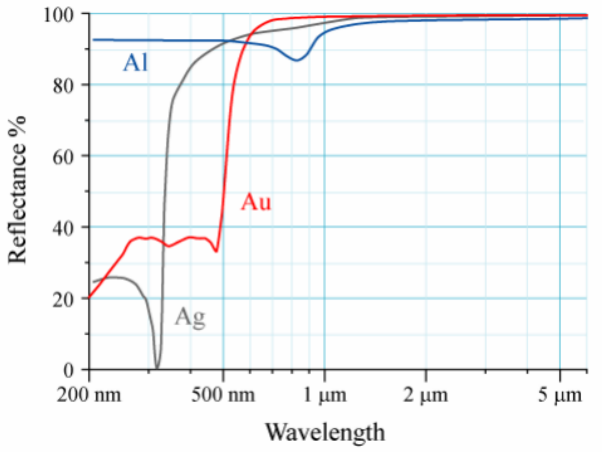


Figure 3.39 Reflectance of aluminum, gold, and silver. [131]

Encapsulation

Ingress of water and oxygen must be prevented through the top and bottom surfaces as well as through the edges of the panels. The barriers that are currently used for surface protection involve alternating inorganic/organic layers. The inorganic films are deposited by plasma-enhanced chemical vapor deposition (PECVD). The necessary equipment requires high maintenance and is very expensive for large substrates. The organic layers by are formed by printing techniques such as slot-die coating or ink-jet printing. This requires a transition from a vacuum chamber to a nitrogen environment. Simpler approaches have been suggested, but their implementation brings difficult manufacturing challenges. [11]

3.2.3 Optical Delivery Efficiency

Significant energy reduction gains are still possible through the optimization of light delivery and light distribution. While improving the LED source efficiency has been a strong focus in the LED industry, how that light is delivered to the lighting application is equally as important. Advances in optical delivery are needed to use light most efficaciously for the application at hand. Understanding the application needs from both a visual acuity perspective, as well as the non-visual benefits, is essential to know how to best deliver the ideal light. Improvement in the optical delivery from the source to the user can enable tailoring the optical distribution for the application while minimizing light that does not contribute to the application. Light intensity distributions that can be engineered in space and time and would reduce the over-illumination and under-illumination of spaces and spectral regions. [132] Such engineered light could thus simultaneously reduce energy use and improve the effectiveness of lighting. All lighting applications would benefit from improvements to optical delivery efficiency which enables effective use of a higher proportion of photons generated by light fixtures. Benefits have already been demonstrated with roadway lighting and retail lighting.

In order to ensure that application efficiency is targeted, different metrics must be considered beyond simply luminous efficacy. It is important to consider the effectiveness of the placement of delivered light for the application. To understand the most effective light for the application, it is important to determine the ideal light pattern required. From there, the luminaire can be designed to deliver an optical distribution designed for the ideal light pattern. This requires a system level optimization since a more efficient source may not deliver the most efficiently generated light pattern the application requires.

This concept is exemplified by the specific example for an automotive welcome lamp illustrated in Figure 3.40. [133] The automotive mirror light is illustrated alongside its ideal light pattern in Figure 3.40. In this particular case, the ideal lighting pattern requires 7.2 lumens to meet the illuminance for the application. A traditional design is illustrated in Figure 3.40 panel (c), whereas an optimized optical delivery design is shown in panel (d). The traditional optics design for the application does not match the ideal light pattern very well; though the LED is producing a high lumen output, those lumens are not all ‘useful’ lumens since they do not contribute as effectively to the target light pattern (only 12 lm/W useful efficacy). Additionally, the uniformity of the light pattern generated does not match the ideal pattern for the application, so regions are over-lit (center) and under-lit (edges). The normalized uniformity – the normalized actual light pattern against the ideal pattern – is fairly low at 12%. If the optical delivery is redesigned to meet the ideal light pattern, a lower power LED can generate the needed lumen output at a higher ‘useful’ efficacy (32 lm/W) while drastically improving the normalized uniformity to 91%.

Improved lighting application efficiency, enabled by developing better optical control, can produce a better lighting solution while consuming less energy. Development efforts that can help enable these gains include studies to determine the ideal light patterns for common spaces and advancements to light sources, optics, and fixtures to produce these ideal light patterns. Moreover, developing a fixture that can be configured in to produce various ideal light patterns provides flexibility in the lighting applications and reconfiguration of the space. Reassessing the metrics of rating efficiency to consider factors such as ‘useful’ light and ‘useful’ efficiency can help ensure the best quality light is provided to the end user in the most energy efficient manner.

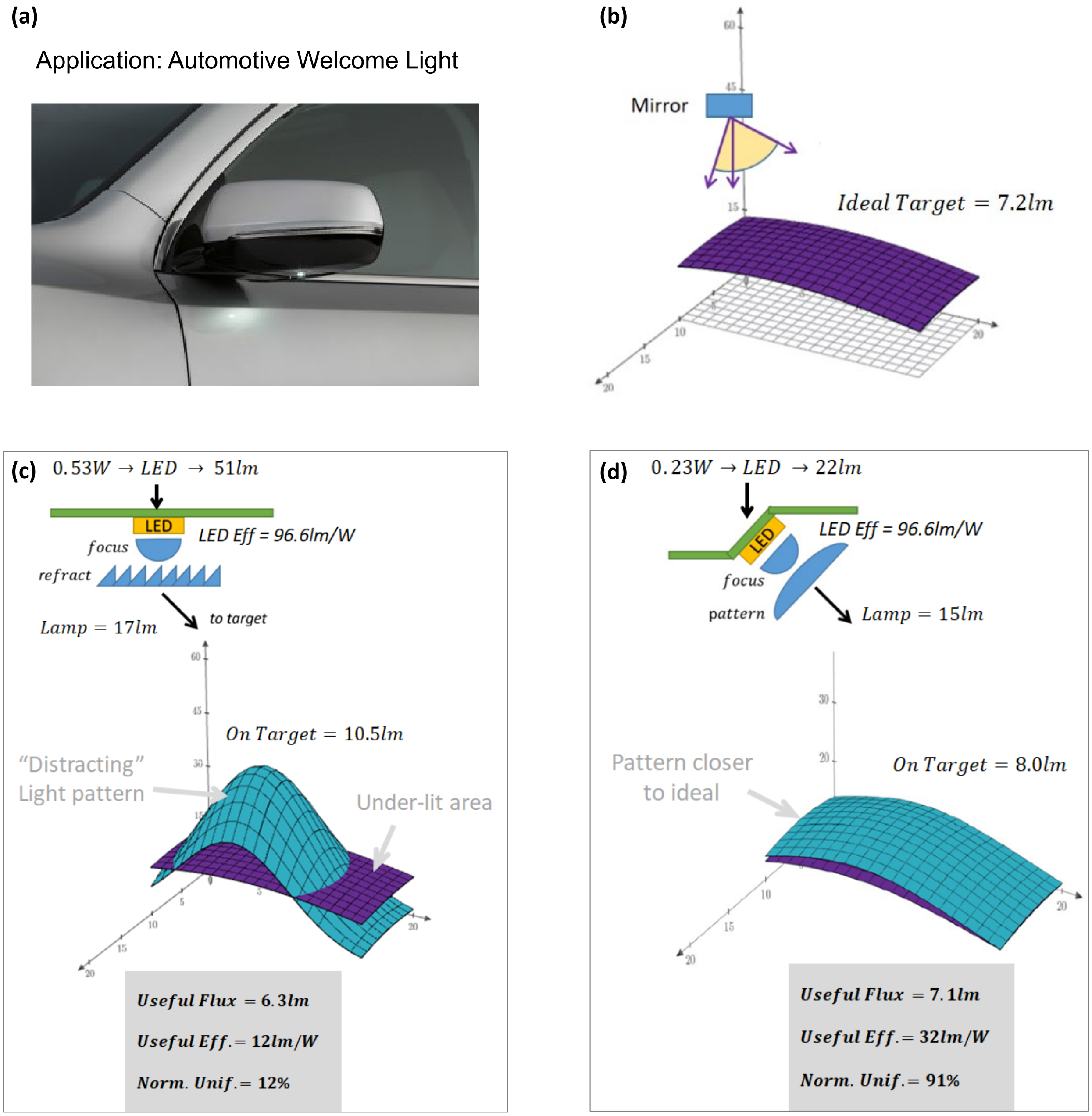


Figure 3.40 Example case study of how improved optical control in an automotive mirror light (a) can lead to better lighting performance at lower energy consumption. The ideal illumination pattern for this application is illustrated in (b). Panel (c) shows the conventional LED optics solution and the resulting light pattern compared to the ideal pattern. Panel (d) shows the optimized optical delivery solution providing a much closer match in light pattern to the ideal, while improving the 'useful' flux and efficacy while utilizing half the input power from the LED. [133]

Optical delivery efficiency can be improved through tailored, controlled, and/or dynamic optical distributions. Improved illuminance and resulting optical control can be designed into a static or configurable lighting product that is installed in a space. Actively, optically controllable lights can deliver light to the targeted areas in a space. Figure 3.41 illustrates some of the different optical delivery approaches. These latest approaches for active optical control of lighting will be discussed in the following sections.

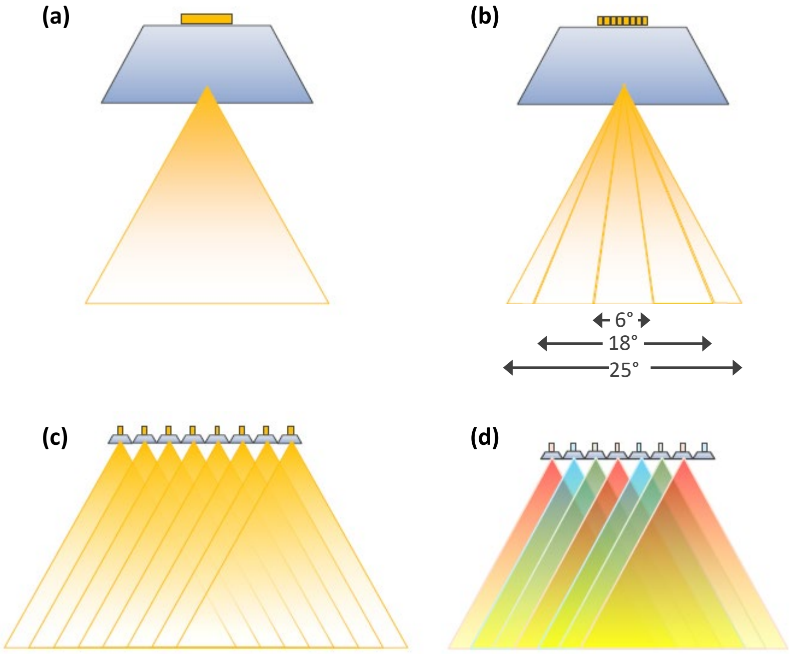


Figure 3.41 Illustrations of different approaches to optical control. A conventional static lens (a) is the traditional solution with a fixed beam angle or illumination pattern. New dynamic lenses can allow for changing the beam spread dynamically (b) by using liquid crystal electro-optic technology. Projection optics using many overlapping LEDs can enable more optical distribution patterns (c) and also allow for further spectral tuning along with the optical tuning (d). [83]

3.2.3.1 Steerable 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. [134]

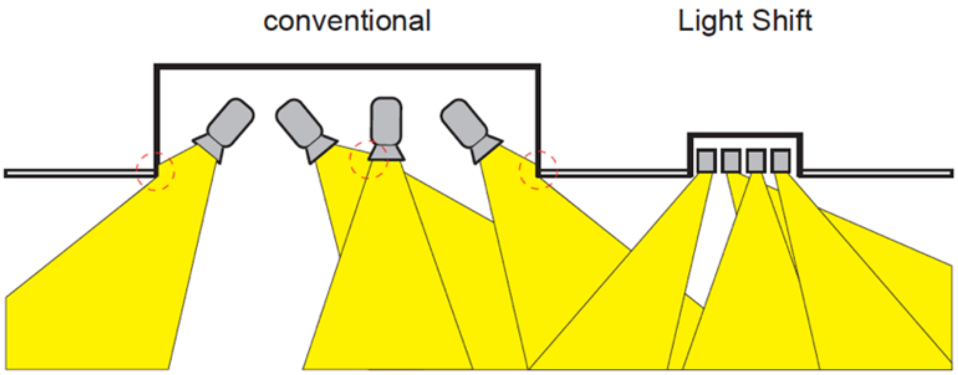


Figure 3.42 Schematic illustration of a matrix of single beams, steered using (left) conventional technologies versus (right) advanced and physically stationary “light shift” technologies. [134] The image on the right shows how steerable LED lights can have much smaller volume while effectively covering the lighted area.

For shaping and steering light, new technologies based on liquid crystal electro-optics have also been demonstrated. [135] 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. The controllable lens is place above the conventional directional optics, as shown in Figure 3.43, and can create a beam angle range of less than 10 and greater than 50 degrees.

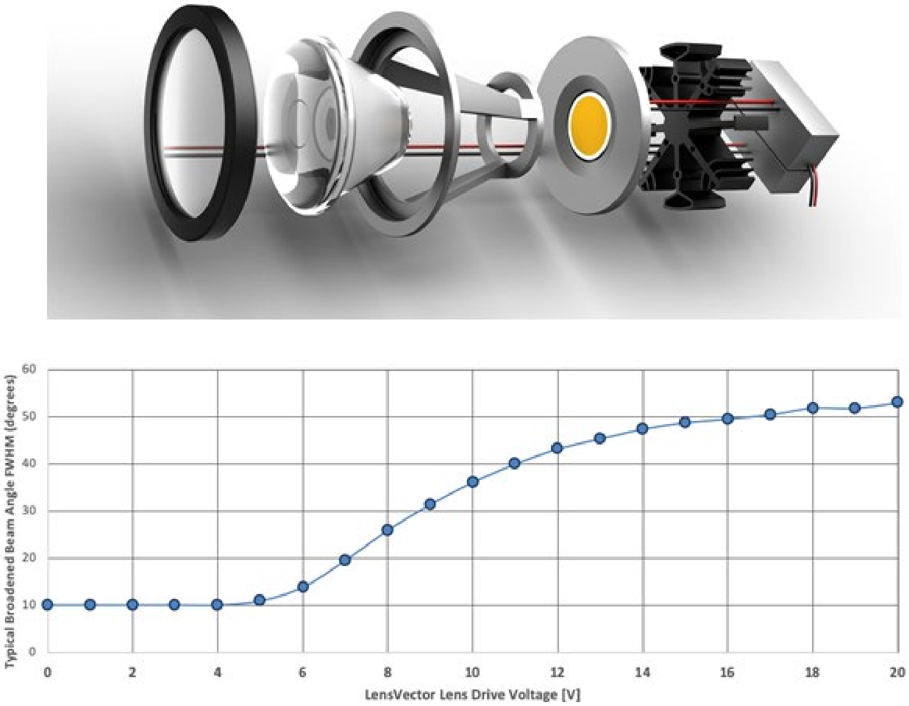


Figure 3.43 A schematic of a controllable lens integrated in a directional lamp (top). The liquid crystal molecules in the lens are oriented with an applied voltage which changes the beam angle between 10 to 50 degrees (bottom). [136]

3.2.3.2 High Luminance Sources

Source etendue is critical for optical control. The smaller and brighter 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 (the luminous flux per unit area emitted from a surface expressed in units of lm/mm^2). Typically, driving LEDs harder results in a lower source efficiency or luminous efficacy (due to current density droop), so there is a trade-off between efficacy and luminous emittance, and hence optical control. Figure 3.44 shows this trade-off by comparing the luminous emittance to LED efficacy for high-power and high luminance LEDs.

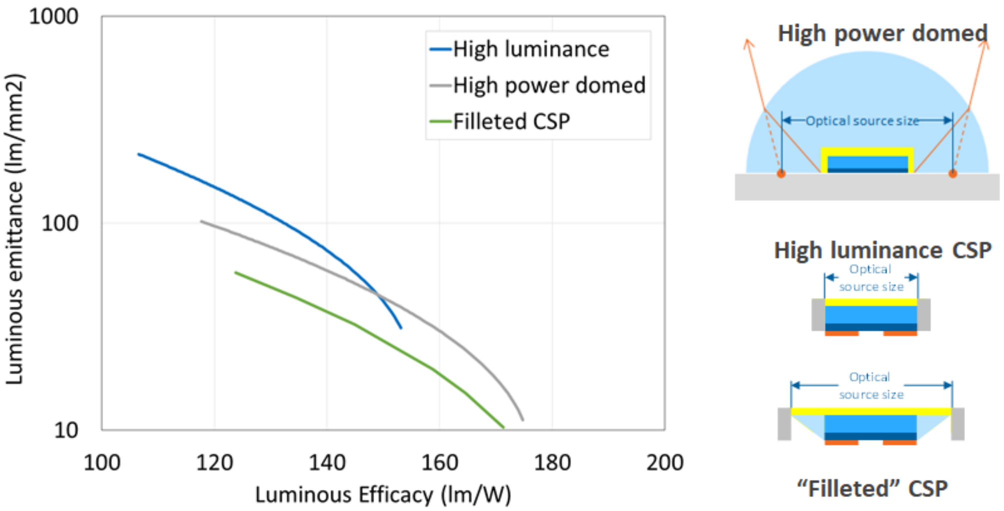


Figure 3.44 The luminous emittance as a function of luminous efficacy for three different LED package styles. The smaller optical source size of the high luminance CSP LED provides higher luminous emittance than the high-power domed LEDs but have a lower efficacy over its operating range. [137]

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. Figure 3.45 shows the impact the optical source size can have on the light delivery into the application. The flat lens high luminance LED design delivers a narrower beam with a 2.5x higher center beam candle power than the high-power domed LED, thus creating more light into the beam angle and providing a higher application efficiency.

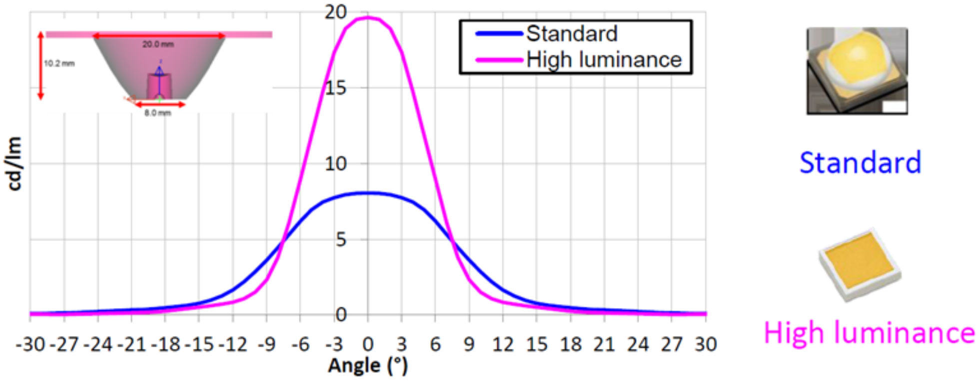


Figure 3.45 Comparison of the center beam candle power (in cd/lm) for a standard domed LED package to a flat lens high luminance LED package results in a 2.5x improvement into a 12 degree beam. While the package efficacy is lower, the delivered light into the application is higher with the high luminance LED. [83]

Further R&D is needed for high luminance sources in the following areas:

- LED efficiency droop to reduce the efficacy-luminance trade-off (Subsection on Current Density Droop in Section 3.2.1.1),
- Down-converter materials efficiency and stability at high luminance (Subsection on Wavelength Downconversion in Section 3.2.1.3)
- Packaging materials improvement to prevent degradation at higher optical flux densities and temperatures (Section 3.2.1.3),

- Optical design for angular uniformity of color.

3.2.3.3 Metasurfaces

New engineered materials such as metasurfaces have promise for beam shaping and steering. While conventional optics use light refraction and propagation, metasurfaces manipulate light via scattering from small nanostructures. [138] Metasurfaces are arrays of subwavelength optical elements, or metaatoms, that are fashioned to produce phase or amplitude changes to an incident wave front. Dynamic tuning of the metasurface can be achieved by using an external stimuli to alter the size, shape, and distance between metaatoms by using an electric field, electrostatic force, optical tuning (plasmonics), or manipulating optical nonlinearity (Mie resonators). This tuning can be designed to deflect the optical beam or change the beam shape. The metasurfaces are created by nanopatterning the surface of a semiconductor, dielectric, or thin metal layer using standard lithographic techniques common in the semiconductor industry. These very small features allow the development of flat, thin optics for design flexibility not available with conventional bulky optics.

One example of using tunable metasufaces for beam steering has occurred in light detection and ranging (LiDAR) research combining the metasurface with liquid crystals where a change in voltage across the metasurface (optical antennas) steer the beam to the angle determined by the spatial frequency of the phase-modulation pattern applied to the array of tunable resonators. [139] Metasurfaces have also been shown to behave as nonlinear beam deflectors and vortex beam generators, as seen in Figure 3.46. [140]

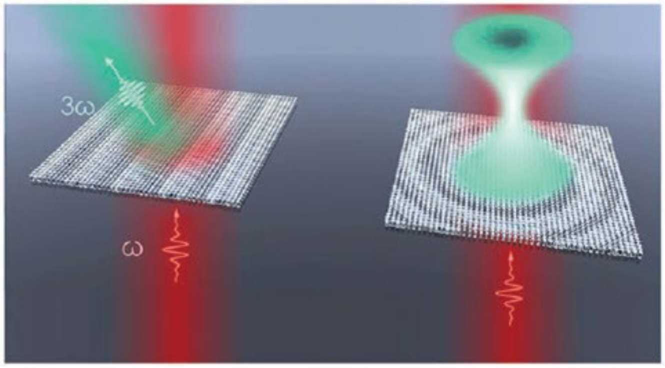


Figure 3.46 Silicon metasurfaces can be designed to act as beam deflectors and vortex beam generators through wavefront control. [140]

Metasurfaces integration into LED devices has been researched in an effort to alter the emission pattern and create directional light sources on chip without the use of external lenses. [141] The challenge faced by researchers was the Lambertian emission profile from the standard LED has a low spatial coherence, which is a hindrance if the metasurface and the LED source are placed in close proximity for compact integration. Therefore, the successful integration of metasurface devices on the LED required further beam narrowing in the LED structure achieved by implementing a resonant cavity LED. This allowed control of the directionality and/or polarization of the emitted light with the metasurface, as illustrated in Figure 3.47, though full wavefront control was not achieved. While metasurfaces is a new and promising area of optical control, further R&D is required for better optical control of LED devices for particular use in lighting applications.

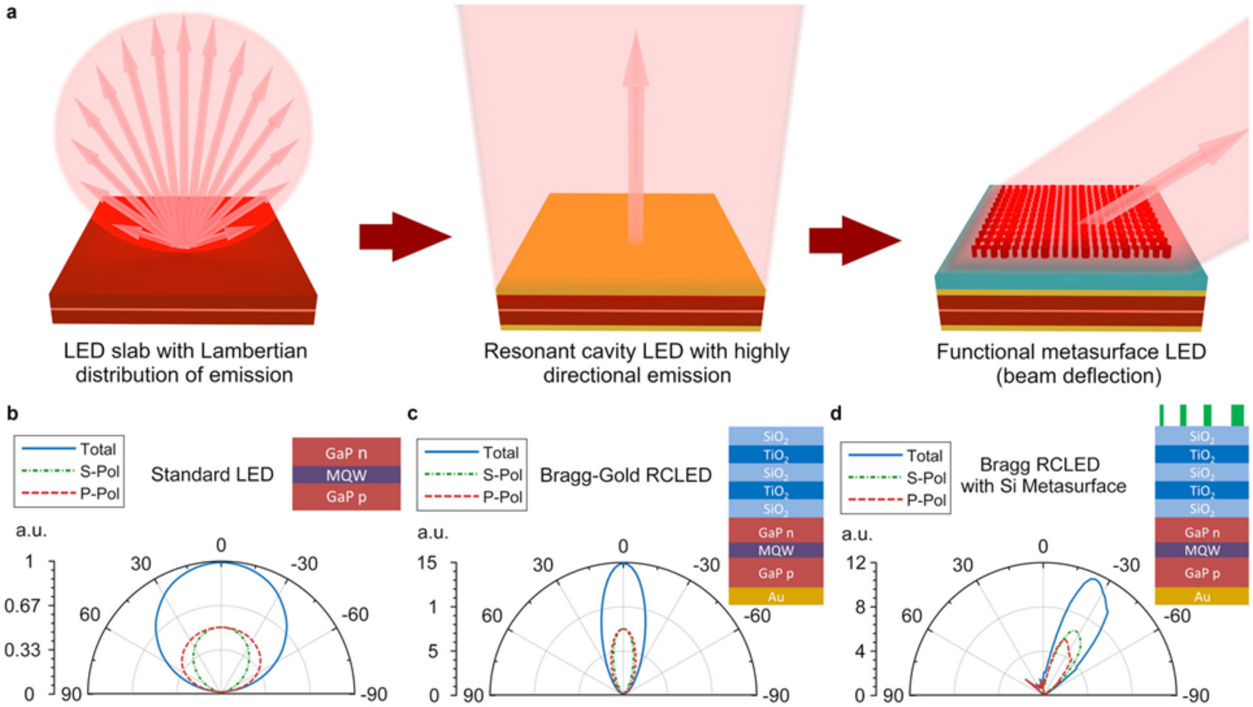


Figure 3.47 (a) Illustration of the Lambertian distribution of the standard LED structure and the directional emission of a resonant cavity LED compared to the beam deflection enabled by a metasurface LED. The optical distribution in (b), (c) and (d) for the standard LED, resonant cavity LED, and metasurface LED, respectively, shows the narrowing beam by the resonant cavity and offset angle created by the metasurface (the device structures are inset). [141]

3.2.3.4 Pixelated Light Source

Creating a dynamic light source will require a high-density array of individually addressable LEDs. A pixelated light source makes use of multiple beams, each originating from a different LED “pixel” element, that can be 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. This pixilation can be at “macro” or “micro” levels.

Initially this pixelated approach was demonstrated at a macro level, with multiple discrete LED packages (“macro-pixels”) placed in a fixture or on a PC board to be independently focused and directed. An early demonstration of this was Osram’s OmniPoint product in which 61 individually controllable LEDs were mounted in a fixture and controlled to ‘steer’ the beam to highlight specific regions of the lighted area. [142] 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 discrete LED pixels provide both vertical and horizontal segmentation for “Adaptive Driving Beam” (ADB) control. [143] 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. Development into a higher pixel density digital beam headlight allows for a higher resolution. The different generations of ADB headlights are compared in Figure 3.48.

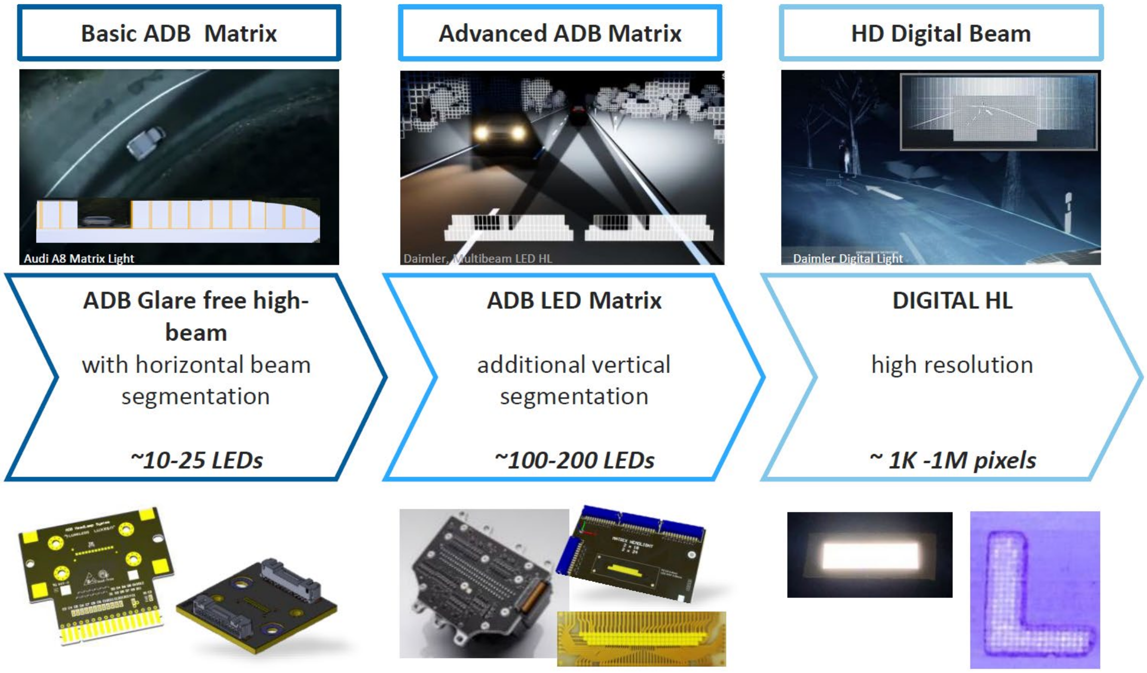


Figure 3.48 Comparison of different generations of adaptive driving beam (ADB) headlights showing in the improving resolution with increasing pixel density. [83]

This pixelated light source concept can be carried out at a micro level, by utilizing an array of micro-LEDs, each with an area on the order of 50 x 50 μm^2 or less. The closely spaced micro-LEDs (each emitting directional light) can be directly addressable resulting in a highly pixelated directly imageable source. This dense individually addressable pixelated array can ‘steer’ the beam to highlight specific regions of the lighted area, just as with the macro-pixel approach. Figure 3.49 shows a schematic of a luminaire with an array of micro-LEDs and how the pixels can be controlled to create different optical distributions in the room. Micro-LEDs can provide the required resolution for the desired spatial control and spectral tuning. Additionally, the compact form factor pixelated light source can offer the lighting of any surface from any angle with any illuminance and spectrum, which is ideal for lighting application efficiency. This can lead to a paradigm shift that allows lighting to be designed by its features instead of its fixture type or form factor.

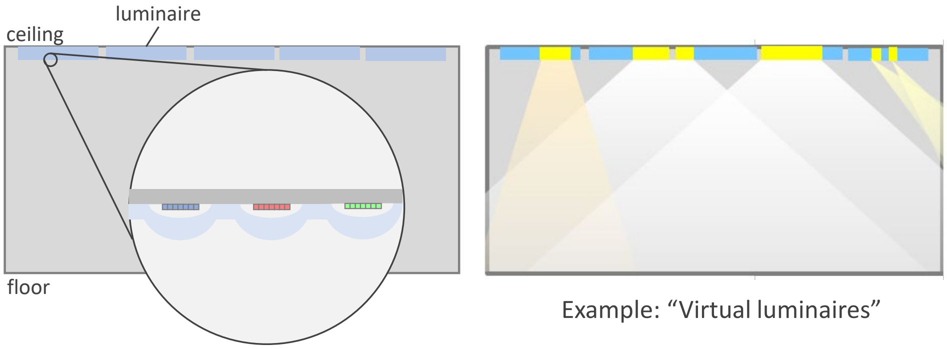


Figure 3.49 Illustration of implementation of pixelated lighting source in luminaire fixtures (left) and the beam steering that can be attained by controlling the pixels (right). [144]

R&D in supporting technologies needs to be developed to realize the pixelated lighting source. These areas include improving the mini/micro-LED efficiencies, and reducing the size of down-converters to work with the miniaturized die sizes. New scalable optics should be designed to provide a variety of beam angles and optical distributions from these miniaturized LEDs at high optical efficiency with good visual comfort. Electronics for driving a large array of adaptive pixels must be developed by considering integrated drivers and backplane integration. Lastly, sensors and controls algorithms should support system level design and interaction with the space to allow for the right dynamic functions over time.

In the long run, these pixelated light sources 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.

3.2.4 Intensity Control

LED and OLED lighting are inherently, instantaneously dimmable. This enables the ability to tune light intensity to achieve optimal light intensity for the intended function of the lighting system. Similar to optical delivery efficiency, which seeks to provide light at the right location, controlling light intensity can save energy and improve effectiveness of lighting. Lights can be dimmed to achieve optimal illuminance levels for the lighting function and also can be dimmed to respond to natural daylight levels and occupancy of a space. Simply put, lights on when no one is using the light wastes energy, too much light intensity for a specific lighting function is similarly wasteful, and too little light for a lighting function results in reduced benefit from the lighting.

Advanced lighting controls to optimize delivered intensity continue to gain attention as a potential method of more intelligently operating lighting systems to save energy and improve lighting performance. On a national scale, lighting controls have the potential to yield significant energy savings and the penetration of lighting controls remains relatively low despite decades of availability. Table 3.2 summarizes the 2017 installed stock penetration for each control type analyzed in the lighting market model of the most recent Energy Savings forecast. The controllability of LED technology favors the adoption of controls; however, the initial cost and other market barriers such as perceived value, complexity, and poor performance continue to inhibit adoption.

Table 3.2 2017 Installed Stock Penetration of Lighting Controls [2]

Installed Stock Penetration (%)	Commercial	Residential	Industrial	Outdoor
None	66%	86%	93%	13%
Dimmer	3%	11%	4%	4%
Daylighting	<1%	<1%	<1%	53%
Occupancy Sensor	6%	<1%	2%	17%
Timer	4%	<1%	2%	17%
Multi	4%	<1%	<1%	12%
EMS	16%	<1%	<1%	<1%
Connected	<1%	<1%	<1%	<1%

The perceived value characterizes the incentive for a builder or designer to specify the use of lighting controls. As LED technology has improved in efficiency and reduced lighting energy cost, the straightforward value of energy savings cost return on investment with controls has been reduced. However, there is still significant energy savings that can be achieved through the use of simple occupancy sensors and controls. Estimates of the energy savings achievable by occupancy sensors are often in the range of 30% to more than 50%. [145] However, commercial building sector adoption of occupancy sensors and other basic lighting controls remains low. For example, as of 2017, it was estimated that only 6% to 10% of commercial buildings are equipped with occupancy sensors, a modest change from 5% seven years earlier. [2] [146] [147] This increase was primarily due to large-scale adoption in the warehouse and storage sector between 2010 and 2015, which saw an increase from 1% to 34% during that period. [147] [148] Notably, these spaces are rarely occupied by people, and thus occupancy-sensor adoption is not necessarily indicative of user acceptability and performance in applications that typically have persistent human presence. Education and office (nonmedical) sectors, on the other hand, saw a decrease in adoption, from 9% to 8% and from 14% to 8%, respectively, evidence that historical performance issues continue to negatively influence adoption. The unrealized energy-savings potential in the commercial sector due to poor performance of installed occupancy sensors or a failure to deploy them properly is substantial. In one study, properly commissioned occupancy sensors were found to deliver an average increase of 13% in energy savings in new-construction buildings and an average increase of 16% in existing buildings, as compared to sensor performance prior to commissioning. [149] If new, easier-to-commission technology increased sensor deployment an additional 6% to 10%, the potential annual energy savings would be an additional 0.116 quads, representing a reduction in annual commercial-sector lighting-energy consumption of almost 4.5% as of 2015. [146] Occupancy sensors with breakthrough performance improvement might deliver energy savings multiple times this estimate. Occupancy sensors that are specified and commissioned in a manner more suited to their application, and that meet user expectations, could reasonably be expected to deliver greater energy savings, and thereby reduce their financial payback periods. [150]

Researchers at the Lighting Enabled Systems and Applications (LESA) Center at Rensselaer Polytechnic Institute have explored the use of color sensors as an alternative to previous work using other sensor modalities for occupancy detection, noting the limitations of common ultrasonic and passive infrared sensors, including false positives and the need for occupant motion for detection. “Whether occupants are moving or stationary, color sensors can detect the time dependent changes in reflected light SPDs caused by occupant presence and use this information to identify not only occupant presence but also localize occupants. Accurate knowledge on occupant location allows for finer control of building systems, e.g., lighting and HVAC, resulting in greater energy savings. The proposed system reacts quickly to changes in occupant state, maximizing occupant comfort and energy savings while reducing false negatives. Color sensors are also passive sensors and therefore, have low power requirements.” [151]

An increasingly appreciated value of ‘occupancy’ controls is the opportunity to dim roadway and outdoor lighting at night when there are few to no viewers, so there is little to no benefit to the lighting. The benefit with these systems is reduced energy, longer lasting lights, and reduction in light pollution, benefiting local dwellers and nocturnal wildlife, which is affected by affected by anthropogenic light at night.

Lighting sensors to adjust light levels for occupancy or activity are a mature technology. A vast array of motion, infrared, light meters, and even spectrometers and cameras exist to support the concept of occupancy controls, dimming, and daylight responsiveness. Sensor technology and light source dimmability is not a fundamental barrier to the increased use of intensity control. Often, the perceived value of controlled lighting system to optimize intensity (dimming) is limited by complexity of the dimming systems. Non-optimized sensor technology, deployment, and commissioning can lead to erratic dimming that results in users bypassing or removing the system. The problem is exacerbated by lighting-sensor-control systems that are proprietary or have issues with interoperability of the different components. Algorithms for lighting responses to sensor signals can also limit effectiveness for lighting intensity controls systems. Finally, excessive system complexity and reliance on neighboring networks, such as Wi-Fi, for communications can reduce resiliency and security of the system creating the possibility for problems caused by systems outside of the lighting system.

An ongoing research project supported by the DOE SSL Program is with the Virginia Tech Transportation Institute (VTTI) to evaluate the impacts of time of night dimming of roadway lighting. VTTI is evaluating the dimming performance of the time of night roadway dimming system in Cambridge, MA. They are also reviewing data on crashes and crime to determine if there are safety impacts from the using time of night dimming. VTTI will also evaluate energy and maintenance impacts and calculate the reduction of anthropogenic light in the environment, the reduction in light pollution. The results from Cambridge will be compared with information from San Jose, CA and Tucson, AZ where similar time of night roadway lighting systems have been installed.

In its role as a Next Generation Lighting Systems (NGLS) Living Laboratory, VTTI has also evaluated the use of wireless lighting controls and proximity sensors in outdoor parking lot lighting. Six different connected outdoor area lighting systems are installed in six parking lots near the VA Tech campus, all with presence (motion) detection (both luminaire-integrated and remote sensors). The NGLS outdoor evaluation protocol requires that lights return from dimmed to full output when motion is detected. The lighting systems are installed on existing 30' poles. The most important takeaways to date:

- Five of the six systems were ultimately able to achieve wireless control, including dimming, scheduling, and reporting. However, significant labor hours, call-backs, and bucket truck lifts were required to achieve functionality. Key problem areas were system configuration, sensor wiring and programming, gateway communications, and replacement of failed hardware. Every system required onsite support from factory personnel.
- Presence detection in the retrofitted parking lots failed. The passive infrared sensors consistently failed to raise dimmed light levels in the presence of moving vehicles and pedestrians. This may have been caused by inadequate sensor sensitivity, or latency of response, or a combination of both. The failure to detect moving vehicles until well past the sensor raises questions of safety. And the failure to detect pedestrians leaving the buildings or entering the drive lanes challenges both the reality and the perception of personal security.
- There was no consistency across the six outdoor lighting systems evaluated. The lack of consistency went beyond the technology and, included the front-end interface for property managers and installation and configuration instructions for installers.

Table 3.3 Number of parking lot lighting systems installed at NGLS Outdoor Living Laboratory at VTTI meeting operation criteria, relative to the total number installed (6 different systems). Source: PNNL

Lighting System Function	Operational at Startup	Reliable, Consistent Operation at Performance Evaluation
Scheduling	6/6	6/6
Dimming	2/6	4/6
Presence Detection	1/6	0/6

Improved ability to use daylight in buildings, and to decrease electric lighting use when daylight is available, has long been a building energy efficiency goal. Daylight is typically desired by building occupants, especially when accompanied by window views. Photosensors that detect light levels in a space and adjust electric light levels up or down as necessary to meet specified levels have been available for many years, but like other lighting controls, they are under-utilized in the building stock. This control function is hampered by disconnects between daylighting and electric lighting design, hardware, institutional barriers, and inconsistent and non-standard metrics. Two research priorities emerged from a recent scoping study on achieving integrated daylighting and electric lighting systems:

- The validation of simulation tools. Although this topic could include both the validation of existing software for computing the non-visual effects of lighting, as well as developing new tools for that purpose, it appears that there is a significant need for the validation of software tools in general (i.e., including tools for computing photopic quantities, particularly in the computation of metrics for visual comfort);
- Making available the inputs that are required for the simulation of non-visual effects of lighting. Sky data are generally not available; other types of data (e.g., spectral reflectance of surface materials,

> spectral power distribution of light sources) are also not easily available for most users of simulation tools. [152]

Another project at VTTI has been evaluating the use of proximity sensors with outdoor parking lot lighting. While this is an available feature with many parking lot lighting systems, the initial research has shown that these systems often perform poorly.

3.2.5 Spectral Efficiency

Spectral efficiency describes the idea that the spectrum of the light is optimized for the intended function of the lighting application. Historically, this has been interpreted into requirements for color fidelity (CRI or IES TM-30 R_f), CCT (a characterization of the hue of the white light), and high luminous efficacy. Incandescent sources have fixed, perfect CRI (by definition) and a CCT of 2700K. However, incandescent lighting also emits a majority of its energy outside the visible spectrum, providing little or no benefit and resulting in wasted energy. Alternatively, fluorescent lighting has gaps in spectral emission within the visible spectrum, which creates challenges in delivering light with good color fidelity. The fluorescent lamp phosphors can be engineered to provide different white color mixes with different CCT values. LED technology allows engineering of the spectral power distribution, not just to achieve desirable color qualities, but also to optimize overlap with the luminous efficiency function, V(λ). Figure 3.50 shows typical spectral power distribution for incandescent, fluorescent, and cool white LED lamps.

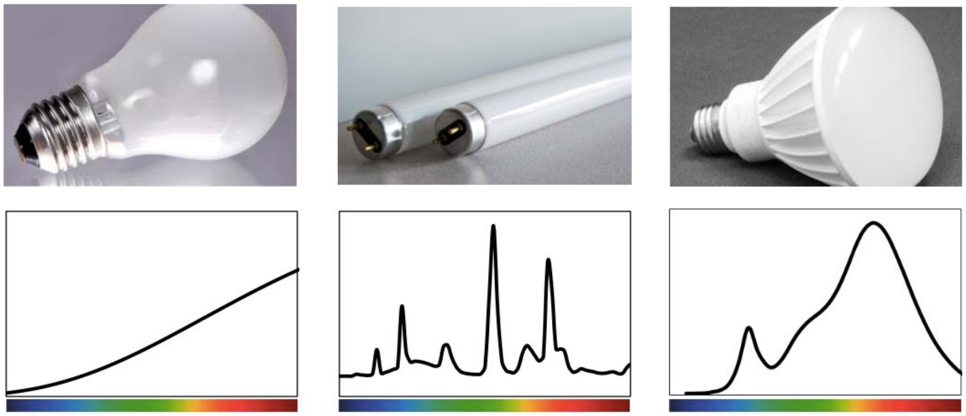


Figure 3.50 SPD for different technology types. SPD on left is for an incandescent lamp, middle is for a typical fluorescent, and right is for a cool white LED. From *Spectral Power Distribution, The Building Block of Applied Lighting* by Michael Royer, presented at the DOE SSL Technology Development Workshop, 2016.

Luminous efficacy – the lumens generated by a watt of radiation of a given spectrum – can be calculated as the overlap of the light source emitted spectrum and action (or response) spectrum as shown below in Figure 3.51. The result is referred to as the luminous efficacy of radiation (LER). For the given spectrum, the LER can then be multiplied by the power conversion efficiency of the source to determine the luminous efficacy (lm/W) of the system. So, optimizing the LER, while meeting color quality requirements, is a means of improving luminous efficacy. However, optima for both the LER and the source power conversion efficiency need to be considered simultaneously. For a typical phosphor converted white LED, the LER is 323 lm/W (3000 K, 80 CRI). [153] Higher color fidelity requirements typically reduce LER, but the use of narrower spectral width light sources can increase LER. For example, with direct emitter color-mixed (no phosphor) generation of white light, the LER is 414 lm/W. Optimizing the source LER and power conversion efficiency, while simultaneously achieving color quality requirements, is one example of spectral efficiency.

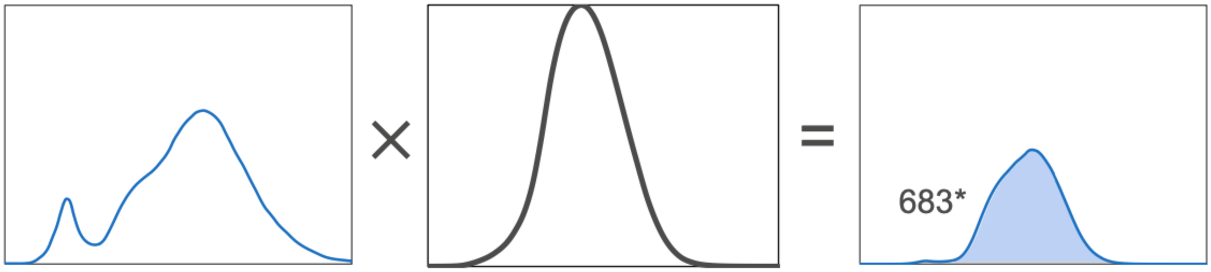


Figure 3.51 Luminous efficacy of radiation can be determined by calculating the overlap of the emitted spectrum with the luminous efficiency function, V(λ)in this case, and multiplying the defined constant 683. In this example the V(λ) is the action spectrum. The result in this case will be the luminous efficacy of radiation for the emitted spectrum. The same essential process can be used with any emitted spectrum and any action spectrum. From *Spectral Power Distribution, The Building Block of Applied Lighting* by Michael Royer, presented at the DOE SSL Technology Development Workshop, 2016.

To determine LER, the overlap of the emitted spectrum with the luminous efficiency function, V(λ), which is a psychometric action (or response) spectrum based on the eye response, is calculated. The same process can be used with other action spectra. For example, melanopic response or individual or cone response can be calculated for different emitted spectrum. Similarly, specific horticultural responses can be calculated as well. The effectiveness of radiation could also be calculated with the melanopic response curve to optimize non-visual physiological impacts of light (Figure 3.52). Action or response spectra can also describe undesirable effects of light with respect to light such as sky glow or specific animal responses. Spectral efficiency of the light sources can be optimized for the applications, and it will likely be necessary to optimize spectral efficiency to consider more than one action spectrum.

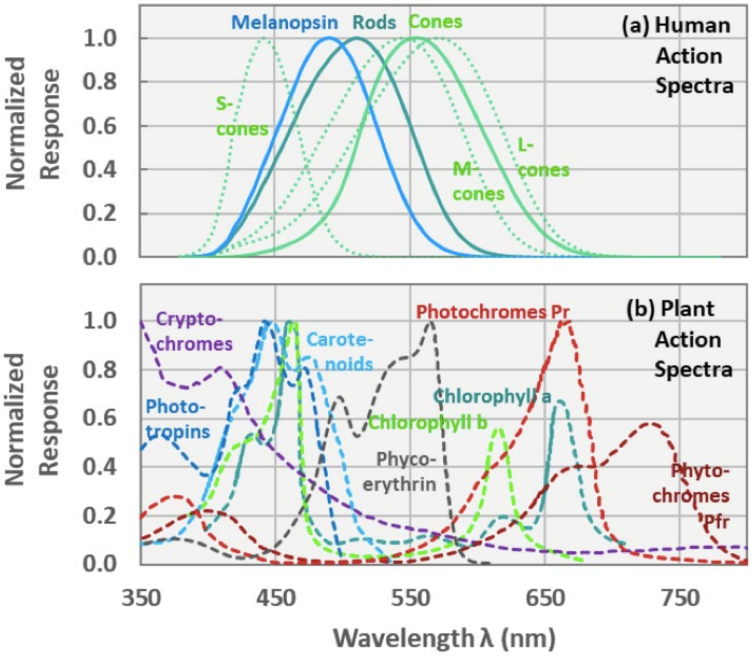


Figure 3.52 Action spectra for humans and plants. [154] [155]

Spectral efficiency considerations are typically constrained by color quality thresholds and metrics. LED technology allows the possibility to achieve much more precise and customized color qualities, optimized for a broader range of specific activities. There is also the opportunity, and need, to consider the color quality of the light after it has been reflected by the objects in the space where it is deployed. This holds true for optical delivery efficiency and intensity as well. As a simple example, the optical directionality, intensity, and spectrum (color quality) of a light source will be highly influenced by a lamp shade. Even for a lamp with a CRI of 100, the light that passes through the lampshade will have different color characteristics depending on the color of the lampshade.

Looking forward, the spectrum and spectral efficiency of delivered light will need to be optimized for multiple functions. At a minimum, light will need to provide good visual function and support healthy non-visual responses to light (which are time of day dependent), though there are numerous additional lighting functions which may have differently optimized spectra. These include, but are not limited to:

- Color fidelity
- Signaling
- Melanopic impact
- Alertness
- Color contrast
- Chlorophyll reception for plant growth
- Roadway visibility
- Ecological impact mitigation
- HDTV cameras
- Machine vision

There are examples of spectral engineering for all of these lighting applications. For example, color fidelity and color contrast can be critical for inspection tasks (medical diagnostics) and object perception (retail). This is also true for roadway object detection where researchers have found that LED roadway lighting with 4100K CCT increases object detection distance compared to HPS or 3000K CCT. [51] The color and intensity of light can affect alertness and melatonin secretion in humans (and other animals) affecting sleep quality. Color quality affects plant growth and morphology, providing a signal for how plants grow and also providing the fuel for growth. TV cameras and other semiconductor detectors also preferentially respond to different wavelengths of light. As machine vision becomes more of a daily interaction, lights could conceivably include consideration of optimal spectra for those applications. LED lighting technology with its range of LED and down-converter emission wavelengths provides the capability of engineering emitted spectra to the needs of the lighting application.

Spectral efficiency calculations show that wavelengths of light that do not support the intended purpose(s) of the lighting application are wasted photons and some wavelengths of photons can be actively detrimental for the lighting function. A more careful consideration of the delivered spectrum for the intended function of the installed light, and its spectral efficiency, will be critical for achieving the full benefit of LED lighting technology.

3.2.6 Lighting System Concepts and Demonstration

3.2.6.1 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 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 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).

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 metrics for LED drivers include efficiency (both at full power and dimmed levels), dimming range, absence of flicker, surge protection, size, weight, accommodation of multiple channels, and alternative input power. Improving these varying driver performance parameters result in design tradeoffs, unless one can leverage new technology approaches.

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. Wide bandgap semiconductors power devices can lead to driver architectures that address these problems by leveraging the higher frequency and innovative circuit topologies. 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 an R&D demonstration in Section 3.2.6. [156]

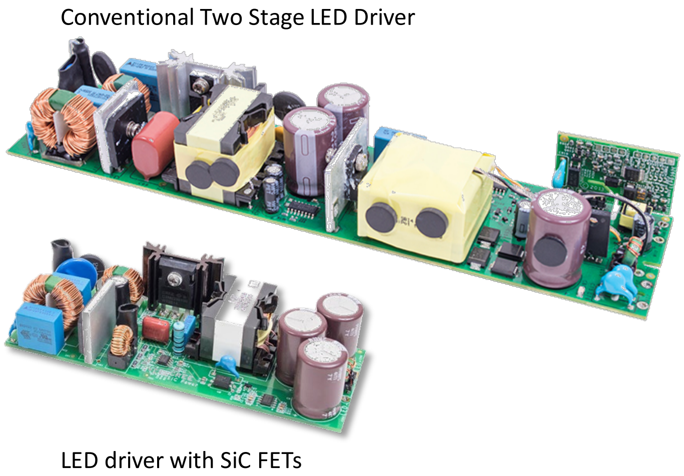


Figure 3.53 Comparison of a 220 W LED driver with and without wideband gap components. The two-stage conventional LED driver employing silicon MOSFETs (top) is about 40% bigger than an equivalent unit based on 900-V SiC MOSFETs (bottom). The driver with SiC MOSFETs has a higher peak efficiency. [156]

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. 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 device performance. For example, 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 SiC semiconductor devices 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. 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.

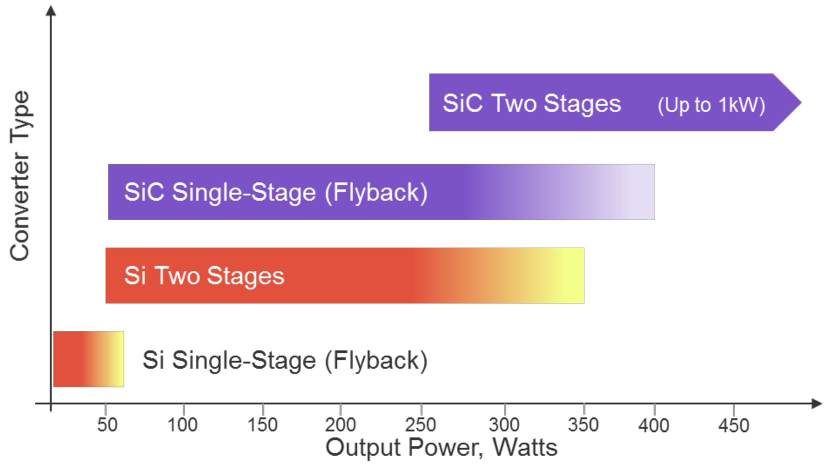


Figure 3.54 LED driver topologies based on semiconductor component types illustrated as a function of power output. [156]

Table 3.4 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. [156]

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

While the benefit of wide bandgap devices has been demonstrated in LED drivers, other industries are driving the implementation of wide bandgap devices in products such as electric vehicles (SiC devices) and for rapid phone chargers (GaN devices). This market pull is improving the availability and cost of wide bandgap devices overall and can help drive implementation into LED drivers. Smaller more compact drivers can be designed using the high frequency available with wide bandgap components and coupling that with high frequency planar magnetics (low profile devices). Planar magnetics also allow for a more automated manufacturing process that can reduce labor costs (eliminate hand winding) and move more of the driver manufacturing to SMT assembly processes.

Further research is needed to develop consistency, improve reliability, and to reduce cost of wide bandgap power devices. 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.

Additional power supply developments include increased integration of drivers and driver functionality at the LED board and component level (e.g., high voltage multi-junction LEDs) can help reduce overall luminaire size and provide more installation flexibility. This requires compact driver schemes and simultaneous consideration of power supply component, circuit, and LED design and fabrication processes. Additionally, innovative circuit topologies, such as a multiplexing based circuit topology, can address the performance of multi-channel drivers with the potential of providing higher efficiency at dimmed operation, no flicker (no pulse width modulation), lower component count, and lower power supply volume.

Driver Reliability

Typically, the driver is one of 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 Figure. 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 (MTBF) 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.

Enhanced Functionality of Drivers

Enhanced lighting functionality will be a vital feature for future deployment of connected lighting systems with advanced capabilities and can 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 from micro-LED arrays could enable not only similar improvements in use efficiency of light, but can also deliver high-precision dynamic beam shaping and color projection (see -3.23) or provide other information to the user. Taken to its logical limit, these pixelated light sources would start to create lighting-display fusion by, which would require drivers with video-display-like driver capability.

Finally, by implementing connectivity, lighting fixtures may well become the most ubiquitous grid-connected endpoint in the Internet of Things (IoT), 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.

Sensors

Sensing can help provide lighting systems that can deliver the best efficiency and functionality to the occupants in the space. SSL has continued to implement new sensor technology that has become available from development in other industries such as smart phones. Sensor advances have resulted in commercially available sensors for color tuning and lumen maintenance, which can be implemented in a closed loop feedback system within a luminaire to improve precision with the potential to also lower cost. Advanced multi-spectral sensors for precise control of spectrally tunable lighting have been developed with 11-channel multi-spectral sensors, which have eight optical channels to cover the visible spectrum, one channel for near infra-red light, one channel for a photo diode without filter, and a dedicated channel to detect 50 to 60Hz ambient light flicker. [157] Additionally, sensor-driven closed loop control systems include color/CCT control (spectral sensors) and/or lumen maintenance tuning and daylighting adjustments (digital ambient light sensors); these sensors connect to the LED drivers through analog 0-10V dimmers or networked lighting controls. Figure 3.55illustrates a sensor package integration into the luminaire driver with a light sensor embedded within the luminaire to allow for the feedback control loop.

To achieve an intelligent dynamic lighting system, high performance sensing technologies are required to better understand the use of the space and occupant information. Advance sensing for presence detection in the space is an area of active research. Some approaches include RGB color sensors for detecting small temporal color shifts and local disturbances in the reflected color signal in a room to detect occupancy. This can be combined with time of flight (TOF) sensors to generate accurate count occupants in the room on the basis of the localized color field deflections. [158] Research into new real time location systems and autonomous control systems employing machine learning for context aware lighting controls is also needed to develop sensing for future lighting functions.

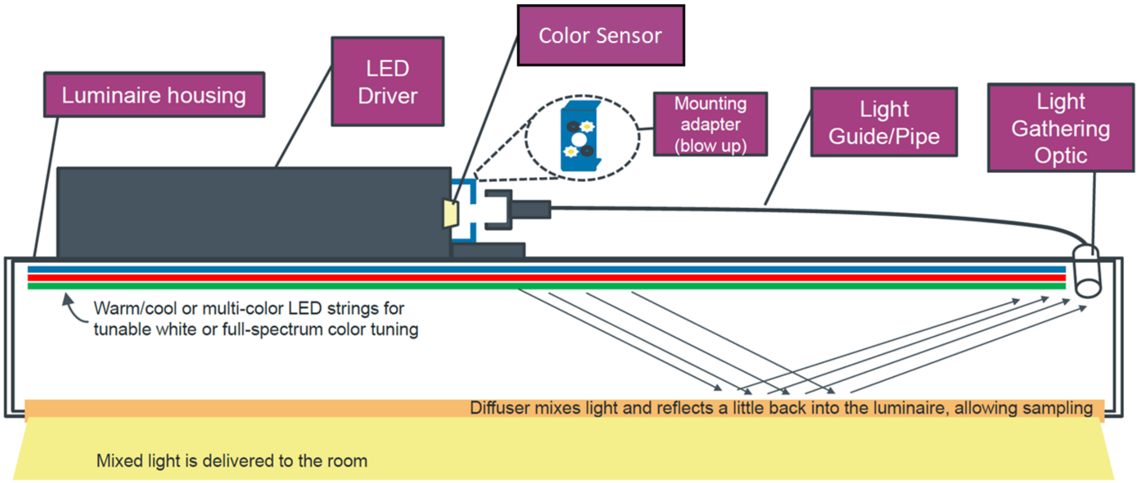


Figure 3.55 Luminaire schematic containing an LED driver with an embedded sensor package. A lightguide is utilized to provide sampling of the light conditions needed for color tuning or lumen maintenance feedback adjustments. [159]

3.2.7 Advanced Manufacturing R&D

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 into the manufacturing supply chain. Manufacturing processes and technologies must adjust to improve lighting product quality, reduce cost, and enable a wider variety of form factors and features as the technologies evolve. The unique technology features available with SSL presents the opportunity to develop new manufacturing technologies and foster domestic manufacturing for portions of the supply chain. SSL manufacturing processes should be developed to improve automation, create flexible manufacturing processes and allow for a manufacturing-on-demand infrastructure. New manufacturing technologies can also influence where, when, and how products are manufactured, possibly enabling more localized production close to the end use market. More details about SSL manufacturing can be found in the DOE SSL Program's Manufacturing Status and Opportunities document. [11]

There are many important manufacturing R&D opportunities that can advance SSL manufacturing and enable improved productivity, reduced cost, and new manufacturing technologies that can impact domestic manufacturing in lighting. The highest priority SSL manufacturing R&D opportunities have been identified below:

LED Chip & Package Manufacturing

- **LED Wafer Wavelength Uniformity:** Development of improved MOCVD hardware platforms to allow an entire LED wafer to yield into a single performance bin.
- **LED Wafer Fabrication Automation:** Creating improved automation and integration within 100 mm and 150 mm wafer fabrication plants (fabs) by developing turn-key manufacturing execution systems (MES), tool-to-tool wafer movement, communication platforms, and statistical process control (SPC) systems not readily available for the compound semiconductor fabs.
- **LED Device Testing Productivity:** Development of unique schemes to test sections of the LED wafer instead of individual die one at a time to improve LED device testing productivity. This will require careful process uniformity understanding of upstream processes.
- **Measurement Innovation for Micro-LEDs:** Implementing micro-LEDs for lighting involves major changes to fabrication and measurement infrastructure used in mass production for LEDs. New measurement techniques need to be developed to identify good performing die at the micro-scale with high throughput.
- **Micro-LED Mass Transfer Processes:** Designing economical mass transfer methods with extremely high yields to make the use of numerous micro-LEDs in luminaire products.
- **Chip-Level Optical & Electrical Integration:** Integrating increasing amounts of functionality (optical control or drivers) at the wafer level can lead to cost savings on the luminaire assembly stage taking advantage of the more automated surface mount technology processes or semiconductor fabrication equipment over current luminaire assembly schemes.

LED Luminaire Manufacturing

- **Universal Voltage Drivers:** Creating universal voltage power supplies cost-effectively for luminaires can simplify the manufacturing supply chains allowing manufacturers to better leverage economies of scale.
- **Luminaire Assembly Automation:** Developing new luminaire designs that are easier for automated assembly by designing around the more manual and difficult to automate assembly processes.
- **Additive Manufacturing of Luminaires:** While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, R&D is required to develop printable materials with the sufficient properties to replace existing manufacturing approaches in electrical, thermal, and optical components for luminaires.

- **Sustainable Materials Supply Chain for Lighting:** There is an opportunity to jump start sustainable supply chains by developing and integrating sustainable materials, and to make every component of a lighting system recyclable, reusable, and free of harmful chemicals.

OLED Manufacturing

- **Customizable Manufacturing of Patterned Substrates for OLEDs:** The development of patterned substrates is required so that multiple panels can be fabricated with edges that are sealed to improve reliability of OLED devices.

- **Rapid Deposition of Organic Materials:** Reducing the deposition time for OLED panels require alternative deposition techniques to increase throughput and lower manufacturing cost.

- **Affordable OLED Encapsulation Techniques:** A simpler, less costly encapsulation technique is required for OLED stability.

3.2.7.1 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.

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 fast, flexible, cost-effective prototyping and direct CAD to fabrication without tooling or inventory. It enables more product performance options through high configurability, enables unique designs that are not possible with traditional manufacturing, reduces parts counts (lower assembly complexity and cost), and eases product lifecycle management (more changes and shorter cycles). In addition, reduced costs can be realized with a lower equipment investment (no tooling) 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 3.56. 3-D printing enables the design of custom fixtures with improved visual appeal from unique designs and reduced costs.

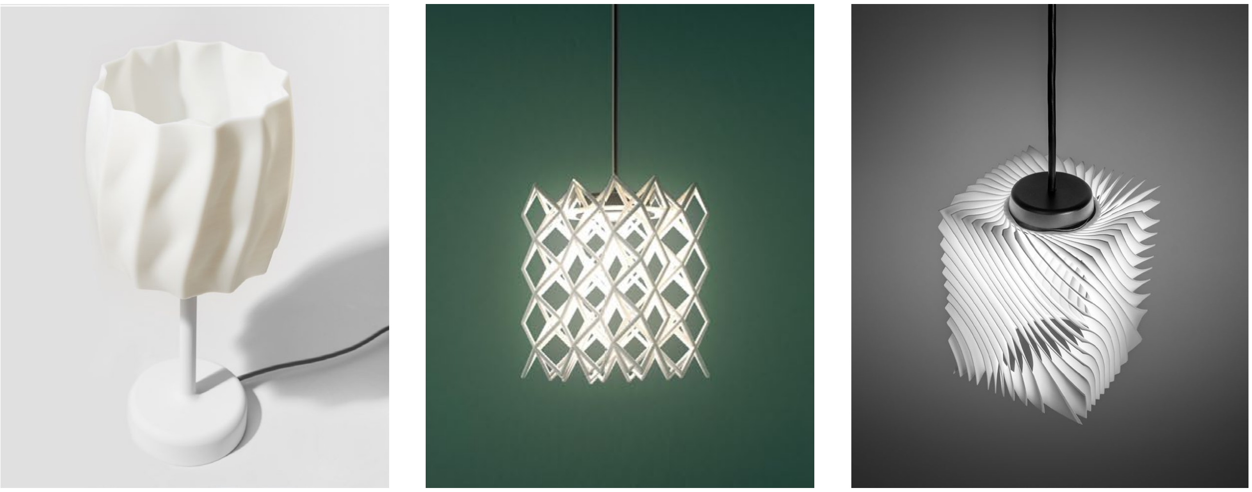


Figure 3.56 Images of 3-D-printed lighting fixtures. [160] [161] Custom optical distribution features of decorative luminaires can be achieved through additive manufacturing approaches that would not otherwise be practical or possible to achieve.

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 3.57. 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.

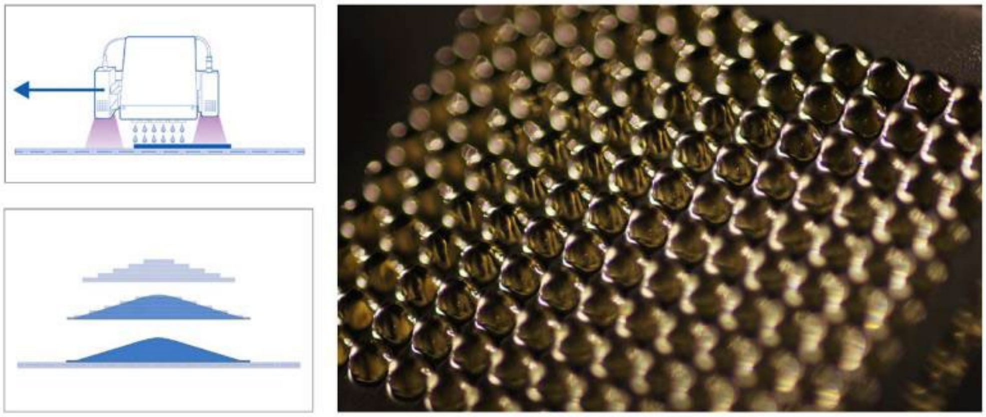


Figure 3.57 Deposition of droplets by UV print head onto substrate material (left-top). Droplets of polymer are allowed to "Flow" under surface tension before curing with UV light, giving smooth surfaces needed for optics (left-bottom). Array of micro-optic lenses (right). [162]

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. [163] 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 3.58.

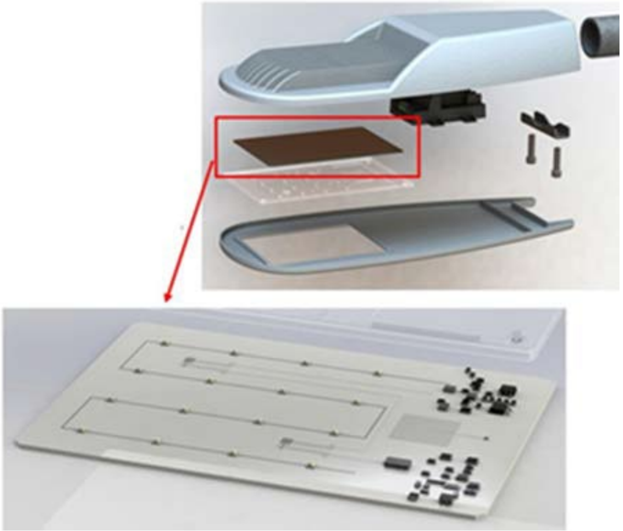


Figure 3.58 Images of integrated roadway luminaires with fully printed, integrated circuitry with LED, driver, sensors, and antennas. [164]

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. It is essential to develop new printable materials with improved optical properties and UV resistance for optics, polymer materials with higher thermal conductivities for heat sinks, and improved UV and IR curing for electronic materials used to generate the circuit. 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 PCBs, and while they can be printed, the resistivity of the traces are higher than copper. [165] 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. Moreover, the developed materials must all be able to pass all safety ratings and standards.

Other technical challenges to enable more additive manufacturing production opportunities, including developing faster additive manufacturing processes by increasing print speeds and creating systems with larger beds and multiple print heads to generate more parts per run, thereby reducing cost. Another area requiring improvement is creating better “net shapes”, so minimal post processing is required. Printing with better surface properties is critical, especially to prevent scattering centers in the optics or to prevent surface roughness on the heat sink from causing shorts in the printed electronic circuit. While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, more R&D 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. The use of additive manufacturing in creating tooling has the potential to create efficiency gains with SSL product manufacturing.

Micro-LED Manufacturing

Another area of advanced manufacturing involves high density LED assembly. The future use of high-density pixel LED sources necessitates new methods to assemble large number of mini and micro-LEDs at speeds and cost levels that can be supported in the lighting industry. The challenge with using these smaller micro-LED die (< 50 µm size) to create small pixel sizes is the conventional manufacturing technologies don't scale effectively – both from the device fabrication side, as well as the die transfer process (at the light engine level). Additionally, when moving to these small LED die dimensions, the efficiency of LEDs can drop rapidly with chip size, as discussed in Section 3.2.1.1.

New approaches such as digital printers for self-assembly offer new promising paths to perform self-aligning mass transfer of chips (both LEDs and control electronics). The display industry is putting considerable resources into innovations for micro-LED mass transfer, which the lighting industry can leverage while also considering new approaches such as digital self-aligning chip printers. Advances in the mini/micro-LED die placement processes is an area of research with a variety of approaches being pursued in display applications, including mass parallel transfer and rapid pick and place schemes. There is an opportunity to develop mass transfer processes to provide more efficient mass transfer of die (both LED and other semiconductor die like control ICs) to creating low-cost roll-to-roll lighting systems. To date, most of the development work in micro-LEDs has been focused on the mass transfer of large arrays of LEDs from the wafer onto a display substrate and the fabrication of high performing micro-LEDs. Traditional pick and place equipment used to place LED packages on PCBs operates at a speed of 8 to 10 LEDs per second with a placement accuracy of 25 microns. Die bonding equipment that places LED die into packages are considerable slower at a rate of one LED per second but more accurate with a placement tolerance of 5 microns. There has been considerable effort in industry the past several years to develop economical mass transfer methods with extremely high yields to make the use of so many LEDs a possibility in a consumer electronics product. New lighting products can also leverage these pixelated light sources to create new or improved functionality.

Currently, techniques such as massively parallel pick and place that use transfer stamps, sequential/semi-continuous placement, and self-assembly processes are being explored by dozens of companies and researchers. These types of transfer processes have different challenges and a clear winner has not yet emerged. Other approaches such as the use of digital printers for self-assembly, illustrated in Figure 3.59 offer new promising paths to perform self-aligning mass transfer of chips (both LEDs and control electronics). The display industry is putting considerable resources into innovations for micro-LED mass transfer, which the lighting industry can leverage while also considering new approaches such as digital self-aligning chip printers. The LED supply chain also must innovate to provide high performing mini/micro-LED die for lighting application requirements since they will differ from the requirements of displays.

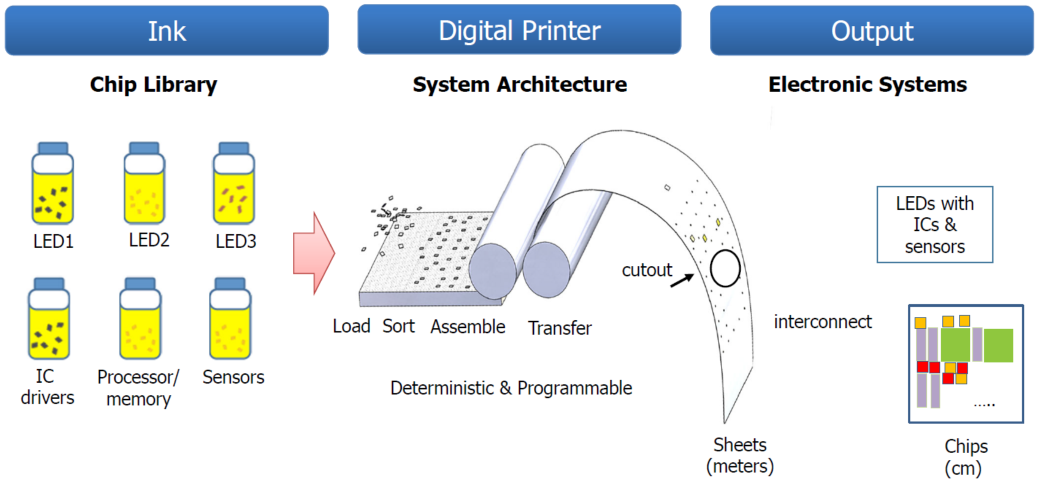


Figure 3.59 Schematic of a novel digital printer approach the illustrates the features of a self-assembly scheme with the use of die-containing inks being applied and assembled onto a sheet in a roll-to-roll format. [166]

Sustainability

As the manufacturing of LED lighting is considered, the environmental impact of today's system designs and production processes should be considered. Developing a sustainable supply chain that feeds into the circular economy is an opportunity for lighting industry to model the transformation needed for a sustainable future. Manufacturers need to design differently by using more sustainable materials and to deconstruct differently by creating intentional designs for disassembly and recycling of luminaire materials.

A sustainable lighting future requires the creation of eco-friendly designs with minimized component count, and the use of low-embodied energy materials, recycled materials, or bioderived materials. The majority of today's SSL luminaires use aluminum and other energy-dense structural and thermal materials in their designs and manufacturing processes. The use of recycled materials can help save energy and repurpose items from the landfill. Extracting and processing raw resources to make usable materials requires a lot of energy, whereas recycling often requires much less processing to turn previous products into usable materials.

There is an opportunity to jump start sustainable supply chains by developing and integrating bioderived materials like bamboo or flax seed into the luminaire, producing lenses and other components out of ocean plastics, exploring repurposed "trash" for 3D printing source materials, and making every component of a lighting system recyclable, reusable, and free of harmful chemicals. Ocean plastics are currently being repurposed to make many different products from bottles to knit caps. These materials have potential for replacing some of the plastics used in luminaires. Similarly, creative use of existing "trash" can help drive the circular economy. Distributed recycling and additive manufacturing (DRAM) enable reusing materials by cleaning waste plastics, mechanically grinding them into pellets, and then turning those pellets into the feedstock used to create low-cost filament sources for 3D printing. Beyond the use of sustainable materials, it is important to eliminate unsafe chemicals from every component and for manufacturers to provide materials transparency through certification bodies, such as the Living Building Challenge and their "Declare" label. The Declare label contains information on the life cycle impacts of the product and shows the Red List status, which has more than 800 chemicals listed as hazardous to the environment or human health.

The approach of sustainable supply chains and the circular economy can create a local economic advantage by embracing the concept of upgradeable or repairable fixtures and allowing for more maintenance and servicing local revenue streams. Additionally, maintaining more bio-friendly materials and an emphasis on reducing transportation waste can help improve the local supply chains. If a sustainable design rating was a competitive barrier, then categories such as reduction in transport waste, sustainable materials use, and efficient recycling could be differentiators in rating. It is not essential to wait for every component, luminaire, or supporting process to be sustainable to start on the path to sustainability. Moving forward one step at a time is important.

3.2.8 LAE Framework and Model Development

LAE considers the quantity and quality of light delivered to an intended location at a specific time using lowest energy consumption possible to optimally achieve the intended lighting function. A conceptual depiction of a LAE framework is shown in Figure 3.60, below.

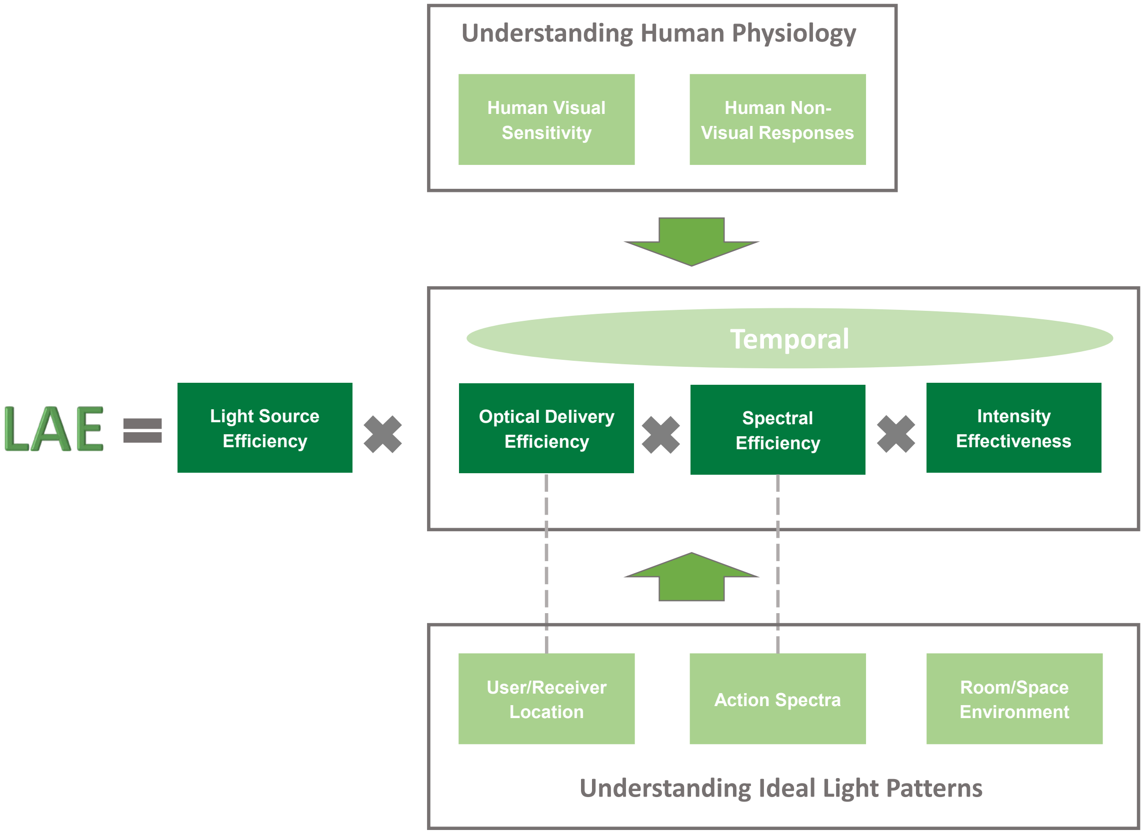


Figure 3.60 LAE conceptual framework is a tool to identify to balance considerations of light source efficiency, optical delivery efficiency, spectral efficiency, and intensity effectiveness at a given point in time for specific activities. LAE will need to be considered within the contexts of the geometry of a space and occupant location and action spectra for desired (or avoided) physiological response. In this framework, human visual function and human non-visual responses (shown at top of figure) guidance are inputs to framework.

LED technology offers greatly increased capabilities in terms of precision of optical delivery, instantaneous intensity control, and an almost infinite color palette. In parallel, there is ever increasing understanding of the best light for different lighting functions, including color fidelity, exemplified by the recent development of IES TM-30, and non-visual physiological responses to light with evolving guidance for light intensity and spectrum. These new levels of precision in lighting control and application guidance also support the need to specify lighting qualities as those of light at the intended target instead of light generated at the light source. Light qualities from a light source will be mediated by the properties, surface finishes, geometry, furnishings of the room or lighted space. While we understand that there is a need for light with excellent color quality for visual function, or light with increased blue content for physiological benefit, or other spectral requirements, the lighting parameters should be evaluated at the application target, not when emitted from the light source. This requires light intensity and spectral power distribution to be modeled at any plane in a space, given the SPD, optical distribution, lighting layout, geometry of the space, and fixtures and finishes in the space as well as dynamic capabilities of a light source. This concept also requires lighting guidance or targets for the light intensity and SPD of light for target planes within the space. These targets describe the ideal lighting for the lighting function and might require a compromise in lighting quality selection to balance the different considerations for lighting the space.

Modeling capabilities to predict light intensity, optical distribution, and SPD at different target areas in a space do exist but need refinement to properly describe all the dimensions involved in the lighting specification. New modeling platforms are a logical extension of existing lighting models that can predict illuminance on a plane but cannot readily consider SPD and dynamic tuning of a light source. It would be beneficial if models and algorithms could generate optimized lighting product properties (SPD, optical distribution, need for dynamism) to provide light most effectively and efficiently in a space.

In particular, the LAE framework and accompanying modeling capabilities need to be developed so that ideal lighting targets can be achieved and balanced within a given space. The framework and model should be able to identify and evaluate different lighting solution for achieving combinations of lighting functions with the least possible energy for any lighting targets and for any space.

3.3 Lighting Science

The development of SSL technology with new levels of control of optical distribution, intensity, and color, as well as new engineering solutions, can enable the tools to develop new understanding in lighting science. New and refined understanding of lighting science is necessary to leverage the full functionality, productivity, and energy benefits of SSL. Previous (pre-LED) research in lighting science focused on existing lighting technologies and their capabilities. With the LED technology platform there is an almost limitless range of lighting configurations that can be envisioned and achieved. It is critical that new lighting science guidance is developed quickly to get the most benefit and minimize undesirable side effects from SSL technology as it is deployed across the globe at large scale

3.3.1 Non-visual Physiological Responses

General illumination meets two critical needs for human health and productivity: it allows humans to see their surroundings and supports the regulation of circadian, behavioral, and endocrine responses. While research related to light and melatonin suppression has been occurring since the 1970s, it was the discovery twenty years ago of another class of photoreceptors in the eye, ipRGCs, that has spurred recent research on the physiological impacts of light. Since then, more has been learned about the two primary neural pathways that transmit light information for these needs, as shown in Figure 3.61, with some interaction between the pathways.

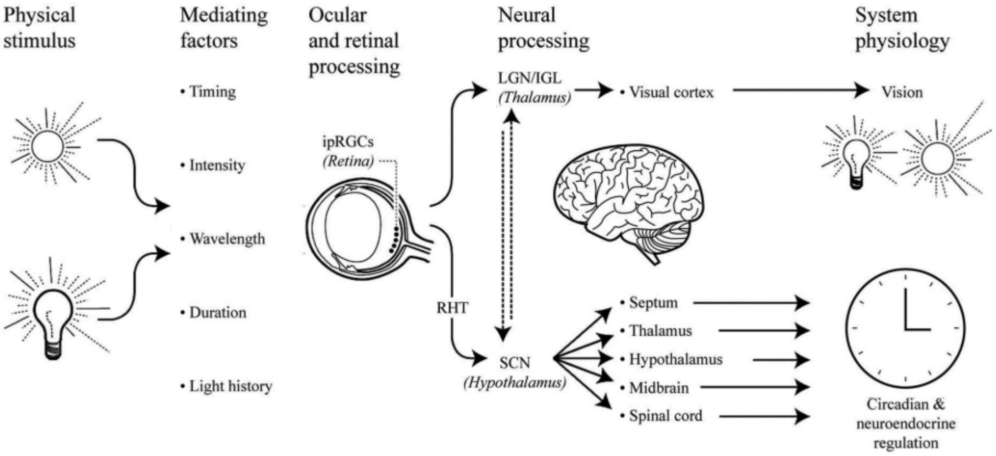


Figure 3.61 Schematic illustration of the neuroanatomical underpinnings of physiological effects of light. The ipRGCs transmit environmental light information via the retinohypothalamic tract (RHT) to the central clock in the brain (SCN, suprachiasmatic nuclei); other direct projections of ipRGCs include thalamic and other brain regions. The response will depend on the light characteristics and/or mediating factors. LGN: lateral geniculate nucleus; IGL: intergeniculate leaflet. [167]

Much of the research on non-visual responses has been focused on laboratory settings where the lighting stimulus and human behavior can be carefully controlled. While further understanding of the basic non-visual responses to light is helpful and necessary, it is also necessary to understand and optimize light spectrum and intensity to support non-visual physiological responses in realistic lighting settings with less controlled human behaviors and external factors. The link between real world exposure with real world outcomes requires studies in naturalistic settings where objective responses can be measured and related to light exposure and other potential factors. For example, in workplaces, quantitative outcomes related to health, productivity, and absenteeism can be evaluated and related to light exposure and other potential factors. Figure 3.62 illustrates some of the differences between circadian research that is conducted in a laboratory and in the field, including the variability of the sample of participants. Laboratory studies are typically conducted using highly screened populations, which often do not reflect the diversity in age, ethnicity, gender, and health status of the general population. Both approaches are valid. Laboratory studies minimize noise in the signal by selecting homogeneous samples, and thereby can detect even small effects. However, generalizability is limited. In view of our improved understanding of circadian organization, including the relevance of peripheral clocks, future work is needed to harmonize conceptual approaches and operationalization of circadian disruption in the context of mechanistic, observational and intervention studies.

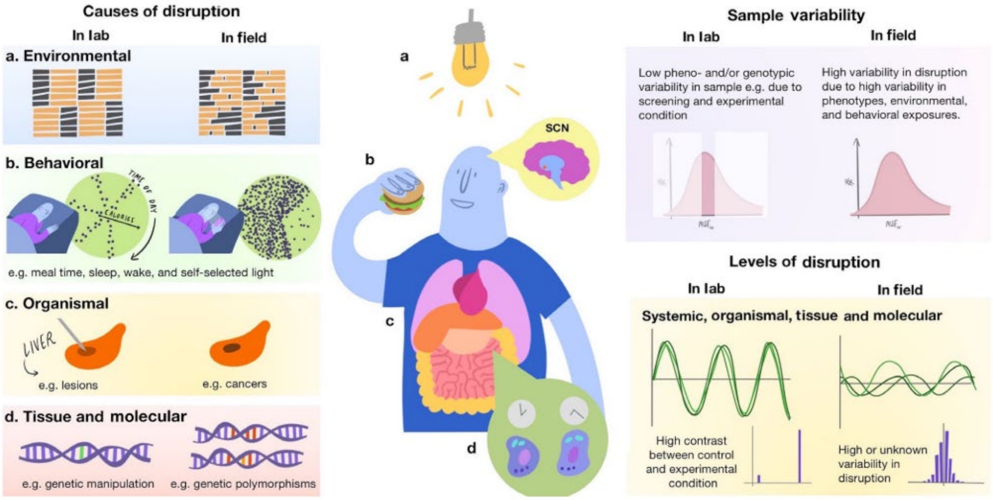


Figure 3.62 Circadian Disruption in laboratory and field settings. The left panel displays potential causes of disruption and how they might differ between laboratory and field settings. The upper right panel illustrates sample variability of the study population. While laboratory studies usually target specific populations in a smaller number of individuals, field studies include larger and more heterogeneous samples. The resulting levels of disruption (lower right panel) should differ between laboratory and field settings, with high contrast conditions and little inter-visual variability in laboratory settings, and higher variability in field ones. [168]

Field studies require researchers to account for a number of factors, including timing and duration of exposure, the spectrum and intensity of the light exposure, and prior light exposure. In the field, the challenge is that confounding factors can obscure the direct lighting effects in this type of research, thus necessitating both laboratory and field studies to further understanding. Advanced lighting systems now have the ability to optimize light levels, spectral content, and timing to provide the most benefit, while minimizing energy consumption in general illumination applications. Factors beyond this also need to be considered, including negative side effects, such as minimizing glare while providing increased light levels. Research has shown that a certain amount of light is needed to suppress melatonin, but there is a plateauing of this effect where more light no longer increases melatonin suppression; however, this remains to be better understood outside of laboratory settings. [169] [169] Lighting research of physiological benefits in realistic settings should be focused in the settings where there is the most to be gained in terms of understanding health benefits and energy impacts, to achieve clear and significant results.

Identifying the range of individual responsiveness is an additional challenge for interpreting research results in and developing lighting guidance. The impact of these factors needs to be understood, so research findings can be translated into practical, beneficial implementation. Recent research conducted in the laboratory highlights the difficulty in accounting for the wide variability of individuals in their physiological response to light at night. [170] Additionally, a field study recently documented the wide variability of the amount of light reaching the eye within a single office space. [171] These results underscore why understanding the relationship between light exposure and response is so challenging. The ecological validity of research in environments outside the laboratory is much higher, but it is also much more difficult to understand the effects of light given the variability of both the amount of light reaching the eye and the variability of individuals. These variabilities may be why, in real environments, it has been found that increasing the light level was counter-productive and inconclusive, while other studies have shown an increase in productivity. [171] [172] [173] To address the variability of response outcomes, Vetter et al. suggest further research to understand if differences are due to the light source, time of day, outcome measures, or other methodological factors. [167]

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. Day-active populations comprise the vast majority of lighting deployments and, as such, should be the focus of research and implementation supported by the DOE SSL Program to achieve maximum health, productivity, and energy savings benefits. 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.

Metrics are also key to furthering understanding and application of light for human health considerations. The only standards developing organization to establish a metric is the CIE. m-EDI is the circadian metric adopted through a consensus process by the CIE. The international standard CIE S 026:2018 (CIE 2018) defines a system for studying the measurement of circadian lighting.[43] Other metrics include equivalent melanopic lux (EML), used in the WELL Building Certification system, and circadian stimulus (CS) published in an Underwriters Laboratories (UL) Recommended Practice; however, neither is a standards developing organization.[44] The recommendations by WELL are untested, and the target values have changed considerably over time. Additionally, CS has recently undergone a fundamental change, following two other changes to its calculation method since its development in 2005.

More recently, a diverse group of researchers suggested thresholds for daytime, evening and nighttime light levels; however, these recommendations lack specificity related to duration of exposure. [174] The researchers also note that daylight should be used to meet the daytime and evening light levels when possible, yet this is difficult for most locations within a building. Multiple factors that influence the amount on penetration of daylight into architectural spaces include building orientation, seat location, view direction, surrounding buildings and foliage, window glazing and shading. Advanced lighting systems should be designed to meet these high light levels assuming a minimal contribution of daylight, while efforts need to continue to be made to better integrate electric lighting, daylighting and facades.

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[43] https://www.techstreet.com/standards/cie-s-026-e-2018?product_id=2030705

[44] WELL Standard: https://standard.wellcertified.com/light/circadian-lighting-design. UL Standard: https://www.shopulstandards.com/ProductDetail.aspx?productId=UL24480_1_D_20191219

The research opportunities remain numerous, including better understanding of fundamentals with the different classes of ipRGCs, action spectra, and the neural pathways that transmit light information. This research thrust will primarily come from controlled laboratory environments. Additionally, continuing to translate this to field research and being able to provide clearer guidance to lighting practitioners is crucial for realizing the full productivity benefits afforded by advanced lighting systems.

3.3.2 Flicker

Flicker or temporal light artifacts perceived by occupants are unhealthy, undesirable, and unnecessary with LED lighting technology. The flicker produced by electric light sources can be a function of how AC electricity to light, or the result of noise or transient events with AC electrical supply. LED flicker characteristics are entirely a function of the LED power supply and cost-performance trade-offs within the power supply architecture. Dimming presents an additional challenge with flicker since LED lighting must be compatible with different types of dimmer circuits, particularly circuits where the supplied electrical power is chopped in different ways to reduce the incoming power. There is also 0-10V dimming and other dimming signals that work apart from the supplied power. Different dimming circuit architectures present different sets of performance trade-offs, with cost and form factor restrictions further limiting the choices available. Fundamentally, LED technology can be dimmed, flicker-free, using pulse width modulation (PWM) which modulates current to the LEDs at frequencies well beyond human perception. To dim the light, the width of pulse is reduced while keeping the on-current a consistent level. This keeps the appearance of the light consistent, avoiding changes in color due to different LED current levels and also allows for deep dimming, where the application of low currents to the LED may result in non-linear light output levels. The challenge with flicker is to ensure that the LED lighting product can effectively handle the dimmed input power, for different dimmer types, and translate this signal to a dimmed LED output. [175]

Photometric flicker is a concern because of its potential deleterious effect on humans, which range from distraction or mild annoyance to neurological problems. Low-frequency flicker can induce seizures in people with photosensitive epilepsy, and flicker has been linked to headaches, fatigue, blurred vision, eyestrain, and reduced visual task performance for certain populations. There are at least three forms of visual responses to temporal light modulation (TLM): the direct flicker effect, the stroboscopic effect, and the phantom array effect. At present, only direct flicker has reliable metrics for visibility prediction. There are several unevenly predictive metrics for the stroboscopic effect, which may result in the mistaken perception of slowing or stopping of moving machinery in an industrial setting, for example, but target values for these are in discussion. Metrics for the phantom array effect – which may lead to distraction when driving at night, for example – have not been established because it is still being explored as a new phenomenon related to solid-state systems. There is little performance data to guide specifiers or product manufacturers in avoiding "flicker."

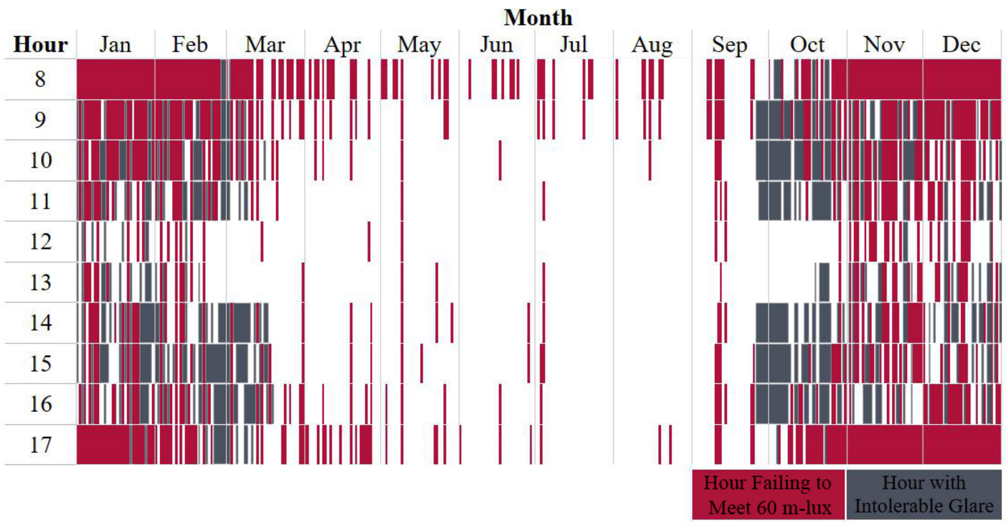
When discussing flicker, it is important to understand the difference between sensation and perception. Sensation is the physiological detection of external conditions that can lead to a nervous system response, while perception is the process by which the brain interprets sensory information. Some sensory information is not perceived, and some perceptions do not accurately reflect the external conditions. As a result, some people who suffer from flicker sensitivity may not be aware that flicker is the reason they are suffering, or even that the light source responsible for their suffering is flickering. Furthermore, not all human observers are equally sensitive to the potential effects of flicker. Populations that tend to be more susceptible to the effects of flicker include children, people with autism, and migraineurs. Opportunities remain for improving flicker meters and metrics, developing test-procedures to better characterize flicker, particularly related to the pairing of LED sources and drivers, and better understanding the physiological responses of the sub-populations that are more sensitive to flicker. [175]

Finally, validation of new metrics is needed in naturalistic viewing environments, to increase understanding of how TLM parameters (e.g., frequency, modulation depth, duty cycle, spectrum) affect stroboscopic effect and phantom array effect visibility in the real world. This will help support development of specification guidance that considers sensitive and general populations. These metrics can build on standardized TLM measurement methods introduced through the IES and CIE. With education and industry buy-in, the metrics and guidelines can help improve product performance and allow specifiers to choose appropriate products for the application. The ultimate goal is improved health, visual comfort, and task performance for both the sensitive and general populations. Research is also needed to understand the relationships between TLM and non-visual responses, such as headaches.

3.3.3 Glare

As with all previous lighting technologies, the high brightness of LEDs sources requires that they are hidden from direct view using reflectors or waveguides to direct the light to the target while avoiding direct light in the field of view. As defined by the IES, glare is the sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance or visibility. [176] Research on glare aims to understand the basic principles of glare perception, such as source size, luminance, luminance distribution, background luminance, spatial location, SPD, etc. With a better understanding of these factors and their interactions, obtained through laboratory-based human factors experiments, the principles can be applied to architectural spaces and outdoor environments. This will lead to improved glare metrics for real environments, and potential glare metrics for individual luminaires—although context will remain a critical issue when evaluating luminaire glare. More effective, physiologically based glare metrics can assist luminaire developers and specifiers in analyzing tradeoffs between visual comfort and luminaire efficiency and can also contribute to novel optical material and optical system design. These outcomes will contribute to the overarching goals of limiting energy use and improving occupant wellbeing. There is also a need for better understanding of how discomfort from glare varies among different populations, such as older and younger people, or pedestrians and drivers. This can facilitate solutions tailored to specific space occupants and ensure that sensitive populations are considered when establishing specification guidance.

Quantification of glare is complicated by certain metrics being favored for studying daylight while another is favored for electric light. Future glare metrics need to take into account all light sources, the room or outdoor environment and the viewer and be based on a psychophysical understanding of visual perception. In fact, current circadian wellness guidelines suggest the need to have significantly higher indoor light levels compared to standard recommended practice, which would increase lighting energy consumption by 10%-100%. [177] Good daylighting design could help by supplementing electric light and preventing large increases in lighting energy use, but there are trade-offs with glare. In-progress research by PNNL has examined the number of times that daylight in a simulated open office space fails to provide the recommended circadian light levels and/or exceeds current glare metrics, in this case simplified daylight glare probability (DGPs), over the course of a year.



Hour	Fail EML	Fail Glare	Total
8	56%	3%	59%
9	35%	16%	51%
10	24%	19%	44%
11	17%	18%	35%
12	10%	4%	14%
13	11%	10%	21%
14	15%	24%	39%
15	17%	24%	41%
16	21%	21%	42%
17	45%	5%	49%

Figure 3.63 Ability of daylight to meet WELL building standard daytime recommendations of equivalent melanopic lux, vertically (EMLv) at all desks. Assumes electric light provides at least 180 EMLv, with 60 EMLv being provided by available daylight. Simulated open office model with 40 desks, 32 luminaires, 90% window-to-wall ratio, 40% visible transmittance and south-facing glazing, location Eugene OR. Source: PNNL. Preliminary (unpublished) simulation results.

As with many LED lighting application topics, the underlying physiological understanding of glare needs to be advanced so that clear application guidance can be provided. While new lighting product form factors and configurations enabled by LED technology also need to be considered to minimize glare. These simultaneous developments need to be included in consideration of optical delivery efficiency for LAE and increased light levels to support non-visual physiological benefits. Also, glare is an important consideration for safety offered by roadway lighting. Conceivably, LED technology with new form factors could deliver light for improved roadway safety with reduced glare, but novel lighting form factors, arrangements, mounting schemes, and possibly active controls would need to be considered.

3.4 Lighting Integration and Validation

SSL technology is enabling benefits in energy savings, productivity, and human health and well-being. It also enables related benefits such as improved roadway safety, ease of integration with local renewable energy sources, and reduced ecological impacts. Since lighting is a ubiquitous element in the built environment these impacts can be provided at a very large scale. However, it is critical that energy, productivity, health and well-being, and other impacts are validated at meaningful scale to ensure the benefits are realized and there are not unintended negative side-effects. This validation research can also guide best lighting practices that go beyond previous, typical lighting considerations.

Integration and validation R&D seeks to convert research findings and new technologies into lighting industry practices. The validation of new LED technology benefits in real-world installations has been supported by the DOE since the early days of LED lighting adoption. DOE GATEWAY demonstrations reviewed numerous installations of LED lighting technologies from outdoor street and area lighting to classrooms to medical facilities.[45] GATEWAY projects have documented energy savings, lighting performance metrics, reliability in extreme conditions, occupant responses , and control system performance and real-world challenges. Field

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[45] More information on DOE GATEWAY projects can be found at: https://www.energy.gov/eere/ssl/gateway-evaluations

studies provide essential, objective information on the performance and impacts of the still evolving technology.

As new features, impacts, and technologies come into play, it is necessary to validate these impacts. The translation of new technological advancements from outside and inside the lighting industry continues to move the lighting industry forward. There continues to be improved methods of sharing information between lighting devices, and some are seeking to apply new technology and computational methods to improve lighting calculation accuracy, speed and integration with other building software programs.

3.4.1 Building Level Energy Savings Validation

There is an opportunity to advance the ability of market-available digital tools to implement automated validation and verification throughout the design, configuration, and initial operation of advanced lighting systems. Lighting design as currently practiced delivers construction documents that attempt to communicate what is referred to as "design intent". These documents can include schematic drawings, performance specifications or specific product details that are sufficient for soliciting a bid, control strategy narratives, and other notes. These documents are handed off to the construction team, who is responsible for procuring, installing, and configuring actual products. During the construction phase, a wide variety of considerations can affect what products actually get installed and configured. For example, cost and lead-time – which may have been considered in design – might be reconsidered due to changes in the market or relationships that the construction team has with certain manufacturers or manufacturer representatives. Installer and integrator experience with a given product, or lack thereof, might be a determining factor in pursuing or rejecting a particular product or technology, or might not be considered at all if the installer and integrator are not yet part of the project team. The net result is that "design intent" is interpreted or translated multiple times in a subjective and limited way, typically resulting in the deployment of a system that does not fully meet all envisioned objectives. While the design team may be made aware of choices and changes that occur in the construction phase and have some input on them, the impact of those choices and changes is typically not fully evaluated – in large part because doing so requires manual, time-consuming and thus expensive efforts.

Examples of envisioned verifications and validations include:

- Verify that the lighting design meets prescriptive (i.e., not measured) energy code requirements (e.g., maximum lighting power density)
- Verify that annual energy consumption is as expected, accounting for lighting control strategies and varying occupancy. Verify expected daily demand profile and associated grid flexibility, including statistical variation resulting from varying occupancy
- Automatically configure and integrate with other systems from verified digital representation, leveraging metadata in semantic model
- Validate that performative (i.e., measured) codes are complied with using emulated stimuli. For example: validate that maximum current draw for all loads on the same circuit is within electrical safety code limits; validate that emergency lighting luminaire schedule and intensity meet path of egress requirements.
- Validate that fault diagnostics are performing as expected using emulated stimuli. For example: validate that voltage and currents that exceed fault thresholds create event reports as expected; validate that a luminaire device failure can be differentiated from an electrical circuit failure.

3.4.2 Validation of Physiological Impacts

To have the greatest potential to influence lighting practice, validation research in physiological responses 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 research typically requires more coordination than lab-based studies with more variability in research participants and occupants than often occurs with lab-based research. [178]

The application of LED lighting in senior care provides a considerable opportunity, with research in senior care facilities already showing promising results in terms of sleep, cognitive performance and reduction in falls, among other benefits. While there have been promising research results, often the sample size is relatively small, and facilities with the ability to install tunable lighting tend to be higher performing facilities with more resources. Increasing the installation of LED lighting systems with best-practice design based on research is critical so that more can benefit from this technology. To increase adoption, research that further clarifies the relationship between the lighting stimulus and the resulting benefit is needed for a variety of facility types using a variety of practical and advanced approaches that could be implemented in facilities with varying levels of financial resources.

3.4.3 Safety Validation

Another application of considerable interest is roadway lighting, which impacts every individual in the U.S. either directly or indirectly. LED lighting can 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. There remains significant opportunity to understand how different spectra affect visibility, along with increasing interest in adapting the intensity and spectrum of roadway lighting based on traffic level, time of night and other factors. This has the potential to deliver considerable energy savings; however, the potential implications beyond energy savings need to be better understood before municipalities feel confident making these types of modifications. Research is currently underway to assess statistical changes in vehicle crashes in municipalities that have completed LED roadway lighting conversions, compared to those that have not (yet) converted from high-pressure sodium sources.

Commercial and industrial warehouse facilities are another area of considerable potential that thus far have not received much attention from researchers. In this application safety is often a top priority; therefore, researchers should consider this carefully in any study. There is also potential for understanding the non-energy benefits from advanced control systems. The potential for supporting worker well-being is particularly of interest in night-shift applications, both from a biological health perspective as well as a safety perspective.

3.4.4 Lighting Performance Feedback

Traditionally, lighting systems are often installed with little or no effort to evaluate the performance of the system. After installation, light levels, reliability, energy savings, occupant satisfaction, productivity enhancements are almost never reviewed. Even in lighting as a service or energy service agreements there is seldom ongoing energy monitoring to evaluate system performance. At a minimum, it is desirable to integrate the ability to monitor energy performance of lighting systems. This provides validation of the energy benefits and also provides significant building usage information and maintenance insights and provides an actual, rather than theoretical, baseline for ongoing lighting energy improvements. Other lighting factors and benefits can also be monitored at regular intervals. Light levels can be monitored through judicious use of sensors. However, there can be problems with too much data that is not necessary or being reviewed and feedback systems that create complications with or even failures of the lighting systems. Ultimately, the building operator needs to engage monitoring options that enable best practices.

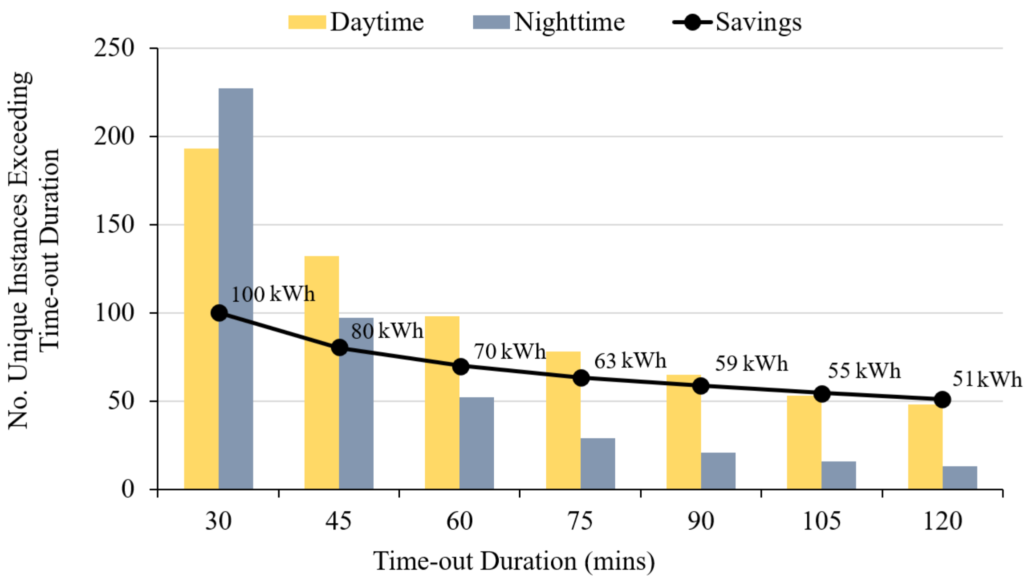

Figure 3.64 Potential energy savings from implementing a time-out option in a neonatal intensive care patient room. Graph shown by the number of instances exceeding the time-out duration decreasing as a function of time-out duration. [179]

Figure 3.64 shows the potential energy savings possible from implementing a time-out option for the Exam mode in a neonatal intensive care patient room. Energy savings for five rooms are calculated by identifying extended instances of the Exam mode during the daytime and nighttime hours, with the bars showing the frequency. The difference in energy resulting from a switch from Exam mode to the ambient lighting mode is summed over the 25 week monitoring period. This detailed lighting system use data was collected by the lighting control system that was connected to a building automation system.

4 Targets for Select R&D Priorities

The following list of current R&D priorities has been identified through stakeholder engagement and analysis. The priorities can be grouped into topics within Platform Technology, Lighting Science, and Lighting Integration & Validation. **Platform Technology** describes advancements to light source and system technology and manufacturing. **Lighting Science** describes advancement in understanding of lighting applications, including visual and non-visual lighting functions, safety, and counter-productive impacts, in order to achieve desired, optimal lighting functions with minimal energy inputs. Lighting Integration and Validation describes research on transitioning new lighting technologies, capabilities or understanding into large scale practice.

Descriptions of specific R&D opportunities are provided below. Some descriptions of research reference color or descriptive terms for color temperature. Table 4.1 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.

Table 4.1 Assumptions for wavelength and color as used in the task descriptions.

Color	Dominant Wavelength or CCT	CRI
Blue	440-460 nm	N/A
Green	530-550 nm	N/A
Amber (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

4.1 Platform Technology R&D

4.1.1 LED Materials, Chips, and Packages

Table 4.2 LED Material and Device Science

Light-Emitting Diode Material and Device Science

Description: Develop new or improved emitter materials or device structures. Improve 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.

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 DOE SSL Program performance targets described in table below.

Metrics	2021 Status	Interim 2025 Targets	2035 Targets
EQE (peak value)	80% (Blue) 62% (Green) 63% (Near Red[*]) 22% (Amber[*])	88% (Blue) 60% (Green) 69% (Near Red) 33% (Amber)	93% (Blue) 78% (Green) 70% (Near Red) 53% (Amber)
PCE[†] - 35A/cm^2, 25^{o}C	71% (Blue) 27% (Green) 51% (Near Red[*]) 19% (Amber[*])	80% (Blue) 50% (Green) 60% (Near Red) 35% (Amber)	86% (Blue) 70% (Green) 75% (Near Red) 60% (Amber)
PCE[†] - 100A/cm^2, 85^{o}C	54% (Blue) 19% (Green) 30% (Near Red[*]) 7% (Amber[*])	65% (Blue) 30% (Green) 43% (Near Red) 22% (Amber)	80% (Blue) 55% (Green) 60% (Near Red) 45% (Amber)

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

[†] Power conversion efficiency (PCE) is defined as optical power out divided by electrical power in for the LED package.

Table 4.3 Diffuse Light Source Materials and Devices

Diffuse Light Source Materials and Devices			
Description: Develop 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, light extraction efficiency or system reliability. Approaches should demonstrate a path to achieving efficient, low profile, diffuse lighting performance with good color quality and lifetime at reasonable cost. 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 or surpass all aspects of OLED device performance.			
Metrics	2021 Status	Interim 2025 Target	2035 Targets
Internal Quantum Efficiency (white emitter)	62%	80%	85%
Light Extraction Efficiency	55%	60%	75%
White Light Efficacy at 10,000 lm/m^2	85 lm/W	120 lm/W	150 lm/W
Operating life L70:B50 from 25,000 lm/m^2	30,000 hours	50,000 Hours	50,000 Hours
Voltage per stack at end of life @ 25,000 lm/m2	3.7 V	3.3 V	3.0 V

Table 4.4 Down-Converter Materials

Advancing Down-Converter Technology
Description: Explore new, high-efficiency wavelength conversion materials for the purposes of creating warm white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and spectral coverage and improved thermal stability and longevity to enable use of materials in high-brightness LED packages. 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. Focus for phosphor materials should be on high photothermal excitation conditions for high luminance applications. Research to advance understanding of on-chip quantum dot (QD) down converters to match or exceed performance of conventional on-chip phosphor materials is also encouraged. Research directions 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 and QDs used for LED lighting to provide targets for down converter performance.

Metrics	2020 Status	Interim 2025 Targets	2035 Targets
Phosphors Quantum yield (QY) at 25°C across the visible spectrum	98% (Green) 90% (Red)	99% (Green) 95% (Red)	99% (Green) 95% (Red)
Phosphors Thermal stability – Relative QY at 150°C vs. 25°C	90%	95%	96%
Phosphor Spectral FWHM	100 nm (Red/Green)	30 nm (Red) 70 nm (Green)	30 nm (across visible spectrum)
LED color shift over time (when integrated into pc-LED or with QD + phosphor)	$\Delta u'v' < 0.007$ at 6,000 hours	$\Delta u'v' < 0.002$ over life	$\Delta u'v' < 0.002$ over life
Quantum Dots Quantum yield (QY) at 150°C across the visible spectrum and at 1 W/mm^2	88% (Green) 81% (Red)	91% (Green) 88% (Red)	99% (Green) 95% (Red)
Quantum Dots* Spectral FWHM	35 nm (Green) 35 nm (Red)	30 nm (Green) 30 nm (Red)	30 nm (at all wavelengths)
Quantum Dots* On-chip stability (QY) under stressed operating conditions	> 80% flux maintenance (Red/Green) after 1000 hours at 60°C and 90% RH at 0.4 W/mm^2	> 85% flux maintenance % (Red/Green) at 1000 hours at 85°C and 85% RH at 0.5 W/mm^2	>90% flux maintenance (Red/Green) at 6000 hours at 85°C and 85% RH at 1 W/mm^2

* *The status of QD down-converters is based on commercial CdSe QDs. However, there is the possibility of developing InP or other material system-based QDs that emit at these wavelengths.*

4.1.2 Luminaires and Lighting Systems

Table 4.5 Luminaire Power and Functional Electronics

Power and Functional Electronics			
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.			
Metrics	2021 Status	Interim 2025 Targets	2035 Targets
Power supply efficiency, multi-channel	88%	93% at full power 90% in dimmed state	95% at all operating conditions
Power supply reliability	Applicant estimated lamp/luminaire survival factor (various methods used)	95% survival rate with a 90% confidence level across reported case temperature curve	99% survival rate with a 90% confidence level across reported case temperature curve
Size-volume-form factor: Lumens (or watts) per volume (or mass)	100 W Driver: 650 g 475 cm^3	100 W Driver: 300 g 275 cm^3	150 W Driver: 200 g 175 cm^3

Table 4.6 Advanced Lighting Application Concepts

<table>
<tr><th colspan="4">Advanced Lighting Application Concepts</th></tr>
<tr><td colspan="4">Description: Develop subsystem or full lighting product concepts that demonstrate new or advanced lighting features to target or energy savings and improved effectiveness through improvements to lighting application efficiency (LAE). Improvements can be to the LED chip, package, module, or integrated lighting product, but must show improvements at the application level. LAE can be addressed with spectral content matched to an action spectrum, improved optical delivery to the end user, better intensity control, or a combination of these areas. Concepts could also demonstrate favorable form factors for improved LAE, lighting performance, ease of installation, or building integration, or could demonstrate the use of 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. Improvements to aspects of LAE should outweigh negative impacts to other aspects of LAE for net energy savings and improvement of effectiveness of lighting.</td></tr>
<tr><th>Metrics</th><th>2021 Status</th><th>Interim
2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Color-mixed luminaire performance across operational range (user may define metrics for specific application use case)</td><td>133-158 lm/W
(3000-4000 K, 80 CRI)
Depends on application</td><td>204 lm/W
(3000-4000 K, 80 CRI)</td><td>281 lm/W
(3000-4000 K, 80 CRI)</td></tr>
<tr><td rowspan="3">Improved Lighting Application Efficiency (user may define metrics for specific application use case)</td><td rowspan="3">Energy savings through increased light source efficiency</td><td>Increase the optical delivery efficiency to the end user by 2x</td><td rowspan="3">60% decrease in energy consumption based on LAE improvement (not including source efficiency improvements)</td></tr>
<tr><td>Increase effectiveness and efficiency of spectral power distribution with action spectra for the application</td></tr>
<tr><td>Demonstrate and quantify energy savings through aggressive intensity control</td></tr>
<tr><td>Productivity Improvement</td><td>Lights only optimized for visual function</td><td>Demonstrate and quantify improvements to health and well-being, productivity, safety, and/or reduction in counter-productive aspects of lighting.</td><td>Demonstrate a quantifiable increase to health and well-being, productivity, safety tied to the lighting design.</td></tr>
<tr><td>Form Factors</td><td>Legacy luminaires</td><td>Luminaires optimized for application efficiency and architectural integration</td><td>Luminaires with weight and volume reduction by 50%.</td></tr>
<tr><td>Sustainability</td><td>Traditional luminaire materials of construction</td><td>Eco-friendly designs with minimized component count, and the use of low-embodied energy materials, recycled materials, or bioderived materials.</td><td>Luminaire with content that is 70% recyclable, reusable, bio-derived, and free of harmful chemicals.</td></tr>
</table>

4.1.3 Lighting Manufacturing Technologies

Priority R&D topics in Lighting Manufacturing Technologies are described in detail in the 2021 DOE SSL Program's Manufacturing Status and Opportunities document, which can be found at www.energy.gov/eere/ssl/articles/2022-doe-ssl-manufacturing-status-opportunities, and a summary list of manufacturing R&D priorities is provided below.

LED Chip & Package Manufacturing

- **LED Wafer Wavelength Uniformity:** Development of improved MOCVD hardware platforms to allow an entire LED wafer to yield into a single performance bin.

- **LED Wafer Fabrication Automation:** Creating improved automation and integration within 100 mm and 150 mm wafer fabrication plants (fabs) by developing turn-key manufacturing execution systems, tool-to-tool wafer movement, communication platforms, and statistical process control systems not readily available for the compound semiconductor fabs.

- **LED Device Testing Productivity:** Development of unique schemes to test sections of the LED wafer instead of individual die one at a time to improve LED device testing productivity. This will require careful process uniformity understanding of upstream processes.

- **Measurement Innovation for Micro-LEDs:** Implementing micro-LEDs for lighting involves major changes to fabrication and measurement infrastructure used in mass production for LEDs. New measurement techniques need to be developed to identify good performing die at the micro-scale with high throughput.

- **Micro-LED Mass Transfer Processes:** Designing economical mass transfer methods with extremely high yields to make the use of numerous micro-LEDs in luminaire products.

- **Chip-Level Optical & Electrical Integration:** Integrating increasing amounts of functionality (optical control or drivers) at the wafer level can lead to cost savings on the luminaire assembly stage taking advantage of the more automated surface mount technology processes or semiconductor fabrication equipment over current luminaire assembly schemes.

LED Luminaire Manufacturing

- **Universal Voltage Drivers:** Creating universal voltage power supplies cost-effectively for luminaires can simplify the manufacturing supply chains allowing manufacturers to better leverage economies of scale.

- **Luminaire Assembly Automation:** Developing new luminaire designs that are easier for automated assembly by designing around the more manual and difficult to automate assembly processes.

- **Additive Manufacturing of Luminaires:** While proof-of-concept demonstrations exist for the use of additive manufacturing in many areas of the SSL value chain, R&D is required to develop printable materials with the sufficient properties to replace existing manufacturing approaches in electrical, thermal, and optical components for luminaires.

- **Sustainable Materials Supply Chain for Lighting:** There is an opportunity to jump start sustainable supply chains by developing and integrating sustainable materials, and to make every component of a lighting system recyclable, reusable, and free of harmful chemicals.

OLED Manufacturing

- **Customizable Manufacturing of Patterned Substrates for OLEDs:** The development of patterned substrates is required so that multiple panels can be fabricated with edges that are sealed to improve reliability of OLED devices.
- **Rapid Deposition of Organic Materials:** Reducing the deposition time for OLED panels require alternative deposition techniques to increase throughput and lower manufacturing cost.
- **Affordable OLED Encapsulation Techniques:** A simpler, less costly encapsulation technique is required for OLED stability.

4.2 Lighting Science R&D

Table 4.7 Lighting Application Efficiency Framework

<table>
<tr><th colspan="4">Lighting Application Efficiency Framework</th></tr>
<tr><td colspan="4">Description: Develop a general framework and computational model 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 can have temporal dependency as occupant positioning and activities in a space change over time. The framework should also work to develop general LAE metrics to calculate the LAE for various applications. The proposed R&D and resulting models should be validated with lighting mock-ups with optimized light placements and optical distributions and then measured.</td></tr>
<tr><th>Metrics</th><th>2021 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td><i>Lighting Application Efficiency</i> framework and computational model</td><td>No comprehensive framework or model</td><td>Application agnostic model that can be used to optimize total <i>Lighting Application Efficiency</i> with respect to application setting
Define application agnostic metrics to calculate LAE
Quantification of energy savings and improvements to lighting function through LAE improvements</td><td>Ubiquitous use of <i>Lighting Application Efficiency</i> modeling for building, room, lighting layout, and product design</td></tr>
<tr><td>LAE: Optical Delivery Efficiency</td><td>Limited understanding</td><td>1) Develop estimates of proportion of emitted light that supports the function(s) of the lighting.
2) Optimize optical distribution, lighting layout, and/or active control of optical distribution to increase this proportion.
3) Develop target for further improvements
4) Understand glare</td><td rowspan="3">Holistic understanding of LAE aspects, trade-offs, and energy impacts to guide lighting design</td></tr>
<tr><td>LAE: Spectral Efficiency</td><td>Spectral efficiency is understood and somewhat optimized for eye response</td><td>Quantification of effectiveness of delivered spectrum compared to a defined ideal for a given application</td></tr>
<tr><td>LAE: Intensity Control</td><td>Limited use of automatic and manual controls to control light intensity</td><td>Quantify benefits of simple, resilient controls to achieve optimal light levels at relevant surfaces according to function(s) of lighting and temporal need in different applications</td></tr>
</table>

Table 4.8 Human Physiological Impacts of Light

<table>
<tr><th colspan="4">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 for health and well-being of general, day-working population
Relating biomarkers to lighting stimulus and physiological responses
Environmental and behavioral mediating factors that affect physiological responses to light in realistic settings
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. Lighting Integration and Validation 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>2021 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Human physiological responses to light understanding and design guidance</td><td>Preliminary field studies with early lighting design guidance for improved health and well-being</td><td>Lighting design guidance for day-working institutional settings for optimal health and well-being</td><td>Broad implementation of efficient lighting that reduces or eliminates negative physiological impacts of lighting</td></tr>
<tr><td>Human physiological impacts: quantification of health benefits of improved lighting</td><td>Lab-scale understanding of individual health impacts</td><td>Quantification of nationwide health impacts of improved lighting for health and well-being</td><td>Verification of large scale health impacts due to improved lighting application for human physiological responses</td></tr>
</table>

4.3 Lighting Integration and Validation

Table 4.9 Lighting Integration and Validation R&D Opportunities

<table>
<tr><th colspan="4">Validating Lighting Research in Practice</th></tr>
<tr><td colspan="4">Description: This topic describes research and efforts to transition research and lighting technology capabilities and lighting science understanding to broad-scale practice to achieve the objectives of the DOE SSL Program, specifically lighting energy savings and occupant health and productivity.</td></tr>
<tr><th>Metrics</th><th>2021 Status</th><th>Interim 2025 Targets</th><th>2035 Targets</th></tr>
<tr><td>Technology transition to practice: Office, Manufacturing/Production, Senior Care (similar institution), Roadway</td><td>Lab-scale/small scale studies demonstrating initial prospects for energy savings, health/well-being, productivity, safety improvements</td><td>Realistic scale demonstration and quantification of benefits and best practices developed</td><td>Broad implementation of energy savings technology or understanding to lighting practice</td></tr>
<tr><td>Evaluation and quantification of large scale impacts of SSL technology</td><td>Limited direct validation of lighting impacts on:
Energy Savings
Productivity
Health/Wellbeing
Safety</td><td>Initial quantification of impacts of light based on lighting validation research findings</td><td>Measured and validated understanding of impacts of light on:
Energy Savings
Productivity
Health/Wellbeing
Safety</td></tr>
</table>

5 Appendix

5.1 Ongoing R&D – Currently Funded Projects

5.1.1 FOA

Table 5.1 SSL R&D Portfolio: Current Research Projects, August 2021

Research Organization	Project Title
Arizona State University	Improved Light Extraction by Engineering Molecular Properties of Square Planar Phosphorescent Emissive Materials
Columbia University	Environmentally Robust Quantum Dot Downconverters for Highly Efficiency Solid State Lighting
Eaton Corporation	Additively Manufactured Solid-State Luminaire
Eaton Corporation*	Automated Luminaire Design and Local Manufacturing for Highly Efficient, Customized Lighting Solutions
Iowa State University	Enhanced Light Outcoupling from OLEDs Fabricated on Novel Low-Cost Patterned Plastic Substrates of Varying Periodicity
Lumileds, LLC	Efficient Green and Yellow LEDs for Solid-State Lighting Applications
Massachusetts Institute of Technology	Multifunctional Optical Outcouplers for Efficient and Stable White Organic Light Emitting Diodes
Nanosys Inc.	Stable Cadmium-Free Down-Converters for Solid State Lighting
North Carolina State University	Manufacturable Corrugated Substrates for High Efficiency OLEDs
Ohio State University	High Efficiency InGaN LEDs Emitting in Green, Amber, and Beyond
OLEDWorks, LLC	High Efficacy, Long Lifetime Flexible White OLED Lighting Panels
Osram Opto Semiconductors*	Cd-Free QD Building Blocks for Human Centric Lighting
Pacific Northwest National Lab*	Development and commercialization of design tools for predicting occupant and energy impacts of building lighting systems
Palo Alto Research Center*	Scalable Thin LED Light Sheet Platform
Pennsylvania State University	Low Refractive Index OLEDs for Practical High Efficiency Outcoupling
Pennsylvania State University*	Development of Lighting Application Efficacy Measurement Framework
Pennsylvania State University*	High Aspect Ratio OLEDs
Rensselaer Polytechnic Institute	Spatially Adaptive Tunable Lighting Control System with Expanded Wellness and Energy Saving Benefits
Thomas Jefferson University*	Applying Tunable Solid State Lighting to Physiological Parameters for Health and Wellness
University of California, Santa Barbara*	Solutions to Droop and the Green Gap by Novel Carrier Injection
University of Michigan	From Deposition to Encapsulation: Roll-to-Roll Manufacturing of Organic Light Emitting Devices for Lighting
University of Michigan*	Increasing the Radiative Rates of Triplet Emitters to Achieve Long-Lived and Efficient White-Emitting OLEDs
Virginia Polytechnic Institute and State University	Investigating the Health Impacts of Outdoor Lighting
Virginia Polytechnic Institute and State University	Adaptive Lighting for Streets and Residential Areas

***New selections as of August 2021**

5.1.2 SBIR

Research Organization	Project Title
Electroninks	High Performance Substrate Embedded Microgrids for High Efficiency, Flexible Organic Light Emitting Diodes
Glint Photonics	Antireflective Materials for High-Efficiency Lighting
Glint Photonics	Lossless beam-width adjustment with low-cost mechanics
InnoSys	Novel Materials for Flexible Solid-State Lighting
MONDE Wireless	Novel Materials Structure for Efficient and Cost-Effective Direct Emission Solid-State Lighting
OLEDWorks	Printed Anodes and Internal Light Extraction Layers on Flexible Glass to Create Cost Effective High Efficacy Bendable OLED Lighting Panels

5.1.3 OLED Testing Opportunity

DOE implemented the collaborative R&D testing opportunity in 2014 to enable U.S.-based OLED component developers and manufacturers to incorporate various R&D-stage components into a high-quality baseline OLED device.

The OLED testing opportunity is an open process with no closing date. OLED component developers and manufacturers can apply to have a product tested, or to become a test facility, at any time. Applications are evaluated as they are received. The program was initiated following requests from the community for a more rapid process to obtain support for smaller projects than those funded through FOA solicitations. The process is suitable for materials that are almost ready for commercialization or can provide independent evaluations of innovative materials or structures before submission of proposals for SBIR or FOA projects.

Seventeen rounds of testing, involving 11 different organizations, have been completed as of August 2021. Some of the organic stack materials that have been evaluated have already been incorporated in commercial products. Early stage testing has been mainly focused on alternative transparent conductors and integrated substrates.

More background information on the program can be obtained from the DOE SSL web site.[46]

5.1.4 PNNL

PNNL's current research in support of the DOE SSL Program is organized into six high-level topics:

5.1.4.1 Lighting Visual Science

Includes four focus areas: ***color science, glare, flicker, and luminance patterns/uniformity***, all aspects of lighting quality that relate directly to the development of energy efficient lighting products, as well as environmental satisfaction and behaviors of building occupants. This research aims to better understand human responses to illuminated environments, develop evidence-based metrics to characterize lighting product/system performance, and standardize guidelines to facilitate technology development and use. Ultimately, the results of this work are expected to reduce energy use intensity, improve the quality of the built environment, and maximize lighting benefits delivered per Watt. To achieve these goals, PNNL has developed state-of-the art apparatuses for conducting human factors research in a laboratory setting, while simultaneously working to develop novel research methods that address experimental bias and validity concerns. While laboratory-based research is core to this research topic area, simulations sometimes serve to extend the applicability of the lab

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[46] https://www.energy.gov/eere/ssl/oled-testing-opportunity

findings, and field-based work may also help to validate the results obtained in simulations and under lab-based controlled conditions.

5.1.4.2 Data-Driven Lighting Systems

Focuses on using data to improve the design, configuration, and operation of advanced lighting systems. Research explores how data generated during lighting system design and integration with modular assembly technologies, reported energy data, and operational data that informs maintenance status and needs (e.g., remotely monitored electrical conditions, asset information) can drive the development and deployment of next-generation high-performance lighting systems in both retrofit and new construction environments. Targeted outcomes include lighting systems that facilitate data-driven energy management, automated fault detection, diagnosis, and prediction, reducing maintenance costs, and improved building flexibility, resilience, and grid interaction. Key research topics include: 1) Exploration of ***digital validation & verification design tools*** to increase lighting system performance and decrease costs; 2) Validation of ***data-driven energy management*** ability to save energy and improve lighting system performance; 3) Validation of operational data to improve and ***streamline lighting system maintenance***; 4) Exploration of potential for lighting systems to be integrated with ***modular assembly technologies*** and thereby both contribute to and benefit from potential advantages over traditional building construction methods.

5.1.4.3 Lighting Interactions & Outcomes

Seeks to realize the range of potential benefits of advanced lighting systems with a focus on the people involved in installing and configuring these systems and the occupants who work, live, learn, heal, and play in spaces lighted by these systems. The research has two primary domains: 1) ***Installation and configuration complexity*** of advanced lighting systems in various interior and exterior applications. This research occurs through observational studies conducted in “Living Laboratories,” organized under the Next Generation Lighting Systems (NGLS) program. These are real-world indoor and outdoor spaces where the process of lighting system installation, configuration, commissioning, and operation can be objectively observed; 2) ***Occupant responses*** to and interactions with advanced lighting systems in hospitals, schools, senior care centers, offices, warehouses, and outdoor areas. This research primarily takes place through field studies in realistic settings where lighting system performance can be assessed, and data can be collected indicating how occupants use the lighting system and how the lighting conditions affect occupants’ health, productivity, and satisfaction. The facility types targeted for this research were chosen for the large proportion of lighting energy use they represent nationwide, the potential for energy savings, and the potential for lighting improvements that can provide specific benefits to occupants and workers in those spaces.

5.1.4.4 Emerging Lighting Technologies

RD&D activities for near or new-to-market lighting technologies and practices that contribute to reduced energy, enhanced environments, and improved economics. Focus topics include: 1) New ***L-Prize competition*** announced in FY21, which calls for innovation in LED luminaires and systems, providing cash awards to lighting innovators that develop lighting systems with breakthrough lighting energy efficiency, quality of light, connectivity, and life cycle performance. The prize has three distinct phases: concept, prototype, and the final manufacturing and installation phase where competitors will realize the economic and energy savings benefits by manufacturing and installing the L-Prize technologies in US buildings. In all three phases, the competition encourages and rewards innovation for diversity, equity, and inclusion, as well as in technology and design. 2) Since the SARS-CoV-2 pandemic, ***germicidal ultraviolet (GUV) disinfection*** products have been introduced, many with questionable effectiveness, inflated performance claims, and/or safety concerns. Coordinated testing and analysis of commercially available GUV products in both laboratory and field settings will assess product effectiveness, safety, and energy performance. This process will also assess current metrics, standards, and testing methods. The goal of the program is to improve GUV product performance while reducing inflated performance claims and safety risks to users. 3) ***Sustainability and life cycle*** impacts of lighting and building systems are topics of growing interest and importance for both economic and environmental benefits. Potential issues to be pursued in this effort: a) Life cycle energy use of LED luminaires compared to fluorescent luminaires; b) Availability of waste management and recycling services applicable to LED lighting systems across the country; c) Relative importance of luminaire material selection and durability, light source efficacy and rated life, component replaceability, and maintenance practices in improving lighting life cycle environmental performance; and d) Potential of contract-based lighting maintenance and installation services (such as Lighting as a Service) to provide LED luminaire maintenance, reuse and remanufacturing.

5.1.4.5 Digital Electric Systems & Grid Interaction

Explores existing and emerging synergies between ***building lighting systems and other electrical systems*** that might be leveraged to enhance their ***flexibility to provide grid services*** by responding to grid signals (e.g., dynamic electricity prices) or via connected community coordination (e.g., reducing or increasing generation or demand in coordination with other assets located on the same distribution feeder). Research will focus on exploring the capabilities and synergies enabled by market-available "digital" DC electrical distribution technologies and the integration of battery energy storage systems (BESS). Digital DC distribution technologies such as Power Over Ethernet (PoE) and Universal Serial Bus (USB) deliver both electric power and network communication over a single plug-and-cord cable. Such "digital electrical systems" might offer technical and market transformation advantages over traditional AC distribution approaches, enabling greater potential to provide grid services, and possibly easier integration into microgrids and other higher-level DER systems or aggregations, supporting accelerated electrification. BESS offer the ability to shift power draw from the electric grid to different times of the day to serve a variety of electricity cost management, grid service, and resilience use cases. Research questions will target specific synergies between lighting and other electrical systems; specific digital DC distribution technologies, system architectures, and BESS integrations that maximize those synergies; and the potential for those synergies to deliver increased flexibility and grid service potential.

5.1.4.6 Daylight and Electric Light Integration

Supports improved daylighting and electric lighting systems design and implementation in buildings, extending the prior knowledge in several important ways: 1) ***Spectral modeling***: prior simulation work has focused almost exclusively on determining illuminance levels in buildings, which are based only on the photopic human response. This project will simulate the spectral interactions of light sources, building surfaces and objects across a full range of narrow spectral bands (e.g., 5 nm widths), using new tools such as the Adaptive Lighting for Alertness (ALFA) software. 2) ***Calculating metrics for occupant needs***: in addition to occupant visual needs, this project will estimate metrics related to the emerging science on so-called non-visual effects of light in buildings, such as circadian rhythms and acute alerting. These metrics require accurate determination of the spectrum and intensity of light at expected occupant eye positions throughout the occupied spaces, for different times of day, throughout the year, as both daylight and electric light are dynamically changing in spectrum and intensity. 3) Defining ***performance characteristics for connected sensor systems***: Prior research on integrated daylight-electric lighting systems has explored optimized positioning of sensors on the ceiling or other building locations, direction of view, responses to daylight or electric light only or to the combination of both, and innovative sensing devices such as high dynamic range imaging devices. Future characteristics of connected lighting systems may include the ability to sense spectral and directional lighting information and the ability to share this data with other building systems. Planned simulations will include evaluations of the flow of light throughout spaces, including at various possible sensor locations, to form the basis for recommendations of sensor characteristics that would best support these expected functions of connected systems in future buildings.

PNNL employs a range of research approaches to the multi-disciplinary science and practice of energy-efficient lighting, and to the realization of technology adoption, energy savings, and lighting benefits in the built environment. In the figure below, the topic areas are listed in the first column, along with sub-topics to be addressed. The topic areas are matrixed with research methods and approaches, from lab and simulation work to field research to market transformation activities.

5.2 New Frontiers R&D

The DOE SSL 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 in lighting effectiveness and productivity in 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 SSL Program is developing a framework for evaluating the energy savings and productivity benefits for these new frontiers in lighting 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 SSL 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

5.2.1 Germicidal Ultraviolet

The primary application space for germicidal ultraviolet (GUV) over the past decade has been for water treatment. Other applications include HVAC (coil and air disinfection), surface disinfection (e.g. in UV robots), and some upper air disinfection applications. The COVID-19 pandemic has greatly increased the spotlight on GUV irradiation for air and surface disinfection, especially outside of hospitals in both occupied and unoccupied rooms. When considering the potential jump in electricity load with increased implementation of GUV in buildings, this area represents a growing opportunity to embed energy saving luminaire designs. Currently GUV sources and luminaires have low efficiencies but there is much headroom to improve the application efficiency design with technology advancements. There are a number of areas in GUV technology that require further research and development. A few of these key areas are described below.

UVC Source Efficiency: When considering different UVC radiation source technologies, the factors to consider include size, lifetime, turn-on time, emission wavelength, undesirable elements (e.g., mercury and ozone), energy consumption, and cost. Currently, mercury lamps are the incumbent sources for GUV, while LEDs lag in terms of efficiency. Low pressure mercury vapor lamps (LPMV) have high efficiency (30-40%), low cost, a variety of sizes and shapes, and years of field experience, but they also contain mercury (similar to all existing fluorescent light technologies). Quartz glass is used for these lamps to filter out the ozone generating peaks, thus leaving the 254 nm UVC emission line. Lifetimes of the lamps are typically around 9000-10,000 hours. KrCl excimer lamps provide a lower wavelength peak around 222 nm, which has potential benefits for reduced skin and eye hazard. These lamps also must also filter out the low wavelength peaks (which create ozone), thus dropping the source efficiency from ~ 6-8% unfiltered down to 2-3% once filtered. The lifetimes for these KrCl excimer lamps are in the range of 3000-5000 hours.

Today, UVC LEDs are less efficient than LPMV and excimer sources. The efficiencies are low (~ 2-4% power conversion efficiency at 260 nm) due to difficult materials challenges, which are exacerbated as the wavelength decreases. Figure 5.1 surveys UV LED R&D performance results from many labs and manufacturers across the globe. The majority of research in the field has been focused on the 260-280 nm wavelength range, since this is where devices are more efficient in the UVC band, though there is a steep efficiency drop off as the wavelengths approach the deep UV wavelength range (< 240 nm). The advantage of deep UV wavelengths is that the photons cannot penetrate past the epidermis layer of human skin, meaning that disinfection can occur without causing damage to the skin. [180]

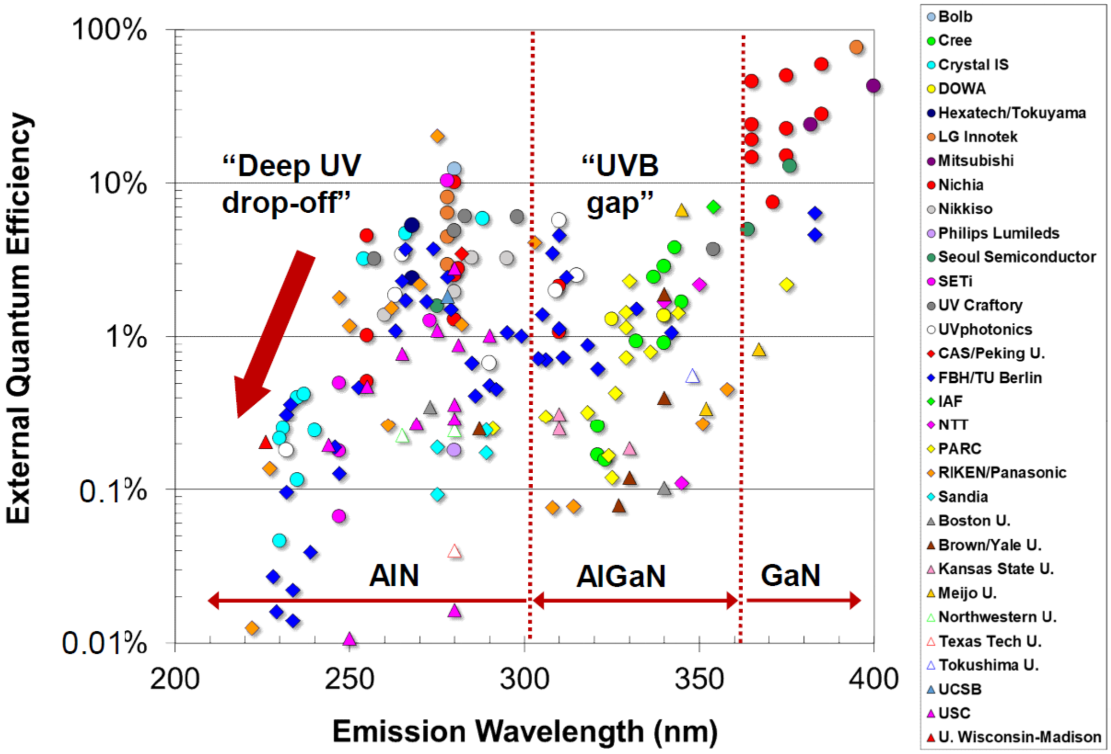


Figure 5.1 A survey of the external quantum efficiency of UV LEDs from researchers around the world. There is a steep efficiency drop off moving from the longer UV-C range (270-280 nm) down to the deep UV-C range of 230 nm. [180]

Though the UVC LED efficiencies are low, they potentially have much headroom to improve efficiency, unlike the existing lamp technology which does not have the same latitude for significant performance improvements. Lifetimes also have the potential to surpass conventional UV lamps; today's devices available have a variety of lifetimes from 4000 hours up to 10,000 hours for 280 nm LEDs.

The past two decades of learning in GaN-based semiconductors for visible LEDs can provide a solid materials foundation to leverage for future innovation in materials research. The current performance challenges of deep UV LEDs, in addition to the steep drop in EQE as wavelengths decrease, include the drop in radiative recombination efficiency, current injection efficiency, and light (photon) extraction efficiency. R&D approaches for improving the efficiencies of deep UV LEDs include:

- Reducing defect density for both threading dislocations (developing low-cost, low threading dislocation density templates) and point defects (epitaxial growth conditions of the AlGaN active region);
- Advanced heterostructure designs for improved carrier injection;
- Implementing UV-transparent layer structures (p-type epitaxial layers and p-contact materials) to improve light (photon) extraction;
- Employing tunnel-junctions and UV-reflective contacts to improve device performance;

- Developing UV transparent encapsulants (for LED packages).

GUV Luminaire Designs: Since UV photons are expensive and potentially dangerous, care must be taken in controlling the distribution of UV radiation leaving the source. Figure 5.2 shows a typical upper room air disinfection set up where the upper air is irradiated with UVC and then natural convection mixes the "cleaned" upper air with the lower air being breathed in by the occupants. Air movement in the room is critical for effective upper room GUV installations.

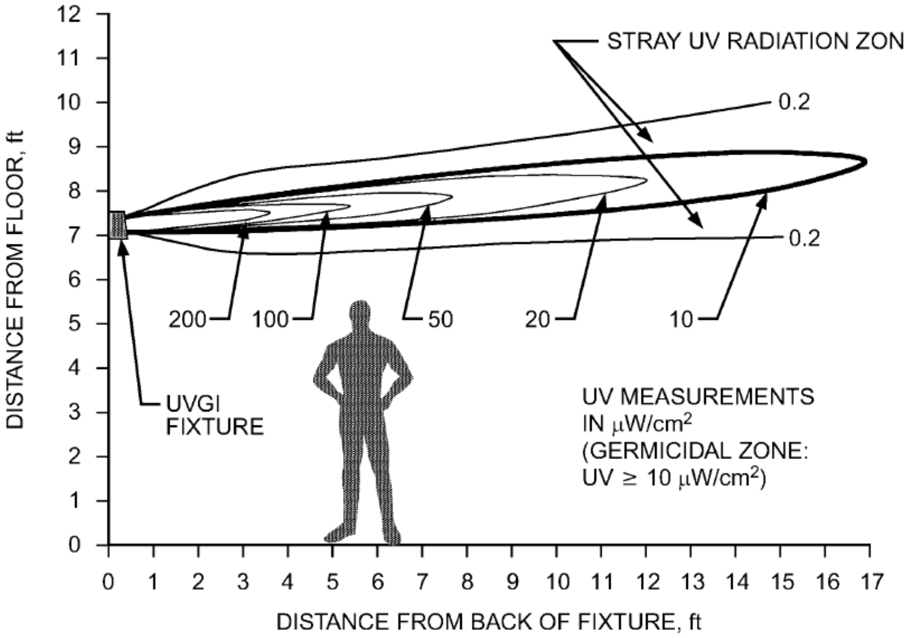


Figure 5.2 Typical elevation view showing GUV fixture placed above the room occupants for safety. [181]

GUV luminaire designs include upward emitting luminaires used in installations with high ceilings to irradiate the upper room air, though many designs employ louvres for lower ceiling heights to reduce direct downward UV radiation to ensure it stays away from the occupants of the room. Louvres also reduce reflectance of UV from the ceilings to the room occupants. These configurations and representative products are shown in Figure 5.3. While GUV luminaires have existed for a while, effective delivery of UVC from the radiation source to the room can be greatly improved.

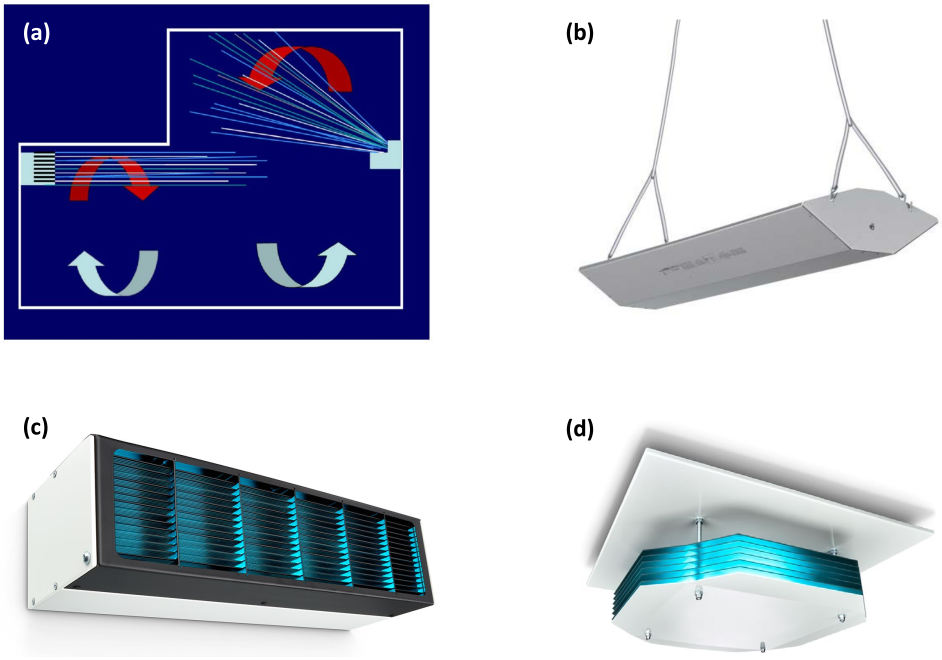


Figure 5.3 GUV luminaires designs. (a) Schematic of UV radiation pattern for an open top luminaire and a louvered luminaire design. Images of (b) open top GUV luminaire, (c) louvered wall-mounted GUV luminaire, and (d) louvered ceiling-mounted GUV luminaire. [182] [183]

Current GUV luminaires have a very low application efficiency of radiation delivery. Though the LMPV UVC lamp (254 nm) is quite efficient, nearing 40%, the GUV luminaire has low efficiency with only 2% or less of the total input power contributing to UVC optical power delivered. [182] The deep UVC KrCl excimer lamp (222 nm) is only 2-3% efficient when filtered, leading to even lower efficiencies out of the fixture. The omnidirectional emission of the conventional UVC LPMV source must be reflected out of the luminaire and through the narrow louvres leading to large optical losses. A cross-sectional image of a louvered wall-mounted GUV luminaire is seen in Figure 5.4, highlighting the key elements. A parabolic reflector is used to direct UV rays from the omni-directional LPMV lamp out at a slightly upward angle, and the louvres block rays that are not parallel to the louvres to prevent downward UV emission from the fixture into the room.

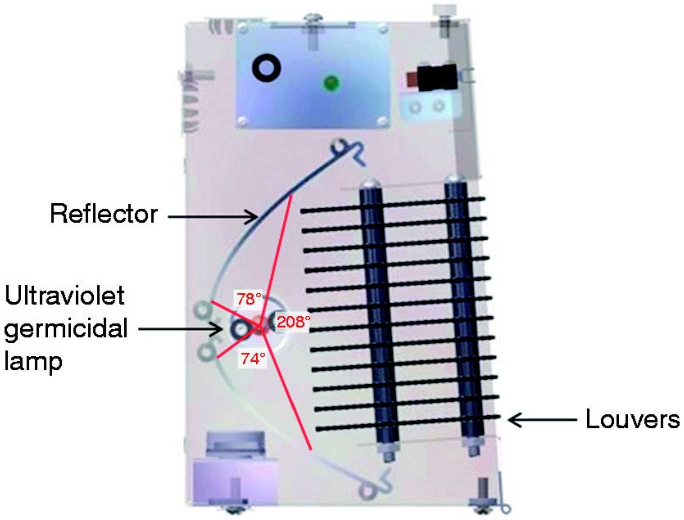
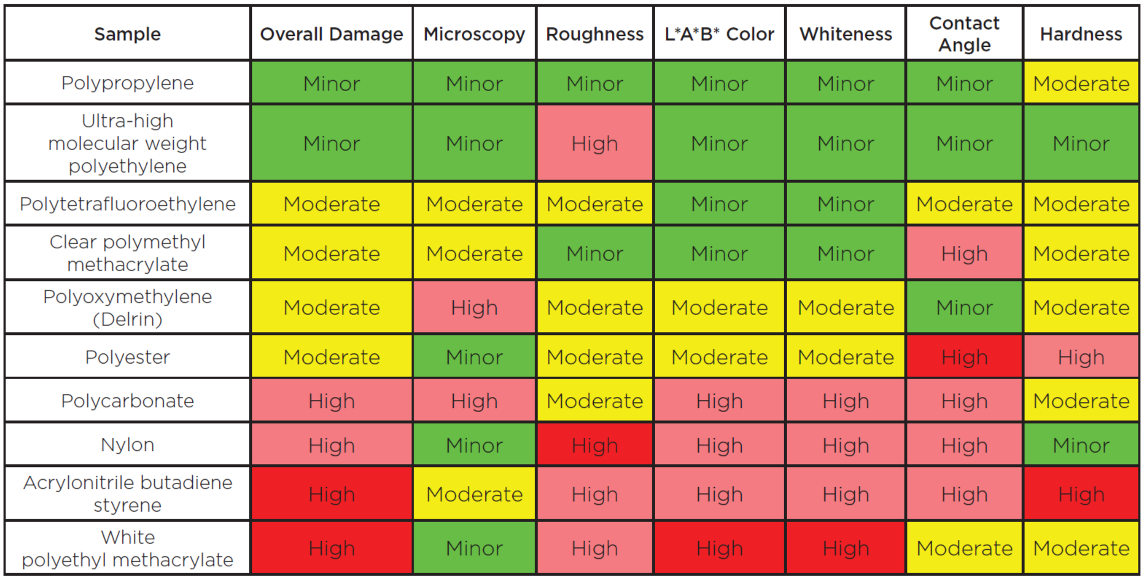


Figure 5.4 Cross-section of a wall-mounted GUV luminaire showing the key elements, including a parabolic reflector to direct UV rays out at a slightly upward angle, and louvres to block rays that are not parallel to the louvres. [184]

UVC LEDs have the potential to provide a more efficient lighting application efficiency since they are directional light sources that can eliminate the loss associated with reflecting the backward emission from the omnidirectional light source out the luminaire. Additionally, the angle of the UV output can be more effectively controlled with a directional source. Luminaires with UVC LEDs are beginning to enter the market for air disinfection, though the efficiency of UVC delivery cannot yet be ascertained from the information on the product specification sheets.

Materials Reliability: The application of UV radiation in the built environment can damage and discolor objects in the space, including building materials, as well as generate particulate matter. UVC is damaging radiation for many common polymers; fabrics, paint, and other organic materials will also undergo UV damage under prolonged exposure used in air or surface disinfection techniques.

One study assessed the damage for a range of polymeric surfaces commonly found in healthcare facilities under UVC radiation. [185] It found that detecting when microscale damage has occurred is predictive of early stage surface damage and also that a group of characterization techniques is needed to better detect early onset damage. A cumulative UVC dose of 28.8 J/cm^2 was used, consistent with the Business and Institutional Furniture Manufacturer's Association test conditions for surface damage. This dosing level was equivalent to using a typical portable UVC device that treats a surface weekly for seven years and the needed dose to achieve appropriate biocidal efficacy. For the test, this cumulative dose was applied in a single exposure, and then the surface was analyzed for color shift to assess whether surface damage has occurred. Figure 5.5 shows a summary of the tests, finding that four plastic surfaces – acrylonitrile butadiene styrene (ABS), nylon, polycarbonate (PC), and white acrylic – consistently showed the most evidence of damage across multiple characterization methods.



Sample	Overall Damage	Microscopy	Roughness	L*A*B* Color	Whiteness	Contact Angle	Hardness
Polypropylene	Minor	Minor	Minor	Minor	Minor	Minor	Moderate
Ultra-high molecular weight polyethylene	Minor	Minor	High	Minor	Minor	Minor	Minor
Polytetrafluoroethylene	Moderate	Moderate	Moderate	Minor	Minor	Moderate	Moderate
Clear polymethyl methacrylate	Moderate	Moderate	Minor	Minor	Minor	High	Moderate
Polyoxymethylene (Delrin)	Moderate	High	Moderate	Moderate	Moderate	Minor	Moderate
Polyester	Moderate	Minor	Moderate	Moderate	Moderate	High	High
Polycarbonate	High	High	Moderate	High	High	High	Moderate
Nylon	High	Minor	High	High	High	High	Minor
Acrylonitrile butadiene styrene	High	Moderate	High	High	High	High	High
White polyethyl methacrylate	High	Minor	High	High	High	Moderate	Moderate

Figure 5.5 The damage for a range of polymeric surfaces commonly found in healthcare facilities under UVC radiation is assessed using a variety of characterization techniques. Four surfaces – acrylonitrile butadiene styrene (ABS), nylon, polycarbonate (PC), and white acrylic – consistently showed the most evidence of damage across multiple characterization methods. [185]

The higher energy UVC photons can also degrade materials used in luminaire construction (optics or polymer based diffuse reflectors). A better understanding of materials degradation issues under UVC excitation is important to enable GUV systems with long lifetime and to prevent damage to the objects in the space. Research is needed to develop new materials with better UVC resistance to mitigate the effects of GUV irradiation in buildings and to help create long-lifetime GUV luminaires. Further research on UVC and materials interactions must be conducted to ensure the lifecycle of common materials is not adversely impacted.

GUV Deployment in Applications: Lighting application efficiency (LAE) describes the amount of generated light (or UV radiation) that reaches the final target for the intended application (i.e. microbes in air or on surfaces). Designing GUV products with LAE in mind is important to reduce energy consumption since GUV luminaires are typically louvered fixtures, which are quite inefficient. Research into the application understanding of GUV deployed in a variety of spaces is needed to create energy efficient GUV delivery designs within the built environment safely and effectively. These application spaces can include new upper room implementation for safety and efficacy of disinfection, implementation in challenging occupied environments (e.g., big box stores) where the breathing zone is far from upper room, and in-duct disinfection of HVAC systems. Innovative use of ceiling designs and luminaire placement to help reduce the use of louvres is one path to improving LAE. Additionally, considering the building design to incorporate GUV can help improve energy consumption. For example, building integration strategies for air disinfection can balance GUV in HVAC equipment and in the upper room air disinfection. UVC disinfection upstream of the HVAC cooling coils can help with air disinfections and the UVC downstream of the coils help keep the coils clean and improves the energy efficiency of the HVAC system overall. The development of simple in-situ measurement systems for GUV luminaire setup, commissioning, and validation is also important in safe and effective use.

GUV Modeling Software: Modeling software that can calculate the radiometric UVC needs (such as absorption/reflection and fluence) will help aid the development of more efficient GUV luminaire designs. Challenges in modeling UVC fluence include:

- The difficulty of predicting surface irradiance and determining disinfection efficacy of surfaces;
- Determining fluence in upper room disinfection applications;
- Simulating complex architectural spaces (e.g., airport, movie theaters, and other geometrically complicated and physically connected) where irradiance distribution from UVC lamps is complicated;
- Establishing accurate gonioradiometric intensity distributions for the UV luminaires and surface reflectance distributions (both diffuse and specular).

Furthermore, the software may need to consider additional factors, such as airflow and room motion, which is different than traditional light modeling. Development work to improve GUV modeling software packages is necessary including implementing computational fluid dynamics models to address the airflow impacts, developing surface reflectance data in the UVC wavelengths (architectural materials catalog required), and developing virtual spherical irradiance meter to calculate the fluence rate.

UV Characterization Methods and Tools: Characterization tools for accurate UV measurements and sensors for airborne pathogen detection must be developed and validated. One challenge with UV measurements is accessing calibration samples required for the calibrating the radiant flux of integrating spheres in the UVC range. Another is optimizing the polytetrafluoroethylene (PTFE) reflective coating of integrating spheres for the low fluorescence of UVC sources. Further, UV detector performance has shown varying levels of accuracy due to poor cosine response behavior leading to inaccurate readings in the 2π measurement geometry. More research is required to deliver accurate detectors and sensors for the GUV application. There is an opportunity to develop innovative sensors for airborne pathogen detection, auditory detection of events (e.g., coughs), or for “biovigilant” systems that have the potential to use UVC as a counter measure for biological threats; this could be done by feature integration added alongside the LED chip or packages, essentially leading to a bio lab on-chip.

Understanding Photobiological Effectiveness: There is a need to better understand the photobiological effectiveness with GUV, both for the safety (dose that is safe for skin and eyes), as well as dose levels that can inactivate the pathogens at various wavelengths. UVC radiation deactivates pathogens by damaging their DNA so the dose needed to deactivate microbe, virus, or fungus depends on the type of pathogen, the UVC wavelength, the environment around the pathogen (e.g., a droplet with a virus inside), and aerosol droplet size surround virus (if applicable). Figure 5.6 shows germicidal action curves for bacteria and other common pathogens as a function of wavelength. Different pathogens have different wavelength sensitivity and will also require different doses of UVC for deactivation depending on its type and its local environment.

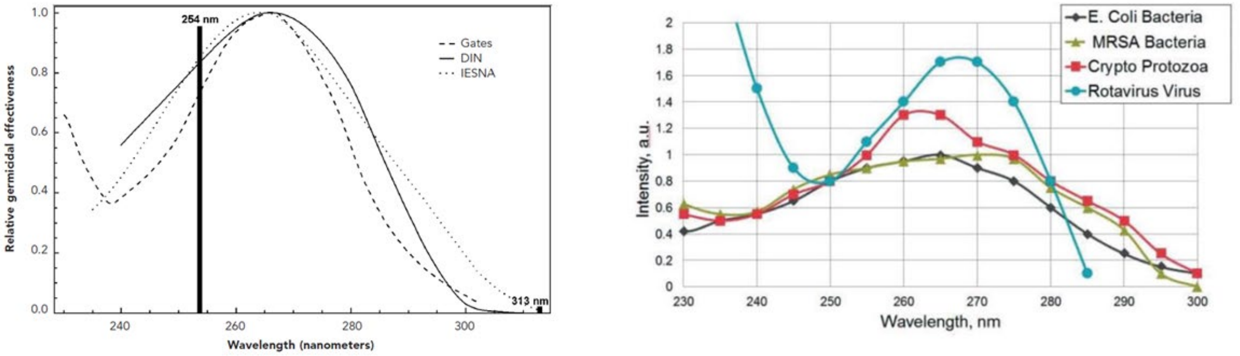


Figure 5.6 The modern germicidal action spectrum developed from a study of bacteria by F. Gates is plotted (left) along with the action spectrum derived by the Deutsches Institut für Normung (DIN) and the Illuminating Engineering Society(IES); the relative output of a low-pressure mercury germicidal lamp is overlaid on these action spectrum. Examples of germicidal action curves indicating the wavelength sensitivity for bacteria and other pathogens is plotted on the right. [186] [187] [188]

More studies to relate the pathogen deactivation level are required to better understand the dose levels and wavelengths required to provide reduced transmission for specific pathogen types and viral loads. Further, studies to understand the action spectrum for various microbes and pathogens at varying UV wavelengths, including how much proteinaceous materials surround the microbes and how it affects the deactivation efficiency of UVC radiation, are also essential. There is an opportunity to develop a standardized library of inactivation constants (D90) at different wavelengths of UVC radiation for a wide range of pathogens in all common states: surface, aqueous, aerosol, etc. Another area for development is the determination of dosing criteria to efficiently disinfect surfaces and/or air in the application. Questions to be answered include how to define the parameters that go into the dosing criteria – e.g. room volume vs. irradiated volume or the quantitation of air mixing. A better understanding of how different room/space geometries affect efficacy and hence dosing criteria will be important.

While UVC is quite effective in inactivating pathogens and microbes, it can be a concern for occupants in terms of eye and skin hazard. The ability of UV radiation to penetrate human tissue depends on its wavelength. A CIE technical report on the potential carcinogenic risk of 254 nm UVC radiation emitted from LPMV lamp systems for GUV applications was authored to review the scientific knowledge on the impact of UVC radiation to health hazard. [189] Overexposure to UVC radiation can result in transient corneal irritation (photokeratitis), conjunctival irritation (photoconjunctivitis) and skin irritation (erythema) are considered to be without lasting biological damage since these effects dissipate within a 24 to 48 hour period.

The American Conference of Governmental Industrial Hygienists (ACGIH) developed guidance for occupational exposure to UVC radiation and have established exposure guidelines to define threshold limit values (TLVs) for exposure. The TLV is the dose to which a worker can be exposed eight hours a day, 40 hours per week for a working lifetime without adverse health effects—as a guideline for avoiding skin and eye injuries. Figure 5.7 plots the action spectra for ACGIH UV hazard, CIE erythema, and CIE non-melanoma skin cancer (NMSC). The decreasing values of the action spectra in the UVC region results from the absorptance of the stratum corneum (erythema) and epidermis (NMSC). UV radiation must penetrate most of the epidermis to reach the germinative layer of the epidermis to pose a NMSC risk. [189] Some researchers have reservations about the interpretation of the ACGIH published TLVs, arguing that time-motion considerations are required for the rational application of UV exposure TLVs. Questions to answer through further research include:

- How much exposure is safe considering the duration and movement in of occupants in a particular space?
- Should TLV be considered as an 8-hour running average or daily dose?
- What eye height is appropriate?
- How to determine if/when to "adjust" for photosensitive individuals?
- If GUV is applied to a non-occupational setting such as schools, places of worship, homes, healthcare facilities, etc., how can the cumulative dose from other daily exposures be determined?

Understanding the safe limitations and exposures in a variety of use-cases to create safe TLVs for different installations would be beneficial for GUV adoption.

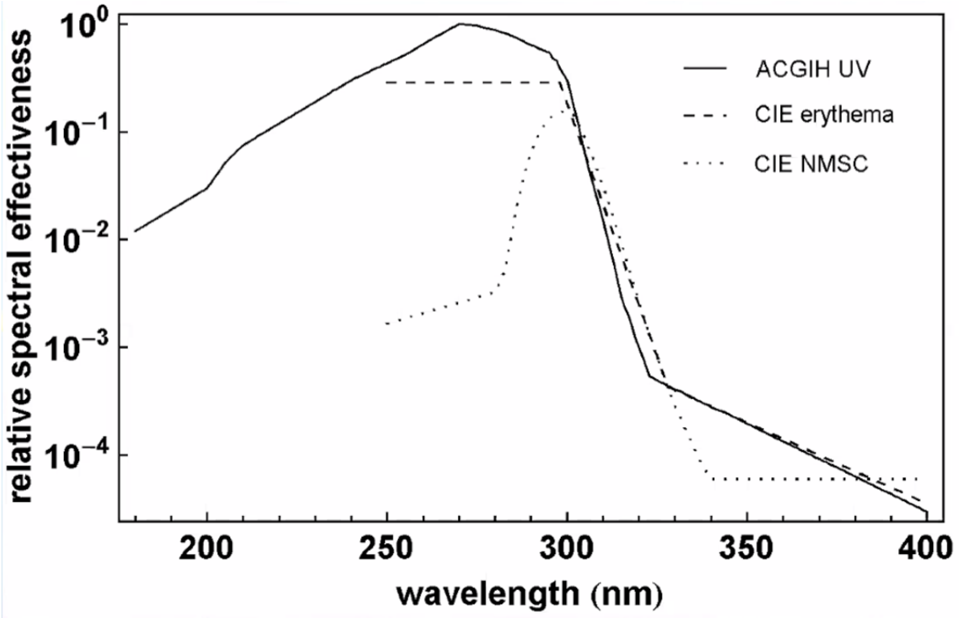


Figure 5.7 The action spectra for ACGIH UV hazard, CIE erythema, and CIE non-melanoma skin cancer (NMSC) are compared. This decreasing of the action spectra values in the UVC region results from the absorptance of the stratum corneum (erythema) and epidermis (NMSC). UV radiation must penetrate most of the epidermis to reach the germinative (basal) layer of the epidermis to pose a NMSC risk. [189]

Standards Development and Guidelines: Forming standards and crafting implementation guidelines for GUV in buildings is a necessary area of development work. As described above, there is a need for standards in areas such as UVC dose guidelines (considering wavelength, time-motion, and pathogen types), product characterization methods, measurement procedures and instrumentation calibrations, and clear guidance for best practice implementation in buildings. Training and education on what is safe and effective germicidal radiation is essential as well. Many different bodies are working on developing these standards and guidelines for GUV. More specifically, work is underway as the Illuminating Engineering Society (IES) and the International Ultraviolet Association (IUVA) signed a memorandum of understanding (MOU) in 2020 to assemble experts in the measurement of UVC emissions to develop American National Standards (ANSI Standards) for the measurement and characterization of UVC device performance. [190] These methods under development include methods for electrical and UV measurement of different UV source types (including LPMV, excimer, and LED sources), the electrical and UV measurement of UVC disinfection products, and finally the calibration and characterization of UVC detectors.

Regulatory bodies must ascertain if GUV products are safe and effective and bring some order to the performance claims GUV products are marketing. Left unchecked, the GUV market for disinfection can lead to major user acceptance issues if products do not perform as advertised. Regulating an uncontrolled GUV market can be done by reviving and adapting some of the mechanisms and programs the DOE SSL Program put in place to support a new and growing SSL industry more than a decade ago (including Lighting Facts, CALiPER, Gateway, technology roadmaps, and fact sheets).[47] [48] [49] [50]There is also the opportunity for DOE to foster and engage collaboration between multiple government agencies to identify and target synergies in the different programs approaching this topic area.

5.2.2 Displays

The energy used for powering televisions and displays in buildings has continued to rise with the implementation of more screens in homes and offices. The combined contribution of televisions, computers and related electronics has approached similar levels of electricity use as general lighting; a substantial fraction of that energy is used by the displays. Although the introduction of LEDs had led to a significant efficiency increase in the backlights that are used to create light in the displays, the demand for improved image quality means that more of that light is absorbed internally. In most high-performance displays, only ~ 5-10% of the light is transmitted through to the observer, so that the overall efficacy is rarely above 10 lm/W – similar to the efficiency of an incandescent light bulb.

The many layers through which the light must pass in a basic liquid crystal display (LCD) are shown below in Figure 5.8. The great majority (probably over 95%) of displays produced currently use liquid crystals to modulate light emitted by LEDs which are placed either at the edge or at the rear of the backlight. Most LCD displays use white phosphor-converted LEDs, but the high-end displays use individual red, green and blue sub-pixels. For example, in “QLED” TVs, quantum dots are used to down-convert light created by blue LEDs to generate the red and green sub-pixels.

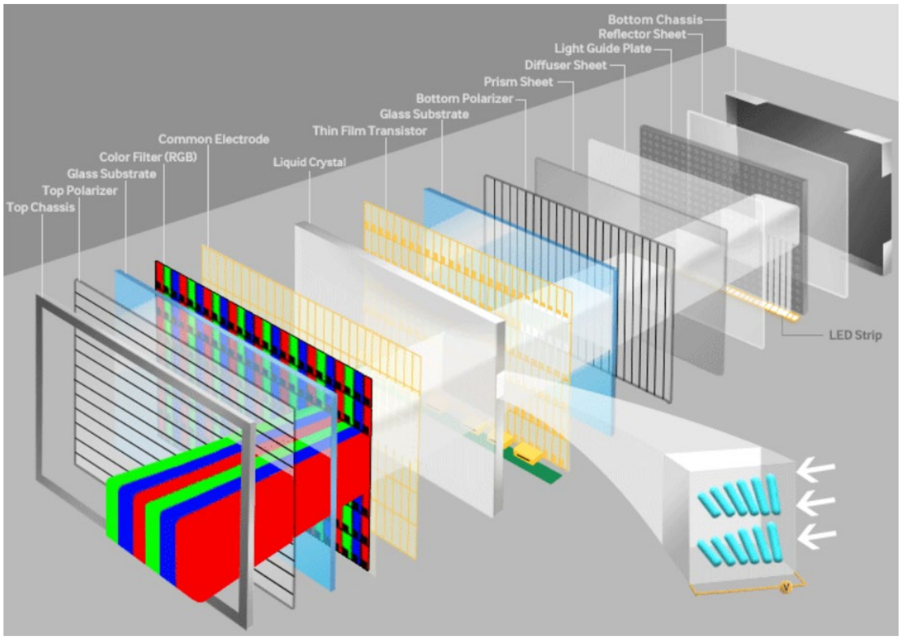


Figure 5.8 Layers in a basic liquid crystal display. [191]

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[47] Lighting Facts: https://www.energy.gov/eere/ssl/led-lighting-facts
[48] CALiPER: https://www.energy.gov/eere/ssl/caliper
[49] Gateway: https://www.energy.gov/eere/ssl/gateway-evaluations
[50] Technology Roadmaps: https://www.energy.gov/eere/ssl/technology-roadmaps

OLEDs are also challenging LCDs at the high end of the market, in both small and large displays. In principle, OLEDs ought to be more efficient, since the light created in each sub-pixel can be controlled independently. However, the need for additional structures to create high-quality images means that there is still significant absorption, and the OLED sources are not yet as efficient as inorganic LEDs.

The largest opportunity for energy savings is addressing the massive optical losses in displays. The transmission of light through an LCD display optical stack is illustrated in Figure 5.8. One of the most critical steps is the use of liquid crystals to control the fraction of light that is blocked in order to vary the intensity in each pixel. This is achieved by applying an electric field to change the orientation of the molecules in the liquid crystal layer, which in turn rotates the polarization of the passing light. The size of the electric field in each sub-pixel is controlled by the array of TFTs. Two polarizers are inserted, one in front of and one behind the liquid crystal layer. The presence of these two polarizers leads to the absorption of at least 60% of the light (100% in the black pixels).

The second essential step is the separation of colors in the sub-pixels. This has traditionally been achieved using color filters, which leads to the absorption of about 70% of the light. The amount of absorption can be reduced by adding white sub-pixels or may be increased to expand the color gamut. The combined effect of these two factors is that a maximum of 12% of the light is transmitted. Each of the other layers in the complex structure lead to additional absorption. Figure 5.9 shows how light for LEDs on the back plane of the display is distributed uniformly across the screen, turned towards the liquid crystals and collimated for optimal control. Around 20% of the light can be lost even before it reaches the polarizers.

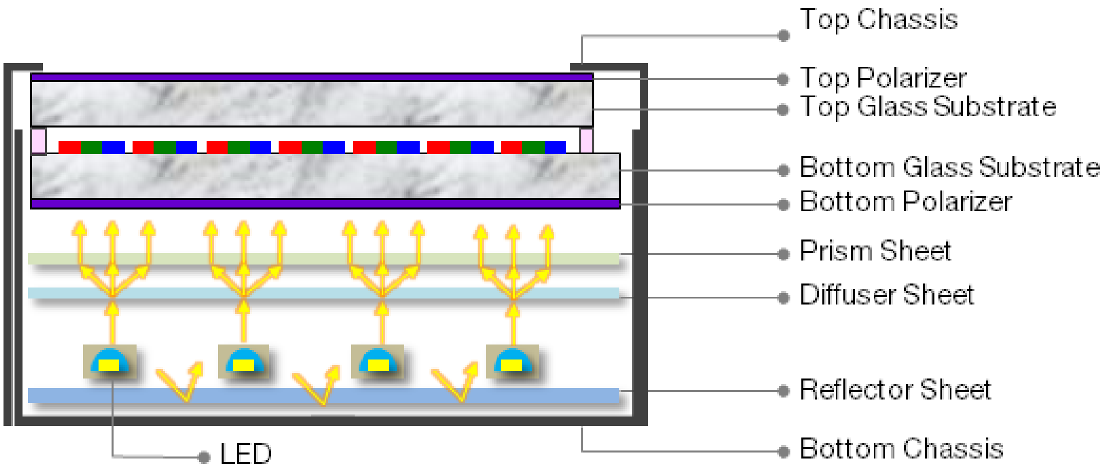

Figure 5.9 Optical film stack cross-section of a direct-view display backlight. [191]

An emissive display architecture can lead to much higher efficiencies by eliminating in the lossy polarizers and color filters present in the LCD approach. There are two primary SSL technologies for producing emissive displays today: OLEDs and micro-LEDs. Each have R&D challenges to improve the performance and implement in mass production, but these technologies provide pathways to significantly decrease display power consumption. The R&D required for each technology approach is highlighted below.

5.2.2.1 OLED Displays

OLED TVs have challenged aggressively for the high end of the market. The major advantages are:

- Better images at wide viewing angle – the intensity and color vary little with angle, while off-axis images are fainter and discolored with traditional LCD displays.
- Wide color gamut – LCD manufacturers have responded by using blue LEDs with quantum dot down-converters to allow the production of more saturated colors

- Faster response time – this is important when viewing movies or sports events
- Higher dynamic range – since no light is created unless needed, OLEDs produce deeper blacks. The energy required to produce very bright spots is limited, since the extra power is confined to the bright area.

Although it was initially thought that OLED structures are much simpler displays, since color filters and polarizers are not needed, that has not proven to be true in practice. One polarizer has been necessary to reduce reflected light. Some manufacturers use white OLEDs and use color filters to separate the sub-pixels. In addition, multiple stacks of OLEDs have been required to achieve the desired luminance. Figure 5.10 shows a typical OLED display stack. Each of the emitter stacks typically contain five or six separate organic layers.

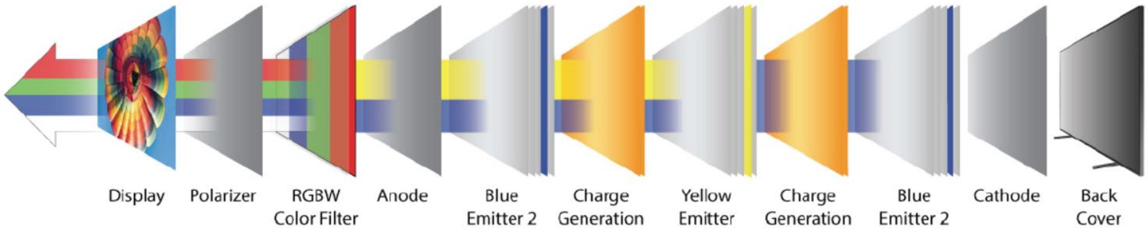

Figure 5.10 OLED display structure as used by Samsung and others. [192]

Since light is created only when needed, OLEDs should in principle be much more efficient. However, this potential has not yet been achieved, due to several factors, including the absorption in the added layers, the low efficiency of stable blue emitters, and light trapping in the layers with high refractive index.

OLED Materials and Structures: The red and green emitters in OLED displays use phosphorescent materials, however, the only blue emitters with the required lifetime are fluorescent materials. These materials produce light only from singlet excitons and not from the dominant triplets, so that their internal quantum efficiency is less than 25%. R&D on more efficient, stable blue emitters is being pursued aggressively for both display applications and lighting (Section 3.2.2.1). Reduction in light trapping is also a major thrust of R&D among the OLED lighting community and would be of value also in display applications (Section 3.2.2.2). The ability to reduce the reflected light in the OLED display will allow removing the polarizer layer currently required.

5.2.2.2 Micro-LED Displays

Micro-LEDs have been hailed as the optimal future light sources for displays of many sizes, from Augmented Reality or Virtual Reality (AR/VR) headsets to smart watches, computer monitors, TVs and video walls. The promise is that three micro-LEDs can be placed in each pixel, so that the intensity and color can be controlled at the source, rather than by modulated absorption. Benefits of micro-LEDs in displays include fast refresh rates, high pixel density, wide color gamut and high dynamic range (with near-infinite contrast ratios because black pixels are entirely off). While there is great promise in the performance characteristics in micro-LED displays, there are a number of technical challenges to address including fabrication of efficient micro-LED devices, mass transfer of the devices to the system backplane, and the driver technology to control a vastly increased number of pixels.

Micro-LED Fabrication: The fabrication of micro-LED chips is a critical area of R&D for displays. While LED die in conventional packages are quite efficient with external quantum efficiencies (EQEs) reaching 80% for blue InGaN LEDs, the efficiency drops as the die are scaled down from a few hundred microns to tens of microns in size. This effect is even stronger in the AlGaInP materials system used for red LEDs due to the higher recombination velocity allowing carriers to reach a defect in the mesa sidewall. Further R&D is necessary to develop fabrication techniques to reduce sidewall damage during the mesa etching process and to passivate the sidewalls to limit carriers recombining with defects present there, as discussed previously in Section 3.2.1.1.

While the performance of the micro-LEDs is one technical challenge, another key issue in implementing micro-LEDs is the major change to fabrication and measurement infrastructure used in mass production for LEDs. LEDs devices are fabricated at the wafer level and then each die is measured for its optical and electrical properties to properly place the LED die in their performance bins. Failing die would be screened out and not sold to the customer. The customer would then receive a sorted die sheet of LEDs from the performance bin they requested. The major difference with micro-LEDs is that they are too small to be probed by conventional test methods, therefore each die cannot be shipped with known performance parameters. Thus, display manufacturers cannot differentiate between conforming on non-conforming die (e.g. if the wavelength is out of range or there is a short). This puts a burden on both the micro-LED manufacturer (to create wafers with very little performance variation across millions of die) or display manufacturers to handle a larger rework processes scale or place redundancy for failed die (i.e. put two die for every pixel in case of a failing die). New methods of measuring micro-LED wafers are required to help ensure the devices shipped are conforming.

Micro-LED wafers require unprecedented levels of uniformity for optical and electrical properties since binning die is no longer practical. This necessitates investing in development of improved metalorganic chemical vapor deposition (MOCVD) hardware platforms to allow an entire wafer to yield into a single performance bin. The wavelength uniformity across a 6” wafer needs to be 1-2 nm. Figure 5.11 shows the wavelength distribution across a 6” blue LED wafer grown in an MOCVD reactor, which still varies to be ~ 4nm for the majority of the wafer area. Veeco and Aixtron both realize the potential of the micro-LED market and have been putting effort into this, though more attention than their internal R&D budgets can support is likely required to overcome this barrier.

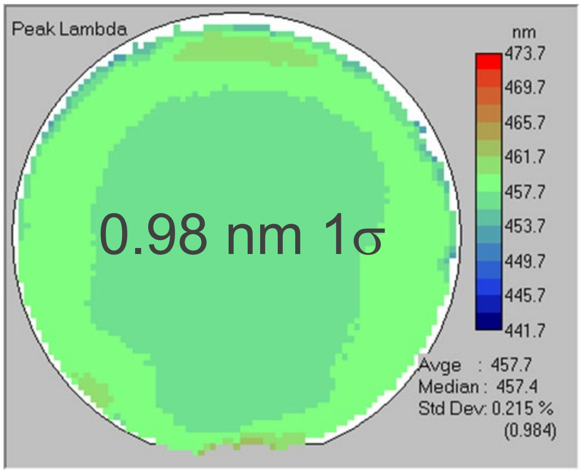

Figure 5.11 Wavelength distribution of a 6” blue LED wafer grown in a Veeco Epik 14x6” MOCVD reactor. The wafer shows ~ 4nm distribution across the majority of the wafer area. [193]

Mass Transfer: Much of the development work in micro-LEDs has been focused on the mass transfer of large arrays of LEDs from the wafer onto the display substrate. Traditional pick and place equipment used to place LED packages on printed circuit boards (PCBs) operates at a speed of 8-10 LEDs per second with a placement accuracy of 25 microns. Die bonding equipment that places LED die into packages are considerable slower at a rate of 1 LED per second but with more accuracy with a placement tolerance of 5 microns. To place the 100 million LEDs required for an 8K display at 10 LEDs per second would take nearly 4 months, making today’s current methods impractical. There has been much effort in industry the past several years to develop economical mass transfer methods with extremely high yields to make the use of so many LEDs a possibility in a consumer electronics product. To date, techniques such as massively parallel pick and place using transfer stamps, sequential/semi-continuous placement, and self-assembly processes are being explored by dozens of companies and researchers. These types of transfer processes, illustrated in Figure 5.12, have different challenges and a clear winner has not yet emerged.

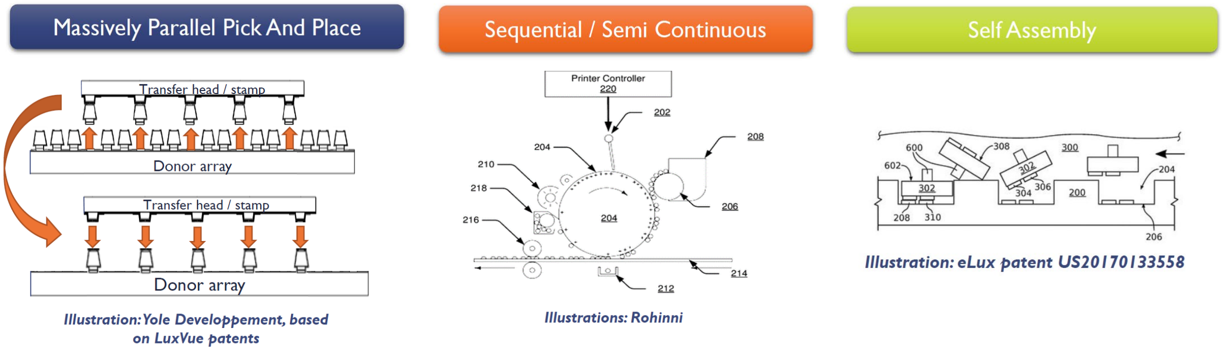

Figure 5.12 Major types of micro-LED assembly and transfer processes. [194]

The speed of transfer of massive numbers of LEDs is only one of the challenges. The transfer process must also provide extremely high yield (99.999% and above) to be viable for mass production. There is the possibility of repair of misplaced or non-functional LEDs, though it must be limited to only a few failures per TV to be viable. Automated rework processes and equipment is another focus of development for micro-LED mass production. There is less effort in this automated rework equipment area, though no less essential to make micro-LEDs viable.

Backplane Technology: Several backplane technologies have been implemented in the design of micro-LED displays depending on the design constraints of the system. With micro-LEDs, the backplanes are not limited to TFT-LCD glass substrates; they can be made of other materials including glass, flexible substrate, silicon substrates and printed circuit boards (PCBs). Often, monolithic displays use micro-LED arrays that are bonded to a CMOS backplane to control those integrated pixels. These are more suited to micro-displays such as for AR/VR. Large displays more often use a TFT backplane where individual micro-LEDs (or groups of micro-LEDs) are transferred using a “pick and place” like technology. These two backplane processes are illustrated in Figure 5.13.

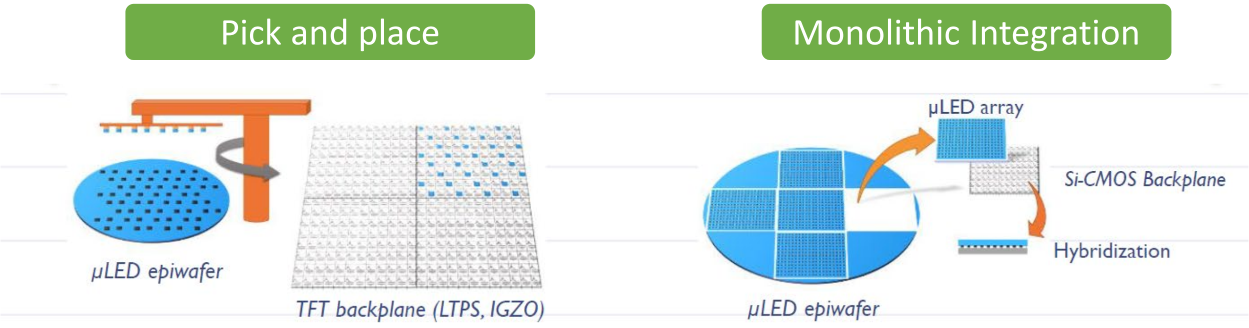

Figure 5.13 Schematic illustration of the micro-LED transfer onto a TFT backplane and the monolithic integration of a micro-LED array on a CMOS backplane. [194]

The TFT backplanes can use amorphous silicon (a-Si), low temperature polycrystalline silicon (LTPS), or indium gallium zinc oxide (IGZO) for the transistor materials. As shown in Figure 5.14, the different TFT technologies can provide better performance leading to smaller traces and transistor sizes to allow for tighter pixels on the panel (higher resolution) or increase the aperture ratio of the panel (higher light transmissivity).

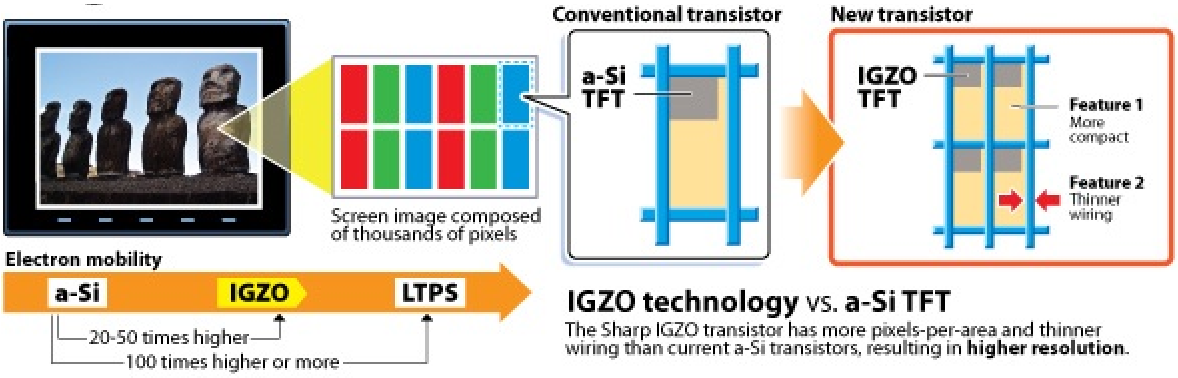

Figure 5.14 Comparison of different TFTs and their impact on speed and performance. The oxide (IGZO) TFT can provide smaller transistors and allow thinner traces and thus allow tighter pixel packing or can improve the transmissivity of the LCD panel. [195]

Micro-LED Driver ICs: A final challenge that deserves more attention is the design and efficiency of the driving circuit for the LEDs. An active-matrix drive array allows each pixel to be connected and driven separately by the circuit resulting in a low operating current while maintaining brightness. This extremely low drive current and the dense layout of the micro-LEDs makes the circuit design more complex. [196] In addition, the sheer number of pixels requires controlling many more zones. New IC designs are being created to address the micro-LED display market. Macroblock recently released a 48-channel highly-integrated LED display driver IC, which was designed for the need of super fine pitch for micro-LED TVs using a common cathode architecture. The design included a power saving function to reduce the power consumption of direct view micro-LED TV systems and hence heating.

5.2.2.3 Micro-LEDs and Quantum Dots

An approach to simplify the micro-LED supply chain and transfer process involves using blue micro-LED die in combination with red and green quantum (QDs) to create RGB pixels with only one LED type. Utilizing only blue micro-LEDs allows for the use of the most efficient LEDs and simplifies the placement process by only needing to place a single color instead of transferring three different color LEDs (which come from three different wafers). These two different assembly schemes – RGB micro-LEDs and blue micro-LEDs with RG QDs – are illustrated in Figure 5.15 and Figure 5.16.

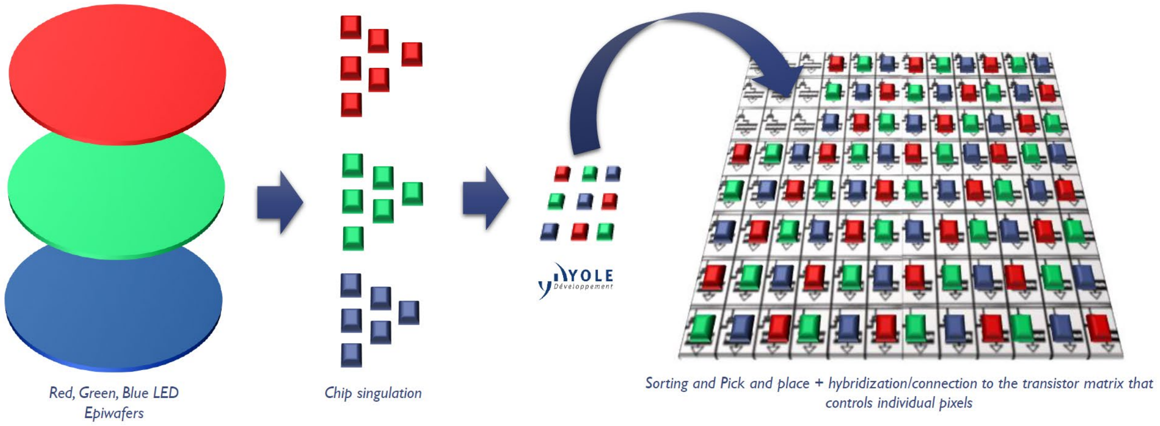

Figure 5.15 Schematic illustration of the assembly process of an RGB micro-LED display. [194]

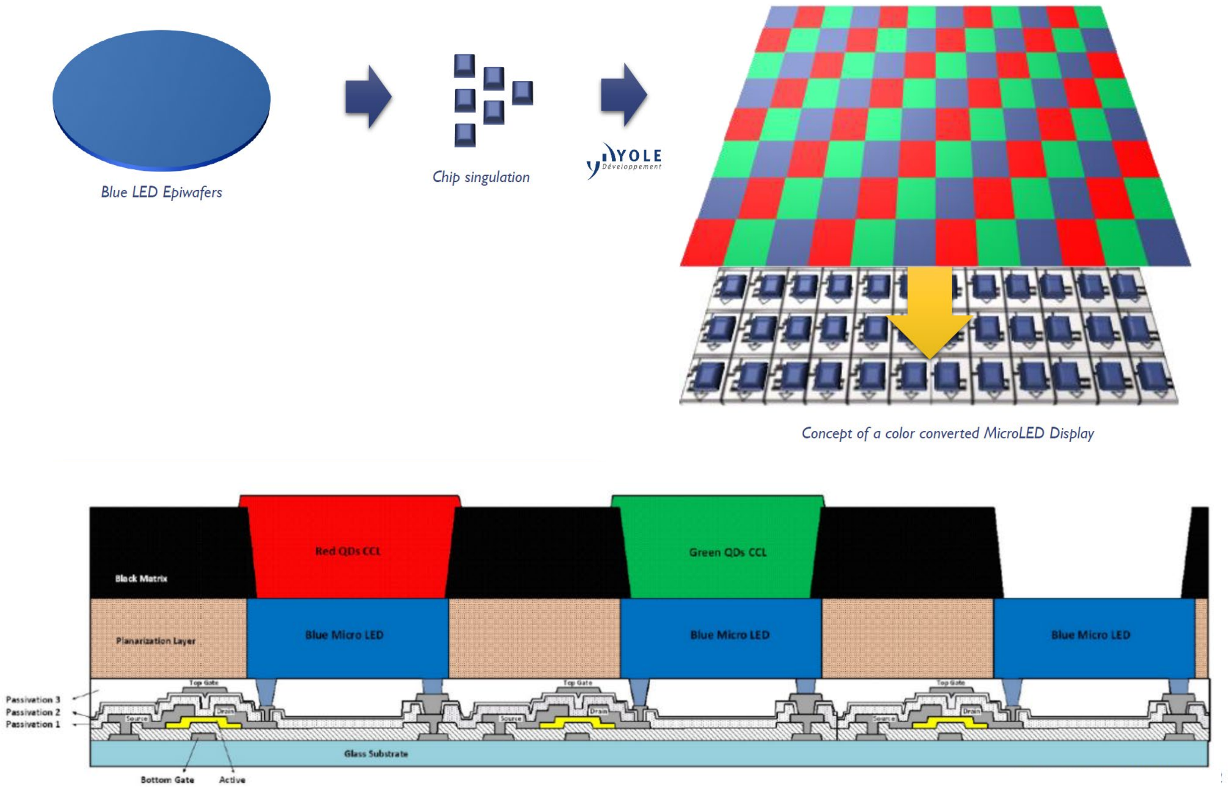

Figure 5.16 Schematic illustration of the assembly process of a micro-LED display with patterned QDs (top). [194] Cross-sectional view of the micro-LED & QD hybrid display (bottom). [197]

The use of a single color micro-LED also simplifies the drive circuitry for the display since all the LEDs operate at the same voltage. With the RGB approach, the InGaN blue and green micro-LEDs have a different turn on voltage than the AlGaInP red micro-LEDs due to the different band gap of the semiconductor material. This reduced complexity is another benefit of this hybrid QD/micro-LED approach.

The use of the hybrid process requires fine scale patterning of the QDs over the micro-LEDs to create the sub-pixel. The methods being explored to generate the patterned QDs include inkjet printing, lithography and transfer printing. While a hybrid approach simplifies the micro-LED mass transfer issue, the complexity comes with developing QD stability in the ink for printing and the operational stability of the QDs under the photothermal flux densities in the display. The environmental stability of QDs has been one of the big barriers of implementing them in different device schemes. Currently, they are limited to implementation in hermetically sealed films in the display stack. This environmental stability issue is a common challenge that QDs face for on-chip application into LED packages for SSL, as described earlier in the section on Wavelength Downconversion.

5.2.2.4 Technology Comparison

Many of the new display technologies that can provide desired features such as high color gamut, resolution and peak brightness do not require the use of the lossy LCD polarizer. Micro-LEDs, OLEDs and QDs and have the potential to be substantially more energy efficient than LCDs along with other performance advantages highlighted in Figure 5.17. Improvements in features such as resolution, contrast ratio, color gamut, refresh rate favor these new technologies which are driving manufacturers to pursue these convince consumers to upgrade their TVs.

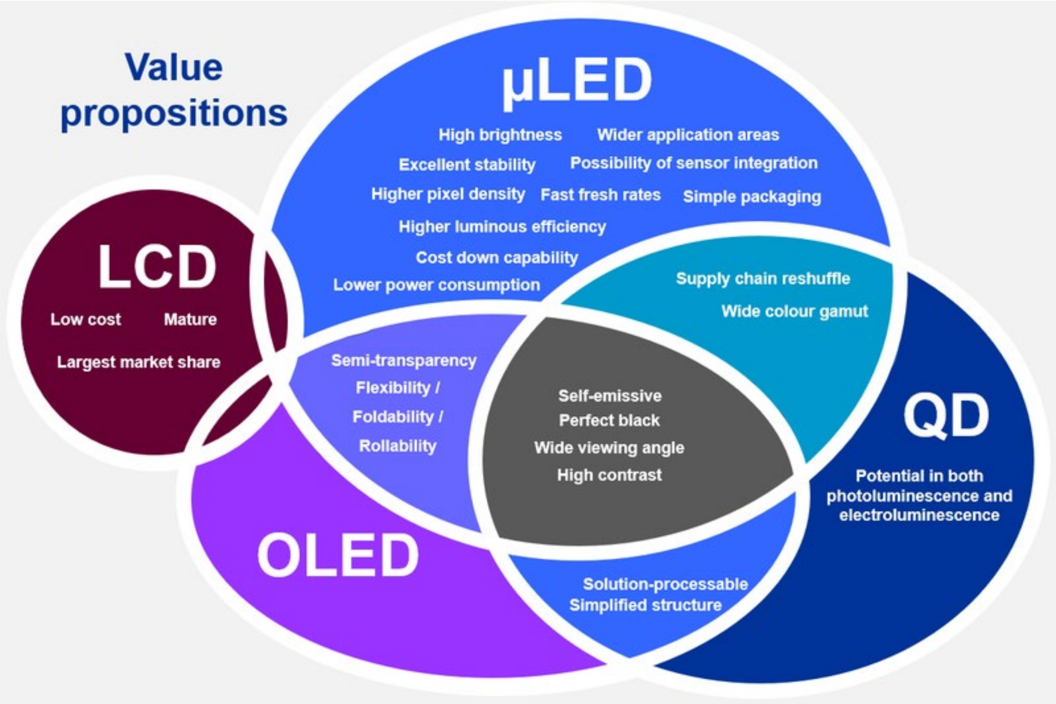

Figure 5.17 Comparison of the performance benefits of various display technologies. LCDs are the incumbent and have the dominant market share today but are unable to provide some of the benefits available with emissive display technology like micro-LEDs and OLEDs. [197]

With significant fraction of the nation's electricity is consumed by displays in such applications as TVs, computer monitors and digital signage, the inefficient use of light from SSL sources must be addressed. There is growing interest among the display community in eliminating the components, such as polarizers and color filters, that cause this inefficiency, and developing displays that are just arrays of LEDs. The display industry is investing far more in R&D than the lighting industry and there are a number of areas of technology crossover, which allows for synergistic R&D opportunities between the two applications. For example, both communities are eager to develop more efficient, stable blue OLEDs and to reduce the amount of trapped light. The demand for higher color gamut has motivated R&D on QDs which has reawakened interest within lighting applications. The development of edge-lit display backlights has led to performance improvements and substantial cost reduction in slim planar ceiling lights as alternatives to troffers.

The growing interest in micro-LEDs will stimulate research into LED mechanisms and fabrication techniques for a much smaller size scale and may open up opportunities to design SSL fixtures that avoid the glare associated with many current luminaires and enable new forms of building integration. In addition, new functionality such as animation and way finding can be integrated into buildings with mini and micro-LED technology. This development comes at a time when the major lighting companies are cutting back on R&D spending on fundamental issues.

5.2.3 Horticultural Lighting

Indoor horticulture, also known as controlled environment agriculture (CEA) is a relatively new application for LED lighting. In this application, electric lighting is used for plant growth and development. All of the features that motivate the use of LED lighting for general illumination apply to horticultural lighting applications as well. LED lighting is efficient, long lasting, can be dimmed, and the spectrum can be engineered for maximum effectiveness.

The DOE report, *Energy Savings Potential of SSL in Agricultural Applications*, published in June 2020 showed that LED lighting has the potential to save 34% out of a total of 9.6 TWh/yr of total energy used for horticultural lighting. [52] Within horticultural lighting there are three primary types of applications. There is lighting used in greenhouses to supplement natural daylight. There is the indoor, high intensity sole source lighting application, and there is the indoor vertical farm application. With vertical farming plants are grown on stacked shelves to maximize the indoor grow area. LED lighting is an enabling technology for this type of grow arrangement since LED lighting is much more efficient than fluorescent light technology which was used prior to the introduction of LEDs. The light source efficiency in this application is critical since high light intensity is required and the lights are on for an extended portion of the day, which results in high lighting energy costs.

Figure 5.18 Image of Aerofarms, world's largest vertical farm in Newark, NJ, from Roger Buelow presentation 2019 DOE SSL R&D Workshop. The stacked arrangement requires extensive use of electric lighting.

With horticultural application, plants are the primary receiver of the light emitted from a fixture and plants have multiple receptors with unique response spectra as shown in Figure 5.19 below.[51] 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. A plot showing the number of photons per second per watt (equivalent to µmol/joule) is provided below in Figure 5.20. Photosynthetic photons are only considered to be photons with wavelengths between 400 and 700nm. By convention, photons are counted in units of micromoles of photons per second.

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[51] 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.

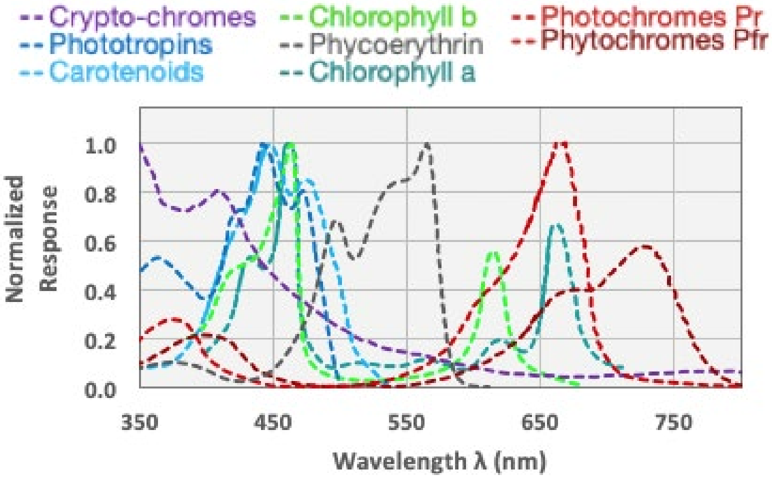

Figure 5.19 Plant action spectra associated with the primary classes of photosensitive molecules in plants. [41]

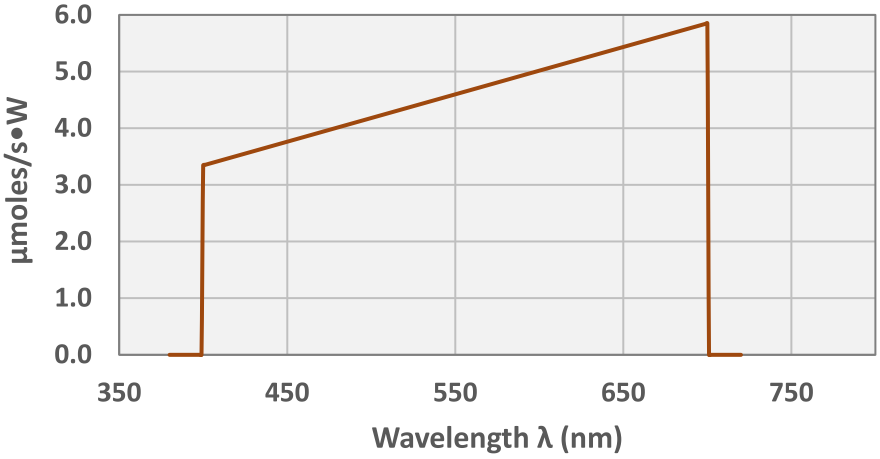

Figure 5.20 Micro-moles per second per watt of photosynthetic photons (400-700nm). At longer wavelengths (~red) there are more photons per watt of light.

The analogous lumen-based metrics and accepted plant metrics are provided in Table 5.2. 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.

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)

Table 5.2 General illumination and horticultural metrics.

Horticultural lighting products can now routinely 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 5.21 below and considering 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 + 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. White + red LED combinations will achieve an LED efficacy between the blue + red and white projections. Also, the projections below constrain LED performance to a current density of 35A/cm^2 in order to keep a consistent record of LED performance advancements (and not just show advancements due to different drive conditions). State of the art LEDs used in horticultural have demonstrated higher performance by increasing emission area and therefore operating at reduced current density. In fact, state of the art deep red LEDs can now achieve over 70% power conversion efficiency.

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. [201]

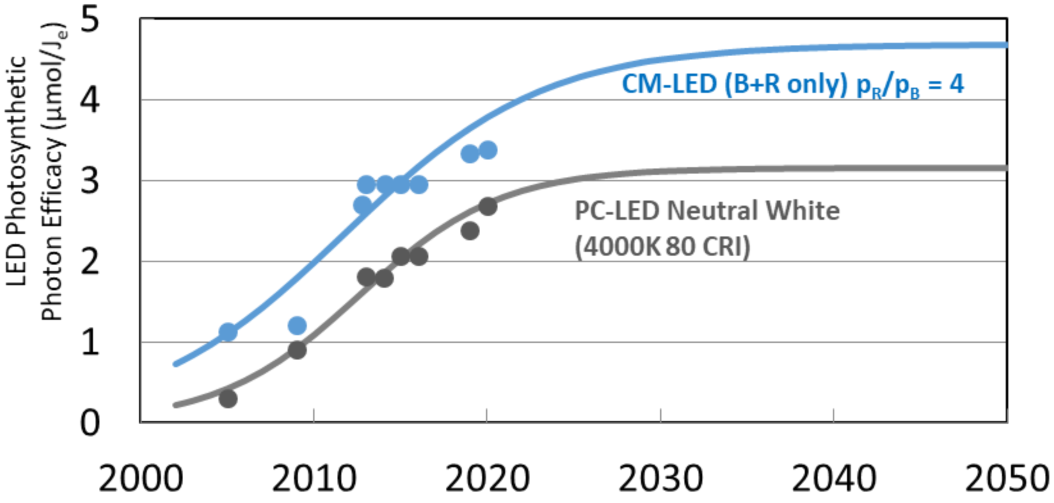

Figure 5.21 LED photosynthetic photon efficacy measured at 25°C and 35 A/cm2 input current density. PPE for a typical PC-LED architecture with a neutral white color temperature, and for a hypothetical CM-LED architecture containing only red and blue LEDs with an optical power ratio of 4:1. The points and lines represent the photosynthetic efficacies of source assuming the same historical (points) and projected (lines) efficiencies of the underlying LED technologies. [198] The efficacy of the LED integrated fixture will be less than the LED efficacy since there will be additional optical, electrical, and thermal losses in the system.

As with lighting for human visual function, there are considerations beyond pure PPE. Light spectrum will affect plant growth and development and historical research on photosynthetic effectiveness is getting updated. There is also new appreciation of the important role of green light in the horticultural setting for human visual function for inspecting and evaluating growth conditions and for visual comfort.

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