U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Solid-State Lighting 2017 Suggested Research Topics

September 2017

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List of Acronyms

CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
EQE	external quantum efficiency
IQE	internal quantum efficiency
K	kelvin
LED	light-emitting diode
lm/W	lumens per watt
nm	nanometer
OLED	organic light-emitting diode
PCE	power conversion efficiency
pc-LED	phospher-converted led
QY	quantum yield
RYGB	red, yellow, green and blue
R&D	research and development
SSL	solid-state lighting

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Introduction

To reach the full potential of solid-state lighting (SSL), continued research is required. Despite rapid advances, SSL technology remains in its early years. When it comes to U.S. energy savings from SSL, 90% of the potential remains untapped. Ongoing innovation and breakthroughs in materials, devices, processes, and control systems are still needed to realize the full potential of the technology. All the suggested research areas in this document are foundational to the field of SSL. Solid-state lighting is still an immature technology and research advancements and breakthroughs are being rapidly integrated.

1 Suggested Research Topics

The suggested priority topics described in this document are inputs from DOE SSL R&D Program stakeholders. Stakeholders include academic, national laboratory, and industry researchers who provide feedback and inputs to the DOE SSL Program team. The suggested priority topics in this document are not guaranteed topics for the annual DOE SSL R&D funding opportunity, but represent a 'short list' from which the DOE may choose to select. Similarly, these topics do not represent forward looking directions by the DOE SSL Program, but rather stakeholder suggestions as to the most critical areas for advancement of SSL technologies.

1.1 Process and Discussion

The DOE SSL Program has responded to the SSL opportunity by providing direction and coordination of multiple R&D efforts intended to advance the technology and to promote the ultimate energy savings offered by the technology.[1] All DOE SSL Program funding goes to early stage research, but the research can be applied across the SSL value chain. The DOE SSL Program seeks to fund only research that clearly has the potential to offer new materials and device structures, to create radically new integration concepts, or to develop new understanding of the underlying technology and application.

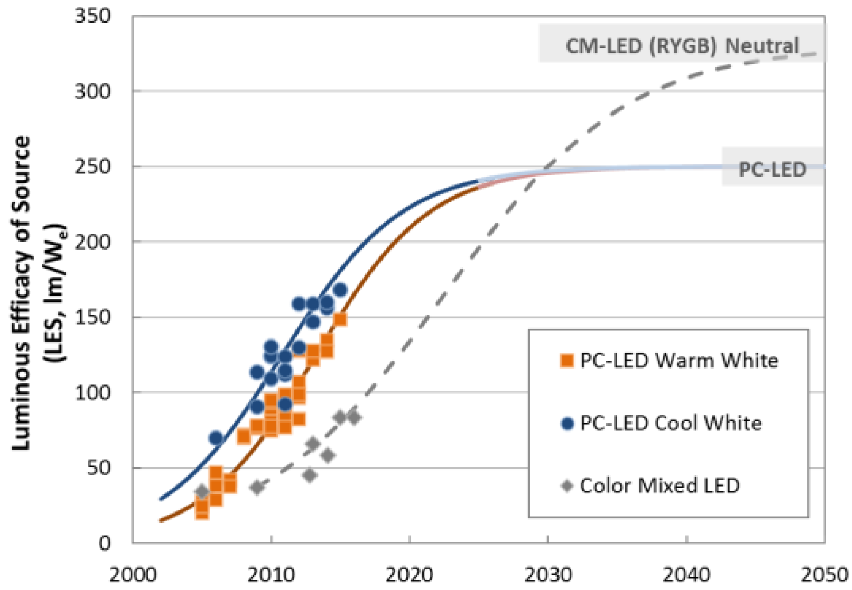
1.1.1 Goals and Projections

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

Efficacy Projections for LEDs

Figure 1 and Table 1 project LED package efficacy over time for warm white and cool white phosphor converted-LEDs (PC-LEDs), based on a logistic fit to experimental data, and assuming an upper asymptote of 255 lm/W. The assumed operating conditions for qualified data points may not correspond to practice, particularly with respect to the increasing use of lower drive currents to minimize current droop. Nevertheless, using a standard current (or power density) at a fixed operating temperature and selecting devices within limited ranges of CCT and CRI allow researchers to evaluate developments in emitter efficiency (including the reduction of current and thermal droop) and down-converter performance.

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



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

Figure 1 LED Package Efficacy Projections for Commercial Products

Table 1 Phosphor-Converted LED Package Efficacy Projections

Metric	Type	2014	2016	2020	2025	Goal
LED Package Efficacy (lm/W)	Cool White	158	168	218	240	255
	Warm White	131	137	208	237	255

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

Efficacy Projections for OLEDs

OLED efficacy has been improving, but not at the expected pace. Though scalable technology has been demonstrated for achieving OLED panels of more than 100 lm/W in the laboratory, low light extraction efficiency remains a key technical challenge. Integrating light extraction technology without disrupting the yield and stability of devices has presented a major challenge. Figure 2 and Table 2 project OLED panel efficacy based on past performance and anticipated progress. The dashed curve presents DOE OLED panel efficacy goals put forth in 2014, whereas the solid curve shows projections based on performance to date.

Data on OLED panels remain rather sparse and show a lot of variation, so there is considerable uncertainty in the projected curve. The average of qualified data for each year was used to fit the data. Qualified points reflect efficacy reports for panels with a minimum area of 50 cm2 and CRI greater than or equal to 80, with CCT between 2580K and 3710K. Where these parameters are known, the data point is considered qualified.

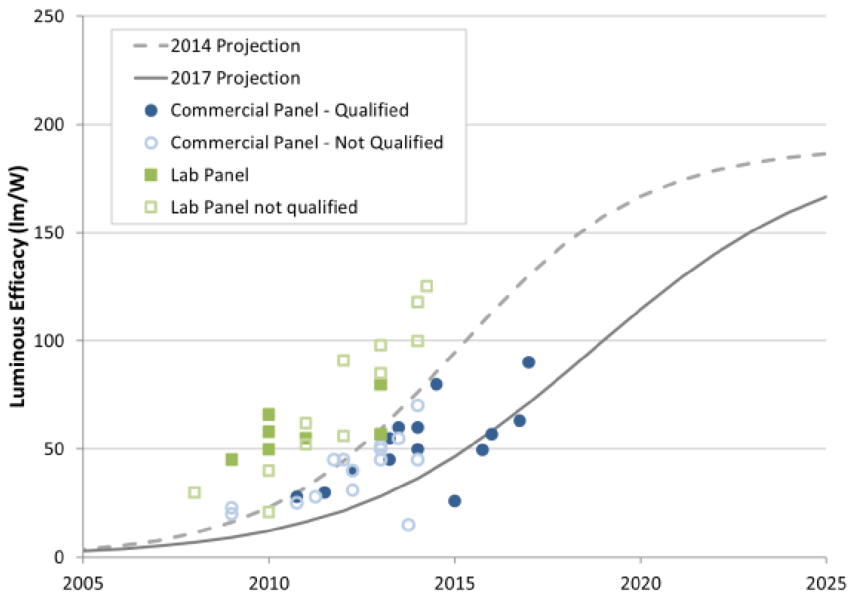


Figure 2 White-Light OLED Panel Efficacy Projections

Table 2 summarizes a path toward achievement of an efficacy of 190 lm/W with low rates of lumen depreciation. The table is constructed on the assumption that all-phosphorescent emitters will be used in conjunction with a two-stage tandem structure, but there may be other routes to achieve the same goals.

Table 2 OLED Panel Efficacy Projections

Metric	2016	2020	2025	Goal
Panel Efficacy (lm/W)	60	110	150	190

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

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

1.2 LED Priority Research Areas

Specific critical R&D priority tasks were suggested by DOE SSL Program stakeholders. The limited number of priority R&D tasks reflects the practical reality that DOE must leverage limited research funding for early stage research activities to achieve the most meaningful advancements possible.

The specific task tables that follow reference color or descriptive terms for color temperature. Ranges of the various color wavelengths and explanations of the meaning of the color temperature terms are shown in Table 3.

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

Color	Peak Wavelength or CCT	CRI
Blue	440-460 nm	N/A
Green	520-540 nm	N/A
Amber	580-595 nm	N/A
Red	610-620 nm	N/A
Warm White	3000K	≥80
Cool White	5700K	≥70

The milestones provided in the tasks described below represent the minimal descriptions for progress and provide initial, interim targets for quantitative evaluation of progress. All these tasks will require some additional system-level performance description, though the specifics of the system vary widely. Researchers in these areas are expected to possess and communicate a system-level understanding of the role of the described research.

1.2.1 Suggested LED Research Priority Tasks

Table 4 Emitter Materials

Emitter Materials			
Description: Identify fundamental physical mechanisms of efficiency droop for blue LEDs through experimentation using state-of-the-art epitaxial material and device structures in combination with theoretical analysis and advanced characterization approaches. Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. Develop efficient red, green, or amber LEDs that allow for optimization of spectral efficiency with high color quality over a range of CCT, and that also exhibit color and efficiency stability with respect to operating temperature.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
IQE at 35 A/cm^2	79% (Blue*) 39% (Green) 75% (Red**) 13% (Amber**)	90% 54% 87% 32%	95% 59% 94% 36%
EQE at 35 A/cm^2, 25°C	69% (Blue) 32% (Green) 54% (Red**) 10% (Amber**)	81% (Blue) 46% (Green) 65% (Red**) 24% (Amber**)	88% 56% 76% 30%
PCE† at 35 A/cm^2	66% (Blue) 22% (Green) 44% (Red**) 8% (Amber**)	80% (Blue) 35% (Green) 55% (Red**) 20% (Amber**)	86% 50% 65% 25%
Current droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	85%	95%	96%

* LED structures with improved droop characteristics but with reduced peak IQE may result in improved IQE at typical operating conditions.

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

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

Table 5 Downconverters

Downconverters			
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 improved thermal stability and longevity to enable use of materials in high-brightness LED packages. Downconverters that are non-toxic and do not contain scarce materials are encouraged.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Quantum yield (QY) at 25°C across the visible spectrum	98% (Green) 90% (Red)	99% (Green) 95% (Red)	99% (Green) 95% (Red)
Thermal stability – Relative QY at 150°C vs. 25°C	90%	95%	96%
Spectral FWHM	100 nm (Red/Green)	30 nm (Red) 70 nm (Green)	30 nm (across visible spectrum)
Color shift over time (when integrated into pc-LED)	$\Delta u'v' < 0.007$ at 6,000 hours	$\Delta u'v' < 0.002$ over life	$\Delta u'v' < 0.002$ over life
Flux density saturation – Relative QY at 1 W/mm^2 (optical flux) vs. peak QY	-	95%	96%

Table 6 LED Encapsulation

LED Encapsulation			
Description: Research new concepts for light extraction/light mixing/optical control/absorption in LEDs through development of new encapsulant-phosphor-LED chip materials and configurations. Develop new encapsulant formulations that provide a tuned refractive index to improve light extraction from the LED package. Explore new materials such as improved silicone composites or glass for higher temperature, more thermally stable encapsulants to improve light output, improve long-term lumen maintenance, and reduce color shift. Develop matrix materials for phosphor or quantum dot down-converters with improved understanding of how the chemical interactions affected performance and reliability.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Refractive index across the visible spectrum	1.54	1.8	Tunable
Thermal conductivity	0.2 (W/mK)	1.0 (W/mK)	1.4 (W/mK)
Thermal stability (at given temperature and optical flux density) – user defined for specific use case	User defined # of hours at given operating condition	Proposed improvement in # of hours or increase temperature and/or flux density	Not the lifetime or temperature limiting factor in high brightness LED packages operating at or beyond 1 watt per square meter (W/mm^2) power density

Table 7 High Efficacy LED Prototypes

High Efficacy LED Prototypes			
Description: Demonstrate novel package integrations schemes that focus on improved epitaxy, phosphors, optical performance, and electrical efficiency to surpass DOE SSL Program interim efficacy targets and accelerate achievement of ultimate DOE SSL goals. Furthermore, LEDs should enable advanced luminaire performance to meet target by integrating luminaire functionality into prototype LED concepts. Advanced features such as optical components that can shape the beam or mix the colored outputs from LED sources evenly across the beam pattern are encouraged, along with novel thermal handling and electrical integration while also advancing efficiency.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Luminaire Efficacy	Approx. 140 lm/W Depends on CCT, CRI, beam angle, luminance distribution, etc.	200 lm/W	225 lm/W
New Package/Module functionality	Applicant Defined	Proposed impact on manufacturing, performance, or adoption case	Proposed impact on manufacturing, performance, or adoption case

Table 8 Advanced LED Lighting

Advanced LED Lighting			
Description: Develop entirely novel, fully optimized concept luminaires or lighting system architectures that take advantage of the unique properties of LEDs to demonstrate improved performance, connectivity, and advanced lighting values, e.g., human physiological benefits. Proposed prototypes should provide a clear demonstration of maximum efficacy and what can be possible with LED lighting technology. Novel form factors, advanced luminaire system integration, optimized performance for specific lighting applications, and improved utilization of light are aspects that should be included.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Luminaire efficacy (depends on application – user may define metrics for other use cases)	Approx. 140 lm/W Depends on CCT, CRI, beam angle, luminance distribution, etc.	200 lm/W	225 lm/W
Light utilization efficiency (depends on application – user may define metrics for other use cases)	Applicant defines light delivery efficiency, spectral efficiency,* and controls and communications effectiveness	Applicant defines light delivery efficiency, spectral efficiency, and controls and communications effectiveness	Applicant defines light delivery efficiency, spectral efficiency, and controls and communications effectiveness
Energy Savings	Applicant Defined	Applicant demonstrates clear energy savings through source efficacy, controls, and effective delivery of light	Applicant demonstrates further energy savings through source efficacy, controls, and effective delivery of light

* Spectral efficiency refers to the overlap of the emitted spectrum with the application action spectrum

Table 9 LED Power Electronics

LED Power Electronics			
Description: Develop advanced prototype power delivery concepts for luminaires with improved efficiency, reliability, and functionality using new devices, materials, circuit, and system designs. Additional advancements could include systems with full dimmability, minimal flicker, and maximum efficiency at extended operating ranges; enhanced functionality through low-cost modular control and communication systems integrated with the power supply, and/or high efficiency multi-channel control for multiple strings of LEDs.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Power supply efficiency	88%	93% at full power 90% in dimmed state	95% at all operating conditions
Flicker	Application dependent/Applicant define and substantiate	No perceptible flicker across luminaire operating range	No perceptible flicker across luminaire operating range
Power supply reliability	Applicant estimated lamp/luminaire survival factor	95% survival factor at claimed L70 life	95% survival factor at claimed L70 life
Power supply functionality	User defined functionality	Proposed impact on performance and/or adoption case	Modular interoperability with multiple communications protocols

Table 10 Advanced Manufacturing

Advanced Manufacturing			
Description: Research novel fabrication technologies for state-of-the-art LED lighting concepts. Suitable development activities would likely include one or more of the following areas: ○ Advanced LED integration for enabling an array of lighting applications ○ More efficient use of components and raw materials ○ Use of novel, low environmental impact materials ○ Reduction in part count using multi-functional components			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Reduced materials use for lighting products	User defined status based on lighting application	User defined status based on lighting application	User defined status based on lighting application
Manufacturing Simplification	User defined status	User defined status	User defined status

1.3 OLED Priority Research Areas

Specific critical priority research tasks were suggested by DOE SSL Program stakeholders. The limited number of priority R&D tasks reflects the practical reality that DOE must leverage limited research funding for early stage research activities to achieve the most meaningful advancements possible.

The OLED priority tasks identified based on stakeholder suggestions are outlined below.

1.3.1 Suggested OLED Research Priority Tasks

Table 11 Stable, Efficient White Devices

Stable, Efficient White Devices			
Description: Develop novel materials and structures that can help create a highly efficient, stable white device. The device should have good color, long lifetime, and high efficiency, even at high brightness. The approach may include development of highly efficient blue emitter materials and hosts, or may comprise a device architecture leading to longer lifetime such as graded doping approaches or tandem structures with improved charge generation layers to maximize EQE. Materials/structures should be demonstrated in OLED devices that are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate high stability, while maintaining or improving other applicable metrics.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Lumen maintenance (L70) from 10,000 lm/m^2	50,000 hrs	50,000 hrs	50, 000 hrs
Efficacy without extraction enhancement (lm/W)	35 lm/W	50 lm/W	60 lm/W
Voltage per stack @ 10,000 lm/m^2	3.3 V	3.0 V	3.0 V
CRI (R_a,R_9)	>90, >50	>90, >50	>90, >50
Δu'v' @ end of life	-	<0.02	<0.02

Table 12 OLED Fabrication Technology

OLED Fabrication Technology			
Description: Novel approaches and advancements in materials deposition, device fabrication, or encapsulation of high-performance OLED panels are desired. In addition to refinements on traditional approaches, solution-based deposition (of organic materials or electrodes), fabrication on flexible substrates, flexible encapsulation, and novel patterning schemes are also considered under this task.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Processing Area	390 mm x 490 mm	1100 mm x 1300 mm	
Cycle Time	3 minutes	30 seconds	10 seconds
Yield	>80%	95%	98%
Early Failures	1:1,000	1:10,000	1:10,000

Table 13 Light Extraction and Utilization

Light Extraction and Utilization			
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state-of-the-art performance of OLED panels. Applicants should consider how their approach affects the energy loss due to wave-guided and plasmon modes in state of the art structures and should include modeling or quantitative analysis that supports the proposed method. Solutions can also explore light-shaping techniques that can be integrated with the proposed light extraction technology to attain increased utilization efficiency of the generated light. Such methods should allow some control of the angular distribution of intensity, but minimize the variation of color with angle.			
Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Extraction efficiency (EQE/IQE)	50%	70%	75%
Color variation with angle ($\Delta u'v'$)	$<\pm 0.003$	-	
Light delivery efficiency	-	20% efficiency improvement	50% efficiency improvement

Table 14 OLED Prototype Lighting Platforms

OLED Prototype Lighting Platforms				
Description: Demonstrate OLED lighting platforms that highlight capabilities of OLED lighting technology. OLED platforms should combine one or more high performance OLED panels with driver electronics to achieve efficient, long-life systems. Advanced custom drivers should efficiently convert line power to acceptable input power for the OLED source(s) and maintain their performance over the life of the device. Advancements may include, but are not limited to: high performance (efficacy, long lifetime, color quality); spectral tunability; modularity; unique form factor (thin, flexible); efficient power supplies; and improved electrical connections. Proposals should provide quantitative targets for distinctive performance.				
	Metrics	**2016 Status**	**Interim 2020 Targets**	**2025 Targets**
Light Engine	Driver efficiency	50-80%	90%	95% at all operating conditions
	Harmonic Distortion	8-190%	<10%	<10%
	Dimmability	10-100%	1-100%	1-100%
Luminaire	Efficacy	20-50 lm/W	100 lm/W	150 lm/W
	Lumen Maintenance (L70)	50,000 hours	50,000 hours	50,000 hours
	Cost	3x panel cost	2x panel cost	5x panel cost

1.4 Lighting Priority Research Tasks

Table 15 Physiological Impacts of Light

<table>
<tr><th colspan="4">Physiological Impacts of Light</th></tr>
<tr><td colspan="4">Description: Develop an improved understanding of the underlying physiological responses to light for humans, livestock, plants, or nocturnal animals. Researchers in this area should define the status of the underlying physiological responses to light and describe research targets as well as the impact of the proposed research in terms of energy savings, productivity, well-being, and ecological impacts. Work to develop novel, specialized LED research tools that enable specific R&D in this topic may also be considered.</td></tr>
<tr><th>Metrics</th><th>2016 Status</th><th>Interim 2020 Targets</th><th>2025 Targets</th></tr>
<tr><td>Human Physiological Impacts</td><td rowspan="4">Applicant define and substantiate</td><td rowspan="4">Applicant define and substantiate</td><td rowspan="4">Clearly defined best lighting practices with validated benefits for general and specific physiological impacts</td></tr>
<tr><td>Livestock Production Impacts</td></tr>
<tr><td>Horticultural Production Impacts</td></tr>
<tr><td>Ecological Impact Minimization</td></tr>
</table>

Table 16 Lighting Application Efficiency

<table>
<tr><th colspan="4">Lighting Application Efficiency</th></tr>
<tr><td colspan="4">Description: Develop an improved understanding of the underlying demands of specific lighting situations, including optical efficiency of light delivery, overlap of the delivered spectrum with the application action spectrum, and control over the intensity of the delivered light to maximize efficiency – a DOE goal. This topic includes developing improved characterization metrics and methodologies, improving understanding of lighting requirements, and developing novel platforms to meet the demands of the applications.</td></tr>
<tr><th>Metrics</th><th>2016 Status</th><th>Interim 2020 Targets</th><th>2025 Targets</th></tr>
<tr><td>Efficiency of Lighting Delivery</td><td rowspan="3">Applicant define and substantiate</td><td rowspan="3">Applicant define and substantiate</td><td rowspan="3">Applicant define and substantiate</td></tr>
<tr><td>Spectral Efficiency</td></tr>
<tr><td>Control Efficacy</td></tr>
</table>

2 Conclusion

Solid-state lighting technology has advanced significantly in the past decade and offers clear energy savings, reduced cost of ownership, and even improved lighting performance compared to conventional lighting products. However, the market and technology transition to SSL is still in the early phases. When it comes to U.S. energy savings from SSL, 90% of the potential remains untapped and ongoing innovation in materials, devices, processes, and control systems is still needed to realize the full potential of the technology.

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For more information, visit:
energy.gov/eere/ssl/solid-state-lighting

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