U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Advancements in LED Technology and Application

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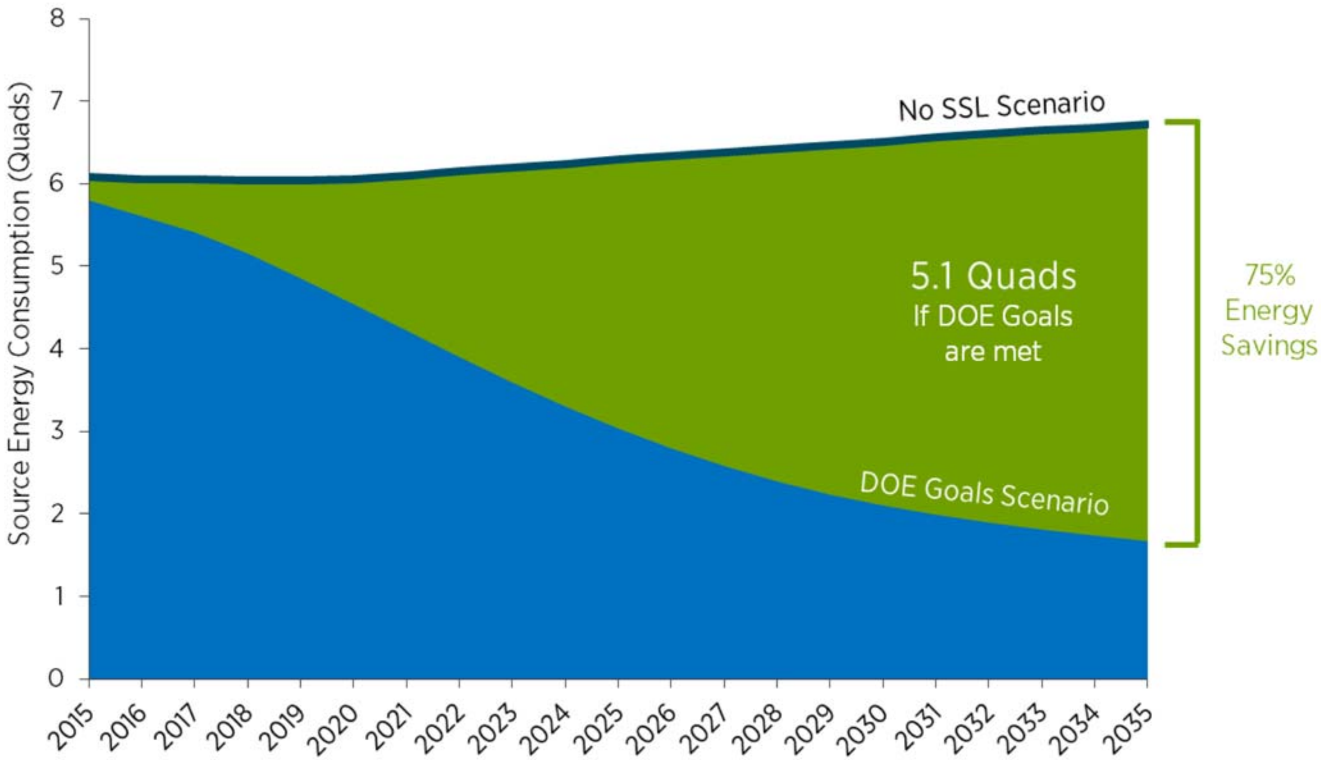
Consulting Senior Technical Advisor, US DOE SSL R&D Program

IES ALC, October 24, 2017, Dallas, TX

Energy Savings from SSL



Can’t save this amount of energy with a compromised product. LED technology will actually improve lighting performance in every way.

DOE SSL R&D Program

Funded R&D

Internal R&D

R&D Leadership

Information Resources

DOE SSL R&D Program – Funded R&D

Funded R&D

Internal R&D

R&D Leadership

Information Resources

SBIR

Funding Opportunity-
Currently funding 20 projects, $29M

R&D Topics-
Emitter materials and devices
Advanced Manufacturing
Advanced luminaire concepts
Physiological Response to Light

New funding opportunity coming soon-

DOE SSL R&D Program – Internal R&D

Funded R&D

Internal R&D

R&D Leadership

Information Resources

Gateway Demonstrations-
Yuma Border,
Philadelphia Airport Apron Lighting,
Tunable lighting in classrooms, senior care, medical behavior unit

Connected Lighting Test-Bed

Studies-
Dimmer compatibility,
Color quality,
Pedestrian Lighting

https://energy.gov/eere/ssl/gateway-demonstrations

DOE SSL R&D Program – R&D information

Funded R&D

Internal R&D

R&D Leadership

Information Resources

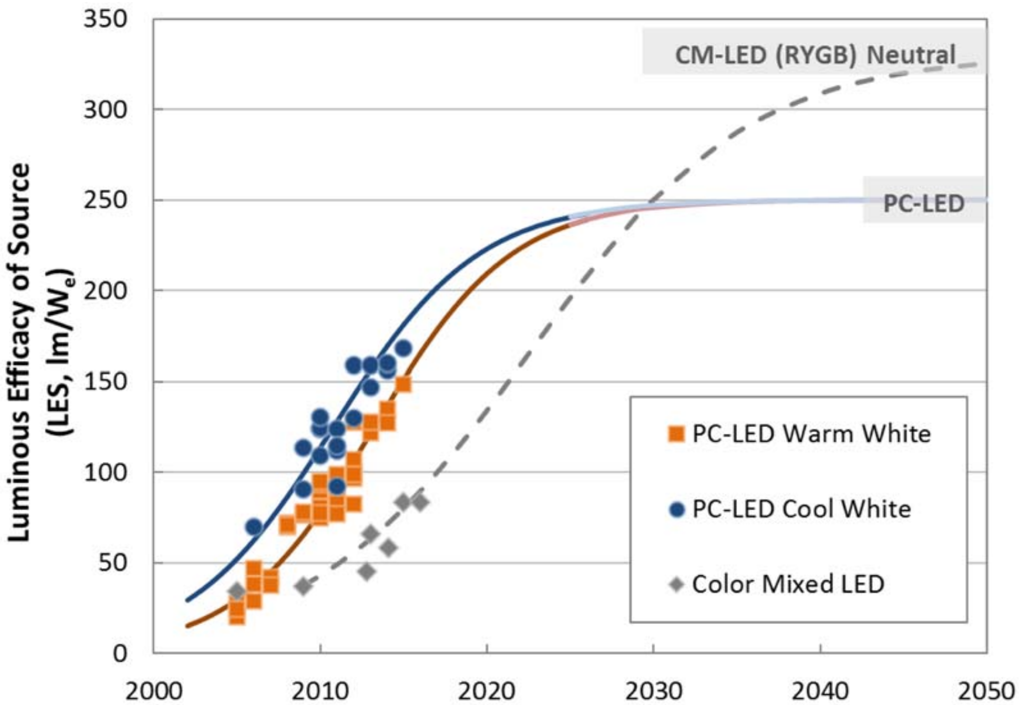
SSL Technology R&D Workshop
Portland, OR
November 8-9, 2017

DOE SSL R&D Workshop
Nashville, TN
January 30 – February 1, 2018

2017 DOE SSL R&D Plan

Many additional information resources- https://energy.gov/eere/ssl/solid-state-lighting

LED Technology Advancements



https://energy.gov/eere/ssl/downloads/solid-state-lighting-2017-rd-plan-suggested-research-topics

Note:

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

Figure 4.4 Efficacies of Commercial LED Packages Measured at 25 °C and 35 A/cm² Input Current Density

LED Lighting Architecture

https://energy.gov/eere/ssl/downloads/solid-state-lighting-2016-rd-plan

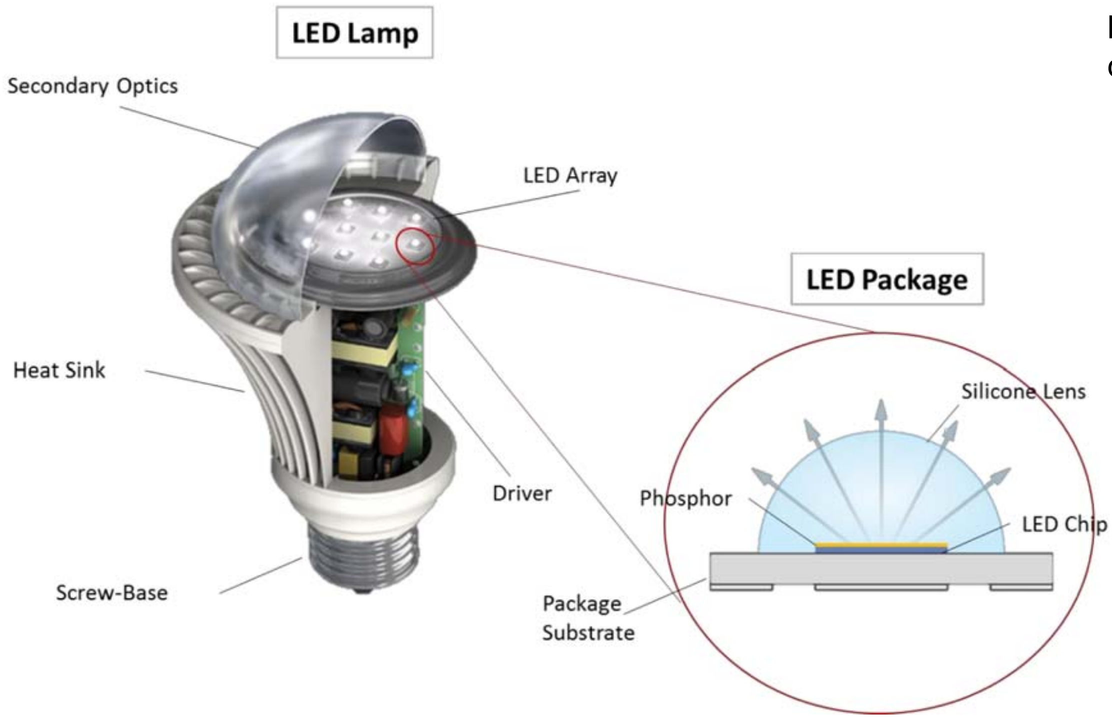
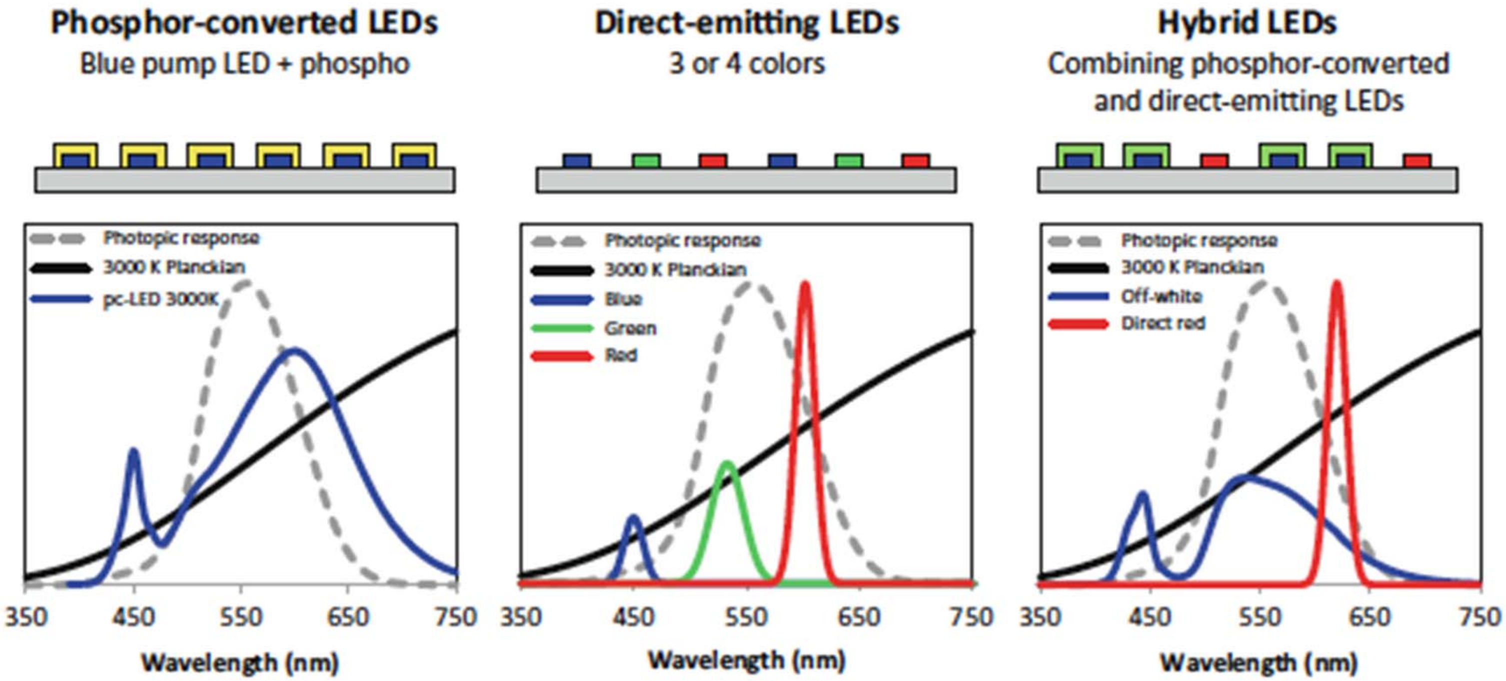


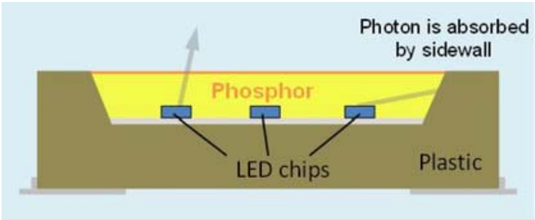
Figure 8.1 Components of an LED Lamp

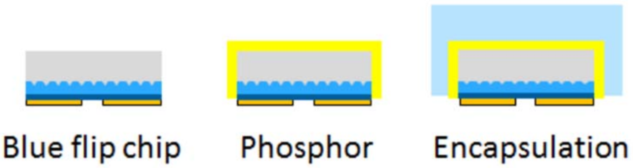
Image Sources: a) Lamp: http://electronics.stackexchange.com/questions/76883/how-do-led-light-bulbs-work, b) Package: Tuttle & McClear, LED Magazine Feb. 2014.

LED white light



Shchekin, O., & Craford, M. G. (2016). History of Solid-State Light Sources.

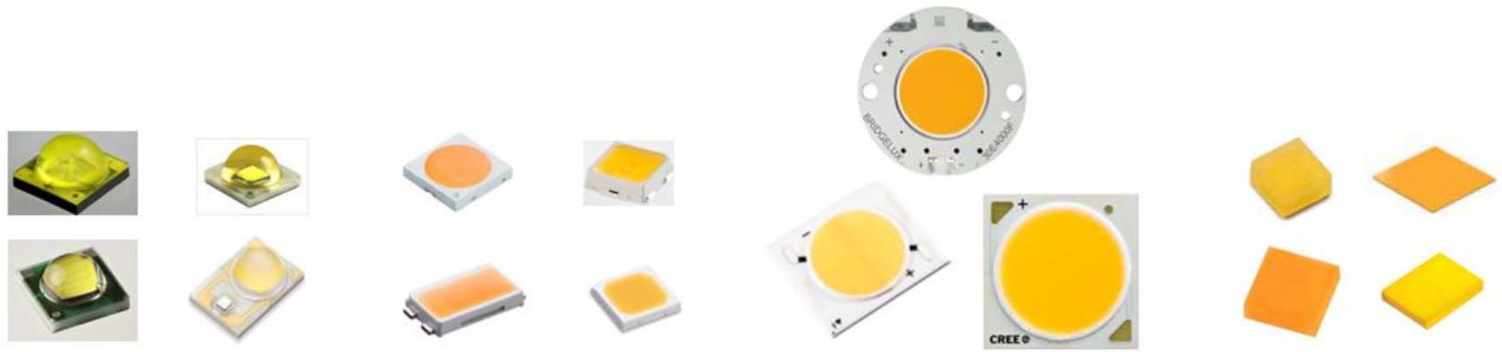




Source: Monica Hansen, Strategies in Light 2015

Shatil Haque, DOE SSL R&D Workshop, Raleigh, NC, February 2016

LED Package Architecture



High-power: ceramic substrates, molded lens

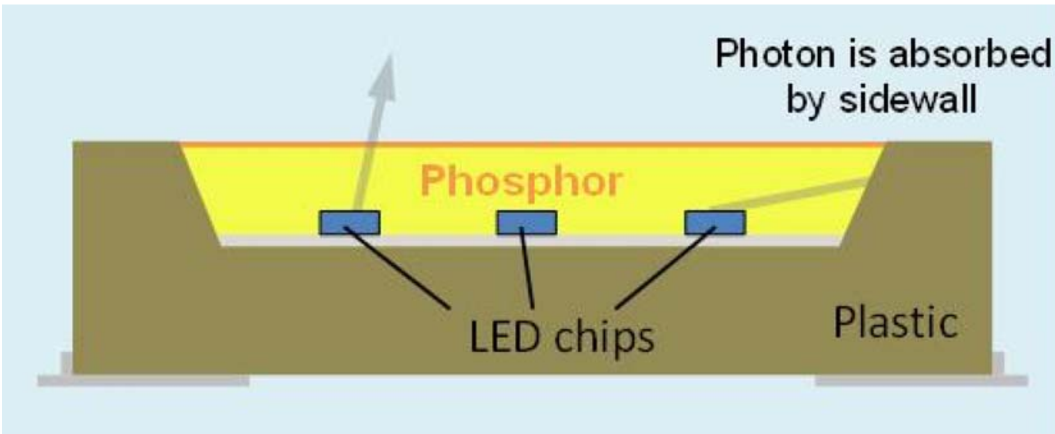
Mid-power: leadframe, polymer package

Chip on Board: metal-core PCB, ceramic PCB

Chip Scale Package: flip-chip with phosphor

https://energy.gov/eere/ssl/downloads/solid-state-lighting-2016-rd-plan

pc-LED lighting Architecture



Source: Monica Hansen, Strategies in Light 2015

GaN LED Chip | Phosphor | Package

$\eta_{chip} = (0.9)*(0.9)*(0.9)$

$\eta_{phosphor} = (0.9)*(0.8)$

$\eta_{package} = (0.9)$

Cascading losses

Monochromatic LEDs

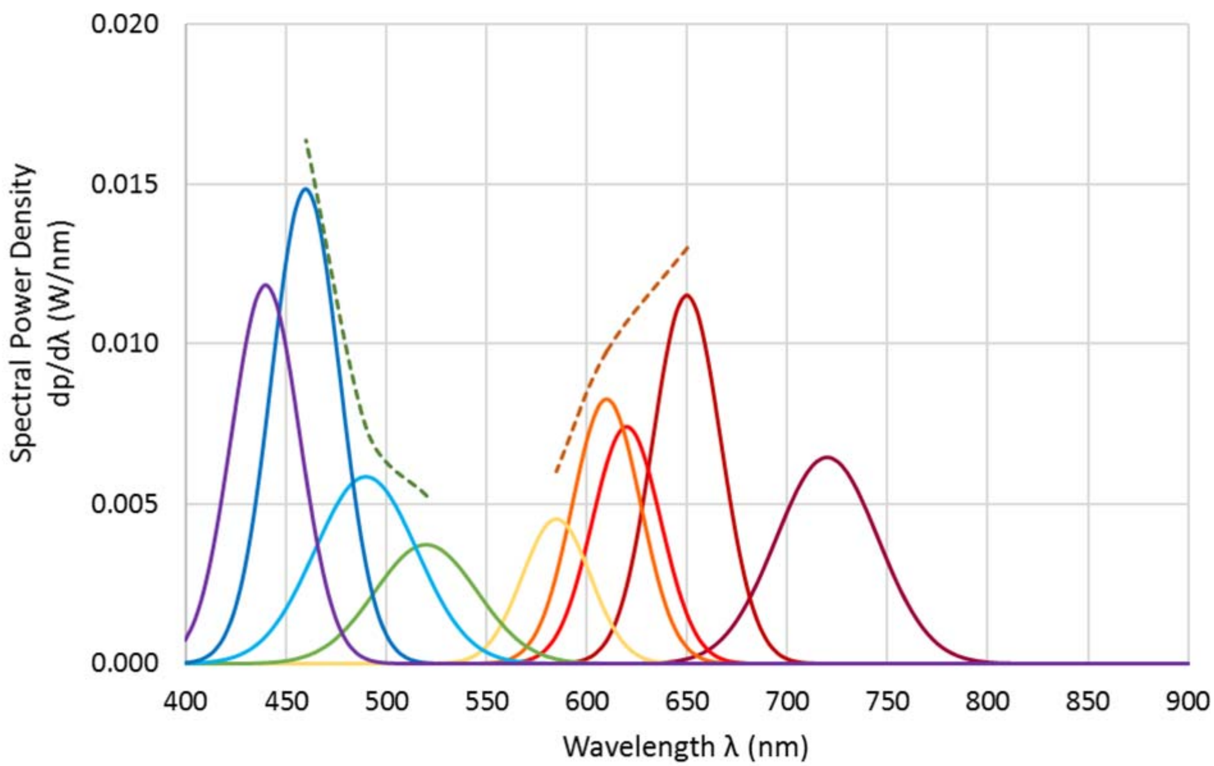


Figure 4.7 Spectral Power Densities of State-of-the-Art Commercial LEDs vs. Wavelength.
Dashed lines are guides to the eye, illustrating the "green gap:" the decrease in efficiency from the blue to the green-yellow and from the red to the green-yellow.

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

https://energy.gov/eere/ssl/downloads/solid-state-lighting-2017-rd-plan-suggested-research-topics

Other Solid State Lighting Emitters

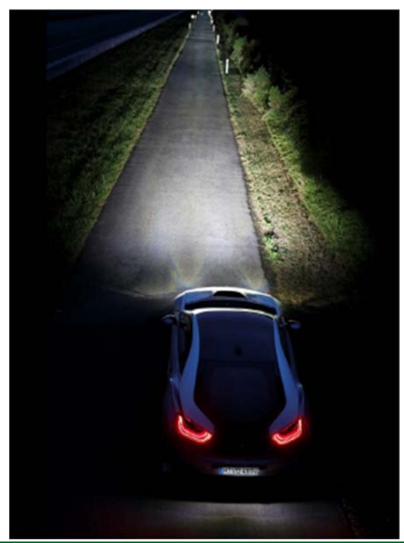
OLED (1000–3000 cd/m^2)

Chalina™
- Pendant-mount and wall-mount
- Uses (5) LGC 100x100 mm^2 panels
- 345 lm, CCT 3000K, 40,000 hrs expected life
- 0-10V dimmable, 46.9 lm/W

Acuity Brands

LG Display OLED Light Catalog

Laser Lighting (834 cd/mm^2 or 834 Mcd/m^2)

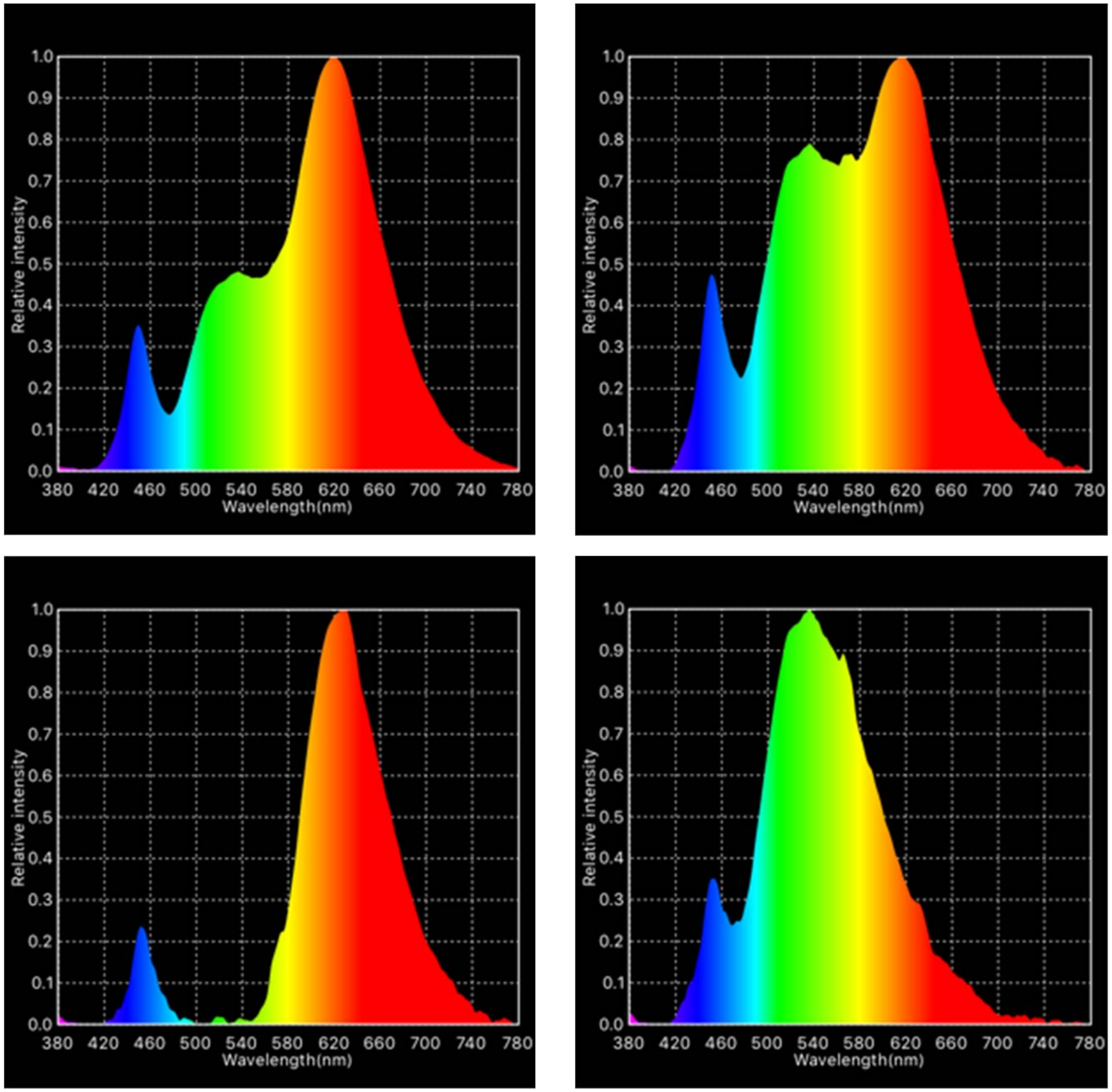


Abdel Hanafi, BMW, 2014
DOE SSL R&D Workshop

Enabling features of LED technology

1. Tailored and/or tunable spectrum
2. Precise optical control
3. Precise intensity control
4. Ready integration with controls, sensors, and communications
5. Extended reliability

Tailored/Tunable Spectrum



LEDs + phosphors can be combined in infinite ways to make different flavors of light

LEDs can make white light with any CCT and any CRI. Blue pump can be completely absorbed or a violet pump used.

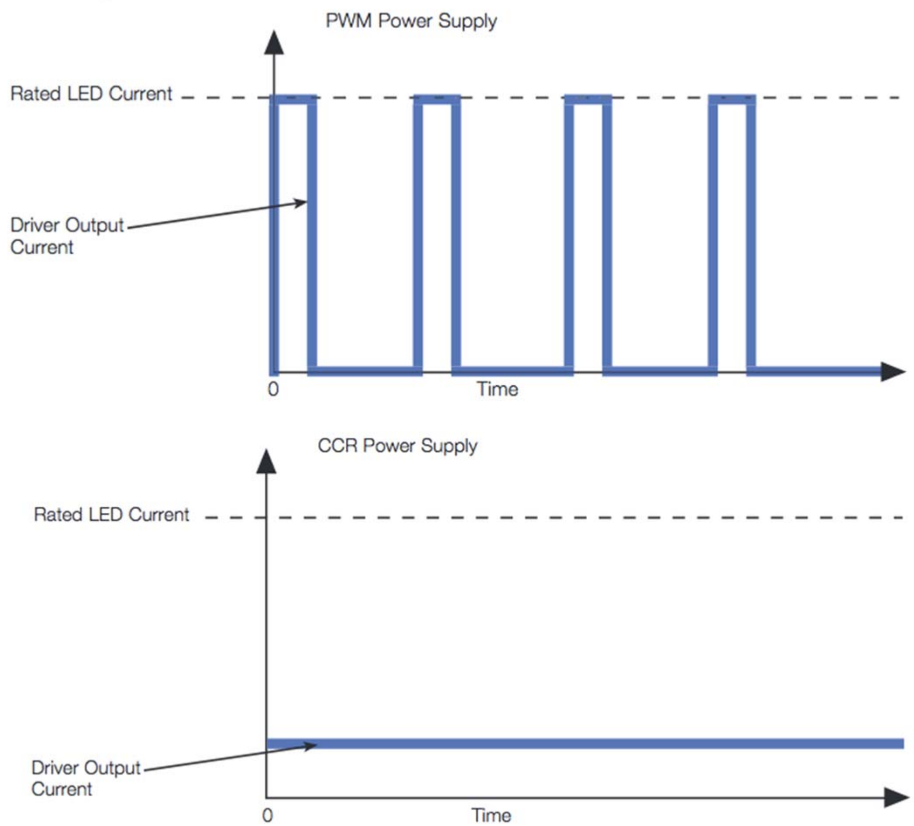
Precise Optical Control

Small, bright source size of LEDs enables low cost, precise optical control which enabled reduction in total amount of light, control of glare, minimized light trespass

John Edmond, Cree, DOE SSL R&D Workshop 2015

Precise intensity control

Unlike high intensity discharge light sources, LEDs are inherently dimmable and can be dimmed by reducing applied current or by pulsing the applied current at a very high frequency.



Lutron Application Note 360
http://www.lutron.com/TechnicalDocumentLibrary/048360.pdf

Integration with controls, sensors, and communications

Figure 4.6 Services that can be Provided to a City when Utilizing LED Lighting Street Lights Integrated with Sensors

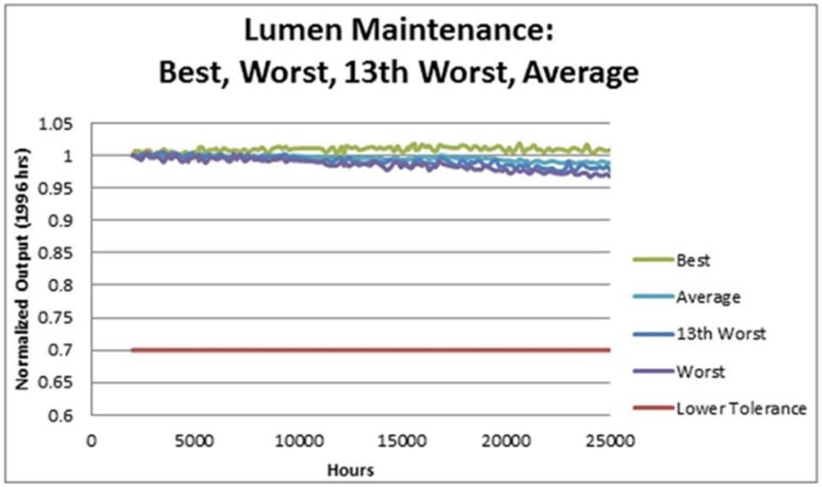
Source: Himamshu Prasad, DOE SSL R&D Workshop, Raleigh, NC, February 2016 [71]

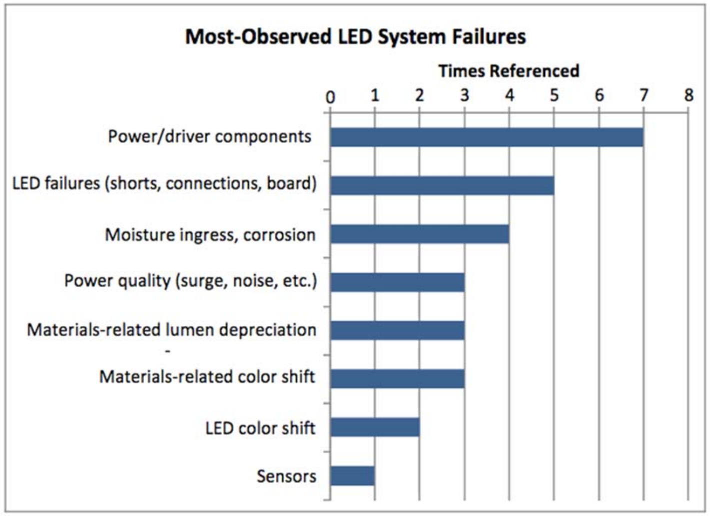
https://energy.gov/eere/ssl/downloads/solid-state-lighting-2016-rd-plan

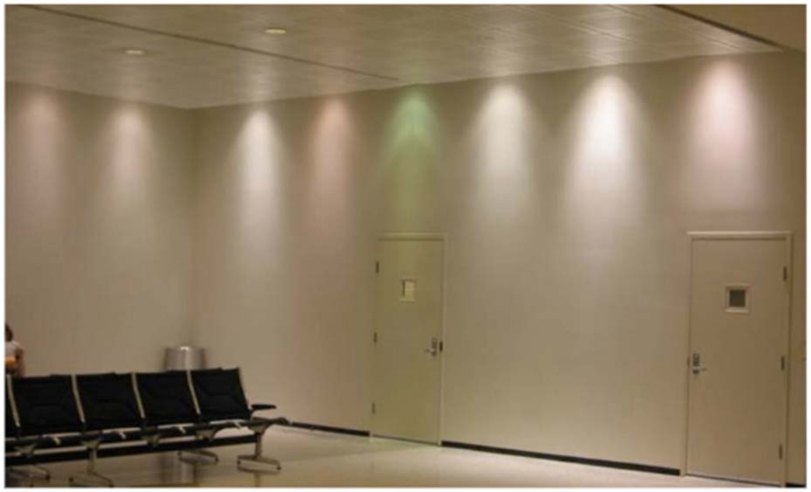
Reliability

LED Lighting Reliability is defined by:

1. Catastrophic Failure
2. Lumen Depreciation
3. Unacceptable color shift







LED Lighting

Table 2.1 Comparison Among Typical and Top-Performing SSL Products

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

Notes:

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

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

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

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

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

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

* Includes ballast losses

LED Lighting-

- More efficient
- Lasts longer
- Can be controlled
  - Spectrum
  - Intensity
  - Optical Distribution
- Ready integration with controls, sensors, and communications

So – what are the issues

Barriers to Adoption-

- First cost
- Not just changing a bulb
- Vestigial form factor
- Poor quality products
- Poor product selection
- Lack of test standards, performance communication – performance claims
- New application (mis)understanding

First Cost

Philips L-Prize lamp

Compatibility Considerations

Not just changing a bulb!

Expanded capabilities of LED lighting technology means more decisions

- Color qualities
- Dimmer compatibility
- Form factor
- Light distribution
- Controls compatibility

Vestigial form factors and building integration

Figure 2.6 Lamps without Aluminum Heat Sinks: (a) the Philips SlimStyle, (b) Cree 4-flow, (c) OSRAM Filament-Style LED

Source: (a) Philips website, May 2016 [19]*; (b) Cree website, May 2016* [20]*; (c) OSRAM website, May 2016* [21]

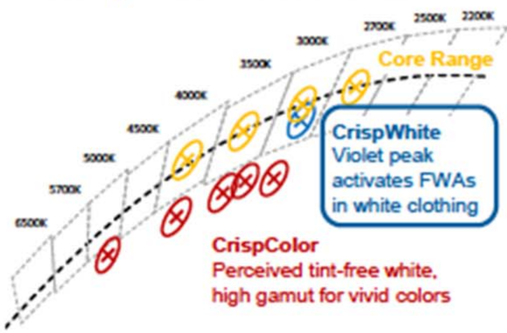
Poor quality, selection, deployment

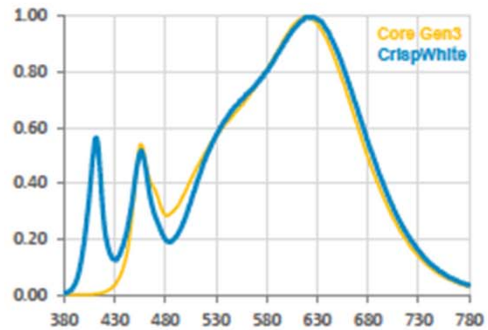
- Salesmanship – insufficient test standards, performance characterization standards to debunk claims – Wild West
- Misunderstanding of new technology – not always a 1-for-1 replacement, don't have to accept previous design constraints/trade-offs
- Misunderstanding of intent of lighting
- Misunderstanding of new aspects of lighting – early days
- Bad advice

New Application - Visual Preferences

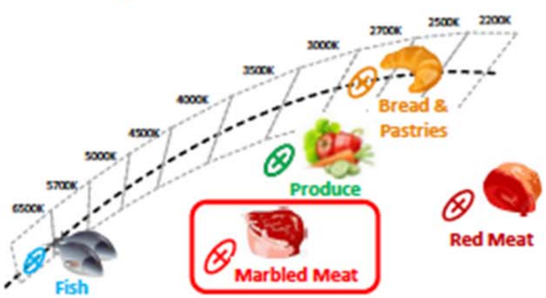
Spectral engineering for visual preferences

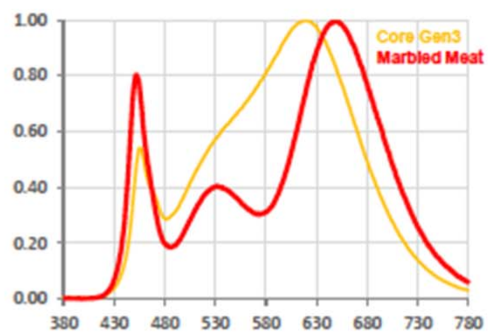
COB spectra for Fashion Retail

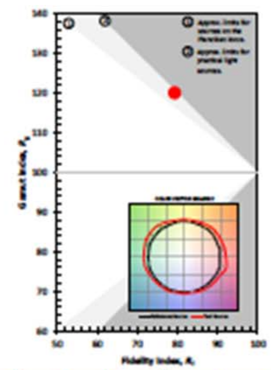




COB spectra for Fresh Food







Engineered spectra are preferred for various applications despite sometimes lower efficacy

Model	CCT	CRI	Rf	Rg	Efficacy (lm/W)
Core Gen3	3,000K	93	89	97	120
CrispWhite	3,000K	90	87	102	100
Marbled Meat	~3,000K	67	79	120	70

Wouter Soer, Lumileds, DOE SSL LED Roundtable 2016

New Application - Physiological Responses

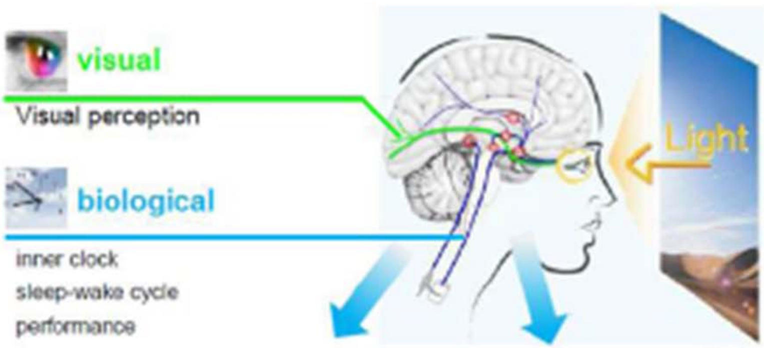


Figure 2.7 How Light Affects a Biological Systems
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [22]

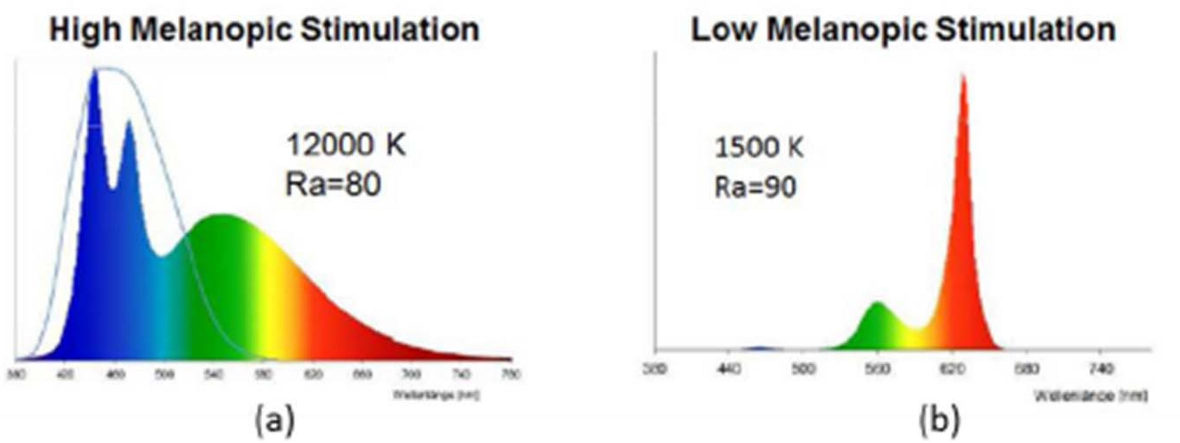
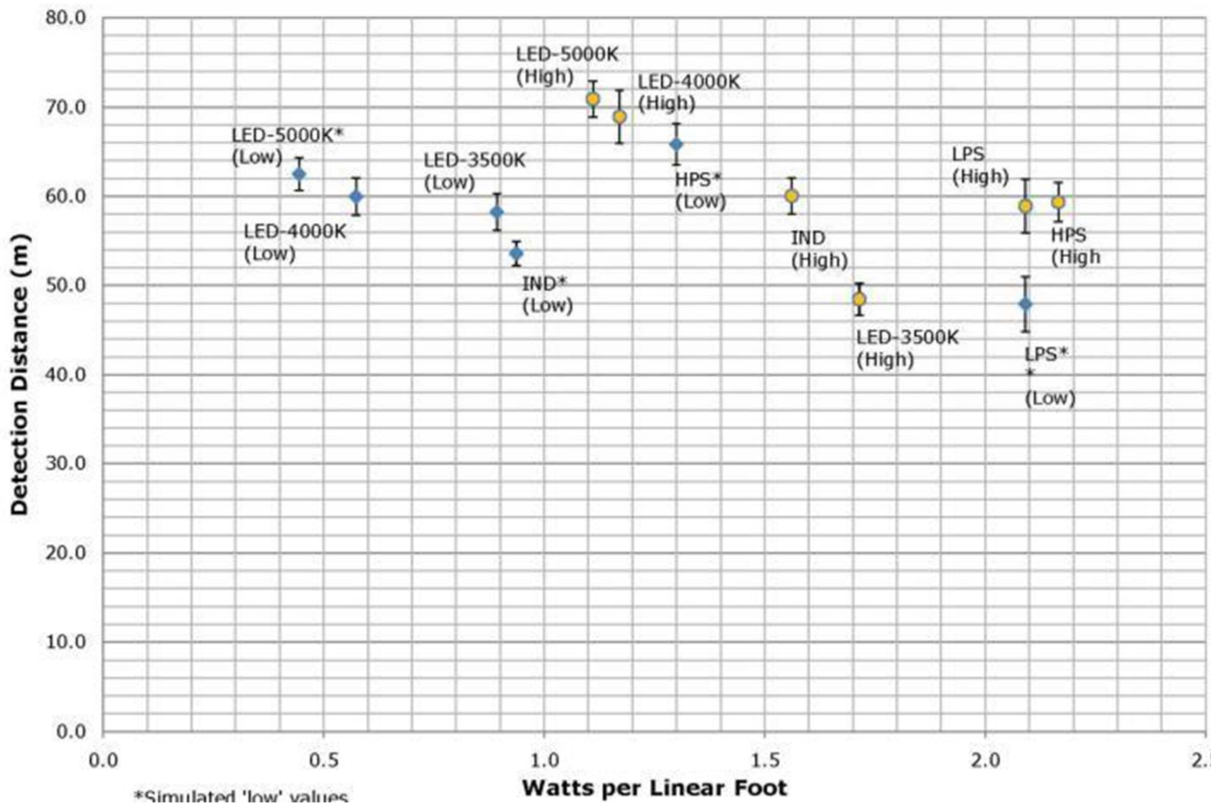


Figure 2.8 (a) Daytime Activation by Light and (b) Less Circadian Light Effects in the Evening and Night
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [22]

New Application – Roadway Safety

Detection Distance, San Jose, CA



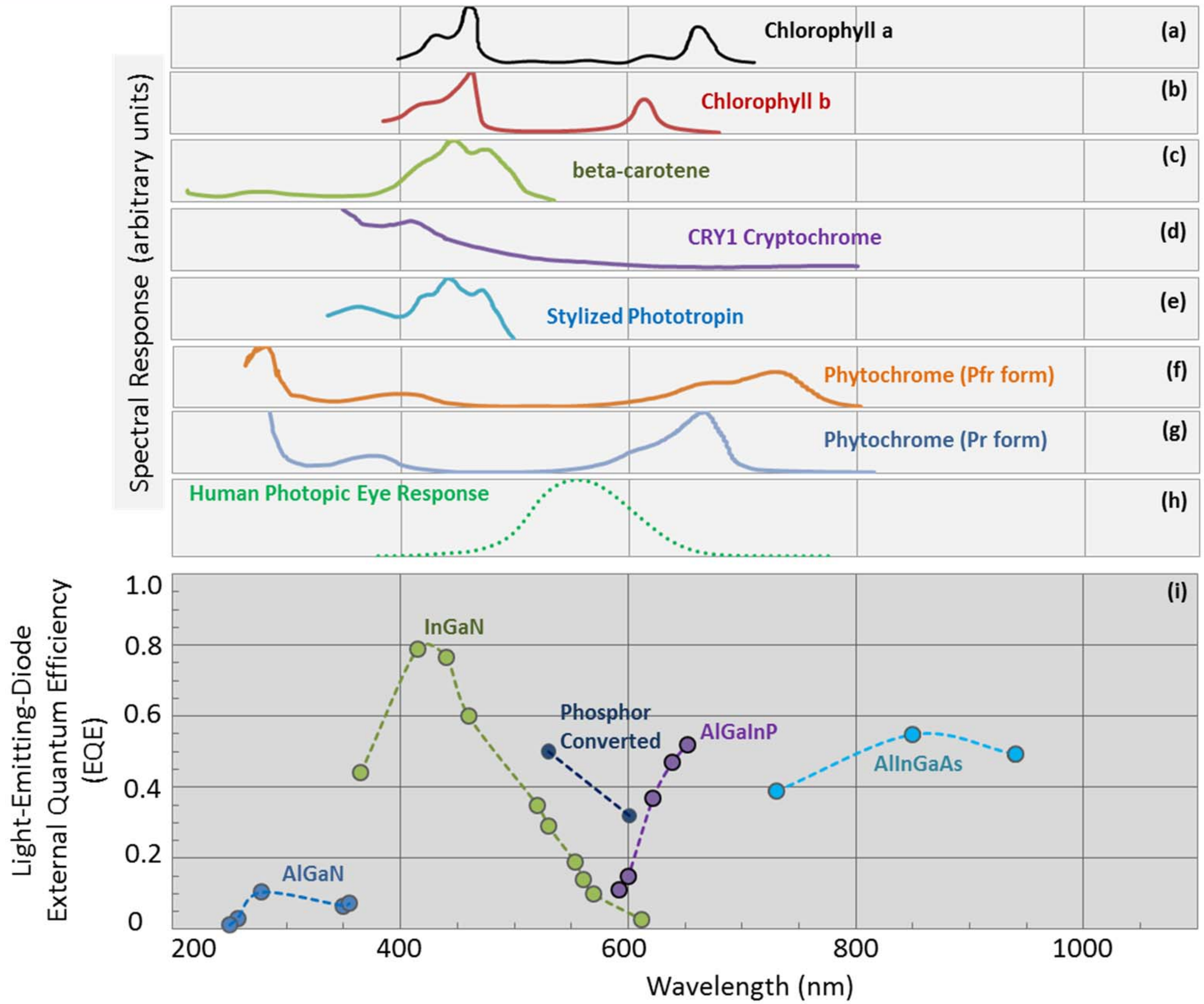
Ron Gibbons, Virginia Tech Transportation Institute..” Presented at 2016 U.S. Department of Energy Solid-State R&D Workshop,

VirginiaTech Transportation Institute

New Application – Roadway Safety

- LED lighting can be tuned to optimum spectrum for roadway safety and precise optical distribution can be engineered to minimize glare. Safety first!
- Secondary, negative impacts of electric light at night can be mitigated-
  - Precise optics to minimize total amount of light, sky-glow, and light trespass
  - Adaptive or timed controls can reduce light when unnecessary
  - Alternative spectrum can be used in ecologically sensitive areas (as long as roadway or pedestrian safety is maintained)

New Application – Horticulture



Pattison, P. M., Tsao, J. Y., & Krames, M. R. (2016). Light-emitting diode technology status and directions: Opportunities for horticultural lighting (No. SAND--2016-0136J). Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States).

New Application – Horticulture

Figure 2.11 The Influence of Spectra on Anthocyanin Production in Red Lettuce

Source: Tessa Pocock, Rensselaer Polytechnic Institute, SSL Technology Development Workshop, Portland, OR, November 2015 [5]

Conclusions

LED Lighting-
New technology with new capabilities

- Can be used as a 1-1 replacement but not optimum
- Need clear understanding of intent of lighting
- Need clear understanding of application requirements
- New features, new values, additional roles for lighting

- Energy savings now table stakes
- New value in pre-existing applications
- Enabled new high value applications
- Advice – understand exactly what you need/want from your lighting system and ask for it. Don’t just accept what is being ’sold’. Don’t rely on historical solutions.

Transitioning to LED lighting is a much bigger job than just replacing a light bulb, but benefits are also much, much bigger

Contact

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