LED Lighting Revolutions- Technology, Design, and Application

California Energy Alliance
UC Davis
February 5, 2020

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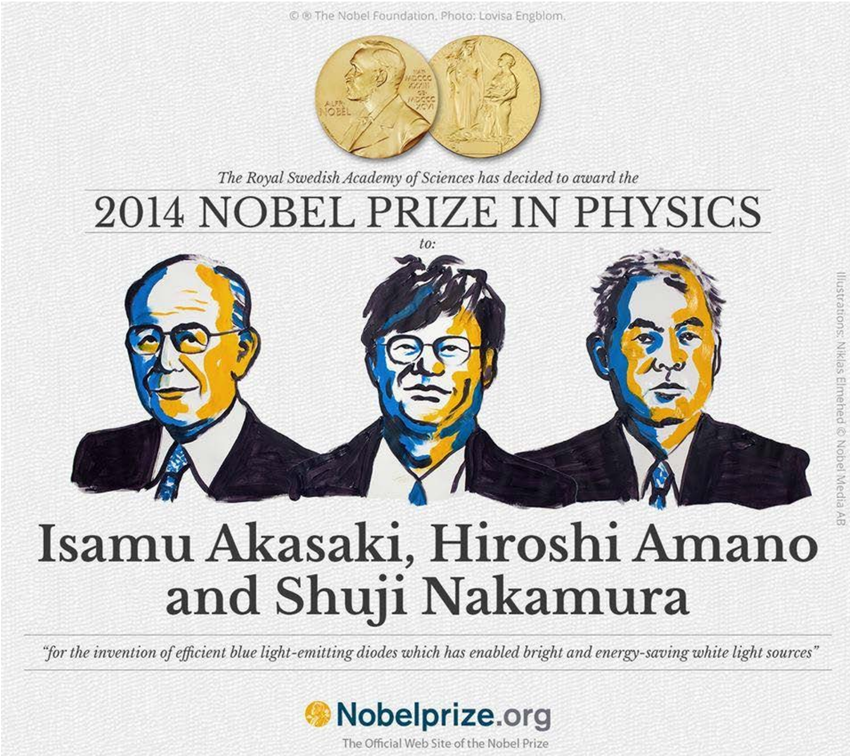
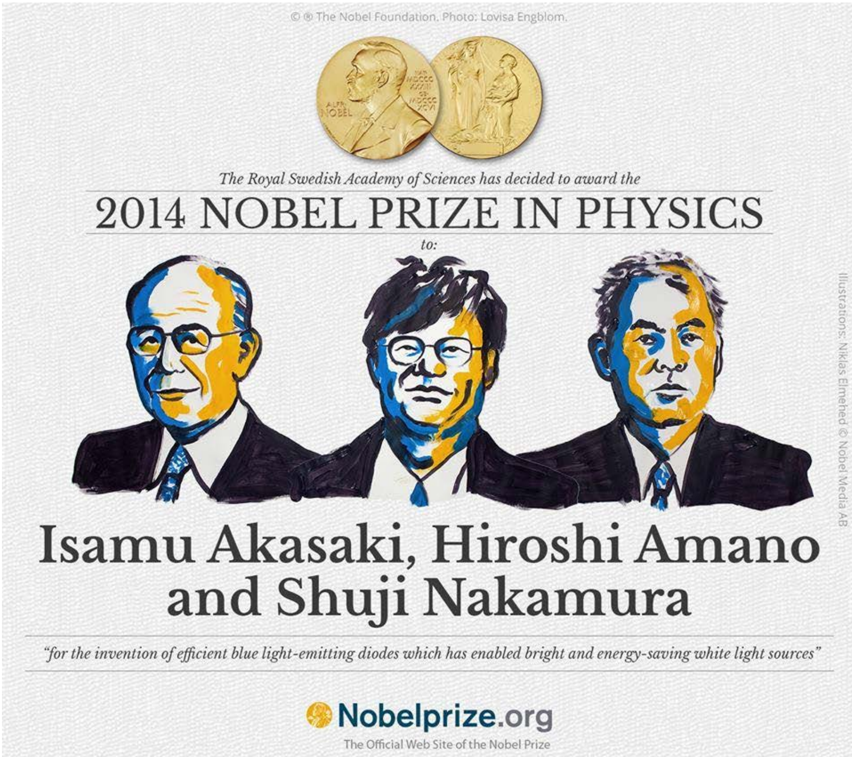
SSLS, Inc.

LED Technology Revolution



LED Technology Revolution



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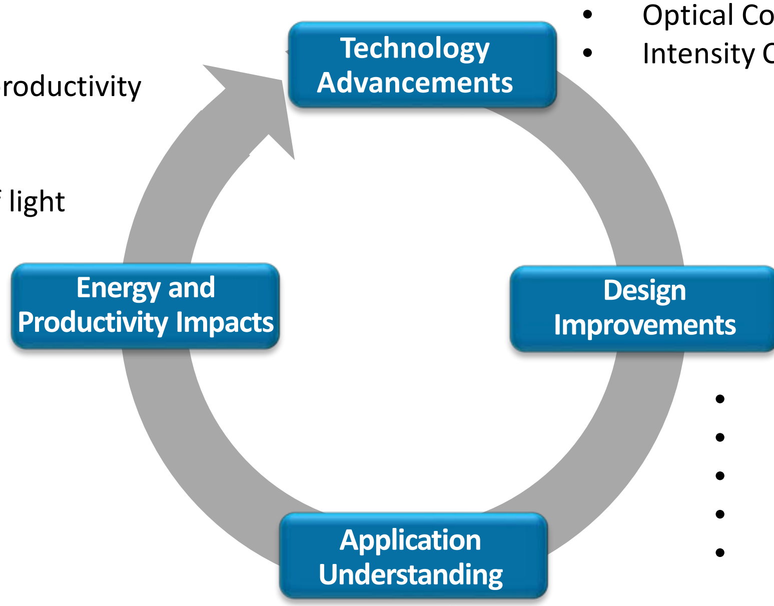
Inter-acting Revolutions

- Efficiency
- Spectral Control
- Optical Control
- Intensity Control

- Massive Energy Savings
- Improved human health and productivity
- Horticultural productivity
- Animal productivity
- Reduced ecological impacts of light



- Form factors
- Layouts
- Building integration
- Electrical integration
- Manufacturing technologies

- Illumination
- Color discrimination
- Glare
- Non-visual stimulus
- Horticulture
- Animal responses

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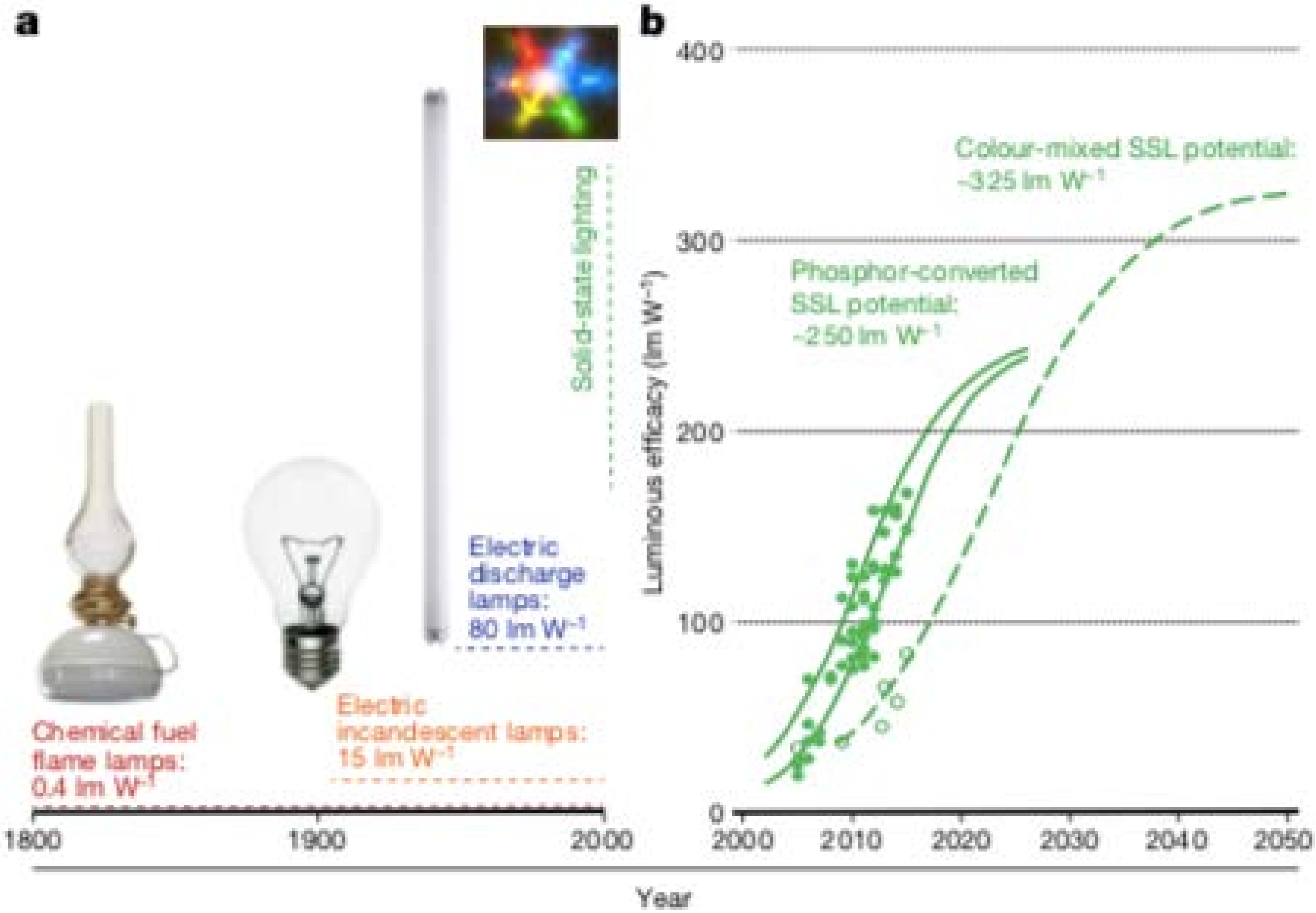
High Efficiency/Efficacy

Lighting efficiency



Pattison, P. M., et al. "LEDs for photons, physiology and food." *Nature* 563.7732 (2018): 493-500.

Spectral control

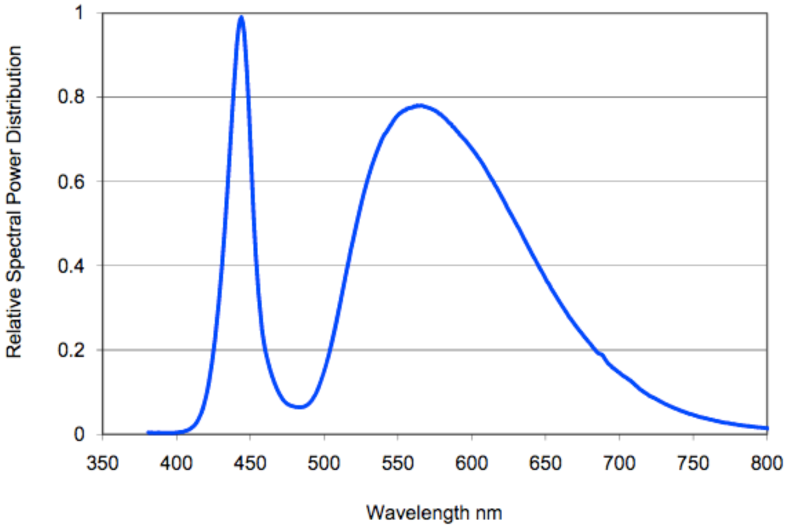
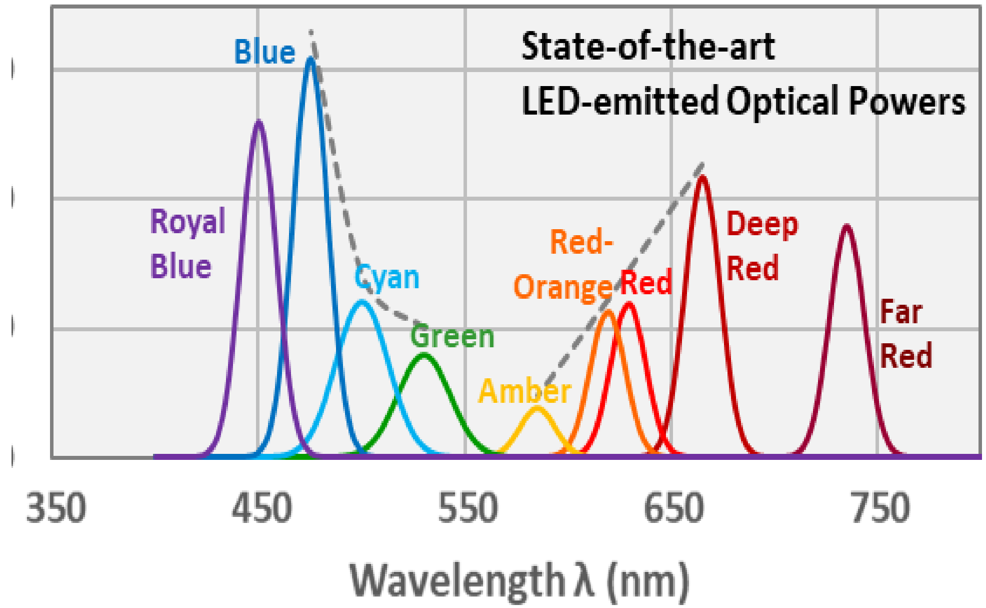
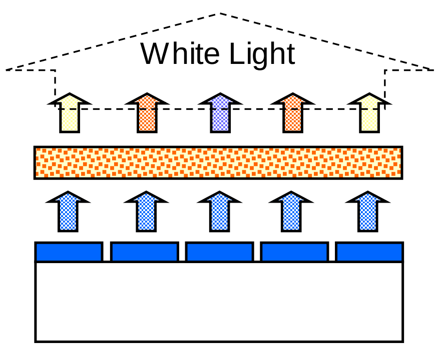


Figure 4. Color spectrum of LXML-PWN2 emitter, integrated measurement.

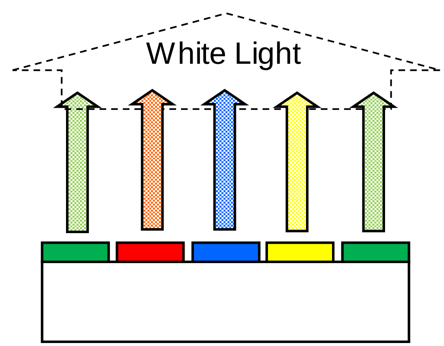


PC-LED



Blue LEDs + Phosphor

CM-LED



Direct Emission LEDs

2018 Solid-State Lighting R&D Plan

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Optical control and intensity control

An Investigation of LED Street Lighting's Impact on Sky Glow, DOE SSL Program 2017

Intensity control –

Time of night dimming of roadway lights in Cambridge, Tucson, San Jose

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LED- Intensity control

LUMEWAVE
By ECHELON

CASE STUDY

CAMBRIDGE, MA: SETTING THE EXAMPLE FOR ADAPTIVE STREET LIGHTING

Project Highlights

Energy savings
80%

Energy cost savings
$500,000 per year

Rebates
$820,000+

Payback period
4.36 years

Neighborhood-specific adaptive controls
Dimming to 30% at 8 p.m. or 10 p.m.

When a city is home to two of the most renowned universities of academics and innovation in America, Harvard and MIT, it too had better embrace innovation and smart thinking. Cambridge's commitment to sustainability as a key initiative goal demonstrates its mission to provide advanced energy efficiency and climate protection for its citizens. Cambridge successfully implemented what few cities have attempted:

Time of night dimming-
Cambridge, MA
Tucson, AZ
San Jose, CA

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Design Improvements

Form Factors

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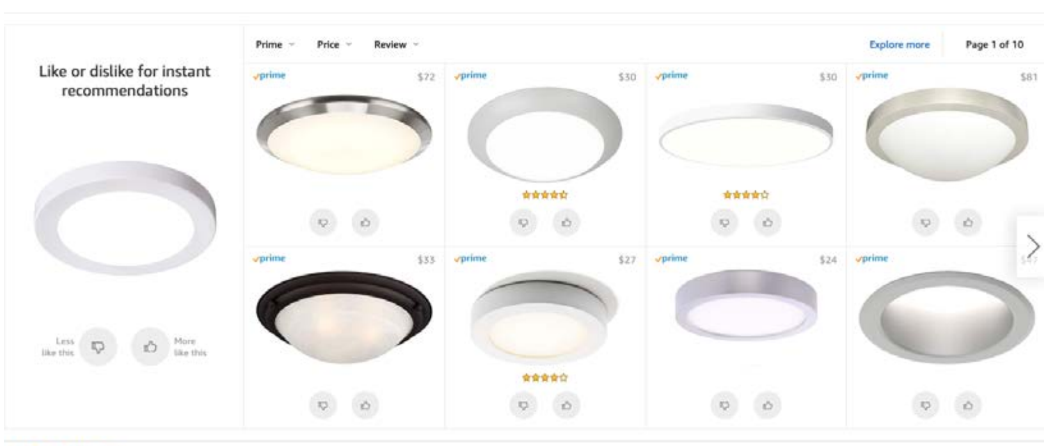
Form Factors



Philips Dubai Lamp

Bulb 2 Watt

With a light output of 400 lumen, this lamp can replace a 40W incandescent bulb, for example in decorative fixtures or areas where not much light is needed. Its filament LED technology gives the same decorative impression as the original incandescent lamps. The lamp is available in warm white and cool daylight. The lifetime is 25,000 hours. The lamp has an E27 base and is not dimmable. This product contains no mercury.

New Materials

The Bamboo Pendant designed by Brad Koerner of Koerner Designs has won the US Department of Energy's Manufacturing Innovator Challenge for Sustainable Manufacturing of Luminaires. (Image credit: Illustration courtesy of Lucept.com, Koerner Design.)

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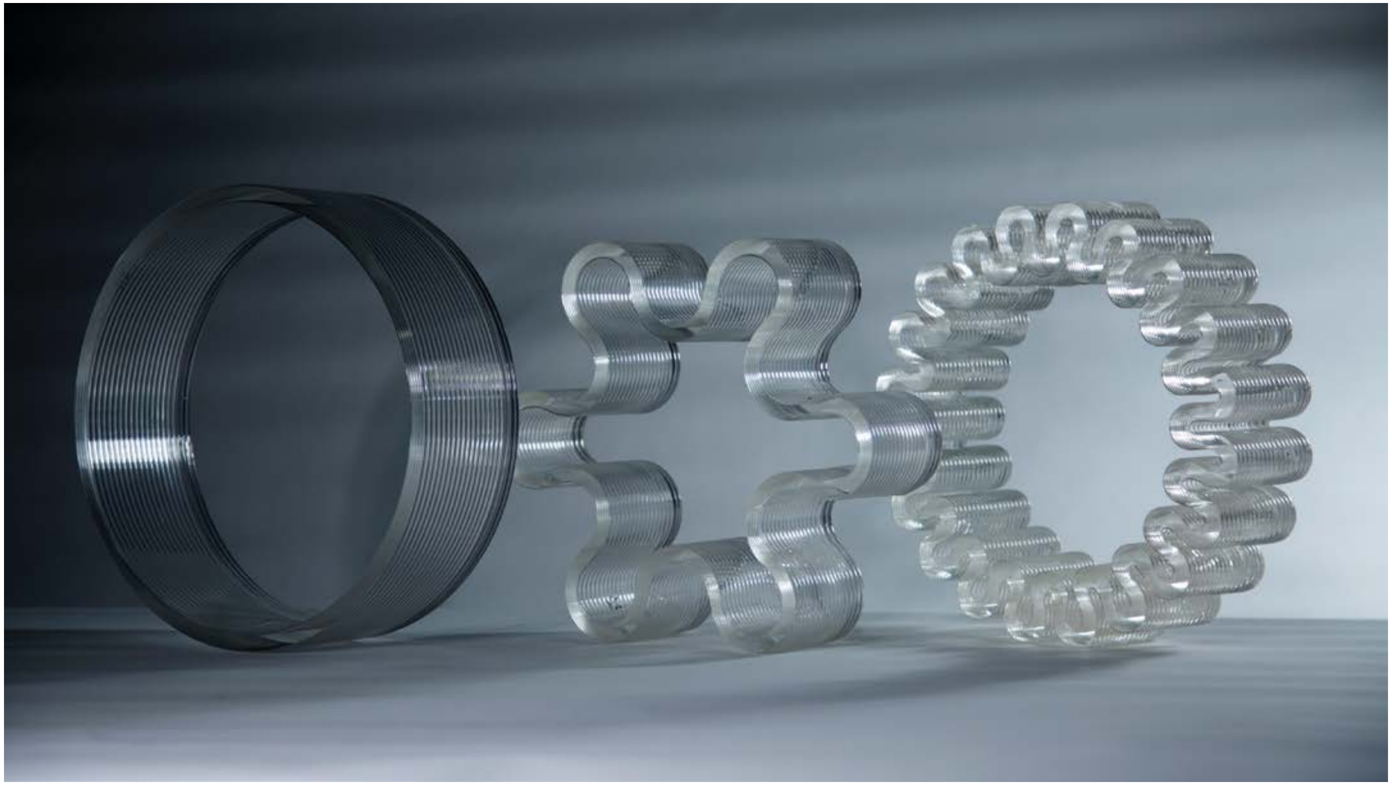
Additive Manufacturing



Inamura Presentation, 2020 DOE Lighting R&D Workshop

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Application Understanding

Lm/W ?

Efficiency Programs always focused on the denominator

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Light and Health

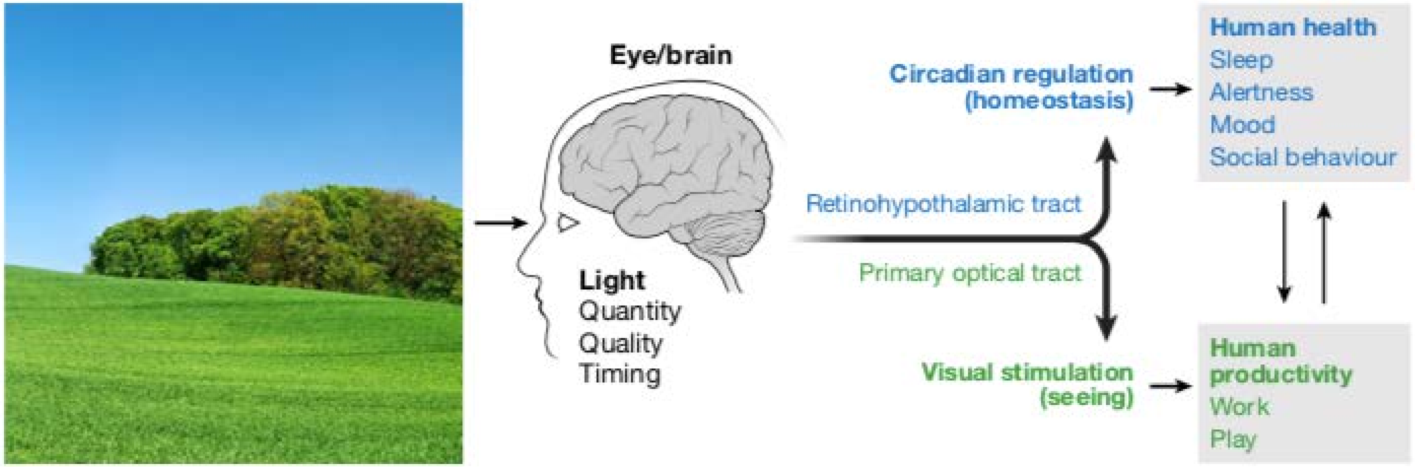

Fig. 3 | The two photoreceptor pathways between the human eye and the brain. The primary optical tract (green text) originates in the retinal rods and cones. Cone photoreceptors in the fovea provide higher-light-level photopic colour vision with a peak sensitivity in the green at a wavelength of approximately 555 nm, the colour of green foliage; rod photoreceptors provide the lower-light-level scotopic black, grey and white vision with a peak sensitivity at about 498 nm. The retinohypothalamic tract (blue text) originates with ipRGCs, the peak sensitivity of which is at about 480 nm, approximately the colour of the blue sky. This regulates the circadian, neuroendocrine and neurobehavioural systems that ultimately impact human health and productivity. Photograph from iStock/Getty.

Pattison, P. M., et al. "LEDs for photons, physiology and food." *Nature* 563.7732 (2018): 493-500.

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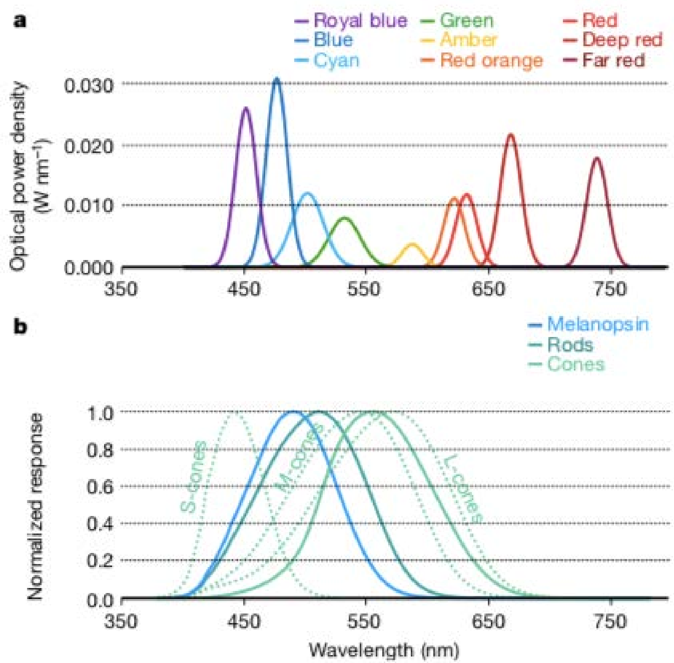
Colors and Health



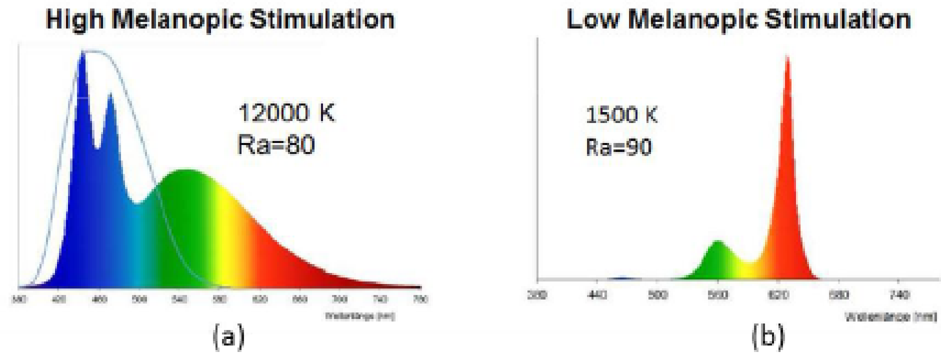


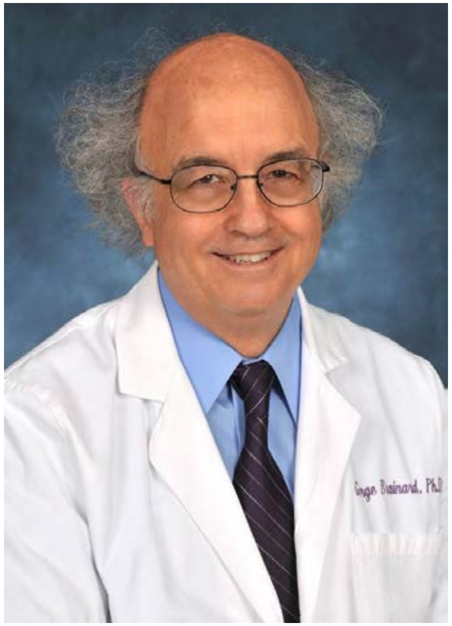
Figure 2.8 (a) Daytime Activation by Light and (b) Less Circadian Light Effects in the Evening and Night
Source: Andreas Wojtysiak, OSRAM, SSL R&D Workshop, San Francisco, CA, January 2015 [22]

Pattison, P. M., et al. "LEDs for photons, physiology and food." *Nature* 563.7732 (2018): 493-500.

Mediating Factors for physiological responses

Elements involved in light transduction

- Conscious and Reflex Behavior
- Ocular Media Transmission
- Iris/Pupil Dilation
- Photoreceptor Sensitivity
- Photoreceptor Distribution
- Neural Integration of Time/Space
- State of Retinal Adaptation



George Brainard, TJU

“A maxim for optimizing circadian regulation is increased light exposure at the beginning of and during the wake cycle, and decreased light exposure before sleep.”

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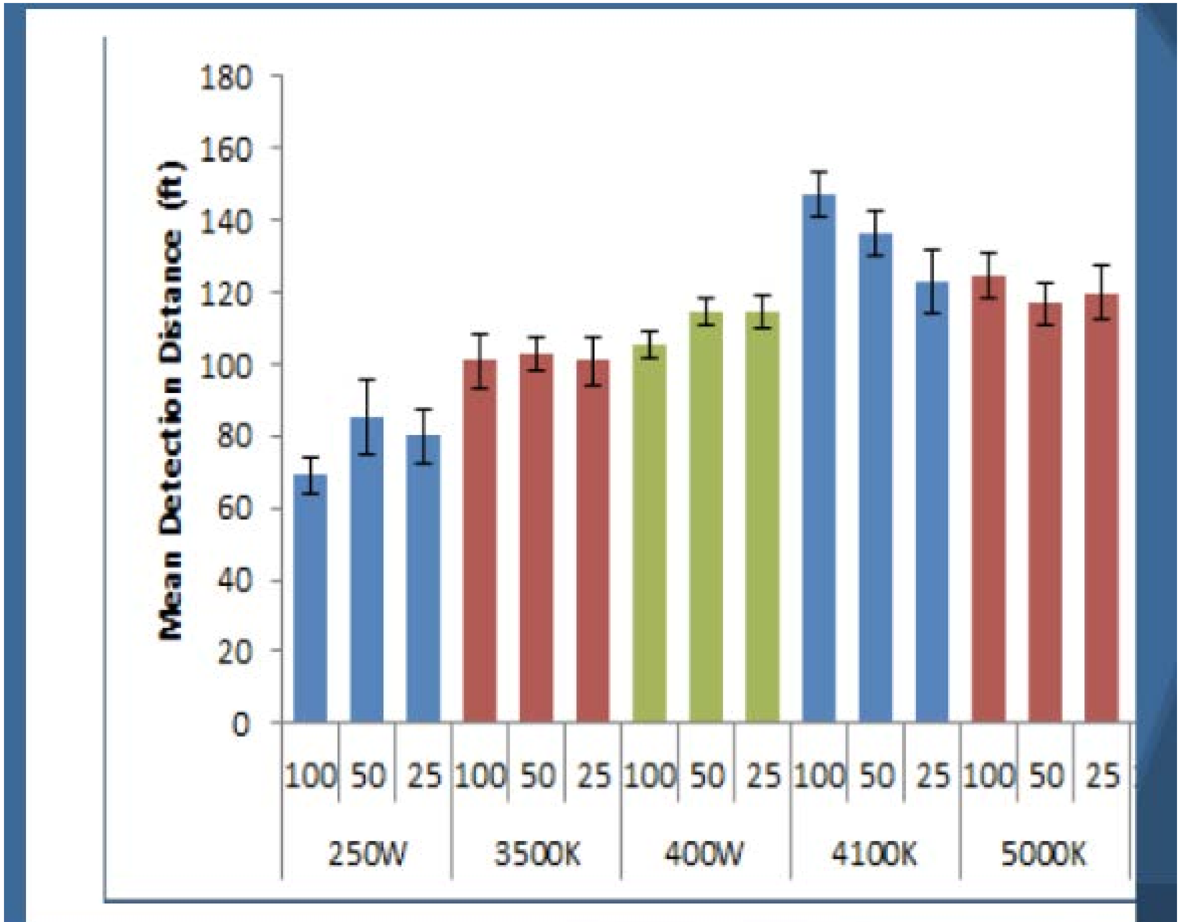
Roadway Safety



2014 REPORT #E14-286 Seattle LED Adaptive Lighting Study

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Horticultural Lighting

Aerofarms, Newark, NJ

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Horticultural Lighting – Redefining efficacy

	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/ft²) or Lux (lm/m²)	Photosynthetic Photon Flux Density (µ-moles/second·m²)
Efficacy of Radiation	Luminous Efficacy of Radiation (LER) (lm/Optical Watt)	Photosynthetic Photon Efficacy of Radiation (µ-moles/second Optical Watt)

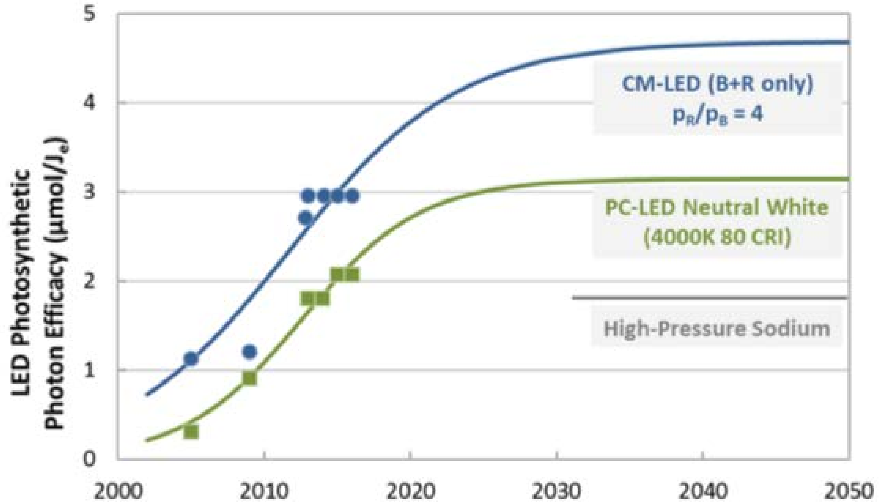

Figure 3.16 LED Photosynthetic Photon Efficacy (or LED Photosynthetic Efficacy of Source) for a Typical Pc-LED Architecture with a Neutral White Color Temperature and for a Hypothetical Cm-LED Architecture Containing Only Blue (455 nm) and Deep Red (665 nm) LEDs With an Optical Power Ratio of 1:4

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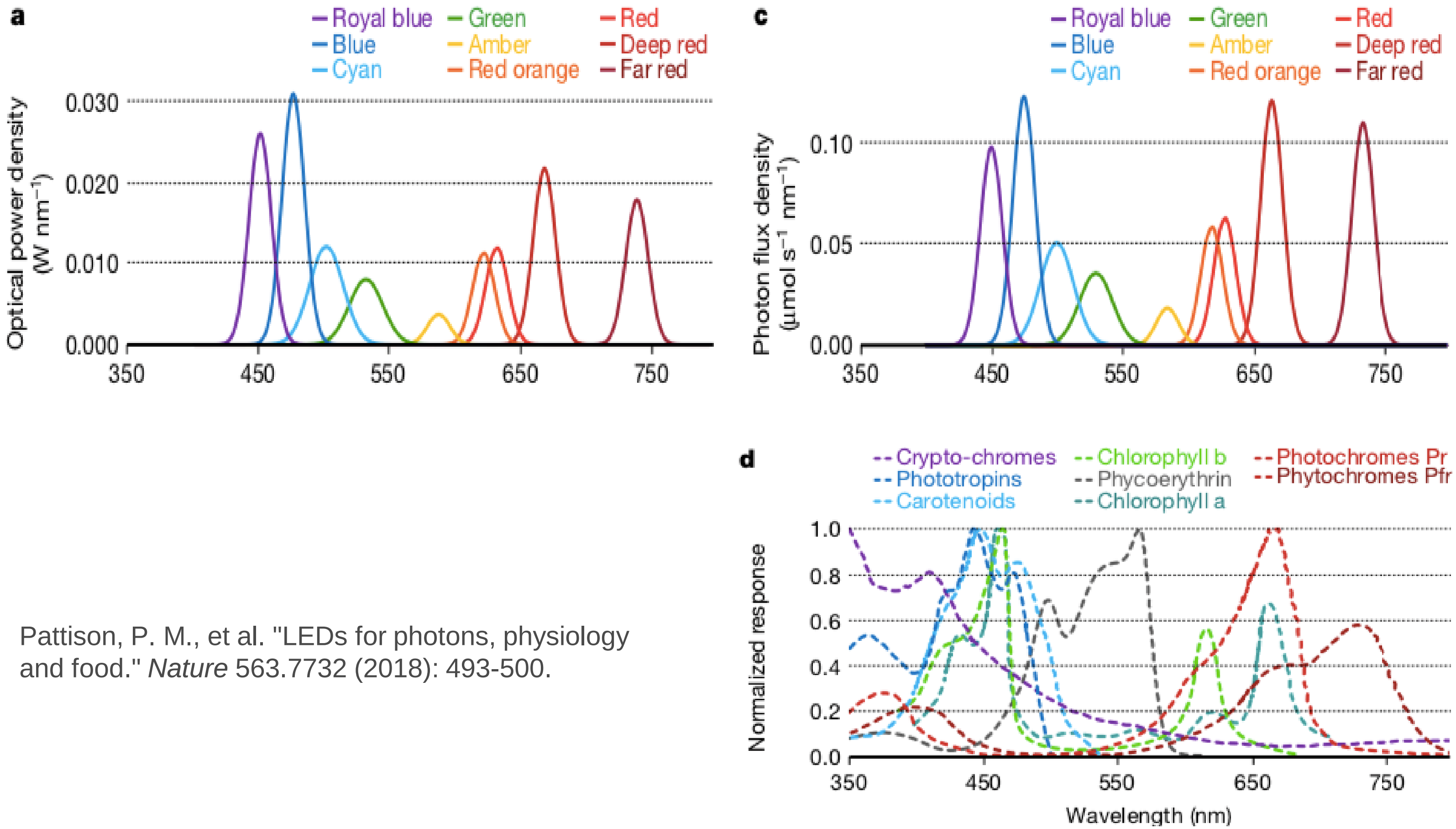
Horticultural Lighting – Plant Responses



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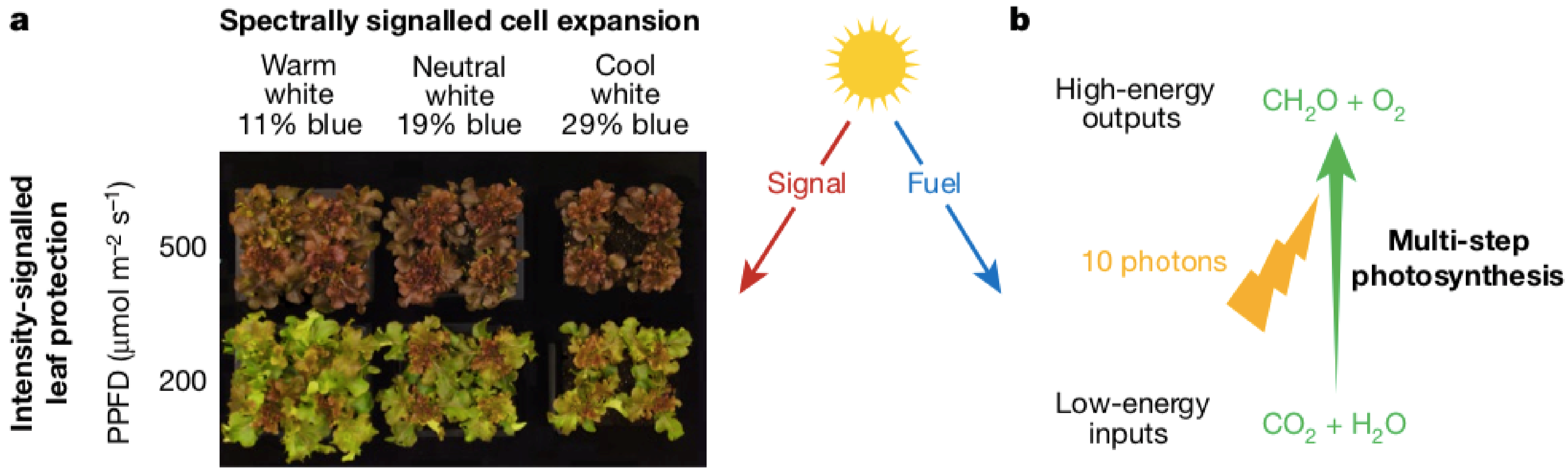
LED specifics

LED	Efficiency W per W	Efficacy µmol per J	relative Price
Blue	0.88	3.3	30×
Red	0.69	3.8	10×
Far-red	0.66	4.0	30×
Cool White	0.80	3.0	1×

Kusuma, Pattison and Bugbee.
From physics to fixtures to food: Potential efficacy of LEDs.
In review.

Bruce Bugbee
Utah State University

Horticultural Lighting – Plant Responses



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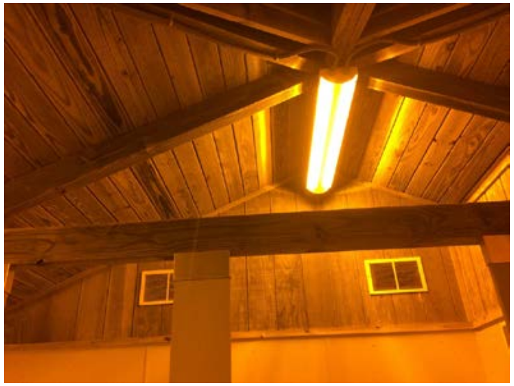
Animal Responses to light



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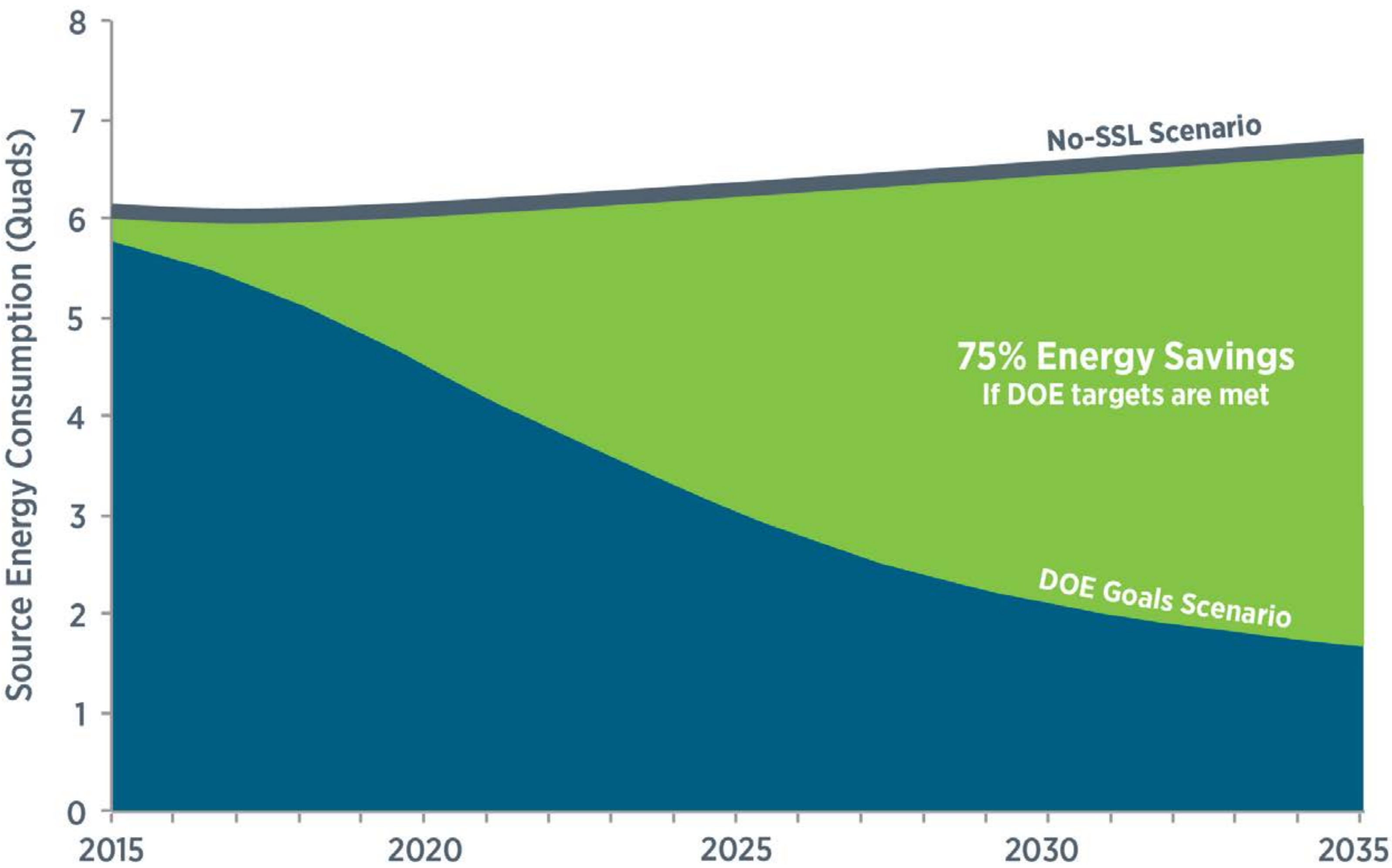
Lighting Energy Projection – U.S.A.



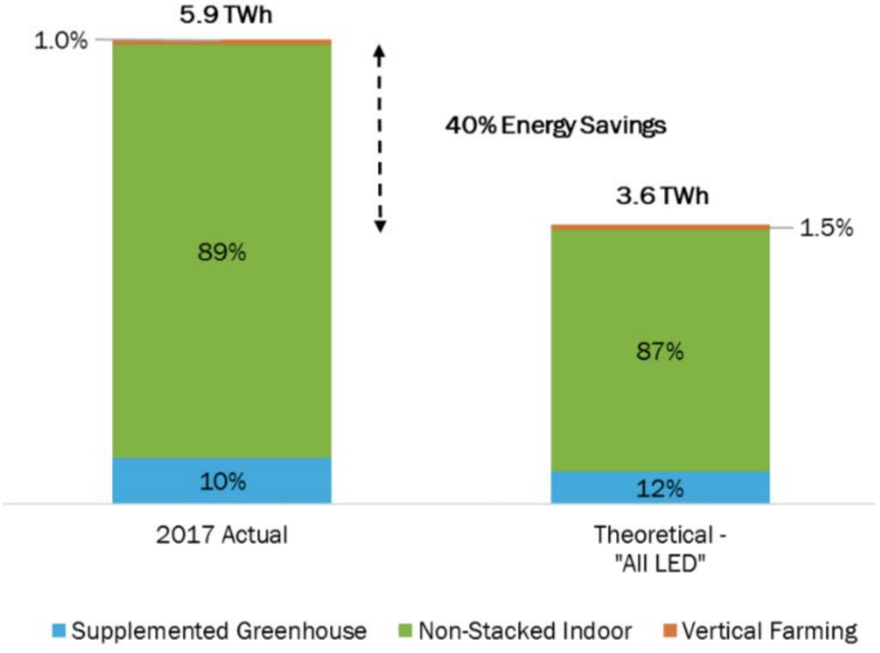
 Energy Savings Forecast of Solid-State Lighting in General Illumination Applications, 2016. http://energy.gov/eere/ssl/ssl-forecast-report

Horticulture Lighting – Energy Savings

(a)

(b)

(c)



(24 tBtu/yr)

Energy Savings Potential of SSL in Horticultural Applications, DOE SSL Program 2017

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Horticulture Lighting – Energy Savings

Table E.1 Summary of Horticultural Lighting Analysis

Analysis Outputs	Units	Vertical Farming	Supplemented Greenhouse	Non-Stacked Indoor	Total[1]
Estimated Total Lit Grow Area	**Million ft^2**	0.5	26.8	18.7	46.0
Annual Operating Hours	**Hours/year**	6278	2120	5475	--
Average Electricity Consumption					
LED	**W/ft^2**	17.4	7.3	41.8	--
HPS/MH		N/A	10.4	60.8	--
Fluorescent		22.8	N/A	60.0	--
2017 Technology Mix					
LED	**%**	66%	2%	4%	--
HPS/MH		<1%	98%	89%	--
Fluorescent		34%	--[2]	7%	--
2017 Annual Energy Consumption					
Current	**GWh/year (tBtu/year)**	60 (0.62)	588 (6.1)	5300 (55)	5940 61
Theoretical "All LED"		55 (0.57)	416 (4.3)	3100 (32)	3570 37
Theoretical % Energy Savings[3]	**%**	10%	29%	41%	40%

1. Values may not add due to rounding.
2. Supplemented greenhouses may sometimes use a small number of fluorescent fixtures in a separate room or facility for the purpose of cultivating seedlings and grafted plants. However, these lights were not included as part of the study.
3. The theoretical percent energy savings given current technologies were all converted to LEDs, which is the percent difference in energy consumption of the Current and the Theoretical "All LED" scenarios. (Note percent energy savings are calculated from raw data, as opposed to rounded values presented in the table and, therefore, may not match.)

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Key Takeaways

- Lighting revolution enabled by efficiency
- New technology and application needs new design thinking
- Need updated lighting science understanding and guidance
- Energy, health, productivity, and environmental impacts will be immense

Thank You!

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Morgan Pattison, background

- PhD, Materials Science, UCSB
- 14 years with DOE Lighting R&D Program – Senior Technical Advisor
  - Scout new technologies/materials
  - Understand barriers to adoption
  - Develop R&D strategies for new application understanding
  - Lead author of DOE R&D plans
  - Coordinate lighting efforts with other government agencies (USDA, NIH, NIOSH, DOD, DOT
- Consultant to National Park Service
- Consult to VC/investors
- Advisor-
  - GLASE, Resource Innovation Institute, Cyclotron Road, Phosphor Global Summit, Member IES Horticultural Lighting Committee

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Recent Publications

- 2019 U.S. DOE Lighting R&D Opportunities (lead author)
- 2018 Pattison Nature
- Comptes Rendue
- Annalen der Physik
- Acta Horticultural

- *Upcoming*
  - *2019 Energy Savings Potential of SSL in Agricultural Applications*
  - *From physics to fixtures to food: Current and Potential LED efficacy*
  - *A review of human physiological responses to light: Significance to the development of innovative lighting applications*