How LED lighting changes the world

Outline

- How LED Lighting changes the world
- Comparison of today's light sources
- Myths and truths about LED lighting
- Future light sources and solutions
- The business case for LED lighting
- New career opportunities for engineers

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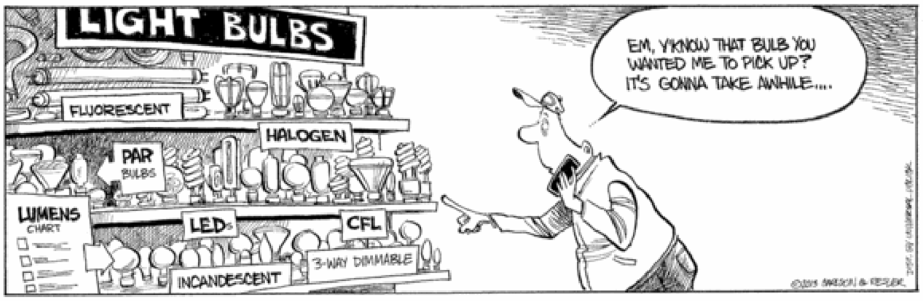
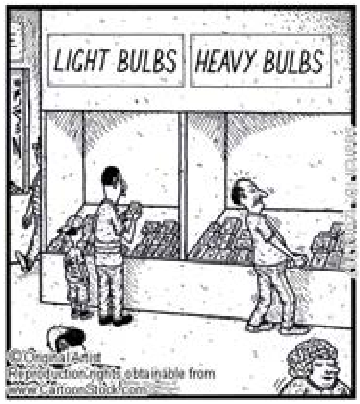
Customer education is required …



… because there are so many choices and decisions to make.



Quality of light

- Consistent lighting over time
- Uniform lighting in the beam
  - Luminance, Color
- Consistent lighting from unit to unit
- High color reproduction
- Low maintenance – no dark light points
- Flexible controls
- No glare or light trespassing

Quality of life

- Quality of light = quality of life
  - Work and school environment
    - Flexibility in lighting design
    - Spectrum of light can be “engineered” or adjusted to set the mood
  - 3rd world countries still use kerosene lamps
    - 10s of thousand burn victims every year
- Aesthetic
  - Architectural lighting, City beautification
- Controls
  - Adjust color, brightness following the circadian rhythm

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Public safety

- Crime rate is related to lighting on roadways and public places
  - People feel safer
  - Negative impact on real estate market
    - Los Altos, Ca. has no streetlights to imply a safe community
- Reduction of accidents at night
  - Low pressure sodium (orange street lights) has very poor color rendition
  - Some objects are hard to distinguish from background
- Controls
  - Highlight emergency response areas
  - Dim light to avoid light trespassing

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Sustainability

- Energy savings from LEDs in 2012 US alone
  - $675 million
  - Despite 18 percent increase in installed lamps from 2001 to 2010, annual lighting **electricity consumption has decreased by 9 percent**
- Possible energy savings at 100% LED penetration
  - $37 billion
  - LED lighting will represent over 75 percent of all lighting sales by 2030
- City of San Jose (example)
  - 62,000 street lights
  - 13,000 outages annually (all city lights)
    - 50,000 miles driven to maintain
    - $35,000 disposal annually
- Controls
    - Turn off or dim lights when no one is around
      - Homes, shops, offices, public spaces

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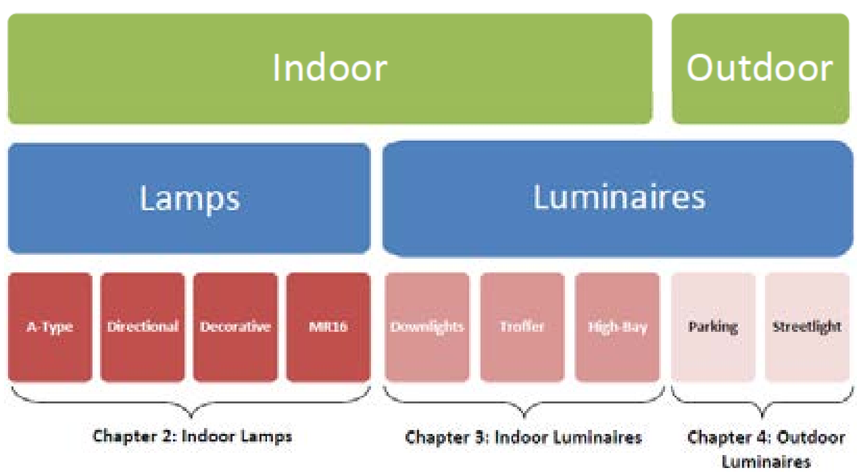
Comparison of light sources

- Filament
- Fluorescent
- HID (High Intensity Discharge)
  - High Pressure Sodium
  - Low Pressure Sodium
  - Ceramic Metal Halide
- SSL (Solid State Lighting)
  - LED
- Other light sources

Common lighting applications



Definition of lamp efficacy

- The **amount of light** (luminous flux = measure of the perceived power of light) produced by a lamp usually measured in lumens, **as a ratio of the amount of electrical power** consumed to produce it, usually measured in watts.
  - Unit – lm/W (Lumens per Watt)

- Not to be confused with "Wall Plug Efficiency"
  - It is defined as the ratio of the radiant flux (the total optical output power) to the input electrical power. Usually used for lamps outside of the visual spectrum

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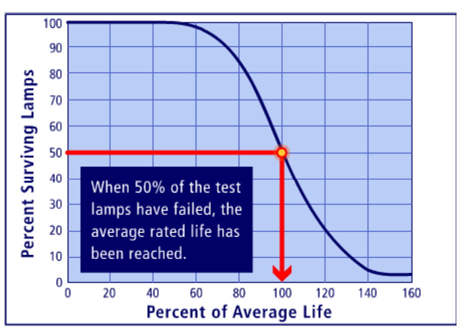
Definitions of Lifetime

- For incandescent, fluorescent and HID lamps
  - Rated lamp life is the time until 50% of lamps is expected to have failed.



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Definitions of Lifetime

- For LED based lamps
  - **Rated Lumen Maintenance Life** is commonly understood as the time to which the lumen output has degraded to a particular percentage of the original light output.
  - In most cases the **time to 70% light output** (LOP)
    - Also known as the time to L_{70}
- For OLED based lamps
  - Rated Lumen Maintenance Life
    - Time to L_{50}

Definition of Lumen Maintenance

- Fluorescent and Metal Halide
  - Expected lumens at 40% of rated life
- Most other lamps
  - Expected lumens at 50% of rated life
- Lumen maintenance for LED based lamps is usually not given
  - It is part of the Rated Life definition (L_{70})

Filament lamps

- Standard Tungsten
  - Efficacy: 8-13 lm/W
  - CRI: 97+
  - Rated Life: 750-1500h
  - Lumen maintenance: fair*
- Halogen
  - Efficacy: 15-36 lm/W
  - CRIL 97+
  - Rated Life: 3000-5000h
  - Lumen maintenance: excellent*

  - operated at 5% higher than its design voltage would produce about 15% more light, and the luminous efficacy would be about 6.5% higher, but would be expected to have only half the rated life

  - *usually fails before reaching noticeable lumen depreciation

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Fluorescent lamps

- Linear Fluorescent (LFL)
  - Efficacy: 70-110 lm/W
  - CRI: 50 – 90+
  - Rated Life: 15,000 – 46,000h*
  - Lumen maintenance: good – excellent

- Compact Fluorescent (CFL)
  - Efficacy: 36-80 lm/W
  - CRI: low 80s
  - Rated Life: 6000-8000h*
  - Lumen maintenance: fair

  - *depending on ballast starting and on/off cycles

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High Intensity Discharge lamps

- High Pressure Sodium*
  - Efficacy: 70-145 lm/W
  - CRI: low 20s
  - Rated Life: 16,000 – 55,000h
  - Lumen maintenance: good – excellent

- Low Pressure Sodium
  - Efficacy: 60-150 lm/W
  - CRI: negative -40 (orange)
  - Rated Life: 12,000 – 18,000h
  - Lumen maintenance: good - excellent

  - *Start times ~5min.

High Intensity Discharge lamps

- Ceramic Metal Halide*
  - Efficacy: 80-125 lm/W
  - CRI: 80+
  - Rated Life: 10,000 – 30,000h
  - Lumen maintenance: good

  - *Start times ~5min.

LED based lamps

- LED based lamps
  - Efficacy: ~ 100 lm/W increasing rapidly
  - CRI: wide range depending on phosphor conversion
  - Lumen Maintenance Life (Time to L_{70}): 50,000h*
  - Lumen maintenance: good – excellent**

- *LED based lamp rated life definition is not always consistent
  - Not to be confused with LED component lumen maintenance
    - Usually there are more than 1 LED per lamp or luminaires
  - Life may be limited by driver electronics not the LED component
- **Lumen maintenance depends on operating conditions and quality of LED component

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OLED

- OLED
  - Efficacy: 25lm/W
  - CRI: wide range depending on phosphor conversion
  - Lumen Maintenance Life (L_{50}): 5000h
  - Lumen maintenance: poor

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Myths and truth about LEDs

- LEDs “last” 50,000h and longer
- LED light is cold and uninviting
- The higher the CRI the better
- LED lamps are not “bright enough”
- ENERGY STAR® qualified illumination products are more reliable
- Light from LEDs is hazardous
- LEDs contain hazardous materials

LED lamps “last” 50,000h +

- LED components can emit light for a very long time – proven fact
  - How much light at 50,000h depends on many factors and is not easy to verify
  - LEDs operated at high stress can degrade faster
  - NOT ALL LEDs are equal
    - Materials and manufacturing methods are key
- LED lamps consists of many components
  - The LED driver has 50+ components of which the electrolytic capacitors are considered the weakest link
- Consumers primary concern is cost at a good enough “rated lifetime” ~10,000h

LED light is cold and uninviting

- High CCT LEDs (cool light) is more efficient
  - Lower losses when phosphor converting
- Warm CCT with high color representation qualities
  - Are on the market for years, but most people don't "see" them as LED based
  - Are less efficacious due to the "conversion distance"

Correlated Color Temperature, CCT

- IESNA (Illumination Engineering Society of North America) Definition:
  - The absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source.
- The correlated color temperature (CCT) designation for a light source gives a good **indication of the lamp's general appearance**, but does not give information on its specific spectral power distribution.
  - Therefore, two lamps may appear to be the same color, but their effects on object colors can be quite different.

Color Temperature Chart

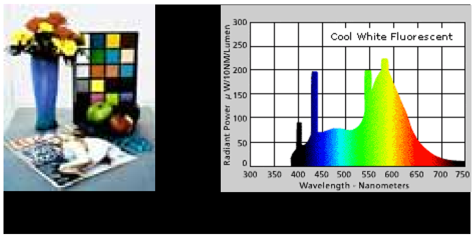
Degrees Kelvin	Type of Light Source
1700-1800K	Match Flame
1850-1930K	Candle Flame
2000-3000K	Sun: At Sunrise or Sunset
2500-2900K	Household Tungsten Bulbs
3000K	Tungsten lamp 500W-1k
3200-3500K	Quartz Lights
3200-7500K	Fluorescent Lights
3275K	Tungsten Lamp 2k
3380K	Tungsten Lamp 5k, 10k
5000-5400K	Sun: Direct at Noon
5500-6500K	Daylight (Sun + Sky)
5500-6500K	Sun: through clouds/haze
6000-7500K	Sky: Overcast
6500K	RGB Monitor (White Pt.)
7000-8000K	Outdoor Shade Areas
8000-10000K	Sky: Partly Cloudy

Source: http://myphotographylessons.com/photography-basics-color-temperature-chart/

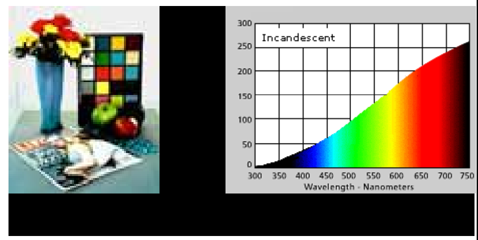
Spectral Power Distribution, SPD

- IESNA Definition:
  - A pictorial representation of the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum (360 to 770 nanometers)
- Combining wavelengths in different amounts can produce light that appears white to the eye.
- It is possible that the light from two lamps can have different wavelength combinations and yet appear exactly the same color (same nominal correlated color temperature [CCT]) but their effects on objects may be very different (refer to CRI).

Spectral Power Distribution, SPD



This particular fluorescent lamp has more power in the short wavelength of the visible spectrum (below 450 nanometers) - blue colors appear more vivid.



The incandescent light source depicted has more power in the longer wavelengths (above 650 nanometers) of the visible spectrum and therefore renders red colors most effectively.

Myth: The higher the CRI the better

- Color rendering index (CRI) is a measure of how accurately an artificial light source displays colors.
- CRI is determined by comparing the appearance of a colored object under an artificial light source to its appearance under incandescent light.
- The higher the CRI, the better the artificial light source is at rendering colors accurately. High (above 80) CRI is preferred in the home.

Source: http://www.energystar.gov/index.cfm?c=fixture_guide.pr_fixtures_guide_lightquality

Myth: The higher the CRI the better

- Where does it say "LED"?

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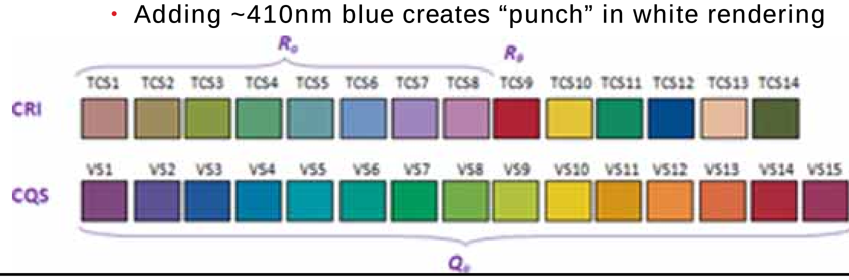
Myth: The higher the CRI the better

- CRI (Color Rendering Index) misrepresents LED lit object appearance
  - It uses only the first 8 (pastel) color references
  - Higher CRI values doesn't mean better color rendition.
    - The spectrum can be "engineered"
      - Improve flux by adding more green
      - Adding ~410nm blue creates "punch" in white rendering



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Shortcomings of CRI


Photo: Javier Ten

Since the CRI rating for any given lamp is an average of eight test results, it can give no particular insight into the effect of the appearance of any one color.
In this case, the two light sources illuminating the object have a CRI of 70, however the light source on the right renders blue more naturally than the one on the left.

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Tips

- Try different product to determine which one is best for the particular illumination purpose
  - CRI doesn't represent saturated colors – look for "R9" to get a measure of red
  - R9 >0 is usually satisfying
- Higher CRI products are less efficient
  - More blue led light is converted into red which the eye can't see most of it
  - For outdoor CRI of 60 is the best compromise

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Light Output — Making sure it's bright enough

- Light output is measured in lumens at the light source. To determine if the light is bright enough, be sure that it produces sufficient lumens to meet your needs.

Incandescent Bulb Wattage	Light Output in Lumens
40 watt	400-450
60 watt	870–890
75 watt	1,190–1,200
100 watt	1,680–1,750

Source: http://www.energystar.gov/index.cfm?c=fixture_guide.pr_fixtures_guide_lightquality

Myth: ENERGY STAR® qualified illumination products are more reliable

- The ENERGY STAR® programs intent is to speed up customer adoption of new energy conserving technology
  - By ensuring customer satisfaction
    - Specifying quality of light
      - Color reproduction
      - Correlated Color temperatures
      - Light output pattern
    - Min. 3 Year product warranty
    - 25,000 hours "rated lifetime" claims

Myth: ENERGY STAR® qualified illumination products are more reliable

- The program relies on industry standards
  - There are no standards for LED based product rated lifetime claims
  - IESNA LM-80-08 is used to determine lamp lifetimes
    - LM-80 is a test method for measuring LED components lumen maintenance for min.
    - Another standard TM21 is used to extrapolate

- Lumen maintenance of the LED component is not system reliability
- The industry doesn't have sufficient reliability data to make any system lifetime claims

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Myth: Light from LEDs is hazardous

- In 2011 a French test lab announced that light from LEDs is dangerous
  - Referring to blue light hazard
- There is no fundamental difference regarding photo biological safety, to lamps using traditional technologies*
- The portion of blue light in LED is not higher than the portion of blue light in lamps using other technologies at the same color temperature*

*Source: CELMA (European Lamp Companies Federation) Optical Safety of LED Lights report July '11

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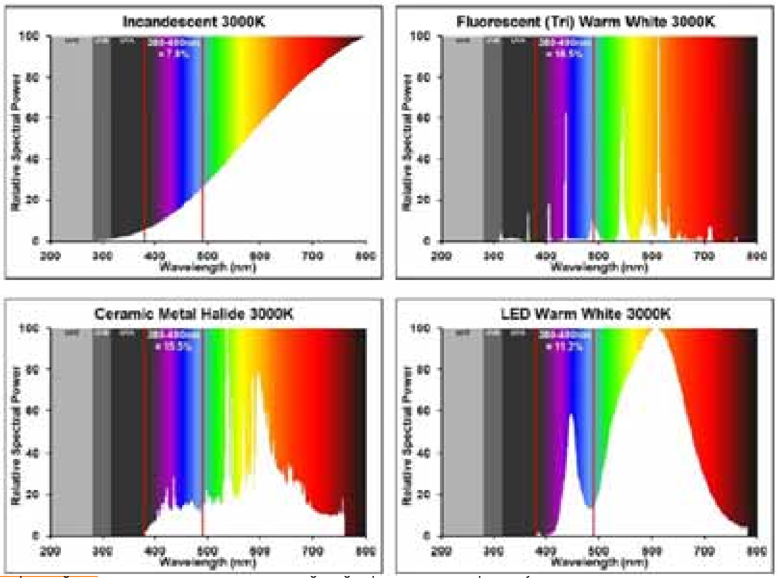
Light from LED is hazardous



Myth: LEDs contain hazardous materials

- Life-cycle **environmental impact** of a given lamp is **dominated by the energy used** during lamp operation
- The selected models were generally found to be **below thresholds for Federally regulated elements**
- Nearly **all of the lamps (regardless of technology) exceeded at least one California threshold—typically** for copper, zinc, antimony, or nickel;
- The **greatest contributors were the metal screw bases, drivers, ballasts,** and wires or filaments

*Source: Department of Energy: Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products March 2013

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Future lighting technologies

- OLED
- Induction
- Plasma
- ESL (Electron Stimulated Luminescence)

- Lighting Controls and Services

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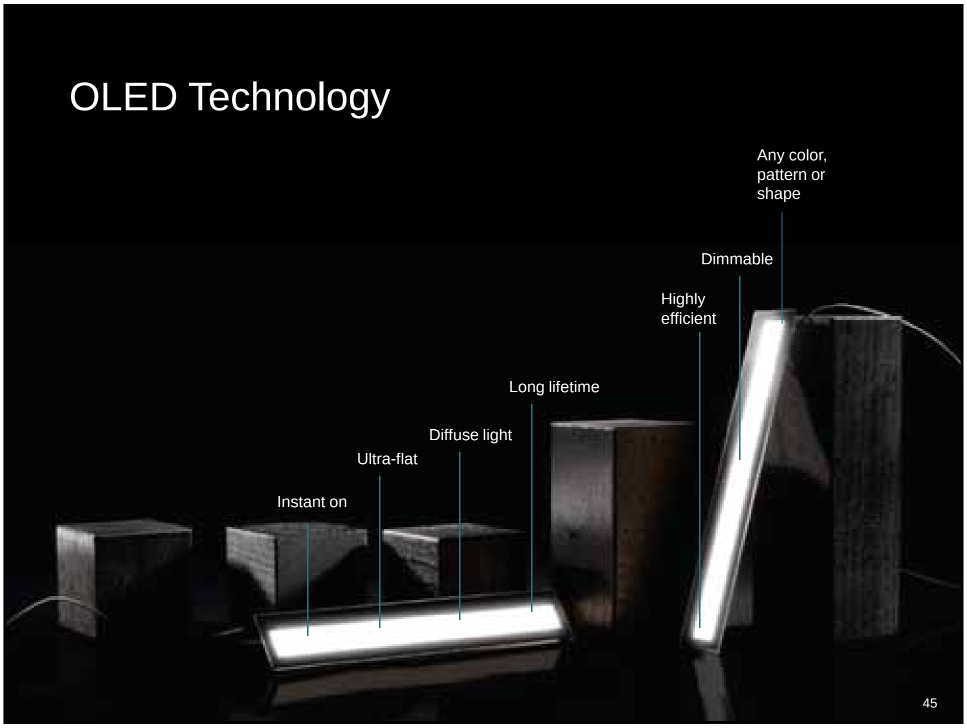
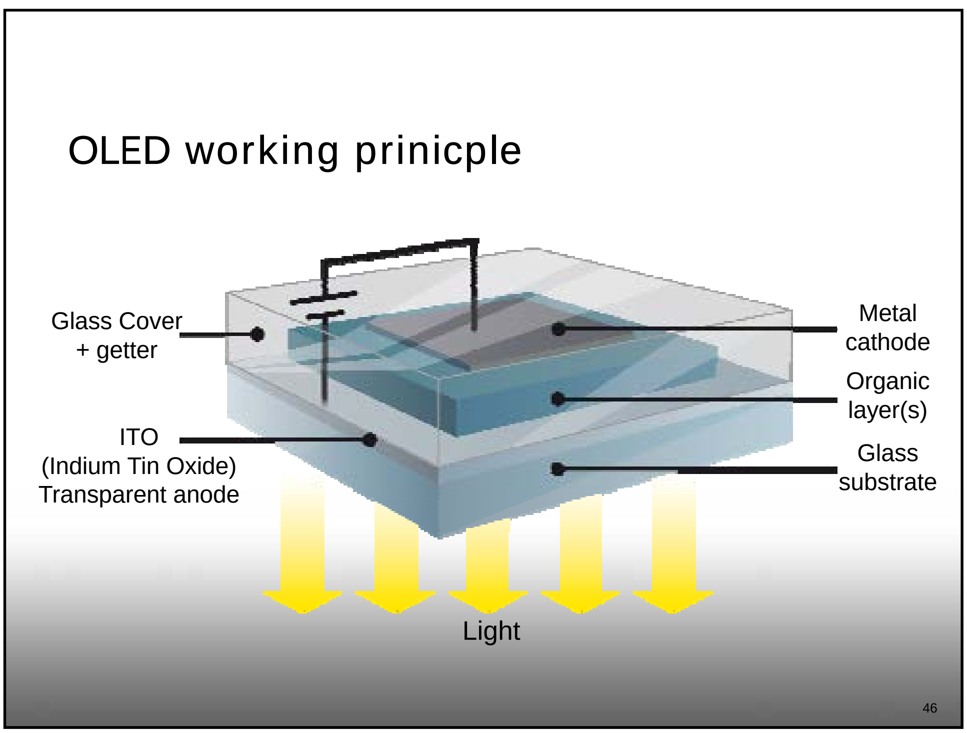

OLED Technology
Any color, pattern or shape
Dimmable
Highly efficient
Long lifetime
Diffuse light
Ultra-flat
Instant on
45


OLED working prinicple
Glass Cover + getter
ITO (Indium Tin Oxide) Transparent anode
Metal cathode
Organic layer(s)
Glass substrate
Light
46

Organic vs. Inorganic

- The major distinction between inorganic and organic LEDs for the application of lighting is the form factor. OLEDs produce light at relatively low intensity spread over large areas, while LEDs are more compact sources.
- In order for the light to escape from the device, at least one of the electrodes must be transparent. When both electrodes are transparent, an OLED can be made to be transparent in the off-state and emit light from both faces of the panel in the on-state, allowing for unique luminaire design opportunities and light distribution profiles.
- Because of the high sensitivity of organic materials and cathode metals to oxygen and water, the OLED structure must be encapsulated using a non-porous substrate, cover and edge seals.
- It is projected that the performance gap between LED lamps and OLEDs with respect to the basic metrics, such as efficiency, lifetime, color quality and cost per kilolumen will be reduced significantly by 2020

What is Induction Lighting?

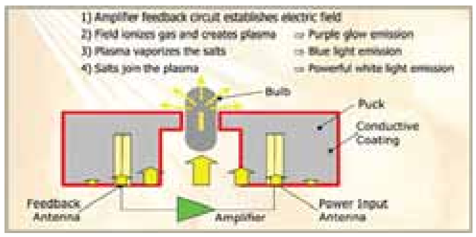
- An **Induction Lamp** is similar to a fluorescent lamp in that mercury in a gas fill inside the bulb is excited, emitting UV radiation that in turn is converted into visible white light by the phosphor coating on the bulb.
- Fluorescent lamps, however, use electrodes inside the bulb to strike the arc and initiate the flow of current – each time the arc is struck, the electrodes degrade a little, eventually causing the lamp to flicker and then fail.
- Induction Lamps do not use internal electrodes, but use a high-frequency generator with a power coupler. The generator produces a radio frequency magnetic field to excite the gas fill
  - The exact frequency varies with lamp design, but popular examples include 13.6 MHz, 2.65 MHz and 250 kHz
- With no electrodes, the lamp lasts longer
  - 100,000 hours, with the lamp producing 70% of its original light output at 60,000 hours.

*manufacturers claim

LEP Light Emitting Plasma

- Efficacy: 115-150 lm/W*
- CRI: 75 – 95*
- Rated Life: 50,000h* L_{70}
- Lumen maintenance: good - excellent

Application Example: Stadium lighting



*manufacturers claim

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ESL – Electron Stimulated Luminescence

- ESL lighting uses an electron gun to stimulate a phosphor coated surface for illumination, much like an old CRT or television tube.
- The bulb is actually a vacuum, with no mercury
- The Vu1 bulb has an expected lifespan* of 11,000 hours **

*not a define term
**manufacturers claim

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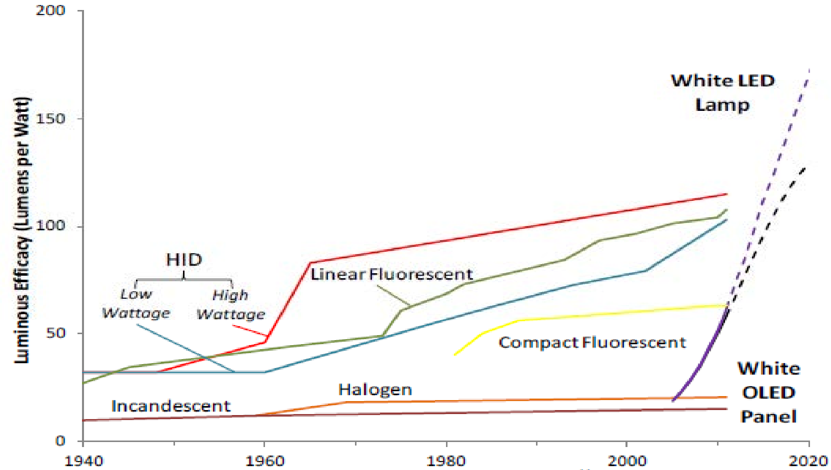
The Business Case for LED Lighting

- Total available illumination Market
  - Replacement market
- New markets
  - Consumer electronics
    - LED TV, Camera Flash
  - Automotive
    - Headlamps
  - Next generation lighting design
  - Controls and automation
  - Lighting services

Historical and Predicted Efficacy of Light Sources



Source: Navigant Consulting, Inc - Updated Lumileds chart with data from product catalogues and press releases
Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses.

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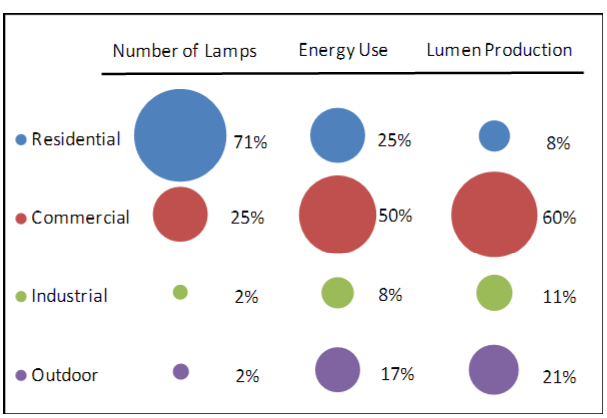
2010 U.S. Electricity Consumption and Lumen Production

- In 2010, there were approximately 8 billion lamps installed in the U.S. consuming nearly 700 TWh of electricity



Source: 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.

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EPA reports

- In 2012 there were an estimated 8 billion light points in the US alone
- In 2012 there were 3.3 billion A-type lamps installed within the U.S., of which about 97 percent are in residences.

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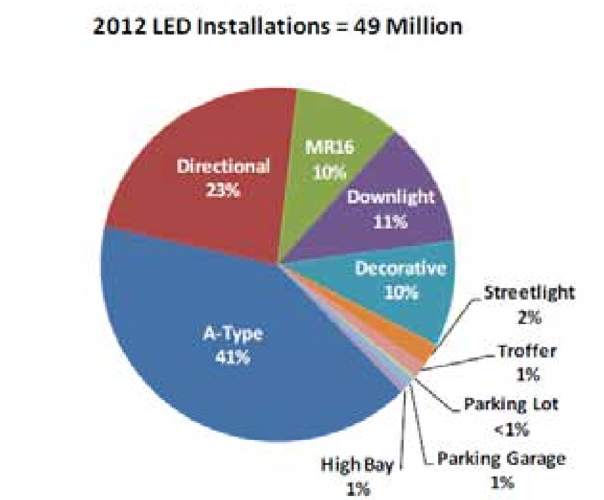
LED penetration in 2012



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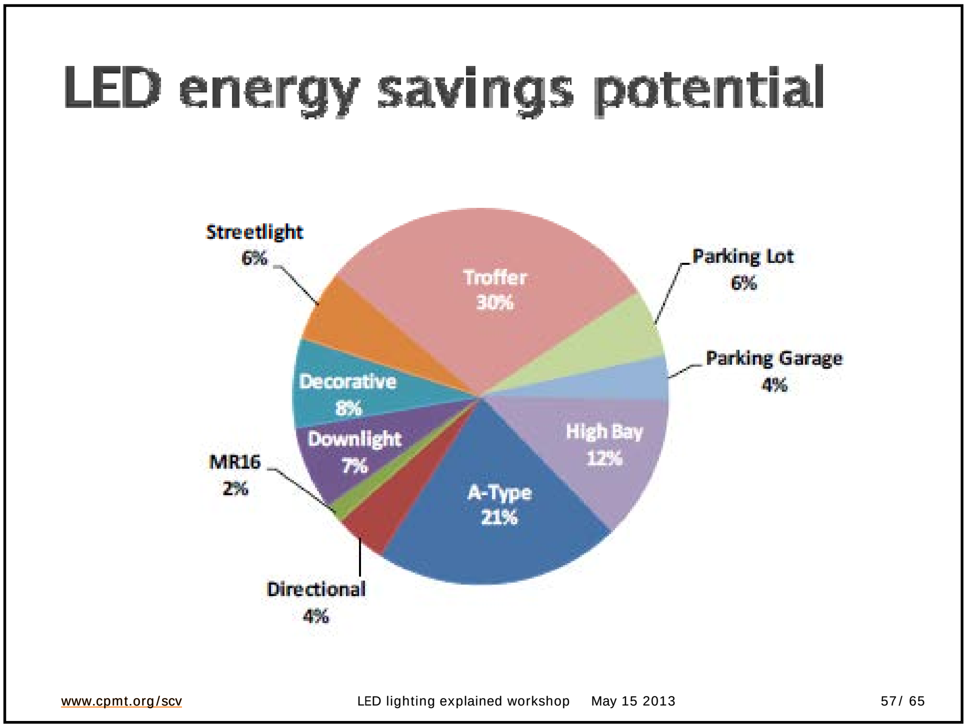
LED energy savings potential
Streetlight 6%
Troffer 30%
Parking Lot 6%
Parking Garage 4%
Decorative 8%
Downlight 7%
High Bay 12%
MR16 2%
A-Type 21%
Directional 4%
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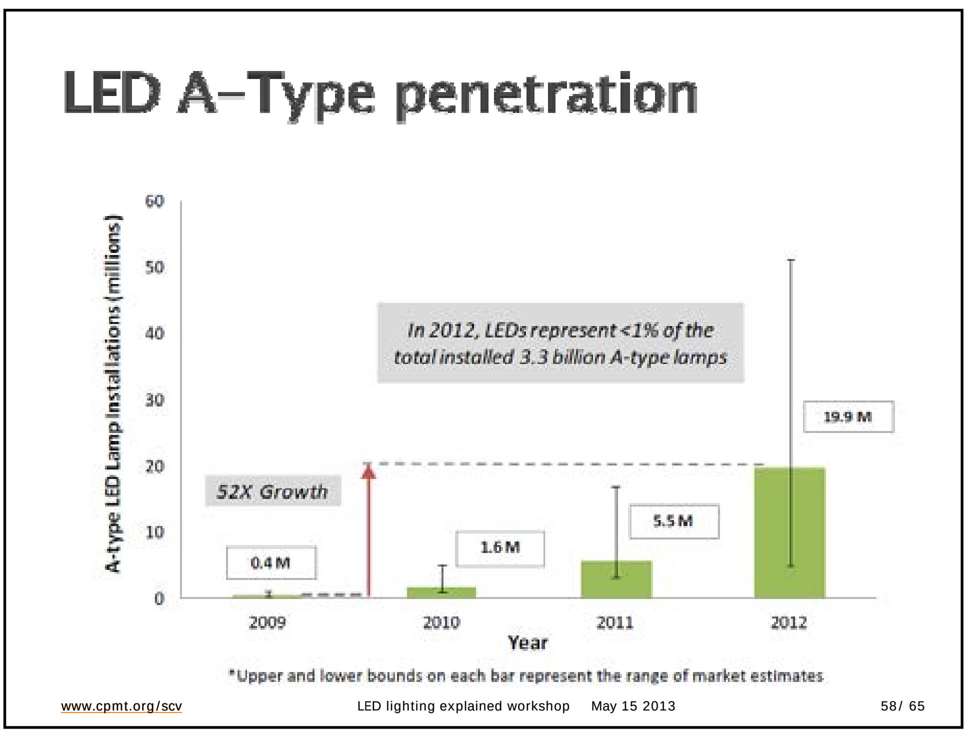
LED A-Type penetration
A-type LED Lamp Installations (millions)
0
10
20
30
40
50
60
In 2012, LEDs represent <1% of the total installed 3.3 billion A-type lamps
52X Growth
0.4 M
1.6 M
5.5 M
19.9 M
2009
2010
2011
2012
Year
*Upper and lower bounds on each bar represent the range of market estimates
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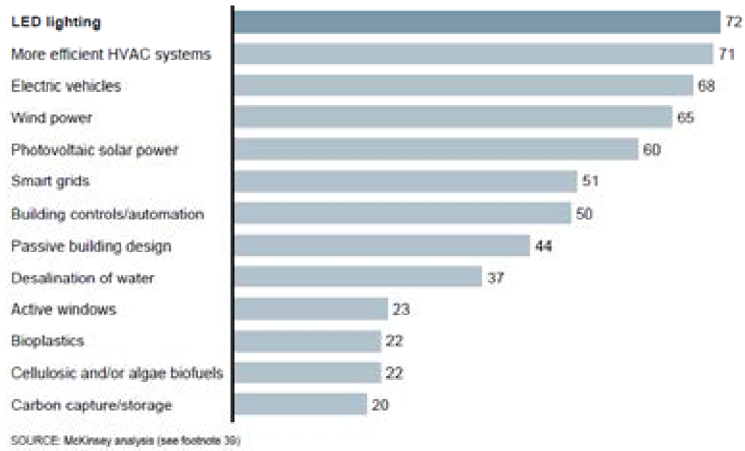
Which one of these technologies is commercially viable in 2020



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Open positions at Philips Lumileds San Jose (12), worldwide (37)

Requisition NO	Requisition Justification	Req. Title	Req. Job Field Level 1	Req. Category	Req. Job Type
037596	New Position	Sales Development Specialist	Sales Support	Internal/External	Experienced
036457	Replacement	Director, Integral Programs	Research and Development	Internal/External	Experienced
037350	Replacement	LED Systems Modeling Engineer	Research and Development	Internal/External	Experienced
037587	New Position	Marketing Administrative Assistant	Administrative	Internal/External	Experienced
039307	Replacement	Director Process Integration	Research and Development	Internal/External	Experienced
039926	Replacement	Device Scientist - Device Architecture	Research and Development	Internal/External	Experienced
037296	New Position	Human Resource Program Manager	Human Resources	Internal/External	Experienced
032715	Replacement	Optimization Engineer	Engineering Manufacturing	Internal/External	Experienced
034013	New Position	Reliability Engineer	Manufacturing	Internal/External	Experienced
036993	Replacement	Manufacturing IT Architect	Quality – Compliance	Internal/External	Experienced
038312	New Position	Failure Analysis Technician	Engineering Electrical	Internal/External	Experienced
041220	Replacement	Sr Director, Quality	Quality – Product	Internal/External	Experienced

www https://philips.taleo.net/careersection/2/jobsearch.ftl?lang=en

Glossary

- http://www.lrc.rpi.edu/education/learning/glossary.asp

Questionnaire

- 1: List attributes of LED lighting ... add to the list as you go through this workshop
- 2: White light is produced by (i) combining red, green, and blue OR (ii) a (......) color phosphor
- 3: List uses of light that LED lighting make possible
- 4: What percent of US energy consumption is for residential lighting?
- 5: What factors will influence you migrating to LED lighting in your home?
- 6: Define lumen
- 7: Define binning in the LED context
- 8: How does junction temperature affect the performance and life of an LED?

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Questionnaire

- 9: What material system is the majority of white LEDs using?
  - A) AlInGaP
  - B) CMOS
  - C) InGaN
  - D) GaAs
- 10: How is the “rated life” of an Incandescent lamp defined?
  - A) The time until 50% of the lamps in a large population have failed
  - B) The rated life is 2000 hours
  - C) The time until the lamp has reached 50% of its initial lumen output
- 11: What is the rated lifetime of an LED lamp?
  - A) 50,000 hours or longer
  - B) The time until the lamp has reached 70% of its initial light output
  - C) LED lamps last forever
- 12: What is the efficacy of a lamp?
  - A) Should be efficiency – must be a typo
  - B) The ratio of the luminous flux produced relative to the electrical power consumed
  - C) The ratio of the radiant flux produced relative to the electrical power consumed
- 13: How many light points are in the US
  - A) 22 billion
  - B) 8 billion
  - C) 2 billion
  - D) 31 billion

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Questionnaire

- 14: What is the average daily use of an incandescent bulb in a residential home (US)
  - A) 4.2 hours
  - B) 1.8 hours
  - C) 0.6 hours
- 15: How much annual energy savings could be achieved by switching to 100% LED lighting (US at today's energy cost)
  - $37 billion
  - $54 billion
  - $12 billion
- 16: : What are some ways of classifying quality of light?
- 17: Distinguish between LED efficacy and efficiency
- 18: If LEDs are as efficacious as the marketers claim, why is thermal management a concern?
- 19: What is the expected life of an LED light in a residential application?

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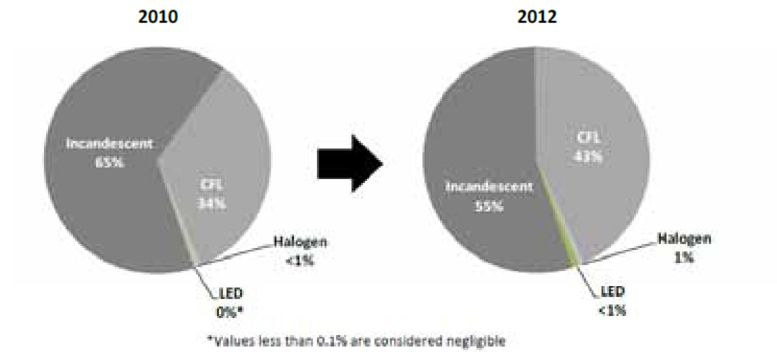
Appendix



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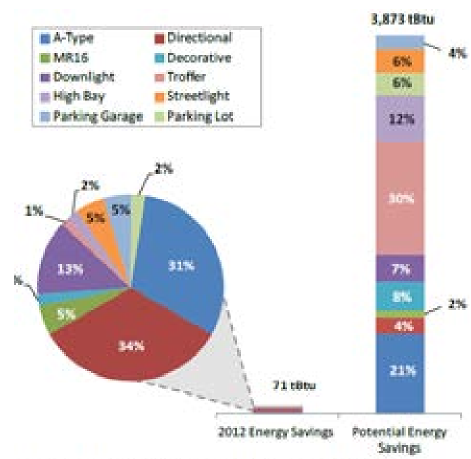

Figure ES. 1 – Comparison of Current and Potential Source Energy Savings

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Table 5.1 – Installations and Energy Consumption and Saving by Application

Applications	Unit Installations (millions)	LED Penetration (%)	Total Application Energy Use Source– tBtu (Site – TWh)	2012 LED Energy Savings Source– tBtu (Site – TWh)	Potential LED Energy Savings Source– tBtu (Site – TWh)
Indoor Lamp					
A-Type	19.9	<1%	1,057 (101.8)	22 (2.1)	822 (79.1)
Directional	11.4	4.6%	195 (18.7)	24 (2.3)	174 (16.7)
MR16	4.8	10%	70 (6.7)	3.7 (0.4)	65 (6.2)
Decorative	4.7	<1%	367 (35.4)	1.4 (0.1)	298 (28.7)
Indoor Luminaire					
Downlight	5.5	<1%	382 (36.8)	9.3 (0.9)	278 (26.8)
Troffer	0.7	0%*	2,374 (228.6)	0.9 (0.1)	1,146 (110.4)
High-Bay	0.3	<1%	1,096 (105.6)	1.5 (0.2)	483 (46.5)
Outdoor Luminaire					
Streetlight	1.0	2.3%	452 (43.5)	3.5 (0.3)	238 (22.9)
Parking	0.6	1.2%	622 (60.0)	5.1 (0.5)	370 (35.7)
Total	**48.8**	--	**6,614 (637.1)**	**71 (6.8)**	**3,873 (373.1)**

* Values less than 0.1% are considered negligible

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Table A.1 –Most Efficacious LED Products from the LED Lighting Facts Database[60]

Application	LED Replacement Criteria: Manufacturer	Product Description	Performance: Wattage (W)	Lumens (lm)	Efficacy (lm/W)
A-type	Philips Lighting	L-Prize Winner A-Type	10.0	940	94
Directional	Lumena SSL Inc.	PAR38 replacement	13.7	1,226	89
MR16	Halco Lighting Technologies	MR16 25W replacement	6.5	500	77
Decorative	Philips Lighting	B12 Dimmable Candle	4.0	320	80
Downlights	Acuity Brands	6-inch downlight	11.6	1,026	88
Troffer	Cree	4-ft Linear Luminaire	34.6	4,139	119
High-Bay	LSI Industries Inc.	High-Bay Luminaire	196.7	21,686	110
Parking Garage	Kenall Lighting	Parking Garage Luminaire	54.7	5,814	106
Parking Lot	Cree	Flood/Area Luminaire	129.5	13,083	101
Streetlights	Kenall Lighting	Post-mounted Luminaire	108.9	12,019	110

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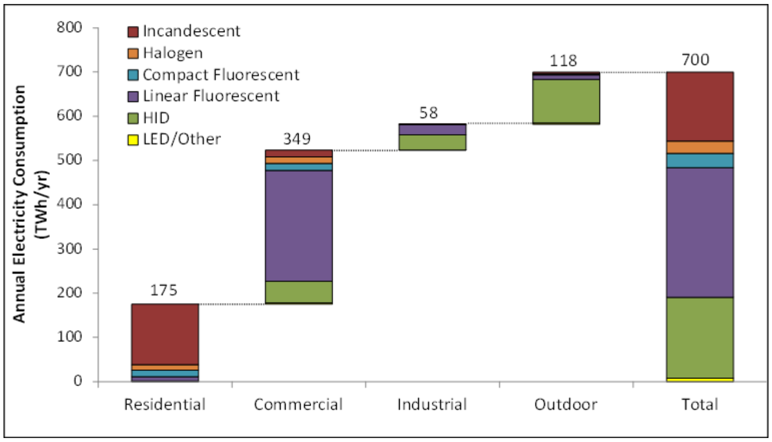
U.S. Lighting Electricity Consumption by Sector and Lamp Type in 2010



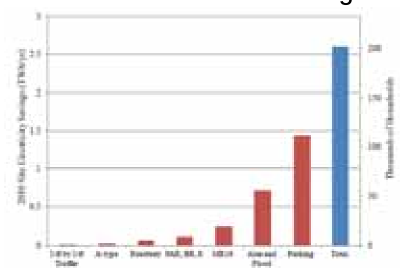
Source: 2010 U.S. Lighting Market Characterization. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.

Interesting facts

- Despite an approximately 18 percent increase in the quantity of installed lamps from 2001 to 2010, annual lighting electricity consumption has decreased by about nine percent.
- The number of incandescent lamp installations has decreased from approximately 62 percent in 2001 to 45 percent in 2010 while CFL's market share rose from about three percent in 2001 to nearly 19 percent a decade later.
- by 2020, the efficacies of general service lamps must be at least 45 lm/W. Currently, the only technologies capable of meeting these second tier efficacy standards are fluorescent, HID and LED-based lighting.
- Solid-state lighting represents one of the most efficacious lighting options available. In 2001, the number of LED lamps installed in the U.S. was just under 1.6 million, which equates to less than 0.1 percent of the total lamp base. Almost 90 percent of the 2001 LED lights were exit signs from the commercial and industrial sectors and traffic lights from the outdoor sector. In 2010, the installed base soared to an estimated 67 million LEDs, but still only represented roughly one percent of the total lighting inventory.
- In some cases, people are unaware of newer, more efficient lighting technologies or they are opposed to the technology's appearance and inherent characteristics. In other cases, the higher first cost will deter the consumer in spite of a lower total cost of ownership. In some instances the people who decide which lighting system to purchase (typically building contractors or landlords) are rarely those who pay the electricity of the building (building owners or renters).
- packaged LEDs in lighting applications increased from $1.2 billion in 2010 to $1.8 billion in 2011, a growth of 44 percent.

2010 Electricity Saving from the Selected Niche Applications

- In 2010, the penetration of LED-based luminaires in the seven general illumination and outdoor applications analyzed in this report resulted in a total realized electricity savings of 2.6 TWh per year, which is equivalent to the electricity needed to power over two hundred thousand average U.S. households.

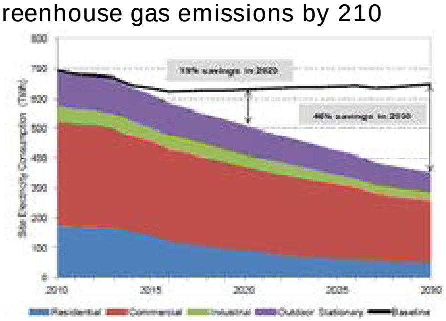


Source: Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2011.

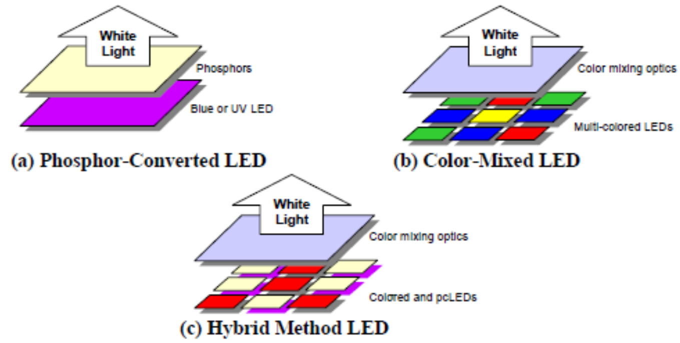
Forecasted U.S. Lighting Energy Consumption and Savings, 2010 to 2030

- The analysis indicates that if LED lighting technology meets its expected efficacy, lifetime, and price targets, by the year 2030, LED lighting would save the U.S. approximately 300 terawatt-hours of site energy, or the equivalent annual electrical output of about fifty 1,000-megawatt power plants. At today's energy prices, that would equate to approximately $30 billion in energy savings in 2030 alone. Assuming the current mix of generating power stations, these energy savings would reduce greenhouse gas emissions by 210 million metric tons of carbon.

Source: Energy Savings Potential of Solid-State Lighting in General Illumination Applications. Prepared by Navigant Consulting, Inc. for the Department of Energy. Washington D.C. January 2012.



General Types of White Light from LEDs



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SSL Performance Compared to Other Lighting Technologies

Product Type	Luminous Efficacy	Luminous Output	Wattage	CCT	CRI	Lifetime
LED White Package (Cool)	144 lm/W	144 lm	1.0 W	2600-3700K	70	50k hours
LED White Package (Warm)	111 lm/W	111 lm	1.0 W	5000-8300K	80	50k hours
LED A19 Lamp (Warm White) [1]	93 lm/W	910 lm	9.3 W	2727K	93	25k hours
LED PAR38 Lamp (Warm White) [2]	74 lm/W	1,000 lm	13.5 W	3000K	92	25k hours
LED 2'x4' Troffer (Warm White) [3]	110 lm/W	4000 lm	36 W	3500K	90	75k hours
OLED Panel [4]	60 lm/W	76 lm	1.3 W	3500K	80	15k hours
HID (High Watt) Lamp and Ballast	123 lm/W 115 lm/W	38700 lm	315W 337W	3100K	90	30k hours
Linear Fluorescent Lamp and Ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26W 56W	4100K	85	25k hours
HID (Low Watt) Lamp and Ballast	110 lm/W 103 lm/W	7700 lm	70W 75W	3000K	89	16k hours
CFL	63 lm/W	950 lm	15W	2700K	82	12k hours
Halogen	22 lm/W	1100 lm	50 W	3000K	100	5k hours
Incandescent	15 lm/W	890 lm	60W	2760K	100	1k hours

Source: Cree 2012, Philips Lighting 2012, OSRAM Sylvania 2012 product catalogs, LED lamp based on Lighting Facts product registrations.
Based on Philips' L-Prize winning A19 lamp.
Based on Lighting Facts Label data for Cree LRP38-10L-30KCree
Based on Cree CR24-40L-HE-35K-S.
LG Chem, 2012. -For LED packages (defined in Section 5.1.1) -drive current density = 35 A/cm2, Tj=85°C.,

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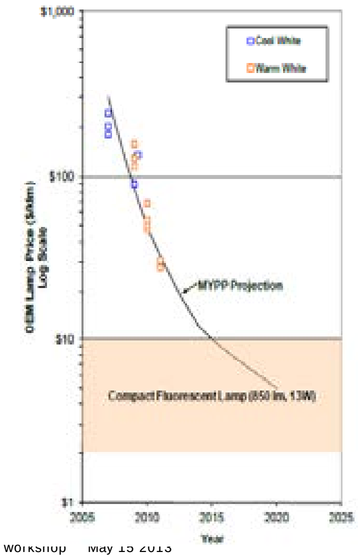
Application	Lighting Type	System Wattage (Watts)			Daily Operating Hours (hrs)		
Indoor Lamps		RES	COM	IND	RES	COM	IND
A-type	Incandescent	64	58	46	1.8	10.5	12.7
	Halogen	50	48	36	2.0	12.1	11.7
	CFL	17	20	17	1.8	10.7	13.0
Directional	Incandescent	69	79	65	1.7	9.8	11.9
	Halogen	68	78	64	1.9	12.4	11.7
	CFL	17	20	16	1.8	10.0	13.0
MR16	Halogen	44	60	–	1.7	12.6	–
Decorative	Incandescent	44	44	–	1.8	10.5	–
	CFL	11	11	–	1.8	10.7	–
Indoor Luminaires		RES	COM	IND	RES	COM	IND
Downlights	Incandescent	69	79	65	1.7	9.8	11.9
	Halogen	68	78	64	1.9	12.4	11.7
	CFL	17	20	16	1.8	10.7	13.0
	CFL - pin	22	19	19	1.9	10.4	13.2
	Metal Halide	–	32	32	–	10.4	13.2
Troffer	T5	38	72	113	2.5	11.7	12.8
	T8 Less than 4ft	31	40	47	2.1	11.2	12.6
	T8 4ft	52	60	60	1.9	11.1	12.6
	T8 Greater than 4ft	82	109	147	1.7	11.0	12.6
	T12 Less than 4ft	32	70	65	2.0	11.3	12.0
	T12 4ft	58	86	77	1.9	11.1	12.4
	T12 Greater than 4ft	101	157	169	1.7	11.1	12.5
	T8 U-Shaped	54	62	60	2.1	11.0	12.6
	T12 U-Shaped	53	83	81	1.8	11.0	12.5
High-Bay[7]	High Pressure Sodium	–	295	295	–	11.0	17.9
	Mercury Vapor	–	451	451	–	11.1	16.5
	Metal Halide	–	434	434	–	11.1	16.5
	T5	–	231	231	–	11.7	12.8
	T8 4 ft	–	240	240	–	11.1	12.8
	T8 Greater than 4ft	–	293	293	–	11.0	12.6
	T12 4ft	–	310	310	–	11.1	12.4
	T12 Greater than 4 ft	–	333	338	–	11.1	12.5
Outdoor Luminaires			OUT			OUT	
Parking[10]		Garage		Lot	Garage		Lot
	Incandescent	79		50	15.9		15.9
	Halogen	114		75	17.8		17.8
	Linear Fluorescent	71		–	18.0		18.0
	Mercury Vapor	198		307	13.5		13.5
	Metal Halide	203		449	15.0		15.0
	High Pressure Sodium	190		230	16.0		16.0
	Induction	97		–	13.1		–
Streetlights	Mercury Vapor		243			12.0	
	Metal Halide		233			12.0	
	High Pressure Sodium		230			12.0	
	Low Pressure Sodium		78			12.0	

Source: Navigant, 2010 U.S. Lighting Market Characterization, January 2012

Halogen Lamp (A19 43W; 750 lumens)	\$2.5	per kilolumen
CFL (13W; 800 lumens)	\$2	per kilolumen
CFL (13W; 800 lumens dimmable)	\$10	per kilolumen
Fluorescent Lamp and Ballast System (F32T8)	\$4	per kilolumen[39]
LED Lamp (A19 60W; 800 lumens dimmable)	\$30	per kilolumen[40]
OLED Luminaire	\$1,700	per kilolumen[41]

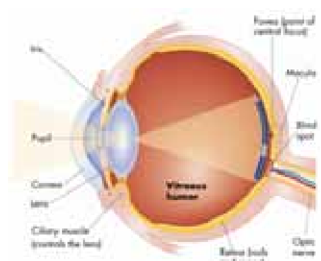
On a normalized light output basis (dollars per kilolumen), LED lamps remain around twelve times the cost of the halogen bulb and around three times the cost of an equivalent dimmable CFL,[42] but the price of LED lamps is expected to continue its rapid decline and the performance is expected to continue to improve. As a consequence, LED light sources are projected to become increasingly competitive on a first cost basis.

White Light Integrated LED Lamp Price Projection



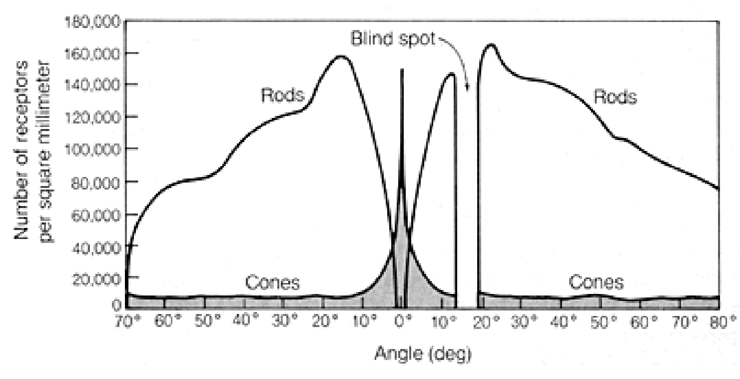
Note: Assumes current prices for compact fluorescent price range (13W self-ballasted compact fluorescent; non-dimmable at bottom, and dimmable at top). MYPP – Multi Year Program Plan

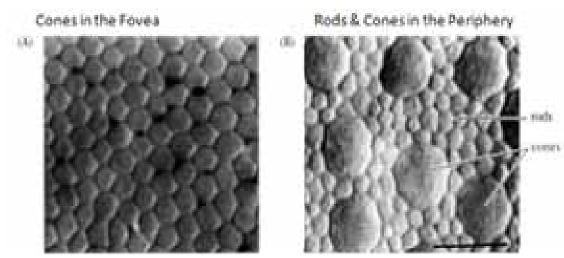
The human vision



- Rods and Cones
- The retina contains two types of photoreceptors, rods and cones. The rods are more numerous, some 120 million, and are more sensitive than the cones. However, they are not sensitive to color. The 6 to 7 million cones provide the eye's color sensitivity and they are much more concentrated in the central yellow spot known as the macula. In the center of that region is the " fovea centralis ", a 0.3 mm diameter rod-free area with very thin, densely packed cones.

- **Distribution of Light Sensors**
- The light sensors are not evenly distributed across the retina. Cones are concentrated at the center of the retina, called **macula** or**macula lutea** (yellow spot). At the center of the macula is the **fovea centralis**, which has the highest cone density and therefore is critical in visual perception (ca. 150.000 receptors per square mm at maximum): As sharp vision is restricted to the fovea, our eyes are in steady movement to focus targets and to give us the impression of a "sharp" environment. Cones are fairly thinly distributed over the periphery of the retina (ca. 10.000 receptors per square mm).
- Rods are absent from the central area of the retina. Their distribution reaches its peak at an angle of about 20 degrees from the center of the retina (ca. 160.000 receptors per square mm) and decreases to about half of it at about 60 degrees.

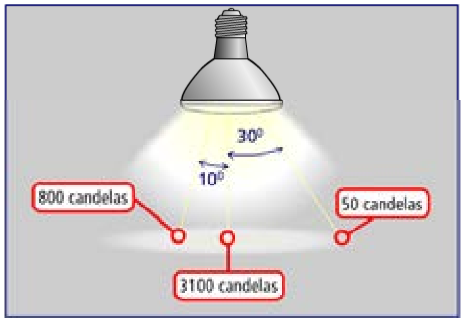




Candela

- IESNA Definition: the Standard International unit of luminous intensity. One candela is one lumen per steradian. Formerly, candle.
- The intensity of a light source in a specific direction is expressed in candelas (cd). Any given light source will have many different intensities, depending upon the direction considered. Since intensity is a property of the source itself, the candlepower (luminous intensity expressed in candelas) for a specified direction remains the same, regardless of distance from the source.
- It is interesting to compare lamps of the same wattage with regard to luminous intensity. In the following examples, imagine the lamps aimed straight down, with 0° representing a point directly beneath each one, and 20° representing a point 20° up from 0°. Although not true for all sources, the highest candela values occur at 0° in these examples:

Candela



Lamp	Candelas at 0°	Candelas at 20°
150-W R40 Flood	1,100 cd	820 cd
150-W R40 Spot	5,800 cd	780 cd
150-W PAR38 Flood	4,000 cd	1,100 cd
150-W PAR38 Spot	11,800 cd	500 cd

Steradian

- http://www.mathsisfun.com/geometry/steradian.html

Luminous Intensity

- **luminous intensity** is a measure of the wavelength-weighted power emitted by a light source in a particular direction per unit solid angle, based on the luminosity function, a standardized model of the sensitivity of the human eye. The SI unit of luminous intensity is the candela (cd), an SI base unit

Luminous intensity	I_v	candela (= lm/sr)	cd

Illuminance

Illuminance: The areal density of the luminous flux incident at a point on a surface.

The recommended illuminance value for a private office, for example, is 500 lx or 50 fc on the work surface. Visual performance in this kind of space is considered important since visual tasks may include reading small print

Two common units used to measure illuminance are:

footcandles (fc) = lm/ft^2

lux (lx) = lm/m^2

For conversion purposes:

1 lx = .0929 fc

1 fc = 10.76 lx

Illuminance	E_v	lux (= lm/m^2)	lx

Luminance

- Luminance is the photometric quantity most closely associated with one's perception of brightness. It usually refers to the amount of light that reaches the eye of the observer measured in units of luminous intensity (candelas) per unit area (m^2).

Photo: Lighting Research Center Resource Collection

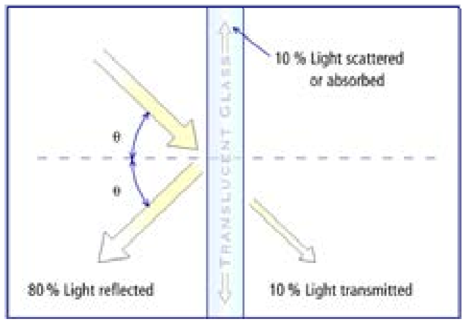
All surfaces have luminances.
Luminance in this case depends on the surface's reflectance.

Luminance	L_v	candela per square metre	cd/m^2

Reflectance

- IESNA Definition: the ratio of the reflected flux to the incident flux.
- Reflectance values express the percentage of light that is reflected back from a surface, the difference having been absorbed or transmitted by the surface. Reflectances of room surfaces are used in determining coefficient of utilization values for luminaires. Reflectance is also commonly used as an evaluation criterion for luminaire reflectors.

Reflectance



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Correlated Color Temperature, CCT

- IESNA Definition: the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source.
- The correlated color temperature (CCT) is a specification of the color appearance of the light emitted by a lamp, relating its color to the color of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K). The CCT rating for a lamp is a general "warmth" or "coolness" measure of its appearance. However, opposite to the temperature scale, lamps with a CCT rating below 3200 K are usually considered "warm" sources, while those with a CCT above 4000 K are usually considered "cool" in appearance.
- The correlated color temperature (CCT) designation for a light source gives a good indication of the lamp's general appearance, but does not give information on its specific spectral power distribution. Therefore, two lamps may appear to be the same color, but their effects on object colors can be quite different. Examples of the CCT of some common light sources are:

Source	CCT
Tungsten Halogen	3000 K
"Cool White" Linear Fluorescent	4200 K
High Pressure Sodium	1900 K
"Warm" Compact Fluorescent	2700 K

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Different types of lamps

- http://www.lrc.rpi.edu/education/learning/terminology/lamp.asp