Unraveling the Mysteries of Solid-State Lighting

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On behalf of the U.S. Department of Energy
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1. Concepts unique to LED technology such as directionality
2. The critical link between thermal management and lifetime
3. How to choose wisely when selecting LED-based luminaires
Course Outline

1. Introduction – Why should I care about LEDs?
2. What’s different – LED technology as compared to traditional light sources
3. Technology Limitations – Characteristics to be aware of with solid-state lighting
4. Environment – Its effect on LEDs
5. LED Products – Where to turn for guidance
6. Applications – What are the good ones?
7. Final Thoughts – Some general rules

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Introduction

Why Should I Care About LEDs?

• By 2030 the US Department of Energy has estimated that LED technology has the potential to produce yearly energy savings of 190 terawatt-hours
  - Equivalent of 24 large (1,000 MW) power plants
  - Reduction of 25% of present energy consumption for lighting
  - Equates to approximately $15 billion savings in today’s dollars
  - Greenhouse gas emissions reduced by 31.4 million metric tons of carbon

• Spanning 2010 – 2030, the cumulative energy savings are estimated to total approximately 1,488 terawatt-hours
  - Representing approximately $120 billion at today’s energy prices
  - Over that same time period, greenhouse gas emissions would be reduced by 246 million metric tons
Why Should I Care About LEDs?

LEDs are like no other conventional lighting source

+ Potentially longest\(^1\) life of any lighting sources
+ Very high energy efficiency
+ Small size and instant on allows new applications
+ Produces color light directly without filtering
+ Integrates will with other semiconductor electronic elements

- Thermal management requirements
- Cost
- New technology brings unfamiliar issues to architects, lighting designers, building owners and facilities managers

\(^1\)Note: Some manufacturers have introduced products claiming long lifetimes: fluorescent tubes (40,000 hours); induction (100,000 hours)
Why Should I Care About LEDs?

LED market growth over the next 3 years

Source: Vrinda Bhandarkar, Strategies Unlimited
What have you heard about LEDs?

- They don’t produce any heat
- They last forever
- Anyone who isn’t installing LED-based products everywhere is foolish
- There is a conspiracy to limit the use of LEDs
- There is a conspiracy to force the use of LEDs
- They don’t work
- They are too expensive
What is the truth about LEDs?

- They do produce heat – just not as much
- They don’t last forever – just longer than other sources
- Anyone who isn’t considering installing LED-based products for some applications is foolish
- They don’t work if misapplied
- They are expensive but costs continue to drop
- There is a conspiracy by physicists to force the metric system on everyone but that has nothing to do with LEDs
What is an LED?

An LED (Light Emitting Diode) consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction.

The heatsink is what allows the high flux LED to generate much more light.
How does the LED make light?

Bandgaps – Different gaps, different colors

Smaller bandgap ➔ Lower energy ➔ Longer wavelength photon ➔ Red

Larger bandgap ➔ Higher energy ➔ Shorter wavelength photon ➔ Blue
How does the LED make light?

Sometimes it works – Radiative Recombination
How does the LED make light?

Sometimes it doesn’t – Non-radiative Recombination

Creates heat instead of light
How does a white LED work?

### Downconverting Phosphor
- Blue LED + YAG **Cool White**
- Blue LED + YAG + Other phosphor (red, green, etc.) **Warm White**
- UV LED + Red phosphor + Green phosphor + Blue phosphor

![Diagram of a white LED with InGaN Die and Phosphor](image)

**Cool White LED Spectra**

![Graph showing Cool White LED Spectra](chart)

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What’s Different

Long Lifetimes

• Traditional light sources fail catastrophically due to electrodes which weaken or become contaminated and eventually fail, causing the lamp to stop working.

• LEDs rarely fail catastrophically
  – Light output gradually decreases over operating time
  – End of life defined to be when light output reaches 70% of initial value
    ▪ Raises issue for designers – how to warn users that product has exceeded end-of-life and is producing less light than the application may require
  – Lifetime highly dependent on temperature (ambient and device as well as operating current)

![Lifetimes for various light sources](image_url)
What’s Different

Long Lifetimes – A Measurement Issue

• It is difficult to predict the long term performance of a device with only early lifetime data

6,000 Hours of data

34,800 Hours of data

Almost 3.5 X’s longer predicted lifetime than the 6,000 hour results

Source: Cree
What’s Different

Highest Energy Efficiency

Efficiency lumens/watt (lamp + ballast)

- White Sodium
- High Pressure Sodium
- Compact Metal Halide
- Metal Halide
- Fluorescent Tubes
- Compact Fluorescent (>27 W)
- Compact Fluorescent (<27 W)
- Mercury Vapor
- Halogen (Infrared Reflecting)
- Tungsten Halogen
- Incandescent

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What’s Different

Small Size

T5 Fluorescent
1350 lumens

75W PAR 38 Halogen
1100 lumens

75W Incandescent
1200 lumens

Cree MP-L LED
1200 lumens

Source: Cree

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What’s Different

Rate of Development

LEDs follow a development rule known as Haitz’s Law

Source: Roland Haitz & Lumileds
New Names in Lighting

Traditional Lamp Suppliers
• Sylvania
• Philips
• GE

LED Suppliers
• Osram
• Lumileds
• Cree
• Bridgelux
• Nichia
• Seoul Semiconductor
• Toshiba
• Sharp
• Toyota Gosei
• Edison Opto
• and many more…
### What’s Different

#### New Shapes in Lighting

<table>
<thead>
<tr>
<th>Traditional Lamp Suppliers</th>
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<tr>
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• Bridgelux
• Nichia
• Seoul Semiconductor
• Toshiba
• Sharp
• Toyota Gosei
• Edison Opto
• and many more...

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What’s Different

Direct Color Creation

• For color lighting applications, traditional light sources use energy to create white light which then is filtered to create the desired color. The energy used to create the other colors is wasted.

• LED light sources create the color directly leading to greatly improved energy efficiency.

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Power Conversion Comparison
For Various Light Sources

LED
Metal Halide
Fluorescent
Incandescent

Visible Light
Heat (Infrared)
UV
Heat (Conduction)

Scaled based on source efficacy
Technology Issues

Effect of Heat on Lifetime

LED Lifetime with ambient temperature of 55°C is 148,000 hours

LED Lifetime with ambient temperature of 85°C is 67,000 hours

Source: Lumileds
Luminaire Orientation Can Effect Lifetime

Luminaire manufacturers must take desired orientations into account when designing thermal management system for products.

LM-79 testing standard requires the luminaire be tested in the orientation in which it will be mounted.
Effect of Drive Current on Lifetime

At a junction temperature of 130°C lifetime is

- 28k hours (1 A)
- 33k hours (0.75A)
- 48k hours (0.350A)

Source: Lumileds Data Sheet
Luminaire Lifetime – A Luminaire is a System

The failure of any one component can cause the entire system to stop functioning.

Luminaire designers make trade-offs among the components, depending on the desired performance criteria – for example the number of LEDs ($$\$$) versus drive current (lifetime).
Technology Issues

Color Matching / Color Shift

Supplier quality and testing is critical to successful projects

White is white is white?

Particularly in linear wall wash applications, this lack of color consistency is non acceptable

Is blue?

Source: Cree
Technology Issues

Color Matching / Color Shift

What causes this shift from white to blue? Phosphor degrades faster than the blue die over time shifting light output to blue.

Change in Spectra Over Time

Overall effect is to shift CCT higher (toward blue)

Source: Cree
Color Binning

Solid-state lighting manufacturers cannot control the exact color characteristics of LEDs when they are fabricated. To compensate they sort the finished LEDs into color bins. Customers purchasing the widest range of bins get the lowest prices. It then becomes their responsibility to produce consistent color products. At least one manufacturer with a multi-chip product is mix/matching within the device to provide consistent color.
Technology Issues

Standards

• LM-79-08  *Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*  
  – Describes testing procedure for evaluating light distribution from LED-based luminaires

• LM-80-08  *Approved Method for Measuring Lumen Depreciation of LED Light Sources*  
  – Describes testing procedure for measuring lumen depreciation of LED devices  
  – Does not describe how to evaluate data taken

• No approved standard available for driver lifetimes
LED Light Output – “Equivalent” to conventional sources?

• LED devices have highly directional light output unlike conventional light sources

• In directional fixtures such as downlights, this results in much less wasted light trapped in the fixture
Incandescent lamp light output can be accurately conveyed by listing the lamp’s power (wattage).

LED-based lamps do not show the same linear relationship due to the differences in device efficacy.

Source: LED Transformations
However there are other parts of the lighting system besides the LED devices themselves that can fail or require maintenance:

- Driver and Control Electronics (including dimmers, energy management systems) – component failures, lightning strikes and other electrical transients
- Optics – yellowing, cracking, voids, dirt buildup
- Heat sinks – bird droppings, insect nests
- Housings – mechanical stress, water intrusion, connectors

How easy is it to repair/replace damaged components?
Many times, maintenance costs make or break the project.

LED Economics

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Source</td>
<td>LED Source</td>
</tr>
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</table>

LED Savings

Initial Fixture Cost + labor
Energy Costs
Replacement costs (source + labor)
Because LED systems work differently from those of incandescent lamps, dimming is often an issue.

LED drivers must be designed to be compatible with line-voltage dimmers (of which there are many types):

- Many line-voltage products not compatible (like CFLs) with certain dimmers
- Many low voltage LED systems with certain step-down transformers are not compatible with certain dimmers

One dimmer manufacturer provides a matrix showing compatibility and functionality with various manufacturers’ luminaires/or drivers.
LED provides lower average light levels at this point.
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Average nighttime temperature is well within reasonable limits for LEDs

Units typically do not operate during daylight hours

Average Daily Minimum Temperature

Source: NOAA

Data from 1971 thru 2000
Light output increases slightly at lower temperatures.

Source: Lumileds
Environmental

Vandal Prone Areas

Which of these two devices looks more likely to survive a vandal attack in a school or prison?

Again taking advantage of LED’s small size and directionality

LED Emergency Light

Traditional Emergency Light

Source: Dual-Lite
Environmental

Vibration Resistance

With no filament or electrodes to break, LEDs offer significant improvement over conventional light sources in high vibration and shock environments

Wingtip light of an Eclipse VLJ

Source: LED Transformations

Interior of the Boeing 787 Dreamliner
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LED Products

One Way to Determine What’s Good - CALiPER

The DOE CALiPER program supports testing of a wide array of SSL products available for general illumination, using industry-approved test procedures. CALiPER test results:

• Guide DOE planning for SSL R&D and market introduction activities, including ENERGY STAR® program planning
• Support DOE GATEWAY demonstrations and technology procurement activities
• Provide objective product performance information to the public in the early years, helping buyers and specifiers have confidence that new SSL products will perform as claimed
• Guide the development, refinement, and adoption of credible, standardized test procedures and measurements for SSL products
Dozens of manufacturers are offering LED replacements for halogen MR-16 lamps. Many of these claim to be “equivalent” to 35W or 50W halogen lamps. However...

“In CALiPER testing to date, the performance of LED MR16 replacement lamps varied greatly. Power usage for the LED replacements is considerably lower than for halogen MR16 lamps. However, light output and intensity for the tested LED products falls significantly short of the halogen benchmark levels, limiting the usefulness of LED MR16 lamps as a one-for-one replacement in typical highlighting and accent applications.”

Source: CALiPER Benchmark Report Nov. 2008
Results from Round 9 CALiPER testing (October 2009) show that a large number of LED product manufacturers are still not providing accurate performance data.

CALiPER results are available at: http://www1.eere.energy.gov/buildings/ssl/caliper.html
Another Way

Lighting Facts Label

Clear Representation of

- Light Output
- Power
- Efficacy
- Color
  - CRI
  - CCT

Results verified by third party testing using LM-79 testing methods
Energy Star – SSL Luminaires General Requirements

Highlights

• Indoor luminaires shall have a minimum CRI of 75
• Requires *zero* off-state power draw for the fixture; PFC ≥ 0.7 residential, PFC ≥ 0.9 commercial
• Lumen Maintenance:
  — Residential – 25k hrs Indoor, 35k hrs Outdoor
  — Commercial – 35k hrs commercial
• Luminaire efficacy requirements ratchet up over time to take into account technology improvements
• CCT shall be within one of the following groups: 2700K, 3000K, 3500K, 4000K, 4500K, 5000K, 5700K, 6500K
• Standard was published December 3, 2009 and becomes effective August 10, 2010

• Scope
  – Omnidirectional replacement lamps
  – Directional replacement lamps
  – Decorative lamps
  – Non-standard lamp forms
  – ANSI lamp bases

• Not included in standard
  – Linear fluorescent replacement lamps
  – HIS replacement lamps
Lighting for Tomorrow – 2009 LED Winners

Architect LED Flat Panel
MaxLite

eW® Cove QLX Powercore
Philips Color Kinetics

Eco-Counter - 120V LED Under Cabinet Task Light
CSL - Creative Systems Lighting

Par 38 Track Fixture
Cree LED Lighting
The Next Generation Luminaires™ (NGL) Solid State Lighting (SSL) Design Competition was created to recognize and promote excellence in the design of energy-efficient LED commercial lighting luminaires.

*Stile Styk* by STILE, a brand of SPILIGHTING Inc

*Evolve™ LED R150* by GE Lighting Solutions

*CURVE* by Finelite, Inc

*VizorLED* by Philips

*Wide-Lite*
Demonstrations showcase high-performance LED products for general illumination in a variety of commercial and residential applications. Results provide real-world experience and data on state-of-the-art solid-state lighting (SSL) product performance and cost effectiveness.
Third-party test results

• Don’t just take the luminaire manufacturer’s word
• Reputable photometric test labs
  – DOE certified for CALiPER testing
  – NVLAP certified for LM-79 testing

Warranty Policy

• Is there a written end-of-life policy? How will spares be made available?
• Do all system components from SSL manufacturers have a warranty and labor to fix/replace?
• How long is the warranty? What exactly is covered?
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Downlight – Good

Friendly’s Restaurant, Westfield MA

Incandescent 5,135 W

LED (2 Years Later) Makes use of directionality

LED 948W

Source Cree
Applications

Street Lighting – Good

- 15% energy savings over previous HPS
- Makes use of directionality

Source: Eric Haugaard, Ruud Lighting
Source: Photonics Industry and Technology Development Association
Cove Lighting – Good

LED Cove Lighting In Resort Casino
-30% Energy Saved vs. Proposed Neon
-No Mercury, Recyclable = Green Value for Hotel

Source: GreenLight Initiative
Task Lights / Bollards – Good

Makes use of directionality and small form factor

Source: Philips Gardco

Source: Luximo

Source: Lightscape Concepts & Design
Incandescent Replacements – Good and Bad

Wide range of product performance available, from good to poor

Makes use of small form factor and high efficacy
Fluorescent Replacements – Depends

2x4 parabolic louver
Fluorescent T8

0.92 LLD
0.95 LDD
0.88 BF (n/a)

0.65 W/ft²
25 fc (average)
1.9 max/min

Source: Tuenge & Myer, DOE PNNL
Fluorescent Replacements – Depends

2x4 parabolic louver
LED Replacements

0.70 LLD
0.95 LDD
1.00 BF

0.44 W/ft²
10 fc (average)
2.3 max/min

Source: Tuenge & Myer, DOE PNNL
Applications

Fluorescent Replacements – Depends

2x2 parabolic
Fluorescent T8U

0.92 LLD
0.95 LDD
0.94 BF (n/a)

0.64 W/ft²
20 fc (average)
2.5 max/min

Source: Tuenge & Myer, DOE PNNL
Fluorescent Replacements – Depends

2x2 lensed
Integral LED

0.70 LLD
0.95 LDD
1.00 BF

0.45 W/ft²
17 fc (average)
2.6 max/min

Source: Tuenge & Myer, DOE PNNL
High Power MR-16s – Not So Good

- The design envelope for a standard MR-16 allows for a limited surface area to dissipate heat generated by the LEDs.
- This, in turn, limits the light output possible for the device based on present LED efficacy values and required lifetime – 50W MR-16 not possible.

Source: Aavid Thermalloy Heat Sinks
High Power MR-16s – Not So Good

Halogen versus LED-based MR-16 test results

[Graph showing Center Beam Intensity for MR16 Equivalent Lamps]
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Final Thoughts

From the Specifier’s Side

If you are a Lighting Designer, Architect, Utility, Municipality, etc.

• You and others in your firm need to become familiar with these issues if you (or they) are not presently up to date

• You should evaluate whether your supplier has addressed these issues adequately

• If they are new to you:
  – Find someone who is familiar with them and work with or hire them
  – Review literature available at DOE-SSL web site [www.ssl.energy.gov](http://www.ssl.energy.gov) as well as various manufacturers’ web sites
  – Link up with some of the many groups involved in the solid-state lighting marketplace
    • Expect to hear conflicting viewpoints and strong opinions
Final Thoughts

From the Supplier’s Side

Luminaire Manufacturers should provide a complete product:

- Quality of white light including color rendering, color temperature, radiation pattern, etc. Applications where the end-user must settle will be unsatisfactory no matter what “benefits” the product provides

- Consistency of light from fixture to fixture over temperature. In general, it is what the end-user is accustom to and expects

- Accurate lifetime reliability estimates – it is a fundamental premise of Solid-State Lighting and one of the things that justify the higher cost

- Support in volume; Device manufacturers promise a lot—the question is whether or not they can deliver

- Education of the customers including application engineering—so that they are applying the technology correctly to appropriate environments
From the User’s Side

1. Temperature range specification for operation
   How does that compare with the maximum junction temperature for the LEDs used in the product?

2. Luminaire manufacturer
   - How long has the manufacturer been in business? What business?
   - Does the firm use brand name LEDs?
   - Were the LEDs tested to LM-80?

3. Warranty
   - Life expectancy of product (Energy Star requires at least a 3-year warranty)
   - What replacement costs are covered (e.g. installation labor, shipping, etc.)
   - What performance elements are warranted (e.g. CCT shift, lumen output, luminaire efficiency, etc.)
Final Thoughts

From the User’s Side

4. Power Issues
   - Power Factor
   - Off-state power consumption (Energy Star requires < 0.5W)
   - Is the unit dimmable? With what controllers?
   - Step-down transformer compatibility for low-voltage retrofit products

5. Does it have a UL / ETL / CSA / applicable safety mark?

6. Chromaticity
   - Shift over time/temperature
   - Variation from fixture to fixture

7. Luminaire performance
   - Fixture efficiency (in lumens/Watt)
   - Delivered lumens (not just LED device performance)
   - IES files
   - LM-79 test results from approved third party laboratory
   - Lumen maintenance
Final Thoughts

From All Sides

Do not underestimate the use and practical application of simple COMMON SENSE\textsuperscript{Note 1}

- If it seems too good to be true, it probably is
- If you can’t understand how a product could do “that,” there is a high likelihood that it probably “doesn’t”
- If nobody else’s product does “that” maybe this product does not do it either

\textsuperscript{Note 1} Requires ownership of at least a limited quantity
Final Thoughts

Where are LED-Based Products Appropriate?

- Outdoor area & street lighting
- Downlighting
- Task lighting
- Display lighting
- Cove lighting
- “Architainment” environments
- Other applications that make use of LED’s unique attributes
  - Small size
  - Directionality
  - Low temperature performance
  - Improved secondary optics performance due to die size

Source: Kelly Gordon, PNNL
Final Thoughts

You Can’t Ignore It

Solid-state lighting technology is coming whether you like it or not, leaving you with two choices:

• Embrace it wisely
  – Learn all you can about it
  – Choose a pilot project to try it out
  – Acknowledge that as with all electronics, LED products will always be less expensive tomorrow

• Ignore it foolishly
  – Dismiss it as a fad
  – Keep saying “It isn’t ready yet”
  – Find excuses to avoid testing it
Final Thoughts

A Lesson From History

• Think of how the microprocessor has changed the world over the last 30 years.

• The lighting world is about to undergo a change not seen since the invention of the incandescent lamp, and driven by that same semi-conductor industry.

Are you going to be ready for it?
The Department of Energy offers a number of useful program to insure that quality products are available to the public and to further the adoption of efficient LED lighting

- SSL Quality Advocates
- Gateway Demonstration Program
- CALiPER
- Lighting for Tomorrow
- Next Generation Luminaires
- Municipal Consortium on LED Street Lights
- Technical Information Network for Solid-State Lighting
- DOE Funded R&D Programs

www.ssl.energy.gov
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Questions?
Thank You

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