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Illuminating Solar Decathlon Homes

Exploring Next Generation Lighting Technology – Light Emitting Diodes

Resources for 2009 Solar Decathlon Teams

KL Gordon
TL Gilbride

May 2008

Pacific Northwest
NATIONAL LABORATORY

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For the Buildings Technologies Programs
Office of Energy Efficiency and Renewable Energy
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Under Contract DE-AC05-76RLO 1830

Prepared by

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Foreword

The goal of the Solar Decathlon is to design a home that uses efficient design and solar power to achieve a net zero energy balance. We know that lighting accounts for about 30% of building electricity use in residential and commercial building (DOE MYPP 2008). So one significant way to help achieve that net zero balance is to minimize the energy used by lighting. You have many options for lighting your Solar Decathlon home, including daylighting, incandescent, halogen, metal halide, compact and linear fluorescent. This document provides you with ideas and suggestions for a relatively new form of lighting on the general illumination scene – LED lighting.

LEDs (light emitting diodes) are solid state devices that convert electricity to visible light. Huge advances have been made in LED lighting technology in recent years and increases in light output and efficacy are announced frequently. In terms of light output (lumens) per watt of electricity consumed, good quality, high-power white LEDs are more than twice as efficient as incandescent sources and fast approaching and even surpassing the efficacy of linear and compact fluorescent products.

LEDs are very small, they are largely impervious to vibration, have instant start, are amenable to controls like dimming, provide a directional light, work great in cold weather, and can be combined to produce fantastic displays of color. Their tiny size allows them to be used individually or clustered in lines, squares, or other arrays, in groups of two or three to dozens to provide anywhere from a pinpoint of light to enough light to power a street light or fill an auditorium. They can even be embedded in clear plastic "ropes" to edge stair railings, highlight building outlines, and light fountains. All of these features make LEDs a fun and versatile, as well as energy-efficient light source to work with.

The purpose of this document is to provide the university teams competing in the 2009 Solar Decathlon with a resource of information about solid-state lighting technology as well information on products, applications, retailers, and services now available. The energy efficiency, size, durability, and packaging options of LEDs lend themselves to innovative, practical, and artistic treatments. We hope this document is not only an information resource, but also an inspiration to demonstrate the *Next Generation Lighting Technology*.

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Light Emitting Diodes - Technology Overview

As a nation, the United States spends about one-quarter of our electricity budget on lighting, or more than $37 billion annually. Yet much of this expense is unnecessary. Technologies developed during the past few decades can help us cut lighting costs by 30% to 60%, while enhancing lighting quality and reducing environmental impacts (http://www.netl.doe.gov/SSL/faqs.htm). White light LEDs are one of these technologies.

The LED Advantage

LED lighting starts with a tiny (about 1 mm^2) chip of semi-conducting material, mounted on heat-conducting material and enclosed in a lens or encapsulant (Figure 1). The resulting device is mounted separately or in arrays of LEDs on a circuit board, which is then installed in a fixture, ideally one designed to effectively manage heat generated by the LEDs.

LEDs are solid-state devices that convert electrical energy directly into radiant energy (Figure 2). While incandescents convert 8% of the power they consume into visible light and fluorescents convert 21% into visible light, LEDs now convert 15% to 25% into visible light. While incandescent and fluorescent are relatively mature technologies, LED is an emerging technology that has the potential to achieve higher efficiencies. The U.S. Department of Energy (DOE) is calling for extraction efficiencies of 50% by 2012.

In task lighting applications, LEDs represent a great energy saving opportunity. LEDs emit light in a less diffuse, more directional, pattern than other light sources. In contrast, standard incandescent bulbs and fluorescent lamps emit light in all directions and much of the light output is absorbed inside the fixture, for example, fixture losses in recessed cans and track lighting fixtures can be as high as 50%.

Because LEDs are solid state devices they are safer too. Incandescent, fluorescent, and high-intensity discharge (HID) lamps are all based on glass enclosures containing a filament or electrodes, with fill gases and coatings of various types and breakage during transportation, installation, or operation is common. With LEDs, this problem is virtually eliminated.

A Brief History

The first LED was developed at General Electric (GE) in 1962; it was a red LED producing .001 lumens. During the 1960s through 1980s, first red then green LEDs were developed and light output grew from 0.01 to 0.1 lumens. In the 1990s Nichia created the first blue LED; it emitted 1 lumen and led the way to the development of white light from LEDs (achieved either by mixing the light from red, green, and blue LEDs, known as RGB systems, or by coating a blue LED with phosphor to emit white light, known as phosphor-converted or PC LEDs) (Figure 3). In 2008, white LED devices capable of emitting close to 100 lumens from a nominal 1-watt device have become commercially available.

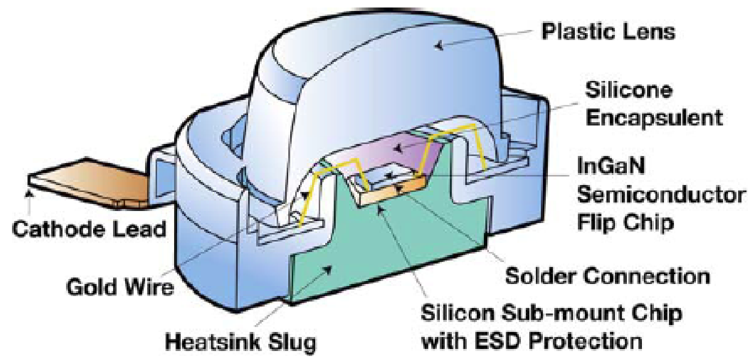
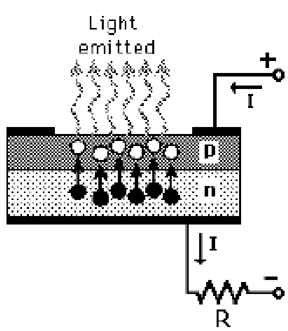
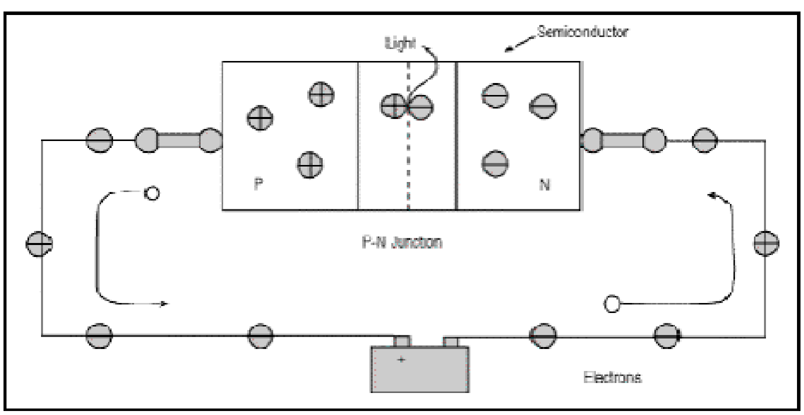


Figure 1. The typical LED emitter device houses the die (a chip composed of crystalline layers of semiconductor material), optics (a lens), encapsulant, and heat sink slug (used to draw heat away from the die). The device is soldered to a metal-core printed circuit board (MCPCB) (not shown in this drawing). The MCPCB is a special form of circuit board with a dielectric layer (non-conductor of current) bonded to a metal substrate (usually aluminum). The MCPCB is then mechanically attached to an external heat sink which can be a dedicated device integrated into the design of the luminaire or, in some cases, the chassis of the luminaire itself. The size of the heat sink is dependent upon the amount of heat to be dissipated and the material's thermal properties. The heat must be dissipated because continuous operation at elevated temperature dramatically accelerates lumen depreciation resulting in shortened useful life.



Side view of p-n junction

Figure 2. The LED is a p-n type device. In a p-n junction, the p side contains excess positive charge ("holes," indicating the absence of electrons) while the n side contains excess negative charge (electrons).



p-n Junction in LED

Figure 3. LEDs emit energy in narrow wavelength bands of the electromagnetic spectrum**.** The composition of the materials in the semiconductor chip determines the wavelength and therefore the color of the light. A chip of aluminum gallium indium phosphide (AlGaInP) produces light in the red to amber range, while indium gallium nitride (InGaN) LEDs produce blue and green light. With the use of suitable phosphors, the blue InGaN LEDs can generate white light. White light can also be produced by combining light from LEDs that are red, green, and blue (the primary colors of light).

Getting Better All the Time

LEDs have made phenomenal improvements in both light output and cost decreases during the past 5 years, with the output per watt improving at a compound rate of about 35% per year while the cost per lumen has decreased 20% per year (Dowling 2005). LED device efficacy (lumens per watt) has increased from about 10 lm/W in 2005 to 50 lm/W for warm white LEDs in 2008 and from 30 lm/W in 2005 to 80 lm/W for cool white LEDs (as of October 2007). In fact, the technology is changing so fast that DOE has revised its projections three times in the past three years and as of March 2008 predicts that commercially available cool white LED devices will reach an efficacy of 188 and commercial warm white LED devices will achieve an efficacy of 162 lm/W by 2015 (http://www.netl.doe.gov/SSL/faqs.htm).

At the same time, retail prices for LED devices have dropped dramatically, from more than $200 per thousand lumens (/klm) in 2001 to $30/klm in 2007 and they are predicted to drop to $3/klm by 2015, which will make solid state lighting less expensive than compact fluorescents on a first-cost basis (DOE 2008a). For reference, 1,000 lumens is approximately the amount of light produced by a 60-watt incandescent light bulb.

While industry has pushed much of this development to expand the commercial potential of LEDs beyond indicator lights and consumer electronics in the general illumination market, the U.S. Department of Energy (DOE), through its Solid State Lighting (SSL) Research and Development (R&D) program, is focused on increasing the energy efficiency of LED lighting, an emphasis that might otherwise be lost on the path to commercialization. Congress has given DOE the responsibility to ensure that SSL reaches its full energy saving potential, with the goals of significantly reducing building energy use and costs, and contributing to our nation's energy security. Congress has appropriated $60.75 million for SSL between 2003 and 2007 and proposes $350 million more between 2007 and 2013. DOE directs these research dollars to the national laboratories, industry, and universities and it has yielded 71 patent submissions since 2000. In the next few decades, general illumination technology will undergo a remarkable transformation through improvements in solid-state lighting. No other single lighting technology offers as much potential to conserve electricity and enhance the quality of our building environments.

Major research challenges must still be addressed before the full promise of solid-state lighting is realized. Color quality continues to improve; many white LEDs available today have high color temperature, meaning they look very cool/blue, and there is significant drop-off in efficacy with warm white LEDs. Thermal management is critical to LED system operations. While LEDs don't emit infrared radiation from the front (i.e., the "bulb" is cool to the touch), they do produce heat that has to be removed from the diode to avoid a decrease in light output and shortened life.

In partnership with industry leaders, research organizations, academic institutions, and national laboratories, DOE is working to accelerate technology developments that deliver substantial energy savings for all lighting users, and position U.S. companies for technology leadership in global markets (http://www.netl.doe.gov/SSL/).

What Are LEDs and How Do They Work?

LED lighting starts with a tiny chip (typically 1 mm^2) comprising layers of semiconducting material. LED packages may contain just one chip or multiple chips, mounted on heat conducting material and usually enclosed in a lens or encapsulant. The resulting device, typically around 7 to 9 mm on a side, can produce 30 to 150 lumens each and can be used separately or in arrays. The LED devices are mounted on a circuit board and attached to a lighting fixture, architectural structure, or even a "light bulb" package.

Light is generated inside the chip, a solid crystal material, when current flows across the junction of two carefully engineered, different materials known as a p-n junction.

As with other light source technologies, such as fluorescent and high intensity discharge (HID), lighting systems using LEDs can be thought of as having a light source (typically, the individual LED sources), a ballast or control gear (for LEDs, often called a driver), and a luminaire (the surrounding materials for optical control of the emitted light, thermal control of the overall system, and connection to power). Unlike luminares for traditional lamps, which typically contain four or fewer lamps (bulbs), LED luminares can contain arrays of many (even dozens of) individual LEDs (Figure 4).

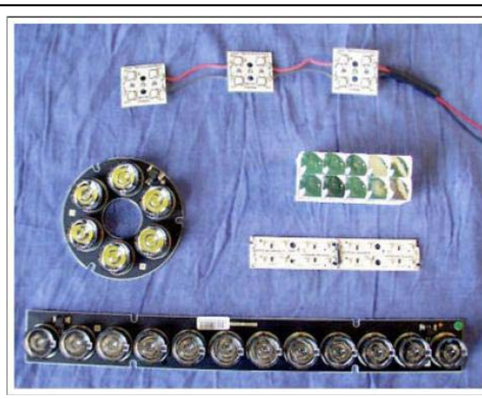


Figure 4. Commercially Available LED Arrays

LEDs don't typically burn up or burn out as much as burn down. Over time they get dimmer and dimmer and their light output diminishes faster in high-temperature environments. Fortunately designers are continuing to make improvements in LED light output and lifetimes. ENERGY STAR® guidelines that will become effective September 30, 2008, require that LEDs maintain 70% lumen output over 25,000 to 35,000 hours of operation.

Are LEDs Ready for General Lighting?

The number of white light LED products available on the market continues to grow, including portable desk/task lights, under-cabinet lights, recessed downlights, retail display lights, and outdoor fixtures for street, parking lot, path, and other area lighting. Some of these products perform very well, but the quality and energy efficiency of LED products still varies widely, for several reasons: 1) LED technology continues to change and evolve very quickly. New generations of LED devices become available approximately every 4 to 6 months. 2) Lighting fixture manufacturers face a learning curve in applying LEDs. Because they are sensitive to thermal and electrical conditions, LEDs must be carefully integrated into lighting fixtures. Few lighting fixture manufacturers are equipped to do this well today. 3) Important differences in LED technology compared to other light sources have created a gap in the industry standards and test procedures that underpin all product comparisons and ratings. ENERGY STAR criteria were approved in 2007 and will take effect September 30, 2008. Commercially available products are being independently tested through a testing program called CALiPER (Commercially Available LED Product Evaluation and Reporting) run by DOE. You can find out what products have been tested and results of testing through the CALiPER website, http://www.netl.doe.gov/ssl/comm_testing.htm

Are LEDs Energy Efficient?

The best white LED products can meet or exceed the efficiency of compact fluorescent lamps (CFLs). However, many white LEDs currently available in consumer products are only marginally more efficient than incandescent lamps. The best warm white LEDs available today can produce about 45-50 lumens per watt (lm/W). In comparison, incandescent lamps typically produce 12-15 lm/W; CFLs produce at least 50 lm/W. Performance of white LEDs continues to improve rapidly. However, LED device efficacy doesn't tell the whole story. Poorly designed luminaires using even the best LEDs may be no more efficient than incandescent lighting. Good LED system and luminaire design is imperative to energy-efficient LED lighting fixtures. For example, there is a commercially available LED recessed downlight that combines multicolored high efficiency LEDs, excellent thermal management, and sophisticated optical design to produce more than 700 lumens using only 12 watts, for a luminaire efficacy of 60 lm/W, which exceeds even the most efficient CFL downlights available today.

How Long Do LEDs Last?

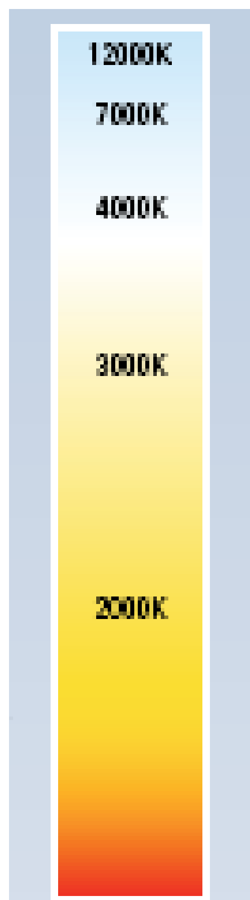
Unlike other light sources, LEDs usually don't "burn out;" instead, they get progressively dimmer over time. LED useful life is normally defined as the number of operating hours until the LED is emitting 70% of its initial light output. Good quality white LEDs in well-designed fixtures are expected to have a useful life of 30,000 to 50,000 hours. A typical incandescent lamp lasts about 1,000 hours; a comparable CFL lasts 8,000 to 10,000 hours, and the best linear fluorescent lamps can last more than 30,000 hours (see Table 1). LED light output and useful life are strongly affected by temperature. LEDs must be "heat sinked," placed in direct contact with materials that can conduct heat away from the LED. Off-the-shelf LED fixtures should have heat sinking materials incorporated into the fixture; if you are building your own fixture, you'll need to take this into the account. On the plus side, LEDs perform very well in cold weather environments with instant startup (unlike fluorescent sources, which do not perform as well in cold temperatures).

Table 1. Comparison of Life Times for Different Light Sources

Light Source	**Range of Typical Rated Life (hours)*** (varies by specific lamp type)
Incandescent	750-2,000
Halogen incandescent	3,000-4,000
Compact fluorescent (CFL)	8,000-10,000
Metal halide	7,500-20,000
Linear fluorescent	20,000-30,000
High-Power White LED	35,000-50,000
*estimated. Source: lamp manufacturer data.	

Do LEDs Provide High-Quality Lighting?

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit light in a very narrow range of wavelengths in the visible spectrum, resulting in nearly monochromatic light. This is why LEDs are so efficient for colored light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or near-ultraviolet (UV) chip is coated with phosphor(s) to emit white light; and 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light. Most currently available white LED products are based on the blue LED + phosphor approach. Phosphor-converted chips are produced in large volumes and in various packages (light engines, arrays, etc.) that are integrated into lighting fixtures. RGB systems are more often custom designed for use in architectural settings.



CCT Scale

The color quality of light is described in two ways: CCT (correlated color temperature) and CRI (color rendering index).

Until recently, almost all white phosphor-converted LEDs had very high correlated color temperatures (CCTs), often above 5000 Kelvin. High CCT light sources appear “cool” or bluish-white. Neutral and warm white LEDs are now available and are becoming more efficient. They are still less efficient than cool white LEDs, but have improved significantly, to levels almost on par with CFLs. For most interior lighting applications, warm white (2700K to 3000K), and in some cases neutral white (3500K to 4000K) light is appropriate. (For a more indepth explanation of CCT see the glossary in this report.)

The color rendering index (CRI) measures the ability of light sources to render colors, compared to incandescent and daylight reference sources. In general, a minimum CRI of 80 is recommended for interior lighting. The CRI has been found to be inaccurate for RGB (red, green, blue) LED systems. A new metric is under development, but in the meantime, color rendering of LED products should be evaluated in person and in the intended application if possible. The leading high-efficiency LED manufacturers now claim CRI of 80 for phosphor-converted, warm-white devices. (For a more indepth explanation of CRI see the glossary in this report.)

See Table 2 for a color quality comparison of LED and traditional light sources.

Table 2. Color Quality Comparison of LED and Traditional Light Sources

Lamp Type	CCT	CRI
Incandescent A lamp	2700 K	100
Compact Fluorescent	2700-3000 K	80
Warm White LED	2600-3500 K	80
Cool White LED	5000 K	75

Are LEDs Cost-Effective?

Costs of LED lighting products vary widely. Good quality LED products currently carry a significant cost premium compared to standard lighting technologies. However, costs are declining rapidly. In 2001, the cost of white light LED devices was more than $200 per thousand lumens (kilo-lumens). In 2007, average prices have dropped to around $30/klm. It is important to compare total lamp replacement, electricity, and maintenance costs over the expected life of the LED product.

How Efficient Are They?

Energy efficiency of light sources is typically measured in lumens per watt (lm/W), meaning the amount of light produced for each watt of electricity consumed. This is known as luminous efficacy. DOE’s long-term research and development goal calls for white-light LEDs producing 161 lm/W for cool white and 139 lm/W for warm white light in cost-effective, market-ready luminaires by 2015. The LEDIndustry announces improvements in efficacy regularly.

Standard incandescent A-lamps provide about 15 lumens per watt (lm/W), with CCT of around 2700 K and CRI close to 100. ENERGY STAR-qualified compact fluorescent lamps (CFLs) produce at least 50-70 lm/W at 2700-3000 K with a CRI of at least 80. Efficacies of currently available LED devices from the leading manufacturers range from about 30 to 50 lumens/watt for warm white (2600-3500 K) to 70-90 lm/w for cool white (5000K CCT) (not including driver or thermal losses).

Fluorescent and high-intensity discharge (HID) light sources cannot function without a ballast, which provides a starting voltage and regulates electrical current to the lamp. LEDs also require supplementary electronics, usually called drivers. The driver converts line power to the appropriate voltage (typically between 2 and 4 volts DC for high-brightness LEDs) and current (generally 200-1000 milliamps or mA), and may also include dimming and/or color correction controls. Currently available LED drivers are typically about 85% efficient. So LED efficacy should be discounted by 15% to account for the driver. For a rough comparison, the range of luminous efficacies for traditional and LED sources, including ballast and driver losses as applicable, are shown in Table 3.

Table 3. Ballpark Comparison of Light Source Efficacies as of October 2007

Light Source	Typical Luminous Efficacy Range in lm/w (varies depending on wattage and lamp type)
Incandescent (no ballast)	10-18
Halogen (no ballast)	15-20
Compact fluorescent (incl. ballast)	35-60
Linear Fluorescent (incl. ballast)	50-100
Metal Halide (incl. ballast)	50-90
Cool white LED 5000K (incl driver)	59-76
Warm white LED 3300 K (incl. driver)	25-43

Comparing LEDs to Traditional Light Sources

Energy efficiency proponents are accustomed to comparing light sources on the basis of luminous efficacy. To compare LED sources to CFLs, for example, the most basic analysis should compare lamp-ballast efficacy to LED+driver efficacy in lumens per watt. Data sheets for white LEDs from the leading manufacturers will generally provide "typical" luminous flux in lumens, test current (mA), forward voltage (V), and junction temperature (Tj), usually 25 degrees Celsius. To calculate lm/W, divide lumens by current times voltage. As an example, assume a device with typical flux of 45 lumens, operated at 350 mA and voltage of 3.42 V. The luminous efficacy of the LED source would be:

45 lumens/(.35 amps × 3.42 volts) = 38 lm/W

To include typical driver losses, multiply this figure by 85%, resulting in 32 lm/W. Because LED light output is sensitive to temperature, some manufacturers recommend de-rating luminous flux by 10% to account for thermal effects. In this example, accounting for this thermal factor would result in a system efficacy of approximately 29 lm/W. However, actual thermal performance depends on heat sink and fixture design, so this is only a very rough approximation. An accurate measurement can really only be accomplished by measuring the actual luminaire in operation.

Designing with LEDs

LEDs' energy efficiency, small size, directionality, durability, long life, color options, and packaging options make them a great choice for Solar Decathlon homes. Their low energy consumption makes LEDs well suited for solar energy power and there are many commercially available LED products designed for this purpose. A wide variety of LED colors, arrays, components and products are available giving you the freedom to choose from many off-the-shelf options or to customize your own installations to fit the needs of your space.

LEDS are no ordinary light bulb. The unique attributes of the light source offer a host of benefits when it comes to designing with LED lighting:

- Directional light emission – directing light where it is needed.
- Size advantage – can be very compact and low-profile.
- Breakage resistance – no breakable glass or filaments.
- Cold temperature operation – performance improves in the cold, good for outdoor and holiday lights
- Instant on – require no "warm up" time.
- Rapid cycling capability – lifetime not affected by frequent switching.
- Dimming and color controls – compatible with electronic controls to change light levels and color characteristics (although not all are compatible with dimmers designed for incandescents).
- Design versatility – small size and ability to be arranged in various arrays enables many options for lighting configurations and light output.
- No IR or UV emissions - LEDs intended for lighting do not emit infrared or ultraviolet radiation.
- Potentially significant energy-cost savings compared to incandescent
- Potentially long life of up to 50,000 hours
- Save maintenance and costs of replacing burned out bulbs
- Low-voltage operation
- Compatible with integrated circuits.

Here are some of the general illumination applications that can benefit the most from LED's unique attributes:

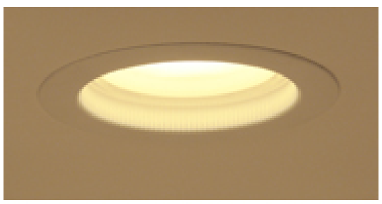
- undercabinet lighting
- in-cabinet accent lighting
- adjustable task lighting
- outdoor area lighting
- recessed downlights
- desk lighting

- accent lights
- step and path lighting
- cove lighting
- spaces with occupancy sensors
- food preparation areas
- display cases
- art display lighting.
- architectural and garden lighting
- in fountain lighting
- night lights.

LED Lighting Showcase[1]

Below are a number of examples of LED lighting products. These photos are provided to give you some ideas of the state of current technology and how existing products can be used. The products in Table 4 are winners of the 2007 Lighting for Tomorrow energy-efficient design contest sponsored by DOE, the Consortium for Energy Efficiency (CEE), and the American Lighting Association (ALA) (http://www.lightingfortomorrow.com). They have been tested by independent testing laboratories to verify wattage, light output, color characteristics, and other attributes. Please note that technology continues to change very rapidly, with new products introduced to the market regularly. Check with vendors for the latest product information.

Table 4. Winners of 2007 Lighting for Tomorrow SSL Competition





Grand Prize winner - "LR6 Recessed Downlight"

CREE LED Lighting Fixtures (LLF), Inc. Morrisville, NC, www.llfinc.com

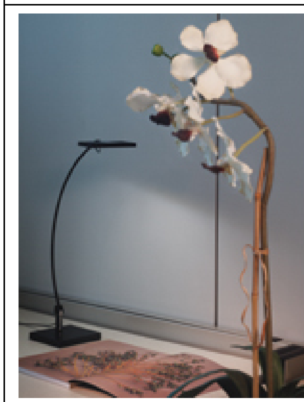
The LR6 is a complete recessed downlight trim kit and LED light engine in one unit. It fits standard recessed housings in new construction or as retrofit for existing fixtures. The 6-inch-diameter unit is installed via a dedicated GU-24 base or standard Edison socket, supported by a rotating clip retention system. The light output and color quality are very similar to incandescent reflector lamps typically used in residential downlights, for less than one-fifth the wattage. This product exceeds the luminaire efficacy of even the most efficient fluorescent downlight systems. This product was tested through DOE's CALiPER program (test product 07-31). Photometric results are as follows: Wattage: 11 watts, Light output: 600 lumens, Luminaire efficacy: 54 lm/W, CCT: 2758 K or 3500 K, CRI 95.

[1] Information on products is provided to help readers make choices about light fixture and source selection. DOE does not endorse or guarantee the performance of any particular product or company.


Winner - "PLS Undercabinet"

Finelite, Inc. Union City, CA, Finelite.com

At only 0.8 inches tall and 2.5 inches wide, PLS Undercabinet fixtures fit seamlessly under binder bins, kitchen cabinets, or shelving, revealing vertical textures while bathing task surfaces in evenly distributed light. Fixtures may be used individually or in continuous rows, supplied standard with mechanical or magnetic mounting means. This product was tested through DOE’s CALiPER program (test product 07-32). Photometric results are as follows: Wattage: 8 watts, Light output: 344 lumens, Luminaire efficacy: 43 lm/W, CCT: 3552 K, CRI 71.



Winner - "PLS Desk Lamp"

Finelite, Inc. Union City, CA, Finelite.com

This versatile PLS Desk Lamp available with interchangeable mountings allows users to quickly tailor illumination patterns and levels to specific tasks by simply adjusting the fixture’s head with ever-so-slight hand movement. This product was tested through DOE’s CALiPER program (test product 07-33). Photometric results are as follows: Wattage: 10 watts, Light output: 430 lumens, Luminaire efficacy: 43 lm/W, CCT: 3631 K, CRI 71.

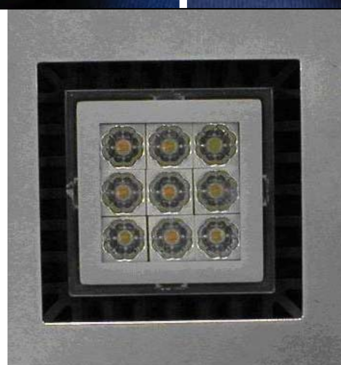
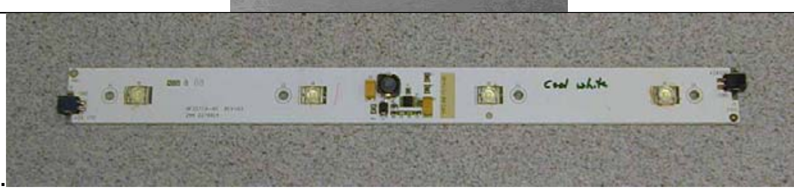
Winner - "Strata Outdoor"

Progress Lighting Greenville, SC, ProgressLighting.com

The Strata fixtures take advantage of the small size and directionality of LED sources. Featuring a low-profile, modern housing design, the Strata fixtures direct light downwards for glare-free, dark-sky friendly illumination. This product was tested through DOE’s CALiPER program (test product 07-34). Photometric results are as follows: Wattage: 5 watts, Light output: 125 lumens, Luminaire efficacy: 25 lm/W, CCT: 3270 K, CRI 70.

Table 5 shows commercially available products that have been tested through DOE's CALiPER program. Some of the CALiPER-tested products were also winners in the Lighting for Tomorrow contest, these are noted above.

Table 5. CALiPER Tested Products[1]

 	Light*Waves Concept Par-30 72 LED Bulb Replacement Lamp for a Par 30 in recessed can or flood light fixtures (CALiPER ID 07-19)
	Color Kinetics eW™ Downlight SM Powercore Downlight (CALiPER ID 07-35) Photo source: Independent Testing Laboratories, Inc.
	Osram Sylvania; HF2Stick XB Undercabinet lighting stick (CALiPER ID 07-29, this is the warm white model; a cool white and soft white version were also tested ID 07-27 and 28)
	Lightolier Linear LED Undercabinet luminaire (CALiPER ID 07-30)

[1] DOE SSL CALiPER results may not be used for commercial purposes under any circumstances; see **"**No Commercial Use Policy**"** (http://www.netl.doe.gov/ssl/comm_testing.htm) for more information.

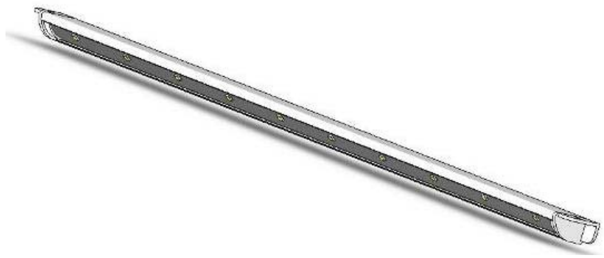
	Color Kinetics (now Philips Solid-State Lighting Solutions) eW™ Task Powercore 2 foot 2800K Undercabinet (CALiPER ID 07-36) Image courtesy of Color Kinetics
	Beta (Ruud Lighting) Security light BLD-SEC, Outdoor Wall light with 3 light bars (CALiPER ID 07-25) Photo source: www.betaled.com

Table 6 shows additional examples of LED residential lighting application. These examples are included to showcase the possibilities of LEDs. Products shown in this section have not been tested by DOE, and inclusion here does not imply endorsement by DOE. New products come on the market frequently and it is likely that there are several manufacturers producing products in each of these applications.

Table 6. Showcase of LED Lighting Applications

<table>
<tr><td colspan="2">Under Cabinet and In-Cabinet Lighting
Strip lighting is ideal for under-counter, work areas, cabinets, closets, and garages. Small LED accent lights can fit well inside cabinets to highlight objects.</td></tr>
<tr><td></td><td>Undercabinet lighting
Photos source: http://www.albeotech.com/</td></tr>
<tr><td></td><td>In-Cabinet and Back Lighting
Photo source: http://www.colorkinetics.com/
(Philips Solid State Lighting Solutions)</td></tr>
<tr><td></td><td>Accent Lighting
Photo source:
http://www.crescent.co.uk/led_lumin/led_track.htm</td></tr>
</table>

<table>
<tr><td colspan="2">Pendant Lights
Pendant lights are decorative and provide useful light over countertops, dining tables, and work areas.</td></tr>
<tr><td></td><td>Pendant Lights
Photo source:
http://www.permlight.com/images/pc_ENBJ_l.jpg</td></tr>
<tr><td></td><td>KramerLED Pendant
Photo source:
http://www.kramerlighting.com/kramerled/</td></tr>
<tr><td></td><td>KramerLED Linear
Photo source:
http://www.kramerlighting.com/kramerled/</td></tr>
</table>

<table>
<tr><td colspan="2">Task Lights
The ability to direct the illumination of LEDs in a variety of angles, intensity, and colors results in precise lighting for the task.</td></tr>
<tr><td></td><td>Desk lamp
Photo source: www.konceptech.com</td></tr>
<tr><td></td><td>Desk Lamp
Photo source:
http://www.sylvania.com/content/display.scfx?id=003691548</td></tr>
</table>

Outdoor Lighting Pathway lights, spotlights and floodlights can highlight features of a garden, architecture, or artwork, and provide additional safety and security in outdoor areas.	
	The Edge Pathway Light Photo source: http://www.betaled.com/
	Landscape Spotlighting Photo source: http://www.residential-landscape-lightingdesign. com/
	Landscape Spotlighting Photo source: http://www.ledtronics.com/ds/gdl002-200/

	Inground Uplighting Photo source: http://www.theledlight.com/
	Wall Recessed Spotlight Photo source: http://www.lumileds.com/
	Deck Spotlights Photo source: http://www.theledlight.com/

Rope and Tube Lighting Rope and tube lighting are ideal for outdoor use and indirect or architectural lighting.	
	Underwater Tube Lighting Photo source: http://www.platinumlightinginc.com/
	Rope Cove Lighting Photo source: http://www.lumileds.com/
	Above-Cabinet Lighting Photo source: http://www.lumileds.com/
	Rope Cove Lighting Photo source: http://www.wiedamark.com/

	Deck and Step Lighting Photo source: http://www.delighting.com/Hottub.jpg
	Deck and Step Lighting Photo source: http://www.platinumlightinginc.com/

Small Replacement Lamps
Low wattage screw-in replacement lamps may be suitable for accent lighting or sparkle effects.

	Dynasty S14 LED lamp 1.7 watt, 120/240 volt. Photo source CAO Group Inc., www.caogroup.com
	Dynasty B10 LED Candelabra lamp 1.7 watt, 120 volt. Photo source CAO Group Inc., www.caogroup.com

Solar Powered LED Illumination LEDs are durable which makes them ideally suited for solar applications. The products pictured below are waterproof and do not require hard wiring.	
	Solar LED Address Numbers Photo source: http://www.sonriselighting.com/docs/solar/
	Solar Path Lights Photo source: http://www.sonriselighting.com/docs/solar/
Ambient and Decorative Lighting Whether using candle-like light to set a romantic mood, or colored lighting to create an artistic statement, LEDs are excellently suited for the task and come in a variety of colors and price ranges. Most of the portable products are battery operated and come with a recharger. Following are a few examples of LED products and systems that provide energy efficient, safe, mood enhancing light.	
	Color Changing Light Panels Photo source: http://www.lumileds.com/

	Flickering LED "Candles" with Recharger Photo source: http://www.nam.lighting.philips.com/us/ssl/display.php?mode=4
	LED Flickering Candle Lights Photo source: http://www.lightcrafters.com/

Resources

There are several sites that provide general information about LEDs. These are listed below. Some of the leading SSL manufacturers and products and services companies are also listed below. Industry groups including standards organizations are also listed.

General Information on SSL and LEDs

U.S. Department of Energy Solid State Lighting Program
http://www.netl.doe.gov/ssl/

DOE ENERGY STAR Program for Solid-State Lighting ENERGY STAR standards for SSL were released in Sept 2007 and will go into effect Sept 30, 2008
http://www.netl.doe.gov/ssl/energy_star.html

Standards Development for Solid State Lighting http://www.netl.doe.gov/ssl/standards_dev.html

DOE Technical Information Network for Solid-State Lighting (TINSSL)
http://www.netl.doe.gov/ssl/technetwork.htm

DOE Solid-State Lighting GATEWAY Demonstrations
http://www.netl.doe.gov/ssl/techdemos.htm

Fact Sheets on LED basics, applications, and metrics
http://www.netl.doe.gov/ssl/publications/publications-factsheets.htm

IESNA TM-16-05 IESNA Technical Memorandum on Light Emitting Diode (LED) Sources and Systems
http://www.nema.org/prod/lighting/solid/upload/IES-LED-Doc-TM16.pdf

The Next Generation Lighting Industry Alliance (NGLIA formed in 2003 to foster industry-government partnership to accelerate the technical foundation, and ultimate commercialization, of solid state lighting systems.
http://www.nglia.org/

The Rensselaer Polytechnic Institute Lighting Research Center
http://www.lrc.rpi.edu/programs/solidstate/index.asp

A comprehensive resource of technical information on LEDs from research group of E. Fred Schubert at Rensselaer Polytechnic Institute
http://www.lightemittingdiodes.org/

Publishers of LightTimes Online
http://www.solidstatelighting.net/

LEDs Magazine
http://ledsmagazine.com/

http://www.photonics.com/

http://compoundsemiconductor.net/

LED Manufacturers and Products

The following list includes NGLIA members and other weel-known manufacturers. This is not an exhaustive list but is provided for information purposes.

3M http://solutions.3m.com/en_US/

Acuity Brands Lighting http://www.acuitybrands.com/

Air Products & Chemicals Inc. http://www.airproducts.com

CAO Group Inc.http://www.caogroup.com

Corning, Inc. http://www.corning.com/

Cree Lighting: http://www.cree.com/

Dow Corning Corporation http://www.dowcorning.com/

Eastman Kodak Company http://www.kodak.com

GE Lumination: http://www.lumination.com/

Light Prescriptions Innovators, LLC (LPI, LLC) http://www.lpi-llc.com/

LSI Industries http://www.lsi-industries.com/

OSRAM Sylvania, Inc. (Osram Opto-Semiconductors) http://www.osram-os.com/;

Philips Solid-State Lighting Solutions http://www.colorkinetics.com/

(Philips Luxeon/Lumileds): http://www.lumileds.com/

Qunano Inc. http://www.qunano.com/

RUUD Lighting, Inc. http://www.ruudlighting.com

Dialight: http://www.dialight.com/Products/SolidStateLighting.cfm

Lamina: http://www.laminaceramics.com

LED Product Competitions and Testing Results

DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) Program – tests products and provides results
http://www.netl.doe.gov/ssl/comm_testing.htm

http://www.netl.doe.gov/ssl/energy_star.html

DOE/Consortium for Energy Efficiency/American Lighting Association annual design competition for SSL
http://www.lightingfortomorrow.com/

LightFair International 2008 Trade Show and Conference May 28-30, 2008 Las Vegas.
http://www.lightfair.com/lightfair

LightFair 2007 Innovation Award Winners
http://nps.elumit.com/

Examples of Some LED Home Lighting Products and Services

Again, this is not an exhaustive list and inclusion does not imply endorsement but it is an example of some of the companies offering products as of mid 2008.

Albeo Technologies: http://www.albeotech.com/

CAO Group, Inc.: http://www.caogroup.com/SSL/

ETG Corp: http://www.etgtech.com/

FiberMagic: http://www.fibermagic.com/

Gilway Technical Lamp: http://www.gilway.com/

Hess America: http://www.hessamerica.com

Holly Solar Products/Suntronics: http://www.hollysolar.com/

LED Lighting Supply: http://ledlightingsupply.com (Eastern US)

The LEDlight: http://www.theledlight.com/

LEDtronics: http://www.ledtronics.com/

MCD Electronics Incorporated: http://www.mcdelectronics.com/

Permlight: http://www.permlight.com/

SemiLEDs: http://www.semiphotonics.com/

Tri North Lighting: http://trinorthlighting.com

Waldmann Lighting: http://www.waldmannlighting.com/

Xenon Light: http://www.xenonlight.com/

Industry Groups

The Illuminating Engineering Society of North America: http://www.iesna.org/

International Association of Lighting Designers: http://www.iald.org/

National Electrical Manufacturers Association: http://www.nema.org/

Next Generation Lighting Industry Alliance: http://www.nglia.org/

Optoelectronics Industry Development Association: http://www.oida.org/

References

U.S. Department of Energy. 2008a. *DOE Multi Year Program Plan FY 08-13, Solid-State Lighting Research and Development*, prepared for the U.S. Department of Energy by Navigant Consulting, Inc. and Radcliffe Advisors, Washington DC, available at http://www.netl.doe.gov/ssl/publications/publications-techroadmaps.htm

U.S. Department of Energy. 2008b. *DOE Solid-State Lighting CALiPER Program Summary of Results: Round 4 of Product Testing,* DOE Building Technologies Program, Energy Efficiency and Renewable Energy, Washington DC, available at http://www.netl.doe.gov/ssl/PDFs/CALIPERROUND4summaryFINAL.pdf.

Glossary

Aluminum Indium Galium Phosphide (AlInGaP) - Semiconductor material used to make LEDs. LEDs made with mixtures of these elements produce red and amber light.

Aluminum Indium Gallium Nitride (ALInGaN) - Semiconductor materials used to make LEDs. LEDs made with mixtures of these elements produce blue, green, and white light.

Ambient lighting - Lighting throughout a general area.

Application efficiency – While there is no standard definition of application efficiency, we use the term here to denote an important design consideration: that the desired illuminance level and lighting quality for a given application should be achieved with the lowest practicable energy input. Light source directionality and intensity may result in higher application efficiency even though luminous efficacy is lower relative to other light sources.

Candela - The unit of luminous intensity emitted in a specific direction by a source, equal to one lumen per steradian. For example, a source with luminous intensity of 1 candela would provide one footcandle of illuminance on a surface one foot away.

Color Rendering Index (CRI) - CRI indicates how well a light source renders colors, on a scale of 0 to 100, compared to a reference light source with 100 being identical to the reference source. The test procedure established by the International Commission on Illumination (CIE) involves measuring the extent to which a series of eight standardized color samples differ in appearance when illuminated under a given light source, relative to the reference source. The average "shift" in those eight color samples is reported as Ra or CRI. In addition to the eight color samples used by convention, some lighting manufacturers report an "R9" score, which indicates how well the light source renders a saturated deep red color. Incandescents have a CRI close to 100, CFLs 80+, LEDs 70-90. CRI is not the best descriptor of LED color quality especially for white light from RGB LEDs. Research is being conducted to find a better color rendering scale for LEDs.

Conduction – transfer of heat through matter by communication of kinetic energy from particle to particle. An example is the use of a conductive metal such as copper to transfer heat.

Convection – heat transfer through the circulatory motion in a fluid (liquid or gas) at a non-uniform temperature. Liquid or gas surrounding a heat source provides cooling by convection, such as air flow over a car radiator.

Correlated Color Temperature (CCT) - a measure of the color appearance of a white light source. CCT describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white. CCT is given in Kelvin (SI unit of absolute temperature) and refers to the appearance of a theoretical black body heated to high temperatures. As the black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source is the temperature (in K) at which the heated black body matches the color of the light source in question. Incandescents typically have a CCT of 2700K, CFLs have a CCT of 2700-3000K, warm white LEDs have a CCT of 2500-3500m, cool white LEDs have a CCT of 3500-5000L.

Die - A small piece of semiconductor material that is the active light emitting component in LEDs.

Diode **-** Usually a semiconductor device that conducts electric current in one direction only.

Efficacy - A measure of the luminous efficiency of a light source; efficacy is the quotient of the total luminous flux emitted by the total power input (usually expressed in lm/W).

Efficiency or efficacy? – The term “efficacy” normally is used where the input and output units differ. For example in lighting, we are concerned with the amount of light (in lumens) produced by a certain amount of electricity (in watts). The term “efficiency” usually is dimensionless. For example, lighting fixture efficiency is the ratio of the total lumens exiting the fixture to the total lumens produced by the light source. “Efficiency” is also used to discuss the broader concept of using resources efficiently.

Heat sink – thermally conductive material attached to the printed circuit board on which the LED is mounted. Myriad heat sink designs are possible; often a “finned” design is used to increase the surface area available for heat transfer. For general illumination applications, heat sinks are often incorporated into the functional and aesthetic design of the luminaire, effectively using the luminaire chassis as a heat management device. Source: Enlux

Illuminance - Density of the luminous flux incident at a point on a surface. It is the quotient of the luminous flux divided by the area of the surface when the surface is uniformly illuminated.

Junction temperature (Tj) – temperature within the LED device. Direct measurement of Tj is impractical but can be calculated based on a known case or board temperature and the materials’ thermal resistance.

LCD - Liquid crystal display.

LED – light-emitting diode.

LED array - Clusters of LEDs assembled into a mechanical surface.

LED driver - LED drivers effectively provide the same function as ballasts in fluorescent and high-intensity discharge products. Drivers regulate power to the LED, thereby controlling the brightness or intensity of the LED. The driver system converts the supply voltage to a DC voltage and provides a DC output current to the LED. It holds the current at constant level/output over variable supply voltage ranges.

Life performance curve – a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) throughout the life of the source. Also called lumen maintenance curve. Source: Rea 2000

Light Emitting Diode (LED) **-** A solid-state semiconductor that converts electrical energy into visible light.

Lumen – the SI unit of luminous flux. The total amount of light emitted by a light source, without regard to directionality, is given in lumens.

Lumen depreciation - the decrease in lumen output that occurs as a lamp is operated.

Lumen, lm - The SI unit of luminous flux, equal to the luminous flux emitted per unit solid angle by a standard point source having a luminous intensity of one candela.

Luminaire efficacy – the total luminous flux emitted by the luminaire divided by the total power input to the luminaire, expressed in lm/W.

Luminance - Density of luminous flux leaving a surface in a particular direction. It is the quotient of the luminous intensity of the source in direct measurement by the projected area of the source in the direction.

Luminous efficacy – the total luminous flux emitted by the light source divided by the lamp wattage; expressed in lumens per watt (lm/W).

Luminous intensity - A measure of the directional quantity of light expressed in candelas. It is defined as luminous flux per unit solid angel in a given direction.

N-type semiconductor - A semiconductor that has an excess of conduction electrons. Adding trace amounts of other elements to the original semiconductor crystal produces it.

OLED - Organic light emitting diode. A light-emitting device built with organic plastic semiconductors.

PC – phosphor conversion. White light can be produced by a blue, violet, or near-UV LED coated with yellow or multi-chromatic phosphors. The combined light emission appears white.

p-n junction - The actual junction of the two types of semiconductor materials used in the construction of the LED die.

P-type semiconductor - A semiconductor that has an excess of conducting holes. Adding trace amounts of other elements to the original pure semiconductor crystal produces it.

Radiation – energy transmitted through electromagnetic waves. Examples are the heat radiated by the sun and by incandescent lamps.

Rated lamp life – the life value assigned to a particular type lamp. This is commonly a statistically determined estimate of average or median operational life. For certain lamp types other criteria than failure to light can be used; for example, the life can be based on the average time until the lamp type produces a given fraction of initial luminous flux.

RGB – red, green, blue. One way to create white light with LEDs is to mix the three primary colors of light.

SSL – solid-state lighting; umbrella term for semiconductors used to convert electricity into light.

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