fundamentalseries10

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Current thinking on...

Solid-state lighting (LED lighting)

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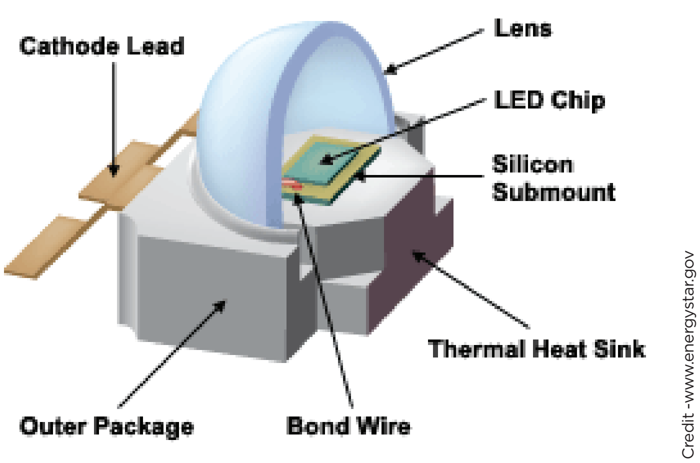
The term solid-state lighting refers to the use of semiconductor light-emitting diodes (LEDs), organic light-emitting diodes (OLED) or light-emitting polymers for lighting applications. Unlike incandescent or fluorescent lamps, which create light with filaments and gases encased in a glass bulb, solid-state lighting uses semiconductors to convert electricity into light.

LEDs have been around for nearly 50 years and over the last couple of decades have found application firstly as indicator lamps and then in signal devices such as traffic lights and exit signs. Recent years has seen the rapid advancement of LED technology specifically for general domestic and commercial illumination applications.

Improved performance and reduced cost has led to a significant increase in the number and variety of market-available LED lighting products. In fact an internal marketing study by a global lighting manufacturer estimated that whilst LEDs only accounted for 7 per cent of the total lighting market in 2008 this would grow to 75 per cent by 2020. An earlier study for the US Department of Energy predicted a lower but significant market share for LEDs of 50 per cent by 2027.

Figure 1: Power LED for general illumination



Greater life cycle savings

While the development of lighting technology such as T5 fluorescent tubes, electronic ballasts, CFLs and high intensity discharge lamps has made possible significant reductions in the lighting energy consumption solid state light sources technology is seen by many as having the potential to deliver greater energy and life cycle cost savings. LED technology may also enable new approaches to lighting to be developed with perhaps entire walls and ceilings becoming the lighting source.

A BRE publication1 concludes that solid-state lighting using LEDs is set to radically alter the profile of lighting and has the potential to deliver substantial energy savings but that LEDs vary in their properties: light output and colour quality can vary substantially between manufacturers and sometimes in different ranges from the same manufacturer. To ultimately meet its potential as an energy-saving technology and achieve widespread market penetration, LED technology has a number of hurdles to overcome including continued improvement in light output and colour quality as well as reduced costs.

This CPD module covers the basic characteristics of LED lighting so that LED performance between different manufacturers can be evaluated and compared against traditional light sources.

LEDs differ from traditional light sources in the way they produce light. In an incandescent lamp, a tungsten filament is heated by electric current until it glows or emits light. In a fluorescent lamp, an electric arc excites mercury atoms which emit ultraviolet (UV) radiation and after striking a phosphor coating on the inside of a glass tube the UV radiation is converted and emitted as visible light.

A light-emitting diode, in contrast, consists of a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction. When connected to a power source, current flows from the p-side or anode to the n-side, or cathode, but not in the reverse direction. Charge-carriers (electrons and electron holes) flow into the junction from electrodes. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).

The specific wavelength or colour emitted by the LED depends on the materials used to make the diode, for example red LEDs are made from aluminium-gallium-arsenide, blue from indium-gallium-nitride and green from aluminium-gallium-phosphide.

Making white light

There are currently two ways to make white light with LEDs. One method mixes wavelengths from red, green and blue LEDs to make white light. The second, and the more common method, uses a blue LED with a phosphor coating.

Organic Light Emitting Diodes (OLEDs) comprise sheets of carbon-based compounds that glow, when a current is applied through transparent electrodes, to provide a large surface of diffuse light. The cathodes used in an OLED are very sensitive to moisture so the devices are generally sandwiched between protective glass layers although flexible plastic substrates are being developed. While not yet market ready OLEDs could function like a thin film on a wall or ceiling to provide illumination.

LEDs and OLEDs require a constant current power source to provide the correct DC voltage and current from the mains supply. A LED lamp or luminaire is, therefore, a combination of one or more LED modules, a driver, heat sink and optical components to modify the distribution of the light together with a protective case.

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Light output from a source (luminous flux) is measured in lumen (lm), which is a measure of the power of light perceived by the human eye. Luminous efficacy is measured in lumens per watt (lm/W) - see definitions in the box below.

Definition of terms

Efficacy: This term is used where the input and output units differ. For example in lighting we are concerned with the amount of light (lumens) produced by a certain electricity input (watts). The term efficiency is usually dimensionless for example the light fixture efficiency is the ratio of the total lumens exiting the fixture to the total lumens produced by the light source.

Lumen (lm): Is the SI unit of luminous flux and is the total amount of light emitted without regard to directionality.

Luminous efficacy: Is the total luminous flux emitted by the luminaire divided by the total power input and is expressed in lm/W.

LEDs require a power supply (commonly called a driver) to convert (AC) power to the appropriate DC voltage (typically 2 to 4 volts) and current (typically 350mA to 1,000mA) and may include supplementary electronics to control changes in light output and colour or for dimming purposes. LED drivers are typically 85 per cent efficient which means that the LED efficacy must be discounted by up to 15 per cent to account for these losses.

A comparison of the approximate luminous efficacies for traditional sources (including ballast losses where applicable) is shown in Table 1. This can be compared to the current eligibility criteria for LED luminaires listed on the Energy Technology List of the Government's Enhanced Capital Allowance Scheme. As an example for white light down light LED luminaires a minimum luminaire efficacy of at least 60 lumens per circuit watt is required.

The electrical power consumed (circuit watts) is defined as the total power consumed by the whole lighting unit from main circuit connection point to 'LED module', including losses in the power supply and constant current source and losses due to the effects of temperature. It is not the 'rated wattage' of the LED chip. The product must also perform at the minimum required efficacy at each drive current for which the product is designed to operate, when tested after 100 hours of continuous operation.

Table 1: Typical luminous efficacy of different light sources (including ballast where appropriate)

Light source	Typical luminous efficacy range (lm/W)
Incandescent	10 - 18
Halogen	15 - 20
Compact fluorescent (CFL)	35 - 60
Linear fluorescent	50 - 100
Metal halide	50 - 90

Source: Reference 1

Luminous flux is measured and quoted by lighting manufacturers for all types of lighting product but this is not straightforward for LED sources because the LED light output varies with a number of factors. For example the LED can be driven at a range of currents (typically 350mA). Higher currents give a greater light output but can reduce efficacy and LED lifetime. The light output of a LED is also sensitive to the LED junction temperature. These aspects of LED performance are discussed later in this module.

Efficacy of the LED

The luminous efficacy of the LED module accounting for the driver efficiency is an indicator of the efficacy of the LED lamp itself but overall efficacy of the luminaire is a function of additional factors such as optical losses and is of greater importance.

In fact the Government's consultation document for potential changes to the 2013 revision to Part L of the Building Regulations may make efficacy of the entire luminaire the criteria for compliance rather than the current requirement for a minimum efficacy of the lamp. Alternatively compliance may be based on the predicted energy consumption of the luminaire in operation using a methodology known as the Lighting Energy Numerical Indicator.

All light sources convert electricity into radiant energy and heat in various proportions as shown in Table 2.

LEDs generate little or no IR or UV, but convert only 20 per cent-30 per cent of the power into visible light; the remainder being heat that must be conducted from the LED die to the underlying circuit board and heat sinks.

Thermal management is arguably the most important aspect of successful LED lighting design. The key factor is the temperature at the LED junction which is affected by the drive current, the heat sink design and the ambient temperature which dictates the rate of heat dissipation. In general, the higher the drive current, the greater the heat generated at the LED die and this must be removed to maintain the expected light output, life and colour.

Temperature directly affects both short-term and long-term performance of a LED. The short-term (reversible) effects are colour shift and reduced light output while the long-term effect is accelerated lumen depreciation and thus shortened useful life. The light output of different coloured LEDs varies differently with increasing temperature as shown in Figure 2.

LEDs are tested during the manufacturing process under conditions that may differ from actual operating conditions in a lighting fixture. In general, luminous flux is measured under instantaneous operation (typically a 350mA pulse for 20ms in open air conditions). The manufacturer then sorts (bins) LEDs according to luminous flux and colour performance from this test. However, under constant operation at room temperature the junction temperature will be higher. White LEDs in a well-designed luminaire with adequate heat sinking can produce 10 per cent-

Table 2: Power Conversion for "White" Light Sources

	Incandescent (60W)	Fluorescent (Typical linear)	Metal Halide	LED[1]
Visible light	8 per cent	21 per cent	27 per cent	20-30 per cent
Infrared	73 per cent	37 per cent	17 per cent	~0 per cent
Ultraviolet	0 per cent	0 per cent	19 per cent	0 per cent
Total radiant energy	81 per cent	58 per cent	63 per cent	20-30 per cent
Conduction & convective heat	19 per cent	42 per cent	37 per cent	70-80 per cent
Total	100 per cent	100 per cent	100 per cent	100 per cent

Source: Reference 1
Note 1 Varies depending on LED efficacy. This range represents best current technology in colour temperatures from warm to cool.

15 per cent less light than indicated by the manufacturer's typical luminous flux. The reduction in light output for products with poor thermal design can be significantly higher.

Continuous operation of a LED at an elevated temperature, in addition to reducing light output, also accelerates the rate of lumen depreciation resulting in shortened useful life. Testing2 in the US demonstrated that the estimated life (defined as life to 70 per cent of the initial lumen output) reduced by 57 per cent with a junction temperature increase of 11°C from 63°C. However, it should be noted that LED manufacturers continue to improve the durability of LEDs at higher operating temperatures.

Light output declines

The light output from a LED slowly declines over time but it will continue to operate even after the light output has decreased to very low levels. The LED itself, therefore, has a long life expectancy and is unlikely to completely fail but the life and reliability of other essential components, such as the driver and control electronics, have to be factored in when considering luminaire life and reliability.

Life testing for LEDs is impractical due to the long lifetimes but the method gaining acceptance is based on the concept of useful life i.e. the operating time in hours at which the LED light output has declined to a level deemed to no longer meet the needs of the application.

For general lighting, research has shown that the majority of occupants in a space accept light level reductions of up to 30 per cent, particularly if the reduction is gradual. Therefore, a level of 70 per cent of initial light level could be considered an appropriate threshold to represent useful life. In this case the useful life, designated the L70 life, would be the average number of hours that the LED will operate before depreciating to 70 per cent of initial lumens. The leading LED manufacturers have started publishing using L70, L80 or L90 performance.

Electrical and thermal design of the LED system determines light output and LED life. Driving the LED at higher than rated current will increase relative light output but decrease useful life. Operating the LED at higher than design temperature will also decrease useful life significantly.

Standards for testing LED performance, such as light output over time at different junction temperatures, have been developed and manufacturers are beginning to publish such data allowing users and luminaire manufacturers to make informed choices.

Light that appears white is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. Conventional light sources radiate across the entire visible spectrum but with varying intensity at different wavelengths.

The typically "warm" colour appearance of an incandescent lamp is due to the relatively high radiant power in the orange and red regions of the spectrum. In contrast a LED is a near-monochromatic light source with an individual LED chip emitting light at a specific wavelength. This is why LEDs are efficient for coloured light applications but they are not inherently white light sources.

The lighting industry use colour temperature (or correlated colour temperature) to describe the relative colour appearance of a white light source. Colour temperature is measured in Kelvin 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 colour temperature of a light source is the temperature (K) at which the heated black body matches the colour of the light source.

LEDs with the highest efficacy and lowest cost tend to have a high colour temperature, often above 5000K, producing a "cold" bluish light which will not suit applications where a warm feel to the space is important. However, warm white LEDs (2600K to 3500K) are improving and now approach the efficacy of CFLs.

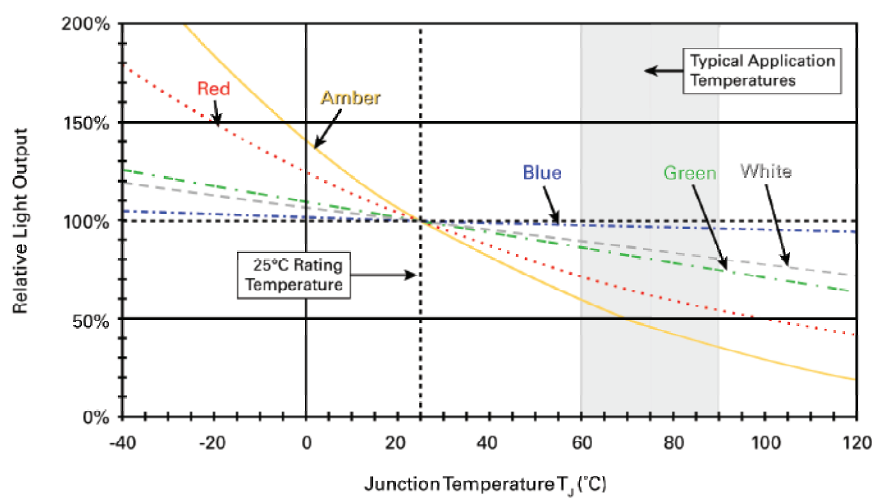
Another important measure of colour quality is the colour rendering index (CRI). Colour rendering is the ability of a light source to show surface colours as they should be. The CRI measures the colour quality of the source on a scale of 0 to 100, compared to a reference light source of similar colour temperature. A low CRI value indicates poor colour rendering and lamps with excellent colour rendering properties have CRI between 90 and 100. LED colour rendering is improving with leading warm white LEDs now available with colour rendering index of 80, equivalent to CFLs.

Although the LED chip is small and lightweight the sensitivity to operating temperature means that a relatively bulky and heavy heat sink is required to dissipate heat and this can impact on the lamp or luminaire size and design. However, as the industry develops LEDs of higher efficacy less heat will be generated meaning that smaller heat sinks will be required.

LEDs start instantly and switching does not significantly affect life which makes them suitable for occupancy type switching control. LEDs are normally straightforward to dim and in fact their efficacy can improve when dimmed as they run cooler.

This CPD module has covered the basic characteristics of LED lighting. The technology promises to deliver life cycle cost and carbon emission savings compared with traditional light sources but to ultimately meet its potential as an energy-saving technology and to achieve widespread market penetration continued improvement in performance and reductions in capital cost are required.

Figure 2: Effect of junction temperature on LED light output (Source Reference 1)



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This is the seventh module in the tenth series and focuses on LEDs. It is accompanied by a set of multiple-choice questions. To qualify for a CPD certificate readers must submit at least eight of the ten sets of questions from this series of modules to ***Energy in Buildings and Industry*** for the Energy Institute to mark. Anyone achieving at least eight out of ten correct answers on eight separate articles qualifies for an Energy Institute CPD certificate. This can be obtained, on successful completion of the course and notification by the Energy Institute, for a fee of £15 (for members) or £25 (for non-members).

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SERIES 10 MODULE 7: QUESTIONS

Solid-state lighting (LED lighting)

Please mark your answers on the sheet below by placing a cross in the box next to the correct answer. Only mark one box for each question. You may find it helpful to mark the answers in pencil first before filling in the final answers in ink. Once you have completed the answer sheet in ink, return it to the address below. Photocopies are acceptable.

1. Which of the following is a type of solid-state lighting?

☐ Fluorescent tube
☐ Light-emitting diode
☐ High intensity discharge lamp
☐ Compact fluorescent lamp

2. Which of the following produces white light?

☐ Red LED with phosphor coating
☐ Blue LED with phosphor coating
☐ Green LED with phosphor coating
☐ Amber LED with phosphor coating

3. Luminous efficacy is measured in what units?

☐ Lumens
☐ Watt
☐ Lumens/watt
☐ Lumens/m2

4. What is the minimum luminaire efficacy for a white light LED down light luminaire to be listed in the ECA Energy Technology List?

☐ 40 ☐ 50 ☐ 60 ☐ 70

5. What percentage of input power to a LED is converted to visible light?

☐ 20-30 ☐ 10-15 ☐ 30-40 ☐ 60-70

6. What is the efficiency of a typical LED driver?

☐ 65 per cent ☐ 75 per cent ☐ 85 per cent ☐ 99 per cent

7. For a LED operating at a temperature higher than its test temperature which is not true?

☐ Its colour may shift
☐ Light output will reduce
☐ Life will be shortened
☐ Light output will increase

8. Which of the following is not a characteristic of a LED with a colour temperature of ~5,000K?

☐ High efficacy
☐ Lowest cost
☐ Warm white light output
☐ Cold bluish light output

9. The life of a LED is reduced by which factor?

☐ Operating with a lower junction temperature
☐ Operating with a higher driver current
☐ Frequent switching on/off
☐ Operating in a lower driver current

10. Which colour LED has the most significant reduction in light output as junction temperature increases?

☐ Blue ☐ Green ☐ White ☐ Red