PDHonline Course E412 (4 PDH)

Energy Efficiency – LED Lighting

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Energy Efficiency LED Lighting

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Introduction

Lighting represents a significant portion of the total electrical energy consumption in the United States and Solid State Lighting (SSL) offers a way to reduce energy consumption. One form of solid state lights is LED lamps. An LED lamp is a solid-state lamp that uses light-emitting diodes (LEDs) as the source of light. The LEDs involved may be conventional semiconductor light-emitting diodes, organic LEDs (OLED), or polymer light-emitting diodes (PLED) devices, although PLED technologies are not currently commercially available.

It is estimated that switching to LED lighting over the next two decades could save $120 billion in energy costs, reduce the electricity consumption for lighting by 25%, and avoid 246 million metric tons of carbon emission.

Since the light output of individual light-emitting diodes is small compared to incandescent and compact fluorescent lamps, multiple diodes are often used together. In recent years, as diode technology has improved, high power light-emitting diodes with higher lumen output are making it possible to replace other lamps with LED lamps. One high power LED chip used in some commercial LED lights can emit 7,500 lumens for an electrical power consumption of 100 watts. LED lamps can be made interchangeable with other types of lamps.

Diodes use direct current (DC) electrical power; to use them from standard AC power they require internal or external rectifier circuits. LEDs are damaged by operating at high temperatures, so LED lamps typically include heat management elements such as heat sinks and cooling fins. LED lamps offer long service life and high energy efficiency, but initial costs are higher than those of fluorescent and incandescent lamps.

In this course we will look at the size of the U.S. lighting market, give an overview of the physics of lighting, the basics of LED lighting, and discuss how LED lamps may be used in residential and commercial applications. First, let’s look at the lighting market.

Chapter 1
The Lighting Market

This chapter discusses the size of the U.S. lighting market, recent changes in the market and describes lighting intensities by sector (residential, commercial, industrial, and outdoor lighting).

The total energy consumption in the United States is about 100 quadrillion BTUs (quads) of primary energy. Roughly 39 percent of this energy is consumed for electricity use.

For the purposes of this course, the lighting industry is divided into four sections:

1. Residential
2. Commercial
3. Industrial
4. Outdoor Lighting

Data in this chapter is derived from the latest edition of the DOE report "U.S. Lighting Market Characterization."

The total amount of electricity consumed by lighting technologies is estimated to be 641,000 GWh of site energy, or 6.9 quads of primary energy. Thus, lighting accounts for 7 percent of the total energy and 18 percent of the total electricity consumed in the U.S.

The residential sector accounts for the overwhelming majority of installed lamps, at 71 percent of installed base of lighting. However, in terms of electricity consumption, the sector only consumes 149,000 GWh, or 23 percent of the total. Due to the relatively low efficacy of residential light sources (primarily incandescent), the residential sector only accounts for 8 percent of the lumens produced.

The commercial sector is the greatest energy consumer, accounting for half of the total lighting electricity consumption. In addition, the commercial sector represents the sector in which the greatest number of lumens is produced. This is largely due to the longer operating hours found in the commercial sector as compared to the residential sector. Both the industrial and outdoor sectors make up a relatively small portion of the total installed stock of lamps, each approximately two percent. However, the use of high lumen output lamps and high operating hours result in these sectors consisting of greater shares of total electricity consumption and lumen production.

Residences account for 71 percent of all lamp installations nationwide, at 6.2 billion lamps. The commercial buildings sector is the second largest sector with 24 percent of all installations and 2.1 billion lamps. The outdoor and industrial sectors are significantly smaller, each accounting for roughly 2 percent of all lamps installed, 170 million and 260 million lamps, respectively.

With regard to average daily operating hours, while lamps in the commercial, industrial, and outdoor sectors typically are used for half the day (working hours for commercial and industrial sector lamps and night time hours for outdoor lamps) residential lamps are only used a couple hours a day on average. As for the average wattage characteristics, the residential sector average wattage of 38 watts per lamp represents the mix of low wattage, high efficacy CFLs and higher wattage, lower efficacy incandescent lamps installed in the sector. The commercial, industrial and outdoor sector's average wattages are characteristic of the high installed base of fluorescent lamps and high wattage high intensity discharge lamps. These inputs combined result in a total annual electricity use of U.S. lighting of 641,000 GWH, or approximately 18 percent of total U.S. electricity use.

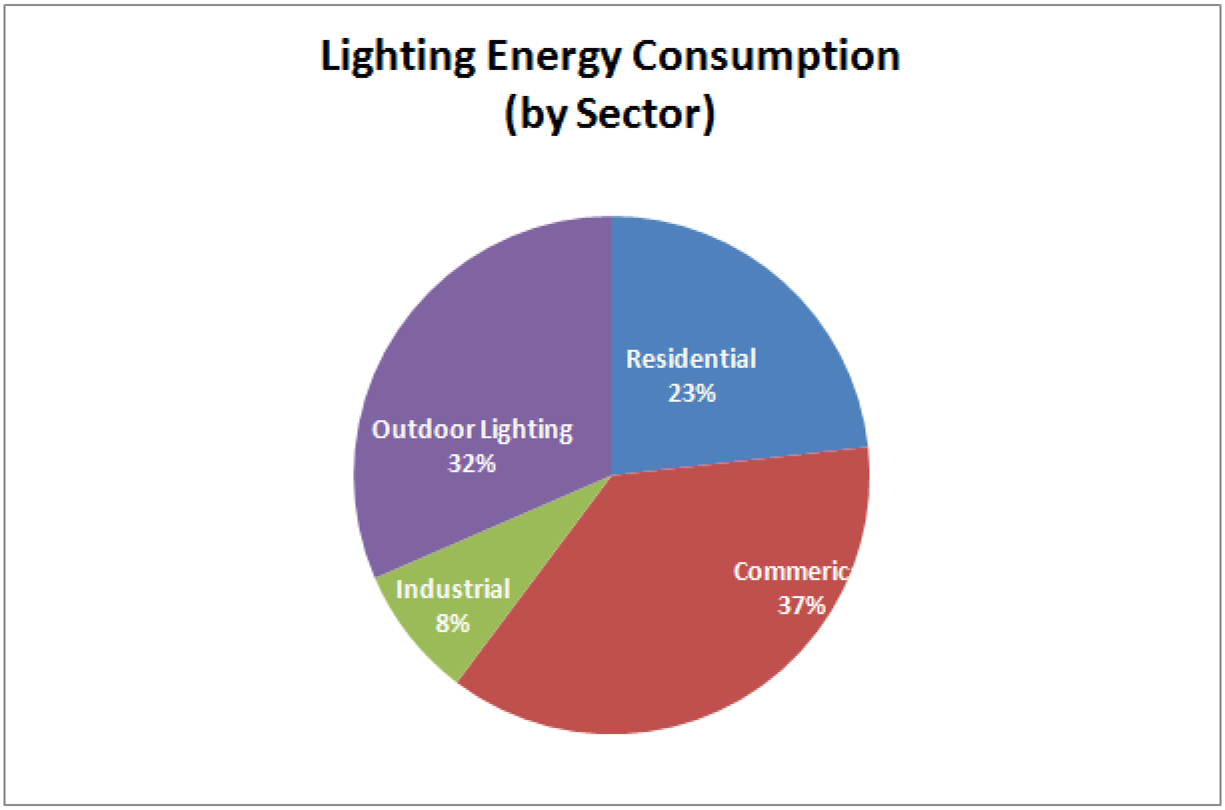


Figure 1

See Figure 1, we see that 37% of the lighting electricity is consumed in the commercial sector, which also represents the sector in which the majority of lumens are produced. This sector is dominated by linear fluorescent area lighting. Outdoor lighting follows at 32% and the residential sector, at 23%, is lower than past years due to CFLs and LED lighting though it still is responsible for 149,000 GWH per year.

The outdoor stationary sector accounts for the remainder of lamps not installed inside buildings. The outdoor subsectors are based on the application where the lamp is used. This includes lamps that may be associated with a specific commercial or industrial building but are installed on the exterior, such as parking lot lights or exterior wall packs.

Lighting Inventory and Energy Consumption Estimates

The light sources are grouped into six broad categories: incandescent, halogen, compact fluorescent, linear fluorescent, high intensity discharge, and solid state/other. Within each of these are subgroups of commonly available lighting products (e.g., reflector lamps, T8 fluorescent tubes, metal halide lamps). In total, 28 lamp types are included.

The lamp technologies have been categorized as displayed below in Figure 2.

Figure 2

While LED lighting had previously been limited to mostly niche applications, such as traffic signal lighting and exit lights. In recent years LEDs penetration into general illumination applications in the building sectors has grown.

There have been significant changes in the lighting stock and energy consumption characteristics during the past decade. Two notable trends include:

- Increased demand for light. The total number of lamps installed in U.S. applications grew from just under 7 billion in 2001 to over 8.7 billion in 2015. The majority of the growth occurred in the residential sector, primarily due to the increase in number of households and the rise in the number of sockets per household, from 43 in 2001 to 52 in 2015.

- Push towards higher efficacy lighting. Investment in more energy efficient technologies, lighting regulations, and public awareness campaigns has been effective in shifting the market towards more energy efficient lighting technologies. Across all sectors the lighting stock has become more efficient, with the average system efficacy of installed lighting increasing from 45 lumens per watt in 2001 to 58 lumens per watt in 2015. This rise in efficacy is largely due to two major technology shifts; the move from incandescent to compact fluorescent lamps (CFLs) and LED's in the residential sector, and the move from T12 to T8 and T5 fluorescent lamps in the commercial and industrial sectors.

The total installed base of lamps in 2015 was estimated to be 8.7 billion. This represents an overall growth of 17% in the past decade. In general, the bulk of lamp inventory growth has been in the residential sector, which accounts for more than double the number of lamps in the remaining sectors combined. The lamp inventory in the residential and commercial sectors have increased largely due to an increase in number of homes and floor space. In contrast, the industrial sector lamp inventory has decreased over the past ten years, mostly due to a reduction in manufacturing floor space and a movement toward higher lumen output technologies, such as HID. The outdoor sector has seen an increase relative to 2001.

In the residential sector, the most obvious trend is a transition from general service incandescent lamps (decreasing from 79 percent to 52 percent in 2010) to screw-base general service CFLs (increasing from 2 percent to 19 percent in 2010). In addition, there has been significant movement toward directional lamps (such as incandescent reflector, halogen reflector, and halogen low voltage display), which now comprise 10 percent of the residential installed base.

In the commercial sector, there has been a migration from T12 linear fluorescent lamps to T8 and T5 linear fluorescent lamps. In 2001, T8 lamps comprised less than 34 percent of the commercial installed base of linear fluorescent lamps, with the remaining base being overwhelmingly T12 lamps. In contrast, in 2015, T5s, T8s, and T12s constituted 7 percent, 61 percent, and 33 percent of the installed base of linear fluorescent lamps, respectively.

While the industrial sector depicts many of the same trends as the commercial sector, one unique trend is an increase in the prevalence of HID lamps, which doubled in share relative in the past decade. This movement from lower lumen output fluorescent lamps to higher lumen output HID lamps may also account for part of the reduction in overall number of lamps installed in the industrial sector. Although the data indicates a migration toward HID sources (likely in high bay applications), it is uncertain whether this trend will persist as fixture sales data indicates a recent increase of high lumen output linear fluorescent systems in the industrial sector, potentially replacing HID systems in low-bay applications.

The outdoor sector groups all incandescent, halogens, CFLs, and linear fluorescents in miscellaneous categories. This was done as many of the data sources used for the outdoor sector did not provide inventory detail beyond the general lamp technology level. The primary trend evident in this sector is a movement from mercury vapor lamps toward HPS, which now accounts for 32% of the installed base.

Table 1 presents the distribution of lamps by end-use sector. Linear fluorescent and incandescent lamps are estimated to comprise the majority of the installed base. While the overall shares of linear fluorescent and HID lamps have remained largely unchanged, incandescent lamp shares have decreased from 62 percent to 25 percent, while the CFL inventory shares have correspondingly increased from 3 percent to 25 percent and LED’s have captured approximately 8% of the market, all in the past decade.

Table 1
Lamp Inventory by Sector
(Percent)

Lamp Category		Residential	Commercial	Industrial	Outdoor	Total
Incandescent		**34.6**	**1.3**	**0.0**	**3.1**	**25.1**
	General – A type	12.5	0.1	0.0	0.0	8.9
	General – Deco	14.6	0.3.	0.0	0.0	10.4
	Reflector	6.9	0.2	0.0	0.0	5.0
	Miscellaneous	0.6	0.7	0.0	3.1	0.7
Halogen		**16.8**	**0.7**	**0.0**	**2.3**	**12.3**
	General Service	11.1	0.1	0.0	0.0	8.0
	General - Deco	0.6	0.0	0.0	0.0	0.4
	Reflector – Other	3.4	0.0	0.0	0.0	2.4
	Reflector – Low Voltage	1.0	0.5	0.0	0.0	0.8
	Miscellaneous	0.7	0.1	0.0	2.3	0.6
CFL		**33.2**	**8.0**	**0.2**	**4.3**	**25.7**
	General – Screw	0.5	3.9	0.1	0.0	1.3
	General – Pin	29.2	3.0	0.0	0.0	21.5
	Reflector	2.9	0.3	0.1	0.0	2.1
	Miscellaneous	0.7	0.8	0.0	4.3	0.8
Fluorescent		**8.2**	**78.1**	**89.8**	**21.2**	**26.9**
	T5	0.2	4.5	17.7	0.0	1.6
	T8 < 4ft	0.0	1.0	0.3	0.0	0.2
	T8 4ft	3.3	55.4	50.7	0.0	16.6
	T8 > 4ft	0.1	0.8	6.9	0.0	0.4
	T12 < 4ft	0.0	1.7	0.2	0.0	0.4
	T12 4ft	0.0	0.1	0.0	0.0	0.0
	T12 > 4ft	4.1	12.9	6.9	0.0	6.1
	T8 U-Shaped	0.3	1.2	5.9	0.0	0.6
	T12 U-Shaped	0.0	0.4	0.0	0.0	0.1
	Miscellaneous	0.0	0.3	0.9	21.2	0.7
HID		**0.0**	**1.2**	**5.7**	**41.4**	**1.6**
	Mercury Vapor	0.0	0.0	0.0	0.7	0.0
	Metal Halide	0.0	1.1	4.3	18.0	0.9
	High Pressure Sodium	0.0	0.0	1.4	22.4	0.7
	Low Pressure Sodium	0.0	0.0	0.0	0.4	0.0
	Miscellaneous	0.0	0.1	0.0	0.0	0.0
Other		**7.0**	**10.7**	**4.2**	**27.5**	**8.4**
	LED	6.7	10.5	4.0	22.8	8.0

	Miscellaneous	0.3	0.2	0.2	4..7	0.4
Total		**100%**	**100%**	**100%**	**100%**	**100%**

The following four sections examine the cumulative results for all lamp technologies by sector focusing on the subsector level results. Specifically, details on the installed base, average system wattage and operating hour characteristics of all lamps are evaluated by the defined subsectors within the residential, commercial, industrial and outdoor sectors.

Residential

> "Intensity Rank" is a measure of how much energy is expended per year per square foot of lighted space.

In the residential sector, the number of lamps grew faster than the growth in residences due to the larger floor space and a greater number of lamps per square foot in newer homes. However the prominence of CFLs and LED's caused a large decrease in average wattage. See Table 2. Single family housing has the highest *intensity rank* at 0.78 kWh/yr/ft^2.

Table 2
Lighting Use by Residence Type

	Floor Space	Wattage (Watts/Ft^2)	Energy Use (Kwh/yr)	Intensity (Kwh/yr./ft^2)	Intensity Rank
Single Family Detached	1,957	1.21	1,525	0.78	1
Multifamily	951	0.98	602	0.63	2
Mobile Homes	1,220	0.83	757	0.62	3

Commercial

In the commercial sector, food services have the highest intensity rank at 6.9 kWh/yr/ft^2.

The commercial sector uses more light than all the other sectors combined, largely due to its high average operating hours and large floor space. The outdoor sector produces second greatest amount of lumens, also due to the use of high lumen output lamps for long operating hours (in this case, during most of the night). The industrial sector uses the third most light. The residential sector, which houses the largest quantity of installed lighting stock predominately utilizes low lumen output lamps for relatively few hours per day and thus uses the least amount of lumens relative to the other three sectors.

Across all sectors, HID lamps, responsible for approximately 34 percent of annual lumen production nationally, produce the most lumens of all the technologies. Fluorescent light sources are the second most important, producing about 33 percent of the total national light output. Because incandescent lamps are most often found in sockets that are turned on relatively infrequently, and given their characteristically low lumen outputs, the total lumen production of the technology only accounts for 11 percent of the total. See Table 3.

Table 3

Lighting Use by Commercial Building Type

	Lamps per 1,000 ft^2	Wattage (Watts/Ft^2)	Energy Use (kWh/yr)	Intensity (kWh/yr/ft^2)	Intensity Rank
Education	38	1.4	117,100	3.7	3
Food Service	29	1.1	48,900	6.9	1
Food Store	24	0.7	15,700	3.3	6
Health Care Inpatient	17	0.5	471,200	2.0	11
Health Care Outpatient	19	0.6	22,700	1.9	12
Lodging	25	0.6	138,000	3.7	2
Offices	19	0.6	27,900	1.8	13
Other	24	0.8	44,900	2.8	8
Public Assy	21	0.8	40,400	2.6	9
Public Safety	17	0.7	60,500	3.5	4
Churches	30	1.0	19,500	1.8	14
Retail	20	0.8	59,700	3.2	7
Services	33	1.3	25,300	3.4	5
Warehousing	20	0.8	37,200	2.3	10

In the commercial sector, the installed lamp base has increased but this increase lagged the growth in commercial floor space.

Industrial Results

In the industrial sector, wood products have the highest intensity rank at 11.4 kWh/yr/ft^2 and textile product operations are second at 9.5 kWh/yr/ft^2. See Table 4.

Table 4

Lighting Use by Industrial Building Type

	Lamps per 1,000 ft^2	Wattage (Watts/Ft^2)	Energy Use (kWh/yr)	Intensity (kWh/yr/ft^2)	Intensity Rank
Apparel	14	1.0	74,400	4.0	13
Beverage	17	1.5	222,500	6.2	6
Chemicals	7	1.0	86,500	4.8	9
Electronics	7	0.3	85,200	1.6	21
Appliances	19	1.1	194,300	4.5	11
Metal Fabrication	12	1.2	178,700	5.7	8
Food	12	0.6	98,100	2.9	15
Furniture	19	1.3	276,400	6.3	5
Leather	14	1.0	67,100	2.3	18
Machinery	10	0.4	80,600	2.0	19
Miscellaneous	29	1.3	133,700	5.9	7
Mineral Products	25	0.9	60,300	3.8	14
Paper	11	0.6	125,400	2.6	17
Petroleum & Coal Products	14	1.0	32,800	4.5	10
Plastics & Rubber Products	7	0.5	160,000	2.7	16
Primary Metals	13	0.4	65,900	1.8	20
Printing	41	2.0	209,100	8.5	3
Textile Mills	58	1.9	581,500	7.7	4
Textile Products	33	1.8	292,000	9.5	2
Transportation	8	0.9	292,000	4.2	12
Wood Products	23	2.3	201,600	11.4	1

Outdoor Lighting

As can be seen in Table 5, parking and roadway lighting comprise the majority of outdoor lighting with metal halide (MH) and high pressure sodium (HPS) being the predominate lamp types.

Table 5
Energy Use by Outdoor Lighting
(000's GWH/yr)

	Incandescent	Halogen	CFL	Fluor. Tube	MV	MH	HPS	LPS	LED	Other	Total
Airport	0	0	0	0	0	0	0	0	0	0	**0**
Billboard	0	0	0	0	0	1	0	0	0	0	**1**
Bldg Ext.	1	1	1	6	1	18	5	0	1	0	**33**
Towers	0	0	0	0	0	0	0	0	0	0	**0**
Parking	1	2	0	1	0	61	19	0	13	6	**103**
Railway	0	0	0	0	0	0	0	0	0	0	**0**
Roadway	0	0	0	0	0	1	55	1	5	0	**63**
Sports	0	0	0	0	0	0	0	0	0	1	**1**
Traffic Signals	1	0	0	0	0	0	0	0	0	0	**1**
Total	**3**	**3**	**1**	**7**	**1**	**81**	**79**	**1**	**19**	**7**	**202**

Solid-State Lighting

Solid-state lighting is one of the most efficacious lighting technologies available. In 2001 SSL, specifically LEDs, was found in approximately 1.6 million lamps or installations, or less than 0.1 percent of the total installed base of lighting. The majority, nearly 90 percent, were exit signs in the commercial and industrial sectors. The remainder of the LED installations was in outdoor traffic signal applications. Over the last decade the installed base of LED lighting has grown to over 700 million lamps, luminaires, and exit signs. While this represents a 440 fold increase in installed lamps, LEDs still only represented approximately 8 percent of the total installed base of lighting. This section details several characteristics of the LED installations in the residential, commercial, industrial, and outdoor sectors.

It was estimated that in 2015 approximately 418 million LED lamps were installed in the residential sector, accounting for 6.7 percent of the installed inventory of residential lighting.

The outdoor sector has seen the greatest penetration and growth in LED lamps due largely to their long lifetime (low maintenance cost) and high efficacy (low operating cost). While in 2001 it was estimated that 97,000 LED lamps or luminaires were installed in the outdoor sector, this report estimates that in 2015 the outdoor installed base of LED lamps or luminaires grew to 59 million. Across the entire outdoor sector, LEDs comprised 23 percent of the installed stock and experienced far greater shares in certain individual subsectors. Similar to the 2001 analysis, traffic signals still represent the outdoor application in which LEDs have both the greatest percentage penetration (95 percent) and absolute number of installations. LEDs in parking and roadway applications have the next highest number of installed LED lamps or luminaires, representing three to four percent of lighting inventory in those applications.

Overall LED lamps consume approximately 19,000 GWh of electricity per year, constituting approximately 3% of national lighting energy use.

Lighting Controls

In recent years, lighting controls have garnered increased attention as a potential method of more intelligently operating lighting systems to save energy. Lighting controls, which include various dimming and sensor technologies used separately or in conjunction with other systems such as timers and daylighting, can, if used properly, yield very significant energy savings, as they use feedback from the lit environment to provide adequate lighting levels only when needed.

Lighting controls can save energy by either reducing input wattage or limiting hours of operation. The average operating hours presented in this report account for the use of certain controls, such as timers and Energy Management Systems (EMS), because they are based on building surveys and metering data.

The following discussion provides a brief description of each of the lighting control types examined in this study:

- Dimmers allow users to manually regulate the level of lighting in a building by adjusting the voltage reaching the lamp. As voltage input is reduced, either by way of a step function or a continuous function, the lumen output of the system is proportionally decreased.

- Light sensors, or photocells, also work by dimming or by on/off cycling. In response to detected light levels, light sensors regulate the lumen output in order to supplement available natural light with an optimized level of artificial lumen output.

- Motion detectors, or occupancy sensors, switch the lamp on for a set period of time in response to detected motion and are useful in areas that are sporadically occupied. This control type saves energy by reducing hours of operation of lighting.

- Timers provide lighting service on a preset schedule, without the need for manual operation. This control type also saves energy by reducing hours of operation.

- Energy management systems are information and control systems that monitor occupancy and lighting in the built environment in order to provide centralized lighting control. They often combine several of these control technologies to reduce energy consumption.

Lighting controls are more frequently installed in the commercial sector than in the residential, with an estimated 18 percent of lamps in the commercial sector being used in conjunction with lighting controls. This is in contrast to only 10 percent of residential lamps being used with lighting controls.

In contrast to the residential sector the likelihood of finding lighting controls in the commercial sector is not greatly impacted by the lamp type. Approximately 25 percent of all lamp types are used in conjunction with lighting controls. Energy management systems, which often include multiple control types, predominate as the most often utilized controls scheme.

The choice of lighting controls also depends on the building type and how and to what extent the space is used. In the commercial sector, lighting controls are most popular in retail settings, in which 40 percent of lamps operate on an EMS and 7 percent operate on a timer. Lighting controls are also very common in non-medical office buildings and food stores (i.e., not restaurants), where they are used on 48 percent and 40 percent of lamps, respectively. Lighting controls are uncommon in public order and safety, religious worship, lodging, and restaurants.

Lighting controls equate to energy savings only if they are used. For automated control types, such as time clocks and occupancy sensors, this is a nonissue. However, dimmers, the most popular control in the residential sector, typically require users to manually adjust the level of light output. Nonetheless, if used properly, light controls can yield huge energy savings. For example, a recent study found that occupancy sensing, daylight harvesting, and individual occupant dimming control working together in an office building produce average energy savings of 47 percent.

Chapter 2
Lighting Fundamentals

There are two theories about how light travels: wave theory and particle theory. The *wave theory* is most often used to describe the physics of light. According to the wave theory, light is a form of radiant energy that travels in waves. Visible light is a form of electromagnetic energy and like all electromagnetic energy travels at the speed of light and the electromagnetic flux spreads out from its source in waves. The effect is similar to the action created by throwing a pebble in a pond. Wavelength, λ, is the distance between the waves. The number of waves during a given period is known as the frequency. Frequency is equal to the speed of light divided by the wavelength and is measured in Hertz.

Another idea – called *particle theory* - is to consider light as groups of particles emitted by the light source. A ray of light consists of a stream of particles traveling in a straight line. The particles, or photons, vibrate at the frequency of the light.

Both the wave theory and the particle theory can be used to help explain lighting principles and there are advantages to using both theories of light to help gain an understanding of how light is produced and projected.

All forms of electromagnetic energy have a characteristic frequency. Visible light is a narrow band between ultraviolet (UV) and infrared energy on the electromagnetic spectrum. Actually, ultraviolet and infrared energy are considered light because they behave like visible light and both are present when visible light is present. Electromagnetic waves in this frequency band can be focused, reflected and absorbed. See Figure 3.

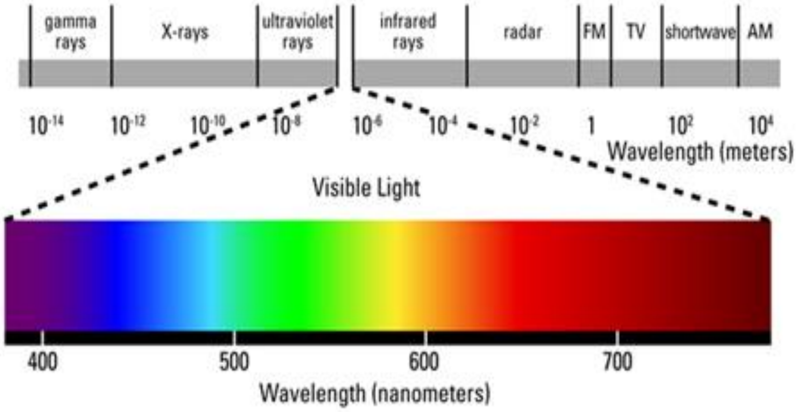


Figure 3

Light is comprised of all wavelengths within the visible portion of the electromagnetic spectrum. The relative balance of the different wavelengths, each corresponding to a distinct color, determines the tint of the light. Color temperature is the measurement used to describe the tint of light.

Measurement of Light

The measurement of light, or *Photometry*, requires knowledge of basic lighting terms. The measurement of light is based on the light output of a candle. Lumen, illumination, foot-candle, candela, exitance, inverse square law, and the cosine law are important terms in the study of lighting.

A *lumen* is the unit used to describe the quantity of light radiated from a light source. Technically, a lumen is the amount of luminous flux (light output) of light radiated into a solid angle of one steradian by a uniform light source of one candela. (A steradian is a unit solid angle subtending an area on the surface of a sphere equal to the square of the sphere radius.) See Figure 4.

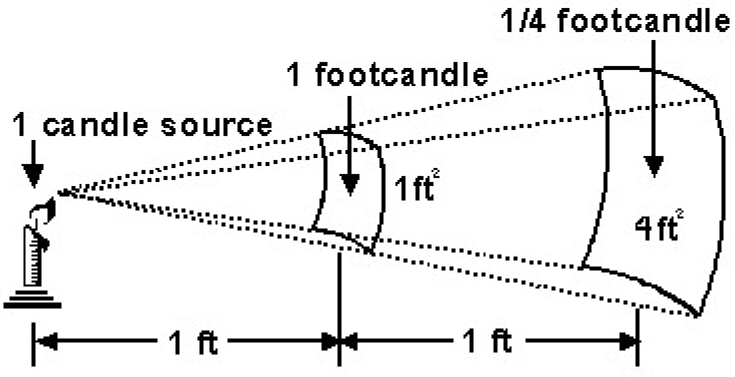


Figure 4

When luminous flux falls upon a surface, it is illuminated, and the effect is called *illumination*. This luminance is the perceived brightness of a light source. The unit of illumination is the *foot-candle* and is equal to a flux density of one lumen per square foot. Illuminance does not account for any of the reflective or transmissive properties of the surface but merely the amount of light the surface receives. One lumen uniformly distributed over 1 square foot produces an illumination of one foot-candle (fc).

$$\mathbf{FC = 1\ lumen/ft^2}$$

A *candela* is the unit of luminous intensity emitted by a light source in a given direction and is used to describe the directionality and intensity of light leaving a luminaire.

Exitance is a term that is used for relative brightness calculations. Exitance measures the total amount of light that leaves a reflective surface, measured in lumens per square foot. Exitance is determined by multiplying the Illuminance (fc) times the reflectance of a surface. Only diffuse, and no specular, reflection is assumed. For example, a 50 foot-candle illuminance on a surface of 90% reflectance will produce an exitance of 45 foot-candles.

Illumination from a single, or point, source behaves according to the inverse square law. The *inverse square law* expresses the relationship between luminous intensity (in candelas) and illumination (brightness). It states that illumination at a point on a surface is directly proportional to the luminous intensity of the light at that point and inversely proportional to the square of its distance from the source. When the point is on a surface perpendicular to the light, the following formula applies:

$$\mathbf{E = fc = Cd / D^2}$$

Where,
E = Illumination.
Fc = foot-candles.
Cd = Candela directed toward the point of interest.
D = Distance form light source to the point of interest.

Referring back to Figure 4 for a sample calculation, assume that a source has 1-candela and is 2-feet from the point of interest. The illumination is:

$Fc = 1 / 2^2$

$Fc = ¼$.

As can be seen from the above formula, the lumens per square foot decreases inversely with the square of the distance. At a distance of one foot from a source of one candela the illumination is one foot-candle.

A beam of light striking a surface at an angle covers a larger area than when the light strikes a surface on the perpendicular. The *cosine law* states that the illumination of a surface is proportional to the cosine of the angle of incidence of the ray of light. See Figure 5.

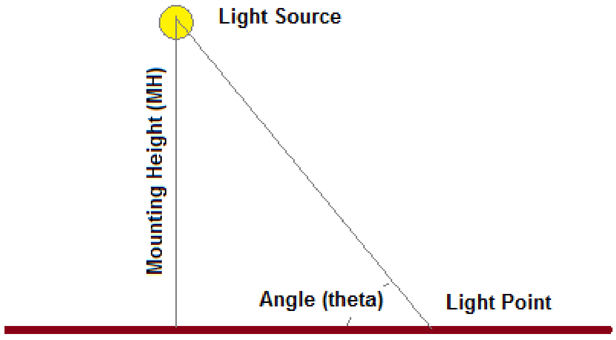


Figure 5

Considering the cosine law, the inverse square law becomes:

$$\mathbf{Fc = Cd/D^2 \times \cos(\alpha)}$$

As an example, if we have 5,000 candela at a distance of 12 feet and the point of interest is 30 degrees from the source the illumination will be:

$Fc = 5{,}000 / 12^2 \times \cos(30)$

$Fc = 35 \times 0.866$

$Fc = 30.$

Optical Characteristics of Light

When light strikes a surface one of three actions will occur: the surface can absorb the light, the surface will reflect the light, or the light will be transmitted through the surface. Transmitting surfaces will exhibit all three traits. Opaque surfaces do not transmit light, but they still have absorptive and reflective properties.

The reflection and transmission of light are important in the design of lighting materials and in predicting lighting levels in a space. The term *transmission*, quantifies the amount of light passing though light fixture lenses and diffusers.

Opaque materials reflect light by both specular reflection and by diffuse reflection. *Specular reflection* occurs when light is reflected at a consistent angle from a surface. The reflected light from a mirror is a good example of specular reflection. Specular distribution is a measure of the reflected light and is expressed as a percentage of the light striking the surface. See Figure 6.

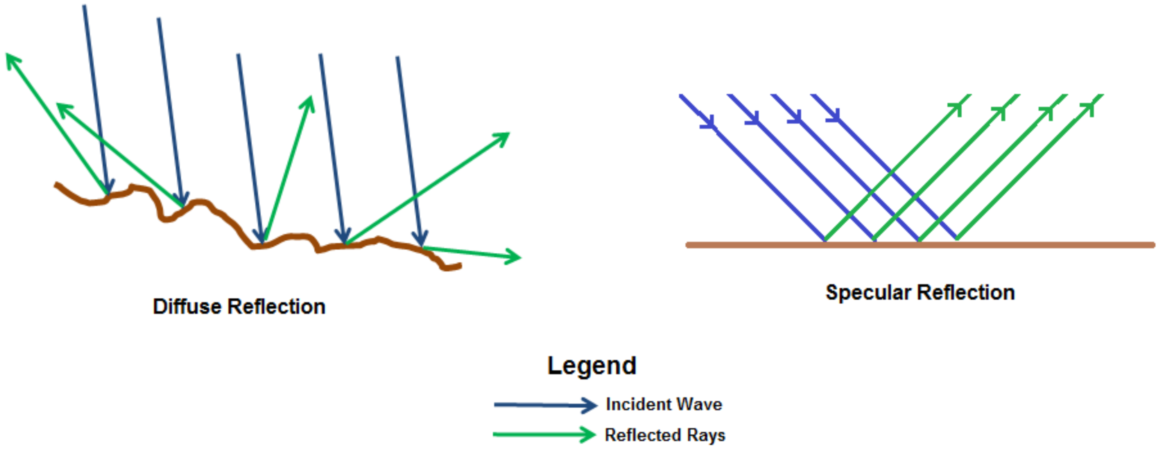


Figure 6

Diffuse reflection scatters reflected light in all directions such as when light reflects from a rough surface. Light reflecting off walls is a good example of diffuse reflection. A glossy paint on a wall is said to be a low diffuse reflector, whereas, a flat paint is said to be almost perfectly diffuse. Like specular reflection, diffuse reflection is expressed as a percentage of diffusion. White ceiling paint has about 85% diffuse reflection. Remember, a high percentage of diffusion means the surface scatters light very efficiently. Diffuse reflection is used to minimize glare, hot spots, and shadows. Most materials exhibit both specular and diffuse reflection and the total reflection is the sum of the specular and diffuse reflections.

Light can be transmitted through both transparent and translucent materials. *Transparent* materials, such as clear plate glass, allow virtually all of the light to move through the material unimpeded and, with very little bending of the light ray. Transparent materials allow objects to be viewed through the material. *Translucent* materials, such as frosted glass, also transmit light but the light is diffused or scattered. Translucent materials transmit light by diffuse transmission and objects are not seen distinctly through it because the light rays are bent as they pass through the material.

Diffuse transmission, such as occurs through frosted glass scatters incoming rays of light in all directions. This is useful is evenly distributing the output of a light source such as a frosted incandescent bulb.

The ratio of light transmitted through a material to light striking a surface is called *transmittance*. Most materials exhibit some qualities of both transparency and translucency.

Refraction causes light rays passing through one material to enter into another material at a different angle and intensity. This bending, or refraction, is important in the design of lighting fixtures.

Lenses use the principles of diffusion and refraction to cause light to travel in a desired direction. Common lens types include plano, concave, convex, fresnel, and diffusing lens. *Plano* lenses are simply flat plate lenses. *Concave* lenses allow light rays to spread while *convex* lenses focus light. A fresnel lens is a special form of either a concave or convex lens. A *fresnel* lens is specially cut to produce a desired focus or spreading of the light rays and can be manufactured to be lighter than a corresponding concave or convex lens. *Diffusing* lenses are used to broadly distribute light and to soften the intensity of the light source.

Chromaticity

Chromaticity is expressed by the Correlated Color Temperature (CCT). *Correlated Color Temperature* (CCT) is a metric that relates the appearance of a light source to the appearance of a theoretical black body heated to high temperatures. As a black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source, given in Kelvin (K), is the temperature at which the heated black body most closely matches the color of the light source in question. It characterizes the color of the emitted light, not the color of illuminated objects. The chromaticity is measured on a Kelvin (K) temperature scale with the high temperatures representing “cooler” light sources. Color temperatures below 3,500K are considered warm, with red, yellow, and orange tints. Color temperatures above 5000K are saturated in green and blue wavelengths lending to the “cool” designation. As a reference, a candle flame has a color temperature of 1,800K and an incandescent lamp has a color temperature of about 2,700K. Daylight has a CCT of at least 5,500K. See Table 6.

Table 6

Color Temperature Examples

Color Temperature	Example
2,000k	Gaslight
2,500k	60w incandescent
2,700k	100w incandescent
3,400k	Halogen
42,00k	Natural outdoors – Moonlight
7400k	Natural outdoors – Cloudy

30,000k	Natural outdoors – Noon sun

Like many color appearance metrics, CCT distills a complex spectral power distribution to a single number. This can create discord between numerical measurements and human perception. For example, two sources with the same CCT can look different, one appearing greenish and the other appearing pinkish. To address this issue, the American National Standards Institute (ANSI) references *Duv* - a metric that quantifies the distance between the chromaticity of a given light source and a blackbody radiator of equal CCT. ANSI has established Duv tolerances for LED lighting products producing white light.

Today's LED systems can produce white light throughout the range of CCTs typically used in general lighting, including both interior and exterior applications. Due to differences in quantum efficiencies, higher-CCT LED sources tend to be more efficacious than lower-CCT alternatives within the same product family. Some mixed or hybrid LED products feature independent control of the different components to allow for dynamic adjustment of CCT.

At least three aspects of color rendition are relevant to light source selection and application. These include the accurate rendition of colors so that they appear as they would under a familiar source, the rendition of colors such that objects appear more pleasing, and the ability of a source to allow for a subject to distinguish between a large variety of colors when viewed simultaneously. For simplicity, these three facets of color rendering may be called *fidelity*, *appeal*, and *discrimination*. The relative significance of these different elements of color rendition depends on the application.

Color rendition metrics attempt to characterize human perception of one or more of these elements using numerical methods, but they are not perfect. Some of the imperfections of well-established metrics have been revealed by the emergence of LED lighting products, which often have spectral power distributions that are different from those that were common when the metrics were developed.

The International Commission on Illumination (CIE)'s *Color Rendering Index* (CRI) is a measure of fidelity (i.e., how "true" a light source is when compared to the reference source), but it does not address the other two aspects of color rendering listed above: appeal and discrimination.

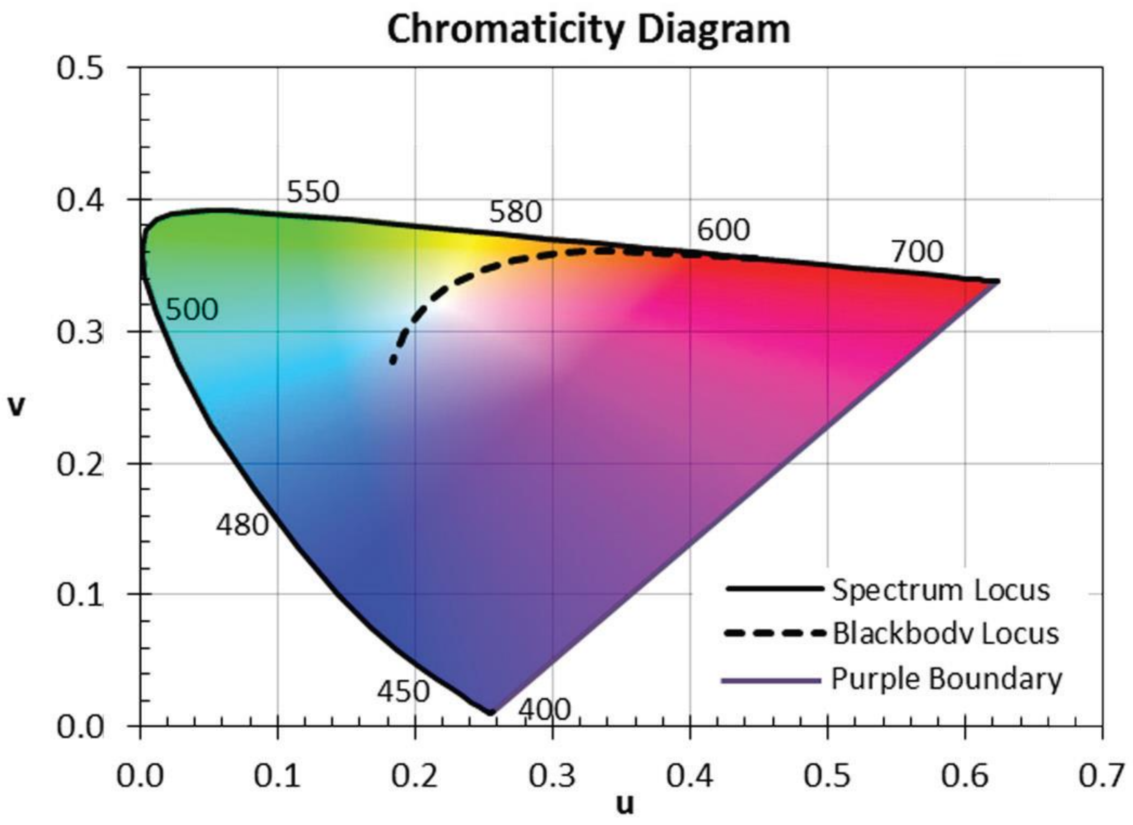


Figure 7

Figure 7, shown above is a CIE 1960 (u, v) chromaticity diagram in which CCT, CRI, and Duv are calculated. A chromaticity diagram should not be interpreted as a two-dimensional map of color, since the bright-dim dimension (lightness) is not represented. Colored backgrounds, as are shown here, are for orientation only.

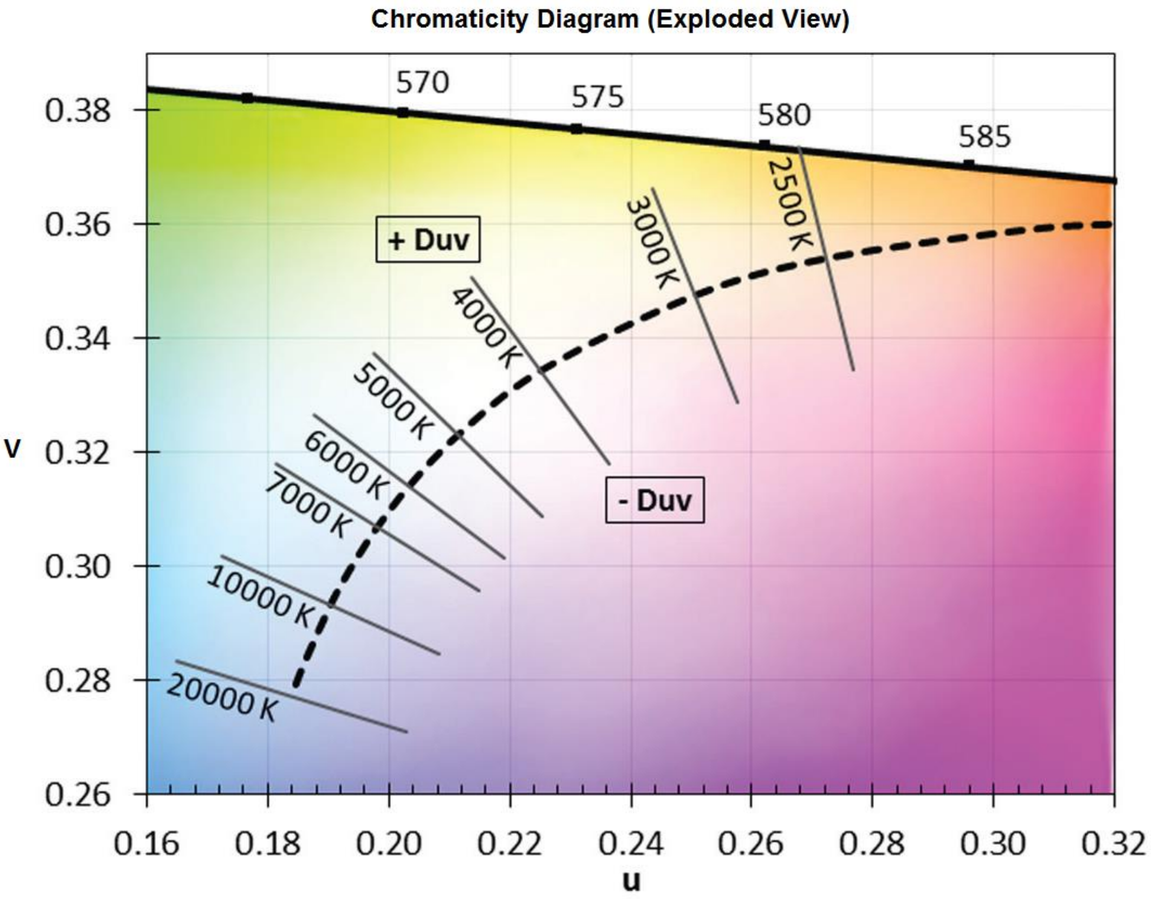


Figure 8

Figure 8, shown above is a close up of the chromaticity diagram showing lines of constant CCT, which are perpendicular to the blackbody locus. For a given CCT, a source with a positive value for Duv has a chromaticity that falls above the blackbody locus (appearing slightly greenish), whereas a source with a negative value for Duv has a chromaticity that falls below the blackbody locus (appearing slightly pinkish). The lines in this chart represent a Duv range of ± 0.02, which is much greater than ANSI tolerances for white light.

The CIE Test-Color Method, shown in Figure 9, utilizes eight standard color samples—having moderate lightness and of approximately equal difference in hue (i.e., equal spacing on a chromaticity diagram)—and six special color samples. It is an approximation of color samples used for the calculation of CRI, R9–R14, and CQS.

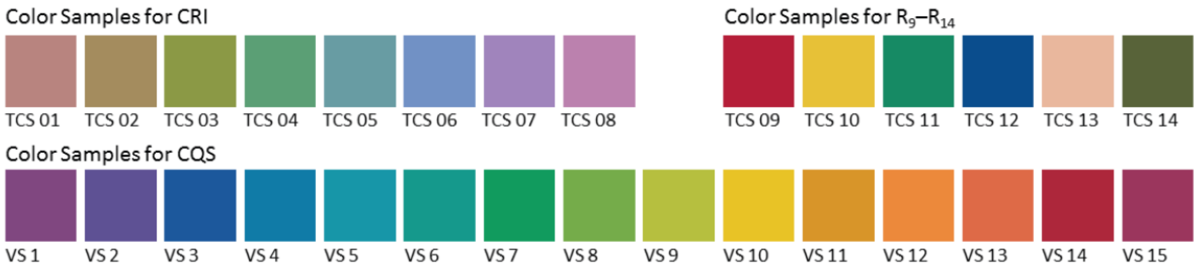


Figure 9

For each color sample, the chromaticity under a given (test) source can be compared to the chromaticity under a reference source of equal CCT, allowing for the measurement of color difference that is then mathematically adjusted and subtracted from 100 (Ri). The principal metric of the CIE system is the Color Rendering Index (CRI), which averages the Ri scores for the eight standard test colors and typically has a range from 0 to 100, though negative scores are also possible. A score of 100 indicates that the source renders colors in a manner identical to the reference. In general, a source with a CRI in the 70s would be considered acceptable for interior applications, whereas the 80s would be considered good and the 90s excellent. Because it is a reference-based metric, comparing the CRI for sources with different CCTs should only be done with great caution. Furthermore, two light sources with the same CCT and CRI may not render colors the same way (i.e., colors may still look different).

The reference is specified as blackbody radiation for CCTs below 5000 K, or a mathematical model of daylight for higher CCTs. Because CRI is a reference based metric, it is not appropriate to compare the CRI values for sources of very different CCTs.

The special color rendering indices, referred to as R9 through R14, are each based on a single test color. They are not used for calculation of CRI but may be used for supplemental analysis when necessary. The “strong red” color sample, R9, is especially pertinent since the rendition of saturated red is particularly important for the appearance of skin tones, among other materials. An R9 score greater than zero is generally considered acceptable since the color space used in the CIE Test-Color Method often causes color shifts in the red region to be exaggerated.

While CRI is the standard for evaluating color rendering, strictly speaking it only captures the ability of a source to render colors similar to the reference source. Consequently, a source with a very low CRI may actually render objects so that they are more pleasing to an observer than a source with higher CRI. Aside from this conceptual concern, CRI has many technical limitations including the chosen color space and the limited number and type of color samples. These limitations are particularly salient when white LED sources are being evaluated. It has been noted that CRI cannot predict the visual ranking of a set of lighting products when white LED sources are included in the set. Although it is possible for LED products to have a CRI greater than 95 and many have a CRI in the 80s, numerical scores should only serve as a rough guideline for true performance. Ultimately, subjective visual evaluation remains the most reliable means of ensuring adequate color quality.

One of the more notable recent attempts to address the imperfections of CRI is the *Color Quality Scale* (CQS), developed by researchers at the National Institute of Standards and Technology (NIST). Although it makes significant updates based on current vision science—including a revised and expanded set of test color samples (see Figure 9)—the basic approach remains similar and the results are highly correlated with CRI. Despite significant initial interest, it has not yet been officially adopted by any standards organization and its use has yet to become widespread. Other recently developed metrics have utilized different methods in their approach, but although some offer significant advantages, none has achieved consensus support.

Many researchers have noted that evaluating color rendition based on a combination of several metrics tends to produce results more representative of human perception. Some newly proposed metrics have addressed this by including multiple numeric ratings to represent the different facets of color rendition, but there has been some reluctance to move away from a single-number metric. Despite the challenges of meeting the needs of different user groups, developing improved metrics remains imperative for improving the effectiveness of specifications and enabling manufacturers to optimize products. This is especially pertinent given the expanding market share of solid-state lighting.

Lighting Types

The process of generating light by heating an object is called *incandescence*. Burning a candle, lighting a match, and heating a filament of wire are all forms of incandescence. An incandescent lamp uses electricity to heat a filament of wire to produce light.

Light sources such as fluorescent lamps, and high intensity discharge (HID) lamps radiate light by passing an electric current through a gas. Certain atomic elements emit light when excited by an energy source such as an electric arc. Sodium vapor emits a yellow light and mercury vapor emits a blue light.

Incandescent lamps generate light by passing electric current through a resistive filament, thereby heating the filament to a very high temperature so that it glows and emits visible light. A broad range of visible frequencies are naturally produced, yielding a "warm" yellow or white color quality. Incandescent light is highly inefficient, as about 98% of the energy input is emitted as heat. A 100 watt light bulb emits about

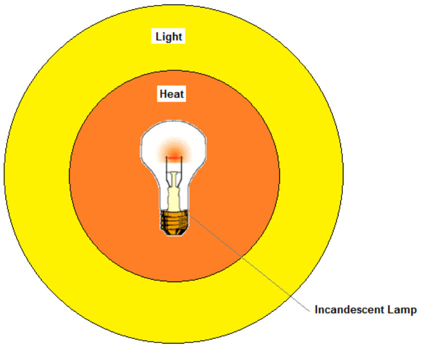


Figure 10

1,700 lumens, about 17 lumens per watt. Incandescent lamps are relatively inexpensive to make. The typical lifespan of an incandescent lamp is around 1,000 hours. They work well with dimmers. Most older light fixtures are designed for the size and shape of these traditional bulbs. See Figure 10.

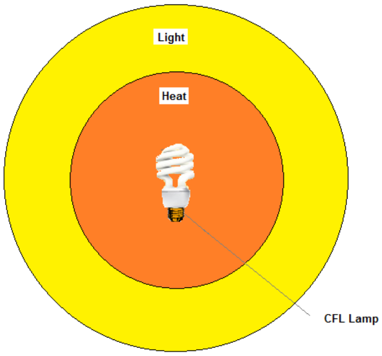


Figure 11

Fluorescent lamps work by passing electricity through mercury vapor, which in turn emits ultraviolet light. The ultraviolet light is then absorbed by a phosphor coating inside the lamp, causing it to glow, or fluoresce. While the heat generated by a fluorescent lamp is much less than its incandescent counterpart, energy is still lost in generating the ultraviolet light and converting this light into visible light. Linear fluorescent lamps are typically five to six times the cost of equivalent incandescent lamps but have life spans around 10,000 and 20,000 hours. Lifetime varies from 1,200 hours to 20,000 hours for compact fluorescent lamps. Most fluorescent lamps are not compatible with dimmers. Those with "iron" ballasts flicker at 100 or 120 Hz, and are less efficient. The life expectancy depends on the number of on/off cycles, and is lower if the light is cycled often. The efficiency of these new lamps approaches 100 lumens per watt. The efficiency of fluorescent tubes with modern electronic ballasts and compact fluorescents commonly ranges from 50 to 67 lumens per watt. Most compact fluorescents rated at 13 watt or more with integral electronic ballasts achieve about 60 lumens per watt, comparable to the LED bulb. See Figure 11.

One of the defining features of LEDs is that they emit light in a specific direction. Since directional lighting reduces the need for reflectors and diffusers that can trap light, well-designed LED fixtures can deliver light efficiently to the intended location. In contrast, fluorescent and "bulb" shaped incandescent lamps emit light in all directions; much of the light produced by the lamp is lost within the fixture, reabsorbed by the lamp, or escapes from the fixture in a direction that is not useful for the intended application. For many fixture types, including recessed downlights, troffers, and under cabinet fixtures, it is not uncommon for 40 to 50% of the total light output of fluorescent and incandescent lamps to be lost before it exits the fixture.

LED's loose heat through conduction, unlike incandescent and CFL lamps which loose heat through radiation. See Figure 12.

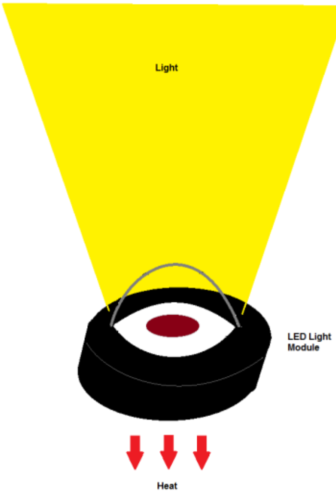


Figure 12

Chapter 3

LED Basics

In this chapter we will look at the how LEDs work, the different types of LEDs, their efficiencies and life expectancies, as well as how "white light" is produced from LED's. LED lighting standards are also reviewed. We will start with the physics of producing light from a solid-state device.

Physics of LED Lighting

As previously mentioned, 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 are excites mercury atoms, which emit ultraviolet (UV) radiation. After striking the phosphor coating on the inside of glass tubes, the UV radiation is converted and emitted as visible light.

An LED, in contrast, is a semiconductor diode. It 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, a 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 semiconductor material is doped with low concentrations of atoms, often silicon or magnesium. Using silicon as a dopant in Gallium Nitride produces excess electrons in the semiconductor creating a negative charge and is referred to as "n-type" material. In contrast, doping the Gallium Nitride with magnesium atoms creates a deficiency of electrons, known as "holes", and results in a positive charge. The material is called "p-type". Therefore, an LED is created layering a piece of p-type material over a piece of n-type material creating a p-n junction, which is the basis for all semiconductor products. Applying approximately 3-volts to the junction will cause the emission of a blue light. The n-side (cathode) of the semiconductor is made of arsenic, phosphorous, or anitmony and has an excess of electrons call "free electrons". When voltage is applied to the semiconductor, holes and electrons are forced into the p-n junction and light photons are emitted as the electrons drop into the holes. See Figure 13.

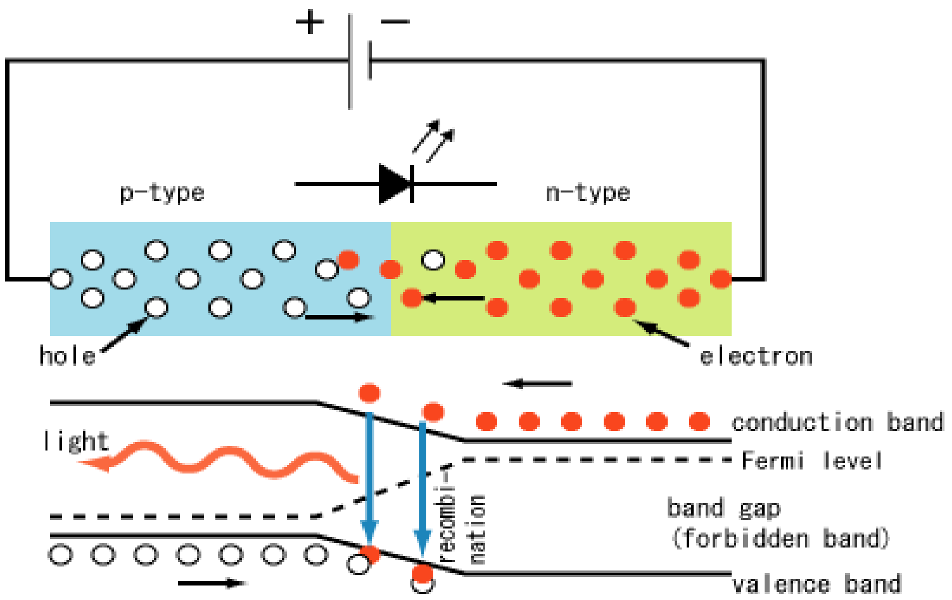


Figure 13

The specific wavelength or color emitted by the LED depends on the materials used to make the diode. Red LEDs are based on Aluminum Gallium Arsenide (ALGaAs). Blue LEDs are made from Indium Gallium Nitride (InGaN) and green from Aluminum Gallium Phosphide (AIGaP). "White" light is more complicated to produce and is created by combining light from red, green, and blue (RGB) LEDs or by coating a blue LED with yellow phosphor.

Table 7 shows the characteristics of the different semiconductor materials used in LED's. Specific color LEDs require different materials and they each have different light output characteristics. For instance, blue LED's, which are made from Indium Gallium Nitride (InGaN) have the lowest light out per and consume the most watts per lumen produced.

Table 7

Characteristics of Different Semiconductor Material

Color	Material	Flux (Lumens)	Watts (per 100 lumens)
Red	AlGaAs	30.6 – 51.7	1.8
Green	AlGaP	67.2 – 100	1.4
Blue	InGaN	23.5 – 30.6	4.2
White	YAG:CE	67.2 – 114	1.2

Notes:

1. Material selection determines colors
2. Different colors require different power
3. White is achieved one of two ways
    - Combine RGB (Red, Green, and Blue LED's)
    - Coat a blue LED with yellow phosphor

The most basic form of LED is shown in the Figure 14.

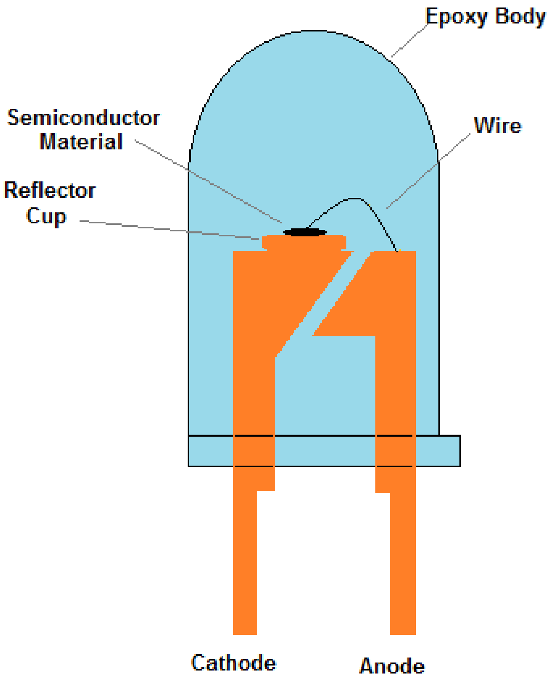


Figure 14

The LED shown in Figure 14 is a T-1¾ (5mm) and consists of a *die*, which is a very minute amount of semiconductor material, a *die cup* (Reflector), which is has reflective sides to reflect light emitted from the die toward the dome of the LED. The epoxy body of the LED is designed to focus the light into a beam emitted from the dome of the LED. The leads are the cathode and anode and the cathode lead is on the flattened side of the T-1¾ LED.

Heat build-up is a critical item in the operation of LED's. LED's operate at the lowest possible temperature and as temperature increases light production is reduced as well as the useful life. The temperature in the p-n junction must be carefully managed to yield the desired light output. Therefore LEDs generally must have some form of heat sink to dissipate heat.

A single LED is a low-voltage solid state device and cannot be directly operated on standard high-voltage AC power without circuitry to control the voltage applied and the current flow through the lamp. In principle a series diode and resistor could be used to control the voltage polarity and to limit the current, but this would be very inefficient since most of the applied power would be dissipated by the resistor. A series string of LEDs would minimize dropped-voltage losses, but one LED failure would extinguish the whole string. Paralleled strings increase reliability by providing redundancy. To be useful for illumination a number of LEDs must be placed close together in a lamp to combine their illuminating effects because the largest available LEDs emit only a small fraction of the light of traditional light sources. When using the color-mixing method a uniform color distribution can be difficult to achieve, while the arrangement of white LEDs is not critical for color balance. Further, degradation of different LEDs at various times in a color-mixed lamp can lead to an uneven color output. LED lamps usually consist of clusters of LEDs in a housing with driver electronics, a heat sink, and optics.

LEDs and "White Light"

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.

Individual LED dies, often referred to as chips, emit light in a narrow range of wavelengths, giving the appearance of a monochromatic source. LED lamps and luminaires combine multiple spectral components, which may be produced directly or through phosphor conversion, to create a mixture that appears white to the human eye. In comparison, incandescent lamps have a broad distribution and fluorescent lamps typically rely on a limited, fixed set of phosphors with specific emission characteristics. Figure 15 compares the spectral power distributions of several light sources, adjusted for equal lumen output.

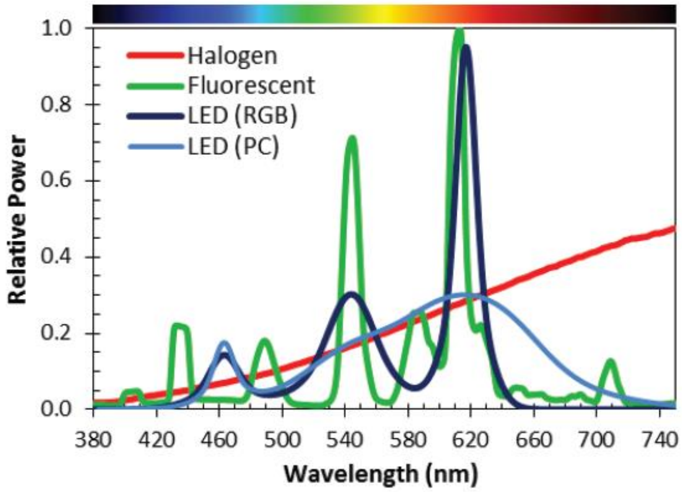


Figure 15

Due to the trichromatic nature of the human visual system, white light of equal appearance can be created with different spectral power distributions. The chart in Figure 1 shows the spectral power distributions for four different light sources, all producing 2700 K white light with a CRI > 80.

LEDs emit light in a very small band of wavelengths, emitting light of a color characteristic of the energy bandgap of the semiconductor material used to make the LED. To emit white light from LEDs requires mixing light from red, green, and blue LEDs, or using a phosphor to convert some of the light to other colors.

We are accustomed to lamps that emit white light. But what does that really mean? What appears to our eyes as “white” is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. Electromagnetic radiation in wavelengths from about 380 to 770 nanometers is visible to the human eye. Incandescent, fluorescent, and high-intensity discharge (HID) lamps radiate across the visible spectrum, but with varying intensity in the different wavelengths. The spectral power distribution (SPD) for a given light source shows the relative radiant power emitted by the light source at each wavelength. Incandescent sources have a continuous SPD, but relative power is low in the blue and green regions. The typically “warm” color appearance of incandescent lamps is due to the relatively high emissions in the orange and red regions of the spectrum.

White light can be achieved with LEDs in two main ways:

1. Phosphor conversion, in which a phosphor is used on or near the LED 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.

See Figure 16 below.

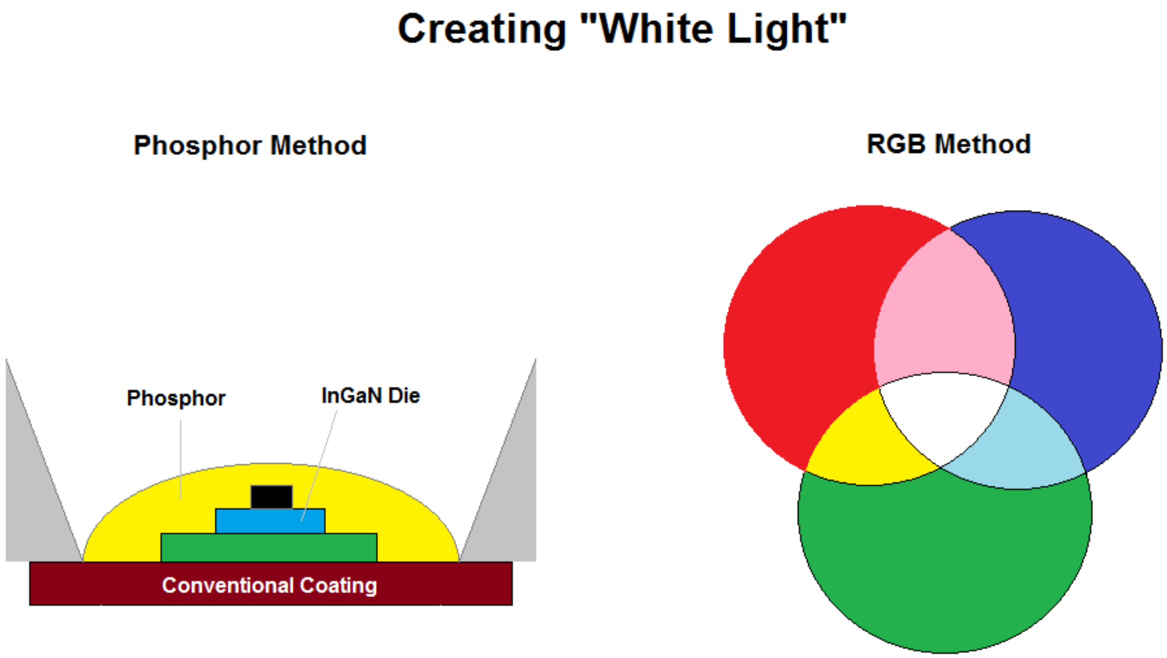


Figure 16

The first method, phosphor converted LEDs (pcLEDs) uses one short wavelength LED (usually blue or ultraviolet) in combination with a phosphor which absorbs a portion of the blue light and emits a broader spectrum of white light. (The mechanism is similar to the way a fluorescent lamp emits white light from a UV-illuminated phosphor.) The major advantage is the low production cost, and high CRI (color rendering index), but the phosphor conversion reduces the efficiency of the device. The character of the light cannot be changed dynamically. The low cost and adequate performance makes it the most widely used technology for general lighting today.

The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. Research continues to improve the efficiency and color quality of phosphor conversion.

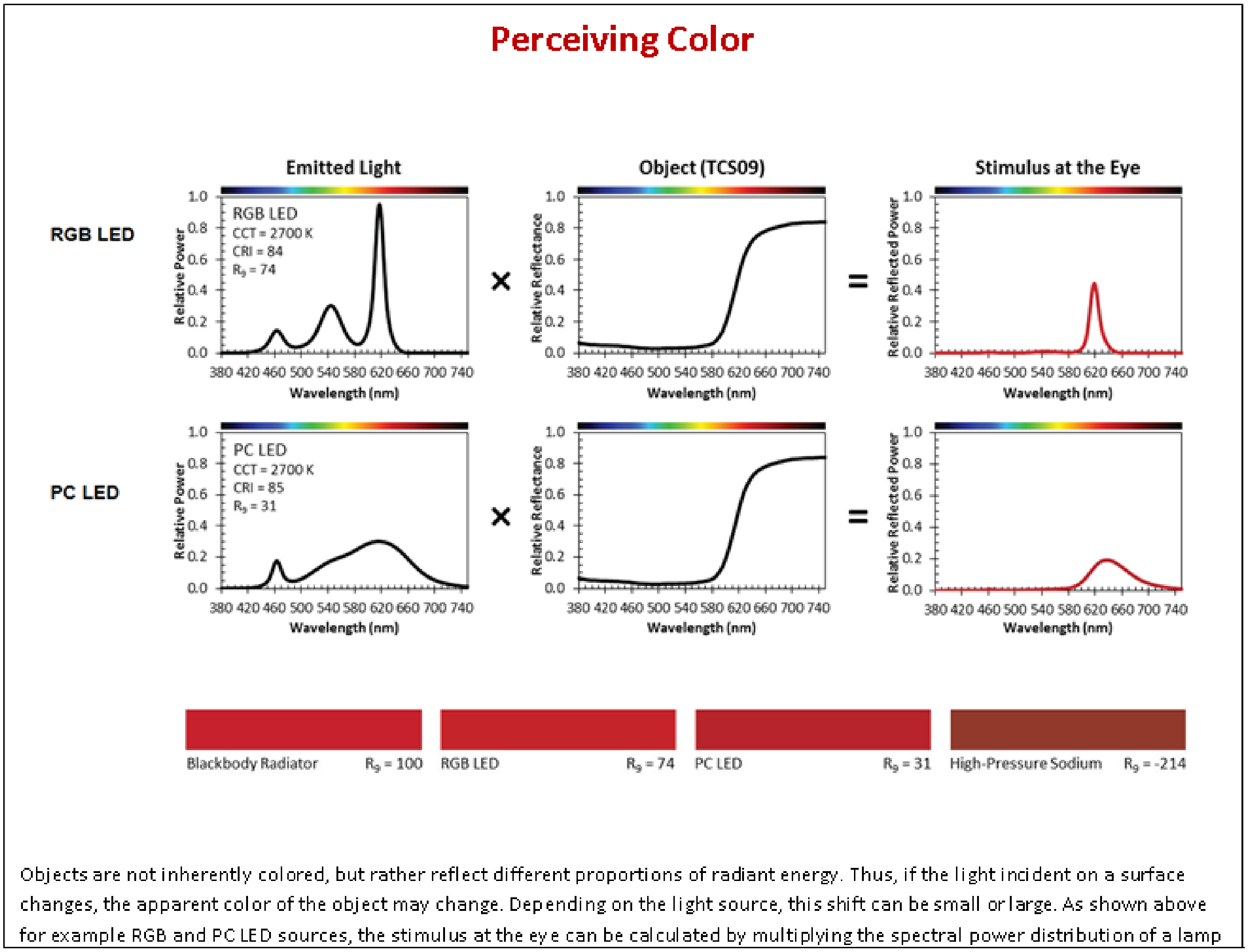
The phosphor may be incorporated into the LED package, or may be located remotely. Fluorescent lamps also utilize phosphor down-conversion. Earlier versions of the technology relied on broad emitting halo-phosphors, but most current lamps, called tri-phosphor fluorescent, utilize a combination of red-, blue-, and green-emitting phosphors.

Mixed LED sources produce white light by mixing two or more colors, called primaries. Although only two primaries are necessary, such systems have very poor color rendition properties and therefore three-primary RGB systems are typically considered a minimum for acceptable performance. Additional primaries, such as amber, can be added to potentially improve the color characteristics, though efficacy is often sacrificed. This is analogous to the practice of adding additional phosphors to broaden the range of emitted wavelengths. Hybrid systems—which might combine PC LEDs with red LEDs, for example—are also possible. PC LEDs utilize the same color mixing principle, but combine a blue component with a broad phosphor emission. This results in a different spectral power distribution, although the light is still nominally white in appearance.

The second method is RGB which uses multiple LED chips, each emitting a different wavelength, in close proximity to generate the broad spectrum of white light. The RGB approach produces white light by mixing the three primary colors - red, green, and blue. The color quality of the resulting light can be enhanced by the addition of amber to “fill in” the yellow region of the spectrum. The advantage of this method is that the intensity of each LED can be adjusted to "tune" the character of the light emitted. The major disadvantage is high production cost. The character of the light can be changed dynamically by adjusting the power supplied to the different LEDs.

Mixed LED sources have a higher theoretical maximum efficiency, potentially longer life, and allow for dynamic control of color. However, they generally have less color consistency both initially and over time, require more elaborate optical systems to ensure proper mixing, and are generally more complex and expensive to manufacture. Currently, mixed LED efficacy is typically lower than PC LED efficacy, limiting their use in general lighting applications. It is important to remember that even within a family of LED sources, or within the products offered by a given manufacturer, color characteristics can vary widely based on the choice of primaries or phosphors. Each individual product should be evaluated on its own merits, regardless of the technology.

Figure 17 expands on the color rendition information from the previous chapter as it pertains to PC and RGB while light sources.



Objects are not inherently colored, but rather reflect different proportions of radiant energy. Thus, if the light incident on a surface changes, the apparent color of the object may change. Depending on the light source, this shift can be small or large. As shown above for example RGB and PC LED sources, the stimulus at the eye can be calculated by multiplying the spectral power distribution of a lamp

Figure 17

LED Efficiency

Two aspects of energy efficiency are important to consider: the efficiency of the LED device itself (source efficacy); and how well the device and fixture work together in providing the necessary lighting (luminaire efficacy). How much electricity is used to provide the intended lighting service depends not only on the LED device, but on the lighting fixture design. Because they are sensitive to thermal and electrical conditions, LEDs must be carefully integrated into lighting fixtures. Poorly designed fixtures using even the best LEDs may be no more efficient than incandescent lighting. Conversely, a well-designed LED-based refrigerated display case light that takes advantage of

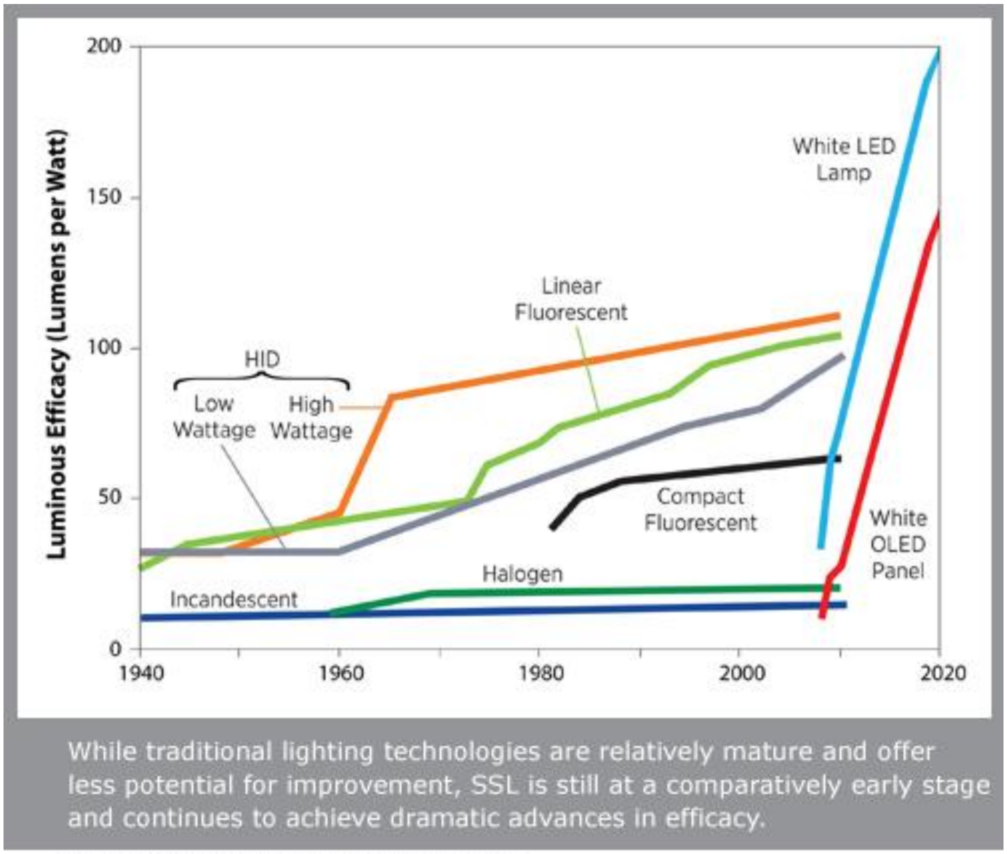
To understand the energy use of lighting and the savings that can be realized by switching to more efficient lighting sources, it is important to recognize the relationship between lumens produced and electricity use. Wattage is a measure of power input while lumens produced is an output measure. The lumen output per watt of electrical power input is the lamp's efficacy (lumens/watt) and is the key measure of a lamp's energy performance.

the directional nature of LEDs may use only about half the total watts of a linear fluorescent system to provide the necessary lighting, even though the LEDs have lower source efficacy than the linear fluorescent lamps. See Table 8 for an overview of the efficacy of various lighting sources.

Table 8
Comparable Lighting Technologies Efficacy

Lamp Type	Efficacy (lumens/watt
Incandescent	15
Halogen	20
CFL	60
Fluorescent	118
High Intensity Discharge	120
LED – A19	64
LED - PAR 38	53
LED - Cool White	130
LED – Warm White	93

Energy performance of white LED products continues to improve rapidly. This graph in Figure 18 shows the improvement in luminous efficacies for traditional and LED sources, including ballast losses as applicable over a period of time.



While traditional lighting technologies are relatively mature and offer less potential for improvement, SSL is still at a comparatively early stage and continues to achieve dramatic advances in efficacy.

Source: DOE SSL R&D Multi-Year Program Plan

Figure 18

As you can see from Figure 18, all lighting sources – except incandescent – have continued to improve in efficacy over time. LED's are a new lighting source and we should expect to see dramatic improvements in efficacy in the next few years.

Quality of LED Lighting

Key aspects of lighting quality are color appearance (whether a white light appears more yellow/gold or more blue) and color rendering (the ability of the light source to render colors, compared to incandescent and daylight reference sources). These factors were thoroughly discussed in the previous chapter but here is a quick review.

Color appearance is measured by correlated color temperature (CCT) on the Kelvin (K) scale. For most interior lighting applications, warm white (2700K to 3000K) and in some cases neutral white (3500K to 4000K) light is appropriate. Many products use cool-white LEDs with very high CCT (bluish in appearance) since they tend to offer higher efficacy at low cost, but an increasing number of LED products are available in warm-white or neutral-white. They are less efficient than cool white LEDs, but have improved significantly, to levels almost on par with CFLs.

The *color rendering index* (CRI) measures the ability of light sources to render colors, compared to incandescent and daylight reference sources. The leading high-efficiency LED manufacturers now claim a CRI of 80 for phosphor-converted, warm-white devices. 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.

CCT and CRI have been used for many years to define *color quality* but they are not adequate for SSL. Two light sources with identical CCTs can render object colors very differently due to the differences in spectra. While CCT provides an indication of whether a light source may appear yellowish or bluish in color, DUV is needed as a supplemental metric to prevent excessively greenish or pinkish hues. Similarly, CRI value is poor at predicting the quality of the appearance of saturated red objects, and doesn't correspond well to human perception of color quality.

Useful Life of LEDs

Long life is potentially a key advantage of LEDs over other light sources. However, the lighting industry currently has very limited direct experience with long-term performance and reliability of LED luminaires. This document outlines the issues and provides suggestions for understanding and interpreting LED product life claims.

Unlike other light sources, LEDs usually don't "burn out"; instead, they get progressively dimmer over time (a process called lumen depreciation). LED useful life is typically based on the number of operating hours until the LED is emitting 70 percent 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.

All electric light sources experience a decrease in the amount of light they emit over time, a process known as lumen depreciation. *Lumen depreciation* is the decrease in lumen output that occurs as a lamp is operated. 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. *Life Performance Curve* (also called a *Lumen Maintenance Curve*) is a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) through-out the life of the source. See Figure 19 for a typical “Life Curve” for an LED lamp.

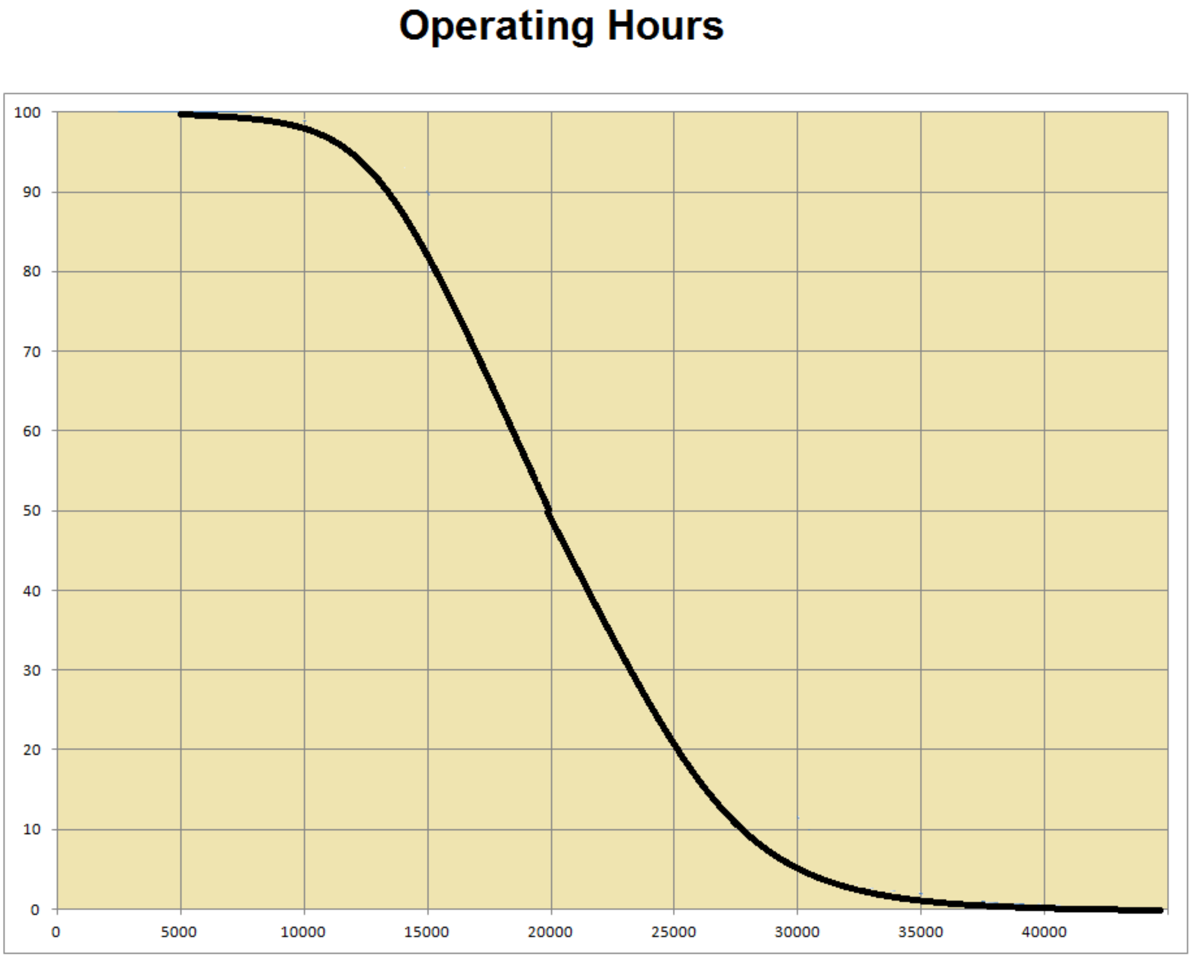


Figure 19

Incandescent filaments evaporate over time and the tungsten particles collect on the bulb wall. This typically results in 10-15% depreciation compared to initial lumen output over the 1,000 hour life of an incandescent lamp. In fluorescent lamps, photochemical degradation of the phosphor coating and accumulation of light-absorbing deposits cause lumen depreciation. Compact fluorescent lamps (CFLs) generally lose no more than 20% of initial lumens over their 10,000 hour life. High-quality linear fluorescent lamps (T8 and T5) using rare earth phosphors will lose only about 5% of initial lumens at 20,000 hours of operation. A primary cause of lumen depreciation is heat generated at the LED junction. LEDs do not emit heat as infrared radiation like other light sources, so the heat must be removed from the device by conduction or convection. Thermal management is arguably the most important aspect of successful LED system design. The primary cause of LED lumen depreciation is heat generated at the LED junction.

LEDs do not emit heat as infrared radiation (IR), so the heat must be removed from the device by conduction or convection. Without adequate heat sinking or ventilation, the device temperature will rise, resulting in lower light output. While the effects of short-term exposure to high temperatures can be reversed, continuous high temperature operation will cause permanent reduction in light output. LEDs may continue to operate even after their light output has decreased to very low levels. This becomes an important factor in determining the effective useful life of the LED.

To provide an appropriate measure of useful life of an LED, a level of acceptable lumen depreciation must be chosen. At what point is the light level no longer meeting the needs of the application? The answer may differ depending on the application of the product. For a common application such as general lighting in an office environment, research has shown that the majority of occupants in a space will accept light level reductions of up to 30% with little notice, particularly if the reduction is gradual. Therefore a level of 70% of initial light level could be considered an appropriate threshold of useful life for general lighting. Based on this research, the useful life is defined as the point at which light output has declined to 70% of initial lumens (abbreviated as L70) for general lighting and 50% (L50) for LEDs used for decorative purposes. For some applications, a level higher than 70% may be required.

Different light sources have different rates of lumen depreciation. High-quality T8 fluorescent lamps maintain 95% (L95) of initial lumens at end of life. B50 – another aspect of LED life projection, used in conjunction with the lumen depreciation (L) metric and a target statistical confidence interval. B50 indicates no more than 50% of a sample of LED devices would be expected to fail before a certain number of operating hours. Failure means light output drops below a target lumen maintenance level (such as L70 or L50). B10 would mean no more than 10% of the sample fails within the given time. See Figure 20 for a graphical view of the lumen maintenance values for various light sources.

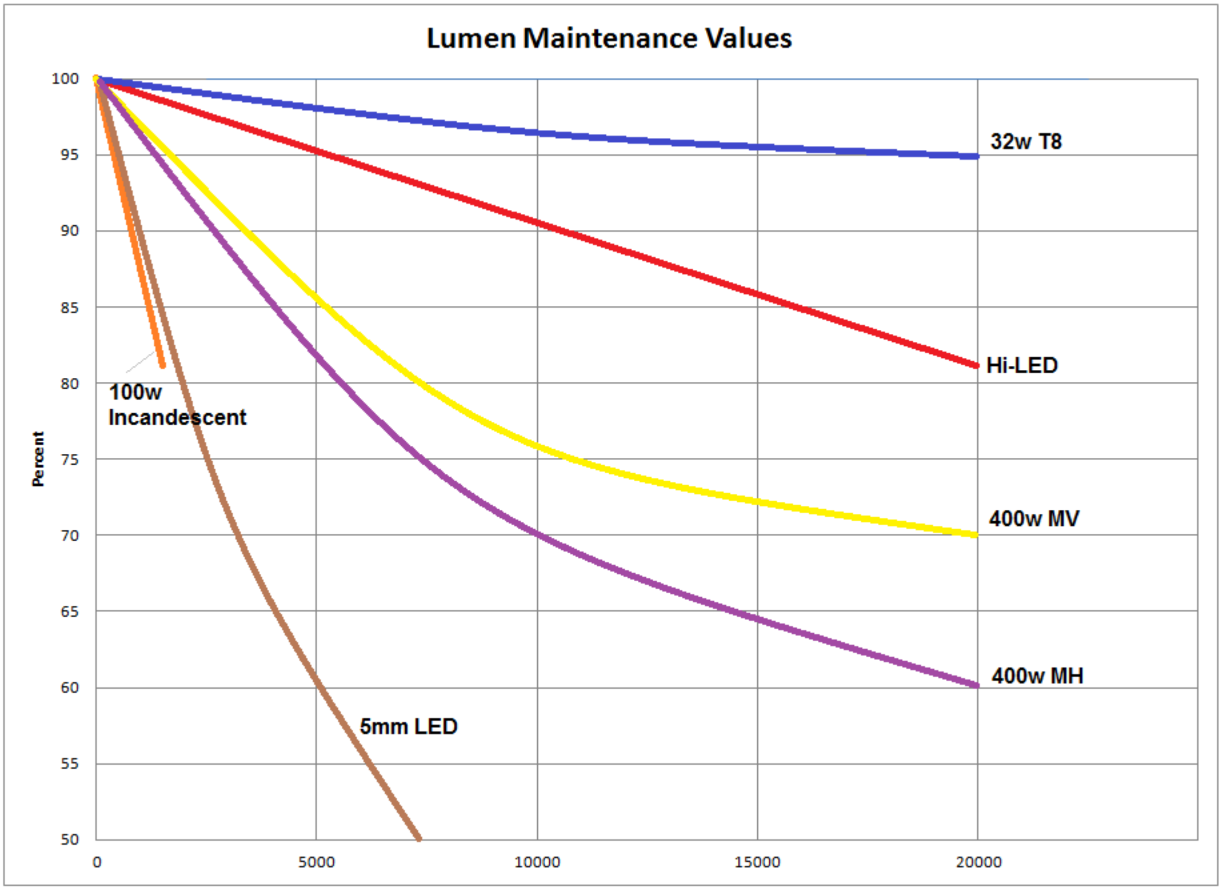


Figure 20

Dimming LEDs

Lack of effective and affordable dimming has hampered the adoption of CFLs in the residential sector. LEDs are in theory fully dimmable, but are not compatible with all dimmer controls designed for incandescent lamps.

Typical residential incandescent lamp dimmers are essentially electronic switches that toggle on and off 120 times per second. By delaying the beginning of each half-cycle of AC power (known as "phase control"), they regulate the amount of power to the lamp filament. Because this occurs so quickly, most people do not detect flicker, but see continuous dimming. Although the general operation of such electronic dimmers is the same, the specific electrical characteristics of residential dimmers can vary considerably. These variations are immaterial to incandescent lamps, but matter greatly when used with electronic devices such as compact fluorescent lamps (CFLs) and LEDs.

Some screw-in (integral) CFLs can be dimmed using line-voltage incandescent dimmers but must be specifically designed to do so. They typically dim only to about 20% of maximum intensity, due to limitations of the low-cost ballast. More sophisticated electronic ballasts providing continuous dimming below 5% are available, but are simply not cost-effective for use in screw-in CFLs. Some fixtures (e.g., torchieres) successfully use pin-based CFLs in combination with on-board dimming controls. Four-pin CFLs using separate dimming ballasts can be dimmed via line voltage or 0-10 volt DC control, with dimming range as low as 1%, but more commonly 5% or 20%.

LEDs face a dimming challenge similar to that of CFLs: their electronics are often incompatible with dimmers designed for incandescent lamps. An LED driver connected directly to a line-voltage incandescent dimmer may not receive enough power to operate at lower dimming levels or it may be damaged by current spikes. Some LED products can be used with line-voltage incandescent dimmers, but the dimmer and the LED driver electronics must be carefully matched. Because of variability in installed dimmers, it is not possible to guarantee that a given LED fixture will work with all dimmers. Some LED light fixture manufacturers publish lists of specific dimmer products tested and approved for use with their fixtures.

More sophisticated LED dimmers use low-voltage controls (either variable resistors or 0-10 volt DC control) connected separately to the electronic driver. Full AC power is provided to the driver enabling the electronic controls to operate at all times, thus allowing LEDs to be uniformly dimmed (typically down to 5% or lower). However, they may require additional low-voltage wiring for retrofit applications.

Color Consistency

To counter variability that is inherent in the manufacturing process, PC LEDs are sorted (binned) post-production based on chromaticity, lumen output, and sometimes forward voltage. This allows both manufacturers and specifiers of LED lamps and luminaires to receive a more consistent product. Recently, NEMA has published an LED binning standard (SSL-3-2010) based on ANSI C78.377-2008. The variability allowed by the NEMA bin sizes and the ANSI tolerances is roughly equivalent to the chromaticity variation seen in currently available compact fluorescent lamps.

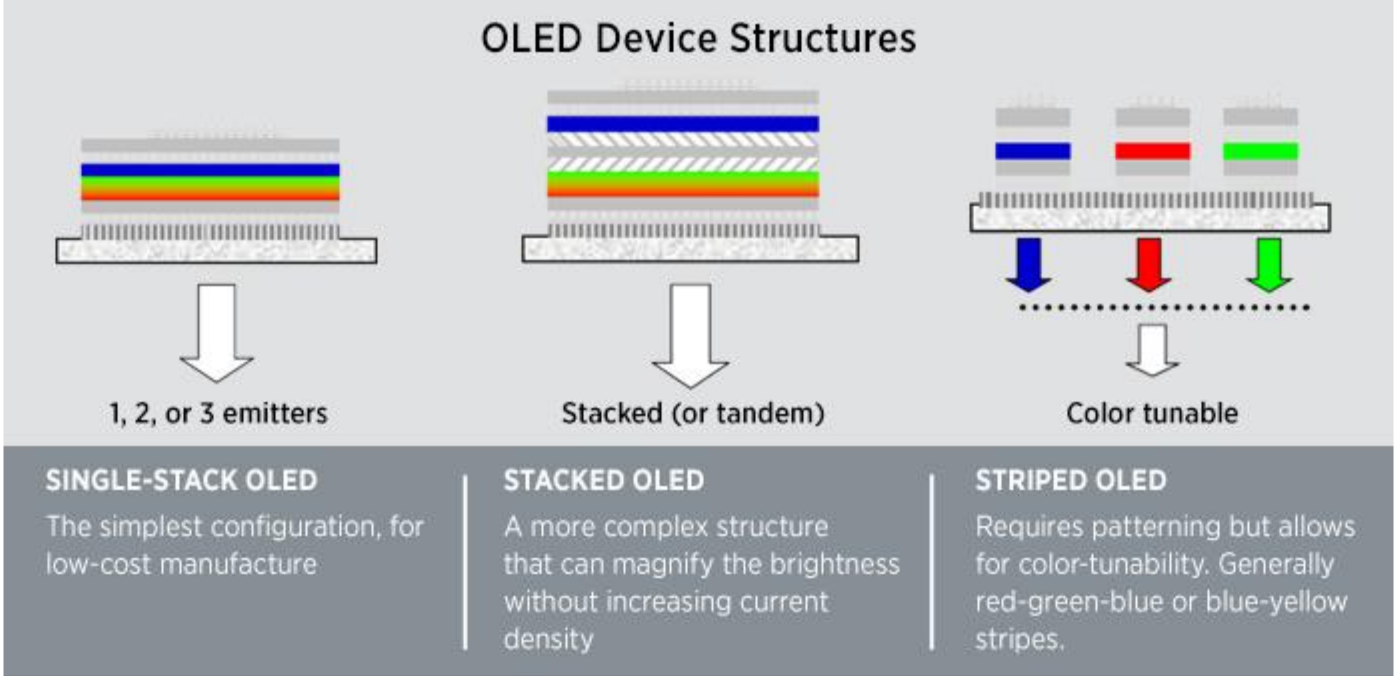
As LED technology continues to mature, binning tolerances remain essential to producing individual products and lighting installations with high color consistency. At this time, there is no industry-wide binning standard for colored LEDs that make up a mixed LED system. Additionally, due to the more consistent and stable output of fluorescence (i.e., the emission from phosphors), PC LED products tend to have greater consistency than mixed LED products.

In addition to the physical properties of each LED chip, differences in operating conditions may affect both initial consistency and constancy over time. Most notably, changes in operating temperature (which may change due to dimming) can result in differences in color appearance. Additionally, color characteristics may change as LED sources age, either due to phosphor degradation or variable lumen depreciation among the primaries in a mixed LED lamp or luminare.

Organic LEDs

Organic LEDs (OLEDs) are LEDs where their key building blocks are organic (i.e., carbon-based) materials. Unlike LEDs, which are small-point light sources, OLEDs are made in sheets that are diffuse-area light sources. Although OLED technology is developing rapidly, it's less mature than LED technology and is still some years away from becoming a practical source of general illumination. Virtually all OLED products on the market today are used for small-area displays, such as those in smartphones, vehicular audio systems, digital cameras, and other consumer electronics.

An OLED is a solid-state device consisting of a thin, carbon-based semiconductor layer that emits light when electricity is applied by adjacent electrodes. In order for light to escape from the device, at least one of the electrodes must be transparent. The intensity of the light emitted is controlled by the amount of electric current applied by the electrodes, and the light's color is determined by the type of emissive material used. To create white light, most devices use red, green, and blue emitters that can be arranged in several configurations, as shown in Figure 21 below.



The simplest configuration, for low-cost manufacture

A more complex structure that can magnify the brightness without increasing current density

Requires patterning but allows for color-tunability. Generally red-green-blue or blue-yellow stripes.

Figure 21 Source: Universal Display Corporation

The energy-saving potential of OLEDs is similar to that of LEDs, but the two technologies differ in a number of ways. For one thing, whereas LEDs are concentrated sources of bright light, OLEDs can be configured as larger-area, more diffuse light sources, which may be more practical for general ambient lighting because the soft light can be viewed directly, with less need for shades, diffusers, lenses, louvers, or parabolic shells. The diffuse light from OLEDs allows them to be used very close to the task surface without creating glare for the user, which means that less total light can be used in order to achieve desired illuminance levels. And OLEDs can be made very thin, increasing their eye appeal and allowing for easy attachment to the surfaces of walls and ceilings. This, coupled with the diffuse nature of OLED lighting, could enable an entirely new type of light and light fixture that's both attractive and highly efficient. OLEDs can also be made in almost any shape, can be deposited on flexible substrates, and can be transparent, emitting light from both sides of the device—features that greatly expand the design possibilities, allowing for a completely new lighting experience. See Figure 22.

Figure 22

OLEDs for general illumination are at a critical stage. Currently, OLED "panels" (the light-emitting devices used to construct a luminaire) are available with excellent color rendering (CRI 80–90) and efficacies of up to 60 lumens/watt. The lifetime of OLED panels is also improving, with many products expecting 10,000–15,000 hours of use before the light output decreases to 70 percent of the initial value. These advancements in efficiency and lumen maintenance are being realized while panels are getting brighter, allowing for smaller devices that achieve the same light output levels. But despite these advances, OLED costs need to come down considerably to make OLED lighting commercially viable. As further performance improvements are made and costs are reduced, OLED products will compete on the market and provide a revolutionary form of high-efficiency lighting.

Polymer light-emitting diode (PLED)

Another form of OLED is the large-molecule, polymer LED, or PLED. Virtually all OLED displays on the market today are using small molecules, as PLEDs are less efficient and suffer from lower lifetime.

PLEDs (or Polymer- LEDs, sometimes called P-OLEDs) are OLED devices made from polymer (large-molecules) materials. PLEDs are light-emitting and can be used to create displays and lighting panels. PLEDs however are more easily adapted for printing (solution-processable) and so several companies believe that P-OLEDs are the best way to create large OLED panels using printing methods.

Polymer (polymeric) Light-Emitting Diode (PLED) is a polymer that emits light when subjected to an electric current. It is used as a thin film for full-spectrum color displays and requires a relatively small amount of power for the light produced. Polymers are substances formed by a chemical reaction in which two or more molecules are combined to form larger molecules. PLEDs are thin film displays that are created by sandwiching an undoped conjugated polymer between two proper electrodes at a short distance. The polymer emits light when exposed to electricity. PLEDs enable full-spectrum color displays and are relatively inexpensive compared to other display technologies such as LCD or OLED and require little power to emit a substantial amount of light. One promising, but still experimental, PLED uses *carbon dot* supported silver nanoparticles (CD-Ag NPs). These devices are yielding luminous efficiencies of between 7 and 19 lumens/watt.

Carbon dots, or CDs, consist of carbon, hydrogen, and oxygen in a structure that carbon presents itself as crystalline graphite.

Advantages of PLEDs include:

- Bright,
- Great variability in emission wavelength,
- Good color rendering index,
- Nearly no limit in screen size,
- No dependency in viewing angle,
- No backlight is needed, and
- Fast fabrication.

The disadvantages of PLEDs include:

- Display pixels have to be encapsulated from air to inhibit degradation by oxygen,
- At present they suffer from a poor lifetime,
- Additionally different color phosphors have different durability, and
- Not suitable for dimmable white while.

LED Lighting Standards

Traditional light sources (incandescent, fluorescent, and high-intensity discharge) are rated for luminous flux according to established test procedures. In contrast, there is no standard procedure for rating the luminous flux of LEDs. LED light output estimates are typically based on a short (<1 second) pulse of power applied to the LED chip, usually with junction temperature held at 25 degrees C. To run them any longer without a heat sink would damage them. LED manufacturers usually list “minimum” and “typical” luminous flux on their product datasheets. There is no standardization of the test conditions, or the meaning of “typical.” Further, there is no standard test procedure for measuring the luminous flux of LED arrays, such as multiple LEDs mounted on a circuit board.

For all light sources, there is a difference between rated luminous flux of the lamp and actual performance in a luminaire. However, traditional light sources installed in luminaires operate relatively predictably because the performance of traditional light sources in a wide range of luminaire types, applications, and use conditions is well documented and understood. LED technology is at a far earlier stage of development, so experience and documentation of performance within luminaires is lacking. The efficiency of LEDs is very sensitive to heat and optical design, which increases the relative importance of luminaire design. Ensuring necessary light output and life of LEDs requires careful thermal management, typically requiring the use of the fixture housing as a heat sink or at least as an element in the heat removal design. Luminaires therefore have a fundamental and typically large effect on the luminous flux produced by the LEDs, and on the rate of lumen depreciation over time. LED “drop-in” replacement lamps are in theory designed to provide the necessary heat sinking for the LEDs, but given their installation in fixtures not specifically designed for LEDs, good heat management will be a challenge. In summary, luminous flux—and by extension, luminous efficacy—must be measured at the luminaire level for two primary reasons: 1) no standard procedures are available for rating LED devices on their own, and; 2) the amount of light emitted by a fixture cannot be predicted reliably based on available information about LED devices and fixtures. The lighting industry has adopted luminaire efficacy as the preferred measure of LED performance, as evident in the development of a new test procedure based on this approach.

The Illuminating Engineering Society of North America, IESNA, or sometimes just referred to as IES, had developed three standards to address LED lighting. They are LM-79, Electrical and Photometric Measurements of Solid-State Lighting Products, LM-80, Measuring Lumen Maintenance of LED Light Sources, and TM-21, Approved Method for Lumen Maintenance Testing of LED Light Sources. The following is a brief description of each.

IES LM-79 - Electrical and Photometric Measurements of Solid-State Lighting Products

This standard provides an approved method describing procedures and precautions in performing reproducible measurements of LEDs including, total flux, electrical power, efficacy, and chromaticity.

The standard applies to LED-based products incorporating control electronics and heat sinks: Products requiring only line voltage or DC power supply, Includes complete LED luminaires and integrated LED sources. It does not cover LED products requiring external operating circuits or heat sinks and fixtures designed for LED products but sold without a light source.

LM-79 requires complete luminaire testing. Traditionally, photometric evaluation of lighting products is based on separate tests for lamps and luminaires ("relative"), but for LED products, lamps typically cannot be separated from their luminaire because of heat effects ("absolute"). SSL Test Procedure: LM-79-08

Key elements of the document include:

- Covers fixtures incorporating light sources as well as light sources used for fixtures (e.g., LED retrofit products),
- Provides test procedures for photometric measurements,
- Photometric information measured may include: total luminous flux (lumens), luminous intensity (candelas) in one or more directions, chromaticity coordinates, correlated color temperature (CCT), and color rendering index (CRI),
- Electrical information measured includes: current, voltage, and power, and
- Products must be stabilized until they reach thermal equilibrium before testing.

IES LM-80 - Measuring Lumen Maintenance of LED Light Sources

This standard approves methods for measuring lumen depreciation of solid-state light sources, arrays and modules, however it does not cover measurement of luminaires, nor does it define or provide methods for estimation of life. Before the advent of LM-80, LED component manufacturers each reported lumen maintenance data using their own disparate and varied systems.

It measures how one part of an LED luminaire—the LED light source—performs over a period of time and under certain set conditions. Other components, including the LED optical system, heat sink, LED drivers and luminaire housing, should also be taken into consideration to form a full picture of an LED luminaire's projected useable life. LM-80 is also not a measure of the "lifetime" of a component or the LED lamps and luminaires that use that component.

While LM-80 doesn't provide a full picture of a LED component's long-term performance, it is an important part of the equation. Luminaire and lamp manufacturers, lighting designers and researchers should know how quickly the light output of an LED will depreciate to help them determine the useful lifetime of the product in which the LED will be used. They should also look at how the LED's light output has degraded under the various temperature and current conditions, as well as how the color point has shifted at those same conditions. Those measurements will enable them to assess how the LED component is expected to perform under similar circumstances.

TM-21 – Approved Method for Lumen Maintenance Testing of LED Light Sources
Provides recommendations for projecting long term lumen maintenance of LED light sources using data obtained when testing them per LM-80, "IES Approved Method for Measuring Lumen Maintenance of LED Light Sources."

With the establishment of TM-21, the industry has taken another big step towards one consistent and reliable model for LED lifetime calculation. It first helps to understand LM-80, which is the IES-approved method of measuring the lumen maintenance of LED packages and modules. Lumen maintenance refers to the number of hours that a light source remains "useful" before its output diminishes to 70%. The creation of the LM-80 standard ensured that manufacturers were testing for lumen maintenance in a consistent fashion – requiring a minimum of 6,000 hours of testing at various temperatures. The lumen maintenance measurement, known as L70, would then be extrapolated from these test results. However, before the arrival of TM-21, there was no standard basis for the extrapolation, and calculations varied from one manufacturer to another.

Rated Lumen Maintenance Life, (Lp) is the elapsed operating time over which the LED light source will maintain the percentage, p, of its initial light output. For example, the time (in hours) to reach 70% of the initial light output is known as L70.

TM-21 standard picks up where LM-80 left off. Since LED sources are capable of lifetimes well beyond 6,000 hours, TM-21 establishes a standard way to use LM-80 data to make consistent lifetime projections beyond the testing period. TM-21 dictates which values can be used in the calculation based on the sample size, number of hours and intervals tested, and test suite temperature. It also puts a cap on the extrapolation – a maximum of 6X the hours tested – which eliminates those infamous 100,000-hour claims of yesterday.

Chapter 4
LED Applications

With their unique design and performance characteristics—such as directional light emission, compact profile, superior optical control, energy efficiency, breakage resistance, reduced maintenance, and long life—LEDs are well suited to a variety of lighting applications. LED products are most competitive in applications where these performance characteristics outweigh their first-cost disadvantages. In addition, since effective thermal management is more difficult to achieve in small LED luminaires and replacement lamps, larger LED assemblies—such as outdoor area lighting—have led the way in market penetration. In recent years, there has been a phenomenal increase in market penetration for LED's in residential and small commercial lighting segments.

LED lamps are used for both general and special-purpose lighting. Where colored light is needed, LEDs naturally emitting many colors are available, with no need for filters. This improves the energy efficiency over a white light source that generates all colors of light then discards some of the visible energy in a filter.

Advantages for LED light bulbs are that they contain no mercury (unlike a Compact fluorescent lamp or CFL), that they turn on instantly, and that lifetime is unaffected by cycling on and off, so that they are well suited for light fixtures where bulbs are often turned on and off. LED light bulbs are also mechanically robust; most other artificial light sources are fragile.

White-light light-emitting diode lamps have longer life expectancy and higher efficiency than most other lighting. LED sources are compact, which gives flexibility in designing lighting fixtures and good control over the distribution of light with small reflectors or lenses. Because of the small size of LEDs, control of the spatial distribution of illumination is extremely flexible, and the light output and spatial distribution of a LED array can be controlled with no efficiency loss.

LED lamps have no glass tubes to break, and their internal parts are rigidly supported, making them resistant to vibration and impact. With proper driver electronics design, an LED lamp can be made dimmable over a wide range; there is no minimum current needed to sustain lamp operation.

LEDs using the color-mixing principle can emit a wide range of colors by changing the proportions of light generated in each primary color. This allows full color mixing in lamps with LEDs of different colors. In contrast to other lighting technologies, LED emission tends to be directional. This can be either an advantage or a disadvantage, depending on requirements. For applications where non-directional light is required, either a diffuser is used, or multiple individual LED emitters are used to emit in different directions.

Cost Effectiveness of LEDs

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.

Lamp sizes and bases

LED lamps intended to be interchangeable with incandescent lamps are made in standard light bulb shapes. LED lamps are made in low voltage (typically 12 V halogen-like) varieties, and as replacements for regular 120-volt AC lighting. These lamps include circuitry to rectify the AC power and to convert the voltage to a level usable by the internal LED elements.

LEDs are more power-efficient than compact fluorescent bulbs and offer life spans of 30,000 or more hours, reduced if operated at a higher temperature than specified. Incandescent bulbs have a typical life of 1,000 hours, compact fluorescents about 8,000 hours. The bulbs maintain output light intensity very well over their life-times. Standards require the bulbs to typically drop less than 10% after 6000 or more hours of operation. They are also mercury-free, unlike fluorescent lamps. LED lamps are available with a variety of color properties. The higher purchase cost than other types may be more than offset by savings in energy and maintenance.

Specialty uses

White LED lamps have achieved market dominance in applications where high efficiency is important at low power levels. Some of these applications include flashlights, solar-powered garden or walkway lights, and bicycle lights. Monochromatic LED lamps are now commercially used for traffic signal lamps, where the ability to emit bright monochromatic light is a desired feature, as well as in strings of holiday lights.

LED lights have also become very popular in gardening and agriculture. First used by NASA to grow plants in space, LEDs came into use for home and commercial applications for indoor horticulture (aka grow lights). The wavelengths of light emitted from LED lamps have been specifically tailored to supply light in the spectral range needed for chlorophyll absorption in plants, promoting growth while reducing wastage of energy by emitting minimal light at wavelengths that plants do not require. The red and blue wavelengths of the visible light spectrum are used for photosynthesis, so these are the colors almost always used in LED grow light panels. These lights are attractive to indoor growers since they use less power than other types for the same light intensity, need no ballasts, and emit much less heat than HID lamps. The reduction in heat allows time between watering cycles to be extended because the plants transpire less under LED grow lights.

An advantage of LED lights is that they are dimmable and they excel in areas that require directional lighting such as illuminated signage, reflector lamps, etc.

In general, LED's may be good substitutes for lighting applications that have:

- High maintenance costs,
- High run time (greater than 8 hours per day), and
- High energy rates (greater than $0.12 per kWh).

Residential Applications

At the present time, there are very few residential applications that make sense for LED's, except for applications that are difficult to access, have high run times, and high energy rates. In most applications, CFL's are superior to LED's from an economic viewpoint. LED's may be good in some special applications such as the need for dimmable lights.

An incandescent "A-base" lamp will generate about 17 lumens per watt with a CRI of 100. Fluorescent lamps will generate about 60 lumens per watt with a CRI of 80 and LED's will generate 30 lumens per watt with a CRI of 75. Clearly, CFL's have the higher efficiency and cost less to purchase than LED's.

LED's are finding applications in the following residential applications,

- Under cabinet lighting
- Accent lighting
- Cove lighting
- Recessed downlights
- Task lighting
- Path & Step lighting

LED's are a better choice for direction lamps in a residential application even given their higher initial cost. Compared to halogen "down lights", LED's are a potential winner in this application. LED's can generate 25 lumens per watt with a CRI of 75, while halogen only generates 12 lumens per watt with a CRI of 100. Generally LED's should be considered for any directional lighting application.

Commercial Applications

There are many different applications in commercial building areas from offices, meeting rooms, manufacturing, and warehouse space. Table 9 shows the characteristics of the typical lighting used in commercial applications.

Table 9
Comparison of Commercial Lighting Types

Lamp Type	Efficiency (Lumens/Watt)	Lifespan (hrs.)	CCT	CRI
Incandescent	17	1,250	2700	100
Halogen	30	5,000	3000	100
Fluorescent	80	18,000	2700	90
Metal Halide	100	20,000	2700	65
HPS	120	20,000	2200	25
LED	100	50,000	3400	80

In commercial office space, the ubiquitous fluorescent tube remains the best choice for lighting. Commonly called "troffers" with either T8 or T12 lamps these fixtures will deliver 80 lumens per watt with a CRI of 90 versus an LED troffer which may only deliver 50 lumens per watt with a CRI of 80.

In commercial applications, LED's may find applications in the following areas,

- Display case lighting
- Accent lighting
- Elevator lighting
- Exit signs
- Food preparation areas
- Task lighting
- High-bay lighting
- In-cabinet lighting

LED's compare favorably to high bay lighting where the lumens per watt is generally very close between the two and the LED's have a better CRI. Given the longer life of the LED's, maintenance costs are also reduced giving the LED's a potential edge in this market.

The clear winner in the commercial market is LED exit signs. The 24-hour per day, 7-day per week, application is well suited for LED's. In this application, incandescent will only last a few months, fluorescents will last 12-18 months, and the LED's may last up to 120 months. The initial cost of an LED fixture is very close to a fluorescent, so the LED fixture will have a very quick payback.

Outdoor Lighting

In outdoor applications, LED's have advantages in traffic lights (always on, high maintenance costs, directional) and in some street and parking lot lighting applications.

Streets lighting has predominately been served with high-intensity discharge lamps such as high pressure sodium (HPS) and metal halide (MH). It appears that LED's are becoming competitive with the incumbent lighting sources. In this application, LED's provide better surface illumination due to the LED's directionality, and improved uniformity and color rendition. Also, due to the directionality LED's provide they are more easily *Dark Sky* compliant than traditional fixtures.

Dark Sky is a program to reduce night time *sky glow* due to inefficient use of outdoor lighting. The luminaire in the above fixture is contributing significant sky glow.

In street lighting, the advantages of LED's include higher lumen maintenance (i.e. lumen output does not decrease as readily with age) and better color rendition. While High Pressure Sodium fixtures will have a slightly higher efficiency, there lifespan is roughly one-half that of LED's have HPS fixtures have a CRI of 25 versus 80 for an LED fixture.

As in just about all applications, LED's lights cost more initially, but their efficiency and longer life offset the initial cost.

Summary

LEDs offer the potential for reducing general lighting energy use by one-quarter, saving energy dollars and carbon emissions in the process. Their unique characteristics—including compact size, long life and ease of maintenance, resistance to breakage and vibration, good performance in cold temperatures, lack of infrared or ultraviolet emissions, and instant-on performance—are beneficial in many lighting applications. The ability to provide dimming and color control is another benefit of LED lights.

The purchase price of LED lighting products is generally higher than that of their conventional counterparts however they are becoming the lighting product of choice for both residential and small commercial applications. With continuing cost reductions LED's will gain even more market penetration.

With ongoing research and product development, SSL performance has been increasing steadily. Today, many well-designed SSL products can achieve appropriate light distribution in addition to high efficacy and adequate light output. Market segments where LEDs have made the greatest inroads include residential recessed downlights, kitchen under cabinet lighting, portable desk lighting, task lighting, and outdoor area lighting. On top of their superior efficacy, SSL products can be more controllable than traditional lighting technologies and their lifetimes are not impacted by frequent on-and-off cycling. Adjusting actual usage to better reflect the application's needs—for example, with an occupancy sensor—could result in even greater energy savings.

There's little doubt that solid-state lighting ultimately will emerge as the technology of choice for an unparalleled variety of applications. At the present time LED's are right for some applications but not for others, so education and due diligence should be key elements in any lighting specification and purchasing process.

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