LEDs: The Next Generation Light Source
A review of the key technology and market drivers and the directions for high-efficiency lighting

Michael Siminovitch
Professor, University of California, Davis
Director, California Lighting Technology Center
Associate Director, Energy Efficiency Center

Abstract

This paper reviews the key market and technology drivers associated with the emerging application of light emitting diode (LED) technology in the lighting of buildings. The primary focus of this paper is to present and discuss the evolving marketplace, the technology, and how current market and regulatory pressures will form the key drivers for near- and long-term market penetration for emerging light sources.

Organization of the paper

An introduction to lighting and its importance for focused policy

LED history, operation, and efficacy characteristics

Innovation and potential efficiency enhancement

Industry structure

Market development and projections

Market forces

Key focus areas for innovation and transformation

Economics issues

Codes and standards process for LED

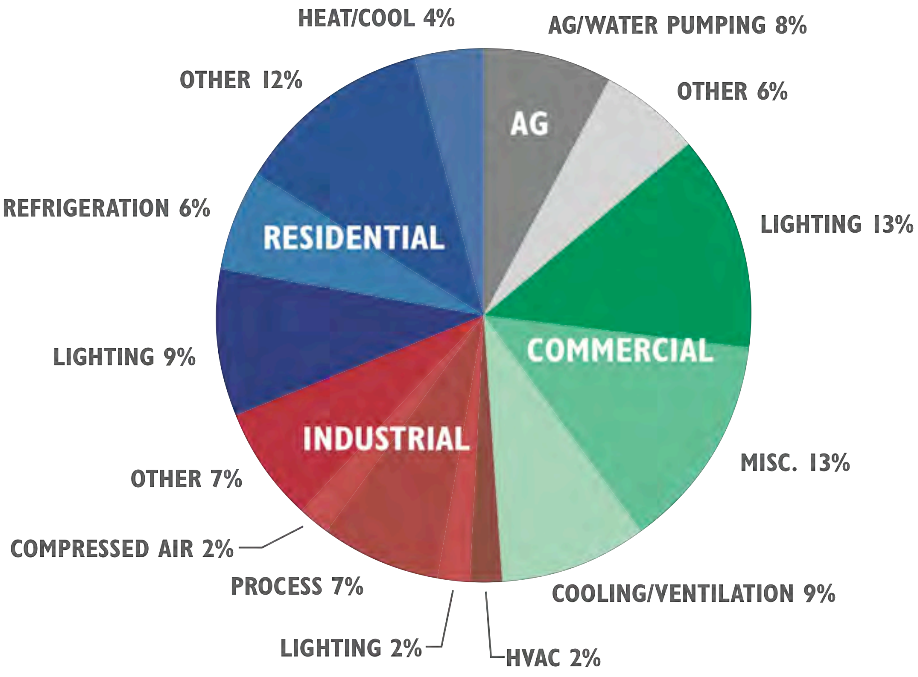
Introduction

Next-generation solid-state lighting has the opportunity to significantly change the lighting marketplace, leading to enhanced quality of life, improved efficiency, and overall sustainability in the operation of our buildings.

There are five principal factors that make illumination one of the most important areas of focus for research and development (R&D) and policy development efforts to encourage this transformation process. These five factors include the following:

1. **Lighting is one of the largest electrical loads**: Lighting accounts for about 20 to 25% of overall electricity use in the United States and represents one of the largest single components of our overall electricity load. In California, even with aggressive appliance and building code standards, lighting represents about 25% of the overall electricity and use. Additionally, lighting represents an important part of our overall peak power demand. Electronic light sources coupled with next-generation digital control systems offer the potential for 60 to 80% net reductions in electrical energy consumption due to lighting, which will significantly limit our need for additional power plants and coal combustion.

CALIFORNIA ELECTRICITY, END USE[1]



2. **Lighting is a significant part of the operational costs of business**: Lighting in commercial, institutional, and public building applications is a significant part of

the utility costs for the operation of buildings. Emerging lighting technologies, including LEDs and controls, will dramatically reduce energy use, leading to significant savings in the operation and maintenance of our buildings. Reducing operational costs will enhance our ability to be competitive within the world marketplace, reduce the burden of our public buildings, and reduce costs to homeowners and business owners.

3. **Lighting is one of the largest contributors to greenhouse gas generation**: About half of the electricity in the United States is produced through coal power generation plants. It has been estimated that building operation contributes to about half of our total greenhouse gas emissions because of coal combustion for electricity production. Given that lighting is one of the single largest end-use components, lighting is an ideal target for energy-efficiency programs. Next-generation lighting systems will dramatically reduce our electricity consumption, leading to reduced reliance on coal combustion.

4. **Lighting has significant consumer impact**: Lighting can have significant implications for quality of life, productivity, and comfort. Our productivity and comfort within workplaces and residences is highly dependent upon the quantity and quality of light. Recent studies demonstrated that the spectral qualities of lighting systems can significantly affect our circadian rhythms and our overall hormonal response, leading to significant health implications associated with lighting. One of the principal product attributes associated with next-generation electronic light sources is the ability to provide a high level of dynamic control capability. This control will allow for a finely tuned capability in terms of spectral output as well as temporal variations to enhance both comfort and health.

5. **Rapid development of new technologies**: The lighting industry is seeing significant development of new emerging technologies that have the opportunity for profound disruptive change in the way we provide light in our buildings. These new technologies offer the opportunity for spectral, temporal, and spatial control that is unparalleled. They include electronic light sources and advanced digital control systems that provide a level of adaptive control capabilities that will enhance the quality of our lives, as well as the efficiency and sustainability in the architecture of our spaces.

The Historical Context for the Current Energy-Driven Marketplace for Next-Generation LED Technology

The current lighting marketplace is seeing a significant transformation because of rapid technological change associated with the emergence of LED and solid-state technology coupled with unprecedented energy-driven market forces. A key driving force behind this rapid change is the sustained market pressure for ever-increased efficiency of light sources/systems stemming from the post-embargo response initiated in the early- to mid-1970s.

The current focus on high-efficiency lighting for buildings stems from some key historical events within the efficiency and regulatory community, resulting from the first energy crisis in the United States. Perhaps the most important of these key developments was California's response to issues related to the perception of energy scarcity. An initial demand from the utility industry was for additional generation and power plants within California. This prompted a reaction from the environmental organizations, which argued for a more balanced approach involving energy efficiency and energy supply. An integral part of this argument, however, is that the costs associated with building power plants included not just the buildings' operational components, but also the environmental costs associated with air pollution, and carbon and environmental issues associated with siting. It was further argued that energy efficiency ultimately could be less expensive on a cost-per-kilowatt basis.

Out of this conflict between the two communities emerged the Warren-Alquist State Energy Resources Conservation and Development Act, which the legislature passed and Governor Ronald Reagan signed in 1974.[2]

This act signified a historic compromise between the utilities and environmentalists and became a model of the efficiency process. This process included the following:

- The utilities accepted a process by which renewable resources would be encouraged and the need for new power plants would be tested against opportunities to decrease the demand for energy.
- In return, the newly developed California Energy Commission would facilitate a centralized process for power plant siting.

After this key legislation, the California Energy Commission was established to help develop regulations and building codes to achieve the broader goals initially established by the legislation.

Early building codes and design standards for buildings via power density requirements initiated a series of market pressures for higher efficiency lighting technologies. A significant and rapid evolution of higher efficacy light sources took place, predominately compact fluorescent, T8 lamps, and electronic ballasts, for the purpose of reducing power densities to meet Title 24 requirements for commercial buildings. One of the central developments was the compact fluorescent lamp for reflector lamp applications and downlighting interiors.[3]

A number of key technological advances involved the development of the compact fluorescent lamp architecture, which included the production of smaller tubular fluorescent lamps in a reduced geometry. Two major efforts included developing tri-chromatic phosphors and small electronic ballasts. The key growth of the tri-chromatic phosphor addressed issues associated with high current density on phosphors. With smaller lamp geometries, a corresponding increase existed in phosphor power density, leading to significant reductions in lamp life. The improved phosphor allowed for higher current densities and the smaller compact fluorescent lamp. In addition, the electronic ballasts allowed for a significant reduction in weight for consumer-oriented lamp products as well as an instant-on feature typically demanded by consumers. These two technological advances led to the rapid development of small compact lamp geometries with significantly higher efficacies compared to the traditional incandescent light source. These early compact fluorescent lamp products principally were targeted at the common R-lamp used in the ubiquitous ceiling-integrated downlight. In addition, the CFLs also were targeted at common A-lamp configurations used in a variety of Edison-based applications in residential situations.

In the mid-1980s, there was a significant push in California to reduce lighting energy use in commercial applications. Regulatory pressures and utility incentive programs resulted in a significant development of R-lamp replacements within the industry. This resulted in the development of both compact fluorescent retrofit systems (Edison-based) as well as dedicated compact fluorescent systems for new construction and major renovation. These regulatory pressures resulted in one of the largest market transformation events associated with lighting and led to the development of electronic ballasts, CFLs, and control systems. Power densities for lighting California have been reduced from about 4 W/ft^2 to 1.2 W/ft^2 over the past 20 years.

Figure 1 shows the changes in lighting power density over time from 1973, before the existence of building standards initiated by the California Energy Commission. The graph shows the retail, commercial, and commercial-office lighting power densities. Of particular note are the changes in commercial-office lighting power density from pre-standards to current Title 24 2005 power density standards. In 1973, a typical commercial office building was in the range of 4 W/ft^2. This power density resulted from the use of fairly standard technology, including T12 lamps, magnetic ballasts, and uniform lighting layouts with illuminance typically in the 75 to 100 footcandles range.

In 1978, Title 24 power density requirements for commercial office lighting were set at 2.5 W/ft^2. This power density requirement resulted in a significant market push for next-generation energy-saving technology. By 2005, the power density requirements in Title 24 for new buildings were set at 1.2 W/ft^2.

These power density requirements have helped generate and sustain a significant technological and market transformation within the lighting marketplace across the industry. In the past 20 years, we have gone from static T12 halo-phosphate fluorescent lamps, operating on magnetic ballasts, providing uniformly high levels of interior illuminance, to a marketplace now characterized by high-performance tri-component fluorescent, operating on electronic ballasts, integrated with control systems, including occupancy and dimming systems as well as almost complete market penetration of compact fluorescent in all commercial downlighting applications.

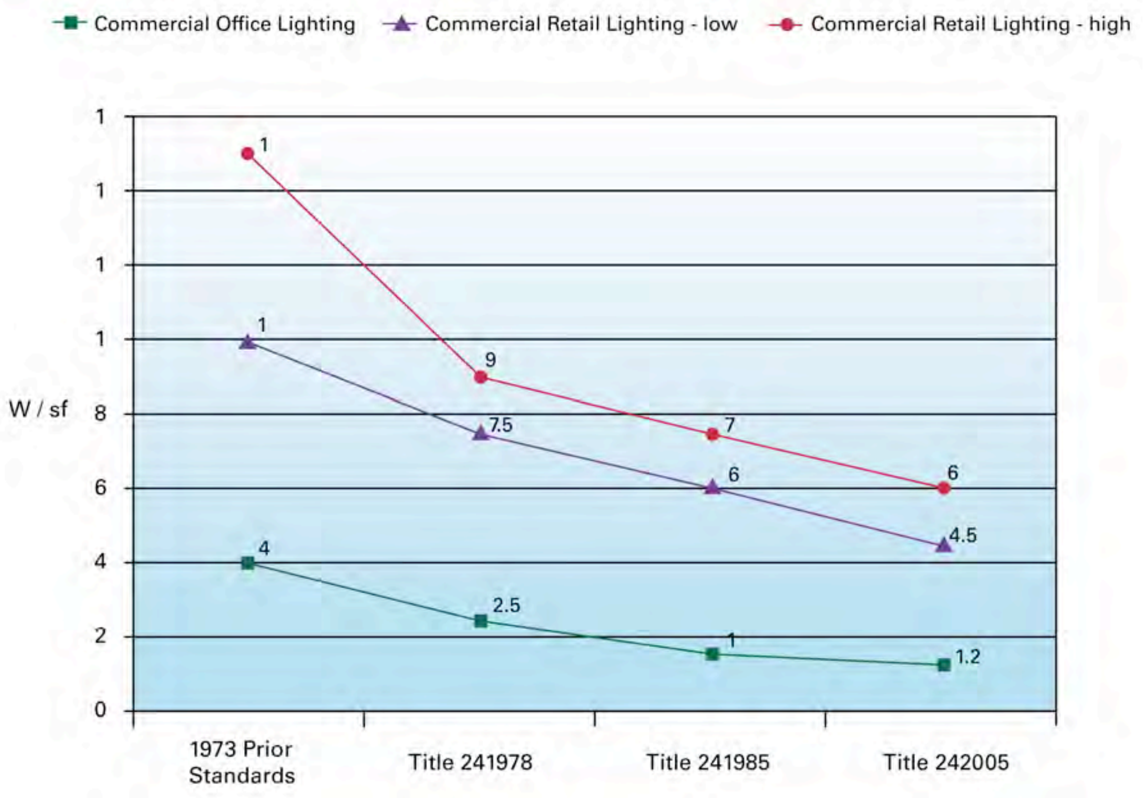
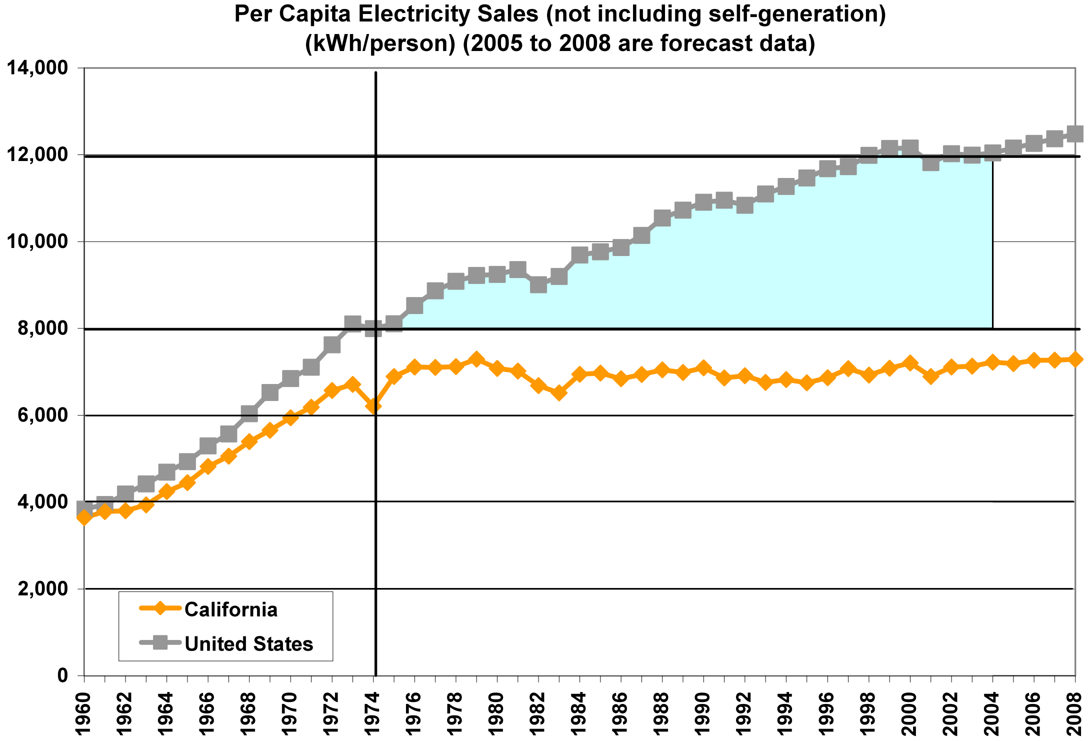


Figure 1: The variations in power density for commercial office and commercial retail applications from 1973 to 2005

This market transformation process illustrates the combined effect of both regulatory and technological advances in lighting similar to the one that is ongoing with LED. In the mid-70s to early 80s, we saw significant regulatory pressures brought to bear in the lighting market that led to advances in efficient building lighting. Many of these early regulatory processes emerged in California, which had an advanced set of tools to help encourage efficient building lighting. This includes the integration of both Title 20 and Title 24 for appliances and new construction. Title 20 typically regulates lamps and ballasts, and Title 24 targets new construction and major renovation. The standards tend to establish minimum performance criteria and expectations for architects and engineers in the design/build process. The results of these standards have had national and international implications for the development of basic technology. Regulatory standards in California have established baseline performance that has led to the development of T8 lamps, electronic ballast lighting controls, and compact fluorescent that are sold both nationally and internationally. The establishment of best practice technology leads to a minimum performance standard that tends to be applied nationally once the market has matured in terms of production and market channel capability.

Figure 2 illustrates the potential associated with appliance and building standards. The graph shows a comparison of the per capita electricity sales for the United States and

California. Since 1974, California has flattened off on per capita electricity sales. The reduction or limiting of the per capita sales is predominantly a result of the existence of appliance and building performance standards that have reduced energy consumption within the state.[4]



A. Rosenfeld California Energv

Figure 2: Per capita electricity sales in California 2005 to 2008

Today we are seeing a similar process for solid-state lighting where concerns about energy efficiency, coupled with a growing awareness of climate change, have heightened the interest in efficient lighting as an effective strategy to address energy-efficiency issues. Furthermore, energy efficiency in buildings has been broadly recognized as one of the most cost-effective means for reducing greenhouse gas emissions. This recognition is based on efficacy associated with the past 20 years of successes with energy-efficiency policy in California.

The regulatory community, the industry, and the California utilities understand that energy-efficient lighting is a highly effective approach to both reduce our energy use within buildings and significantly increase the quality and comfort of end-users.

Many of these lighting energy-efficiency programs conducted by California utilities have demonstrated that energy efficiency is also highly cost effective by addressing the issues associated with our increasing demand for electricity. Studies have shown that energy efficiency regarding cost per kilowatt hour can be significantly less expensive than the cost of new generation through either coal, nuclear, or wind. Energy efficiency has routinely been demonstrated to be a better investment than power generation.[5, 6]

The overall perspective of this paper is that the growing regulatory pressures to address environmental issues associated with greenhouse gases, coupled with rapid technological change, are resulting in a significant market transformation event associated with lighting.

LED Technology

Light emitting diodes (LEDs) are small electroluminescent devices that produce a range of different spectra depending upon the characteristics of semiconductor material. The LED device includes different semiconductor materials that form a P-N (positive-neutral) junction that converts the flow of electrons into the emission of photons within a specific spectrum. The small P-N junction chip is mounted or encapsulated into a package for thermal, electrical, and mechanical control that may or may not integrate a secondary optic for the control of the distribution of flux from the device.

LEDs can produce a variety of different spectra depending upon the material of the P-N junction and the phosphor mix. For general illumination, a broad spectrum of white can be produced in two basic manners. Using three different spectra (red, green, and blue), LEDs can be combined to generate a variety of white colors useful for general illumination.[7] White also can be produced from an LED that emits UV or blue spectra, which then re-activates/re-energizes a small phosphor surface. That surface then re-emits as fluorescence in the visible spectrum. Typically, this white emission combines with the original blue component to produce a broad-spectrum white LED.[8]

Figure 3 shows a typical spectral power distribution for a blue LED with a white phosphor coating. The first peak at the 450 nm corresponds to the blue spectral output from the LED chip itself. This narrowband spectrum provides both the exciting wavelength for the secondary phosphor layer and a blue component to the overall emission. The broader secondary curve peaking at 575 nm corresponds to the broad output from the phosphor layer within the LED package. The secondary fluorescent emission spans all the way from blue to red peaking in the yellow-green wavelengths. Color temperature variations can be achieved by the addition of enhanced phosphors for a shift toward the red or reduction in the blue output, or through the introduction of a secondary array of LEDs that peak predominantly in the red end of the spectrum. Figure 4 shows a comparison between the LED and a typical metal halide light source.

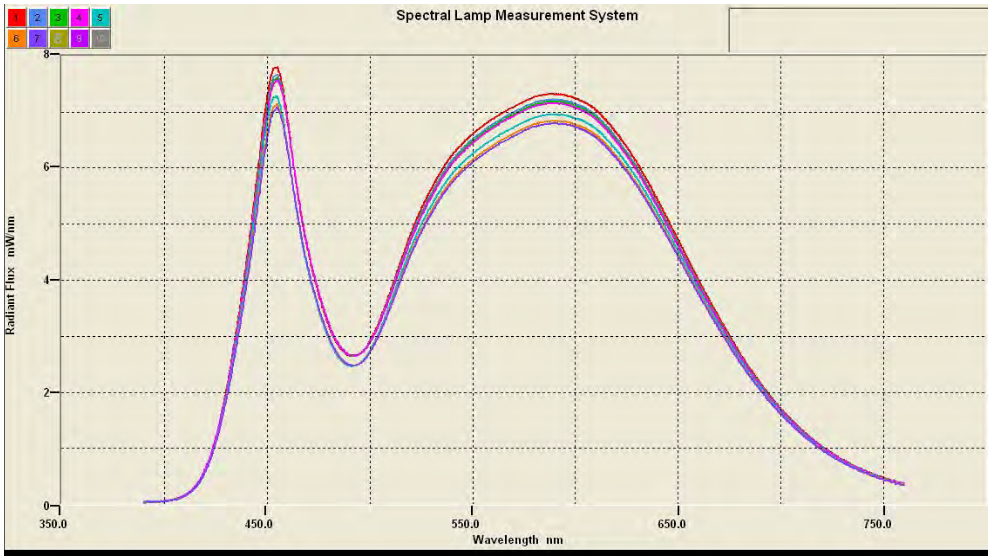


Figure 3: Spectral distribution for a blue LED with a white phosphor coating[9]

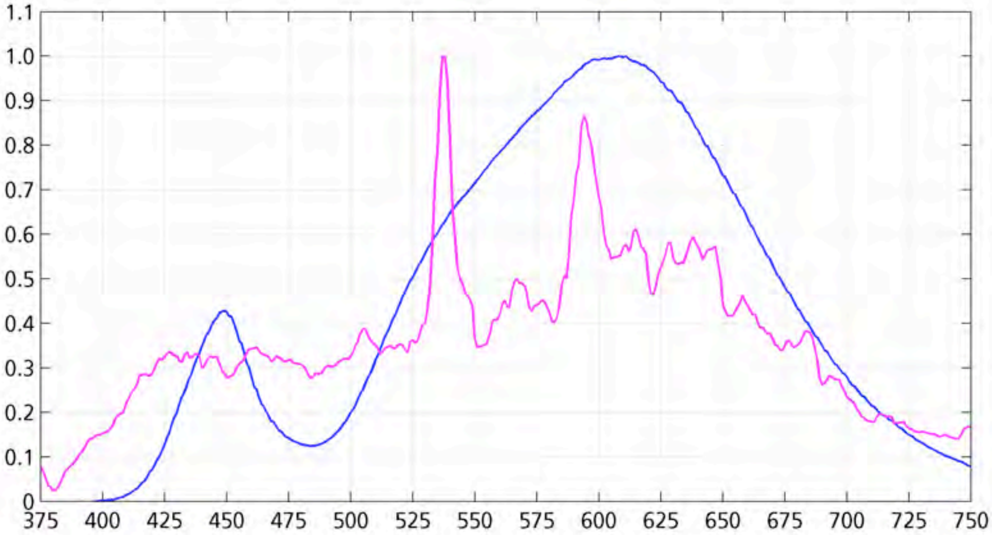


Figure 4: Spectral distribution for a blue phosphor-based LED compared to a typical metal halide high intensity discharge lamp[10]

The anatomy of an LED lighting system includes four principal components:

1. **Electronic driver**: The electronic driver provides the necessary voltage and current characteristics for the semiconductor system. The principal functions of the driver are to convert line voltage to the desired characteristics as well as secondary functions associated with control and safety.
2. **Chip or die**: Typically two- to six-inch diameter epitaxial discs are grown under highly controlled production conditions. This epitaxial layer makes up the P-N

junction, which produces the wavelength specific to the device. These wafers are then diced into smaller individual chips or die for the component packages.

3. **Device or package**: The chip is attached or bonded to a heat sink, a secondary metal surface, to facilitate both electrical connections and to convey thermal loads away from the system. The package also may include the addition of an encapsulation layer such as a phosphor layer for a secondary fluorescent component to the overall emission. The phosphor layer is excited by the blue UV component from the LED junction. The package may include a small internal reflector to convey flux in a directed manner out of the package. In addition, an over optic also may provide optical modifications for specific light distribution characteristics. This plastic optic provides a physical protection of the chip. The package will include electrical attachment points to convey electricity into the LED chip and the bonding wire attachments. Packaging may be done on an individual basis or in multiples extending to larger wafer surfaces consisting of many LEDs on a single surface.

4. **Fixture or secondary optic**: An LED lighting system may include a secondary optic or fixture to match the distribution characteristics of the LED package with the demands of the lighting application. The secondary optical function is similar to conventional fixture design.

Early LEDs in the ’60s and ’70s were simple P-N junctions with relatively narrow spectral emissions. Gallium phosphide LEDs were able to produce a red emission useful for small electronic devices for indicator functions. These devices typically were low efficiency and low brightness. LEDs initially saw large market application for indicator functions in electronic devices including hand-held calculators. The red emission from these devices was enough for an indicator function but not bright enough for illuminance functions.

Further technical enhancement, principally in brightness, efficiency, and in generating different spectral distributions allowing for additional indicator applications, include traffic signals, larger indicator functions, and signage. LEDs, however, were limited in their application to luminance or indicator functions until the late ’90s and early 2000s. This limitation was a function of limited flux output, efficacy, and cost.

Beginning in 2000, white LED devices started to surpass 10 lm/W in commercially available devices in significantly higher lumen packages, making them competitive with incandescent light sources. Since 2000, we have seen a dramatic increase in device efficacy as well as lumen output.

Today the technology has surpassed the hundred-lumen/W device efficacy in significantly higher lumen packages and now is competing well with higher efficacy light sources, including all incandescent, compact fluorescent, linear fluorescent, and high intensity discharge light sources. In the mid-90s, high-performance white-light LEDs first were developed and explored based on the development of blue-emission LEDs, which then activated a secondary layer phosphor that emits in the yellow end of the spectrum. The combined emission produces a broad white light suitable for illumination functions.

Since the early development of these broad white LEDs, significant attention has been focused on three primary efforts, including increasing the inherent efficiency, increasing the absolute flux output, and reducing production costs. Since 2000, we have seen a dramatic increase in device efficacy as well as lumen output, with a progressive reduction in system cost.

Efficacy of LED Light Sources

Efficacy is the key performance attribute leading the development, market penetration, and ultimate transformation of the lighting marketplace from present low efficacy to high efficacy. Efficacy is defined as the amount of visible light-per-unit power. For illumination within buildings, the efficacy is more narrowly defined as photopic efficacy, which relates to the overall spectral sensitivity of the human eye. The photopic sensitivity of the human eye peaks in the yellow-green and reduces toward the red and blue. Typically, light sources are evaluated by comparing the spectral distribution of a specific light source compared to the full topic sensitivity curve. The amount of radiation within the boundaries defined by the full topic sensitivity curve essentially gives us a total amount of useful light flux. This is then compared to the total input power to give us efficacy expressed in lumens per watt (lumens being defined as visually evaluated flux).

For comparison purposes, the following table illustrates a range of typical luminous efficacies for light sources used in illumination. For interior lighting systems, typical white light sources include incandescent in various wattages and lamp types (primarily for residential, hospitality, and retail applications), and fluorescence and high intensity discharge for commercial and institutional applications.[11]

Table 1: Efficacies for common light sources used in illumination

Source	Efficacy (lm/W)
Incandescent	10 – 15 lm/W
CFL	40 – 60 lm/W
T8 / T5	70 – 100 lm/W
Metal Halide	60 – 110 lm/W
High Pressure Sodium	80 – 150 lm/W

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In residential lighting applications, the predominant light sources are incandescent in various wattages with efficacies ranging from 10 to 15 lm/W. Incandescent light sources also are broadly used in retail and the hospitality marketplace. In commercial spaces, efficacies for typical linear fluorescent systems range from 60 to 100 lm/W. Many commercial production spaces, including factories, warehouses, and storage facilities, are illuminated with metal halide high intensity discharge lamps, with efficacies ranging from 60 to 100 lm/W. High pressure sodium light sources are the predominant system used in exterior lighting, which includes street lighting, parking, and façade lighting with application efficacies in the 80 to 150 lm/W range.

LED Development and Key Areas of Innovation

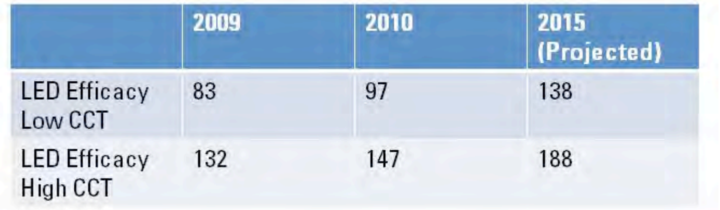
Dramatic increases in LED device efficacy have occurred over the past 10 years.[12] The typical efficacy for LEDs 10 years ago was approximately 10 lm/W. In 2010, laboratory efficacies exceed 150 lm/W, with commercially available systems in the 130-140 lm/W range for general lighting applications. At an LED conference in April in Shanghai, China, CREE reported commercially available LED lighting systems at 130 lm/W.

The principal areas of research that have led to these dramatic increases in system efficacy include the following:[13]

1) Optimizing the extraction efficiency of the device itself. This refers to the development of unique structures that allow the flux produced by the junction to actually leave the structure as useful light and not be trapped within the geometry of the device.
2) The development of high-performance phosphor surfaces that convert the blue light production from the junction into our broader spectrum white light emission. These high-performance phosphors have allowed for a significant increase in the efficiency of the system.
3) Thermal performance. LED devices typically lose efficacy at higher temperatures. Developments in enhanced thermal management and heat sinking have led to the evolution of higher output devices that maintain performance at higher currents.
4) Optimizing electrical characteristics. Significant advancements have been made in LED drivers that operate LED devices at optimal current and voltage characteristics with high conversion efficiencies.

We are seeing significant changes in efficacy as high-performance devices rapidly develop. Table 2 shows the changes in efficacy from 2009 to 2010 and projected efficacies for 2015 for both low Correlated Color Temperature (CCT) and high CCT devices. LED efficacy for low CCT currently is 97 lm/W and is projected to increase to 138 lm/W. The higher CCT devices currently are 147 lm/W with a projected increase to 188 by 2015. The differential in efficacy between low CCT and high CCT devices is because lower color temperature systems tend to have more flux in the yellow-red region of the spectrum and less light in the blue region. This reduces the overall system efficacy of the device as it discounts the primary blue emission of the device.

Table 2: The corresponding efficacies for low CCT and high CCT devices



	2009	2010	2015 (Projected)
LED Efficacy Low CCT	83	97	138
LED Efficacy High CCT	132	147	188

Efficacies for LED light sources have surpassed conventional white light sources, including both incandescent and fluorescent lighting systems. Efficacies for white light devices are projected to reach 250 lm/W, which is close to the theoretical maximum efficacy for a white light source. At 250 lm/W, the primary area of research will focus exclusively on reducing production costs, increasing system life, and enhancing color control characteristics. It's interesting to note that the current perception within the industry is that the major barriers to LED technology are cost and color characteristics and not efficacy. This is similar to what we saw with compact fluorescent lamps, which are currently in the 50 to 60 lm/W range with small (~15%) market penetration in the United States. Compact fluorescent for residential applications does not compete well with conventional incandescent technology in terms of color or cost.

Increasing the efficacy of LED devices is critically important for two basic reasons. First, with higher efficacy comes the ability to lumen match higher white light sources with progressively reduced power consumption. This process extends the market potential for the LED into higher wattage incandescent and fluorescent and ultimately HID light sources. Already, LED devices compete well with conventional incandescent and halogen light sources in terms of efficacy. Typical incandescents are in the 15 lm/W range, and halogen systems can be 19 to 20 lm/W. At 130 lm/W, LED lighting systems can easily match the lumen output with 10% of the input power. Commercially available systems offer comparable lumen packages today at about a third of the input power. With continuing advancements in efficacy, LED technology soon will be commercially available to displace conventional linear fluorescent applications. At 130 lm/W, an LED linear system could match the lumen output with 30 to 40% reduction in power. The current constraints to this type of system include cost in high-efficiency optical systems.

The second opportunity associated with higher efficacy systems is the reduction in component heat sinking required to maintain optimal temperature conditions for the LED device. LED devices are highly temperature sensitive, and a considerable amount of cost goes into ensuring their efficacy and life characteristics. With higher efficacies there is proportionately less heat produced within the LED device itself, and this reduces the overall demand for thermal management via expensive heat sinking. This provides an opportunity to further reduce costs through reduced number of components and assembly.

A significant amount of innovation is occurring in LEDs at the device level, which is being supported by an unprecedented level of industry and government funding. The primary areas of research and innovation for LED development include the following:

Epitaxial layer: Major areas of research are focusing on enhanced performance of the epitaxial layer and its wavelength emission to improve the final color characteristics and uniformity. The focus here is to narrow the fundamental epitaxial emission to a highly defined spectral distribution, which then can be tuned to the phosphor layer to more finely control the final spectral characteristics. Additionally, significant effort is concentrated on improving the efficiency of the epitaxial layer. This includes improving the uniformity characteristics across the epitaxial layer and increasing the size of the final production. Improving the uniformity and the size of the epitaxial layer will result in a significant reduction in costs due to efficiency of production. This means specifically more output per unit wafer. In addition to the epitaxial focus, there is a considerable amount of research being done on the use of lower-cost substrates for the epitaxial layer. This has included examining the replacement of traditional sapphire substrate with silicon substrates with the corresponding potential to reduce costs by as much as 50 to 60%.[14]

Packaging and device development: The second major step involved with the device development is the packaging of the junction. This involves taking the fundamental epitaxial layer and cutting it into specific sizes suitable for the application. This process is called dicing. The small individual die is then bonded to a secondary metal surface with appropriate electrical and thermal connections. A secondary material for encapsulation provides phosphor and protection.

A significant amount of research and innovation is occurring in developing high-performance encapsulations, which includes the phosphor layer or mix for the primary emission for the LED device. The objective of this work is to improve the spectral distributional characteristics of the device for enhanced color performance. This is principally focused on increasing the color rendering properties on the lighting system for illumination purposes. Recent research has resulted in an LED color rendering index of 90 and above. A color rendering index of 90 will compete very favorably with traditional incandescent and high-performance fluorescent light sources, greatly increasing the marketability of LEDs for retrofit lighting applications.[15]

A significant amount of activity also is being directed at enhancing the optical efficiency of the package to reduce losses of flux within the device. The extraction of light from the device is a primary area of research leading to the dramatic increases in efficacy in recent years. The potential for enhanced extraction of flux will allow device efficacies to reach the theoretical maximum of 250 lm/W. This innovation involves the development of fundamentally new geometries for the device itself, which could reduce the internal losses within the device and allow for more enhanced encapsulations with the phosphor layer that reduces back losses. Conventional LEDs can lose as much as 60% of the flux at the phosphor layer where light is redirected back into the device itself. Ongoing research is focused on achieving an ideal conversion of blue to white light with minimal losses. The combination of enhanced geometries, phosphors, and reflectors can lead to blue to white conversions with losses of only a few percent. These enhanced geometries will greatly increase the efficacy of the overall system.[16]

Structure of the LED Lighting Industry

The American lighting marketplace traditionally has been dominated by three light source companies: Osram Sylvania, Philips, and General Electric. Additional market entry points for systems and solutions are made up by a much larger, more fragmented industry, principally in the luminaire fixtures and control gear arena. In the American commercial marketplace, the lighting industry level has been dominated by Cooper Lighting, Lithonia, and Genlyte. This industry includes thousands of entities but traditionally has been dominated by a few larger fixture companies, particularly within the commercial and institutional arena where economies of scale and traditional channels prevail. The residential and hospitality marketplace is made up of a much larger subset of smaller manufacturers with products that rely much more on craft-style than production or economies of scale. Many of these products are a function of craft and involve small production and custom-oriented capabilities. In the past 10 to 15 years there has been a significant shift in primary production capabilities for industry, where the bulk of these materials are made offshore, principally in Asia. Some assembly and component work still exists in the United States.[17]

This shift in production capability for both lamps and fixtures has been quite dramatic. In 1990, the lamp imports were about 20%, and today that import figure has surpassed 50%. The same shift in production is true for fixtures and assemblies, where the majority of fixture systems are now imported to the United States with principal production being in Asia. About 90% of all fixture systems used in the United States are produced offshore. This shift is due primarily to the reduced labor costs in Asia for fairly labor-intensive fixture systems. Conventional fluorescent and incandescent lighting systems are still fairly labor intensive, involving many subcomponents and assemblies to make up the total fixture. A conventional fluorescent trough, for example, may have 10 to 15 different components, each involving multiple forming, handling, and assembly procedures, and therefore costs can be significantly reduced with a fundamentally lower labor cost.[18]

An understanding of the lighting industry also includes a detailed view of how lighting is delivered to the marketplace. Overall, this includes four elements: 1) the manufacturers of light source components and systems, 2) agents and representatives, 3) distributors and retailers, and 4) specifiers and designers. In terms of the current market transformation from conventional light sources to solid-state lighting, this overall delivery chain is fundamentally the same with the addition of some new players in the source and packaging arena.

Some of the evolving energy-based activities and related utility purchases and programs may tend to short-circuit some of these relationships, particularly in the LED procurement effort. In addition, energy service providers will play a larger role in supplying lighting systems to end users and rule broker large purchase agreements with the manufacturing community. Utilities themselves may end up in the lamp procurement business by brokering arrangements or understandings with manufacturers to procure large quantities of LED light sources to displace portions of their load. Buying down large quantities of LED production may actually be significantly cheaper than the alternative of building power generation capabilities. In this case, the utility may become the owner, purchaser, installer, and channel for lighting systems into end use applications.

Ongoing activities within California utility programs that involve large third-party initiatives may replicate this type of activity where programs will make connections between manufacturers and large end users in the lighting arena. This activity will grow substantial as utilities strive for increased savings. However, the conventional production to the end use food chain will remain and thrive under the solid-state lighting era as it did under the conventional light source era.

The overall industry is made up of three basic components of the focused areas of production. The first component involves the epitaxial materials or chipmakers. This part of the industry is dominated by relatively few players being very capital and patent intensive. This industry requires sustained and rapid innovation and therefore requires a significant R&D investment. Furthermore, this portion of the industry is extremely capital intensive, requiring a lot of investment for laboratories and apparatus for the fundamental production of epitaxial materials. The nature of these materials also requires complex laboratories for controlled conditions in a semiconductor marketplace.

Lastly, this marketplace is subject to rapid change involving the expensive modification, addition, or replacement of laboratory and production apparatus. This furthers the need for capital and intellectual capabilities that limits the number of firms engaged in this part of the marketplace. The early roots for this portion of the industry were dominated by Asian players in Japan, Korea, and Taiwan, and they still have a large subset of the overall marketplace. Early American presence was achieved by CREE and Lumileds, which were the two principal drivers in the early American LED development and applications area. Traditionally, larger players such as Philips, Osram, and GE achieved a strong presence in this marketplace through the early acquisition of smaller entities that were highly innovative. CREE, an American manufacturer, also had a strong market presence as an early university spinoff in the epitaxial and chip development area. CREE has a strong market presence all the way from chip production to manufacturing to its recent acquisition of LLF, an innovator in the fixture market arena.

Philips, Osram, and GE have further extended their fundamental production capabilities at the chip level through partnerships and acquisitions in Asia. The rest of the marketplace at the epitaxial layer is dominated by Asian manufacturers from China, Korea, and Japan, and by CREE in United States.

The second large component of the LED industry includes the packaging and integration of the chip into useful lighting subcomponents suitable for the luminaire/fixture industry. This portion of the industry transforms the fundamental chip into a light engine and includes the integration of thermal, optical, and electrical components at multiple levels of scale from single to multiple chip assemblies. These packaging functions also are undertaken by the larger epitaxial chip manufacturers through companies or divisions that they own or operate. This portion of the industry also has seen numerous new entities with the ability to provide packaging functions, as it is significantly less capital and IP dominated in the die manufacturing portion.

The end-use marketplace directed at LED solutions and fixtures is still dominated by a few of the conventional large players, including Philips, Osram, GE, and traditional fixture companies like Acuity and Cooper. However, there has been a significant increase in the number of small LED fixture and solution providers to the end-use marketplace. Entry into this portion of the marketplace requires a relatively small amount of capital and can be based on innovation and key connections to deliver solutions to the market. Many of these entities are relatively small with few employees and are subject to rapid change. This part of the marketplace will see rapid iteration and development of entirely new types of lighting solutions based on the product attributes associated with LEDs. This is in contrast to the conventional fixture manufacturers that typically are adverse and focused more on cannibalistic opportunities associated with solid-state lighting.

The mainstream fixture and luminaire marketplace is currently seeing a market transformation in all product application groups. Virtually all of the conventional offerings and products subgroups include an LED version. Many of these product offerings are cannibalistic in nature, meaning that they essentially displace current market share with products that the company already sells. Some of these products will continue to differentiate and evolve into products subgroups that are truly revolutionary in terms of presenting opportunities for lighting and applications that have not been seen before and truly capitalize on the product and performance attributes associated with solid-state light. This includes the product applications for downlights, recessed, strips, cove lighting, pendants, wall sconces, emergency lights, and decorative lighting for commercial applications. One of the biggest market transformations in terms of product offerings has occurred in the residential downlight marketplace. Virtually all of the mainstream downlight manufacturers now offer an LED version concurrently with CFL and incandescent product offerings.

Significant innovation is occurring at this part of the marketplace at the interface between solution and end-user driving change. Numerous small commercial ventures are being created, offering new and innovative solutions to the end-use marketplace. This activity is helping to define future products and product trends for the larger portions of the LED fixture industry. Many of these entities will not survive the traditional business cycles but are significant to identify market needs and user preferences for innovation. Many of these innovators also are being acquired by larger, more traditional fixture companies to help define the LED market interface for these entities. This type of acquisition has occurred across the marketplace all the way from the chip, package, and fixture levels (Figure 5).

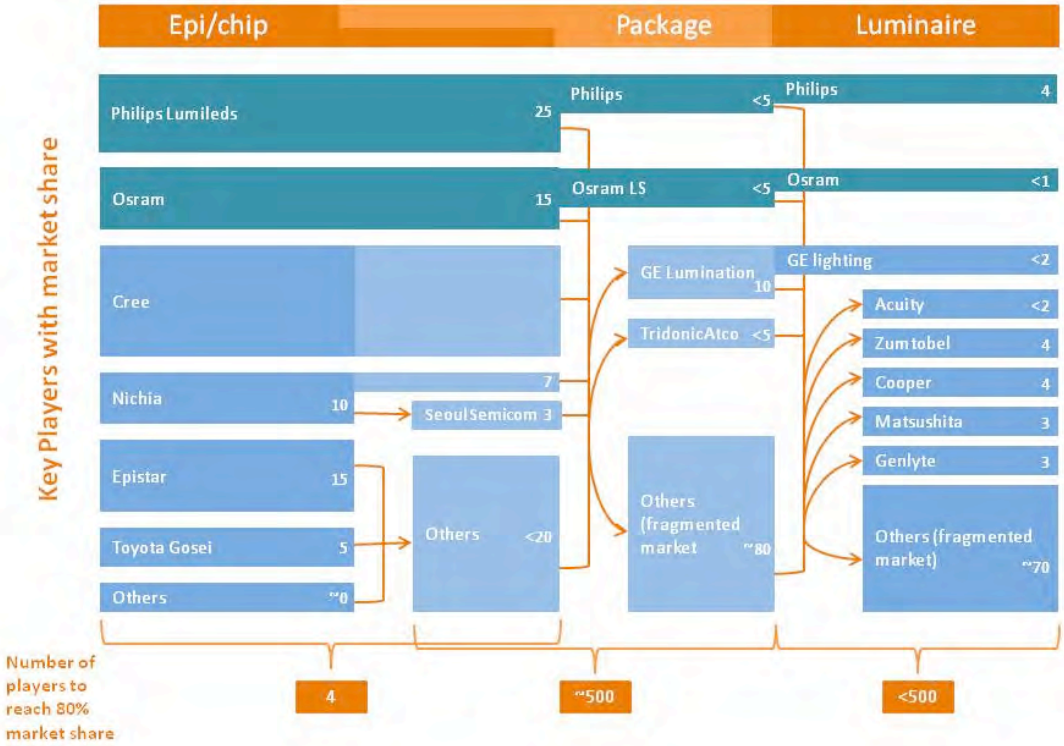


Figure 5: The current LED industry by key players and market share estimate[19]

LED Market Development and Evolution

The current LED lighting marketplace is seeing significant change because of rapid advances in both technology and programs designed to encourage their application. Industry estimates indicate that the global lighting market was approximately $75 billion in 2009. At that point, 99% of the market used traditional lighting approaches relying on incandescent, fluorescent, and high intensity discharge lamps. One percent of the marketplace was using solid-state lighting systems. Industry estimates that by 2015 the lighting industry will grow to $91 billion, and solid-state lighting will make up about 50% of all applications with the remaining being conventional lighting systems. The DOE 2005 application breakout also projected 50% of the LED industry will be directed at illumination by 2015. The vision for 2019 will be for the lighting industry to grow to $122 billion, and solid-state lighting will make up 75% of that market.

There are several key market and product drivers that are advancing the market transformation associated with solid-state lighting:

1) **Product driven developments**: These developments stem from technological advances in efficacy and spectral quality and in reduced production costs.

2) **Parallel and potentially complementary market developments in flat-panel displays**: The rapid evolution of LED lighting systems suitable for flat panel

displays will result in a core development of production and technology that will translate easily to the illumination marketplace. Significant investment and effort is going into the research and development for relatively expensive flat panel display systems. With rapid return on investment potential as market share increases with corresponding production capabilities, the cost reduction potential can be translated over to the illumination marketplace. The development of the LED technologies for flat panel displays is driven by the need for improved color characteristics, reduced cost, reduced power demand for the conventional home television appliance marketplace, and for a reduction in size. In 2009, the industry estimated that about 50% of LED production was for phones and notebook displays, 20% for flat panel, and 12% for illumination (lighting). We are seeing a rapid market transformation for the display marketplace to LEDs with estimates of 50 to 75% market penetration by 2012. The display industry is projecting that by 2015, 100% of the market will be transformed to LED light sources for flat panel displays. This transformation will have significant implications in terms of cost and performance for the lighting industry. Many of the attributes for color, cost, and production can be translated over to the illumination marketplace.

3) **Government-supported R&D**: Early, long-term government investments have occurred in Korea, Taiwan, and Japan in the basic LED science with strong connections to the LED industry. Strong presence in the LED industry from epitaxy through to displays and lighting illustrates the efficacy of these types of early investments in industry partnerships. The United States and now Europe have similar R&D programs to support industry development activities.

4) **Environmental and regulatory developments stemming from government investment and programs**

5) **Market demand**: Architectural and end-use applications including heightened consumer awareness for sustainability and energy efficiency.

Key Focus Areas: Lighting Applications and Markets that are Experiencing Rapid Innovation and Transformation

The following sections highlight specific marketplaces that are experiencing rapid market transformation and are subject to a significant level of innovation. These marketplaces are seeing a significant level of change because of a combination of technological advances within the industry, coupled with unique market forces, including regulatory and government stimulus. Additionally, some of these early market applications are uniquely matched to the product and performance attributes associated with solid-state lighting:

1) Downlights
2) Lamp replacements
3) Exterior lighting

4) Linear fluorescent
5) Display

1) Downlighting/Directional Lighting: A large, near-term, and emerging marketplace for LED lighting systems exists in both commercial and residential directional lighting applications. Directional lighting includes ceiling-integrated downlighting applications as well as various track and display lighting using a variety of incandescent lamp types. A recent report prepared for the Department of Energy indicated that downlighting was one of the larger, near-term opportunities for LED lighting.[20]

These incandescent lamp systems include various styles and wattages but are principally used for directional lighting applications involving displays, highlighting, and accent. The vast majority of directional lamp systems are in the 10 to 15 lm/W range, making them prime candidates for more efficacious alternatives. Directional incandescent lamp types have maintained their market share compared to more efficacious compact fluorescent alternatives. The lack of market penetration of compact fluorescent within this marketplace is because CFLs do not produce the directionality or beam spread control that is so popularly associated with traditional light sources.

In commercial building applications, which include traditional office, retail, institutional, and hospitality sectors, it is estimated that about a third of the lighting energy use is from incandescent lighting applications. Many of the commercial incandescent applications are directional (downlights and track) in nature using a variety of R, PAR, and MR lamp geometries.[21] Industry partnerships have indicated that there are about 800 million recessed downlights in the United States and that 83% use a variety of incandescent lamp types. Transforming these incandescent lamp systems to LED downlights would result in one of the largest lighting energy saving opportunities in the United States, with an estimated savings of 81 trillion kWh per year. This savings potential was based on an industry estimate of 60 W per traditional incandescent moving to 14 W of LED downlight.

Residential downlight applications also are significant opportunities for market transformation with LED retrofits and dedicated systems for new construction. There has been a growing trend over the past 10 years in residential lighting design to use progressively more ceiling-integrated downlights for standard illumination throughout the kitchen, dining room, hallways, and common spaces in the home.[22] The growth in the use of downlights was predominantly driven by changes in the design world with an interest by residential designers to maintain clean ceilings and a downlighting look. This design change has led to one of the largest increases in residential lighting load because the majority of the systems use directional lamp types that typically have lower efficacies than lamp geometries.[23]

Figure 6 shows a scatter plot of the total number of downlights used in new construction based on a survey of new-construction homes in California. The scatter plot shows the distribution from 10 to 40 downlights as typical in a range of square footage for new construction. This trend in downlight use is occurring in other regions of the country and represents a significant opportunity for LED retrofit kits.

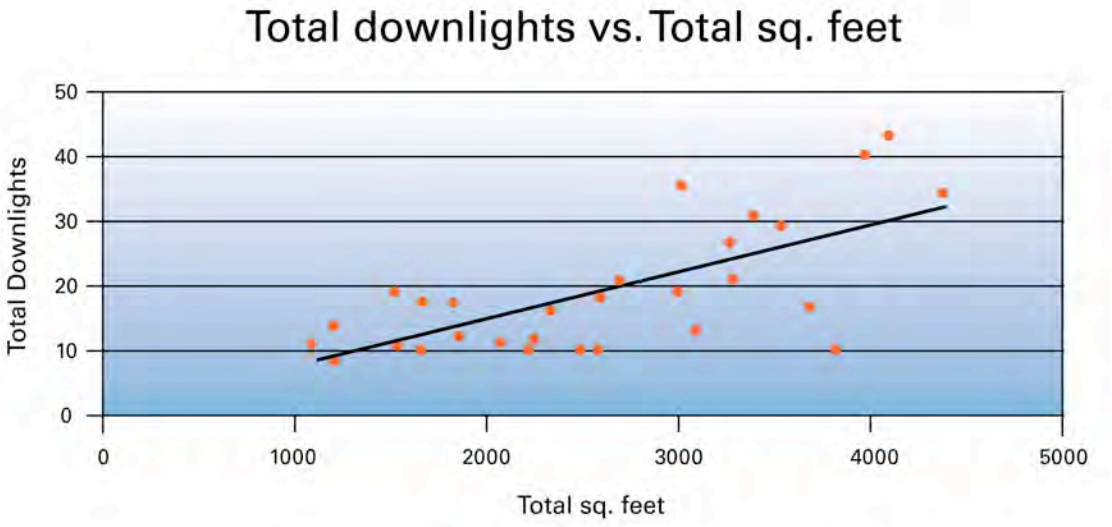


Figure 6: The number of downlights in new construction pre-Title 24/05[24]

In 2005, Title 24 was the first regulatory activity in the country to target residential downlighting applications. It specifically targeted residential kitchens in new construction, requiring high efficacy (+40 lm/W) downlight approaches to be applied. This regulatory activity resulted in a large-scale market transformation from incandescent downlights to compact-fluorescent-dedicated downlights for all new construction. While this regulatory activity has been successful for most new home construction since 2005, it still leaves a significant base of homes constructed over previous years before the new code.

Additionally, there is a significant level of consumer dissatisfaction associated with the compact fluorescent in downlighting applications, predominantly driven by poor color rendering, lack of dimmability, and poor optical distribution compared to traditional lamp geometries. This dissatisfaction has led to discontent within the design community and by consumers and has actually prompted efforts by homeowners to convert back to directional incandescent.

While Title 24 has been a significant step forward in the United States in terms of moving the downlighting marketplace from incandescent to fluorescent, there is still a significant installed base within the residential market of incandescent light sources. In 2005, it was estimated that new construction represented less than 2% of the entire residential base. This installed base market is a significant opportunity for LED retrofit kits that address the primary issues associated with color and dimming that are not adequately addressed by conventional CFL retrofits. Consumers are, by and large, unhappy with traditional Edison-based retrofits that do not produce good color or the dynamic dimming capability needed.

In commercial construction within California, early regulatory activity via Title 24 for new construction and renovation has essentially transformed the downlighting marketplace from incandescent to dedicated compact fluorescent. Many of these commercial applications do not require the dynamic dimming capability or the color demand for the residential marketplace. However, significant potential exists in the retail market that is still predominately incandescent, as current code in California provides significant leeway for low-efficacy light sources.

2) A-lamp replacements: Incandescent A-lamps are some of the most common lamp types in the United States and represent one of the largest near-term opportunities for LED retrofits. In California, studies have indicated that there are about 50 lamps per home, predominantly incandescent light sources.[25] This market arena is highly visible as a significant energy user in this country and is being targeted from multiple fronts to encourage market transformation leading to energy efficiency. Converting incandescent A-lamps to energy-efficient alternatives, principally compact fluorescent, has been one of the largest regulatory and incentives programs in the history of lighting. The vast majority of this activity has occurred in California, the Northwest, and the Northeast through a variety of utility-driven incentive programs where the utility essentially buys down the technology, reducing the cost to the consumer to encourage sales.

In California, utilities actively engage in energy-saving programs and advocate incentives by the California Public Utilities Commission to engage in energy-saving opportunities. Energy-efficient lighting, principally compact fluorescent, has been one of the larger revenue-generating sources for these programs, and therefore has been a better principal target over the past 10 years for forward-thinking rebate activities. Incentive programs coupled with enhancements in production and volume purchases have led to a significant reduction in cost per lamp to approximately $2 per lamp in California. CFLs reduced in cost from approximately $14 per lamp to $2 a lamp in less than 10 years primarily due to incentive and utility rebate programs in California and elsewhere (Figure 7). These forward-thinking programs had a secondary effect as the costs across the United States reduced in parallel to the California-based cost activity, indicating the efficacy of this type of market incentive activity. Compact fluorescent lamp sales from 1999 to 2007 went from 500,000 lamps per year to more than 56 million per year as a function of the utility incentives coupled with large bulk purchases.

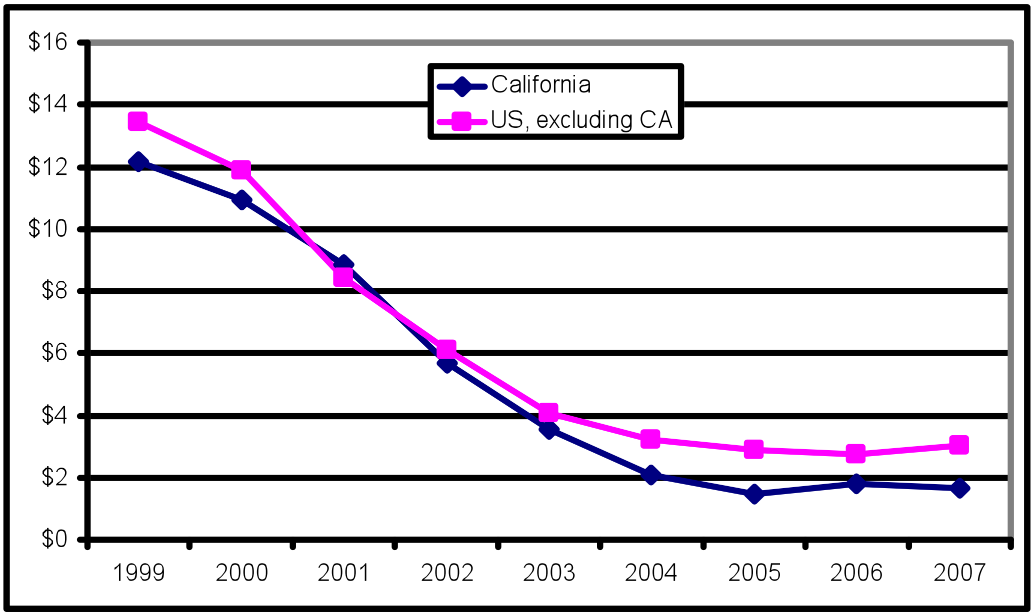


Figure 7: The reduction in compact fluorescent lamp cost to consumers over the past eight years for both California and the United States (excluding California) showing the parallel reduction and similarity in final costs (*from California Residential CFL Market Status*. Rep. CPUC - Energy Division)

Unfortunately, lower prices, incentive programs, and relatively large promotion efforts from federal state and utility entities have not resulted in a large or sustained market transformation. Optimistic estimates in California indicated 20% market penetration of incandescent sockets with compact fluorescent. Industry-based estimates are closer to 15% in California, and the Department of Energy estimates that nationally there is 15% market penetration of CFLs. More conservative estimates are closer to 10% of the marketplace being transformed to compact fluorescent.[26]

The main issues behind poor market transformation include poor color quality, inability to dim, and shape-fit of the technology. These issues are critical to understand for LEDs to be more successful in the A-lamp market transformation.[27]

The compact florescent lamp market transformation effort is an important lesson to understand relative to the innovation and programmatic effort associated with current LED A-lamp replacements. Significant effort is occurring across the industry to target the A-lamp replacement. Cost, again, is being targeted as the main product attribute for both programmatic and technical innovation. However, even at $2 per lamp, the CFL transformation effort has been dismal at best. Technology developers and programmers at the federal and regulatory level need to understand this and target a broader range of performance and product attributes for this transformation effort to be successful.

There are two basic issues the LED industry and regulatory community need to understand in this fundamental process of market transformation that can be gleaned from the past 15 years of activities associated with the CFL lamp:

1) **Unanticipated consequences**: These are related to performance issues that happened in lighting applications that were unexpected. With compact fluorescent lamps, these issues included early failures, flickering, inconsistent color matches, noise, and humming. These negative experiences are the principal reasons why there was a broad marketplace failure with compact fluorescent.

2) **Unfulfilled consumer expectations**: Illumination consumers purchase light sources (A-lamps) to provide a certain level of service in terms of the quantity, quality, and longevity of the light. Consumers have grown up with a set of performance circumstances in terms of spectrum color and performance, and they expect those to be maintained or exceeded. With compact fluorescent, the typical performance usually resulted in a net departure from a level of baseline service. The CFL lamp technology has by and large failed to match the basic performance that consumers had learned to expect. This lesson is critical in the innovation and development process for next-generation lighting.

Cost and efficacy are important issues for the lamp replacement and technology developers. There is a need to critically address user amenity issues and focus on color quality, light distribution,[28] dynamic control capability, and the size and fit of the technology for it to be successfully adapted to this marketplace.[29]

Current barriers at a technical level include thermal dissipation and the ability to lumen match 900 plus lumen packages typically achieved by 60 W incandescent light sources. A-lamp geometries are not ideal for dissipating heat with the minimal surface area volume relationship. This issue is being addressed by novel heat sinking capabilities as well as further increases in efficacy to reduce the thermal dissipation requirement. Most of the commercially available LED packages are highly directional in nature, where a typical A-lamp is usually isotropic. Many early commercial entries to the A-lamp marketplace are highly directional in that the flux is emitted primarily in one direction. These types of LED lamp retrofits may be useful in some downlights, but they will not give the consumer the type of diffuse distribution one would expect for table lamps and lighting fixtures that have traditionally used a broad diffuse light source.

Dynamic control capability is an issue that is easily addressed with LED electronic light sources with the addition of small electronic circuits. The LED light source is also something that is easily dimmed over wide dynamic range without problems. Significant developments are ongoing in addressing the color quality issues, and recent developments and new phosphors have indicated that 90+ CRI is achievable and commercially available.[30]

Key LED Technology Innovations and Product Attributes that Need to be Addressed

1. Efficacy improvements leading to reduced thermal requirements and cost
2. Improved phosphors leading to higher CRI
3. Improved optics for wider distribution optics
4. Reduced packaging costs

Key Market Innovations that could Accelerate Market Transformation

1. Utility upstream incentive programs
2. Programmatic efforts with energy service organizations that own and lease energy savings
3. Aggressive regulations, including appliance and building codes

3) Exterior lighting: Exterior lighting, predominantly street and parking area, has become a primary focus within the LED market transformation arena. This transformation function is a result of a combination of factors, including strong federal interest in funding, significant interest from environmental organizations, municipal interests to reduce cost, and a strong public focus on energy efficiency, dark sky, and energy waste issues.

Exterior lighting represents about 8% of the U.S. lighting primary energy use. The two largest portions of this are street lighting and parking lot applications. LED street and area lighting has been a target for federal, state, and utility efforts because of its visibility and opportunity for significant savings. The primary focus of this has been to replace common HPS and metal halide light sources with an LED retrofit approach. The concept is that a higher efficacy light source in combination with the potential for increased optical performance will achieve a reduction in lighting energy use and light pollution.

Government stimulus funding targeted at states and municipalities has further generated an interest in solid-state lighting as a broad replacement of cities' inventory of older HPS lighting systems. There has been a rapid development of LED-based fixture systems, and the majority of American manufacturers now have a number of product offerings for street and area lighting that use LED systems. Utilities now are rapidly developing rebate programs to further encourage the market penetration and application of LED street lighting.

There has been much discussion centered on the overall savings associated with this market transformation effort, and the most central has been one focused on the integration of dynamic control capabilities. Ongoing studies focused on dynamic control capabilities have demonstrated that 50 to 60% additional savings can be achieved relatively easily with the integration of occupancy and vacancy controls that reduce the light to some preset lower level during periods of vacancy. Unfortunately, the integration of dynamic control capabilities has not been part of the national dialogue on the LED market transformation issue. Significant efforts are ongoing now to incorporate control capabilities into area and street lighting efforts both in California and nationally.[31, 32]

The general process would be that during periods of vacancy, street and area lights would be reduced to some preset lower illuminance level and would automatically increase to a higher level on the detection of movement or occupancy. This dynamic tuning capability would significantly increase the energy savings associated with this national market transformation. It also will increase the potential for enhanced safety and security due to heightened awareness, which is a function of dynamic change of light. There are ongoing demonstrations of this adaptive bi-level smart lighting approach across the United States. The California Energy Commission, through its regulatory activity, now is examining various mechanisms to include this in both Title 20 and in Title 24 for the lighting of all exterior spaces.[33]

Figure 8 shows the dynamic variations in wattage for an LED exterior lighting application at California State University, Sacramento. The before-and-after illustrates the variations in power throughout the day for a static HPS lighting approach versus a dynamic LED lighting approach. In this case, the LED retrofit system was designed to include sensors and controls that dynamically control the light based on occupancy and vacancy. The LED lighting system would be reduced to about 30% of the power when the space is vacant, and upon occupancy, the light would increase to 100% power.

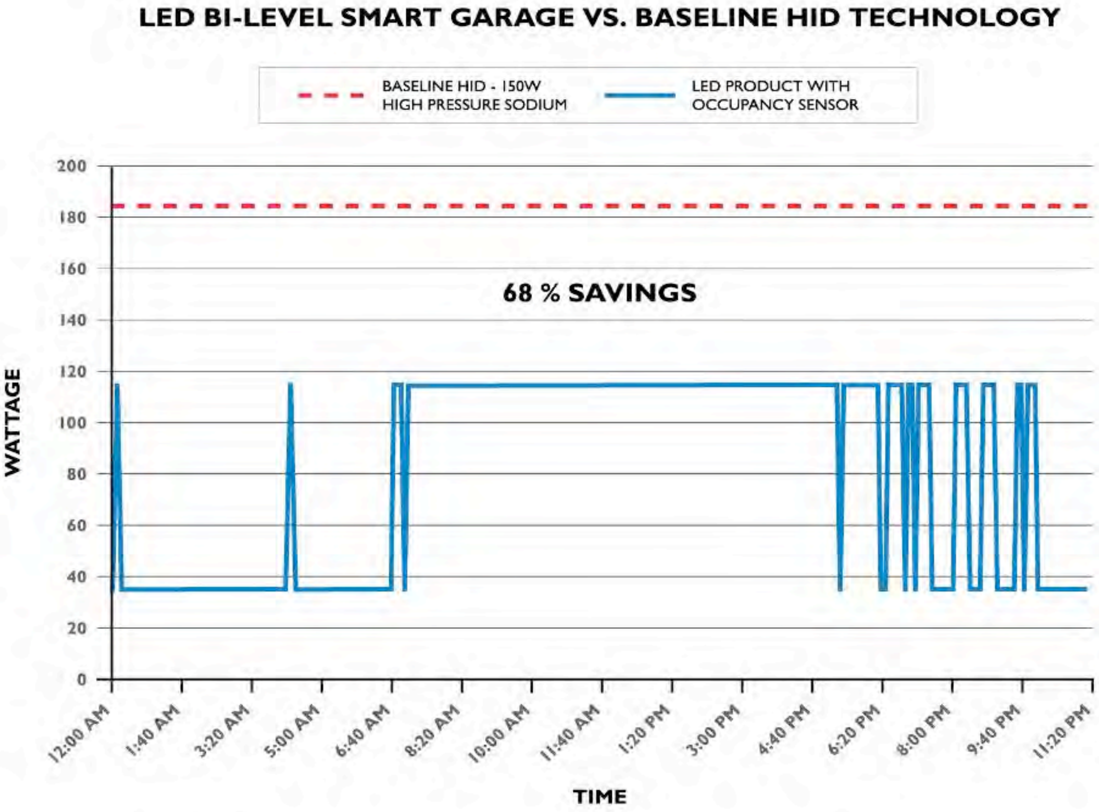


Figure 8: The dynamic changes and wattage for an LED system in an exterior lighting application[34]

The savings associated with dynamic control capabilities is 50 to 60% and is projected nationally to be one of the single largest opportunities for exterior lighting energy savings. LED is essentially the precursor to this with the technology attributes that will allow this process to happen.

This opportunity is both market driven and product driven in that an electronic solid-state lighting system is particularly amenable to dynamic control capabilities. Conventional light sources, such as fluorescent, metal halide, and sodium light sources, are not easily switchable or dimmable given dynamic control signals. This inability to offer dynamic control capabilities has significantly limited the energy-saving opportunities in this marketplace. With the rapid development of LED street lighting systems, we now have a national and international opportunity to significantly enhance the savings opportunities with dynamic controls for street and area lighting.[35] The critical need at this point is a national and international specification that directs all exterior lighting systems to include an adaptive dynamic control capability to address these energy-saving and safety issues in area lighting. This enhanced capability will perhaps be one of the most important market drivers behind achieving widespread application of solid-state lighting in exterior lighting applications.

Key market innovations that could accelerate market transformation

1. Development of a well-thought-out national specification
2. Long-term rebate programs
3. Demonstration and testing

4) Linear fluorescents retrofits: The linear fluorescent marketplace is one of the largest nationally and internationally, and it represents a significant commercial opportunity for innovation. In North America and Europe, the predominant light sources are the T8 and T5 lamp geometries operating on electronic ballasts with efficacies of approximately 100 lm/W. LED linear geometries are being viewed as a potential retrofit for linear fluorescent. At today's efficacies and costs, the retrofit potential is still very limited, using efficiency as the market driver. However, industry estimates are projecting LED performance to approach 200 lm/W by 2015 with an associated cost of about 1 cent per lumen. At these performances, the LED retrofit certainly will become more competitive.

5) Display lighting and retail applications: Retail and service buildings in the United States account for about 20% of all commercial energy consumption and are second only to office commercial construction in terms of energy use.[36] Lighting can make up 30 to 50% of the overall energy that gets used inside retail spaces, principally in display and highlighting applications. Display lighting is typically highly directional in nature, involving accent and highlighting requirements. Light sources for this type of display application include reflector lamps of various wattages and include PAR, R, and MR16 lamps with efficacies in the range of 10 to 15 lm/W. Retail applications are some of the most energy-intensive applications for lighting because of the almost exclusive use of directional incandescent.[37] Compact fluorescent has seen relatively little application in retail lighting because of the inability to create specific beam spread and pattern control with a large area light source typical of fluorescent. LED lighting systems offer the potential for significantly improved beam spread and optical control due to the small size of the light source and the ability to create finely controlled optical systems. Recent advancements in thermal management and increases in efficacy have resulted in the commercial availability of a wide range of products that can be used as substitutes for traditional incandescent or actual light sources. The principal breakthrough in this marketplace has been the ability to lumen match incandescent light sources while maintaining thermal operating characteristics.[38]

Major display lighting applications include the following:

a. Track lighting for highlighting and accent
b. Wall wash using recessed downlights
c. Cooler and freezer case lighting
d. Display and product showcase

LEDs are currently seeing significantly increased usage in cooler case retail display lighting applications. In these cases, linear fluorescents are removed and replaced by a tubular retrofit system employing an array of LEDs. Sixty to 70% savings are achievable primarily because of the increased optical efficiency of the LED. In this case, the directional output of the LED is used to the best advantage, concentrating the flux on to cooler case products within as opposed to the isotropic fluorescent. A secondary advantage of this approach is the potential for improved maintenance characteristics through the long life of the LED lighting system compared to the fluorescent. Many utilities in California offer significant rebates for this energy-efficiency retrofit.[39]

LED Economics

The economics associated with LEDs include an examination of the component costs for LED devices, current trends in cost reduction, and potential for marketplace intervention to accelerate market penetration.

Technology cost components: A typical LED lighting system includes three different subcomponents: the LED device, the LED driver, and a fixture that includes optical and thermal management assemblies making up an overall LED luminaire. For typical LED luminaire systems, the electronics and the LED device can make up 50 to 60% of the overall cost of an LED luminaire. This percentage varies depending upon the complexity and the style of the fixture system, but it is fairly representative of typical indoor commercial fixture applications (downlights, recessed troffers, wall sconces, surface mounts, track, and Edison-base assemblies).

The LED system, including the electronic driver and the LED device, will continue to make up a substantial portion of the overall cost of the luminaire depending upon the complexity and overall style characteristics. This proportion is consistent with conventional fluorescent and compact fluorescent fixture systems included in the interior applications.

For the broad fixture market arena, we expect to see LED luminaire systems reducing cost from present time by about 50%. A good example of this is the LED recessed downlight, which costs $100 to $150. Manufacturers expect the cost to decrease to about $50 per fixture in the next five years. There is already good evidence of this movement with recent market entries of $50-$60 per LED downlight. These cost reductions are being driven predominantly through economies of scale and large reductions in cost for the LED assembly, including both the driver and the LED package. Additionally, the data from the Department of Energy 2009 multiyear program plan has projected cost reductions of 20% per year for luminaire systems, and by 2015, the cost of an LED fixture system will be a third of what it is today.

This kind of cost reduction dynamic is consistent with earlier market transformation events, particularly with CFL downlights and luminaire systems. A compact fluorescent downlight luminaire in 2005 was about $100 per head. Today, the same system is in the $40 region, representing a fairly dramatic reduction primarily because of manufacturing economies of scale.

For the LED device itself, we are currently seeing very significant reductions in costs as a function of economies of scale, more sophisticated production techniques, as well as fundamental breakthroughs in epitaxial production, lower cost substrates, and reduced packaging costs. LED devices are expected to see dramatic reductions in cost over the next five years, with the majority of this reduction occurring in more sophisticated packaging approaches. During a recent meeting of LED manufacturers, there was a general agreement that LED devices would see an 80% reduction in cost by 2015.

Discussions with the manufacturers indicate that significant progress is being made in terms of packaging, development of lower-cost phosphor materials, and reduced substrate costs. Philips Lumileds is projecting a 60 to 80% cost reduction in the development of lower-cost substrates. This effort is focusing on exploring the use of silicon-based substrates to replace traditional, more expensive Sapphire substrates. Manufacturers also are exploring the development of larger diameter epitaxial layers, moving from three-inch to six-inch diameter. This is being projected as a major opportunity to further reduce costs.[40]

Cost trends for technology: Ongoing enhancements in device performance and cost reduction have been described in the LED industry as Haitz law. This law describes the process of innovation, where the cost per lumen and the amount of light from a device reduces by a factor of 10 every decade, and the corresponding amount of light flux from the system increases by a factor of 20. (Dr. Haitz was a scientist at Agilent Technologies.)

An important point is drawn out of Figure 9, a graph corresponding to the performance of characteristics that the industry expects to be obtained by 2015. At this point we show that we have achieved commercially available LED light sources at 200 lm/W at a corresponding cost of about 1 cent per lumen. As a point of comparison, a typical 60 W incandescent lamp used today is about 15 lm/W and produces about 900 lm. A 900-lm package at 200 lm/W could be achieved with a 4 or 5 W LED package at about $10 per light point.

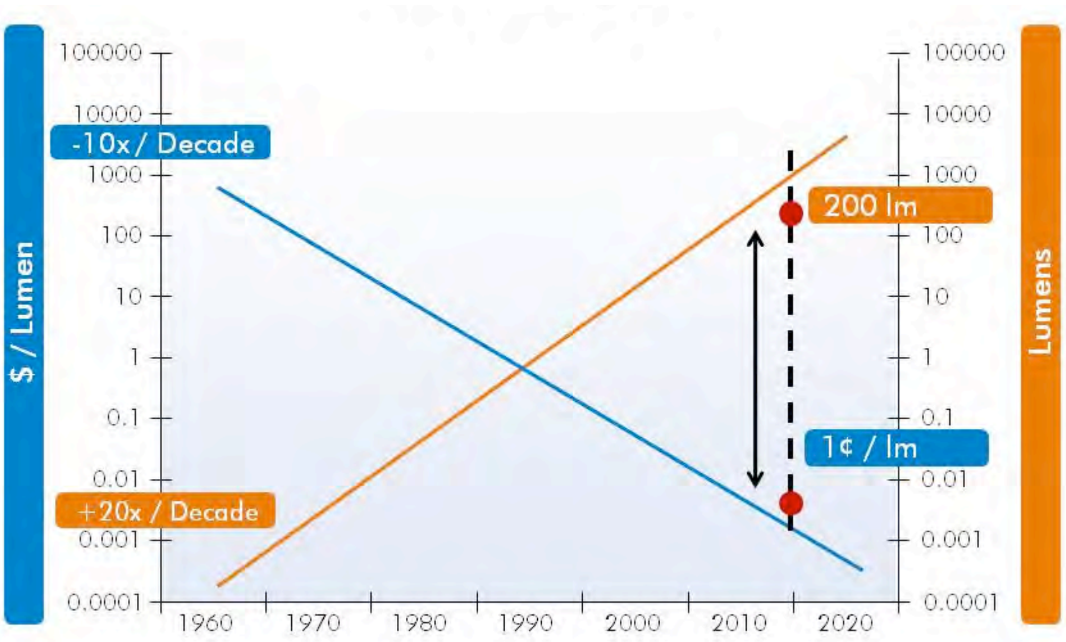


Figure 9: Performance enhancements in terms of device flux output and the reduction in cost per lumen projected from 1960 to 2020 illustrating Haitz Law

The process displayed in Figure 9 shows an approximate reduction in cost by a factor of 10 per decade. This process is highlighted at 2015, where we are seeing projections of 200 lm/W at a cost of approximately 1 cent per lumen. This cost reduction is common in the development of new lighting technologies, and similar cost reductions that occur rapidly over time have been seen in electronic ballasts, T8 lamp technologies, compact fluorescent lamps, and fixtures and systems.

A good representation of this has been the dramatic reductions in compact fluorescent that occurred in the past five years. Compact fluorescent retrofit systems that include A-lamp electronic ballasts and integral housing have gone from about $15 per system to less than $2 in less than 10 years. This cost reduction has been a result of similar forces that we are seeing in the LED industry related to economies of scale, larger production volumes, and more sophisticated production of electronics and circuits. In addition, highly aggressive incentive programs in California and the Northwest have led to upstream rebate programs that have reduced the cost to the consumer through utility incentives.

In this case, the economics are highly influenced by investments from the utility sector to the manufacturing arena to reduce the consumer cost. The thesis behind this economic intervention is to generate larger production and consumer purchases leading the market transformation process. It's interesting to note that the reduction in compact fluorescent lamp costs in California have been "mirrored" in other states that do not have aggressive utility rebate programs.

The following sections show a simple economic comparison of retrofitting from incandescent to LED in two of the most common lighting applications currently being targeted with focused programs: the incandescent downlight, and common incandescent A-lamp, typically used in table lamp or wall sconce systems. For both applications, the combined cost of energy and first costs are projected over time for multiple cases, the first being for the standard incandescent as the baseline. The second includes a compact fluorescent version and opportunities associated with LED representing a near-term and a long-term opportunity. The principal difference between the near- and long-term is one of cost. In all cases, the approximate lumen package is the same so the same delivery of service is maintained.

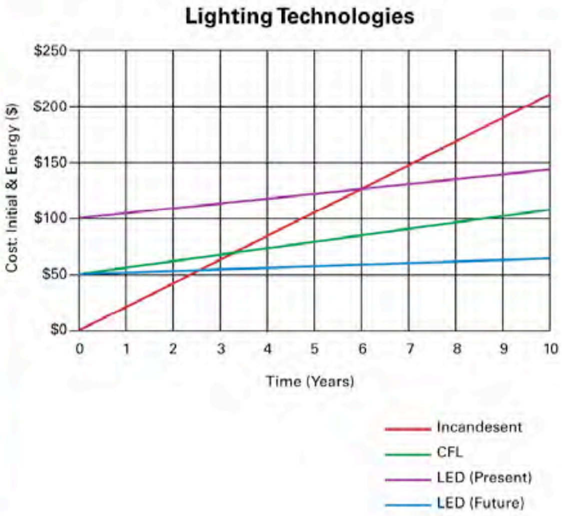
Economic Comparison for LED Downlighting in Commercial Retrofit Applications[41]

Table and graph 3 illustrate a comparison of economic projections for common downlighting retrofit applications. For this illustration, typical baseline conditions were used to compare a 65 W BR lamp, an 18 W compact fluorescent, and a 13 W and 6 W LED downlight. Typical performance characteristics for power input, efficacy, and lumen output were used for the incandescent and compact fluorescent, representing commercially available technology. For the LED retrofit downlight, two different examples were used, illustrating current technology for efficacy and cost and future technology, representing advancements in both efficacy and cost reduction. For all cases, the same approximate delivery of service is maintained for lumen output at ~650 lm).

Table and graph 3: Comparison of economic projections for common downlighting retrofits

Commercial Application	Incandescent	CFL	LED (Present)	LED (Future)
Lamp Wattage	**65**	**18**	**13**	**6**
Lumens	620	1150	910	720
Luminous Efficacy (lm/W)	9.5	55*	70	120
Fixture Efficiency	100%	60%	85%	90%
Electrical Efficiency	100%	90%	85%	90%
Delivered Lumens	**620**	**690**	**650**	**648**
Delivered Luminous Efficacy (lm/W)	9.5	29.7	50.6	97.2
Incremental Cost over Incandescent ($)	$0	$50	$100	$50
Assumed Hours of Operation/Day	10	10	10	10
Days/Year	260	260	260	260
Years	1	1	1	1
Total Energy (kWh)	169	46.8	33.8	15.6
Assume Cost of Energy ($/kWh)	0.125	0.125	0.125	0.125
Total Cost of Energy ($)	$21.13	$5.85	$4.23	$1.95
Payback (Years)	–	3.27	5.92	2.61

* Includes ballast losses



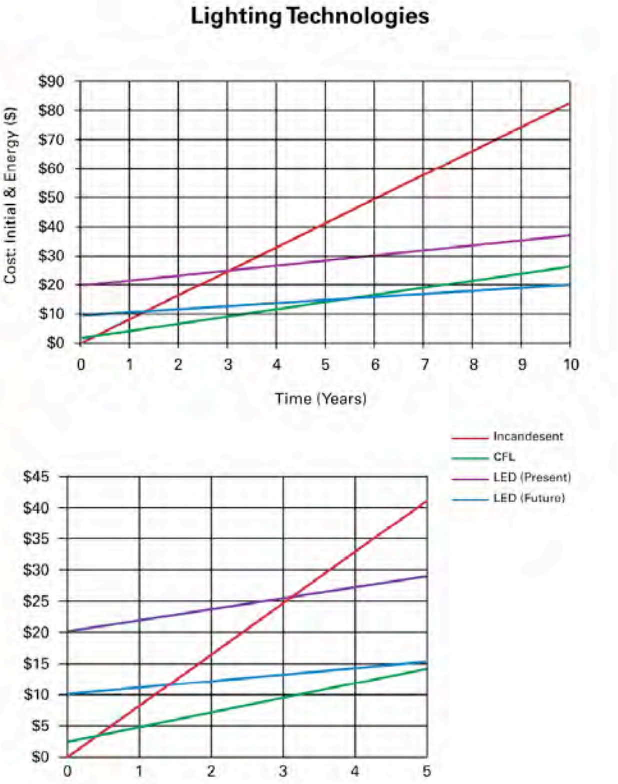
The compact fluorescent retrofit replacement at $50 has a payback of approximately three years when displacing a 65 watt BR lamp. The LED replacement at $100 a unit has an approximately six-year payback. The second LED fixture represents a future commercial potential with both increased efficacy to 120 lm/W and lowered cost to $50. This performance is consistent with LED industry expectation and projections over the next two to three years. At this point, the $50 downlight has a payback of less than three years. The next generation LED downlight is highly competitive with today's compact fluorescent with both increased energy savings as a function of improved efficacy as well as a reduced payback stemming from the reduced system cost.

Economic Comparison for LED in Residential A-lamp Retrofit Applications[42]

Table and graph 4 illustrate a comparison of the economic projections (initial plus energy costs) for a common A-lamp LED retrofit application. For this illustration, typical baseline performance conditions were used to compare a 60 W A-lamp to a 13 W compact fluorescent, and a 13 W and 8 W LED A-lamp retrofit. Typical performance characteristics for power input, efficacy, and lumen output were used for the incandescent and compact fluorescent, representing commercially available technology.

Table and graph 4: Comparison of the economic projections (initial plus energy costs) for a common A-lamp retrofit application

Residential Application	Incandescent (A lamp)	CFL	LED (Present)	LED (Future)
Lamp Wattage	**60**	**18**	**13**	**8**
Lumens	900	900	910	960
Luminous Efficacy (lm/W)	15	50	70	120
Incremental Cost over	**$0**	**$2**	**$20**	**$10**
Assumed Hours of Operation/Day	3	3	3	3
Days/Year	365	365	365	365
Years	1	1	1	1
Total Energy (kWh)	65.7	19.7	14.2	8.8
Assume Cost of Energy ($/kWh)	0.125	0.12 5	0.125	0.125
Total Cost of Energy ($)	$8.21	$2.46	$1.78	$1.10
Payback (Years)	–	**0.35**	**3.11**	**1.40**



For the LED retrofit, two different examples were used, illustrating current technology in terms of efficacy and cost for future technology, representing the predicted advancements. For all cases, the same approximate delivery of service is maintained for lumen output at ~900 lm.

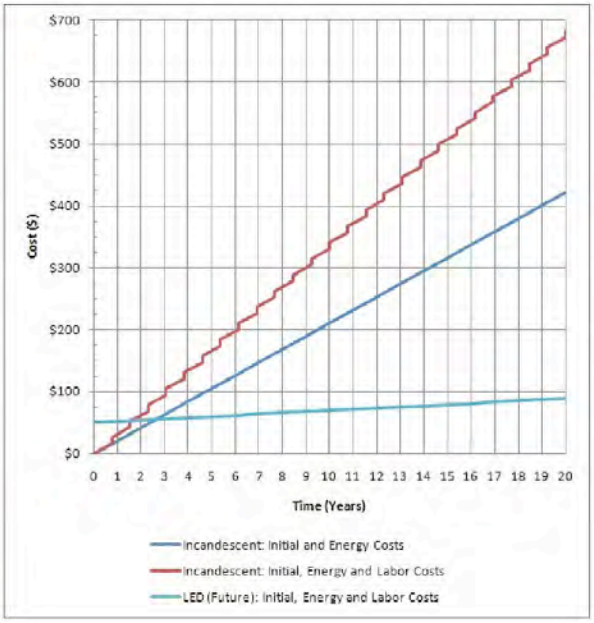
The compact fluorescent retrofit replacement at approximately $2 has a payback of about three months based on three hours a day when displacing a 60 W A-lamp. It is clear from this simple example that economics are not the key issue in the limited market transformation associated with compact fluorescent lamps. Rather, it is the level of performance and user expectation. It is hoped that next-generation LEDs will address the shortcomings. The LED replacement at $20 a unit has an approximate three-year payback. The second LED fixture represents a future commercial potential with both increased efficacy to 120 lm/W and lowered cost to $10. This performance is consistent with industry expectations and projections over the next two to three years. At this point, the $10 A-lamp has a payback of 1.4 years.

Economic Comparison for LED and Incandescent in a Downlight Retrofit Application Including Maintenance Characteristics

Table and graph 5 illustrate the potential associated with the enhanced maintenance characteristics that will be achieved with “near” future LED technology. The industry is projecting 50,000 hour system life with next-generation LED systems. The example compares a 65 W BR (incandescent) lamp with an approximate life of 2,000 hours and a retrofit LED downlight with an estimated 50,000-hour life. With the incandescent light source there is a maintenance cycle every 2,000 hours with a $13 estimated maintenance cost based on typical prevailing labor rates and estimated time requirements. The addition of the labor projection for lamp replacement reduces the estimated payback based on energy alone, from about 2.5 years to 1.5 years. The incandescent maintenance cost adds about 30% to the cost of ownership on top of energy alone. Additionally, by comparison, the LED system represents approximately 15% of the cost of ownership (over the life of next-generation LEDs) compared with the incandescent when adding in the potential for reduced labor costs.

Table and graph 5: The potential associated with the enhanced maintenance characteristics that will be achieved with “near” future LED technology

Commercial Application with Labor Costs	Incandescent (BR lamp)	LED (Future)
Lamp Wattage	**65**	**6**
Lumens	620	720
Luminous Efficacy (lm/W)	10	120
Fixture Efficiency	100%	90%
Electrical Efficiency	100%	90%
Delivered Lumens	**620**	**648**
Delivered Luminous Efficacy (lm/ W AC	10	97.2
Incremental Cost over Incandescent ($)	**$0**	**$50**
Assumed Hours of Operation/Day	10	10
Days/Year	260	260
Years	1	1
Total Energy (kWh)	169	15.6
Assume Cost of Energy ($/kWh)	0.125	0.125
Annual Cost of Energy ($)	$21.13	$1.95
Annual Cost of Maintenance Labor ($)	$13	$0
Source Life (hours)	**2,000**	**50,000**
Payback (Years)	–	**1.55**



Economics Associated with LED Retrofits and Best Practices Approaches

Economic decisions in building lighting involve the selection of one technology or design approach over another based predominantly on a complex comparison of initial and operating costs. Very often, first cost and resulting payback analysis are used to select between two different competing approaches. As a more sophisticated process, one can use lifecycle costing, which includes the more complex comparison of looking at all the costs associated with the lighting product over time.

Advanced guidelines now are reorienting the economic decision to one of applied best practices as opposed to a discussion of isolated payback and initial first cost only. Best practices are defined as “coordinated technology systems and design approaches, which through research and experience, demonstrate the ability to consistently achieve the above standard results while avoiding negative environmental impacts”[43]

Many times, best practice approaches are significantly more expensive than standard practice but may in fact achieve similar performance in terms of payback. Best practice approaches with significantly higher first costs now are being considered important opportunities for the relighting of buildings in order to address our ever-increasing goals associated with carbon footprint.

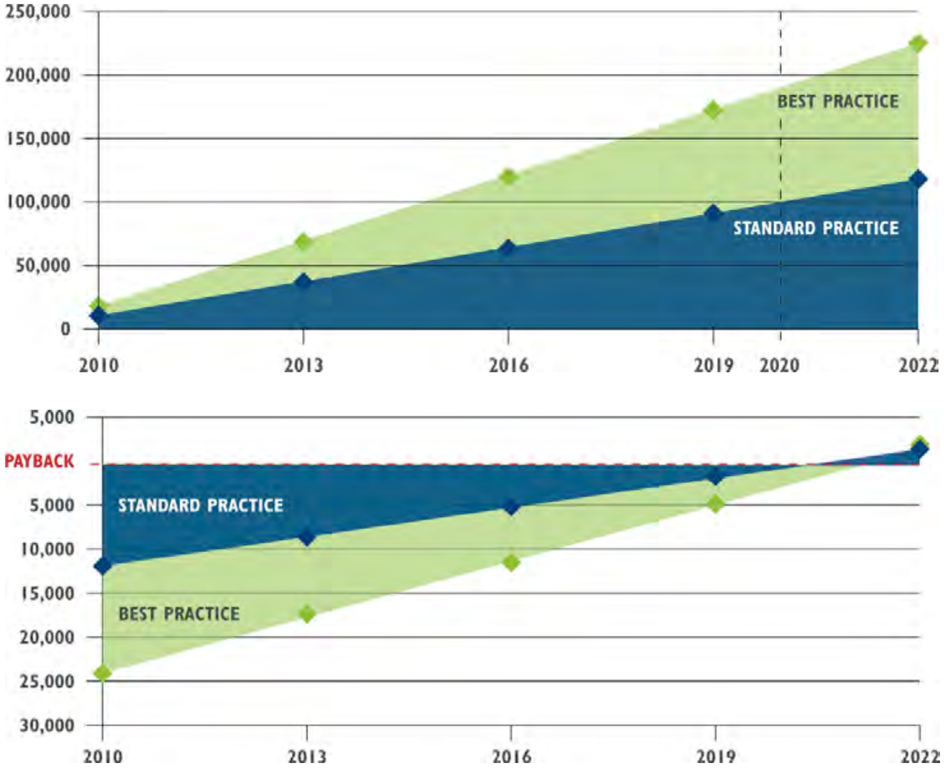


Figure 10: The payback of best practice and standard practice

Figure 10 shows the comparison of projected energy savings and cost recovery on two investments, one for best practice and one for standard practice for a lighting project. The example of the best practice design proposes twice the potential savings in comparison to a standard practice approach projected over a period of 10 years. This savings aggregates together.

The first cost associated with best practice was approximately $24,000. For standard practice, the first cost was $12,000. The best practice approach involved a coordinated series of new LED technologies and design approaches. The second standard practice represents a business-as-usual approach to a lighting change or retrofit. The second part of the graph shows the additional cost for both strategies slowly being recovered over time as a function of the accrued savings occurring for both approaches. It's interesting to note in this comparison that a best practice approach may involve a significantly higher upfront cost, but if the savings associated with it are higher, it may indeed have the same payback as a more traditional design approach in the lighting of buildings. This is an important economic issue that's being developed by advanced lighting plans, particularly LED solutions as an integral part of the best practice approach.

Today, LED technologies have the opportunity to form an important part of the best practice design approach for the lighting of buildings. The following is a list of specific best practice lighting technology approaches that have been identified through a series of recent industry roundtable discussions in California leading to the new strategic lighting plan for California:[44]

1. Task ambient lighting using LED systems
2. Adaptive bi-level exterior lighting, including LED systems
3. LED downlights for residential and commercial applications
4. Integrated daylight harvesting systems
5. Bi-level controls for office lighting
6. Control systems for residential lighting
7. High-efficacy retrofits for Edison-based sockets using LEDs

Many of these best practice lighting approaches for achieving zero net energy goals in California rely on the enhanced performance characteristics associated with next-generation LED lighting systems. The selection of these best practice approaches is based on their demonstrated potential to save energy and to provide the performance attributes needed in each specific lighting application.

Economics Associated with LED Task-ambient Design as a Best Practice Approach for Interior Lighting

Interior lighting represents 29% of statewide electricity usage in California.[45] Of that, commercial offices account for 26% of the total lighting energy usage.[46] Given that California has 1 billion square feet of commercial office space, a strategy to significantly reduce the lighting power density in offices has huge energy-saving potential.

The traditional “standard practice” lighting approach with ceiling-mounted luminaires is designed to provide an overall level of illuminance within the space. This approach is typically inefficient, as it provides the same level of illuminance in all spaces independent of the specific nature of visual tasks. General lighting systems evolved during a period when electricity was inexpensive, and providing a standard level of light throughout an entire space was not considered wasteful. Furthermore, illumination levels drop by the square of the distance from the light source, so lighting the task with a ceiling-mounted luminaire is an inefficient approach. Finally, uniform lighting layouts typical of conventional lighting design are not adaptable to individuals and do not truly address the occupants’ visual requirements to perform tasks, which results in sub-optimal user satisfaction.[47]

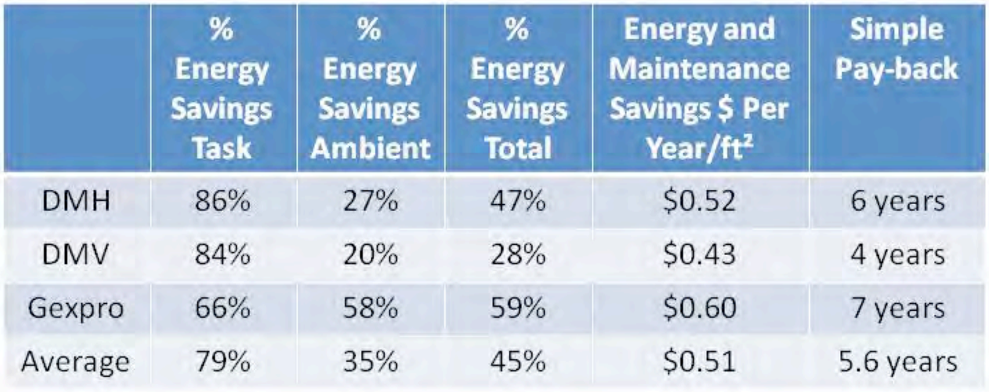
The LED task/ambient approach has the potential to address these shortcomings and yield significant energy savings and increased user satisfaction. Separating task and ambient lighting systems can result in significant energy and lifecycle cost benefits by reducing the light levels produced by the ambient system to significantly lower levels, and by providing separate luminaires for task lighting. In addition, proper controls used with the portable luminaires can enhance the energy-efficiency benefits while providing office occupants greater control over their lit environment.[48, 49]

Thus, the major effort of this project was to develop a high-performance LED task lighting system, with an overall objective of developing, demonstrating, and commercializing an office task/ambient lighting system that would accomplish the following:

1. Operate at about 0.6-0.8 W/ft² of total connected load
2. Provide uniform illumination of at least 30 footcandles
3. Use no more than 25 W of LED task lighting per office

Three of these demonstration projects are presented in this paper and include the Department of Mental Health (DMH) (Sacramento, CA), Department of Motor Vehicles (DMV) (Sacramento, CA), and Gexpro (Hayward, CA). These projects, on average, demonstrated a total lighting energy savings of 45% (Table 6). At DMH and DMV, delamping overhead lighting and replacing fluorescent task lighting with the PLS achieved a four- to six-year payback. At Gexpro, installation of new high performance ambient luminaires and replacement of fluorescent lighting with the PLS achieved a seven-year payback.[50]

Table 6: Energy savings at three sites demonstrating LED task/ambient lighting with the PLS



	% Energy Savings Task	% Energy Savings Ambient	% Energy Savings Total	Energy and Maintenance Savings $ Per Year/ft^2	Simple Pay-back
DMH	86%	27%	47%	$0.52	6 years
DMV	84%	20%	28%	$0.43	4 years
Gexpro	66%	58%	59%	$0.60	7 years
Average	79%	35%	45%	$0.51	5.6 years

The following are key findings of the LED task lighting best practice initiative:

- Reduced energy usage by 28-59% for California office space
- Achievable lower lighting power density ranging between 0.50 and 0.65 W/sf for typical open office space, 45% lower than CA Title 24 2008 and ASHRAE 90.1 2004
- The quality and energy efficiency of office lighting is directly related to the quality and energy efficiency of the task lighting
- The task/low ambient lighting outcome of IOLS results in improved user satisfaction through increases in lighting quality and flexibility to address individual user needs
- The task/low ambient outcome of IOLS is cost effective and will continue to see improvements as costs decrease

Non-Energy-based Economic Consideration LED

Most detailed economic analyses of LED lighting systems focus on the energy efficacy-based projections to develop cost benefit and lifecycle costs. Ultimately, it’s the non-energy product and performance attributes that will help establish and sustain long-term market penetration. Additionally, many of these non-energy-based benefits have a substantial economic value that often is not included in the lifecycle cost analysis associated with traditional economic considerations. The following list describes a number of specific, non-energy-based benefits and the potential to contribute to a broader economic analysis.

Long system life: The potential for enhanced system life has the opportunity for greatly reducing the costs associated with maintenance and lamp replacement. Manufacturers have estimated that the system life for many LED applications may approach and surpass 50,000 hours as a standard performance metric. Facility managers have estimated that the potential for reduced maintenance costs as a function of this greatly extended system life may rival the reduction in energy costs associated with next-generation LED lighting technology.[51]

Waste disposal: The handling of conventional light sources, metal halide, compact fluorescent, and linear fluorescent involves the use of strict waste disposal protocols that results in a cost of ownership to any commercial venture. In addition, the residential applications and disposal of compact fluorescent have become significant issues given the substantial increase in production and future application. At the municipal level, this will involve the development of specific disposal and handling protocols, which also will lead to increased cost at state, municipal, and homeowner level. LED technology does not involve the use of mercury and therefore would not require this level of sophistication in the waste-disposal process, thereby reducing the stress on municipal waste disposal. This ultimately will lead to a reduction in costs

Smaller optical system: The LED light engine involves considerably less material and footprint and therefore requires less handling and packaging at the development and shipping stages of the manufacturing process. This ultimately leads to a reduction in cost of production. Smaller light engines and optical packages also allow for the opportunity for reduced hardware in terms of the fixture or luminaire in addressing mechanical, thermal, and building interface issues. This will lead to reduced costs by having a smaller overall footprint.

Potential for dynamic user control: Electronic light sources are inherently controllable, providing the potential for greatly enhanced user amenity. Specific control capabilities include dynamic spatial and spectral control of the interior lighting systems to suit the demand of end-users and building managers to create any type of end-user luminous environment. This increased user amenity may translate into higher levels of productivity and user satisfaction within a work environment. Studies have shown that small increases in productivity associated with lighting can be highly cost effective for the return on that investment.[52, 53]

The economic benefits connected with productivity and user amenity may actually eclipse the energy-associated benefits of this lighting market transformation. These include benefits associated with accelerating the market transformation due to consumer demand but also enhancing the quality of experience within traditional work environments where people may become more productive. Salaries and cost of employment are significantly higher than the cost of energy in terms of overall operation of the business.

Demand response capability: Electronic solid-state lighting is particularly well-suited for addressable lighting systems that allow the utility to reduce lighting during peak power events. The demand response capability is not traditionally aligned in economic consideration in a purchase process by an end user at this point in time. Enhanced demand response capability achieved with electronic solid-state lighting needs to become part of this decision-making process, either explicitly as an economic opportunity or during a lighting retrofit. This additional economic opportunity is potentially one of the largest market drivers for next-generation lighting technology.

Existing Challenges to Successful Long-term Market Transformation with LEDs

Rapid technological change: Traditionally, purchasers of commercial and residential lighting technology had access to a relatively small subset of lamp control and fixture products for building lighting. Ten years ago, a facility manager purchasing products may have included two or three different lamp types and fixture systems. All of these components had a highly defined set of performance characteristics and were typically operated under a series of very standard specifications and operating conditions. Many of these technologies could be easily interchanged between systems allowing for flexibility both of the purchase and maintenance level. Multiple manufacturers made very similar products and systems within a relatively narrow scope of performance. In addition, the design specification community was very accustomed to dealing with this narrow subset of components and technologies and was able to design and develop lighting applications with a high degree of predictability. Desired outcomes typically were easy to achieve and also easily maintained by facility managers.

This level of simplicity, however, is being challenged by the high level of innovation and the influx of new product entry into a very traditional lighting marketplace. LED technologies are evolving through a series of changes related to efficiency, performance, and product attributes. This level of change in combination with the lack of standards undoubtedly will lead to challenges within this transformation process.
These challenges exist at the commercial design and development level as well as the maintenance and operations level. A facility manager will be dealing with an entirely different technology with different performance attributes at a replacement and maintenance level. Residential consumers also are seeing the same level of innovation in the marketplace with a rapid influx of new retrofit lamp systems for Edison-based sockets. As it was with compact fluorescent retrofits, the consumer will be presented with an even greater array of technologies to choose from. Frustration associated with this high level of choice will be compounded by rapid changes in performance and product attributes stemming from the significant increase in innovation within this field.

Product standards: The product standards process involves a significant level of consensus across an industry and typically evolves over a long period of time. In the traditional lighting marketplace, safety, performance, and product standards existed across the industry. Testing and evaluation processes occurred through well-established mechanisms to provide decision makers and consumers with design, performance, and safety information, allowing them to make effective decisions both in terms of purchasing and design process. Today, this well-established process is being highly challenged by the speed of innovation, the rapid influx of product, and a clear lack of agreement and standards across the industry as to performance. The solid-state lighting industry is evolving entirely new types of products and systems that challenge the way we measure, quantify, and even design lighting systems.

Supply chain and production capability: It's clear that large and sustained market transformation is occurring within the lighting arena and that this transformation is happening quickly as a function of both product and market-driven events. The demand for new lighting sources, systems, and components will be very large, as is evidenced by the market growth projections.

Consumer expectations: As with any early market transformation activity, particularly with the introduction of new technology, the opportunity for consumer issues is extremely high, stemming from unanticipated consequences with product failure. Next-generation solid-state lighting technology is particularly susceptible to unforeseen or unanticipated consequences because of failures brought upon by field application. Electronic light sources are sensitive to thermal and field conditions that may adversely impact the performance of the overall device. Shortened lifetime or unexpected failures will significantly erode consumer acceptance of this technology, potentially creating long-term barriers. This process was clearly evident with compact fluorescent that was heavily marketed by federal and state entities to address energy efficiency. Federal programs targeted cost and not product quality as the key market drivers for consumer acceptance. This led to very significant reductions in lamp cost, but unfortunately, we still have only 15% market penetration at best. Part of this is due to very poor consumer perception of the technology partially driven by product quality and early failures.

There are high expectations associated with LED technology in satisfying the consumer expectations for improved performance, particularly when compared to compact fluorescent. Consumers have a high demand for color performance, dimmability, and product longevity, and departures from this expectation could lead to consumer dissatisfaction. Early failures of LED technology in commercial applications also will have significant influence on long-term market acceptance, particularly by large end-use purchasers and decision makers. Many of the current decisions are being made by early adopters and innovators within the marketplace partially driven through incentive programs and the availability of large publicly-financed programs. Long-term success of this marketplace will be highly dependent upon a sustained marketplace that makes decisions based on product quality.

A Brief Review of Key Regulatory Activities Related to the LED Marketplace

Significant marketplace activity has occurred and will continue to occur that promotes incentives for the development and ultimate market penetration of LED technologies, and this has predominately arisen from interests in energy efficiency. This market engagement activity is principally driven by the development of codes and standards and related regulatory activity that encourages the development and market penetration of technologies and approaches that achieve energy efficiency.

Building codes have been widely recognized as some of the most effective mechanisms to increase the efficiency characteristics for our buildings. The Institute for Market Transformation in Washington estimates that we build or renovate about 10 billion square feet of commercial and residential floor space each year and also tear down about 1.7 billion square feet each year. The Institute has estimated that by 2035, about 75% of the United States building sector will either be new or newly renovated.[54]

California Title 20 and 24 Lighting Regulations

The California regulatory activity is one of the longest series of integrated programs specifically targeted at encouraging lighting energy efficiency. These programs include both a combination of appliance-oriented regulations and building design activities that have led to one of the largest state level reductions in lighting energy use. At a broad level, these continually ratcheted programs encourage the development of new technology and new design approaches that address more difficult and more stringent standards. At a specific level, recent Title 20 regulations, the regulations that target appliances including lamps, have ratcheted efficacy standards to a point that traditional incandescent lamps will no longer be sold in California.[55]

These lamp standards are typically technology neutral, expressing a performance requirement in lumens per watt within a certain time period. The efficacy standards in California are perhaps the most aggressive in the country, requiring a minimum of 25 lm/W by 2013 and 60 lm/W by 2018.

At 25 lm/W, the only lamp technologies that would meet code would be high-performance tungsten halogen with infrared coatings, compact fluorescent, and LED. The 60 lm/W regulation could only be met practically by LEDs or compact fluorescent. The practical result that we would expect to see stemming from these regulations would be a massive market transformation within residential applications from incandescent light sources to high-efficacy lighting. As LED technology improves both in terms of lighting quality and reduced cost, we will see a fairly dramatic increase in market penetration of LED systems compared to compact fluorescent. If all light sources in residential applications were to simply move to 40 lm/W systems, California would realize a more than 50% reduction in lighting energy use. These efficacy regulations within California have sent clear signals to the lighting industry that a definable goal and marketplace is coming within a specific timeframe. The goals of these regulatory activities are perhaps the most effective components, giving highly defined time periods with specific numbers that will guarantee a marketplace to support the longer-term investment of these technologies.

Underwriting this long-term vision has been the development of national and international lamp standards following the same efficacy-based approach.[56]
While not as aggressive as California's broader efficacy standards, as a first step it encourages the development of higher efficacy light sources. The national level regulatory activity has a longer-term vision with a second tier of higher efficacy requirements. By 2020, all light sources will be a minimum of 45 lm/W.[57]
This will essentially eliminate traditional incandescent light sources and very strongly encourage compact fluorescent and LED technology. Again, this type of regulatory activity is highly effective in that it sends a clear signal to the lighting industry that a new and sustained marketplace is being developed and will be maintained.[58]

This regulatory activity supports the massive investment that's ongoing from the lighting industry in LED development. Many parts of the world also are enacting various forms of legislation and related regulatory activity to encourage the phase-out of traditional incandescent lamps in favor of higher-efficacy CFLs and LEDs. Most of these programs follow a ratcheted approach of increasingly more stringent efficacy requirements over time. The essential theme of these combined regulations is that there are clear and sustained signals to both consumers in the manufacturing industry that a long-term market will be developed and sustained for high-efficacy light sources.

Outside of the general purpose A-lamp marketplace, the other principal tool for the regulation process involves building design standards. This regulatory activity primarily targets the building design, and operation is typically technology neutral in that it only defines a desired result, either in terms of energy performance or power density or a combination of the two. The standards are directed more at the construction and major renovation market and are more integrated in terms of effect in change in the marketplace. In residential construction, Title 24/05 directed a uniform requirement for high-efficacy (40 lm/W) dedicated fixtures for the entire home with specific allowances with the integration of controls using dimming or occupancy sensors. The standard forms the platform for a significant transformation effort within the industry to address energy-efficiency opportunities. The manufacturing industry engaged in this process strongly supported the efforts for evolving performance efficacy-based standards for design.[59]

The high-efficacy fixture approach has been adopted in various forms in other states across the United States. For example, Oregon residential building codes require that 50% of all the dedicated fixtures in the home or new construction be high efficacy at 40 lm/W.[60]

The most common form of regulatory activity in commercial applications is power density standards for lighting targeted at commercial buildings. Early power density regulations were highly effective at transforming the marketplace from traditional fluorescent T12 magnetic to T8 electronic technology. These early building standards also were majorly responsible for the market transformation from directional reflector lamps to dedicated pen-based compact fluorescent systems. Today, Title 24 for both residential and commercial applications includes significant modifications to encourage both reductions in power density and installed power as well as the addition of control strategies to reduce time of use. These new standards recognize the performance attributes associated with emerging technology for electronic sources and are including more aggressive opportunities.

Recent modifications to Title 24 residential and 2008 specifically call out LED technology and related efficacy requirements, anticipating that this marketplace is already undergoing transformation. Title 24 is anticipating that all recessed lights in new construction for residential will be solid state.[61]

Regulatory activity within California is highly supportive of the market transformation to LED fixtures as it is believed that the LED-based technology may be more sustainable in terms of performance and consumer issues in the California residential marketplace. Helping to lead the technology development and adoption within the California marketplace are building standards for new construction and major renovation in the following key areas:

Commercial office space: Ongoing activities in the 2011 California code change cycle include adding dynamic lighting control requirements for all interior spaces. The dynamic controllability includes specific functions for occupancy/vacancy sensing for energy efficiency and dynamic addressability for demand response, which involves reducing interior lights by a small percentage during periods of peak power demand. Control capabilities also will include bi-level dimming that will allow for dynamic response relative to daylight availability. This code modification that will require significantly higher levels of dynamic control capability within common interior spaces will be a significant market driver for next-generation lighting technology. Today, most of this capability is achievable with the full range of dimming electronic ballast and conventional fluorescent technology; however, the approach is both costly and hard to commission within typical spaces. Electronic solid-state lighting is inherently easy to dynamically control and will help facilitate the capabilities associated with this code change requirement.

Exterior lighting applications: Significant code modifications are being planned that will encourage dynamic controllability of exterior lighting, including parking, area, and signage. This dynamic control capability includes occupancy and vacancy sensing to vary lighting due to occupancy patterns. Dynamically controlled LED systems provide one of the largest opportunities to save energy in the commercial lighting arena. Regulations will encourage the requirement for all of these exterior lighting systems to include some level of adaptability according to occupancy patterns. There is also an ongoing dialogue to extend these dynamic control capabilities to all street lighting applications.

At a national level, recent proposed modifications to ASHRAE 90.1 include the addition of dynamic control requirements for parking and area lighting. This is an important first step to encourage the application of next-generation technology. Current metal halides and HPS lighting systems are difficult to dynamically tune, and a requirement for dynamic tuning will help encourage the application of next-generation lighting technology with a corresponding increase in energy efficiency and user amenity.[62]

State utility rebate programs: California utilities now are developing aggressive rebate and related incentive programs to encourage the use of next-generation LEDs for lighting. Rebates are available for LED fixture systems for parking and street lighting applications. A second program has targeted freezer cases for the replacement of linear fluorescent lamps with LED replacement systems. These types of rebate programs that encourage emerging technologies are going to see a dramatic increase, particularly with the evolution of LED lighting systems. Principal targets for these rebate programs, which are currently being considered within California, include incandescent A-lamps, reflector lamps, LED downlighting systems, and other types of exterior lighting, including wall sconces and signage.

The California utilities have collaborated on the development of a general A-lamp specification called "super lamp," which defines a higher performance retrofit lamp for common A-lamp application.[63] This specification seeks to evolve a higher performance system that would appeal to a broader cross-section of the public as an energy retrofit. This specification includes the development of higher performance color rendering, dimming capability, longevity, and packaging related to the technology and existing fixture applications.[64] This initiative will tie in with the California Public Utilities Commission program offerings to utilities to encourage the use of more advanced lamp technologies for the California marketplace. This activity is expected to lead the country in the rapid development and market penetration of LED lighting systems for Edison-based sockets.[65]

Advanced programs driving market transformation in the LED arena:
- ASHRAE 90.1 redraft
- American Recovery and Reinvestment Act
- Huffman bill AB 1109
- Title 24/20
- Energy Independence and Security Act 2007
- California Strategic Lighting Plan

Conclusion

The lighting marketplace is experiencing a rapid transformation to solid-state lighting. This transformation is a result of significant technology-based innovation coupled with increased market pressures arising from energy-driven regulation. There is broad agreement from across the lighting industry, the regulatory community, and the lighting design profession that LEDs will be the predominant light source used for illumination, and this transformation will occur within the next five to 10 years.

Specific issues that could impede this market transformation are related to challenges associated with product longevity and quality, compounded by the lack of well-thought-out specifications and industry standards. Rapid innovation coupled with the significant growth of new products has compounded issues of apprehension and uncertainty. The "early innovator" nature of this marketplace also is heavily influenced by emotional decisions driven by myopic interests of energy efficiency only. Uninformed and hasty decisions motivated by efficiency interests also could lead to unforeseen consequences, including early failures due to component quality and system longevity. Early failures and consumer perception could slow the ultimate transformation. There is a clear need for unambiguous and comprehensible product performance data to reduce consumer apprehension but also to address the needs of the lighting specification and design community.

Finally, the true promise of LEDs will only be achieved when the lighting design and innovation community begins to exploit the full potential of solid-state lighting using the temporal, spatial, and spectral control characteristics that are inherent with this technology. This will involve the regulatory efficiency community refocusing their priorities on developing a more holistic and long-term view within the market transformation process.

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