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ADVANCED ENERGY-EFFICIENT LIGHTING SYSTEMS: PROGRESS AND POTENTIAL

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Abstract—From a systems perspective, energy-efficient design should strive to minimize the energy and money required to provide the desired quantity and quality of illumination. A wide spectrum of technologies, design practices, and control strategies exists to increase lighting energy efficiency. We describe the state of the art in energy-efficient lighting (emphasizing field operating conditions rather than product test results) and give an overview of its benefits. We consider existing and emerging lighting components: lamps, ballasts, fixtures, controls, and design issues as well as other building systems and features with which lighting interacts, including HVAC systems. Estimates of the societal cost-effective potential savings from improving lighting energy efficiency range from 50 to 80% of direct lighting energy use in developing and industrialized countries.

BACKGROUND: LIGHTING IN PERSPECTIVE

Illumination is the oldest and one of the most essential services provided by electricity. Lighting today comprises 10 to 25% of total electricity sales in industrialized and developing countries. As an illustration of the amount of energy used, 515 TWh or 20% of national electricity consumption in the U.S. is for lighting;‡ this is equivalent to the output of 100 large, 1000-MW electric power plants. In the U.S., consumers spend approximately $9 billion on lighting equipment each year and $38 billion for the associated electricity. Increasing the energy efficiency of lighting systems can achieve a lower combined (equipment plus energy) cost for illumination with similar or improved lighting quality. This process is already underway.

A century ago, Edison's incandescent lamp operated at an efficacy of about 3 lumens/Watt. Changes in lamp design led to significant improvements by the mid 1930s as competitive pressures contributed to the demise of gas lighting. Because of the variety of lighting technologies available today, the end-use characterization of how electricity is used to provide illumination has become increasingly complex. The International Commission on Illumination (CIE) estimates that overall national lighting efficacy in its sixteen member countries improved from 25 to 50 lumens/Watt between 1960 and 1990 (Fig. 1).[1] This improvement is a result of increased efficiency within each type of light source and of rapid substitution of efficient discharge light sources for inefficient incandescent light sources (Fig. 2). The prevalence of different light sources varies among countries. For example, incandescent and fluorescent lighting respectively represent 5 and 90% of the total lighting-related electricity use in Ireland versus 45 and 55% in the United Kingdom.[2] (Because fluorescent sources are significantly more efficient, these percentages do not correspond to the amount of useful illumination provided by these two light sources.)

In parallel with innovations in lighting equipment, lighting design philosophies are undergoing a process of change. Today's lighting designer can choose from among a plethora of technologies to provide aesthetically pleasing illumination and good visual performance while satisfying clients' economic criteria. Different considerations apply in new buildings design than in the retrofit of

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‡ Estimates (for 1991) from the U.S. Energy Information Administration (Annual Energy Outlook) are 331 TWh (commercial) and 103 TWh (residential). The Electric Power Research Institute estimates 81 TWh for the industrial sector (unpublished). These estimates exclude interactive effects with space conditioning equipment.

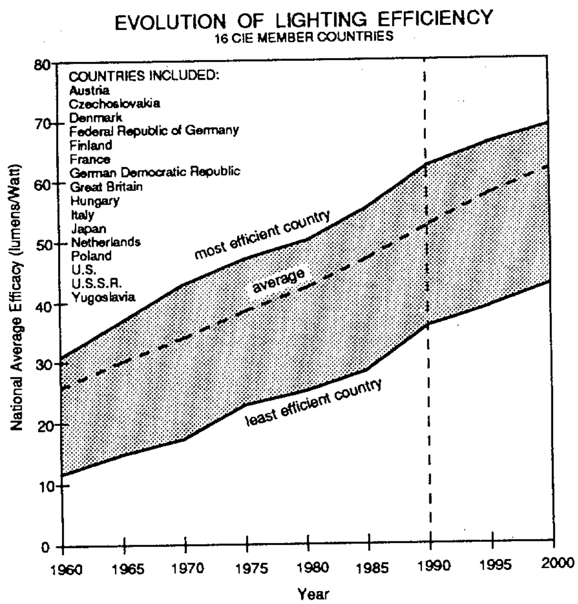

Fig. 1. Evolution of lighting efficacy; range and average values for 16 CIE member countries.

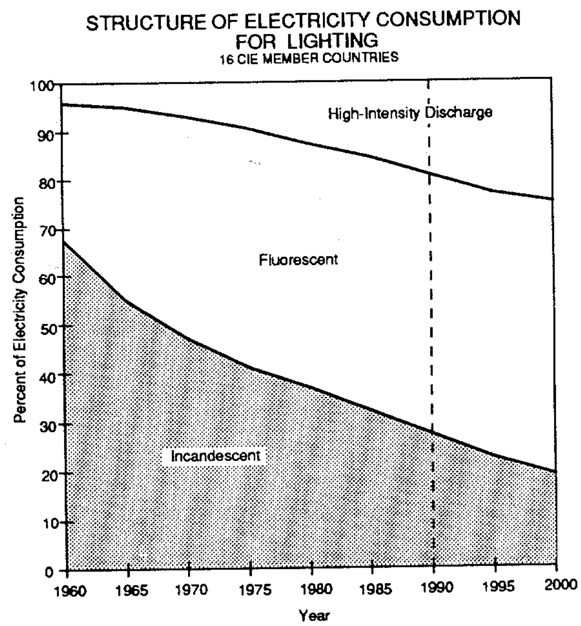

Fig. 2. Structure of electricity consumption for lighting; average values for 16 CIE member countries.

existing buildings; new design guidelines and mandatory standards around the world are increasingly addressing lighting efficiency in new buildings.

Investing in efficient lighting components and design practices can often result in a cost per unit of saved electricity that is less than the cost of producing (or buying) electricity. By this measure, the cost-effective potential for further improvements in the efficiency of lighting systems has in the U.S. been estimated at 66 to 79%.[3,4] Large cost-effective potentials also exist in developing countries. Geller estimates a potential for Brazil (all sectors) of 48% of projected lighting use for the year 2010.[5] An analysis of commercial buildings in Thailand revealed a nearly 70% savings potential.[6]

The performance of cost-effective advanced lighting technologies (and programs to implement them) has been documented in field studies.[7] One international compilation of case studies for nine commercial buildings in five countries showed lighting energy savings of 36 to 86% and

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payback times between one and eight years.[8] Achieving such savings on a national scale, however, requires a concerted policy effort. Many utility and governmental programs have been used: about 200 programs offering financial incentives to electricity consumers, for example, have been offered in the U.S. and Canada.[3] over 50 in 10 Western European countries,[9] and several in developing countries.[10] In the U.S. alone, utility incentives for efficient lighting will likely exceed $500 million per year by the mid-1990s.[2] In addition to voluntary incentive programs, mandatory standards and other innovative initiatives such as organized government-sponsored procurement of efficient lighting products can improve lighting efficiency.[11]

In addition to reducing electricity use and costs, advanced lighting technologies offer a variety of non-economic benefits. New lighting systems can provide improved visual environments, giving users better control over lighting quality and quantity. Improved visual performance translates into increased productivity, which yields tangible economic benefits in non-residential settings. From an environmental perspective, emissions of pollution associated with power production must be considered in conjunction with lighting efficiency. Although electricity meets only 10% of the world's energy needs, its production results in 32% of global carbon dioxide emissions. Among EIA countries the electricity required to provide illumination is responsible for 13% of total carbon dioxide emissions from the residential and non-residential buildings.[12]

An effective approach to understanding and influencing lighting efficiency must be based on a systems perspective. A long chain of relationships connects the electricity fed into a lighting system and the final service delivered, i.e., useful illumination. The chain includes power generation and delivery, electronic components, and architectural features (lighting and furniture layout, daylighting, glare, contrast, optical properties of interior surfaces, etc.). Effects of lighting systems on heating and cooling demands in a building, on occupant response, and on human health[13] must also be considered. Moreover, from a practical standpoint, improving the efficiency of illumination systems requires close cooperation among various trades (manufacturers, designers, electrical contractors, building operators). Lighting design is both an art and a science.

In the remainder of this article, we elaborate on approaches for improving the energy efficiency of lighting systems, with special emphasis on field measurements of lighting components and systems in actual buildings. We review existing and emerging lighting system components (lamps, ballasts, fixtures and optics, and controls) and key issues of design, system considerations and interactions, and economics. We emphasize applications for non-residential buildings, because that is where most lighting energy is used; for example, about two-thirds of U.S. lighting electricity use occurs in non-residential buildings. (A number of relevant terms and unit conversions for describing the design and performance aspects of efficient lighting systems are defined in Table 1.)

COMPONENTS

Lighting technology encompasses both hardware and management strategies. Lamps, ballasts, fixtures, and various types of sensors make up the hardware. Management strategies include control and lighting design methods. Below we describe currently available efficient lighting technologies; emerging technologies are discussed later.

Lamps

The six common lamp types are: incandescent (including tungsten-halogen), fluorescent, low-pressure sodium, high-pressure sodium, mercury vapor, and metal halide. The latter four types are classified as high-intensity discharge (HID) lamps. Operating principles and performance characteristics vary among lamp types. Important features include lumen output, efficacy, color, size, and operating characteristics such as start-up time, dimming capability, and lifetime. Figure 3 shows the general range of efficacies as a function of lumen output for various lamp-ballast systems. The shaded area indicates the typical range of applicability for lighting in commercial buildings, which is about 5,000 to 12,000 lumens per luminaire. These technologies are discussed below. It is important to bear in mind, however, that efficacy (l/W) is not the only indicator of interest. Each light source produces different colors of "white" light. The quality, uniformity, and shape of light distribution also varies among light sources.

Table 1. Lighting terminology.

Measures of Efficacy and Efficiency

Ballast Factor is the (dimensionless) ratio of lumens produced by a lamp with a given ballast to the manufacturer's rated lamp lumens. For some ballasts, the ratio exceeds 1.0.

Coefficient of utilization is a metric for evaluating the effectiveness of an entire lighting system (luminaire), incorporating fixture efficiency, light distribution, room cavity ratio, and the wall, floor and ceiling reflectivities. It is defined as the ratio of lumens intercepting the work plane to total lamp lumens from the fixture.

Efficacy (in lm/W) is the amount of light produced (in lumens) for a given amount of power (in Watts) input to a lamp. The upper theoretical limit is 683 lm/W for an ideal light source emitting monochromatic radiation on a wavelength of 555 nanometers. Efficacy data can be reported with or without ballast power requirements.

Fixture efficiency is the (dimensionless) ratio of total lumens emitted by the fixture to the total *rated* lamp lumen output. Optical efficiency is the same ratio in principle, but is based on the lamp's actual light output in the thermal environment prevailing in the given fixture. Optical efficiency thus isolates the fixture's optical performance from its thermal performance.

Lighting power density (LPD, in W/m^2) is the installed power of a lighting system normalized by the floor area. The LPD may be reported for part of the building area, or for the whole building.

Minimum Lamp Wall Temperature (MLWT) is the lowest temperature of the lamp wall influencing the vapor pressure of the mercury in fluorescent lamps and thus the lamp voltage and energy use. The rated lumen output is based on ambient temperatures of 25°C, which corresponds to a MLWT of about 37°C.

Measures of Color Quality and Illumination

Correlated Color Temperature (CCT) (in Kelvins), a means of characterizing lamp light output, is the temperature at which a black-body radiator produces the same color light as does the lamp. The lower the CCT, the redder and warmer the light source; the higher the CCT, the bluer and cooler the light source.

Color Rendering Index (CRI), ranging from 0 to 100, describes how colors appear under a given light relative to their appearance under a black-body radiator. A value of 100 is theoretically achieved when the CRI is identical to that of a black-body radiator at a the lamp's CCT.

Illuminance (in lux, lm/m^2 or footcandles, fc, lm/ft^2) is the measure of incident luminous flux on a unit area. The illuminance is commonly used in lighting codes to describe lighting requirements for specific tasks. One lux = 1 lm/m^2 = 0.093 fc.

Luminous intensity is a unit of light distribution reported in candelas (cd) or lumens/steradian.

Incandescent Lamps - Incandescent lamps produce light by heating a filament to the point of glowing or incandescence. By virtue of its high melting point and relatively low evaporation rate, tungsten is the most common choice for filaments. The life of an incandescent lamp is limited by the evaporation rate of the filament. The higher the filament temperature, the higher the efficiency and the more quickly the lamp burns out. Incandescent lamps are the least efficient light source, with efficacies ranging from 5 to 25 lm/W.

Four advances that improve either efficacy or efficiency in the application of incandescent lamps are: lens and reflector design modifications, improved filaments fill and krypton, spectrally selective coatings, and halogen chemistry with lowered voltages. Reflector or "R-Lamps" use an aluminum coating to direct light out of a fixture, providing up to 50% savings in comparison to a common household "A-Lamp". Parabolic aluminized reflector (PAR) lamps are floodlamps with both a lens and a reflector. Ellipsoidal reflectors (ERs) focus light a few inches from the lens and are effective for deep recessed fixtures where they match the delivered light of an R-Lamp at half the wattage although in other fixtures they offer no advantage. A-Lamps with krypton gas show a 1 to 5% gain in efficacy over standard lamps. Krypton reduces the evaporation of the filament, allowing the filament to run hotter and increasing its efficacy and/or lifetime. Spectrally selective coatings on the glass envelope of a lamp transmit light in the visible part of spectrum while reflecting infrared (IR) wavelengths (heat) back into the filament to improve lamp efficacy. The reverse can be applied to the reflector on PAR lamps, transmitting IR wavelengths to reduce heating of the object being illuminated. Halogen gas filling reacts with tungsten to re-deposit evaporated tungsten back onto the wire filament. Tungsten-halogen or "quartz" lamps require a quartz encasement because of the high temperature of the bulb; the filament of a quartz lamp can be operated

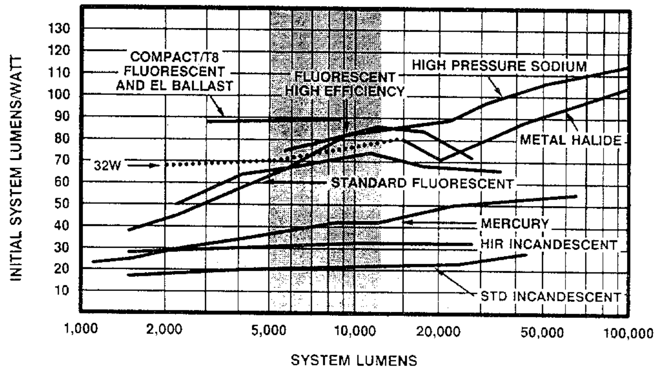


Fig. 3. Range of system (lamp-ballast) efficacies as a function of system lumens for various lamp types.[14]

at a higher temperature to increase efficacy. The MR-16 (multifaceted reflector) is a common tungsten-halogen lamp in the United States. This-low voltage incandescent permits the use of smaller (and higher-current) filaments, resulting in better control of light distribution.

Full-Size Fluorescent Lamps - These lamps use an electric discharge to excite gaseous mercury atoms within a phosphor-coated tube. The ballast provides a high voltage to initiate the discharge and then limits the current. As excited mercury atoms decay back to their ground state, they produce ultraviolet (UV) photons that are absorbed by the phosphor coating, converting the UV into visible light.

Five technical options are available to improve fluorescent lamp efficacy or efficiency in application: higher surface area to volume ratio, reduced wattage, increased surface area, high-efficacy phosphors, and reflector lamps.[4] Small-diameter lamps, such as one-inch (T-8) lamps, increase efficacy by reducing the loss of the ultraviolet radiation within the plasma. Lower-wattage (32-W) lamps are often substituted for 40-W lamps. These lamps initially provide *less* light than 40-W lamps although their lumen depreciation is less pronounced over time. The total (lamp and ballast) wattage reduction typically ranges from about 9 to 20%, depending on the lamp and ballast combinations. Spiral grooves or dimples on the tube bring part of the lamp's inner wall closer to the arc discharge and increase surface area, which improves efficacy by increasing the likelihood that the phosphor will be struck by a UV photon. Costs may be 10 to 15% greater than for conventional fluorescent lamps. Efficacies are increased by about 6 to 14%. Rare-earth narrowband or "tri-stimulus" phosphors improve efficiency for lamps at both lower and higher color temperatures, with improved color rendition as well. Tri-stimulus phosphors also have better lamp lumen depreciation characteristics than the halophosphate phosphors commonly used, and they are required for the smaller diameter lamps and compact fluorescent lamps. Efficacies are 9 to 18% better than for conventional fluorescents. Reflector lamps use an internal reflective coating between the glass tube and the phosphor coating on a 125° to 225° wedge of the upper surface. They are recommended for uses in dirty and dusty environments where cleaning is difficult. Cathode-cutout lamps (34-W) predate the more advanced T-8 lamps and have the undesirable qualities of lower efficacy, limited dimming ranges, and increased lumen depreciation.

Compact Fluorescent Lamps - New compact fluorescent lamp (CFL) technologies have improved since their development in the late 1970s. They are available in many sizes and shapes. These lamps cost substantially more than incandescents but last about eight to ten times longer and are four times as efficacious. As an example, a CFL with an efficacy of 60 to 70 lm/W delivers about the same amount of light as a 15 to 18 lm/W incandescent lamp. There are two common types of CFL assemblies, modular and integral, both available with electronic ballasts. Modular twin-, quad-tube, or large twin-tube lamps attach to adapters containing a ballast that can screw into Edison sockets. Integral compact fluorescents have a built-in ballast that also screws into conventional Edison sockets. CFLs are available in a range of sizes from 5 to 28 Watts.

CFLs are suitable for a broad range of residential and non-residential applications and are especially useful in hard-to-reach places because of their long lifetime (8,000 to 9,000 hours is the typical European rating, 10,000 hours is the typical U.S. rating, based on 3-hour start cycles; lifetimes increase with less cycling, e.g. up to 24,000 hours by U.S. standards). CFLs are often appropriate for incandescent replacement, but their appearance, shape, and size must be considered. Certain versions of the quad-tube lamps can be dimmed, but currently require specialized dimmers and hardwired ballasts to work properly. Good examples of commercial applications include recessed downlights, decorative lighting in wall sconces, exit signs and task lights. Similar to full-size fluorescent lamps, bare CFLs cannot operate efficiently at temperatures below 10°C. Special enclosed fixtures are available for use in sub-zero temperatures.

High-Intensity Discharge and Low-Pressure Sodium Lamps - High-intensity discharge (HID) lamps produce light directly from the excitation of plasma that is at a high pressure. Developed originally for outdoor applications, HID lamps are now increasingly used indoors as their color rendering properties have been improved and lower wattage models have become available. Lower wattage HID lamps are less efficient than the higher wattage lamps.

Mercury vapor lamps use mercury vapor discharge to produce light. The envelope, or bulb, stabilizes lamp operation and safely encases an arc tube to block UV radiation. These lamps take several minutes to reach full brightness. Because of their poor color rendering and low efficacy, high-pressure sodium (HPS) or metal halide lamps are taking their place.

Metal halide lamps have higher efficacies and often better color rendering than HPS or mercury vapor lamps. Lamp life is shorter than that of mercury vapor lamps, averaging 10,000 to 20,000 hours. These lamps are less efficacious and change color when deeply dimmed, which limits their practical dimming range. There is a fair degree of variability in color among lamps, and color changes as they age. In the past they were not available in sizes below 175 W, but now 32-W lamps are manufactured with a color temperature near 3,000 K.

High-pressure sodium lamps have high efficacies, from 50 to 125 lm/W, and some newer versions emit quite pure white light. They consist of an arc tube containing sodium-mercury vapor which operates at high temperatures. Like metal halide lamps, they are significantly less efficacious and change color when dimmed, giving off yellowish light like that emitted by low-pressure sodium lamps. Low-pressure sodium lamps have the highest efficacies and the lowest CRIs. Low-pressure sodium lamps, available in 18- to 180-W sizes, are limited in applicability and are appropriate where color rendition is not important.

Ballasts

Fluorescent ballasts are required to start and operate discharge lamps. They provide a current for electrode heating, supply voltage to start the lamp, and limit current during lamp operation. There are three basic types. *Preheat* ballasts start the lamp by heating the lamp filaments until the starter opens, causing the ballast to provide the voltage across the lamp. Rather than heating the filament, *instant-start* ballasts deliver a high initial voltage to start lamps. *Rapid-start* ballasts heat filaments during startup and operation. Some newer ballasts remove filament voltage after starting lamps (these are known as cut-out ballasts).

Ballasts approved by the Certified Ballast Manufacturers (CBM) Association meet ANSI standards, which include having a ballast factor (see Table 1) of at least 95 ±2.5% of the manufacturer's rated output for a standard F40, rapid-start, argon-filled lamp. The ANSI (American National Standards Institute) ballast factor standard for four-foot energy-saving 34- or 35-W lamps is 85%. For retrofits, designers may want lamp-ballast systems with lower ballast factors to reduce power requirements and provide less light, which may be desirable if an area is over illuminated. Alternatively, high-ballast-factor components can be used in conjunction with dimming or delamping. For standard fluorescent lamp systems, typical ballast factors range from 0.85 to 0.95, with some models approaching 1.15, though the factor can be lower (e.g. 0.6) in some compact fluorescent systems.

Magnetic, core-coil ballasts, also known as electromagnetic ballasts, operate lamps at the normal line frequency and last for about 12 to 15 years (45,000 to 50,000 hours).[4] Standard core-coil ballasts use aluminum wiring and use 10% more energy than high-efficiency ballasts which use copper wiring and better iron cores. In the U.S., Federal standards came into effect in April 1991 to eliminate the sale of standard core-coil ballasts.[3] Such a law has been in effect in California since 1982.

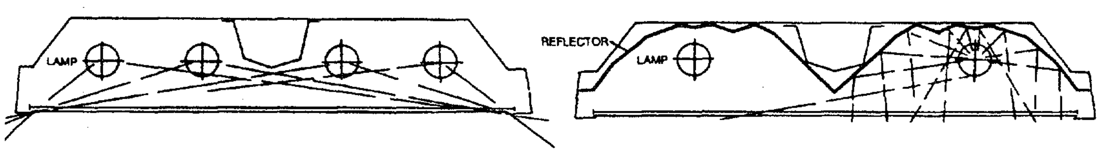
A newer class of ballasts is known as solid-state or electronic ballasts, which operate the lamps at 20 to 50 kHz, reducing flicker and hum while improving ballast efficacy by ~25% compared to standard magnetic ballasts.[15] Electronic ballasts are available for HID applications although their use is not widespread. One common problem with electronic ballasts is that the high-frequency power fundamental and its higher harmonics can be reflected into the power supply and may interfere with other appliances and radio frequency communication systems. Fluorescent ballasts must, however, meet FCC standards. Fortunately, low-cost filters can be added to the ballast circuitry to suppress harmonics.[16] Many high-frequency ballasts are now better in this respect (for CFLs and long fluorescent systems) than the magnetic ballasts they replace.

Luminaires: Fixtures and Optics

The fixture, and other optical equipment such as lenses, reflectors, and louvers, along with the lamp and ballast, make up the complete luminaire. The main purpose of fixtures and optical systems is to distribute, diffuse, and direct light. Higher efficiency fixtures (see Table 1) emit more of a lamp's light. Fixture efficiency depends on geometric design, material properties, and the type of lamp-ballast system inside the luminaire. Another suggested parameter for fixture performance, not in common use, is optical efficiency (see Table 1). This latter measure isolates a fixture's optical characteristics from the fixture's influence on lamp operating temperatures. Both parameters should be considered when comparing fixture performance. Fixture efficiencies vary from less than 40% to about 92%. Claims are made about energy-related benefits from the use of polarizers in fixtures, but the topic is controversial.

Parabolic Troffers and Louvers - Parabolic fixtures are linear parabolic troughs with lamps positioned at the focus. These fixtures came into widespread use during the 1970s. Most parabolic fixtures are louvered luminaires with parabolically shaped white or metallic troffers. The louvers are open grids of opaque, semi-translucent, or reflective shielding and diffusing media that collimate down-coming light rays. These fixtures reduce glare commonly associated with poorly designed or positioned lensed fixtures, and permit cooler luminaire operation.

Specular Reflectors - Fixture components with highly specular reflective surfaces were developed during the 1980s. Specular surfaces have mirror-like characteristics, for which the angle of incidence equals the angle of reflection with no dispersion (in contrast, with diffuse surfaces there is more random light scattering and thus more uniform light). The materials and shape of the reflectors are designed to reduce absorption of light rays within the fixture using aluminum, silver, and multiple dielectric (mirror) finishes in conjunction with efficient geometry. They are well suited for many overlit areas where the installation of a reflector is accompanied by delamping, but they are also available in new fixtures. Figure 4 shows the geometry of light distribution within diffuse and specular fixtures. Figure 5 shows light loss based on the number of reflections within the fixture for two surface reflectivities.



(a) Diffuse reflector in fixture. (b) Specular reflector in fixture.

Fig. 4. Diffuse reflectors (a) result in many reflections within the fixture while specular reflectors (b) ideally result in only one reflection (diagram courtesy of Ontario Hydro).

Air-handling Luminaires - All of the power into a lighting system (except that exiting windows) is eventually dissipated in the building space.[17] About 36% of the power is convected and conducted to the room, plenum, and return air. Air-handling luminaires reduce the heat convected to the room and plenum by increasing the convection to the return air. This has the additional benefit of cooling the lamp-ballast system; as described below, this can also improve lamp performance.

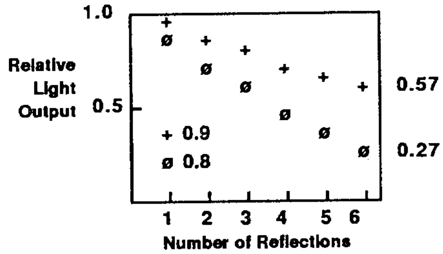


Fig. 5. Light loss due to reflectivity (0.8 and 0.9) and number of reflections.

Lumen Depreciation - The luminaire dirt depreciation factor (LDD) is used to indicate a luminaire's resistance to dirt build-up on its reflective surfaces. The higher the LDD, the less maintenance is required. Most reflective surfaces are baked enamel or aluminum. Aluminum finishes deteriorate at a slower rate, but enamels typically provide higher initial reflectance's and are easier to clean. It is unclear which luminaire systems have high LDDs. In comparison with lensed troffers, open troffers may result in dirtier lamps because their static charge may collect dust from greater exposure to air flow. On the other hand, some manufacturers claim that the airflow reduces dirt buildup.

Controls: Equipment, Applications, and Strategies

Energy is wasted if lighting systems are used when they are not needed. Savings from control technologies depend upon equipment and design of the space. The choice of a control system depends on the application: retrofit, renovation, or new construction. Table 2 links control strategies with applicable systems and technologies.[18]

Table 2. Lighting control strategies associated with four types of control systems.

SYSTEM	DESCRIPTION	STRATEGY						
		Reduced levels	On/off Scheduled	On/off Unscheduled	Task tuning	Lumen maint.	Load-shedding	Day-lighting
Static Control								
Delamping	Reduces light levels and demand up to 50%	X			X			
Impedance modifier	Reduces light levels and demand up to 30 to 50%	X			X			
Dynamic Control								
Switches/relays	On-off switching banks of lights		X				X	X
Voltage/phase control	Continuous dimming of light level 100 to 50%	X	X			X	X	X
Solid-state ballast	Continuous dimming of light level 100 to 10%; operates lamps efficiently	X	X		X	X	X	X
Sensors and Hardware								
Timeswitches	Regulate illumination with time		X					
Personnel	Detects whether or not space is occupied			X				
Photocell	Measures illumination level in space	X				X		X
Communications Hardware								
Computer/ microprocessor	Communicates between sensors and controllers		X			X	X	X
Power-line carrier	Carries information over power lines	X	X		X	X	X	X

Note: An "X" indicates likely applicability to retrofit, renovation, and/or new construction.

If an existing building is overlit, decreasing illuminance levels by delamping or installing impedance-modifying devices (current limiters) represent *static* control strategies for reducing power and light output by up to about 50% under the same minimum lamp wall temperature (MLWT) conditions. Current limiting devices reduce the input current to standard core-coil ballast systems.

Dynamic controls can be used to dim or switch lamps on and off during short intervals. They may also measure light levels or sense the presence of occupants. Dynamic controls used with core-coil ballasts condition the input power to one ballast or a group of ballasts. Solid-state electronic ballast dimming systems can save more energy than dimming systems with standard core-coil ballasts because of their high efficacy and greater dimming ranges. Occupancy sensors are another type of dynamic control. These ultrasonic or infrared sensors are used to detect the presence of people. They are most effective for spaces that have intermittent occupancy such as restrooms, storage areas, and individual offices. Photocells measure illumination levels in a space and signal the electric lights to maintain a prescribed level of illuminance. They can sense daylight and send signals to a controller to continuously adjust or step the controls. Timeclocks provide instructions to a lighting system in real time. Communication equipment provides a method for information to move from sensors to the controller, which may be through dedicated wiring, existing power lines, or radio control, often as part of an Energy Management and Control System (EMCS).

Control strategies fall into the following categories: illuminance reduction, on-off control, task-specific tuning, lumen maintenance, load shedding, and daylighting. Task-specific tuning involves tailoring the illuminance level to the requirements at each workspace. This is especially useful for office buildings where design may be done without information about future tenants' lighting needs. Lumen maintenance controls use dimmers and photocells to compensate for lumen depreciation, allowing a system to be designed with lower initial lighting power. To compensate for the reduction in lumen output of lamps and fixtures as they age, designers often use illuminance levels 20 to 40% higher than needed. Lumen maintenance controls sense the illuminance level in a space and reduce system power input to maintain only the desired level. The savings in lighting energy use decline toward zero as a system ages, with an average of about 10 to 15% at the time when group relamping is typically carried out.

There is growing interest in dispatchable load management to reduce lighting demand on request from the utility. Dimmable ballasts allow for more precise load shedding. In many buildings there are opportunities to shed load, such as switching off perimeter lighting, during utility peaks. One study concluded that a large, modern office building can shed 20 to 30% of its lighting load along the perimeter, with acceptable dimming levels, during "special case" interruptions.[19] Load shedding can be achieved manually or an EMCS can be used to cut out appropriate circuits.

All buildings with windows or skylights receive daylight, but only those with effective controls will save energy. In some cases the control systems are modular and additive, such as a dimmable ballast with a built-in sensor controlling a single fixture. Centralized systems use distributed sensors and on-off or dimmable controls located throughout a number of rooms or zones, all of which are linked back to a central control unit. The contribution of daylight from windows and skylights has a strong spatial dependence. Other considerations include visual tasks of each zone of a building and the use of window shades. The time response of the sensors influences whether lamp dimming is noticeable to occupants. An asymmetric response is the least noticeable; it is a fast response to reductions in daylight and a slow response to increasing daylight.

It is useful to review case study data to illustrate the effectiveness of daylighting technologies. A retrofit project in an office building in Emeryville, California demonstrated the energy and peak demand reduction capabilities of an electronically ballasted lighting control system utilizing several control strategies. Daily lighting energy use for the north daylit, south daylit, and reference zones are shown in Fig. 6. Using an integrated control system that included daylighting, lumen depreciation correction, and scheduling, the lighting control system was found to reduce average lighting energy use on weekdays by 62 and 51% in the north and south daylit zones respectively, compared to a reference zone not equipped with controls.[20] Daily energy use savings in the north daylit zone reached 75% during the summer. A novel photosensor provided control by allowing daylight tracking and lumen depreciation correction strategies to be implemented with the same hardware. The control system maintained design illuminance levels at the workplane regardless of the daylight contribution or age of the lighting system. Note the increase in lighting power over time in response to lamp lumen depreciation. A post-retrofit survey showed that occupants were satisfied with the light levels.

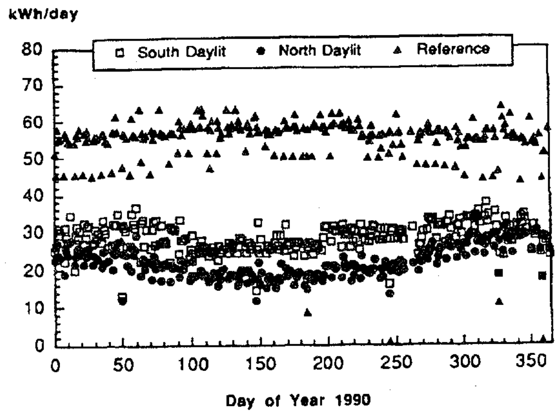


Fig. 6. Measured weekday lighting energy use for the north and south daylit zones using integrated lighting controls compared to the reference zone without controls. Note: Data are from a large office building in Emeryville, California (LBL Lighting Research Group).

The Importance of Commissioning - An important step in achieving optimal energy savings from efficient lighting strategies is commissioning. Systems often do not perform as well as expected at the design stage. Commissioning involves reviewing design documentation, verifying installation and testing of equipment and system performance, training building operators, and analyzing the operation of an energy-saving strategy.

A pilot commissioning study undertaken in the U.S. Pacific Northwest as part of the Bonneville Power Administration's "Energy Edge" research-oriented demonstration program illustrates the impact that control strategies have on energy use. Figure 7 shows average hourly lighting power as a fraction of the maximum peak demand for three different floors of a 7,400 m^2, nine-story office building in Portland, Oregon.[21] The average demand on the fifth floor is much lower (65% of the maximum at noon) than on the other floors (88% on the sixth floor and 86% on floors 1 and 2) because occupancy sensors control half of the lights on the fifth floor. The lighting system on the sixth floor is controlled manually and often left on during the night, and thus consumes almost twice as much energy as the fifth-floor lights. An EMCS controls most of the lights in the retail areas of the first and second floors, so most of the lights are off at night. The EMCS suffers from a common problem; it was originally designed to control the lights throughout the building but was not wired to control the lights on the upper floors.

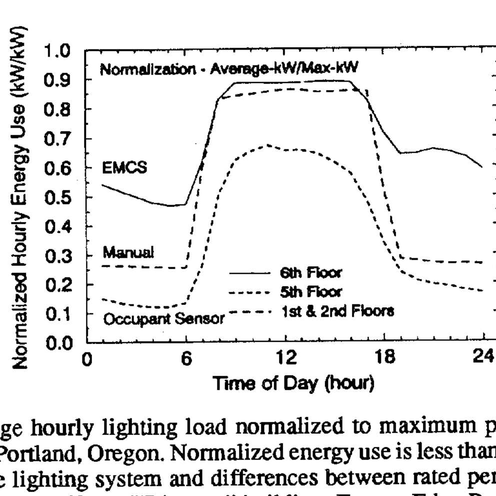


Fig. 7. Measured average hourly lighting load normalized to maximum peak hourly demand for a large office building in Portland, Oregon. Normalized energy use is less than one because of the diversity of peak loads in the lighting system and differences between rated performance and actual performance, including thermal effects ("Director" building, Energy Edge Program).

SYSTEMS CONSIDERATIONS IN LIGHTING DESIGN AND OVERALL EFFICIENCY

Many new lighting components offer significant energy savings. Additional gains in efficiency can be achieved when these components are combined as total systems. Evaluation of lighting systems should consider interactions with heating, ventilating, and air-conditioning systems. Further considerations include the quality of the energy service as measured in lumen output, color rendering, and illuminance (lux), or other visual performance indicators. Designers can benefit from using computer-simulation tools to translate a given lighting quality requirement and lighting level into various hardware configurations. A retrofit situation is less straightforward because fixture locations and other parameters may be preset and only a broad visual performance equivalence can be established.

New Construction Design Issues

A key goal in lighting design is to provide good visual performance. The Illuminating Engineering Society (IES) has recommendations for achieving good visual performance with low-energy lighting designs. These are professional consensus recommendations based on intuitive knowledge and field experience rather than scientifically established visual performance standards. Recommended illumination levels have been decreasing in the past two decades. Between 1972 and 1987, light levels recommended by the IES declined by 15% in hospitals, 17% in schools, 21% in office buildings, and 34% in retail buildings. The most dramatic examples for specific purposes within these general building types are an 85% reduction for showcases, 50% reduction for chalkboards, and 63% reduction for general lighting in hospitals. Optimum lighting levels vary within a given building. For example, the IES recommends that task areas for general office occupancy be illuminated to at least 320 lux (30 fc). The remainder of the room need only be illuminated to one-third of the task illuminance levels, with a minimum of 215 lux (20 fc). There are significant differences in recommended light levels among countries.[22]

Five design strategies contribute to overall system energy efficiency: using task lighting, display lighting, and lighter interior colors; grouping similar tasks; and daylighting. Reflective color schemes and lighter walls and floors require less light to achieve an appearance of brightness than darker surfaces. Grouping similar tasks allows areas needing more intense illumination to be isolated. Window systems can be designed to enhance the use of natural sunlight without introducing excessive glare, contrast, or other visibility problems. Daylighting systems such as light shelves, atria, skylights, clerestories, and shading devices can produce substantial savings when used with electric lighting control technologies. Many designers resist the use of new equipment and standards.[23]

Retrofit Applications

Prior to assessing the cost and performance of lighting equipment, a lighting designer must determine required illumination levels. If the space is currently over illuminated, a reduction in light levels may be appropriate and cost-effective. In deciding among particular retrofits one must consider the effort and cost of properly installing equipment. Key considerations are minimizing installation costs and disruption to occupants. Evaluating new equipment may require coordination with maintenance staff to consider the inventory of lamps and ballasts. Relamping is most simple because it requires, at most, the opening of a fixture. Delamping may require opening the ballast panel to disconnect ballasts from the mains. Ballast and current limiter retrofits may require rewiring these components in the fixture. Specular reflectors for fixtures require repositioning of the sockets and securing the reflector. The installation of controls may also require rewiring of lighting circuits.

When the number of lamps in a fixture is reduced, or the fixture power is otherwise reduced (via current limiters, etc.) the lamps operate at a lower temperature. Thus, a portion of the improvement in efficacy will result from the reduction in lamp-wall temperature. Retrofits of fluorescent lamps already operating at an optimum temperature could reduce the lamp temperature *below* the optimum.

Temperature Sensitivity and HVAC Interactions

Manufacturers' data on lamp output are based on ratings near the optimum MLWT of about 37°C (see Table 1). Standard F40 fluorescent lamps nearly always operate above their optimum temperature, except in open-strip fixtures. Reduced-wattage lamps may be at temperatures near their optimum. Figure 8 shows the light output versus system power for six different lamp-ballast systems in ambient air temperatures from 25 to 55°C.[24] This range of temperatures is consistent with the range encountered in typical fixtures. The light output and power requirements of the system decrease at higher operating temperatures by as much as 10 to 20%. The MLWT will be about 10°C above the ambient temperature. The figure shows the change in efficacy with temperature; efficacy is indicated by the diagonal lines. The most efficacious system shown is the Mark V electronic ballast with T-8 lamps, which ranges from about 82 to 87 lm/W, while light output ranges from 4,900 to 6,350 lumens, and power use ranges from 60 to 74 W.

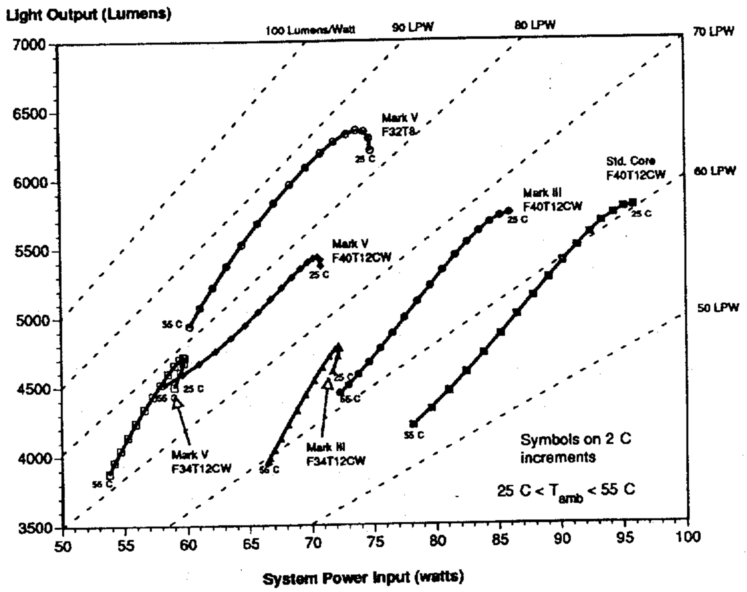


Fig. 8. Light output versus system power for six different lamp-ballast systems (2 lamps) in ambient air temperatures from 25 to 55°C. Standard core-coil, efficient core-coil (Mark III), and electronic ballasts (Mark V, c. 1989/90) are included.

Raising the efficiency of lighting systems can have a positive or negative effect on the energy required for space conditioning. The *net* effect of interactions between lighting systems and heating, air-conditioning and ventilation (HVAC) systems depends on a spectrum of technical and economic factors. Technical factors include the extent to which lighting savings occur during periods when a building requires space conditioning and the relative efficiencies (by fuel and equipment) with which heating and cooling are provided. Other (non-lighting) sources of internal heat gains (e.g. people and equipment) must also be quantified, the value of which in turn depends on the building's thermal integrity and operating schedule. To accurately evaluate a given building and location, it is necessary to employ a dynamic (e.g. hourly) buildings energy simulation model.

Relevant economic factors include the mix and costs of the energy sources affected (electricity and fossil fuels) and the respective tariff structures. In summer-peaking regions, demand charges associated with reduced cooling loads can be substantially greater than charges (if any) linked to increased heating load. In addition, reduced or increased HVAC loads can influence the sizing and thus cost of the HVAC equipment in a building, a consideration that pertains only to new buildings or buildings where HVAC equipment is being replaced. In the extreme case of Thailand, savings resulting from downsizing cooling equipment in non-residential buildings improved cost-effectiveness indicators for various technologies and building types by 10 to 50%.[6]

An analysis of national impacts must correctly account for distinct building types and regional variations in weather, building envelope and equipment efficiencies, and economic variables. The degree of peak-demand impacts at the utility system level may differ from energy impacts depending on the coincidence of lighting energy use with the total load faced by the utility and on whether the utility peak tends to occur during the cooling season or the heating season.

Existing estimates of HVAC energy interactions reflect a lack of consensus on the issue. Some studies identify a considerable net HVAC benefit for non-residential buildings and relatively small penalties for residential buildings. In one national estimate of increased lighting efficiency in the U.S., 35 to 45% additional (non-lighting) energy savings occur in non-residential buildings while a net reduction of about 5% is found in residential buildings.[4] The aforementioned analysis for Thailand identified HVAC energy benefits ranging from 23% of direct lighting savings (in office buildings) to 56% savings (in hotels). A recent simulation study examined representative large U.S. office buildings and found a net reduction in savings for a cold northern climate (Chicago, IL) and small net benefits in a hot climate (Charleston, SC). The corresponding retrofit payback time adjustments were extremely small, only a few months in most cases.[25]

Lamp-Ballast-System Comparisons

To illustrate the influence of temperature, system interactions, and luminaire characteristics on total system performance we present a series of four-foot fluorescent systems data. These data are based on laboratory measurements for commercially available systems.[7,26] We show how the lamp-ballast systems perform in open air and in an enclosed, ceiling-mounted, four-lamp fixture (Table 3).

Table 3. Performance of four-foot (F40) lamp-ballast systems in open air and in enclosed fixtures.

Lighting System	Input power (W)	Light output (lumens)	Efficacy (lm/W)	Ballast factor	Relative Power	Relative Light	Relative Efficacy	Color rendering index	Lamp-wall temperature (°C)	
A. Performance at standard operating conditions: 2-lamps, no fixture										
1. 40-W F40 T-12/CW; 1 lamp only	40	3,150	79	—	1.00	1.00	1.00	67	37	
with 2-lamp ballast system[a]	95	5,990	63	0.95	1.00	1.00	1.00	67	37	
2. 34-W F40 T-12/CW; 1 lamp only	34	2,750	81	—	0.85	0.87	1.03	67	unknown	
with 2-lamp-ballast system[a]	79	4,790	61	0.87	0.83	0.80	0.97	67	unknown	
3. 32-W F32 T-8/41K; 1 lamp only	32	3,190	100	—	0.80	1.01	1.27	85	unknown	
with 2-lamp-ballast system[b]	65	5,820	90	0.91	0.68	0.97	1.43	85	unknown	
B. Effects of replacing 40-W lamps: enclosed four-lamp fixture with ballast										
1. Two 2-lamp 40-W F40 T-12 CW[a]	169	9,340	55	0.95	1.00	1.00	1.00	67	57	
2. Two 2-lamp 34-W F40 T-12 CW[a]	153	8,710	57	0.87	0.91	0.93	1.04	67	49	
3. Two 2-lamp 32-W F32 T-12 41K[b]	135	11,650	86	0.91	0.80	1.25	1.56	85	49	
C. Effects of specular reflector inserts plus delamping: enclosed four-lamp fixture with ballast								Fixture output (lumens)	Optical fixture efficiency	Fixture output (lm/W)
1. Two 2-lamp 40-W F40 T-12 CW[a]	169	9,340	55	0.95	1.00	1.00	1.00	6,070	65%	36
2. One 2-lamp 40-W F40 T-12 CW[a,c]	88	5,210	59	0.95	0.52	0.65	1.25	3,960	76%	45

Notes: (a) standard core-coil CBM ballast; CW = cool-white lamp; (b) 41K = tri-phosphor lamp, 4,100 K color temperature (cool white); high-frequency ballast. The temperature data are based on 25°C ambient temperatures and still-air conditions. The light-output values reflect conditions after 100 hours of lamp operation. (c) The delamped fixture with two 40-W F40 lamps operates at 50 rather than at 57°C for the 4 lamps in the enclosed fixture.

The base-case system is a 40-W, T-12 lamp operated with a standard magnetic core-coil ballast. Table 3 shows the variation in light output, color, and efficacy for the base-case system compared to a 34-W T-12 lamp with a standard ballast and a 32-W, T-8 lamp with an electronic ballast. The first row of data (group A) for each of the three different lamp systems is based on manufacturer's data. The second row shows lamp-ballast system laboratory measurements under ANSI conditions (ambient air temperatures of 25°C). These data should be viewed with caution because actual conditions in buildings, such as temperatures, may differ markedly. The light output of the lamp-ballast system is not twice that of the single lamp's values because output is reduced by the ballast factor of the particular lamp-ballast combination. The 34- and 40-W lamps were all operated with the same standard CBM ballast. There is a small difference in efficacy between the 34- and 40-W lamps because of the change in the efficiency of the phosphor.

In an enclosed four-lamp fixture (group B), the MLWT of the 34-W system is 8°C cooler than the 40-W systems. Because the 34-W system is cooler, it is more efficient, reducing energy use by 9%, not by 17%, as was achieved with the two-lamp system under open-air conditions. The T-8 lamp systems have the highest lamp-ballast system efficacy and reduce power demand by 20%.

When two T-12 lamps are removed from a four-lamp system with magnetic ballasts, the light output and power input decrease by 44 and 49%, respectively, not by 50%, which we might expect. The efficacy of the remaining two lamp-ballast system increases by 7% after the delamping because of the 7°C decrease in the MLWT. Vendors of specular reflectors often claim one can remove two lamps from a four-lamp fixture and maintain similar light levels, and this can be correct, but in some circumstances the light output reductions can be substantial. Group C in Table 3 shows the insertion of a specular reflector in a four-lamp fixture with standard 40-W, F40 lamps, in conjunction with delamping. Lab measurements have shown that with high-reflectance specular reflectors, fixture efficiency is improved by 15% over a new standard fixture with diffuse reflecting material. The table includes tests by General Electric that distinguish between the improved fixture efficiency from the reflector and from the change in MLWT resulting from removal of two lamps (see the column listing the lamp and fixture efficiency improvements). The combination of removing two lamps and adding the improved optical efficiency of the reflector reduces light output by 35%, for a reduction in power of 48%. Unfortunately, the two remaining lamps in the fixture were not repositioned for optimal light output.

Systems Integration: Low-Energy Lighting Systems in New Commercial Buildings

Many commercial buildings' performance standards include upper limits on the total installed lighting power represented as lighting power densities (LPDs) in W/m^2.[27] Consequently, although LPDs are neither a measure of available light nor of lighting quality, they are often evaluated to compare system efficiency.

Surprisingly, among the office buildings in the "Energy Edge" program we found a scatter in the relationship between LPD and annual lighting energy use, reflecting a combination of design factors, thermal performance, and diversity in loads as a result of controls performance.[21] Figure 9 shows two LPDs for eight different office buildings: the LPD from a pre-construction design estimate and the LPD from post-construction building audits. The installed LPDs tended to be greater than the original estimates in all but one case, which may be because the designers were overly optimistic in specifying low LPDs for the design competition. Overall, the increase in the LPD was not correlated with a corresponding increase in energy use from the design stage to actual sub-metered lighting energy use. The average lighting energy use among the offices is a low 39 kWh/m^2-year and was lower than predicted. This average is also well below other comparison data for new commercial buildings in the Pacific Northwest, which range from 51 kWh/m^2-year for simulations of new prototypical offices to 82 kWh/m^2-year from survey estimates. Based on the average characteristics of lighting systems from the late 1980s, the U.S. national average lighting energy use for offices is estimated to be 66 kWh/m^2-year.[28]

The Energy Edge evaluation provides some evidence on how people respond to efficient lighting systems. The technologies used among the 28 buildings in the program include T-8 lamps, CFLs, electronic ballasts, parabolic reflectors, occupancy sensors, and daylighting dimming systems. An extensive segment of a 27-page occupant survey administered at seven buildings included questions covering occupant responses to daylight, appropriateness of lighting for different visual tasks, responses to controls, and general satisfaction levels.[29] More than 70% of the occupants were satisfied with the overall lighting, except in one building where glare was a problem. Two common problems were glare on computer screens and inappropriate levels of illuminance. Lighting was frequently judged as "too bright" for some tasks and "too dim" for others. Occupants were often dissatisfied with the new lighting systems and many of the sensors were disabled because

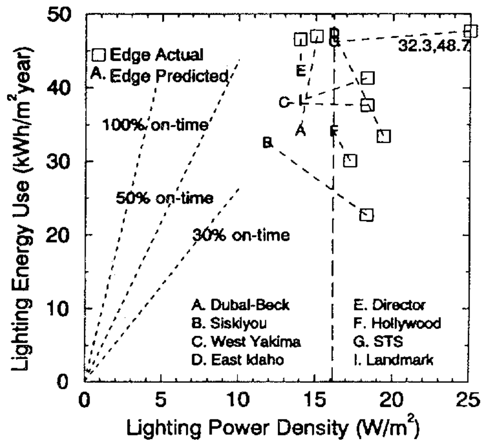


Fig. 9. Lighting power density versus annual lighting energy use for 8 office buildings, based on pre-construction design estimates, post-construction building audits, and end-use metering. The dashed vertical line at 16 W/m^2 represents the maximum lighting power density allowed by the regional building code.

the light was too dim or frequent switching was distracting. These problems are symptoms of poor design. Alternatively, the Emeryville project described earlier demonstrated that adequate light levels can be maintained when sophisticated controls are used. Although the sample size is small, it is notable that there were no more complaints about the lighting systems among the buildings with low LPDs or low lighting energy use than for other buildings.

LINKAGES BETWEEN MERCURY AND LIGHTING

Most non-incandescent light sources use mercury to generate the UV radiation necessary to excite the phosphors located on the interior lamp wall surface which then generate visible light. Gradual absorption of mercury into the glass and phosphors is a primary cause of lamp failure. Concerns about adverse health effects from lighting-related mercury (a toxic heavy metal and bioaccumulator) have been raised mostly in respect to compact fluorescent lamps. However, other light sources (long fluorescent tubes, high-pressure sodium, metal halide, and mercury vapor lamps) contain significantly more mercury per lamp and more mercury on an aggregate scale. In Europe, for example, the mercury in CFLs sold represents 5% of the mercury from all light sources. In turn, mercury from all lamps represents about 0.2% of mercury contained in all consumer products sold annually in Europe.[30]

The trend is towards less mercury per lamp. The quantities used in long fluorescent tubes, for example, have fallen by a factor of two to three in recent decades. In Sweden total lamp-related quantities of mercury continue to decline even as the number of lamps sold increases.[31]

The relationship between mercury levels and *energy-efficient* lighting exemplifies the importance of considering the systems nature of lighting. For example, a direct comparison of mercury-free incandescent lamps and compact fluorescent lamps containing approximately 5 mg of mercury per lamp can be misleading. When the electricity to operate incandescent lamps is generated by fossil fuel, the mercury content of the associated fuel use is three-times greater than that in the alternate CFL. A range of lamp types are compared in Fig. 10, based on the U.S. fuel mix for electricity production. Regardless of the light source, comparisons must be made on the basis of mercury per unit of light produced and the service lifetime of the lamp must also be taken into account. By this measure, longer-lived lamps and management strategies that prolong lamp service life result in lower mercury use. Energy saving strategies such as delamping, increasing fixture efficiency, daylighting, and other practices reducing the numbers of lamps required to provide illumination clearly result in lower amounts of lamp- and electricity-related mercury. In sum, where fossil fuel is used, increased lighting efficacy is generally consistent with reducing lighting-related mercury. The amounts of mercury present in a given utility system or country depend on the fuel mix and power plant thermal efficiencies.

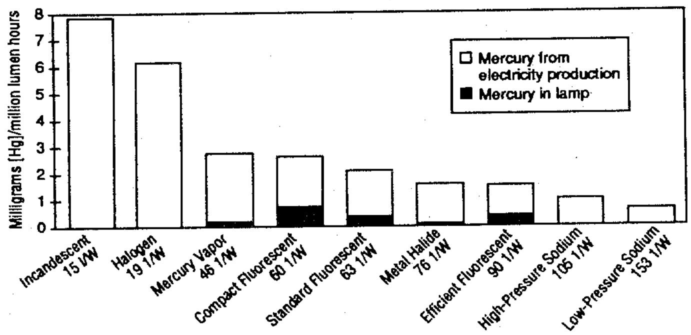


Fig. 10. Mercury and light production. Mercury contained in lamps (ranked by efficacy) plus that associated with power production with fossil fuel is shown, normalized to 1 million lumen hours of light output.†

Mercury releases associated with power production are not well understood. Coal contains more than other fossil fuels but exact concentrations vary, especially when fuel-cycle releases are considered. The mercury content in U.S. coal has been found to vary from 0.01 to 8ppm_w.[32] Furthermore, ultimate health impacts depend highly on the speciation of mercury released during power production, worker exposure (mining and lamp assembly), the mass balance (solid vs airborne), leaching and vaporization of mercury initially contained in solid wastes, emissions control devices used in power plants, and atmospheric residence times of emissions to the air. None of these factors are well understood.

Mercury-containing lamps have been declared a hazardous waste in some parts of the U.S. (e.g. California when more than 25 lamps are disposed of daily) and by the European Community. Recycling should be encouraged. Kvicksilver Återvinning AB (Mercury Recycling Inc.) claims to be recycling 30% of the mercury containing lamps in Sweden.[31] Modular CFLs are easier to process than integral (lamp + ballast) CFLs. Some utilities have established lamp-recovery programs but innovative approaches, such as levying a cash deposit refundable upon return of the lamp, have not been tested. Recycling costs range from 5 to 10¢ per linear foot for fluorescent tubes.

EMERGING TECHNOLOGIES

Current research efforts provide a glimpse of possible future improvements in lighting system efficiency.[6] Table 4 summarizes the performance characteristics we can expect with future lighting equipment. For comparison, the table also shows the characteristics of new lighting equipment as typically installed in 1976 and 1988 (not average stock characteristics for each year). In some cases, the best commercial products are approaching the future specifications shown in the table.

Fluorescent Lamps

Fluorescent lamps can be made more efficacious by mercury (Hg) isotope enrichment, an applied axial magnetic field, the use of two-photon phosphors, and electrodeless high-frequency operation. The most radical improvements would come from the very-high-frequency (MHz) lamp, which relies on electrodeless technology. It has already been tested extensively in the laboratory and is one technology that will contribute to attaining the target of 200 lm/W. This is 57% of the theoretical limit for a white light source. Because it has no filaments, the surface wave lamp could extend fluorescent tube life beyond 50,000 hours. Effective lamp life would be based upon acceptable levels of lamp lumen depreciation.

In the nearer term, new fixture designs are being developed to optimize the thermal operating conditions of fluorescent systems. Some techniques that have been tested include: adding slots to

† Based on average U.S. emissions of 0.12 mg/kWh: 57% coal, 5% oil, 11% natural gas, 27% other. Fuel cycle emissions and releases associated with lamp production are not included. The figure compares the following lamps (wattage [lamp+ballast]/mg mercury, in mg): incandescent (60/0), halogen (90/0), mercury vapor (450/75), compact fluorescent (15/5), standard fluorescent (2 lamp-system) and CBM ballast (95/40), metal halide (450/60), efficient fluorescent (2-lamp system) and electronic ballast (65/30), high-pressure sodium (475/20), low-pressure sodium (215/0).

Table 4. Performance of lighting equipment available in past, present, and future.

Technology Characteristic	1975	1992	2000+
Fluorescent systems			
Lamp efficacy	80 lm/W	100 lm/W	200 lm/W
Lamp life	20,000 hours	20,000 hours	100,000 hours
Ballast efficiency	80%	90%	90%
Fixture efficiency	—	+10%	+10% beyond 1992
Controls (% lighting power affected)	—	25%	50%
HID systems			
Lamp efficacy	100 lm/W	100 lm/W	150 lm/W
Ballast efficiency	—	—	+20%
Edison sockets (U.S. average)	15 lm/W	30 lm/W	80 lm/W
Lighting levels (office building)	100 fc	30–70 fc	30–70 fc
Power density (office building)	4–6 W/ft²	1.5–2 W/ft²	0.5 W/ft²

fixtures to improve natural convection, attaching a thermo-electric Peltier cooling device to the lamp wall, or using a heat pipe to conduct heat away from the wall.[33] Figure 11 shows the variation in MLWT with time for a two-lamp fluorescent system mounted in a lens troffer and an open parabolic fixture.[34] During the first four hours of the test there was no ventilation and the lamps in the parabolic fixture were cooler than those in the lensed troffer. After four hours, 0.56 m^3-minute was added, which provides optimal cooling. After seven hours the ventilation was increased to 1.42 m^3-minute, which overcooled the lamps. The benefits of managing MLWT also apply to compact fluorescent lamps. Researchers have developed a fixture for compact fluorescents with a radial fin heat sink, shown in Fig. 12.[35] Light output is 20% greater with the heat sink.

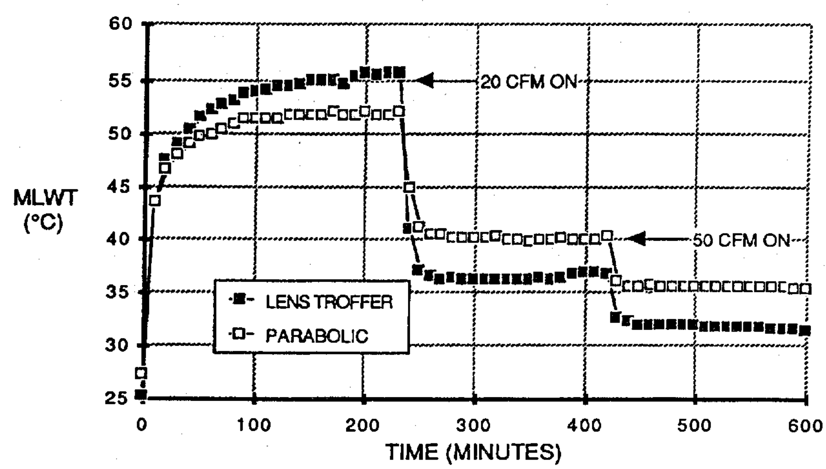


Fig. 11. Dynamic variations in minimum lamp wall temperature (MLWT) over time for a four-lamp fluorescent system mounted in a lensed troffer and an open parabolic fixture with and without ventilation.

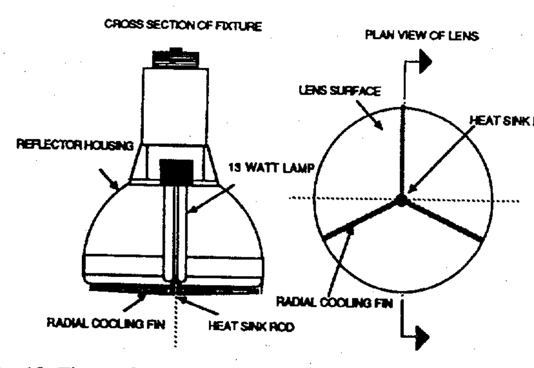


Fig. 12. Fixture for compact fluorescent lamps with radial heat sink.

Compact Fluorescent and HID Lamps

The advent of an electrodeless lamp would be a revolution in fluorescent fixtures allowing for a more compact fluorescent bulb design. Electrodeless HID lamps may also become available with higher efficacies than current models or compact fluorescents, especially at low wattages where HID technology is currently still underrepresented. Future HID lamps will restrike instantly and be dimmable without significant color shifts. Given current uncertainties about price, light output, efficacy, and depreciation characteristics of the recently announced "E-lamp" and other similar products previously introduced by Philips and Matsushita, it remains to be seen whether these light sources will become commercially viable.

Ballasts and Control Technologies

Future gas-discharge lamps can be expected to be controlled with tunable electronic ballasts. Advanced control systems may open up the application of power line carrier technology for targeted communication between sensors and dimming controls. Their versatility can maximize the energy savings from daylighting, task lighting, and occupancy controls while providing optimum lighting conditions for all occupants.

Scotopically Rich Lighting

New research on visual efficiency suggests that optimal use of scotopically rich light sources may result in significant energy savings.[36] Eye pupil size appears to be determined by the scotopic response curve responsible for night vision. Previously, the rods in the human eye were thought to have negligible effect on visual performance at typical interior light levels. Currently, photometric brightness is determined using the photopic response curve of the cones in the human eye. The new findings suggest that energy requirements for lighting a space can be decreased, and visual performance enhanced, if the scotopic content of the light source is increased. Scotopically rich lamps have not been developed, but some lamps with high color temperatures are relatively scotopically rich. Natural daylight is also scotopically rich. Based on a recently developed model for estimating "pupil lumens" a 5,000 K tri-phosphor lamp uses 24% less energy to maintain equivalent pupil size as a cool white lamp. Scotopic content tends to increase with CRI and CCT.

Daylighting

Several advanced daylighting products help enhance the use of natural light. Three such technologies are: light pipes, electrochromic windows, and prismatic panels.[37] Light pipes transmit light up to 100 m. through tubes using reflective, lens, and prismatic guides. Electrochromic windows can be automatically switched to control the transmittance of visible, near infrared, and ultraviolet light, thereby allowing optimal use of daylight while passing or blocking solar heat gains as desired. Prismatic panels refract and reflect incoming daylight using fixed or movable guides.

LIGHTING ECONOMICS

Investments in efficient illumination systems can be highly cost-effective. Cost effectiveness is best analyzed by taking a systems approach. Although not treated quantitatively here, lighting designs that increase efficiency and productivity will be especially cost-effective. Designs that adversely effect productivity should be avoided.

Definitions and Relevant Parameters

The economic performance of energy-efficiency improvements can be evaluated from several perspectives. A policy maker's perspective should capture all costs and benefits experienced by different parties in society (e.g. consumers and utilities). A powerful indicator of societal cost effectiveness is the cost of conserved energy (CCE):

$$\text{CCE} = \frac{\text{(initial investment x capital recovery rate) + incremental annual operations \& maintenance}}{\text{annual energy saved}} \quad (1)$$

The capital recovery rate (CRR) annualizes the initial investment. In terms of the real annual discount rate d and the lifetime n (years), the CRR is given by the expression:

$$\mathrm{CRR} = \frac{d}{(1-(1+d)^{-n})} \tag{2}$$

The CCE is conveniently expressed in the same units as energy price or cost (e.g. cents/kWh), but is independent of any assumption about energy prices. An investment in increasing electric end-use efficiency is considered societally cost-effective if the CCE is less than or equal to the cost of constructing and operating new power plants. Under some conditions, the CCE is less than the marginal cost of operating existing power plants, or even less than zero (if the new device is more than paid for by its saved maintenance cost).

Individual consumers typically measure costs and benefits differently than policy makers do, because policy makers consider a societal perspective, and consumers have relatively more demanding expectations of return on their investment. The consumer perspective is often represented by a simple payback time (initial incremental investment/value of annual energy savings) or by an implicit discount rate. Most consumers expect a rapid payback. The availability of utility rebates or other financial incentives that reflect utilities' low discount rates greatly improve cost effectiveness to the consumer.

A third perspective, that of the electric utility, is important because utilities are concerned about the net economic effect of efficiency program costs, reduced need to finance and operate power plants, and lost revenues resulting from lower electricity sales.[38] Financial impacts of efficiency programs on utilities depend on prevailing rules governing the determination of profits and the way in which costs are folded into tariffs.

The definition of costs and performance of the inefficient base-case system is critical to the evaluation process. Incremental cost and savings factors for an efficient lighting system compared to the base-case system that it replaces vary depending on the strategy chosen but include one or more of the following: (i) first costs for components; (ii) annual energy ($/kWh) and demand-charge ($/kW) savings; (iii) numbers of components (e.g. lamps) required; (iv) installation costs, including design and labor; (v) changes in system wiring costs because of differences in power requirements, power factors, or control methods; (vi) lifetimes of components and light depreciation patterns; (vii) relamping and maintenance costs; (viii) frequency and cost of cleaning; (ix) interactions affecting cooling/heating system size and operation (chillers, fans, pumps, etc.); (x) influence of power factor adjustments on lighting energy costs [some non-residential tariffs]; and (xi) effect of thermal factors on equipment performance and life.

Cost effectiveness is also highly dependent on the hours of use of the lighting system and the prices (retail versus wholesale) paid for the efficient equipment. As an illustration, utilities have purchased CFLs in large quantities (up to 240,000 in one Danish give-away program) at about one-quarter of the prevailing retail price.[9]

Figure 13 quantifies the combined influence of several factors on cost effectiveness, using a series of lighting improvements applicable to common four-lamp fixtures in commercial buildings.[6] Three of these cases were described in Table 3. Most of the investments are cost-effective from a societal perspective but can vary by a factor of two or more depending on the assumptions. The relative output (RLO) of these systems is indicated for each case. Two of the cases result in an increase in light output; three result in a net decrease.

Table 5 exemplifies the cost effectiveness associated with the use of CFLs versus incandescent lamps in a non-residential building. In this case, including only the value of energy savings compared to the incremental cost of the CFL would overstate the payback time by a factor of two in contrast to the case for which a more thorough cost-accounting is performed. The cost of conserved energy takes on a negative sign when the annualized cost savings become larger than the annualized investment.

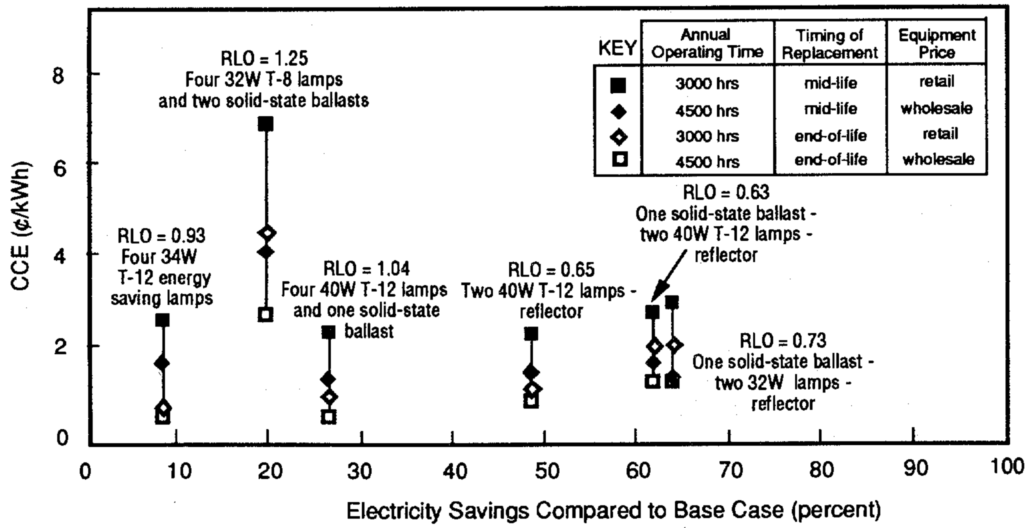


Fig. 13. Energy savings vs cost effectiveness for various efficient fluorescent lighting system retrofits, including thermal factors.[†]

Table 5. Factors influencing the cost effectiveness of CFLs vs. incandescent lamps.

Cost factors (added in successively)	Annual cost or savings	Cumulative annual savings	Simple payback time	Cost of conserved energy
CFL first cost	\$15.00	—	—	—
Energy savings[a]	\$7.89	\$7.98	1.9 years	3.8 ¢/kWh
Demand savings	\$2.74	\$10.72	1.4 years	1.4 ¢/kWh
Incandescent bulbs[b]	\$1.75	\$12.47	1.2 years	– 0.1 ¢/kWh
Labor savings[c]	\$1.75	\$14.22	1.1 years	– 1.7 ¢/kWh
Net HVAC savings[d]	\$1.60	\$15.81	0.9 years	– 3.1 ¢/kWh

Notes and assumptions: (a) One CFL burns for 8,000 hours, replacing 8 incandescent lamps each lasting 1,000 hours. Replacing a 75-W incandescent with an 18-W CFL translates into 114 kWh annual electricity savings worth \$8/year (@ 7 cents/kWh) and demand charge savings of \$2.74/year based on an 80% coincidence factor and a \$5/month-kW demand charge. (b) material cost of an incandescent lamp: \$1.00; (c) labor component of the cost of replacing an incandescent lamp: \$1.00; (d) 0.2 kWh cooling savings per kWh of lighting savings. A real discount rate of 6% is used in computing the costs of conserved energy. The incandescent lamp produces 1,190 lumens, the CFL 1,100 lumens. Annual operating time: 2,000 hours.

Another significant development is the infrared-halogen lamp. Table 6 compares a 60-W PAR IR-halogen floodlamp to the equally bright 150-W PAR floodlamp that it replaces. The substitution results in a 60% energy saving and a payback time of less than three months.

† The basecase is four 40-W lamps, two standard magnetic core-coil ballasts, 9,340 lumens for the system and 6,070 lumens from fixture. RLO = relative light output for fixture. The economic analysis is based on a 6% real discount rate. Equipment costs (1992\$): CMB ballast, \$10; 40-W T-12, \$1.50; 34-W, \$2.00; 2-lamp solid-state ballast, \$30 (4-lamp, \$45); 32-W, \$3.00; reflector, \$50. Excludes savings in costs related to demand charges and heating/cooling interactions. Wholesale prices assume a 33% discount. Lifetimes: ballasts, 45,000 hours; lamps, 20,000 hours; fixtures/reflectors 131,400 hours. Labor costs: \$1 per lamp replaced, \$9 per ballast replaced, and \$15 per reflector installed. Includes thermal effects.

Table 6. Cost effectiveness of energy-efficient PAR lamps (floodlights).

Lamp	Installation labor cost	Retail lamp price	Lamp life (hours)	Power (Watts)	Electricity use (kWh/year)	Payback time (years)	CCE (d = 6%)
150-W PAR/FL	$1.63	$3.60	2,000	150	450	—	—
60-W PAR/HIR	$1.63	$8.20	2,500	60	180	0.2	1.5 ¢/kWh

Note: Assumes an electricity price of 7 cents/kWh and 3,000 hours/year operation.

Systems Aspects: Design, Installation, and Maintenance

Certain energy, labor, and materials costs and benefits can be overlooked if individual components are viewed in isolation from the entire lighting system. Following are examples of important efficiency-economic interactions that arise from the way energy-efficient lighting systems are designed or operated compared to their less-efficient counterparts. Relative labor costs are shown in a few cases, based on cost-estimating conventions in the U.S. published by *Means* and an assumed labor cost of $30/hour.

For existing buildings, component lifetime and timing of efficiency improvements relative to the normal replacement cycle of existing equipment affects incremental labor and capital costs and thus cost effectiveness. Incremental labor costs are minimized if efficient lighting equipment is installed at the time of new design or routine replacement and when multiple measures are installed simultaneously, e.g. group relamping rather than spot relamping. Efficient components may last longer, as in the case of CFLs or some types of HID lamps. For non-residential settings, longer lamp life translates into avoided labor costs. Also, because lumen depreciation is more gradual in tri-phosphor lamps than in conventional lamps (about 8 versus 19% after 20,000 hours), relamping costs ($2.40/lamp for labor alone) are incurred less often. Another consideration is that the benefits of improved thermal performance (longer lamp life, greater light output) can be translated into cost savings in system design (numbers of lamps required) and operating costs (lamp replacements).

Fewer efficient components may be required, in contrast to a less efficient base case. For example, energy-efficient ballasts that can operate more lamps (e.g. four-lamp ballasts versus two-lamp ballasts) mean lower ballast costs per lamp plus avoided installation costs of $6/ballast and reduced replacement costs in the future.

Maintenance can represent a significant fraction of the total cost of providing illumination. Cleaning fixtures more often raises operating costs but also reduces the frequency of relamping required to maintain desired lighting levels. Group relamping more frequently can mean that fewer lamps are needed to provide the desired light level as of the relamping date, i.e. because lamps are operating closer to their initial lumen output than when relamped at a later stage of lamp life. The net economic effect would be the product of higher labor costs and lower installed lamp power. Delamping in overlit areas also means lower future replacement costs.

Finally, rather than oversizing new systems to compensate for future lumen depreciation, applying dimming controls that include lumen maintenance and initial lamp overdriving (perhaps up to 15% beyond normal) could lead to lower first costs in cases where fewer fixtures are needed to illuminate a given area. Fixture installation savings could range from 45 to $75 per avoided fixture. This strategy has yet to be assessed in the field. Practical limits may be imposed by room and luminaire geometry, especially where large fixtures are used. However, some ballasts have ballast factors exceeding one, indicating that the lamp's rated light output can be exceeded. The proliferation of new components, control systems, and design practices offers increased flexibility, making strategies such as this increasingly easy to implement.

CONCLUSION

The goal of energy-efficient lighting design can be characterized as the application of cost-effective systems and practices that minimize energy use while matching lighting quantity and quality to the task at hand. The potential for lighting efficiency improvements is substantial in every part of the world, often exceeding 50%. Emerging technologies and practices promise additional savings. Continued applications-oriented research will yield better understanding of performance and cost-effectiveness in the field. To complement R&D, a concerted effort is needed to implement policies and programs that support the lighting market transformation now underway and to see new efficient technologies through to their intended application.

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