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Technology Assessment: Energy-Efficient Commercial Lighting

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TECHNOLOGY ASSESSMENT: ENERGY-EFFICIENT COMMERCIAL LIGHTING

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PREFACE

This report, one of a series of end-use energy technology assessment reports, investigates the current and potential use of lighting technologies for commercial buildings. The aim of these investigations is to synthesize current information from both published and unpublished sources so that utilities, state regulatory commissions, and others can better identify, evaluate, and select demand-side resources to meet their needs. The material covered in these reports is not limited to "success stories" but also includes failures, barriers, uncertainties, and information gaps. In addition, we attempt to identify and, if possible, reconcile variations or discrepancies among data sources. The technology assessment reports are designed to be easily updated in the future as the technologies develop and better data become available.

1. SUMMARY AND KEY FINDINGS

About one-fifth to one-fourth of total U.S. electricity consumption is consumed by lighting, of which 40-50 percent is used for commercial sector lighting (about 260 BkWh). During the past decade there have been many technical developments in lighting equipment that could greatly reduce lighting energy use. Unfortunately, these products are slow to be incorporated into lighting systems. A significant barrier to achieving significant penetration of energy-efficient lighting technologies is the lack of adequate information regarding their performance characteristics and economic potential.

This report examines cost and performance issues related to energy-efficient lighting technologies, with special emphasis on commercial sector applications and on technologies typically sponsored in utility demand-side management programs. The topics covered include:

- Lighting design and performance issues
- Lighting system component characteristics
- Energy savings from new lighting technologies
- Cost effectiveness of efficient lighting
- Field study results
- Aggregate conservation potential

Major findings are listed below.

1.1 Lighting Design and Performance Issues

- Energy-efficient lighting technologies must be assessed not only from a component analysis perspective, but from a systems perspective that looks at lamps-ballasts-fixture performance, as well as characteristics of the room and task, and occupant behavior combined.
- Energy-efficient technologies must be evaluated in the context of the major changes in lighting design and performance requirements that have occurred during the past 15 years and which have recommended lower levels of illumination and better static controls.
- The use of visual-performance oriented lighting design criteria often has an energy-saving effect. For example, the widespread use of video display terminals (VDTs) leads in many building areas to reductions of conventional lighting levels to minimize glare and enhance productivity.
- Options to meet today's more stringent requirements with new, energy-efficient lighting technologies are not yet widely appreciated in the lighting design community. There is reluctance by the lighting community to employ the most efficient types of hardware. An example is quad lamp compact fluorescents, which overcome most of the size problems of earlier models.
- If correctly applied, energy-efficient lighting systems can not only save large percentages of lighting operating and maintenance costs, but can also enhance lighting

quality. For example, the use of electronic ballasts operating fluorescent lamps at high frequencies has been shown to reduce complaints of headaches and eye strain due to reduced flicker.

- Energy-efficient lamp technologies have employed new phosphors that provide improved color-rendering and other aspects of visual performance. Dimming capability and instant start features are not yet available in some types of efficiency options, such as HID lamps. In retrofits, where fixture location is not altered, changes in fixture lumen output must also be taken into consideration.

1.2 Range of Percentage Savings

- The range of currently commercial energy efficient lighting technologies includes improved incandescents, compact fluorescents, improved fluorescent tubes, high intensity discharge lamps, improved core-coil ballasts, dedicated and tunable electronic ballasts, parabolic fixtures, specular reflectors, occupancy controls, daylighting sensors, timing devices, communications-based controls, new daylighting techniques, improved cavity reflectance, and improved maintenance practices.
- Energy savings from applying each of these technologies individually range from a few percent to more than 80 percent, depending on the technology and the existing system.
- If best commercial technologies are carefully combined to optimize cumulative efficacy gains, energy savings can be very large. For example, in standard fluorescent fixtures they can exceed 70 percent.
- The commonly practiced replacement of 40 W fluorescents with energy-savings 34 W tubes is not an energy efficiency measure, since the efficacy of the systems is about the same. Because of this feature, and because fixtures with 34 W tubes can be easily converted to 40 W tubes, this option is less desirable for utility demand side programs, especially with new construction.
- Although recent federal standards make the use of efficient core-coil ballasts obligatory starting in 1990, the energy savings and system performance benefits from this technology are far smaller than those obtainable with solid-state electronic ballasts.

1.3 Cost Effectiveness of Energy-Efficient Lighting Technologies

- The cost of conserved energy of energy-efficient technologies for common lighting retrofits and new construction options is very favorable. Under most conditions, it will range from about 0.5 cents/kWh to about 3 cents/kWh. This is below the typical short-run marginal costs of operating existing power plants. Payback periods range from a few months to less than three years.

- In the case of compact fluorescents replacing incandescents, the cost of conserved energy can even be negative.
- In new construction, where lighting systems can be designed to fully exploit the efficacy improvement from electronic ballasts, these ballasts are often more cost-effective than improved core-coil ballasts. In retrofits, they can also offer significant cost advantages over improved core-coil ballasts.
- There is little correlation between the percentage saved and the cost of conserved energy. The supply curve of lighting savings from the measures examined in this report is shallow or flat.
- Utility demand-side programs can therefore be tailored to capture a wide range of magnitudes of savings from one and the same customer base, without substantially changing the unit cost of the demand-side resource. **Conversely, suboptimal choices of technology can cost as much as, or more than, optimal selections while saving much less electricity.**

1.4 Projected Improvements in Lighting Technology and Long-Term Savings Potential

- A number of improved lighting technologies are in the prototype or laboratory stage; these could greatly boost the efficacy and other performance characteristics of current technology. They include electrodeless fluorescent and HID lamps with 50-100 percent higher efficacies than current versions, more sophisticated controls of the thermal environment in which lamps operate, and the full exploitation of tunable electronic ballasts and communications hardware to allow the control of individual fixtures.
- These new technologies would allow routine energy savings of more than 80 percent compared to today's lighting systems, a level of savings that can be realized with present technology only if the best commercial products are used and carefully optimized.
- Even if commercial building floor area is assumed to grow dramatically, these emerging lighting technologies would in time reduce lighting electricity requirements in the U.S. by half or more. Savings in the commercial sector alone would free up, at a minimum, the output of 15 to 25 large power plants, and much larger capacities if indirect effects on cooling loads are taken into account.

1.5 Field Studies

- Field measurements are especially important to provide data on savings that can be expected from lighting controls. The field measurements summarized in this report include daylighting, sensor, scheduling, and other lighting control measures. We find a very large range of energy savings. This is partly because very different control strategies were used in each project, and very different baseline conditions were

present in the buildings. Normalized experiments, in which consistent sets of measures are applied to alternative settings, are still lacking.

1.6 Recommendations for Future Work

- There is a need for much expanded programs to familiarize designers, installers, and other lighting professionals with currently available energy-efficient options, including demonstration projects, lighting mock-up facilities, and specialized software.
- More data are needed on the long-term performance of some technologies (operating and maintenance costs, system degradation, effects of operating temperatures, and equipment failure rates).
- The energy savings from lighting system investments should be more broadly verified in field tests. These should include the influence of occupant behavior, interactions between lighting and heating, cooling, and air conditioning demands, and optimization of controls.

2. INTRODUCTION

The 1973 oil embargo initially spurred the lighting community to develop techniques to reduce energy used for lighting. Lighting is the largest single end use of electricity in commercial buildings. Since 1973, government, electric utilities, and industry have played various roles in making lighting more effective and more energy-efficient (Verderber and Rubinstein, 1984). Over the past few years, manufacturers have introduced many new lighting products and technologies, but much of this new equipment has not been readily adopted by the lighting designers, contractors, and their customers. This paper is designed to provide decision makers with information to help them assess new, energy-efficient technologies, and to anticipate the new products that may become available in the next few years.

In addition to innovations in lighting equipment, lighting design philosophies have been changing and are continuing to change. Information on lighting technologies is important to architects, electrical engineers, interior designers, and others who share responsibilities for lighting designs in both new and existing buildings. Today's lighting designer must choose among technologies to provide aesthetically pleasing light and good visual performance. Equipment choices are also influenced by economic criteria related to first costs and operating costs, as well as guidelines or code requirements for lighting energy efficiency. Building owners and operators are faced with similar complexities when evaluating retrofit options. From an energy-efficiency standpoint, the basic goal is to identify lighting system technologies that achieve the lowest life cycle cost, while providing required levels and quality of lighting. Unfortunately, energy efficiency is often not an important issue compared with other decision criteria.

Lighting technologies include both hardware and software options. Lamps, ballasts, fixtures, and controls make up the hardware. Control strategies and lighting design methods can be thought of as software. Below we describe various technologies, their current market status, and their future potential. Since cost-effectiveness is often considered the "bottom line" for assessment of conservation and load management technologies, we present equipment cost data, assess methods of calculating savings, and summarize energy savings and cost-effectiveness results from actual buildings.

We begin with an overview of electricity use in commercial lighting. Next, we introduce the "systems approach" to efficient lighting design, and a discussion of three important performance parameters: efficacy, efficiency, and lighting power densities. This is followed by a review of non-energy performance issues such as visual quality, productivity and health, and power supply effects. In Section 3 we describe the main components of a lighting system and the characteristics of energy-efficient lighting equipment. We return to a systems perspective in Section 4, to describe the performance of typical equipment combinations for both new and existing buildings based on physical and economic performance data. Survey and case study data are presented in Section 5 to illustrate actual applications of many of the techniques described in Sections 3 and 4. Section 6 presents estimates of the aggregate electricity savings potentials in US lighting, including a prospective look at emerging technology improvements. In Section 7 we conclude with recommendations for future research.

2.1 Electricity Consumption by Lighting

About one-fifth to one-fourth of total U.S. electricity consumption is used for lighting. In 1976 this amounted to about 420 BkWh (Krupotich, 1976). Electricity use for lighting has risen since then, to somewhere between 430 to 450 BkWh. About 40-50 percent of the lighting energy is used by the commercial sector, 10-20 percent by the industrial sector, and 10 percent by the residential sector (Lovins and Sardinsky, 1988). Electricity for lighting is particularly important because it contributes a large amount (about 30 to 40 percent) to peak demand hours. Indirect energy use and peak demand from increased cooling loads in commercial buildings are also significant (see Section 4.4).

Fluorescent lamps are the predominant lighting equipment in nearly three-fourths of the U.S. commercial buildings floor stock (EIA, 1988). As shown in Table 2-1, one half of all commercial buildings report standard fluorescent lamps as the predominant lighting type. The next most common lamp type is energy-saving fluorescents, installed in another 21 percent of all commercial buildings.[1] Standard incandescents follow (16 percent) with energy-efficient incandescents (3 percent) and HID lamps (2 percent) completing the list of the most predominant lamp types. Although standard incandescents are predominant in more commercial buildings than HID lamps, HID lamps are found in a greater fraction of the commercial floor area since they tend to be in larger buildings such as warehouses.

The information presented above gives an idea of how much lighting energy is used in the commercial sector and by what type of of equipment. More detailed information on the characteristics of the commercial stock lighting power densities and equipment descriptions are generally unavailable. For example, at the present time the breakdown between the sales of standard and efficient ballasts is not known (Geller and Miller, 1988). One reason for this lack of information is that there is often a variety of lighting systems and lighting power densities within a single building. Based on a survey of experts it was estimated that in 1974 the average connected load of lamps in commercial buildings was 2.9 W/ft^2 (Verderber and Rubinstein, 1983). Lighting power densities in new buildings are lower, due to more stringent building standards and different design strategies. Since 1973, most of the efforts to decrease lighting energy use have arisen from the use of lower light levels. Over the next decade most of the improvements in lighting efficiency will be the result of more efficient equipment. Better system design software tools will also play an important role.

[1] For the purpose of this survey energy-saving fluorescents and incandescents are defined as lamps that have lower lumen output than standard fluorescents and incandescents. These must be distinguished from more energy-efficient lamps.

2.2 Energy-Efficient Lighting Systems

In planning a lighting system a designer must consider factors such as the size, shape, usage of a space, and solar orientation of a space of windows and other daylighting apertures. The use and design intent of a space will affect the quantity and quality of light needed. Technical requirements such as maintenance and system interactions with heating, ventilation, and air-conditioning (HVAC) systems will also influence the lighting design. Other factors influencing design practices are design and construction budgets, initial costs of equipment, flexibility, codes and standards and owner preferences.

There are numerous layers of performance and cost characteristics to consider in designing lighting systems. First are the basic physical characteristics of each component. These are discussed below in Section 3. Next is system performance, which describes how various component characteristics are affected when combined in systems. System performance analysis starts with defining the system boundaries. For example, lighting designers often assess performance of lamp and ballast combinations, or lamp-ballast-fixture systems. System performance also encompasses room characteristics, such as size and color. Most analyses are based on steady-state performance; a broader view would include control strategies, which affect hours of use and levels of use. Overall system performance thus depends on numerous variables, including component performance, component compatibility, age of equipment, operating temperatures, and maintenance. Two important parameters for assessing system performance include system efficacy and lighting power densities (or power budgets). The following two sections describe these terms in further detail.

2.2.1 Efficacy and Efficiency

How efficiently does a lamp, or lighting system, convert electricity into light? The efficacy of a lamp is the amount of light produced (in lumens (lm)) for a given amount of power input (W) to the lamp. The higher the efficacy, the less energy required to achieve a given illumination level. Efficacy (lm/W) values must be interpreted with caution since efficacies are generally reported for the lamp alone, while the important factor is the efficacy of the system, also measured in lumens per Watt. To calculate the lamp-ballast efficacy one begins with the ballast efficiency, which is the ratio of the output power to the ballast (lamp input) divided by the input power to the ballast. The ballast efficiency is multiplied by the lamp efficacy to yield the system efficacy. Further details on and the relationship between these parameters are further discussed below in Section 3.

2.2.2 Lighting Power Densities

One yardstick to assess energy efficiency is the lighting power density, which is the total lighting demand (wattage) divided by the square footage of the area served by the lighting. This parameter is used by lighting designers to assess a layout, and is often used to set lighting efficiency standards in building codes. An important merit of this parameter is that it is relatively easy to measure and monitor. Lighting power budgets of about 1.5 W/ft^2 for office buildings

have been recommended and adopted by various building energy codes around the country (CEC, 1987; NRDC, 1987). A disadvantage of the parameter is that it is an "input" parameter and does not give any information about the quantity or quality of light, or the control characteristics of a lighting system. Its significance must be interpreted in the context of additional lighting system characteristics, as discussed below.

Care must be taken when comparing lighting power densities since calculations methods may differ. For example, it is not always clear what area is "served" by certain lights. Whole-building lighting power budgets may include areas with low lighting levels, such as hallways or reception areas, averaged into the overall value. In addition, a lighting design may utilize significant task lighting power. And finally, energy codes include "power savings adjustment factors" that allow for a higher installed lighting power density when controls such as occupant sensors or daylighting controls are used. A power density may or may not include such adjustments.

2.2.3 Defining a Base Case

The energy savings that are achievable by improvements in lighting efficiency depend on the hardware choices, i.e. the lamp-ballast-fixture and control choices, plus the design strategy. The base case for a retrofit is clearly the pre-retrofit conditions, while for a new building or major renovation the base case for comparison is more difficult to define. However, there is a significant difference between simple, low-cost retrofitting and the cost and performance penalties associated with major redesigns. For example, sophisticated control strategies can require specific circuit distribution configurations, and modifying circuitry in the overhead space is costly (though it can be worthwhile). Fixture modifications, which are less expensive, require rewiring at the fixture location, not relocating the ceiling circuitry. Good lighting design includes optimal placement of fixtures; moving fixtures in an existing building can be costly.

2.3 Non-Energy Performance Criteria

2.3.1 Visual Performance and Productivity

Lighting design is both a science and an art. The quality of light delivered by a lighting system is very important. Color is one of the many characteristics of light. Perceptions of color depend on the light spectrum, the object, the eye, and the brain. The type of lamp (light source) used in a lighting system is the primary determinant of the perceived color; the fixture illumination levels, uniformity, and color scheme of the walls and equipment must be coordinated in a good design. There are important distinctions between visual performance and lumen output. Glare must also be controlled. A room with minimal glare might appear dark if all the lumens are directed horizontally, with no lights washing the walls (little vertical illumination). This occurs by using certain kinds of parabolic reflectors and lenses that direct most of their light down onto work surfaces, and less sideways light, which may not be acceptable.

Another characteristic of 60 Hz fluorescent lighting systems is flicker, which is a measure of the modulation of light output. Fluorescent lighting systems operated at 60 Hz have a 33 percent

flicker. Electronic ballasts (described in Section 3.2.3) which operate lamps at a much higher frequency (20 kHz to 30+ kHz) can eliminate flicker. Flicker, although it generally affects only a small portion of the population, can reduce productivity (Verderber and Morse, 1986).

As computers have proliferated in office and other commercial building environments, glare on video display terminals (VDTs) has become an issue. Glare can produce worker fatigue, discomfort, and decreased productivity. VDT glare can be reduced through improved lay-out, the use of well-designed indirect lighting systems or parabolic fixtures that direct light downward (Wiess and Lyman, 1987). VDT glare can also be minimized by polarizers, and by screen treatments such as anti-reflection coatings and flatter screens. Another characteristic of VDTs is that the rate of lighting flicker may interact with the display refresh rate. Again, higher frequency operation of fluorescent and high-intensity discharge lamps will reduce or eliminate such strobing.

Areas within buildings require widely varying lighting levels. Tasks such as drafting require well-lit spaces to allow good visibility for difficult visual tasks. Hallways, on the other hand, are not areas where people perform tasks that require high levels of illumination. As mentioned, the use of VDTs require attention to glare, but overall *less* light is needed from above, with better task-oriented, or targeted lighting to optimize workplace conditions.

Lighting designers face other new concerns about how occupants respond to various types of lighting controls. For certain types of control systems occupants must be informed of switching configurations and reminded to switch off unused lights. In the case of occupancy sensors there has been some occupant dissatisfaction from lights turning off while occupants are still present, which can occur with poorly adjusted sensors, giving these controls a negative reputation. There is continuing research on the best methods for dimming without occupant perception or dissatisfaction, which indicate promising results for energy-saving potential (see Section 3.4.3).

A less common example, but one that illustrates the importance of overall building "appearance" in relation to lighting design, is the case of a high rise office building in San Francisco recently retrofitted with specular reflectors (see Section 3.3.2). In evaluating the retrofit the building management wanted to ensure that the building preserved "the integrity of its appearance," sustaining the same level of illumination to outside viewers, so that its prominent appearance on the skyline was maintained (*Architectural Lighting*, 1988).

2.3.2 Health and Safety

There is a growing body of knowledge on the health and safety factors associated with indoor lighting. The pros and cons of fluorescent lighting have received substantial attention. Audible ballast hum and visual flicker are commonly associated with traditional fluorescent lights. A recent epidemiological study in England concluded that that occupants working under fluorescent lights with only seven percent flicker had 50 percent fewer complaints of headaches and eye strain (Wilkins et al, 1988). On the other hand, lamps operated at high-frequencies radiate higher levels of electromagnetic (EM) energy, which could affect other electronic equipment.

NEMA and the FCC have recently recommended limits of EM energy emissions for all lighting systems. In addition to the productivity concerns regarding glare mentioned above, eyestrain may also be experienced by VDT users who are exposed to glare. Visual discomfort can also be caused by VDT strobing, as described above.

2.3.3 Power Line Disturbances

Electronic or solid-state ballasts which operate at high frequencies may produce higher harmonics that may be reflected into the power supply and interfere with other applicances (Verderber and Morse, 1986). Activity sponsored by the Institute of Electrical and Electronic Engineers (IEEE Committee 519) is underway to establish standards to limit harmonics generated from lighting equipment. There are four basic types of power line disturbances: surges, dips, outages, and waveshape distortions (Douglas, 1985). Lighting equipment generate the last of these. Harmonics can travel through power systems and may require expensive filtering equipment, or can be minimized in the device design. It is not clear what level of harmonics is acceptable before major costs are incurred. Both the phase relationship between the voltage and current, and the nonsinusoidal waveshape determine the line power factor. Utilities in the U.S. charge customers for whole-building power factors ranging below 0.80 to 0.90. The American National Standards Institute (ANSI) defines a high-power-factor ballast as one with a power factor equal or greater than 90 percent. Nonsinusoidal waveshapes produced by electronic ballast systems reduce line power factor because of the shape component of the harmonic distortion, but do not necessarily influence the generation source (Verderber and Morse, 1986).

Supply lines can also radiate into space, and can thereby interfere with space radiated communications. The problems of interference in power systems from lighting devices are being studied and guidelines are being developed by the Federal Communications Commission (FCC) and the National Electrical Manufacturers Association (NEMA).

Table 2-1. Predominant lighting equipment in all lit commercial buildings

Lighting Type	Number of Buildings (Thousand)	Percent of Total	Area (Bft^2)	Percent of Total
Standard Fluorescent	1958	50 %	22.6	40 %
Energy-saving Fluorescents	830	21 %	19.0	34 %
Subtotal for Fluorescents	2788	71 %	41.6	74 %
Standard Incandescents	643	16 %	6.5	12 %
Energy-saving Incandescent	111	3 %	1.6	3 %
HID	77	2 %	2.7	5 %
Other and Multiple	314	8 %	4.1	7 %
TOTAL	3928	100 %	56.4	100 %

Source: EIA, 1988.

3. COMPONENT CHARACTERISTICS

3.1 Lamps

In this section we discuss the six most common lamps: incandescent, fluorescent, low-pressure sodium, high-pressure sodium, mercury vapor, and metal halide. The latter three types are high-intensity discharge (HID) lamps. Both the operating principles and performance characteristics vary among each lamp type. We discuss efficacy, color, shape, and operating characteristics of each major lamp type. Figure 3-1 shows the general range of efficacies for the six major lamp types (Eley et al., 1985). These efficacies include ballast losses for all of the lamps, except for incandescents, which need no ballast. As shown, the low pressure sodium, high pressure sodium, and metal halide lamps have the highest efficacies, reaching well over 100 lm/W. At the other extreme, incandescent lamps have the lowest efficacy.

Figure 3-1 also includes the *color rendering index (CRI)* range for each lamp type. The CRI is an index which describes the appearance of illuminated materials to a particular light source. The response depends on the spectral distribution characteristics of a lamp. The CRI is equal to 100 for a source that does not change the spectrum relative to the C.I.E. (International Commission on Illumination, (in French)) color triangle of eight specified pastel colors (Eley et al., 1985). The color temperature of a light source is described in terms of temperature measured in Kelvin (K), based upon the color of a blackbody radiator at a particular temperature. The color temperature indicates visual "coolness" (4000 K or higher) or "warmth" (3000 K or lower) of a light source. Light sources with moderate tones have color temperatures between 3000 and 4000 K.

3.1.1 Incandescents

Incandescent lamps use about 40 percent of US lighting energy, roughly three times their share in light output. They produce light through heating a filament to the point of incandescence. About 90 percent of the energy consumed by an incandescent lamp is converted into heat. These lamps are less energy efficient than other light sources. Tungsten has many desirable properties for use as a filament, and is by far the most common choice (Eley et al., 1985, IES, 1981, Lovins and Sardinsky, 1988). As the tungsten filament is heated, it evaporates and eventually burns out. An important characteristic of incandescent lamps is that the hotter they burn, the more efficiently they convert electricity to light, yet the quicker they burn out. CRIs of incandescents reach about 95.

As shown in Figure 3-1, lamp efficacy ranges from 5 to 22 lm/W. Efficiency increases as the wattage increases; a single 100 Watt bulb produces about 1750 lumens while two 60 Watt bulbs (120 W) produce only 1740 lumens. The most common incandescent lamp shape is the "A-Lamp", the common household variety. There are four major strategies for improving the energy performance of incandescent lamps (Lovins and Sardinsky, 1988):

1. *Lens and reflector design modifications* - Reflector, or "R-Lamps", using an interior aluminum coating to direct light out of the fixture on to the area to be lit, can provide up to 50

percent savings over an A-Lamp. They come in a variety of types. Parabolic Aluminized Reflector (PAR) Lamps are floodlamps with both a lens and a reflector. Ellipsoidal Reflectors (ER's) focus light a few inches in front of the lens, rather than behind it, therefore trapping less light and heat. They are effective for deeply recessed fixtures where they can match the light of an R-Lamp at half the wattage. Similar to ERs, "BR" lamps use a parabolic silver reflector with the filament mounted further forward.

2. *Improved filaments and krypton* - A-Lamps with krypton gas have a 1 to 5 percent gain in efficacy over standard lamps. Krypton reduces the evaporation of the filament allowing the filament to be heated hotter and therefore increasing its efficacy, lifetime, or both. Krypton-filled small decorative lamps are also available.

3. *Spectrally selective coatings* - Spectrally selective coatings on the glass envelope of a lamp allow light in the visible part of spectrum to be transmitted, while reflecting infrared (IR) wavelengths (heat) back into the filament to improve lamp efficacy. The reverse application can be applied to the reflector on PAR lamps: transmit the IR wavelengths to reduce heating of the lamp and socket, and reflect the visible wavelengths out of the lamp.

4. *Halogen chemistry and low voltages* - Halogen gas filling reacts with tungsten to redeposit evaporated tungsten back onto the wire filament. These lamps, known as tungsten-halogen or "quartz" lamps, require a quartz encasement because of the high bulb wall temperature. The tungsten cycle allows the filament to operate at higher temperatures, which increases efficacy. The MR-16 (multifaceted reflector) is a common tungsten-halogen lamp in the United States. It is a low voltage incandescent that uses smaller (and higher current) filaments than the 120-volt lamps: this allows better optical control and more effective placement of light where required or desired. Quartz lamps are available in a variety of PAR lamps and MR-16s. See Lovins and Sardinsky, 1988 for further examples.

3.1.2 Overhead Fluorescent Tubes

About half of all U.S. electricity used for lighting is consumed by fluorescent lamps. These lamps, which usually contain mercury and argon gas, convert energy to light by using an electric discharge to excite gaseous mercury atoms within a phosphor-coated tube. The ballast provides the high voltage to initiate the discharge and subsequently limits the current through the lamp. Excited mercury atoms decay back to the ground state, producing ultraviolet (UV) photons. The UV photons that are absorbed by the phosphor coating are converted into visible light as the phosphor fluoresces and emits photons in the visible spectrum (photons with wavelengths of 380 to 760 nanometers (10^{-9} meters)).

Fluorescent tubes come in lengths from 0.5 ft to 8 ft. The 4 ft lamps are the most common, yet the longer the lamp the higher the efficacy. Diameters range from 0.5 inch to 2.5 inch, with the 1.5 inch "T-12" lamp being most common. Efficacies for 4 ft T-12 standard fluorescent lamps, not including the ballast, are about 80 lm/W; at high frequencies these lamps reach about 88 lm/W. The 4 ft T-8 (1 inch diameter) lamps, which also use somewhat different phosphors, approach 100 lm/W when operated at high frequency (not including the ballast).

The color of the light depends on the chemical composition of the phosphor. The six most common terms which describe the color temperature of fluorescent lamps are: Cool White (CW), Deluxe Cool White (CWX), Warm White (WW), Deluxe Warm White (WWX), White (W), and Daylight (D). In Section 4.2 we present performance data for a variety of LW (Lite White) and CW lamp combinations, which have identical power consumption, but different lumen output and color characteristics (CRIs). The color temperature may also be abbreviated: "41K" = 4100 Kelvin.

In this section our focus is on lamp performance, yet an overall understanding of lamp performance must include the ballast, which is an important element in system performance, as discussed in Section 3.2. Ballasts are required to start and operate discharge lamps. There are two stages in starting fluorescent lamps. First, a sufficient starting voltage is needed between an electrode and a grounded conductor to start ionization. Second, a sufficient voltage is needed across the lamp to extend ionization across the lamp. Fluorescent lamps are generally built with one of three types of start-up configurations: preheat, instant start, and rapid start. A further description of lamp-ballast compatibility is given below in Section 3.2.

Ballasts generally deliver less than the rated power to the lamp because of allowed manufacturing tolerances or the desire to provide different light levels. Thus, a lamp's actual light output will be less than manufacturers' ratings cited in catalogs. Light output is also temperature dependent (see Section 4.2). Manufacturer's data on lamp output are based on ratings near their optimum operating temperature (minimum lamp wall temperature, MLWT) of about 40°C, yet most lamps operate above the optimum, reducing efficacy as well as light output. Efficacy and light output also decrease at low operating temperatures, and if the surrounding air is cool enough, lamps may have trouble starting.

Currently available technical options to improve fluorescent lamp efficiency fall into six general categories:

1. *Higher surface area to volume ratio* - Smaller diameters, such as the T-8 lamps, increase efficacy by reducing the loss of the ultraviolet radiation within the plasma (plus they use more efficient phosphors, see item 4 below). These lamps are designed to be part of a system that achieves 90 lm/W with high frequency electronic ballasts operating in an instant start mode. Their slimness can help increase overall luminaire efficiency because they block less of the reflected light in a fixture (see Section 3.3 for a discussion of fixture efficiency). This improvement is only for fixtures designed for T-8s; there may be no improvement in fixtures designed for T-12s or T-10s. Currently, almost all the ballasts required for the T-8 lamps cannot be used with the T-12 or T-10 F40 lamps, although the bipin lamp bases are the same.
2. *Reduced wattage* - Lower wattage (32 W and 34 W) lamps can often be substituted for 40 W lamps. These lamps provide *less* light than 40 W lamps; the decrease may be significant. The total (lamp and ballast) wattage reduction (from a 40 W to a 34 W lamp) typically ranges from about 9 percent to 20 percent, depending on the lamp and ballast combinations. These lamps operate at a higher current and start at a higher voltage, which may shorten the

lamp's lifetime. (In Section 4.2 we present more extensive performance data for typical 40 W and reduced wattage F40s.)

3. *Increased surface area* - Spiral grooves on the tube bring part of the lamp's inner wall closer to the arc discharge, which increases the likelihood that a UV photon will strike the phosphor rather than being absorbed by the mercury vapor. In some cases these dimples run on alternate sides of the lamp and must be installed so that the dimples are on the sides rather than the top and bottom surfaces. Several manufacturers offer these lamps. The comparative performance and economics of these lamps with conventional systems are complex. Costs may be 10 to 15 percent greater than conventional fluorescent lamps, yet lifetime is increased. Efficacies are increased by about 6 to 14 percent (Lovins and Sardinsky, 1988).

4. *High-efficacy phosphors* - The rare-earth narrow-band, or "tristimulus," phosphors provide higher efficiencies for lamps at both lower and higher color temperatures, with excellent color rendition. These phosphors also have better lamp lumen depreciation characteristics. They are particularly effective for low (2800 K to 3500 K) and high (above 4500 K) color temperature applications since their efficacy is maintained for such applications, where that of conventional phosphor (called halophosphates) is severly reduced. The good lamp lumen depreciation characteristics allows them to be used for highly loaded compact fluorescent lamps and high output lamps. Efficacies are 9 to 17 percent better than for conventional phosphors (Lovins and Sardinsky, 1988).

5. *Reflector lamps* - 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 certain dirty and dusty environments where cleaning is difficult (Lovins and Sardinsky, 1988).

For additional information on fluorescent lamp efficiency characteristics such as limitations of krypton filled, reduced-wattage lamps, see Lovins and Sardinsky, 1988. Additional advanced technologies that may be available in the future are discussed in Section 6.3.

3.1.3 Compact Fluorescent

There has been substantial development in this technology over the past decade. Total US sales of compact fluorescents increased from 200,000 units in 1982 to 2.9 million units in 1986, and about 4 million in 1987 (Lovins and Sardinsky, 1988). A basic description of the three main types is given below. Table 3-1 summarizes the wattage savings and lumen reduction that result from the recommended standard replacements. They are available in many sizes and forms, which include bare-tube, globe, reflector, and decorative models. CRIs range from about 82-88. These lamps cost substantially more than incandescents, but last about ten to thirteen times longer (four to five times longer than floodlamps). The basic types are (NRDC et al., 1987) listed below:

1. *Integral compact fluorescents* - Integral compact fluorescents (SL lamps and equivalents) screw into conventional Edison sockets and are typically 15-18 W lamps with an efficacy of 61 lm/W for the more efficient electronically ballasted models (versus 16 lm/W for a standard 75 W incandescent lamp). They are slightly larger than incandescent lamps, with color rendition similar to incandescents, but last about ten to thirteen times longer. The lamp has a built-in electronic ballast that must also be discarded when the lamp burns out. Lamps similar to the SL lamps (manufactured by Philips) are currently being produced by a few other European, U.S., and Japanese manufacturers, but use magnetic ballasts
2. *Modular compact fluorescents* - Modular compact fluorescents, (sometimes also called twin or quad tube fluorescents or PL lamps), attach to adapters that contain a ballast, which screw into Edison sockets. They are available in 5, 7, 9, and 13 Watt sizes. Some modular lamps are available with electronic ballasts. Efficacies range from 50 to 69 lm/W. They are sometimes inappropriate for incandescent replacement because of their appearance and shape. A number of companies now offer fixtures designed to use the modular type lamps that do not require adaptors.
3. *Circline Lights* - These torus-shaped lamps were the earliest compact fluorescent technology. They are much larger than other compact fluorescents, and similarly more limited in applications. Available in 20 to 40 W sizes, they are suitable for diffusing fixtures and hanging lamps. However, they tend to have lower efficacies and poorer CRI's than the integral and modular compact fluorescents.

Given the operating principles similar to those described above for overhead fluorescent tubes, compact fluorescent lamps cannot operate efficiently at temperatures below about 10°C, but special fixtures can be used in outdoor applications that allow application at lower temperatures. They are well suited for use in hotels and motels. For such applications the use of anti-theft devices may be desirable. Compact fluorescent replacement lamps may have (but need not have) lower lumen output than the incandescents they are replacing, as shown in Table 3-1. If the ballast does not supply the wattage specified by the lamp manufacturer, the light will be still lower.

3.1.4 High Intensity Discharge and Low Pressure Sodium

High intensity discharge (HID) lamps produce light as current is passed through a vapor or a gas under high pressure. Like fluorescent lamps, ballasts are required for operation. 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. Figure 3-1 shows the efficacy range and CRI available for various HID lamps. An important characteristics of HID lamps is that lower wattage lamps are the least efficacious.

1. *Mercury Vapor* - These lamps consist of a mercury vapor arc tube in series with a tungsten filament. The outer envelope, or bulb, stabilizes lamp operation and safely encases the arc tube to prevent UV from radiating outward. These lamps take 4 to 7 minutes to reach full brightness. They are available from 40 to 1000 Watts with an efficacies ranging from 23 to

50 lm/W (Eley et al., 1985). Because of their poor color rendering and relatively low efficacy, their application is diminishing in favor of the metal halide lamps.

2. *Metal Halide* - Metal halide lamps have higher efficacies and better color rendition than mercury vapor lamps. They differ from mercury vapor lamps in that the arc tube contains metal halide additives along with the mercury, which increases the efficacy and the color rendering. Efficacies (including the ballast) range from 60 to 100 lm/W. Lamp life is less than mercury vapor lamps, averaging 10,000 to 20,000 hours. These lamps become less efficacious and change color when deeply dimmed, so their range of dimming is limited. There is also a fair degree of variability in color between lamps, and color changes with burning hours. In the past they were not available in sizes below 175 W, but now 70 W lamps 4.5 inches in length are manufactured with a color temperature near 3000 K. Metal halide lamps can be used in indirect systems that reduce glare by reflecting light off a diffuse ceiling with fixtures pointed upward.

3. *High Pressure Sodium (HPS)* - These lamps have high efficacies, from 50 to 125 lm/W. Again, they consist of an arc tube containing sodium-mercury vapor which operates at high temperatures and pressures. CRIs are typically poor, but some lamps are getting close to incandescent CRIs. Wattages typically range from 35 W to 1000 W. Like metal halide, they are significantly less efficacious and change color toward low pressure sodium lamp colors when dimmed. HPS lamps are available to fit incandescent lamp sockets, but replacement packages do not always fit in enclosed fixtures (Lovins and Sardinsky, 1988).

4. *Low Pressure Sodium* - These lamps have the highest efficacies and the lowest CRI (monochromatic yellow light). Low-pressure sodium lamps, available in 18 to 180 W, are limited in applicability, and are appropriate only where color rendition is not important, such as warehouses where items are retrieved by systems other than color coding. The lamps also have restrike limitations.

3.2 Ballasts

3.2.1 Types of Ballasts

Ballasts are required to start and operate discharge lamps. They: 1) provide a current for electrode heating, 2) supply voltage to start the lamp, and 3) limit the current during lamp operation. There are three basic types:

1. *Preheat* - operation uses a starter to preheat lamp filaments (which form a cathode) by sending the power through the filaments. Once the filaments are heated, the starter opens, and the ballast provides the voltage across the lamp.

2. *Instant Start* - The filaments are not heated. Rather, the ballast delivers a very high initial voltage to start the lamps.

3. *Rapid Start* - The filaments are heated all the time during starting and while in operation. Some newer ballasts or thermostat-equipped lamps remove filament voltage after starting the lamps (cut-out ballasts and lamps).

The ballast factor is defined as the ratio of lumens produced by a lamp with a given ballast divided by the manufacturer's rated lamp lumens, which differs for various lamp-ballast combinations and operating temperatures. Ballasts approved by the Certified Ballast Manufacturers Association (CBM) must have a ballast factor of at least 95 ± 2.5 percent of the manufacturer's rated output for a standard F 40, rapid start, argon-filled lamp. The ANSI (American National Standards Institute) ballast standard for 4 ft energy-saving 34 W or 35 W lamps is 85 percent. For retrofits, designers may want lamp-ballast systems with lower ballast factors that reduce power requirements and give less light (if an area is overilluminated). Designers must know a system's ballast factor to determine how much the system will reduce light. A high ballast factor might be more economical for new construction where fewer fixtures, lamps, and ballasts would be necessary to provide a specific illumination level.

3.2.2 Magnetic, Core-Coil Ballasts

There are two major classes of ballasts. The traditional class are magnetic-reactive coils known as *electromagnetic, magnetic*, or *core-coil* ballasts. These ballasts operate lamps at the nominal power distribution frequency of 60 Hertz. They last for about 12 to 15 years (75,000 hours) at 90° C (Lovins and Sardinsky, 1988). Warmer temperatures decrease their life while cooler temperatures increase it. The two subclasses are standard core-coil and high-efficiency core-coil. The standard core-coil ballasts use aluminum wiring, while the high-efficiency core-coil ballasts have copper wiring and better ferromagnetic materials that produce a ten percent improvement in system efficacy. Standard core-coil ballasts can no longer be sold in New York, California, Massachusetts, or Florida, where building standards require the use of the high-efficiency core-coil or other high performance type.

3.2.3 Solid-state (electronic) Ballasts

A newer class of ballasts are known as solid-state, or electronic ballasts. These consume power at 60 Hz, but operate the lamps between 20 kHz and 30 kHz. Solid-state ballasts generally reduce flicker and improve lamp/ballast system efficacy by 20 to 25 percent, with some models offering significantly greater savings. Several manufacturers produce electronic ballasts for fluorescent lamps. Electronic ballasts have recently been introduced for some HID applications, although their use with HID lamps is not widespread.

As mentioned above in Section 2.2.3, the high frequency power fundamental and its higher harmonics can be reflected into the power supply and interfere with other applicances and with space radiated communications. Fortunately, electronic ballasts can be made to suppress harmonics over a wide range of requirements. This is done by designing appropriate filters in the circuit, while not significantly increasing the cost of the ballast.

In a test by LBL, solid-state ballast systems increased the efficacy of standard F40 fluorescent lamp systems by 26 percent (from 63 lm/W with a standard magnetic core-coil ballast to 80 lm/W). Section 4.2 includes additional comparisons between solid-state and core-coil lamp-ballast systems. In addition to the reduced flicker and hum of lamps driven by high-frequency ballasts (see Section 2.2), electronic ballasts can be built to improve controllability for added energy-savings, as mentioned below. The two major classes of solid-state ballasts are the controllable output or "tunable" ballast and the dedicated ballast.

3.2.4 Ballast Controls

Both static and dynamic control systems are used with fluorescent lighting systems. Static controls are designed to be connected at either the input or output side of standard rapid-start fluorescent ballasts, and are further discussed in Section 3.4. Most dynamic control systems can dim fluorescent lamps over a continuous range. Dynamic control devices used with core-coil ballast systems condition the input power to one ballast or a group of ballasts. Controllable solid-state ballasts dim lamps with low-voltage signals. This allows them to dim fluorescent lamps below ten percent of full light output, without loss of lamp life, by maintaining filament voltage to the ANSI specifications. Solid-state dimming systems can save more energy than dimming systems with standard core-coil ballasts because of their high efficacy and greater dimming ranges.

3.3 Luminaires: Fixtures and Optics

Having discussed lamp and ballast performance in some detail brings us to the next component in overall system performance. The fixture, and any other optical equipment, such as lenses, polarizers, and louvers, along with the lamp and ballast, make up the complete luminaire. (Lighting fixtures alone are also often referred to as luminaires.) The main purpose of fixtures and optical systems is to distribute, diffuse, and direct light.

Fixture efficiency, or luminaire efficiency, is the ratio of total lumens emitted by the fixture divided by the total lamp lumen output. Higher efficiency fixtures emit more of a lamp's light. Fixture efficiency depends on geometric design, material properities, and the type of lamp-ballast system in the luminaire. Another suggested parameter for fixture performance, not in common use, is optical efficiency. Optical efficiency is the ratio of the total light flux from the luminaire divided by the total light flux from bare lamps, with the lamps operating at the equivalent minimum lamp wall temperature. This latter measure isolates a fixture's optical characteristics from the fixture's influence on lamp operating temperatures, yet both parameters should be considered when comparing fixture performance.

Again our focus is on fluorescent lighting luminaires, the most common of which is a direct lighting system: the simple lensed troffer, which is a white painted box with a plastic diffusing lens on its lower surface. This design was prevalent during the 1960s, and is used today in the most budget conscious applications.

3.3.1 Parabolic Troffers and Louvers

Parabolic fixtures, which are linear parabolic troughs with the lamps at the focus, reflect light down and out of the fixture. Variations in the geometry produce variations in glare reduction and fixture efficiency, which can be tradeoffs. These fixtures came into widespread use during the 1970s. Most parabolic fixtures are simply louvered luminaires with parabolically shaped standard white troffers. The louvers are open grids of opaque, semitranslucent, or reflective shielding and diffusing media that collimate downcoming light rays. These fixtures reduce glare associated with lensed fixtures and permit cooler luminaire operation.

3.3.2 Specular Reflectors

During the past few years, fixtures components with highly specular reflective surfaces have become available. Specular surfaces have mirrorlike characteristics, for which the angle of incidence equals the angle of reflection (whereas with diffuse surfaces there is a distribution of radiation about the angle of reflection). The materials and shape of the reflectors are designed to reduce absorption of reflected light rays within the fixture while delivering light in the desired angular pattern. Specular reflector equipment can be added to existing light fixtures. They are particularly suited for overlit areas where the installation of a reflector is accompanied by delamping. They are also available in original (new) fixtures. A more detailed discussion of their performance characteristics can be found in Section 4.2.4.

3.3.3 Lenses and Polarizers

To control light distribution, glass or plastic lenses are often used with fixtures. Their control characteristics depend on the type of material used, as well as the light distribution pattern or surface texture. Polarizing lenses cause light to be somewhat polarized, which can increase visual effectiveness by reducing glare. Using the polarizers may allow equivalent visual performance at reduced light levels (Lovins and Sardinsky, 1988).

3.3.4 Air-handling luminaires

Of the power input into a fluorescent system, about 15 percent goes to losses in the (standard) ballast (Treado and Bean, 1988). Of the remaining 85 percent that goes to the lamp, 21 percent is radiated as visible light, while 37 percent is infrared radiation, and 42 percent is convected and conducted to the air and other luminaire components. Convection occurs to the room, plenum, and return air. Air-handling luminaires reduce the convection to the room and plenum air by increasing the convection to the return air. This has the additional positive benefit of cooling the lamp-ballast system. Section 4.4 further describes the relationship between lighting systems and heating and cooling loads.

3.3.5 Luminaire Depreciation

The luminaire dirt depreciation factor (LDD) is used to indicate a luminaire's resistance to dirt build-up on the reflective surfaces. The higher the LDD, the less requirement for

maintenance. Most reflective surfaces are baked enamel or aluminum. Aluminum finishes deteriorate at a slower rate, but enamels typically provide higher initial reflectances and are easier to clean. There is some debate over which luminaire systems will lead to high LDDs. In comparison with lensed troffers, open troffers may lead to dirtier lamps since their static charge may collect dust from a larger air flow. On the other hand, some manufacturers claim that the airflow will clean the lamps.

3.4 Controls

3.4.1 Equipment, Applications, and Strategies

Energy is wasted if lights are used when they are not needed. This waste can be minimized with good controls. Although lighting researchers are generally confident of their ability to analyze the energy savings potential of lamps, ballast, and fixtures technologies, savings from control technologies depend on control hardware and operating strategies. The choice of a lighting control system depends on the application: retrofit, renovation, or new construction. The savings potential from controls are potentially substantial. Electricity use for lighting for the controls case study retrofits described in Section 5 decreased from 9 to 57 percent, and by amounts ranging from 1 kWh/ft^2-year to 4.4 kWh/ft^2-year. Table 3-2 shows the four categories of lighting control equipment characteristics (Verderber, 1988). The first two describe the strategy for control, while the second two describe the hardware components. These are:

1. *Static controls* - Decreasing light levels by a fixed amount through delamping or installing impedance-modifying devices (current limiters) can be thought of as static controls which change light levels semipermanently. Current limiting devices reduce the input current to standard core-coil ballast systems. These systems typically reduce the power and light output by 30 and 50 percent. Under the same MLWT conditions the reduction of power and light output would be 30 and 50 percent. Due to the reduced (more nearly optimal) MLWT the reduction in power and light is less than 30 and 50 percent, so system efficacy is increased by two and four percent.
2. *Dynamic controls* - Dynamic controls can be used to dim or switch lamps on and off over short intervals. They may also measure light levels or sense the presence of occupants.
3. *Sensors* - Personnel sensors detect people by use of ultrasonic sensors or infrared sensors. They are most effective for spaces that have intermittent occupancy such as restrooms or storage areas.
4. *Photocells* - Photocells measure illumination levels in a space and signal the electric lights to maintain the prescribed level. They can sense the presence of daylight and send signals to the controller to continuously adjust or step the controls. Clocks provide instructions to a lighting system in real time.
5. *Communications* - This equipment communicates information from the sensor to the controller, through dedicated wiring, existing power lines, or radio control.

Table 3-2 also shows the control strategies associated with the above four control characteristics, and their applicability for new or existing buildings. The basic categories are: light reduction, predictive scheduling, random scheduling, task-tuning, compensation for lumen depreciation, daylighting, and load shedding. Tuning involves tailoring the illuminance level to the requirements at each workspace. This is a useful characteristic, especially for speculative office buildings where design is often done without knowledge of future tenant lighting needs.

Building managers typically are unaware of how much energy the lights actually consume. Some new innovative control systems actually *measure* lighting electricity consumption and can be used directly to evaluate savings from use of the equipment (*Energy User News*, 1988). Use of such equipment could greatly benefit conservation efforts by informing a building operator of how usage patterns or equipment modification affect energy use.

3.4.2 Lumen Maintenance

Lumen maintenance controls use dimmers and photocells to compensate for system lumen depreciation, allowing a system to be designed with lower initial lighting power densities (W/ft^2). Light levels are often designed 20 to 40 percent over the level needed, to compensate for the reduction in lighting output of lamps and fixtures as they age. Lumen maintenance controls sense the actual illuminance level in a space and reduce system power input to maintain only the desired footcandle level. The savings in new (or recently replaced) lighting system energy use can reach 30 percent initially, declining toward zero as the systems age, with an average of about 10 to 15 percent. The measure of success of this control strategy depends on the characteristics of the installed system compared to what the base case design would have been, which can often be difficult to identify.

3.4.3 Daylighting controls

All buildings with windows or skylights are daylighted, but only those that have an effective means to control light will save energy and moderate peak load. The spatial control of the lighting system plays a key role in the design of daylighting controls. In some cases the systems are modular and additive, such as a dimmable ballast with a built-in sensor controlling a single fixture. At the other extreme are centralized systems using a central control, distributed sensors, and on-off or dimmable controls located throughout a number of rooms or zones, all of which are linked back to the central control unit.

The daylight contribution from windows and skylights has a strong spatial dependence, making zoning decisions very important. Other considerations in the system design include visual tasks of each zone and the use of window shades. The time response of the sensors is important, with an asymmetric response being the best, i.e. fast response to reductions in daylight, with slow response to increasing daylight. The options are diverse and there is little accumulated experience to guide decision-making. See Section 5 for two case studies of energy savings from perimeter daylighting based on actual installations.

3.4.4 Dispatchable Load Management

There is a growing interest in dispatchable load management in which building loads are reduced occasionally on request from the utility. In some large office buildings there are opportunities to switch off perimeter lighting during utility peaks. One recent study concluded that a large modern office building can cut 20-30 of its lighting along the perimeter during "special case" interruptions (Xenergy, 1988). The strategy can be implemented manually or with an energy management system that can cut-out appropriate circuits. Again we reference Section 5 for the case studies of energy savings from perimeter daylighting.

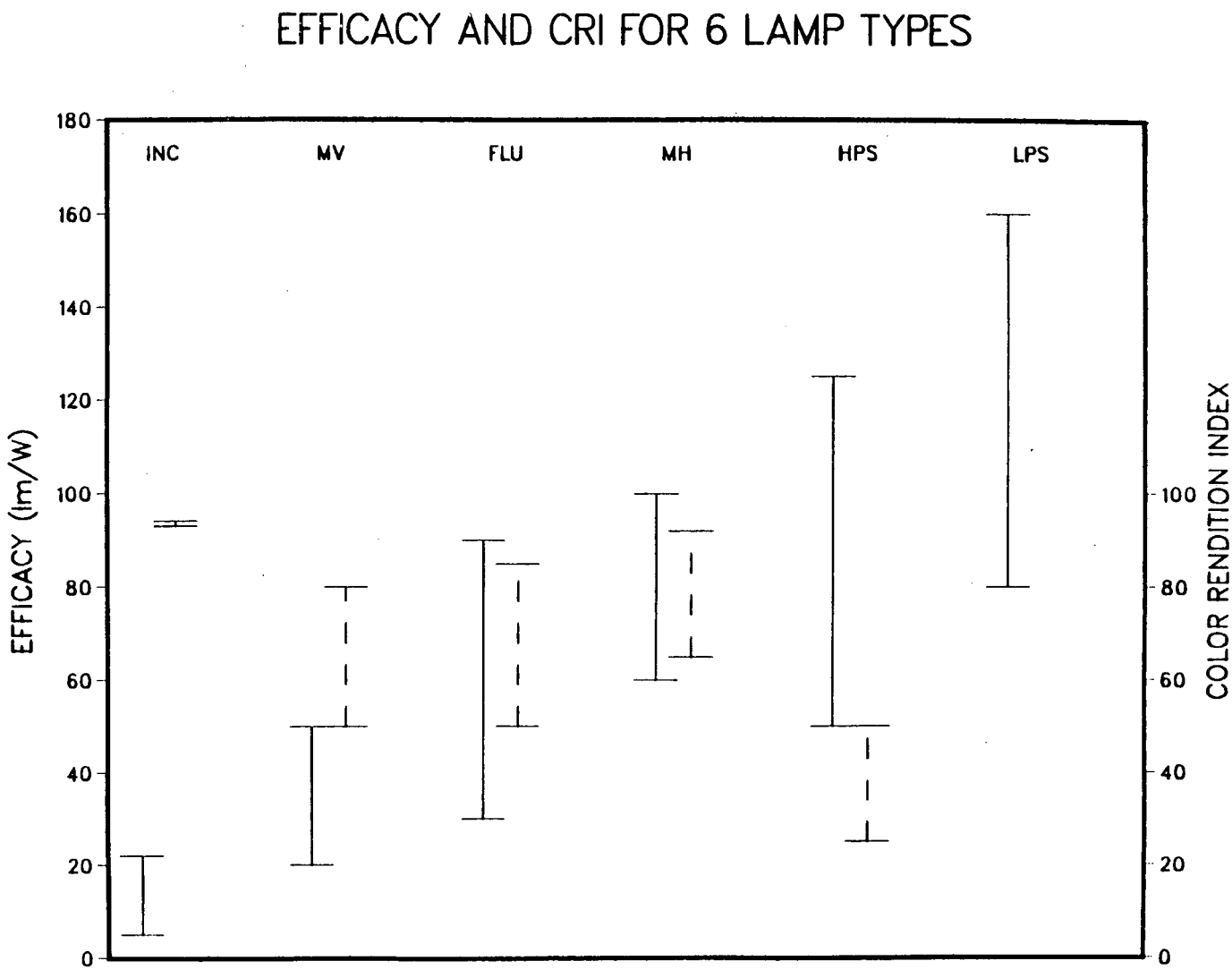

Figure 3-1. Efficacies and color rendering indices for 6 lamp types. Left axis (solid range bar) shows the range of efficacies for the six major lamp types (including the ballast losses for the gas discharge lamps). Right axis (dashed range bar) shows the color rendering index (CRI) range for each lamp type. No value is shown for the low pressure sodium lamp because the CRI is so low.

INC	Incandescent	MV	Mercury Vapor
FLU	Fluorescent	MH	Metal Halide
HPS	High Pressure Sodium	LPS	Low Pressure Sodium

Table 3-1. Standard replacement of incandescent with compact fluorescent

DESCRIPTION		TOTAL POWER (W)	LUMENS (lm)	EFFICACY (lm/W)	RELATIVE EFFICACY
Incandescent	Standard Bulb	40	480	12	1.00
Fluorescent	PL-7	9	400	44	3.66
Difference		31	80		
Incandescent	Standard Bulb	60	870	15	1.00
Fluorescent	PL-9	12	600	50	3.33
Difference		48	270		
Incandescent	Standard Bulb	75	1190	16	1.00
Fluorescent	SL-18	18	1100	61	3.81
Difference		53	90		

Table 3-2. Lighting control equipment, applications, and strategies

SYSTEM	DESCRIPTION	APPLICATION	STRATEGY						
			Reduced Levels	Scheduling Predict.	Scheduling Random	Tuning	Lumen Deprec.	Day-lighting	Load-Shedding
STATIC									
Delamping	Reduces light level & demand up to 50%	Retrofit	x			x			
Impedance Modifier	Reduces light levels & demand up to 30-50%	Retrofit	x			x			
DYNAMIC									
Lighting Controllers									
Switches/Relays	On-off switching banks of lights	Retrofit		x					
		Renovation		x					x
		New Construction		x				x	x
Voltage/Phase Control	Continuous dim of light level 100-50%	Retrofit	x	x					
		New Construction		x			x	x	x
Solid-State Dimming Ballast	Continuous dim of light level 100-10%	Renovation		x		x	x		x
	& operates lamps efficiently	New Construction		x		x	x	x	x
SENSORS									
Clocks	Regulate illumination with time	Retrofit		x					
		Ren./New Construction		x					
Personnel	Detects whether space is occupied	Retrofit			x				
		Ren./New Construction			x				
Photocell	Measures illumination level in space	Retrofit					x		
		Ren./New Construction					x	x	
COMMUNICATION									
Computer/Microprocessor	Communicates between sensors & controllers	Retrofit		x					
		Renovation		x			x		x
		New Construction		x			x	x	x
Power-line Carrier	Carries information over power lines	Retrofit		x					
		Ren./New Construction		x		x	x	x	x

4. SYSTEM PERFORMANCE AND COST-EFFECTIVENESS

In Section 3 we described the technical characteristics of energy-efficient lighting equipment by individual components. We saw that many new lighting components offer significant energy savings in and of themselves. In this section we investigate how the various component technologies perform in combination, and how the economics of system performance varies with these combinations.

In analyzing the economics of various energy saving measures and packages, the concept of an *energy efficiency supply curve* (Meier, 1983) has proven useful. In such a supply curve, the marginal cost of saving a unit of energy is plotted against the percentage or amount of energy saved. A supply curve can be prepared both for an individual building or installation and for all applications in a service territory or state. The former are also called micro supply curves; the latter are called macro supply curves.

In general, such supply curves show an upward-sloping trend: the more energy is to be saved, the greater the cost. However, supply curves can be quite flat, i.e. the cost of increasing efficiency and savings is not very sensitive to the degree of savings over a wide range of improvements (see e.g. Krause et al., 1987). In some applications, costs of conserved energy can even drop as larger savings are realized. Such an unexpected result can occur when quantity turns into quality, i.e. when incremental improvements in a technology are replaced by basic redesign. Here, redesigning typically involves not only the technical system at hand (e.g. lighting), but also the interaction of that technical system with other major systems (e.g. air conditioning plant) and the building as a whole (e.g. daylighting). Another flattening effect on the supply curve comes from the bundling of single measures into packages that save labor costs and capture synergisms. For these reasons, the construction and interpretation of supply curves for lighting efficiency measures is a complex exercise that involves numerous qualifications.

It is interesting to ask what the shape of the micro and macro supply curves of lighting efficiency improvements might be. In developing such a supply curve for lighting, one encounters three practical difficulties. The first has to do with interactive effects among the lighting components. The performance of these components is a function of the system configuration used. We have already mentioned the influence that temperature has on lamp-ballast performance. Extensive measurements for a broad set of conditions are required to yield a satisfactory evaluation. Not only lighting configurations themselves must be considered, but also the various trade-offs between lighting system configurations and other building components and features, as discussed for daylighting above. At this time, only portions of the large range of possible combinations have been well charted in independent laboratory measurements, and even less data are available from field measurements.

The second difficulty in developing micro and macro supply curves for lighting has to do with the wide variations in baseline conditions among buildings and utility customer groups. There are at this time inadequate data on the distribution of lighting technologies in existing installations. Statistics on the light levels required by various building types and floor space fractions and on operating hours and schedules are even less developed.

The third difficulty in creating lighting supply curves has to do with accurately characterizing the economic costs of the various systems, including the crediting of cost savings resulting from interactive effects, in components other than lighting.

Finally, a supply curve is useful only if it compares apples with apples, i.e. energy services of the same quality and usefulness. But the quality of energy service as measured in lumen output, color rendering, footcandles, visual effectiveness, or other indicators often varies with the package of measures. When designing new buildings, one can use computer simulation tools to translate a given lighting quality requirement and lighting level into various hardware configurations. The situation is less straightforward in a retrofit situation, where fixture locations and other parameters may be preset and only a broad visual performance equivalence can be established.

These considerations have shaped the limited scope of our supply curve investigation. In our discussion below, we confine ourselves to the micro-level, i.e. to individual installations, leaving the discussion of macro-level savings potentials for Section 6. We develop a few data points that approximately define the low-percentage-savings portion of the lighting efficiency supply curve, without attempting to characterize this curve comprehensively. Within this low-savings portion, we focus on a subset of hardware-based efficiency options that modify the lamp-ballast-fixture system, but we do not address the control options that could be applied.

The data used in our cost and performance analysis are based on laboratory and field measurements as well as computer simulations. They include only very common commercial technologies that are widely available. These qualifications are important because they limit the conclusions our analysis allows regarding the size and cost of the lighting efficiency potential as a whole. Some analyses have provided energy savings calculations from a broader, more comprehensive perspective and are referenced in Section 6.

We begin with efficient lighting in new construction. Here, we first discuss how energy-efficient design principles can be used to obtain energy savings before any hardware investments are made. Having set sound visual performance and lighting level targets for each building area, one can then search for a least-cost (lowest life-cycle cost) system supplying the specified illumination. We illustrate this second step with the results of a previous LBL study. The majority of our discussion focuses on retrofitting, beginning with a review of laboratory performance data for various lighting system configurations involving four-foot fluorescent lamps and fixtures.

We next introduce criteria for assessing the cost effectiveness of energy-efficient lighting equipment, in particular the concept of the cost of conserved energy (CCE). We apply this framework to the energy savings from 11 prototypical fluorescent lamp retrofit packages. Sensitivity analyses are performed using four different cost scenarios. Finally, we analyze our cost of conserved energy results in terms of the quality of the lighting service provided by each package.

The final subsection reviews measured data and simulations of the interaction between lighting energy use and HVAC energy consumption.

To complement these laboratory-based results, we have also assembled a number of field measurements in occupied buildings. They provide an insight into the range of savings that have been obtained from combinations of limited hardware improvements, improved lighting level specifications, and behavior-related modifications. These field measurements do not, however, allow disaggregation by individual technology. Nor is the range of technologies used in them congruent with our laboratory tested fixture packages. We therefore present these field data in a separate section (Section 5).

4.1 New Construction

4.1.1 Design Issues

A key goal in lighting design is to provide good visual performance. A major feature of a lighting design is the arrangement of luminaires. The Illuminating Engineering Society (IES) has developed recommendations for achieving good visual performance with low-energy lighting designs. Unfortunately, these recommendations are incorporated into only a small fraction of current building designs (Goldstein and Watson, 1988). While some designers may explore the use of new, energy-efficient technologies, others may resist the use of new equipment because of familiarity with traditional design practices. Optimizing for energy efficiency tends to be a secondary concern.

One must also bear in mind that the IES illumination levels are professional consensus recommendations based on intuitive knowledge and experience rather than scientifically established optimal visual performance standards for each type of task.

The following five design strategies contribute to overall system energy efficiency (Goldstein and Watson, 1988).

1. *Task lighting* - The IES recommends that task areas for general office occupancy be illuminated to 30 fc. The remainder of the room need only be illuminated to one-third of the task illuminance levels, but at least 20 fc. Actual illuminance levels almost always exceed IES recommendations (Goldstein and Watson, 1988). A more serious task-lighting design might illuminate remaining space to one-ninth the task intensity, but at least 10 fc.
2. *Display lighting* - Many retail stores over-illuminate general merchandise, almost washing out displays, the IES recommends reducing general illumination levels and concentrating attention on displays.
3. *Lighter colors* - Using reflective color schemes - lighter walls, ceilings, and floors - requires less artificial lighting to achieve the appearance of brightness.
4. *Grouping tasks* - Where various tasks require different illuminance levels, grouping similar tasks allow areas with more intense illumination to be isolated.
5. *Daylighting* - Fenestration window systems can enhance the use of natural sunlight without introducing excessive glare, contrast, or other visibility problems. Technologies include light shelves, atria, skylights, clerestories, and shading devices. New options include light-

pipes and fiber optics which can deliver daylight into core zones. These strategies can produce substantial savings in lighting electricity consumption when used in conjunction with control technologies (See Section 3.4.3).

4.1.2 Computer-Aided Design Performance Evaluation

Many commercial lighting systems are not planned by lighting design experts, which leads to lost opportunities for maximum energy efficiency and visual performance. Fortunately, newly developed computer simulation tools greatly facilitate the design of lighting systems that meet desired levels of lighting performance in an energy-efficient, least-cost manner. To illustrate the general approach, we briefly review the results of an LBL study applying such simulation tools to an office building (Rubinstein *et al.*, 1986). More modern hardware would result in even greater improvements.

The luminaire spacing configuration and inputs were developed to model a 900 ft^2 open-office plan, with floor and ceiling reflectances of 20 percent and 70 percent, respectively, as described in Rubinstein et al., 1986. The computer programs calculated point-by-point illuminance levels. Data such as maintenance factors, ballast factors, and differences in lumen ratings for each lamp were compiled for the program. Annual energy use was calculated assuming 3500 hours of operation. Three lamps, three ballasts, and two fixtures (resulting in the 18 different combinations) were chosen for study to represent the range of performance and efficiency encountered in typical commercial applications.

Table 4-1 shows the 18 lamp-ballast-fixture combinations. The two fixtures consisted of a lensed troffer and a parabolic fixture. The three ballasts were a standard two-lamp CBM core-coil ballast, an energy-efficient, core-coil ballast, and a high-frequency, electronic ballast. The three lamp types were 35 W, F40, krypton filled lamp (2925 lm), a standard 40 W, argon-filled lamp (3150 lm), and a high-output argon filled lamp (3300 lm).

Results of the simulations are also shown in Table 4-1. The choice of ballast had the largest effect on power savings, while the choice of lamp type had a relatively small effect. (Tri-stimulus phosphor lamps would have increased the impact of lamp type). Using the electronic ballast decreased the lighting power density by 20 percent over the base case system, which consisted of the lensed troffer with the standard core-coil ballasts and standard F40s.[1] The choice of fixture had no effect on the lighting power density or efficacy because the better maintenance characteristics of the parabolic fixture offset the higher fixture efficiency of the lensed troffer.

However, these results would differ with other luminaires with different numbers of lamps, different baffles, and different maintenance factors. (See Rubinstein et al. for a discussion of the uniformity of illumination and visibility levels). The authors note, for example, that the parabolic fixtures provide less uniform illuminance distributions than the lensed troffers because parabolic fixtures have a narrower candlepower distribution; but they also produce less glare.

[1] Again, greater savings could be achieved with more recent equipment. Also, some secondary effects of electronic ballast use would increase the calculated savings.

Table 4-1 also shows the present value of life cycle costs for each combination, with costs broken down between first costs for the luminaire, operating costs for energy, and maintenance costs. The assumptions used to derive each of the parameters are listed at the bottom of the table. Energy is clearly the major cost of lighting, representing 55 to 75 percent of total life cycle costs over 20 years. Unfortunately, first costs, rather than energy costs, typically receive the most attention when design decisions are made.

In general, the study showed that the more energy-efficient systems had lower life-cycle costs than standard systems. However, the 35 W "energy saving" fluorescents did consistently worse than standard 40 W fluorescents, which is a telling comment on the inappropriateness of these tubes for true (i.e. constant illumination level) lighting efficiency.

In this particular case study, the lensed troffer configurations did better than the parabolic dish systems. The two lensed troffers with electronics ballasts and the standard and high output lamp configurations had the lowest life cycle costs. At the other extreme, the two parabolic fixtures with the "energy saving" 35 W lamps and the core-coil ballasts had the highest overall costs.

Some caution must be used in interpreting the results. The authors noted that the parabolic fixtures were not the most efficient available and did not have the bat-wing candlepower distribution typical of the high-performance models. Furthermore, visual performance for vertically oriented tasks, such as VDT use, might be improved with the parabolic fixtures. More recent lamp (tristimulus, T-8 and T-10 lamps) and ballast designs, combined with best specular reflectors, would further increase efficacy and cost-effectiveness.

4.2 Retrofit Applications

4.2.1 Introduction: Light Levels, Temperature, and Costs

There are many opportunities to improve the performance of existing lighting systems by reducing on-peak power and energy use while maintaining and even improving occupant satisfaction and the quality of the visual environment. Prior to assessing the cost and performance of lighting equipment, the lighting designer must review the space(s) to be retrofitted in order to determine the required illumination levels. In some cases a space may be overilluminated, in which case a reduction in lighting levels is often the most appropriate and cost-effective option. In other situations it may be inappropriate to reduce illumination levels, or perhaps an increase is desirable. The choice of lighting equipment should consider long-term lighting needs of the occupants, which include possible changes in the usage of a space. Defining these needs may require coordination with maintenance staff, such as considering the inventory of lamps and ballasts, which should be minimized.

When the number of lamps in a fixture are reduced, or the fixture power is otherwise reduced (via current limiters, etc.) the lamps will operate at a lower temperature. The light output and efficacy of the system decreases at high operating temperatures by as much as 10 to 20 percent. Thus, the improvement in efficiency for devices that results from these measures is, wholly

or in part, a result in reduction in lamp-wall temperature. However, some retrofits of fluorescent lamps already operating at an optimum temperature could reduce the lamp temperature *below* the optimum, which would reduce both light output and efficacy. Thus, some estimate of the lamp-wall temperature of the in-place system, and the resulting changes after the retrofit, should be made. Standard F40 fluorescent lamps nearly always operate above their optimum temperature, except in open-strip fixtures. Energy savings lamps may be at temperatures near their optimum.

In deciding among particular types of retrofits one must consider the effort and cost of properly installing the equipment. Key considerations are minimizing installation costs and disruption to occupants. Relamping is the simplest, because it requires at most the opening of a fixture. Delamping may require opening the ballast panel to disconnect the ballast from the mains. Ballast and current limiter retrofits may require rewiring these products in the fixture. Specular reflectors for fixtures require repositioning of the sockets and securing the reflector. Controls may also require re-wiring of lighting circuits. They are therefore often most cost-effective when installed centrally in the electric closet.

4.2.2 Options Investigated (and not investigated)

Section 4.2.3 and Section 4.3.2 discuss the energy and cost performance of specific measures. We focus on four-foot fluorescent lamp-ballast system retrofits for two primary reasons (although Section 4.3.2 also includes an example of the replacement of an incandescent lamp with a compact fluorescent.) First, these systems are the most common commercial lighting systems, especially in office environments. Second, performance data are available for them from laboratory measurements conducted under the Lighting Systems Research Program conducted at LBL (Verderber and Morse, 1988, and Verderber, 1988b).

We begin with a discussion of single lamp and open air lamp-ballast system performance. We then examine how various lamps operate in an enclosed, ceiling-mounted, four-lamp fixture, using a variety of retrofit packages. The base case system is a 40 W T-12 CW lamp operated with a standard magnetic core-coil ballast. Delamping and specular reflector retrofits, and the difference in performance between two-lamp and four-lamp systems, are also discussed.

Although the savings from lighting control retrofits can be substantial (as discussed in Section 3.4), there is a lack of field performance data on such retrofits. Moreover, the available data are difficult to generalize. We therefore have not investigated and presented detailed energy and economic performance data for lighting controls.

4.2.3 System Performance

Two lamps with single ballast in open air - Table 4-2 lists several fluorescent lamps that are widely available and provide a large range of options (light output, color, efficacy) for possible retrofits. The first row of data for each of the six lamp systems is the lamp performance based on manufacturer's data. Presented in the second row are system data that were measured by LBL under ANSI conditions, with ambient air temperatures of 25 °C. These data should be used with

caution since actual conditions in buildings and fixtures, such as temperatures, may differ. Notice that the light output of the lamp-ballast systems is not twice that of the single lamps values because output is reduced by the ballast factor of the particular lamp-ballast combination. The 34 W and 40 W lamps were all operated with the same standard CBM ballast. The column of ballast factors shows that the same ballast will have a different ballast factor for a different lamp type, such as the argon-filled (40 W) and krypton-filled (34 W) lamps. There may be significant changes in a ballast's relative performance when it is used in various system combinations.

Among the F40 T-12 lamps (first 4 options), the small difference in efficacy between the 34 W and 40 W lamps is due to the change in the efficiency of the phosphor. In each case the use of the Light White phosphor increases efficacy but all but the best phosphors also decrease the CRI. The increase in efficacy for option 5 (32 W T-8) is based on both the improved phosphor efficiency and the ballast's ability to remove the lamp's filament power. The T-8 (and also T-10) lamps employ narrow band phosphors, which are more efficient and have good color rendering indices.

Four-lamp system in enclosed fixture - Table 4-3 shows the changes that occur when lamps are replaced with 34 W lamps. In the four-lamp fixture the MLWT of the 34 W system is 8°C cooler than the temperature of the 40 W systems, resulting in a power reduction of nine percent and a decrease in light level of seven percent for the LW system (in comparison to option 1). The light level decrease for the CW system is one percent compared to the LW base case (option 1) but 11 percent in comparison to the CW base case system (option 2). Again, because the 34 W system is cooler than the others, the 34 W energy saving system provides more efficient lighting, reducing energy use by nine percent, *not by 17 percent*, as was achieved with the two-lamp system under open-air conditions (see Table 4-2).

The T-8 lamp systems have the highest lamp-ballast system efficacy and reduce power demand the most substantially, by 22 and 20 percent for the core-coil and electronic ballasts, respectively. Notice that the core-coil ballast T-8 system consumes slightly less energy than the electronic ballast system, yet the electronic ballast system provides much higher light levels, and therefore the highest efficacy. Systems that provide the highest light output are good candidates for retrofit combinations with delamping strategies to maintain proper illumination levels.

Delamping fluorescent lamps - Table 4-4 lists the changes in the performance of a 40 W F40 T-12 CW lamp-ballast system in a 70°F room ambient temperature when two lamps are removed from a four-lamp system, and one of the ballasts is disconnected from the circuit. As shown, the light output and power input decrease by 45 and 48 percent respectively, *not by 50 percent*, which we might expect because we've removed two lamps. The efficacy of the remaining two lamp-ballast system increases by 7 percent after the delamping because of the change in the minimum lamp-wall temperature (MLWT) from 57°C to 50°C.

Specular reflectors - Fluorescent fixtures can be made more efficient by the insertion of suitably shaped specular reflector. The materials commonly used for specular reflectors are aluminum, silver, and multiple dielectric films. The latter two have the highest reflectivity; the aluminum reflectors have the lowest cost. While vendors generally claim one can remove two lamps from a four-lamp fixture and maintain similar light levels, light output reductions can be substantial with poorly designed reflectors. Data in Table 4-5 show the results if one installs a specular reflector in a four-lamp fixture with standard 40 W, F40 lamps, two of which have been removed. LBL measurements have shown that with the high-reflectance specular reflectors, fixture efficiency is improved by 15 percent over a new standard fixture with diffuse reflecting material. The table distinguishes 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 versus fixture efficiency improvements). Removing two lamps (Table 4-4), and adding the improved optical efficiency of the reflector, result in a reduction in light output of 35 percent, for a reduction in power of 48 percent.

General Electric (GE) summarized results from testing specular reflectors from five different manufacturers. In general, removing two lamps from a four-lamp fixture, reduced lumen output by about 30 percent (General Electric, 1987). However, it is not clear that lamps were optimally relocated in these tests. In all of the GE tests, the two-lamp configuration consumed more than 50 percent of the original power consumed with four lamps, because operating temperatures are reduced. Lower temperatures also cause a slight increase in power consumption per lamp. A recent Electric Power Research Institute (EPRI) report on reflector performance showed a 53 percent reduction in power input from removing two out of four lamps with only a 28 percent decrease in lumen output (DiLaura and Kambich, 1987), or a 35% decrease in W/lm. Lovins and Sardinsky find that W/lm requirements can be cut by 35-45% with silver reflectors and careful lamp relocation. However, not all of the above tests distinguished between thermal effects and reflector effects.

4.3 Cost Effectiveness of Retrofit Packages

As discussed in the previous sections, lighting retrofits typically occur under a wide range of conditions and can involve many hardware combinations and control strategies. In addition to variations in utilization and baseline efficiencies, costs for equipment, labor, and financing may also differ significantly from case to case. For these reasons, a detailed cost-effectiveness assessment for retrofit plans should be based on the conditions for an individual building; care must be taken in generalizing about the cost-effectiveness of various strategies.

We limit ourselves to indicating cost ranges for a selected number of retrofit packages. Though these generic cost-effectiveness calculations do not fit all applications, they do indicate the range of economic performance for many lighting measures and applications. When the cost of conserved energy from the proposed measures is far below the cost of new energy supplies,

even significant uncertainty in cost or savings parameters would not alter the overall cost-benefit assessment of energy-efficient lighting.

4.3.1 Cost-Effectiveness Criteria

Lighting projects are usually evaluated by one of a number of methods, including life cycle costs, payback period, cost-benefit ratios, internal rate of return, and cost of conserved energy (CCE). The payback criterion has often been used because customers generally think about their investments in these terms. In the following discussion we supplement the payback criterion with the CCE, which has the advantage of incorporating capital costs, discount rate, and life of a measure, while being independent of electricity prices.

The *cost of conserved energy (CCE)* is defined as the annual cost of implementing an efficiency (or peak demand reduction) measure, divided by the annual energy savings. It is defined by the following formula:

$$CCE = \frac{\textit{initial investment} \times \textit{capital recovery rate} + \textit{O\&M incremental cost}}{\textit{annual energy saved}} \tag{1}$$

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

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

The CCE allows easy comparison with both the electricity rates customers pay, and with the cost characteristics of utility supply sources, which are usually expressed in levelized costs per kWh rather than payback periods.

In addition to energy savings, most lighting measures bring the additional benefit of peak savings. (Time clocks are an example of a measure that in most cases will not provide savings in peak demand.) In most cases, lighting demand in commercial buildings coincides with the afternoon summer system peak. The cost of a lighting measure can therefore also be expressed in terms of dollars per kW of demand avoided at system peak (or during the on-peak period for a given utility). This figure can be compared to the cost per kW of installing electric generating capacity, such as a peaking combustion turbine. From the perspective of the customer, peak load savings are associated with avoided demand charges. These charges are normally based on the highest demand during on-peak hours and are paid on a monthly basis. Increased lighting efficiency typically results in demand charge savings in all twelve months.

The coincidence of building lighting loads with utility peak demand varies as a function of building type, subsector, utility system characteristics, and climate zone. The coincidence of building lighting loads with building peak demand also varies as a function of building characteristics. A study by Synergic Resources Corporation for the city of Austin, Texas used a variety of coincidence parameters to describe the interaction between lighting peak demand and building peak demand (Limaye et al., 1987). The percent of all lights that were on during occupied periods was estimated to range from 50 percent for multi-family buildings to 90 percent for

several types of commercial buildings, including offices, retail establishments, and restaurants, among others. Hospitals, hotels, and motels had the lowest value for commercial buildings at 60 percent. Further estimates were made of lighting coincidence with the utility's 4 pm to 6 pm on-peak period. For the CCE calculations discussed below we chose a value of 80 percent for the coincidence factor between lighting and building loads.

For the purpose of utility resource planning, the cost of conserved energy and the cost of conserved peak power should be assessed separately, to allow separate comparison with the marginal costs of additional peak capacity and of electricity generation. However, in the discussion below we subtract demand charge savings from the annualized investment (net of any changes in operating and maintenance costs) on which the CCE is based. This results in a modified CCE that captures the peak savings as seen in the customer bill. Though this convention means a partial loss of one of the advantages of the CCE concept -- independence from electricity prices -- it offers the advantage of a direct correlation between payback periods and costs of conserved energy as seen by the economically rational customer.

The CCE is then redefined as follows:

$$CCE = \frac{(investment\ rate \times CRR) + (O\&M\ incr.\ cost) - (peak\ kW\ savings \times 12 \times monthly\ \$/kW)}{annual\ energy\ saved} \quad (3)$$

Parameters affecting lighting measure cost effectiveness are:

1. *(Extra) first-cost of hardware* - Perhaps the most important factor in the cost of hardware is who is doing the buying. Small commercial customers may pay prices close to the retail level; however, when lighting hardware is bought in very large quantities, e.g. by the utility itself, cost savings over retail prices can be pronounced. For example, a utility buying 170,000 electronic ballasts reportedly was able to obtain a price significantly below $20 each at a time when wholesalers were selling the same product for more than $30. Lovins and Sardinsky collected price quotations for 14 different electronic ballasts for five different size shipments. These data also showed a reduction of about one-third off the highest prices as larger purchases were made (Lovins and Sardinsky, 1988). Similarly, compact fluorescents have been provided by the manufacturer to utilities conducting direct installation programs at a 60 percent discount below retail price. These examples illustrate that costs could vary by a factor of two.
2. *Labor costs* - In the case of lighting retrofits, labor costs for installation can be a significant term in addition to capital costs. Labor costs associated with energy efficiency investments depend on the timing of such investment relative to the normal replacement cycle of existing equipment. They can be greatly reduced per kWh saved if multiple measures are installed simultaneously. They also vary by region and according to the availability of in-house maintenance staff that can perform lighting retrofits.
3. *Interactive effects on costs* - More efficient lighting can mean significant investment savings in other building components. Notably, more efficient lighting allows for the downsizing of HVAC plant.

4. *Operating hours* - The annual hours of operation vary greatly for commercial buildings, as shown in Table 4-6. These data showed a range of about 2400 hours per year for a school, to 7900 hours for a hotel/motel. For the CCE calculations below we choose a low value of 3000 hours per year for the "worst-case" scenario (lightest cost of conserved energy), and 4500 hours per year for the best case scenario. The latter value is very close to the commercial sector average based on the four data sources in Table 4-7. In many cases actual operating hours are longer and savings will be greater than the ranges discussed below.

5. *Useful technical life* - Estimates of the useful technical life of new components are uncertain. Equipment failure rates with new technologies should also be considered; Some brands of electronic ballasts had relatively high failure rates when they were first produced, a problem encountered elsewhere in the power electronics industry. These problems were overcome, and a recent test of more than 30,000 electronic ballasts showed a failure rate of less than 1-2 percent after three and a half years. This failure rate is no different from that of standard core-coil ballasts. Another variable in determining useful technical life of fluorescent lamps, is the system they are operated in. Table 4-8 shows the range of estimated lifetimes for various equipment. These data are from a study to determine which factors affect equipment life, including maintenance, and environment (Gordon et al., 1988). Another consideration with lamp retrofits is the ease with which a 34 W lamp retrofit can "backslide"; maintenance technicians can easily replace a 34 W lamp with a 40 W lamp negating future energy savings. In our CCE calculations we again chose the lower end of the lifetime ranges to be conservative.

6. *Discount rate* - Cost-effectiveness assessments can vary widely, depending on the discount rate chosen. In absence of utility incentive programs, most commercial customers choose very short payback times (1-2 years) for lighting conservation or other investments. Over a ten-year useful life, a two-year payback requirement amounts to a 63 percent discount rate, compared to real returns on utility shareholder's equity of of 5-7 percent. From a societal perspective, a 3 percent discount rate is often used.

7. *Operating and maintenance costs* - Delamping removes the need for future lamp and ballast replacements, and the longer life of compact fluorescents relative to incandescents and of electronic ballasts relative to magnetic core coil ballasts also saves replacement costs, and in many cases, installation labor costs for lamps and ballasts. The degree to which these savings are taken into account has a significant effect on the cost of conserved energy. For example, where installation labor savings are monetized for the incandescent to compact fluorescent conversion, these labor costs alone can more than pay for the lamp switch, even before electricity savings are counted. This installation labor saving can therefore produce negative costs of conserved energy even before demand savings are considered.

The primary purpose of this technology assessment is to examine the benefits of lighting measures evaluated from the societal and utility perspective. High discount rates as implicitly or explicitly used by commercial consumers may be economically rational from the perspective of

that consumer in the face of significant market barriers and "hassle factors," but are at variance with the goal of societally efficient capital allocation since they could be overcome by lighting efficiency programs. To achieve such allocation efficiency, the implicit discount rates used by individual investors should not differ significantly from the average rate of return on capital that is being realized in the economy as a whole. We base our calculations on a five percent annual real discount rate.[2]

4.3.2 Types of Fluorescent Lamp Retrofits and Sensitivity Analyses

The net cost of lighting measures is substantially influenced by the timing of their installation. The optimal case is one in which the retrofit hardware is introduced when existing lighting hardware needs replacement. In that case, only the incremental costs of the hardware and installation needs to be counted as part of the energy efficiency cost. The worst case is one where conventional hardware is replaced while still fairly new. In that case, the incremental cost of the efficiency improvement would be close to the full hardware and installation cost of the package.

In practice, customer action and utility programs can be geared to maximizing the cost-effectiveness of retrofits by targeting lighting systems for which relamping or remodeling is due. To the extent that utility programs pursue a "blitz" strategy, early replacement of existing hardware may, of course, be unavoidable. On average, existing hardware would be replaced after half its useful life. Therefore, in our cost calculations below, we examine both the mid-point replacement and replacement coincident with the regular life cycle of the system.

We focus on 11 measures. Retrofit combinations chosen are mainly those that are commonly found in current utility lighting programs and for which measured performance results are available, as discussed in Section 4.2.2. All 11 retrofits have been discussed in terms of their technical details in Section 3. Tables 4-2 through 4-6 give further details. To the eight options discussed in Section 4.2.3 above, we have added the replacement of a 75 W incandescent with a compact fluorescent; the use of an efficient core-coil ballast, which will be federally mandated equipment in early 1990 (see Section 6.3); and an electronic ballast that operates four as opposed to two lamps.

Appendix A describes the detailed data, data sources, and assumptions used to calculate the cost of conserved energy of the 11 retrofits under four economic scenarios. The following parameters were varied:

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[2] Many utility programs limit measures eligible for incentives to those with relatively short payback investments of less than 3-4 years although technical measures (efficient ballasts, some fluorescent lamps, and dimming and daylighting controls) have useful lives of ten years or more. This practice still locates the program's economic rationality closer to the high implicit discount rates used by commercial customers than to the lower rates used by utility supply-side planners. A three-year payback time is closer to societal economic rationality than one of six months, but a large payback gap thus remains. For the purpose of designing economically efficient utility programs it is necessary to evaluate demand-side investments at the real discount rate utilities apply in supply-side investment decisions, approximately 3-7 percent.

- first cost of hardware (retail versus wholesale, assuming a 33 percent differential);
- operating hours (3000 hours per year vs 4500 hours per year);
- CCEs with and without credit for reduced monthly peak demand charges.
- Mid-life versus end-of-life replacement of existing equipment.

For other parameters, deliberately conservative fixed values were chosen. We also ignored installation labor savings in the case of compact fluorescents, as well as some smaller secondary savings from multiple replacement cycles in later years. In the case of compact fluorescents, counting labor installation costs could make the conversion from incandescents cost-effective even before electricity savings are factored in, resulting in negative costs of conserved energy independent of savings in demand charges.

Table 4-8 shows a summary of the results and sensitivity tests. The detailed calculations are given in Tables A.2 to A.5. In Table 4-8, the columns called "Min" denote the best case (whole sale prices, 4500 hours, and replacement at the end of useful life), whereas "Max" denotes worst case (retail prices, 3000 hours, replacement at mid-life).

For the best case we discount retail prices by one-third to take into consideration economies of scale for large purchases. Here, we consider only the incremental cost of the energy-saving feature, with no labor charges. An exception is the specular reflector, where the retrofit is not an "end-of-life" replacement.

4.3.3 Results: Cost of Conserved Energy.

The costs of conserved energy and the payback times for the 11 measures are given in Table 4-8.

Range of CCEs under optimum conditions. Under optimum conditions (long operating hours, wholesale prices, end-of-life replacement, and avoided demand charges), the costs of conserved energy for the 11 measures range from -0.5 to 2.1 cents/kWh. All but one measure cost less than 1 cent/kWh. The negative figures for measures 1 and 2 are the result of demand charge savings, without counting installation labor savings. Counting installation labor savings at ca. $1/lamp could save up to $13 per lamp, or as much as the lamp could cost on a wholesale basis.

If we ignore both installation labor and the economic benefit of avoided demand charges, the CCEs based on energy savings alone range from 0.5 to 3.2 cents/kWh. Again, all but measure 9 cost less than 2 cents/kWh.

Range of CCEs under intermediate conditions. Intermediate conditions are represented by end-of-life replacement but retail prices and shorter operating hours (Table A-3), or by mid-life replacement combined with wholesale prices and long operating hours (Table A-4). For these

conditions, most costs of conserved energy are less than 2 cents/kWh if demand charges are included, and less than 3 cents/kWh if only energy savings are included.[3]

Range of CCEs under worst conditions. Under worst conditions (Table A-2), most costs of conserved energy are less than 3.3 cents/kWh if demand charges are avoided, and less than 5 cents/kWh on the basis of energy savings alone.

Outliers. On the low side, the two outliers are the replacement of incandescents with fluorescents, and the replacement of standard 40W tubes with 34W tubes. Note again that the 34W lamp is not an efficiency measure in the true sense, since there is virtually no increase in efficacy. It is more akin to a delamping measure.

The compact fluorescent is clearly in a class by itself because it comes in with negative costs under any scenario if demand charges are avoided, and with less than 1 cent/kWh based on energy savings alone without counting installation labor savings. In a previous analysis, it was shown that the compact fluorescent has a CCE of less than 2 cents/kWh for any installation with at least 300 operating hours (Krause et al., 1987), even when no labor costs for installation of other lamp types are being saved.

On the high side, the two notable outliers are ballast replacements 3 and 9. While accompanied by significant efficacy gains and energy savings, they are burdened by comparatively high costs. In the case of solid-state ballasts for four-lamp fixtures, the economics are significantly improved if the comparatively high cost of solid-state ballasts is spread over more kWhs from combinations with other measures (measures 6 and 11), or if one solid-state ballast is used to operate four lamps rather than just two lamps (measure 8). Simultaneous installation of ballasts and reflectors can also reduce installation labor costs.

CCEs versus percentage savings. Figure 4-1 shows that there is no clear relationship between the amount of energy saved by a certain measure, and the cost of conserved energy. This result is counter-intuitive, since one would normally expect that greater percentage savings would be achieved at greater unit cost. That this is not so underlines the importance of interactive effects among hardware components, both in terms of operating performance (Section 3) and in terms of economics. The figure tells us that savings of eighty percent or more (e.g. from switching to compact fluorescents) can be achieved for the same cost as savings of delivering only ten or twenty percent from other measures.

This finding is relevant for the design of utility demand-side programs. Essentially, utilities could obtain a wide range of magnitudes of GWh and MW saved without having to be concerned over a narrowing margin of cost effectiveness as they aim for greater savings per installation.

Comparison with electricity prices. It is useful to compare these figures with typical commercial sector electricity rates, which range from 3.6 to 11.7 cents/kWh not counting demand charges (*Energy Users News*, June 20, 1988). These proportions indicate that most of the lighting

[3] Where negative costs of conserved energy are observed, these negative figures are actually somewhat larger than in the optimum cases. This is an artifact of the discounting convention, which is oblivious to the sign of the annuity.

retrofits can supply demand-side resources at favorable costs, even after allowances for program administration costs, typically five to twenty percent of measure costs (Vine and Krause, 1989). Because of the large margin between costs of conserved energy and avoided electricity rates and generating costs, and because of the disproportionate on-peak benefits, lighting efficiency offers a particularly flexible demand-side resource for utility programs.

4.3.4 Retrofit Economics vs. Lamp Performance

Although some of the retrofits increase illumination levels, others decrease lamp-ballast output as compared to the base case systems. It is therefore important to analyze the cost of conserved energy not only as a function of the energy savings achieved, but also in terms of system lumen output and efficacy. Table A.6 (in the Appendix) summarizes the changes in illumination output of the 11 retrofits in absolute terms and normalized against the respective base cases. Figures 4-2 to 4-3 represent the costs of conserved energy as a function of relative lumen output and relative efficacy, respectively, for four-lamp systems.[4]

Figures 4-2 and 4-3 show weak correlations between the cost of conserved energy and lumen output or efficacy. For a two-lamp system, anywhere from 10 to 43 percent improvements in efficacy can be obtained with about the same cost effectiveness as measured by the CCE. A somewhat stronger correlation may exist for the four-lamp systems in Table 4-8, which include improvements in fixture efficacy rather than just lamp-ballast efficacy. Most measures reduce lumen output somewhat, but retrofits involving solid state ballasts increase lamp-ballast lumen output. Measure 11 combines a reduction in lumen output with an increase in efficacy. All statements about trends should, however, be interpreted with caution because only a few data points are shown in the figures, and not all potentially attractive measures have been investigated in this report.

As long as post-retrofit lighting levels do not detract from the productivity of building occupants, the CCE can be a useful measure of the economic benefits obtained from lighting retrofits. With this qualification, perhaps the most pertinent conclusion from these results is that low costs of conserved energy (i.e. CCEs significantly less than the price of electricity) can be achieved over a wide range of efficacy improvements. Similarly, low costs of conserved energy are obtainable with measures that maintain or increase lumen output per fixture as well as with measures that reduce lumen output.

4.4 HVAC Interaction

The above cost-effectiveness calculations excluded interactions with the heating and cooling requirements of the building; nearly all of the power input to a lighting system dissipates in the building space as heat. One issue associated with the interaction of lighting and HVAC

[4] The figures are based on CCEs excluding peak demand savings (see Table 4-8 and A.6.).

systems is the energy performance of the combined system (Treado and Bean, 1988). Light output and power consumption of fluorescent lamp systems vary with lamp-wall temperature. Therefore, energy used for lighting will be minimized if the luminaire is at the optimum lamp temperature. Using a luminaire/plenum/HVAC laboratory mock-up facility, LBL found that the lumen output of lamp-ballast systems varied by 20% and system efficacy by 10%, depending on the type of fixture and lamp-component heat extraction technique employed (Siminovitch et al., 1986).

Another important issue in the interaction of lighting and HVAC systems is the relationship between lighting and thermal loads. Of the power input into a standard fluorescent lamp-ballast system, 15 percent goes to the ballast and 85 percent to the lamp (Treado and Bean, 1988). This power is dissipated by the luminaire into heat stored in building components, plenum air, and luminaires themselves. Of the power into the lamp, about 21 percent is radiated as visible light, 37 percent is infrared radiation (radiated heat), and 42 percent is convected and conducted to the air. "Waste" heat from lighting has positive energy impacts during periods of heating but is more commonly associated with increasing cooling loads during cooling periods in U.S. commercial buildings. Peak cooling loads can be controlled by channeling this energy into building components, thereby spreading the cooling load from lighting over a longer period, or exhausting it to the outdoors.

The National Institute of Technical Standards (NITS) currently has a full-scale test facility studying the interaction of lighting, heating, and cooling systems. A recent study determined that "lighting systems can be constrained to operate at their most efficient level through manipulation of the thermal environments via the air temperature, airflow rate, and return air configuration" (Treado and Bean, 1988). Such results point toward the need for strong integration between HVAC and lighting design strategies.

One method of accounting for the relationship between lighting and cooling loads is to use computer simulation models of building energy use, such as DOE-2 or BLAST. Unfortunately, these models use constant values for lighting energy distribution fractions, such as the percentage of input power that reaches the room or enters the return air. In reality these fractions are not constants; they change, for example, with changes in HVAC operation and luminaire temperature. Therefore, there is an uncertainty of *at least five to fifteen percent* in the calculation of cooling loads due to lighting (Treado and Bean, 1988).

Usibelli et al. performed selected DOE-2 computer simulations using different lighting power densities, system configurations, and climate zones (in California only) to estimate the size of cooling energy savings in relation to changes in lighting energy. For a prototypical Fresno office building without economizers, HVAC savings added more than 35 percent to the total savings. With the same building equipped with an economizer in San Francisco, the net savings increase was only 5 percent. Changes in lighting loads also influence the load-profile of a building. Usibelli's DOE-2 simulations indicated that about 30 percent of the building's cooling peak resulted from lighting heat-gains. Section 6, which contains case study results, includes further comments on predicted and measured interactive effects.

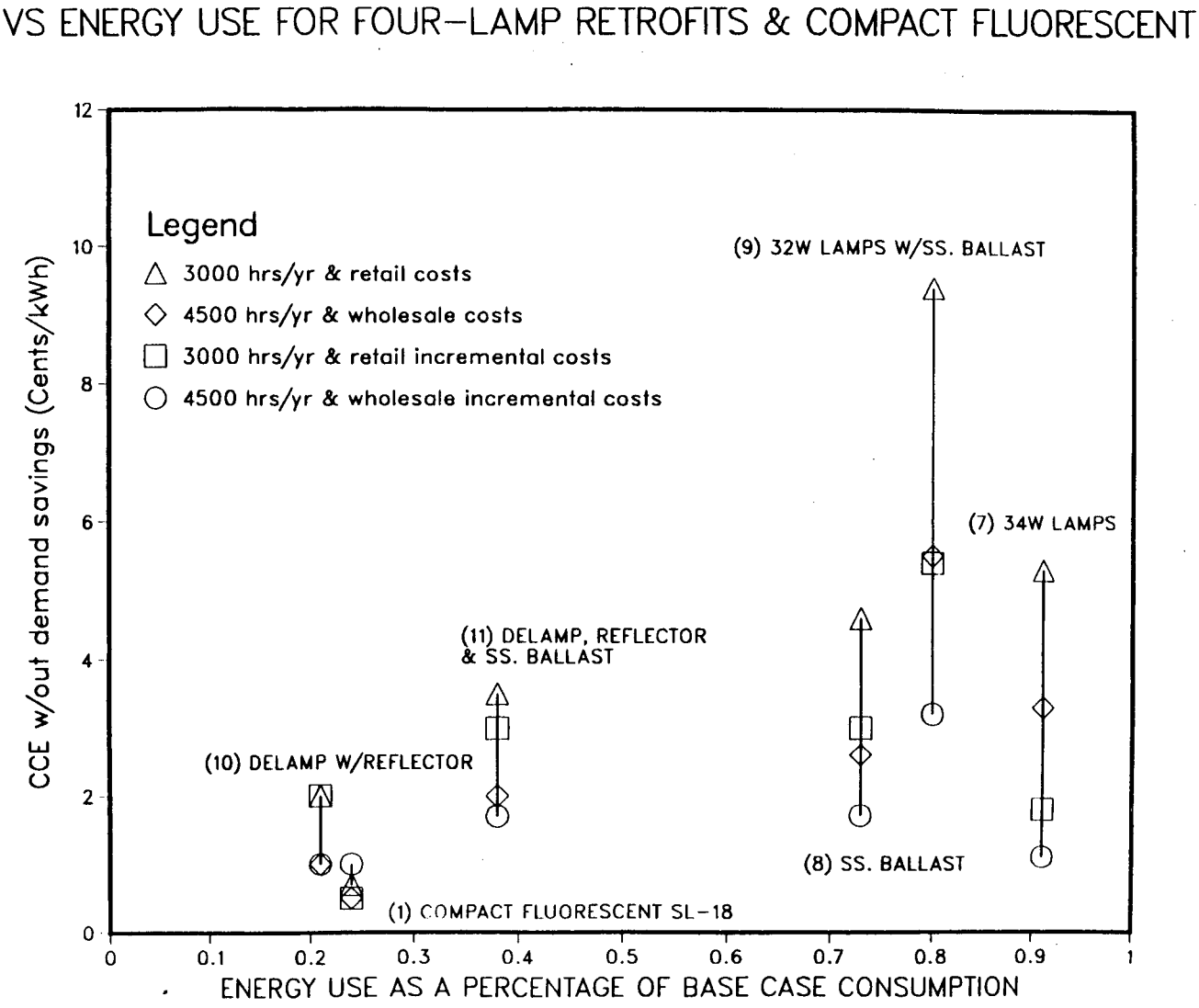

Figure 4-1. CCE versus energy use as a percentage of base case consumption: 4 lamp systems and compact fluorescents. Favorable costs of conserved energy can be realized with both measures that deliver modest (order of 10%) percentage savings and with packages that deliver large (order of 25% to 80%) percentage savings.

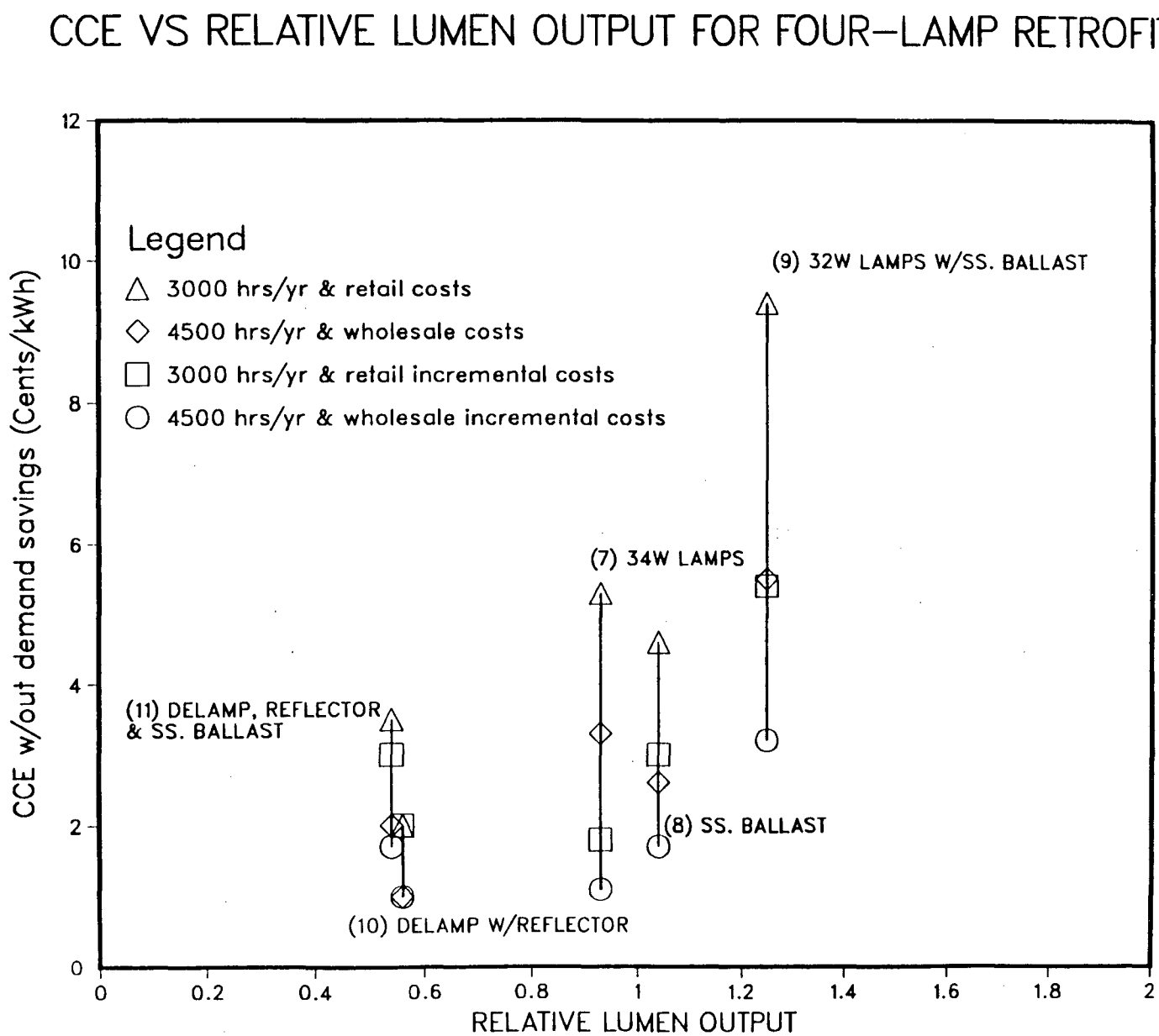

Figure 4-2. CCE versus relative lumen output: 4 lamp systems. Favorable costs of conserved energy can be realized with measures that both increase and decrease lumen output. The base case puts out 9340 lumens.

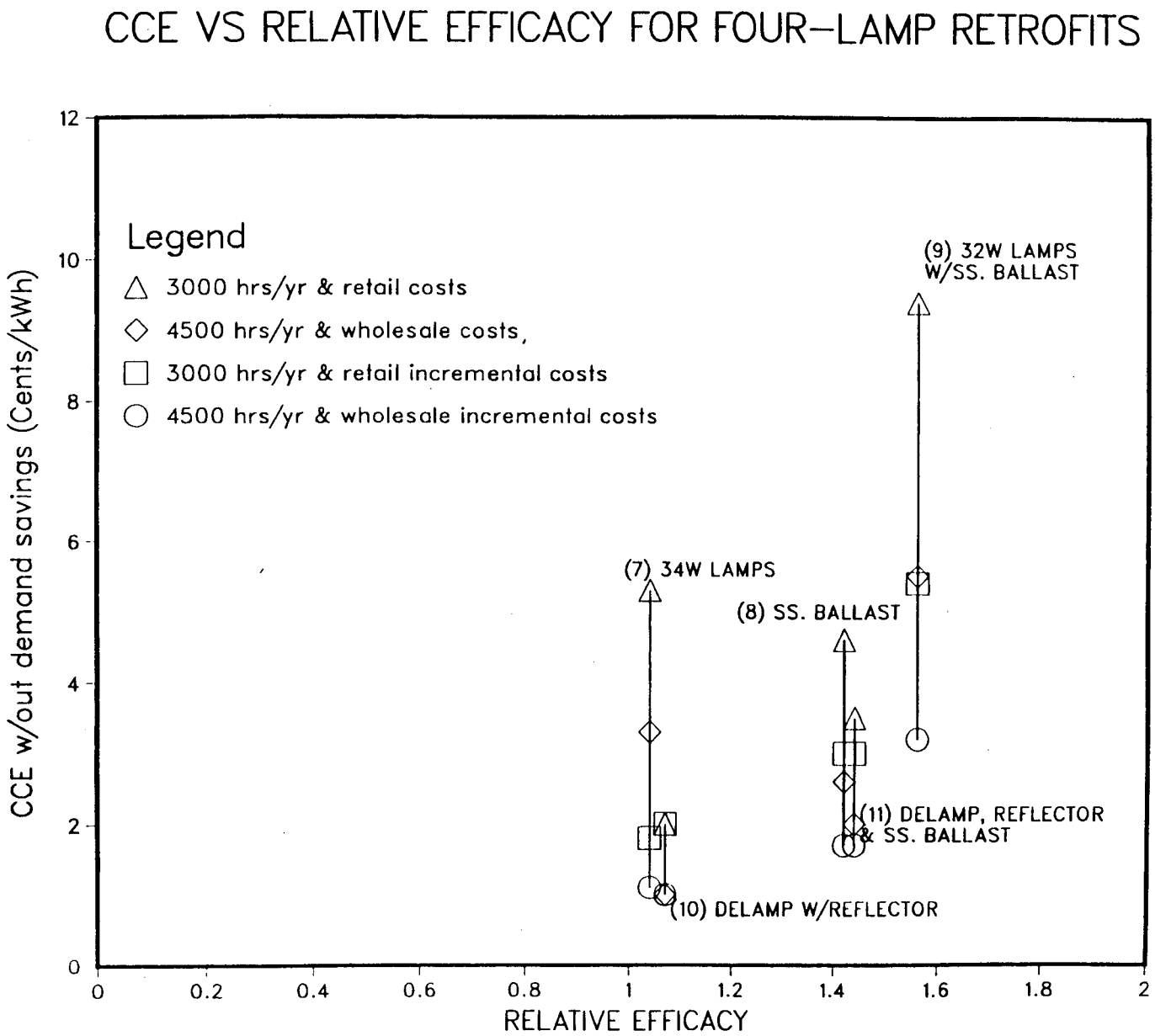

Figure 4-3. CCE versus relative efficacy: 4 lamp systems. Costs of conserved energy should be assessed relative to changes in system efficacy. The base case efficacay is 55 lumens per watt.

Table 4-1. Effect of lumen output and fixture efficiency on luminaire spacing, lighting power density, and cost effectiveness.

Combination	Rated Lamp Output (lumen)	Ballast Factor	Initial[a] Luminaire Output (lumens)	Adjusted[b] Luminaire Output (lumens)	Floor Area Per Luminaire (ft^2)	Power[c] Per Luminaire (Watts)	Maint.[d] Luminaire Efficacy (lm/W)	Power[e] Density (W/ft^2)	Total[f] Initial Costs ($\$/ft^2$)	Annual[g] Energy Costs ($\$/ft^2$)	Pres. Value[h] Energy Costs ($\$/ft^2$)	Pre. Value[i] Maint. Costs ($\$/ft^2$)	Pres. Value[j] Total Costs ($\$/ft^2$)
1. LENSED TROFFER													
1.1 STD. CORE-COIL													
1.1.1 35 W F40	2925	0.88	6785	4750	77	159	29.8	2.08	1.51	0.73	5.54	0.70	7.75
1.1.2 Standard F40	3150	0.95	7888	5522	89	186	29.7	2.09	1.28	0.73	5.56	0.55	7.40
1.1.3 High Output F40	3300	0.95	8264	5785	94	195	29.7	2.09	1.24	0.73	5.56	0.57	7.38
1.2 EFFIC. CORE-COIL													
1.2.1 35 W F40	2925	0.86	6654	4658	75	142	32.9	1.88	1.67	0.66	5.00	0.71	7.39
1.2.2 Standard F40	3150	0.92	7656	5359	87	166	32.2	1.92	1.43	0.67	5.11	0.57	7.11
1.2.3 High Output F40	3300	0.92	8020	5614	91	174	32.2	1.92	1.39	0.67	5.11	0.59	7.09
1.3 ELECTRONIC													
1.3.1 35 W F40	2925	0.79	6114	4280	69	114	37.7	1.64	2.11	0.57	4.37	0.77	7.25
1.3.2 Standard F40	3150	0.86	7180	4975	80	134	37.1	1.67	1.79	0.58	4.45	0.62	6.85
1.3.3 High Output F40	3300	0.86	7446	5212	84	140	37.1	1.67	1.73	0.58	4.45	0.64	6.82
2. PARABOLIC													
2.1 STD. CORE-COIL													
2.1.1 35 W F40	2925	0.88	5580	4743	77	159	29.8	2.08	2.10	0.73	5.54	0.70	8.34
2.1.2 Standard F40	3150	0.95	6488	5515	89	186	29.6	2.09	1.78	0.73	5.56	0.56	7.90
2.1.3 High Output F40	3300	0.95	6797	5777	93	195	29.6	2.09	1.72	0.73	5.56	0.57	7.86
2.2 EFFIC. CORE-COIL													
2.2.1 35 W F40	2925	0.86	5473	4652	75	142	32.9	1.88	2.27	0.66	5.00	0.71	7.99
2.2.2 Standard F40	2150	0.92	6297	5352	87	166	32.2	1.92	1.95	0.67	5.11	0.57	7.64
2.2.3 High Output F40	3300	0.92	6596	5607	91	174	32.2	1.92	1.89	0.67	5.11	0.59	7.59
2.3 ELECTRONIC													
2.3.1 35 W F40	2925	0.79	5029	4274	69	114	37.6	1.64	2.76	0.57	4.37	0.78	7.91
2.3.2 Standard F40	3150	0.86	5846	4969	80	134	37.1	1.67	2.35	0.58	4.45	0.62	7.42
2.3.3 High Output F40	3300	0.86	6124	5206	84	140	37.1	1.67	2.27	0.58	4.45	0.64	7.35

a Rated lamp lumens x 4 lamps x ballast factor x fixture efficiency. Lensed troffer fixture efficiency = 0.66, parabolic fixture efficiency = 0.54.

b Initial luminaire output x maintenance factor (MF = 0.7 for lensed troffer, MF = 0.85 for parabolic).

c Power per lamp-ballast system x 2 pairs per luminaire.

d Total maintained luminaire lumen output per watt input.

e For 70 footcandles maintained.

f Fixture costs: Lensed troffer - $110, parabolic luminaire - $155; Ballast premiums: standard - $0, efficienc core-coil - $5, electronic - $15; Lamp costs: 35 W - $6, Standard F40 - $4, High output F40 - $6.

g 3500 hours/year at $0.10/kWh.

h Present value at 10% interest for 15 years.

i Assuming group re-lamping and cleaning at $20 labor per luminaire every 3 years

j Total costs = initial + energy + maintenance costs.

Table 4-2. Rated flourescent lamp and lamp-ballast optimum performance.

Lamp-Ballast System	Power W	Light Output lm	Efficacy lm/W	Ballast Factor	Relative Power	Relative Light	Relative Efficacy	CRI
1. 40W F40 T-12/CW-lamp only	40	3150	79		1.00	1.00	1.00	67
Two lamp-ballast system*	95	5990	63	0.95	1.00	1.00	1.00	67
2. 40W F40 T-12/LW-lamp only	40	3450	86		1.00	1.10	1.09	51
Two lamp-ballast system	95	6560	69	0.95	1.00	1.10	1.10	51
3. 34W F40 T-12/CW-lamp only	34	2750	81		0.85	0.87	1.03	67
Two lamlp-ballast system	79	4790	61	0.87	0.83	0.80	0.97	67
4. 34W F40 T-12/LW-lamp only	34	2925	86		0.85	0.93	1.09	51
Two lamp-ballast system*	79	5090	64	0.87	0.83	0.895	1.02	51
5. 32W F032 T-8/41K-lamp only	32	2900	91		0.80	0.92	1.15	85
Two lamp-ballast system**	71	5360	75	0.92	0.75	0.89	1.19	85
6. 32W F032 T-8/41K-lamp***	32	3190	100		0.80	1.01	1.27	85
Two lamp-ballast system****	65	5820	90	0.91	0.68	0.97	1.43	85

* Standard core-coil CBM ballast.

** Core-coil ballast for F032 lamp.

*** High-frequency operation.

**** Electronic ballast

Table 4-3. Effects of replacing 40 watt lamps in a four-lamp enclosed fixture.

Lamp-Ballast System	Power W	Light Output lm	Efficacy lm/W System	Efficacy lm/W Lamp	Relative Power	Relative Light	Relative Efficacy	Lamp Wall Temp. (°C)
Two 2-lamp 40W F40 T-12 CW System	169	9340	55	70	1.00	1.00	1.00	57
Two 2-lamp 40W F40 T-12 LW System	169	10,230	61	77	1.00	1.10	1.11	57
Two 2-lamp 34W F40 T-12 CW System	153	8710	57	76	0.91	0.93	1.04	49
Two 2-lamp 34W F40 T-12 LW System	153	9270	61	81	0.91	0.99	1.11	49
Two 2-lamp 32W F40 T-12 41K System	131	9330	71	89	0.78	1.00	1.29	49
Two 2-lamp 32W F40 T-12 41K System*	135	11,650	86	96	0.80	1.25	1.56	49

* High-frequency system.

Table 4-4. Effects of delamping an enclosed four-lamp fixture

Lamp-Ballast System	Power W	Light Output lm	Efficacy lm/W		Relative			Lamp Wall Temp. (°C)
			System	Lamp	Power	Light	Efficacy	
Two 2-lamp 40W F40 T-12/CW System	169	9340	55	70	1.00	1.00	1.00	57
One 2-lamp 40W F40 T-12/CW System	88	5210	59	74	0.51	0.56	1.07	50
One 2-lamp 40W F40 T-12/LW* System	88	5710	65	82	0.52	0.61	1.18	50

* Replace the CW 40 watt lamp with LW 40 watt lamp.

Table 4-5. Effects of specular reflector inserts plus delamping in an enclosed four-lamp fixture.

Lamp-Ballast System	Power W	Light Output (lm) Lamps	Light Output (lm) Fixture	Optical Fixture Efficiency (%)	Relative Power	Relative Light	Relative Efficacy	Efficiency lm/W Lamps System	Efficiency lm/W Fixtures Output
Two 2-lamp 40W F40 T-12 CW System	169	9340	6070	65	1.00	1.00	1.00	55	36
2-Lamp 40W F40 T-12 CW System - specular reflector	88	5210	3960	76	0.52	0.65	1.20	59	45
2-Lamp 40W F40 T-12 LW System - specular reflector	88	5710	4340	76	0.52	0.71	1.27	65	49

Table 4-6. Annual operating hours from four surveys

Building Type	Seton et al.[1]	SCE[1]	PG&E[1]	NBECS[2]
Restaurant	5200	3361	3650	4264
Hospital	6000	6396	5840	-
Retail	4020	2867	5110	3276
Hotel/Motel	6090	7167	-	7904
Office	2730	2610	4380	2652
Warehouse	3120	2631	-	2756
School	2600	2818	3258	2392
Grocery	6240	4514	5110	5044
Average[3]	4440	4395	4558	4041

1. Source: NWPPC, 1987.
2. EIA, 1988.
3. Averages are unweighted. Not all non-residential building types are represented in the above table. Building type definitions differed between the samples.

Table 4-7. Estimated lifetime for lighting equipment

HARDWARE	LIFETIME
Energy saving fluorescent Lamp	20 khrs
w/built in ballast	10 khrs
T-8 system	15 - 25 yrs
Efficient core-coil ballast	45 khrs
Solid-state ballast	70 khrs
Metal halide lamp	10 khrs
LPS Lamp	18 khrs - 35 yrs
HPS Lamp	24 khrs - 35 yrs
Parabolic fixture	15 - 30 yrs
Dimming system	15 - 30 yrs
On-off switching	15 - 30 yrs
Motion sensor	10 yrs

Ranges based on difference for new, retrofit, and renovation applications. Source: Gordon et al., 1988.

Table 4-8. Summary of cost-effectiveness calculations for eleven retrofits

No.	DESCRIPTION	RELATIVE CHANGE LAMP-BALLAST EFFICACY	RELATIVE CHANGE LAMP-BALLAST LUMEN OUTPUT	RELATIVE CHANGE ENERGY USE	RELATIVE CHANGE FIXTURE EFFICACY	RELATIVE CHANGE FIXTURE LUMEN OUTPUT	CCE W/OUT PEAK SAVINGS (cents/kWh) Min.	CCE W/OUT PEAK SAVINGS (cents/kWh) Max.	CCE WITH PEAK SAVINGS (cents/kWh) Min.	CCE WITH PEAK SAVINGS (cents/kWh) Max.	SIMPLE PAYBACK @ 7 cents/kWh (Yrs) Min.	SIMPLE PAYBACK @ 7 cents/kWh (Yrs) Max.
	INCANDESCENT BASE CASE	1.00	1.00	1.00								
(1)	One compact fluorescent SL-18	3.80	0.92	0.24			0.5	1.0	-1.1	-0.4	0.7	1.3
	TWO-LAMP FLUORESCENT BASE CASE	1.00	1.00	1.00								
(2)	Two energy-saving lamps (34W T-12)	0.97	0.80	0.83			0.5	2.2	-0.7	0.6	0.3	1.7
(3)	One efficient core-coil ballast (40W T-12s)	1.10	1.00	0.92			1.3	6.6	0.3	5.0	1.3	8.6
(4)	One solid-state ballast (40W T-12s)	1.24	0.95	0.77			1.9	4.9	0.9	3.3	1.9	6.4
(5)	Combination of (2) and (4)	1.25	0.83	0.66			1.7	4.4	0.6	2.8	1.5	5.2
(6)	Two slimline lamps (T-8s) & solid-state ballast	1.43	0.97	0.68			2.0	4.9	0.9	3.3	1.6	5.7
	FOUR-LAMP FLUORESCENT BASE CASE	1.00	1.00	1.00	1.00	1.00						
(7)	Four energy saving lamps (34W T-12)	1.04	0.93	0.91			1.1	4.5	0.0	2.9	0.6	3.3
(8)	One solid-state ballast (40W T-12s)	1.42	1.04	0.73			1.7	4.2	0.7	2.6	1.7	5.4
(9)	Four energy-saving lamps & solid-state ballast (32W T-12)	1.56	1.25	0.80			3.2	8.2	2.1	6.6	2.8	9.8
(10)	Remove two lamps, insert reflector (40W T-12)	1.07	0.56	0.21	1.25	0.65	1.0	2.0	0.0	0.4	1.7	3.8
(11)	Combination of (4) and (10) (40W T-12)	1.44	0.54	0.38	1.67	0.63	1.7	3.0	0.6	1.4	1.7	4.1

5. LESSONS FROM THE FIELD: CASE STUDIES

5.1 The Status of Current Energy-Efficient Lighting Systems

A recent survey of commercial buildings sought to identify existing case studies of energy-efficient lighting technologies in actual buildings that achieved lighting power densities of less than 1.7 W/ft^2 (NRDC, 1987). The purpose of the survey was to document these case studies. Eighty studies were reviewed, with an average lighting power density of 1.1 W/ft^2. The survey included 30 retrofits and 50 new buildings. Illumination levels were reported for 24 of the buildings, averaging of 51 fc. For buildings that reported task and ambient levels, the averages were 71 and 30 fc.

Early results from an ongoing study in the Northwest revealed ways to achieve efficient lighting systems, based on detailed audits comparing six large Seattle office buildings to 11 similar buildings in nearby cities. (Momentum Engineering et al., 1988). Despite similar luminaires, lighting energy use in these buildings was estimated from 14 to 34 kBtu/ft^2-year, resulting from the ranges of installed power densities and hours of use. The importance of lighting controls was illustrated by the data from one building that showed that the floors with better controls used 30 percent less lighting energy than the floors without the controls. Security lighting left on at night ranged from two to 22 percent of the total lighting load. Lighting power densities where found to be more a function of the size of a space and the fixture types than of required lighting levels. Hallway lighting ranged from 0.9 to 2.5 W/ft^2, bathroom lighting ranged from 1.0 to 7.0 W/ft^2, and small offices had 20 to 40 percent more installed light than open-plan offices.

5.2 Retrofit Savings in End-Use Metered Buildings

In this section we present results from eight case studies of submetered lighting systems. Lighting modifications were completed in conjunction with HVAC measures for two of the buildings. These examples were chosen for because of the availability of data that is more detailed than the whole-building electricity use. The data differ because they come from a variety of sources, ranging from federally-funded commercial passive solar building demonstrations to an electronic ballast demonstration project. The first three case studies involve whole-building retrofits that include HVAC measures in addition to the lighting retrofits. The last five studies were lighting retrofit done in a limited areas of the buildings. Table 5-1 summarizes the basic building characteristics and retrofit descriptions; performance results are summarized in Table 5-2.

These case studies are provided to illustrate the significant potential for energy conservation in existing buildings. From only a small sample of buildings, we see a wide variation in the energy used for lighting, both in magnitude of total consumption (3 to 24 kWh/ft^2-year) and as a percent of total energy use (7 to 70 percent). Lighting power densities ranged from 0.7 W/ft^2 to 3.1 W/ft^2, a range of a factor of four.

The examples above cover a variety of measures: daylighting, relamping to fluorescent, cleaning fixtures, and numerous control techniques: rewiring for stepped control, closer scheduling, dimmable ballasts, and perimeter daylighting. Within these examples lighting energy use savings ranged from 1 to 8 kWh/ft^2-year, or 9 to 59 percent of the pre-retrofit lighting energy use. Clearly, space use and occupancy patterns strongly affect the required lighting levels and lighting energy use. We saw with a daylit retail store (Building 1) that low ambient lighting levels were acceptable. Buildings 2 and 3 offer data on the interactive effects of measures. Occupant response was good in each case, and equipment failures were few.

Although not included in the tables below, comparable studies have been conducted abroad. For example, retrofit analysis of a six story office building in The Netherlands investigated five lighting systems, including several control systems (Commission of the European Communities, 1985). Energy savings from 63 to 84 percent of the previous year's electrical consumption were achieved with payback times of two to five years.

5.2.1 Daylighting in a Retail/Office Building in Wisconsin

This case study illustrates the relationship between owner interests and low energy use; the building does not represent a typical retail/office building. The goal of this renovation project was to create a retail/office space that was pleasant and daylit (Booz, Allen & Hamilton, et al., 1983); reducing energy use was not the primary concern of the project. Consequently the retrofit was expected to increase total energy use over the simulated base case buildings, which was well insulated. The submetering and design information was collected as part of a federally-funded research project on passive solar commercial buildings. Although little information about the renovated lighting system was reported except the low lighting power density (0.7 W/ft^2 post-retrofit) and the IES-recommended average light level (30 fc), this case study illustrates a few points. As shown in Table 5-1, a number of daylighting features were added to the space to satisfy the owner's interest in creating an airy atmosphere to suit the florist who occupied the retail space. Lighting energy use was even slightly less than the low prediction, (which was based on 0.7 W/ft^2 at 40 hours/week) because the occupant tolerated lighting levels below 30 fc. The building used only 4.2 kBtu/ft^2-year (1.4 kWh/ft^2-year) for lighting, only six percent of total energy use. This amounted to a savings of 59 percent of lighting energy use in comparison to the base case building.

5.2.2 Lighting Controls in a Seattle Grocery

End-use energy use data were collected for one year before and one year after the lighting and refrigeration system retrofits at this grocery store (Wong, 1988). The project, sponsored by Seattle City Light, was one of 14 buildings simulated with the DOE-2.1 program and retrofitted to compare predicted with actual energy savings. As shown in Table 5-2 the store was overlit to begin (120 fc) with a lighting load of 2.6 W/ft^2, which was reduced to 100 fc, at 2.4 W/ft^2. Rewiring the fixtures allowed the middle tube of the three lamp eight foot fluorescent system to remain off during daytime operating hours. At night, during shelf stocking periods, the middle

tube is used, and the two outer tubes remain off. Delamping from three to two tubes would have been simpler and less expensive, but the resulting appearance was considered unacceptable by the store management. The refrigeration case lights were also rewired so they could to be turned off at night. Exterior lights were changed from a mercury vapor system to high-pressure sodium with photocell control added. The refrigeration system modifications consisted of installing both strip curtains in the walk-in coolers and freezer doors on the upright freezer cases.

Considerable attention was given to analysis of interactive effects among the retrofit measures, which were complex because of interactions among the refrigeration, lighting, and space heating systems (Cleary et al., 1988). Energy savings estimates based on the DOE-2.1 simulation results, which were calibrated with measured end-use data, showed that natural gas consumption for heating was expected to increase because of lower lighting energy use, therefore offsetting some of the electricity savings. The estimated savings were 6 kWh/ft^2-year for interior lighting (nearly identical to actual savings) and 54 kBtu/ft^2-year for the overall retrofit package. Total lighting energy use decreased 29 percent. Savings in natural gas heating were somewhat lower than predicted because of mild weather. The interior lighting retrofit cost a total of $12,101 (in 1985 dollars) with a payback period of 5.6 years.

5.2.3 Conversion to Fluorescent in a Seattle Retail Store

Like the previous example, this retail drug store was one of the 14 submetered retrofit projects sponsored by Seattle City Light (Cleary and Schuldt, 1986). According to the building owner, the reason for the lighting modifications were made to improve color rendering so the merchandise could be seen well. The 400 W mercury vapor system was replaced with ceiling-mounted, two-tube, eight-foot, high-output fluorescent fixtures. This changed the lighting power density from 4.2 W/ft^2 to 3.1 W/ft^2, while providing approximately the same lighting levels (80 fc) as provided by the previous system. Operation of the new system was slightly different than for the old, especially the switching patterns. The mercury vapor lights had been switched off in stages, but the fluorescent lights were turned off simultaneously. We mention this because the impact of switching modifications must be carefully considered when comparing predicted and actual energy savings in combined retrofits.

The predicted savings were 7.9 kWh/ft^2-year of lighting energy use with another 2 percent net savings in HVAC energy use. Actual savings were greater, totaling 10.9 kWh/ft^2-year (33 percent). Of the total change in energy use, lighting saved the same amount as predicted, but cooling energy use decreased (down 3.4 kWh/ft^2-year), and heating energy use rose (0.2 kWh/ft^2-year). The computer simulation underpredicted the net savings in HVAC energy use. Some of these savings were due to differences in control of the HVAC system, resulting in reduced operating hours during the post-retrofit period. The lighting retrofit also caused a decrease in peak demands. The pre-retrofit peak day occurred in October (5.6 W/ft^2) and the post-retrofit peak demand occurred in January (3.8 W/ft^2).

5.2.4 Occupancy Sensors in a New York Office (1)

This study was performed in one half of one floor (20,000 ft^2) of the 100-plus story building, One World Trade Center (WTC) (Boehm et al., 1982). It was designed to evaluate occupancy-controlled light switching by assessing energy savings, demand savings, cost savings, effect on total consumption, equipment performance, and user reaction. The devices were pre-production infrared motion detectors which consumed a small 0.025 kWh/day per device. Prior to the installation of the occupancy sensors the lighting system was modified. The original fixtures contained six 40 W tubes with three ballasts (2.6 W/ft^2). The fixtures were delamped to four 35 W tubes with two ballasts (1.5 W/ft^2). Lighting on each floor was switched by quadrant. Local switching had been considered too expensive when the building was built because of low electricity prices, and rewiring was later considered prohibitively expensive.

Occupancy control devices were installed in 33 offices, plus a supply room and a lunch room to control 34 percent of the lighting on the panel. An electricity meter was installed on the lighting circuit to measure changes in energy use. Problems were encountered with about 25 percent of the prototype controller units that were later replaced with the improved commercial model.

Figure 5-1 shows the effect of the controllers on lighting energy use; lighting energy use decreased by 57 percent As shown in Table 5-2, this translates into a savings of about 10 percent of total building energy use. Heating energy use was estimated to increase by 3 $kBtu/ft^2$-year and cooling energy use was estimated to decrease 1.4 $kBtu/ft^2$-year. The peak demand of 1.2 W/ft^2 for lighting was reduced 17 percent, or by about 0.2 W/ft^2. Based on 1982 dollars and rates, overall annual savings were $50 per device.

5.2.5 Occupancy Sensors in a Second New York Office (2)

This study was similar to the WTC occupant sensor study but showed smaller overall savings because of different base line conditions (Boehm et al., 1982). Unlike at the WTC, prior to the installation of the occupancy sensors more local switching was available at this office. An even earlier model, pre-production infrared motion detector than that used at the WTC, was used here to study the savings from occupant controls. One floor of the office building, with a lighting power density of 3.1 W/ft^2, was used in the experiment.

Occupancy control devices were installed in 32 offices, a supply room, and a lunch room to control 34 percent of the lighting on the panel. An electricity meter was installed on the lighting circuit to measure changes in energy use. Problems were encountered with about 25 percent of the prototype controller units that were later replaced with the improved commercial model.

Energy used for lighting decreased 27 percent. No saving in peak demand were observed because of the diversity of use at that time. The impact of lighting energy use changes on the central plant was estimated to be small. Heating energy use was estimated to increase by 2.5 $kBtu/ft^2$-year (6 percent) and cooling energy use estimated to decrease 1.4 $kBtu/ft^2$-year (9.2 percent). There were no negative occupant responses except in the cases where the devices failed.

5.2.6 Scheduling and Daylighting Controls in a New York Office (3)

This study was also performed in Manhattan's One World Trade Center (WTC) (Rubinstein and Karayel, 1984 and Rubinstein et al., 1984). The complete 58th floor was instrumented with controls to study energy savings from three scheduling strategies and perimeter daylighting. The lighting on this floor is identical to the above example (Building 4) before the delamping: 2.6 W/ft^2 from six 40 W tube luminaires with three ballasts. Prior to the retrofit, control was on a floor-by-floor basis. Tests were spread over an eight-month period. A programmable lighting control system was installed and tested in three modes: 1) a loose schedule, which turned on lights from 7:30 AM to 5:30 PM with additional staging of the lights during other periods, 2) a tight schedule, which reduced the loose schedule by 1.5 hours and included more severe reductions during night and lunchtime hours, and 3) off-only schedule, which required off-hour users to turn on their sectors with telephone overrides. These reduced lighting energy use 31, 36, and 41 percent, respectively. Decreasing zoning sizes also increased energy savings by 28 percent for 7000 ft^2 zones and 41 percent for 1000 ft^2, as compared to the entire floor.

The control system, using photorelays to detect exterior illuminance levels, was then programmed to reduce perimeter lighting from full to 1/3 and 2/3 levels when 300 fc and 1000 fc of daylight were measured, respectively. This control strategy resulted in savings of 27 percent for the daylit zones and 9 percent for the entire floor.

5.2.7 Scheduling and Daylighting Controls in a San Francisco Office

This Pacific Gas and Electricity Company (PG&E) building participated in the same research project as the last example (WTC), measuring savings from both scheduling and perimeter daylighting control strategies (Rubinstein and Karayel, 1984). The 30th floor of the building, consisting of 26,000 ft^2 and used for drafting, filing, reading, and typing, was instrumented for the study. While the lighting system originally installed used 3.7 W/ft^2, the lighting power densities during the experimental period were 1.5 and 2.0 W/ft^2 for the daylit and interior zones, respectively. As shown in Table 5-1, the additional control equipment consisted of core-coil dimming ballasts, dimming panels on each feeder serving the overhead lighting, rewired circuits, and photosensors in selected perimeter offices.

The savings in energy use from scheduling were substantially lower than the savings from scheduling in the New York WTC, where the baseline lighting operating hours were longer before scheduling. Also, because the switches in the San Francisco building used to override the scheduling were not easily accessible, the scheduling allowed long hours of operation. This ensured that overrides would not be frequently required. Prior to scheduling the lighting system was turned on and off by building security personnel. Based on an baseline monitoring period of four months, the average usage before the scheduling was 16 hours per a day. This reduced to 14.5 hours per day, or about ten percent.

A one-month test was performed during mid-winter to measure the energy savings from reduced lighting when daylighting is available. The photosensors were calibrated to maintain illumination at the level provided by the lighting system at night. Surprisingly, the savings from

daylighting were again similar to those at the WTC building, with savings of 26 percent for the daylit zones and 10 percent for the entire floor. This result was unexpected because the PG&E building used a continuous dimming system, not a stepped switching system. However, the tests were performed at different times of the year. With the use of sky conditions data and extrapolating to the entire year savings would reach a high of 34 percent during the summer.

5.2.8 Electronic Ballasts in a Long Beach Hospital

This study was performed to measure the energy savings from retrofitting a 40 W fluorescent, core-coil ballast lighting system with energy saving (35 W) lamps and (older-model) solid-state ballasts (Verderber et al., 1982). Two areas, a lobby and an office suite, were monitored. As shown in Table 5-2, before the retrofit these spaces had installed lighting power densities of 2.8 and 3.4 W/ft^2, respectively, with illumination levels at an average of 46 and 67 fc. Dimmable ballasts were installed in one of the office suites and energy savings from daylighting were measured.

The first modifications consisted of cleaning the fixtures and relamping with 35 W lamps. In the office space this resulted in an increase in light output of 46 percent and an 11 percent decrease in power. In the lobby area with enclosed fixtures, light output increased 16 percent and power consumption decreased by 11 percent. In the lobby areas with a large grid of closely spaced bare lamps there was no change in illumination levels and a 17 percent decrease in power. The lamp wall temperature in the grid was about 10°C hotter than in the fixtures. Identical core-coil ballasts drew from 70.8 W to 90.0 W depending on the lamp temperature and lamp type, with the 35 W lamps drawing less power. An important reason for the smaller increase in illumination in the lobby area is that the lamps there were newer and had undergone less lumen depreciation.

Installing the solid-state ballast further reduced power consumption in the office area by another 17 percent, or 26 percent overall, with an increase in light output of 39 percent overall. In the lobby area with enclosed fixtures, the solid-state ballasts reduced power consumption by another 19 percent, or 28 percent overall, with an increase in light output of 12 percent overall. And, in the lobby area with the grid, the solid-state ballasts reduced power consumption by another 6 percent, or 22 percent overall, with an increase in light output of 25 percent overall. Table 5-2 shows the percent savings averaged over both areas.

A dimmable ballast system was installed in one of the offices, which was designed to maintain illumination between 87 and 89 fc. Based on two days of measurement, energy savings were between 20 and 25 percent.

Table 5-1. Building and retrofit characteristics for eight submetered lighting case studies.

	BUILDING CHARACTERISTICS					RETROFIT CHARACTERISTICS					
Bldg #	Type	State	Year Built	Gross Floor Area (kft^2)	Pre-Retrofit Condition	Lighting Retrofit Description	Other	Year	Cost[1]	Area Covered (kft^2)	Pay-back (yrs)
1	RETL	WI		3.2	No daylighting	Sunspace Roof monitors Light shelves	Wind turbine exhaust Direct gain sunspace	1981		Total	
2	GROC	WA	1960	16.8	Exterior: Merc. Vapor Interior: 8 ft fluorescents 3 tubes per fixture	Exterior: HPS & photocells Interior: rewired for control On/off freezer light switch	Freezer case doors Strip curtains on walk-ins	1986	$23,000 overall $12,101 int. lights	Total	5.4 overall 5.6 int. lights
3	RETL	WA	1973	22.3	Merc. Vapor Manual controls	Fluorescent fixtures		1984	$11,334	Total	
4	LOFF	NY		4400	Quadrant switching	IR occupancy controls		1981		20.0	
5	LOFF	NY			Local wall switching	IR occupancy controls		1981			
6	LOFF	NY		4400	6-lamp ceiling mounted 35 W fluorescents Floor by floor computer controlled	A - Programmable control rewired & scheduled B - Photorelays		1981		40.0	
7	LOFF	CA			40 W fluorescents 2 X 4 recessed fixtures On/off switched by building security	A - Programmable control rewired circuits B - Dimming core-coil ballast added photosensors & dimming panels		1981		26.0	
8	HOSP	CA			40 W fluorescents Core-coil ballast	A - 35 W fluorescents clean fixtures B - Solid state ballasts		1980			

NOTES:

1 - Cost data are reported in the retrofit year's dollars.

Table 5-2. Measured savings for eight submetered lighting case studies

Bldg#	1	2	3	4	5	6A	6B	7A	7B	8A		8B
	RETL	GROC	RETL	LOFF	LOFF	LOFF		LOFF		HOSP		
RETROFIT AREA (kft^2)	3.2	16.8	22.3	20	-	40		26		L	O	O
PRE-RETROFIT												
Total (kBtu/ft^2-yr)	41	336	117	99	121							
Elec. (kWh/ft^2-yr)	5.4	84	34									
Gas (kBtu/ft^2-yr)	23	50	0									
Annual Peak Demand (W/ft^2)		11	5.6									
Light (kWh/ft^2-yr)	2.9	21	24	6.0	11.2	10.9	10.9					
Illumination (fc)		120	80			70-130	70-130	100		46	67	98
Installed Power (W/ft^2)		2.6	4.2	1.5	3.1	2.6	2.6	1.5-2.0	1.5-2.0	2.8	3.4	3.0
% of total energy use	24	21	70	21								
POST-RETROFIT												
Total (kBtu/ft^2-yr)	63	245	80	89	113							
Elec. (kWh/ft^2-yr)	2.6	71	23									
Gas (kBtu/ft^2-yr)	54	50	0									
Annual Peak Demand (W/ft^2)		9	3.8									
Light (kWh/ft^2-yr)	1.2	13	16	2.6	8.4	7.6-6.5	9.9					
Illumination (fc)	30	100	80			70-130	70-130	55-105	55-105		98	93
Installed Power (W/ft^2)	0.7	2.4	3.1	1.5	3.1	2.6	2.6	1.5-2.0	1.5-2.0		3.0	2.5
% of total energy use	7	18	69	10.2								
PREDICTED SAVINGS												
Total (kBtu/ft^2-yr)	-24	54	27									
Light (kWh/ft^2-yr)	1.5	6	7.9									
ACTUAL SAVINGS												
Total (kBtu/ft^2-yr)	-22	44	37	10	8.4	11.2-15	3.3					
Light (kWh/ft^2-yr)	1.7	6	7.9	3.4	3.1	3.3-4.4	1.0					
% decrease in lighting EUI	59	29	33	57	27	31-41	9	10	10	13		13

NOTES ON BUILDING DATA:

Building 4: Whole-building use is estimated. Lighting energy use savings based on half a floor of submetering over 6 month period. Data are corrected for malfunctioning sensors.

Building 5: Whole-building energy use also estimated. Lighting energy use savings based on half a floor of submetering over 6 month period. Data are corrected for malfunctioning sensors.

Building 6: Lighting energy use is based on eight months of submetering prorated to an annual average using 261 work days, therefore a low estimate. Illumination (fc) differs between interior to perimeter zones.

A - Range in savings is due to the 3 control strategies.

B - Savings from perimeter daylighting is 9% of energy use over total submetered area, but 27% of daylit zone.

Building 7:

B - Savings from perimeter daylighting is 10% of energy use overall total area, but 26% of daylit zone.

Building 8: Data are shown for Lobby area (L) and Office area (O). An additional savings of 20% to 25% was measured with perimeter daylighting.

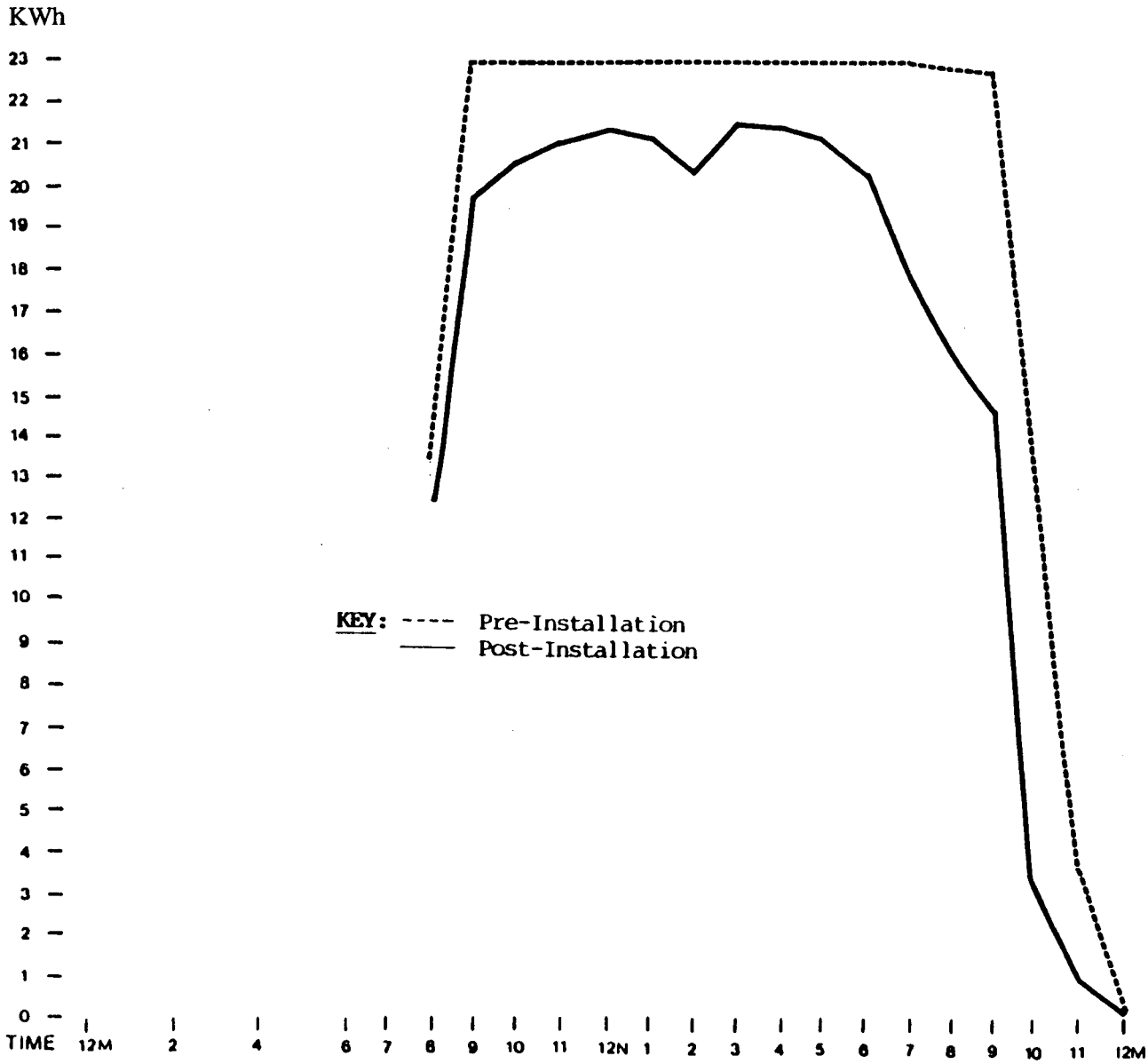

Figure 5-1. Submetered lighting energy use showing the impact of occupancy-controlled light switching on average weekday consumption. Data are from one floor of Building 4, the World Trade Center office building in New York. Load shape modifications will vary in other buildings depending on switching and room layouts and occupancy patterns.

6. CONSERVATION POTENTIAL AND MARKET TRENDS

6.1 Combined conservation potential from fluorescent-fixture technologies

It is interesting to ask what the aggregate conservation potential or demand-side resource from commercially available efficiency improvements might be for all lighting applications and what the average unit cost of this demand-side resource would be. Although such an analysis goes beyond the scope of this report, it is useful to review estimates made by others. In reviewing these estimates we should keep in mind that all such calculations are somewhat uncertain because it is difficult to determine the exact mix of retrofit opportunities in the U.S. building stock. Also, the performance of some important lighting technologies (daylighting, occupancy control, task lighting, etc.) cannot at present be accurately gauged for the building stock at large.

A simple reference point for exploring the potential of lighting efficiency is to calculate the approximate percentage savings that could be achieved in a commercial building lit by the most common type of lighting system, standard fluorescent fixtures. We show a compilation of two such estimates in Table 6-1. Both estimates omit potential savings from delamping, phosphor improvements, polarizers, or installing improved reflectors. Nevertheless Verderber calculates that, in combination, electronic ballasts, more efficient lamps, better controls, and daylight dimming could provide the same lumen output for 66 percent less power than a standard fixture (Table 6-1, column 2). This estimate is based on the most conservative assessment of performance data (column 1), and assumes that a number of the more subtle savings opportunities offered by energy-efficient lighting equipment, notably by tunable electronic ballasts, would not be fully utilized.[1]

Lovins and Sardinsky (1988) show that some of the indirect efficacy gains from the use of tunable electronic ballasts could — if fully exploited by the designer (column 3) — yield even higher savings, or 74 percent, using exactly the same equipment (Table 6-1, column 4). Lovins and Sardinsky also show higher estimates reaching more than 90 percent of savings, which would be applicable in buildings where daylighting controls and other energy management options can be maximized. It is not clear to what extent these higher numbers can be generalized as a potential for the average application. The savings from scheduling and other lighting control applications are inherently difficult to predict on a stock-wide basis. Much more field monitoring will be needed to firmly establish the appropriate rule-of-thumb saving from these options, as already discussed in Section 5.

However, even with the more conservative figures of Table 6-1, these potentials calculations do establish an important fact:

- The percentage savings potential in standard fluorescent fixtures from lamp-ballast changes and controls is about as large as the savings potential from incandescent fixtures when these are converted to compact fluorescents. In both cases, energy savings far in excess of 60

[1] Even the limited indirect savings listed in the "low" column of Table 6-1 were not included in the CCE calculations presented in Appendix A and Table 4-8, a significant further conservatism.

percent are feasible, and savings may reach more than 80 percent. For example, the 66-74% ballast and control savings shown in Table 6-1, if combined with a 25% further W/lumen reduction from specular reflectors and 15% from tristimulus phosphors, imply total potential savings of 78-83%.

How much of this potential might be available if practical constraints (both economic and other) are taken into account? As usual, opinions and assumptions can strongly shape the answers. A recent statewide analysis of aggregate economic potentials performed in Rhode Island found that 42 percent of the state's lighting electricity consumption could be cost-effectively saved with presently commercial technology (Xenergy 1988). Of the 11 lighting conservation strategies recommended in the study, the top three technologies were electronic ballasts (33 percent of the savings), energy-saving fluorescents (19 percent), and compact fluorescents (13 percent). The study relied on more detailed data on the stock of lighting systems than previous analyses, and attempted to reflect important practical constraints that might limit the application of some measures in certain situations. Stock data were primarily obtained from large numbers of on-site commercial energy audits. However, a number of technological options were not fully exploited.

A recent national analysis has been provided by Lovins and Sardinsky (1988), who estimate that about 90 percent of U.S. lighting electricity could be saved by complete retrofit in the commercial and industrial sector, at an average cost of 0.6 cents/kWh for tubular fluorescent retrofits. (Note that these savings estimates include some use of daylighting, but do not include additional indirect savings from HVAC in their CCE calculations.) In arriving at their estimate, the authors emphasize that full application of the most recent commercial products in all buildings is a goal that can be achieved only over the longer-term.

Lovins and Sardinsky also find that the cost of conserved energy of various retrofit combinations does not increase significantly even as high combined savings are sought. This finding is in good qualitative agreement with the pattern observed for the more limited range of savings from the measures analyzed in this report (see Section 4.3).

Other estimates of lighting conservation potential are component-specific. In 1988, a national minimum efficiency standard for fluorescent ballasts became law. This standard prohibits the manufacturing and use of standard magnetic ballasts and requires the use of energy-efficient magnetic ballasts or electronic ballasts as of January, 1990. As mentioned in Section 4, an efficient core-coil ballast reduces demand on a two-lamp fixture with a standard core-coil ballast by about eight percent. Geller and Miller estimated that by the year 2000 the use of efficient core-coil ballasts would save about four percent of 1987 commercial electricity use. Based on electricity costs of 7 cents/kWh, a five percent annual real discount rate, and the cost of an

[1] We did not analyze the cost-effectiveness of such very high savings packages in detail. They could be about as cost-effective as other packages if the extra first cost of higher quality reflectors and tristimulus lamps is controlled through careful shopping and/or bulk purchases.

efficient magnetic ballast at $14.00 ($4 more than a standard ballast), they calculate that the net cumulative savings to U.S. consumers will be $10.7 billion by the year 2000.

6.2 Energy Savings from Future Lamp Technologies

A glimpse of possible future improvements in lighting system efficiency can be gleaned from current research efforts, especially those that have already demonstrated viable products. Column three of Table 6-1 summarizes what performance characteristics one might expect from future lighting equipment. For comparison, the first two columns show the characteristics of new lighting equipment as typically installed in 1976 and 1988 (not average stock characteristics for each year). It should be noted that the separation of "future" and "present" is somewhat fluid here. In some cases, commercial products are getting close to the future specifications shown in the table. We briefly review some of the technologies that could become standard equipment in the relatively near future.

Fluorescent lamps. In Section 3.1.2 we described some of the characteristics of fluorescent lamps and methods to improve their efficacy. Fluorescent lamps can be made more efficacious by 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 surface wave lamp, which relies on megahertz electrodeless technology. It has already been tested extensively in the laboratory and seems likely to achieve 200 lm/W lamp. This is not too far away from the theoretical limit for a white light source, which is 350 lm/W.

The surface wave lamp could extend fluorescent tube life to 50 000 hours, because it has no filaments. Thus, lamp life would be based solely upon acceptable levels of lamp lumen depreciation. However, this new lamp technology is farther away from commercialization than other modifications.

In the nearer term, fixture efficiency is likely to improve as the lampwall temperature of fluorescents is controlled with Peltier devices, heat pipes, or venting fixtures. Peltier devices are thermoelectric devices that, when bonded to the lamp wall, can regulate the lamp wall temperature to an optimal level. Today fluorescent lamps in most fixtures operate 10°C to 20°C above the optimum temperature of 40°C, reducing their light output and efficacy.

Compact fluorescents and HID lamps. The advent of the electrodeless lamp would not only mean a revolution in fluorescent fixtures, it would allow a much more compact fluorescent bulb design, so fluorescent lights could replace more incandescent lights in use now.

Electrodeless HID lamps would 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 may restrike instantly and be dimmable without significant color shifts.

Ballasts and control technologies. All future gas discharge lamps can be expected to be controlled with tunable electronic ballasts. Control systems will probably be widely used and

will open up the application of power line carrier technology for targeted communication between sensors and dimming controls. These systems will be capable of controlling the light level of lamps in individual fixtures independently of the lamps in other fixtures. This versatility can maximize the energy savings from daylighting, task lighting, and occupancy controls, as well as providing optimum lighting conditions for all occupants.

6.3 Aggregate Efficiency Potential -- A Scenario

In view of the rapidly evolving field of energy-efficient lamp technologies, it is interesting to ask what level of savings could be achieved and what aggregate trends in lighting electricity demand would be experienced once the above-mentioned efficiency improvements are fully deployed.

Taking an indefinite point in time after the year 2000, Berman (1988) constructs a simple scenario which takes into account economic growth and growth trends in building floor space. He estimates for the commercial sector that efficiency improvements from technological innovation now under way would overwhelm demand growth and reduce lighting energy use to about half of the 1976 level, even if commercial floor space were to grow by a factor of 3. The scenario results are summarized in Table 6-3. The high growth scenario assumes a growth rate of 3 percent per year in commercial floor space, and results in a 117 BkWh lighting energy demand. The low growth scenario (2 percent per year) yields a total of 76 BkWh.

The estimates are based on improvements in and changes in the percentages of, fluorescent, incandescent, and HID lighting systems, as listed in Table 6-2 and Table 6-3. Verderber calculates that on a weighted average basis, the savings per building or installation from future lamp technologies will be about 85-90 percent. This range is about the same as the one calculated by Lovins and Sardinsky for the full application of the most advanced technologies already on the market. There is a certain amount of technological overlap between the estimates. The similarity of the two savings percentages suggest that close to 90 percent of lighting electricity demand could indeed be substituted by technological know-how, if not today with careful combination of presently commercial lamp, ballast, reflector, and control technologies, then in the future with less meticulously optimized system design. Such substitution will be aided by emerging high efficiency lamp technologies and powerful off-the-shelf control systems.

Although it is not possible to estimate the cost of prototype lamps and technologies still under development, it is instructive to express the meaning of such large electricity savings in terms of power plants saved. The BkWh savings shown in Table 6-3 correspond to the output of 17 to 25 large (1000 MW) baseload power plants. Based on a rough estimate of 3000 hours of use per year, the total lighting demand for the commercial sector would drop to about 25 to 39 GW in the Verderber scenario. If lighting controls are assumed to be widely in place, this could shed another 10 to 20 percent of the peak demand (excluding cooling). With HVAC savings, the potentially avoided capacity would be still larger.

6.4 Uncertainties and Barriers

Perhaps the two most significant barriers to achieving significant penetration of energy-efficient lighting technologies are lack of adequate information, and absence of ambitious targets. The conservative nature of the lighting community is also a hinderence; there is resistance to change. Examples of the mechanisms to encourage more efficient lighting include building energy codes and standards, aggressive utility conservation programs, and demonstration projects of advanced low-energy design (Krause et al., 1989). Special training programs for lighting designers is also needed. The California Energy Commission (CEC) is considering supporting education programs in lighting design that would include courses in the fundamentals of energy efficient lighting equipment and design.

The products described in Section 3 are, in general, widely available; their technical performances have been proven in the laboratory and in the field. Those described above in Section 6.2 will be available in the next decade or so. The reliability of lamp and ballast systems is definitely improving. Questions remain regarding the lifetime of some of these measures, such as the degradation of reflector performance. However, the products described above are not thought to have shorter lifetimes than standard lighting equipment. The costs of such equipment continue to decrease as the products gain greater market acceptance.

Table 6-1. Technical savings potential of F40 lamps with successive components

COMPONENT DESCRIPTION	SAVINGS POTENTIAL			
	LOW[1]		HIGH[2]	
	COMPONENT	ACCUMULATED	COMPONENT	ACCUMULATED
Baseline		1.00		1.00
Intrinsic Savings (lamps and ballast)	(20%)	0.80	(30%)	0.70
Improved Voltage & Temperature Stability[3]	(0%)	0.80	(12%)	0.62
Compensation for Lumen Depreciation	(14%)	0.69	(14%)	0.53
Task Tuning	(12%)	0.61	(12%)	0.47
Occupancy Scheduling	(25%)	0.45	(25%)	0.35
Daylighting Controls	(25%)	0.34	(25%)	0.26

1. Verderber, 1988, unpublished.
2. Lovins and Sardinsky, 1988, p. 185.
3. The savings potential from improving voltage and temperature stability is not included in the "low estimate" scenario because of the uncertainty of the technology characteristics in relation to design techniques.

Table 6-2. Performance of lighting equipment available in 1976, 1988, and 2000+

	1976	1988	2000+
Fluorescent Lamp (Efficacy)	80 lm/W	100 lm/W	200 lm/W
Life	20,000 h	20,000 h	100,000 h
Ballast (Efficacy)	80%	90%	90%
Fixture (Efficiency) Fluorescent	--	+10%	+10%
Ballast (Efficacy) HID	--	--	+20%
Light Level	100 fc	50-70 fc	50-70 fc
Power Density	4-6 W/ft^2	1.5-2 W/ft^2	0.5 W/ft^2
Edison Sockets (Efficacy)	15 lm/W	30 lm/W	80 lm/W
HID Lamp (Efficacy)	100 lm/W	100 lm/W	150 lm/W
Controls	--	25%	50%

Table 6-3. Estimated past and future energy consumption for the commercial sector

	1976 Estimated Energy Use		2000+ High Growth Energy Use (3%/year)		2000+ Low Growth Energy Use (2%/year)	
	(BkWh)	%	(BkWh)	%	(BkWh)	%
Incandescent	50	25	25	21	16	21
Fluorescent	140	70	82	70	54	71
HID	10	5	10	9	6	8
TOTAL	200	100	117	100	76	100

7. RECOMMENDATIONS FOR FUTURE WORK

In this report we have presented a brief overview of lighting design concepts, described the characteristics of energy-efficient lighting equipment, and examined the cost-effectiveness of a variety of readily available products. We have also presented eight case studies to illustrate actual performance results from an assortment of retrofits. A variety of questions remain regarding the use of energy efficient lighting equipment. We make the following recommendations for future work to augment the subjects covered in this report.

System Design Information Needs

- Designers need to have greater familiarity with energy-efficient lighting equipment and more ambitious lighting targets for low energy design. Research based guidelines on how to design systems that provide good visual comfort in an energy efficient manner is needed. Demonstration projects and lighting mock-up facilities are needed to educate designers on the use of such equipment.
- Internally generated cooling loads are a growing concern to utility planners and building operators. A better understanding of how lighting systems interact with HVAC systems is needed.
- Definitive information on the health effects associated with various lighting systems is needed for lighting designers, conservation program analysts, and building occupants. An example of such research is the recent evidence of positive health effects from the reduced flicker and hum associated with the use of high frequency ballasts, as opposed to standard 60 Hz ballast operation.

System Performance Data Needs

- On the demand side, better data on currently installed lighting equipment are needed to support more precise assessments of the applicability of energy-efficient lighting equipment for the existing building stock.
- On the equipment side, more attention to and better data on lighting system performance (lamp-ballast or lamp-ballast-fixture combinations) are needed for a better understanding of lighting system energy consumption and lumen output.
- Electric utility companies and other organization that encourage the use of energy-efficient lighting equipment should study the field and long term performance of the equipment. Better information is needed on issues such as operation and maintenance costs, system degradation levels, effects of operating temperatures, and equipment failure rates. Customer usage patterns and occupant satisfaction should also be studied.
- Better understanding is needed of how much energy is saved (or demand reduced) from the use of various control systems. For example, most commercial building energy codes give credit for the use of various control systems, with savings based on engineering estimates.

- Continued development of new energy-efficient lighting products is needed, with field demonstrations to educate users and measure actual savings.

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APPENDIX A
ECONOMIC PERFORMANCE CALCULATIONS

This section describes performance and cost data developed for eleven retrofit packages. We calculate the cost of conserved energy (CCE) and simple payback time for each measure using the assumptions described below. Table A.1 shows a brief description of the three base case lighting systems, and eleven retrofits. Below we present notes on each of the retrofits from the table, as well as references for our sources of information.

Data from Table A.1 were incorporated into a spreadsheet to calculate the CCE under four costs scenarios designed to conservatively bound the cost-effectiveness of these retrofits under various conditions. Our "worst-case" scenario is shown in Table A.2, for which the CCE calculations are based on retail prices and 3000 hours of operation per year. We assumed that the equipment being replaced had operated for half of it's lifetime. Therefore in calculating the installed cost of the retrofits we subtracted off half of the equipment cost for the system that was being replaced. To consider the savings from large purchases in Table A.3 we show the CCE calculations for the same eleven retrofits with the equipment and labor costs reduced by 33 percent of the retail price, and 4500 hours per year of operation.

The "best-case" scenario is to replace lighting equipment at the end of its useful lifetime. To consider replacement upon end of useful life Tables A.4 and A.5 show the same data as in Table A.2 and A.3, but with initial costs calculated as the incremental cost between the standard equipment and energy conserving equipment.

Table A.6 shows the changes in lumen output that result from each measure in comparison with the respective base case.

A.1 NOTES ON BASE CASE CONDITIONS AND RETROFIT CHARACTERISTICS

75 W Bulb Incandescent Base Case - Performance and cost data based on Xenergy, Inc., 1988.

(1) *Replace Incandescent with SL-18 Compact Fluorescent* - Performance and cost data are based on Xenergy, Inc., 1988, which assume that no adapter is needed (p. 3-11). Lovins and Sardinsky, 1988 also use $15.50 for SL-18, with 7,500 to 10,000 hour lifetime. In the Traer lighting program the utility was able to purchase the SL-18 for $7, a bulk purchase discount of 50 percent, well beyond our conservative 33 percent. (California utilities have bulk-purchased Japanese magnetically ballasted lamps at even lower cost). The use of the integral compact fluorescent lamp for our calculations is a conservative approach. Modular compact fluorescents cost as little as $4 to replace once the initial lamp plus ballast base have been purchased. Tables A.2 and A.3 show that based on an incandescent bulb lasting 750 hours, we save $4.00/year in lamp replacement (maintenance) costs for 3000 hour per year operation and $6.00/year for 4500 hours. These values are again conservative, in that they ignore installation labor savings. Small commercial customers may not use contractors or paid maintenance staff to do such installations, but larger commercial customers often rely on outside contractors or in-house maintenance staff. Assuming a lamp installation charge of about $1, monetary savings for these larger customers would more than double. Costs of conserved energy would then be negative even without demand charge savings.

2 40 W Fluorescent Lamps with CBM Ballast Base Case - Lamp price based on average of 3 major manufacturers from *Energy Users News (EUN)*, Jan. 12, 1987. Ballast price based on Verderber and Morse, 1986, which coincides with Xenergy, Inc. 1988. Lifetimes based on Verderber and Morse, 1986. Performance from Verderber, 1988, as shown in Table 4-2.

(2) *Replace 2 40 W Fluorescent Lamps with 2 34 W Lamps* - Lamp price based on average of LW lamps from 3 major manufacturers from Energy Users News Jan. 12, 1987. Lifetimes from EUN articles. Labor cost from Xenergy, Inc., 1988, $1.00 per lamp. Performance based on Verderber, 1988, as shown in Table 4-2. At 3000 hours per year the life of the measure is 6.7 years; at 4500 hours--4.4 years. Zero annual maintenance costs of measure.

(3) *Replace CMB Ballast with Efficient Core-Coil Ballast* - Ballast price, labor price, and power reduction based on Xenergy, Inc., 1988 (p. 3-20). Using an estimated 10 percent increase in efficacy the lamp-ballast system output totals 6003 lm (69 lm/W). While the NWPPC, 1987 shows that efficient core-coil ballasts cost one to two dollars than standard ballasts, Geller, 1988 reports their cost at one dollar less than the above $15.00 price. With a 45,000 life the measure lasts 15 years at 3000 hours and 10 years at 4500.

(4) *Replace CMB Ballast with Solid-State Ballast* - Ballast price based on Geller, 1988. Performance based on an average of 19 lamp/ballast systems, operating at 100 percent of current voltage, Verderber et al., 1988. The average efficacy was 78 lm/W. Labor based on Xenergy, Inc., 1988 (p. 3-20). Xenergy study shows the price at $1 greater than Geller. Verderber and Morse, 1986 show an average incremental cost of $5 for a dedicated electronic ballasts, or $1 less than Geller. Lifetime based on Verderber and Morse, 1986.

(5) *Replace 2 40 W Fluorescent Lamps and CBM Ballast with 2 34 W Lamps and Solid-State Ballast* - Combination of example (2) and (4). Also based on an average of 19 lamp/ballast systems, operating at 100 percent of current voltage, Verderber et al., 1988. The average efficacy was 79 lm/W. Lifetimes for solid-state ballasts were assumed to be the same as those for CBM ballasts. We have taken into account the cost of the lamp over the 15 (or 10) year ballast lifetime in the following manner. At 3000 hours per year the life of the ballast is 15 years and the lamps lasts 6.7 year. The lamps costs $2.20 every 6.7 years, or $0.33/year. This annual charge is present valued based on a discount rate of 7 percent over 15 year. This cost is added to the ballast cost, and the sum is annualized. At 4500 hours thee $2.20 is spent every 4.4 years, costing $0.50/year. Reducing this cost by one-third for bulk purchases the value becomes $0.34/year, as shown in Table A.4.

(6) *Replace 2 40 W Fluorescent Lamps and CBM Ballast with 2 32 W, T-8 Lamps and Solid-State Ballast* - Lamp price based on average of 3 major manufacturers from *Energy Users News* Jan. 12, 1987. Performance based on Verderber, 1988 (see Table 4-2).

4 40 W Fluorescent Lamps with 2 CBM Ballast Base Case - Base case costs are twice the 2 Lamp base case. Performance based on Verderber, 1988 (see Table 4-3).

(7) *Replace 4 40 W Fluorescent Lamps with 4 34 W Lamps* - Costs are same as (2) but for 4 lamp fixture. Performance based on Verderber, 1988 (see Table 4-3).

(8) *Replace 2 CMB Ballast with 1 Solid-State Ballast* - Similar to (4) but for 4 lamp fixture with one ballast. Based on an average of 4 lamp/ballast systems, with an average of 78 lm/W (Verderber et al, 1988). Costs are an average of 4 values for dedicated electronic ballasts from Lovins and Sardinsky, 1988. We neglected avoided future ballast replacements due to the fact that only one ballast will have to be replaced in future cycles.

(9) *Replace 4 40 W Fluorescent Lamps and 2 CBM Ballasts with 4 32 W, T-8 Lamps and 2 Solid-State Ballasts* - Same as (6) but for 4 lamp fixture. Performance based on Verderber, 1988 (see Table 4-3).

(10) Delamp from 4 to 2 40 W Fluorescent Lamps and Install Specular Reflector - Silver reflector equipment and labor price (1/2 an hour at $30/hr) based on Xenergy, Inc., 1988 (p. 5-4). Aluminum reflectors are less expensive ($35.00). Performance based on Verderber, 1988 (see Table 4-5). Lifetime based on 15 year reflector life: (8760 hrs/years)*15 years = 131,400. Savings in lamp replacement of $2.00 for each relamping, every 6.7 years for 3000 hours per year and 4.4 years for 4500 hours per year.

(11) *Delamp from 4 to 2 40 W Fluorescent Lamps, Install Specular Reflector, and Replace CMB Ballast with one Solid-State Ballast* - Combination of example (4) and (10). The new lamps are assumed to operate at 48°C. Data for the lamp-ballast system are from Verderber and Morse, 1988, based on an average of eleven lamp-ballast systems. Reflector performance from Table 4-5. Note that in Table A.4 and A.5 (where the costs reflect incremental costs of equipment in order to estimate cost-effectiveness upon the end of the useful life of the base case equipment) we use the full cost of the reflector throughout, but not of the ballast. Avoided labor costs in these relampings were ignored. We also neglected avoided future ballast replacements due to the fact that only one ballast will have to be replaced in future cycles.

A.2 NOTES ON CCE CALCULATIONS (TABLES A.2 THROUGH A.5)

A. *Base Case or Retrofit Description*

B. *Annual Energy Use (kWh/year)* - (kW (C) x Number of Hours/Year (F))

C. *Peak Demand (kW)* - from Table A.1

D. *Hours of Operation (Hrs/year)*

F. *Annual Energy Use Savings (kWh/year)* - Difference between system energy use (B) and base case energy use.

G. *Peak Demand Savings (kW)* - Difference between system demand (C) and base case demand.

H. *Initial Cost ($)* - Includes equipment and labor cost to perform the retrofit, as shown in Table A.1.

I. *Maintenance Cost ($/year)* - Cost for replacement of certain equipment, such as lamps, when in combination with ballasts, due to shorter lifetime.

J. *Present Value of Maintenance Costs ($)* - Based on discount rate of 7 percent and lifetime of measure. Can be positive or negative depending on whether maintenance costs are increased or decreased. Costs for relamping during a lamp and ballast combination retrofit are included here. Whereas in Column J the total purchase price was included for a measure, here only the incremental cost over the conventional equipment are used. Retrofit No. 5 is such an example: the incremental cost of two 34 W lamps over two 40 W lamps is $2.20. This is an average of $0.33/year for maintenance.

K. *Lifetime of Measure (Yrs)* - Based on life of measure (Table A.1) and hours of use (F).

M. *Total Present Value ($)* - Sum of initial costs and present valued maintenance costs (I+K).

N. *Average Annualized Cost ($)* - Cost of measure (N = initial cost (I) plus present value of maintenance costs (K)) times the capital recovery rate (CRR) based on the measure's lifetime (L) and a 7 percent discount rate.

P. *Cost of Conserved Energy (Cents/kWh) Without Peak Demand Savings* - CRR/(annual energy saved), or O/G.

R. *Cost of Conserved Energy (Cents/kWh) With Peak Demand Savings* - (CRR - Peak Demand Savings)/(annual energy saved). A coincidence factor of 80 percent is assumed. Peak demand charges of $5/kW are used.

S. *Simple Payback Period (Yrs)* - Calculated using energy costs of 7 cents/kWh, and no demand charges.

A.3 NOTES ON CHANGES IN LUMEN OUTPUT (TABLE A.6)

A. *Base Case or Retrofit Description*

C. *Efficacy (lm/W)* - Data from Tables 4-2 through 4-5 or other source, as referenced in section A.1 above.

D. *Relative Efficacy* - Normalized to base case.

E. *Lumen Output (lm)* - Data from Tables 4-2 through 4-5 or other source, as referenced in section A.1 above.

F. *Relative Lumen Output* - Normalized to base case.

H. *Fixture Light Output (lm)* - Data from Table 4-4.

I. *Fixture Efficiency (lm/W)* - Data from Table 4-4.

J. *Relative Fixture Efficiency* - Normalized to base case.

The remaining 12 columns of data are the CCEs with and without the peak demand savings, and the simple payback data contained in Tables A.2 through A.5 for each of the 4 cases.

Table A.1 - Base case and retrofit descriptions for CCE analysis

CASE	DESCRIPTION	POWER (W)	Δ (W)	COSTS LABOR ($)	COSTS EQUIP. ($)	LIFE (Hrs)
INCAND. BASE CASE	1 75W Inc. Bulb	75	-	-	1.00	750
(1) REPLACE LAMP	1 Comp. fluor. SL-18	18	57	0.00	15.00	10,000
2 LAMP BASE CASE	2 40W T-12, 1 CBM Bal	95	-	-	14.80	
	2 Lamps				4.80	20,000
	1 Ballast				10.00	45,000
(2) REPLACE LAMP	2 34W T-12, 1 CBM Bal	79	16	2.00	7.00	20,000
(3) REPLACE BALLAST	2 40W T-12, 1 Effic. CC Bal	87	8	9.00	15.00	45,000
(4) REPLACE BALLAST	2 40W T-12, 1 SS Bal	73	22	9.00	30.00	45,000
(5) LAMP & BALLAST	2 34W T-12, 1 SS Bal	63	32	11.00	37.00	
	2 Lamps			2.00	7.00	20,000
	1 Ballast			9.00	30.00	45,000
(6) LAMP & BALLAST	2 32W T-8, 1 SS Bal	65	30	11.00	38.00	
	2 Lamps			2.00	8.00	20,000
	1 Ballast			9.00	30.00	45,000
4 LAMP BASE CASE	4 40W T-12, 2 CBM Bal	169	-	-	29.60	
	4 Lamps				9.60	20,000
	2 Ballasts				20.00	45,000
(7) REPLACE LAMP	4 34W T-12, 2 CBM Bal	153	16	4.00	14.00	20,000
(8) REPLACE BALLAST	4 40W T-12, 1 SS Bal	124	45	9.00	57.00	45,000
(9) LAMP & BALLAST	4 32W T-12, 2 SS Bal	135	34	22.00	74.00	
	4 Lamps			4.00	14.00	20,000
	2 Ballasts			18.00	60.00	45,000
(10) DELAMP & ADD REFLECTOR	2 40W T-12 w/Reflect.	88	81	15.00	50.00	131,400
(11) DELAMP, REFLECTOR & BALLAST	2 40W T-12 w/Reflect., 1 SS Bal	64	105	24.00	80.00	45,000

NOTES:

CBM Bal - Certified Ballast Manufacturer's Ballast

CC Bal - Core-Coil Ballast

SS Bal - Solid State Ballast

Table A.2. Economics parameters for mid-life replacement, retail prices @ 3000 hrs/yr (worst-case)

		Baseline Usage Ann. kWh	Baseline Usage Peak kW	Yrly Hrs of Use	Annual Measure Savings kWh	Annual Measure Savings kW	Measure Cost Initial $	Measure Cost Maint. /yr $	PV $	Life-time Yrs	Tot. PV Cost $	Avg. Ann. Cost $	Marg. Energy ¢ kWh	CCEs w/Pk$ ¢ kWh	Pay back (7¢) Yrs
	A	B	C	D	F	G	H	I	J	K	M	N	P	Q	R
BASE:	INCAND. CASE 75W BULB	225	0.075	3000			1.0			0.3					
(1)	REPLACE W/SL-18	54	0.018	3000	171	0.057	15.0	-4.00	-11.5	3.3	3.5	1.20	0.7	-0.9	1.3
BASE:	2 FLUOR. 40W, CC BAL.	285	0.095	3000			14.8								
(2)	REPLACE W/34W LAMP	237	0.079	3000	48	0.016	5.6	0.00	0.0	6.7	5.6	1.08	2.2	0.6	1.7
(3)	REPLACE W/EFFIC. CC BAL.	261	0.087	3000	24	0.008	14.5	0.00	0.0	15.0	14.5	1.59	6.6	5.0	8.6
(4)	REPLACE W/SS BAL.	219	0.073	3000	66	0.022	29.5	0.00	0.0	15.0	29.5	3.24	4.9	3.3	6.4
(5)	COMBO OF (2) & (4)	189	0.063	3000	96	0.032	35.1	0.33	3.0	15.0	38.1	4.18	4.4	2.8	5.2
(6)	T-8s W/SS BAL.	195	0.065	3000	90	0.030	36.1	0.48	4.4	15.0	40.5	4.44	4.9	3.3	5.7
BASE:	4 FLUOR. 40W, 2 CC BAL.	507	0.169	3000			29.6								
(7)	REPLACE W/34W LAMP	459	0.153	3000	48	0.016	11.2	0.00	0.0	6.7	11.2	2.16	4.5	2.9	3.3
(8)	REPLACE W/1 SS BAL.	372	0.124	3000	135	0.045	51.5	0.00	0.0	15.0	51.5	5.65	4.2	2.6	5.4
(9)	32W W/2 SS BAL.	405	0.135	3000	102	0.034	70.2	0.66	6.0	15.0	76.2	8.37	8.2	6.6	9.8
(10)	DELAMP W/REFLECTOR	264	0.088	3000	243	0.081	65.0	-0.30	-3.7	30.0	53.8	4.33	2.0	0.4	2.9
(11)	COMBO OF (4) & (10)	193	0.064	3000	314	0.105	89.5	-0.30	-2.7	15.0	84.3	9.25	3.0	1.4	2.5

Table A.3. Economics parameters for mid-life replacement, wholesale prices @ 4500 hrs/yr

BASE:	INCAND. CASE 75W BULB	338	0.075	4500			0.7								
(1)	REPLACE W/SL-18	81	0.018	4500	204	0.057	10.0	-4.0	-8.0	2.2	2.0	1.02	0.5	-0.8	0.7
BASE:	2 FLUOR. 40W, CC BAL.	428	0.095	4500			9.9								
(2)	REPLACE W/34W LAMP	356	0.079	4500	72	0.016	3.7	3.7	0.00	0.0	4.4	3.7	1.01	1.4	0.3
(3)	REPLACE W/EFFIC. CC BAL.	392	0.087	4500	36	0.008	9.7	0.00	0.0	10.0	9.7	1.38	3.8	2.8	3.8
(4)	REPLACE W/SS BAL.	329	0.073	4500	99	0.022	19.7	0.00	0.0	10.0	19.7	2.80	2.8	1.8	2.8
(5)	COMBO OF (2) & (4)	284	0.063	4500	144	0.032	23.4	0.34	2.4	10.0	25.8	3.67	2.6	1.5	2.3
(6)	T-8s W/SS BAL.	293	0.065	4500	135	0.030	24.1	0.49	3.4	0.0	27.5	3.92	2.9	1.8	2.5
BASE:	4 FLUOR. 40W, 2 CC BAL.	761	0.169	4500			19.7								
(7)	REPLACE W/34W LAMP	689	0.153	4500	72	0.016	7.5	0.00	0.0	4.4	7.5	2.01	2.8	1.7	1.5
(8)	REPLACE W/1 SS BAL.	558	0.124	4500	203	0.045	34.4	0.00	0.0	10.0	34.4	4.89	2.4	1.3	2.4
(9)	32W W/2 SS BAL.	608	0.135	4500	153	0.034	46.8	0.66	4.6	10.0	51.5	7.33	4.8	3.7	4.4
(10)	DELAMP W/REFLECTOR	396	0.088	4500	365	0.081	43.6	-0.30	-3.2	20.0	35.2	3.32	1.0	-0.0	1.7
(11)	COMBO OF (4) & (10)	290	0.064	4500	471	0.105	60.0	-0.30	-2.1	10.0	55.9	7.96	1.7	0.7	1.8

Table A.4. Economics parameters for end-of-life replacement, incremental retail prices @ 3000 hrs/yr

	A	Baseline Usage Ann. kWh B	Baseline Usage Peak kW C	Yrly Hrs of Use D	Annual Measure Savings kWh F	Annual Measure Savings kW G	Measure Cost Initial $ H	Measure Cost Maint. /yr $ I	PV $ J	Life-time Yrs K	Tot. PV Cost $ M	Avg. Ann. Cost $ N	Marg. Energy ¢ kWh P	CCEs w/Pk$ ¢ kWh Q	Pay back (7¢) Yrs R
BASE:	INCAND. CASE 75W BULB	225	0.075	3000			0.0								
(1)	REPLACE W/SL-18	54	0.018	3000	171	0.057	14.0	-4.00	-11.5	3.3	2.5	0.85	0.5	-1.1	1.2
BASE:	2 FLUOR. 40W, CC BAL.	285	0.095	3000			0.0								
(2)	REPLACE W/34W LAMP	237	0.079	3000	48	0.016	2.2	0.00	0.0	6.7	2.2	0.42	0.9	-0.7	0.7
(3)	REPLACE W/EFFIC. CC BAL.	261	0.087	3000	24	0.008	5.0	0.00	0.0	15.0	5.0	0.55	2.3	0.7	3.0
(4)	REPLACE W/SS BAL.	219	0.073	3000	66	0.022	20.0	0.00	0.0	15.0	20.0	2.20	3.3	1.7	4.3
(5)	COMBO OF (2) & (4)	189	0.063	3000	96	0.032	22.2	0.33	3.0	15.0	25.2	2.77	2.9	1.3	3.3
(6)	T-8s W/SS BAL.	195	0.065	3000	90	0.030	23.2	0.48	4.4	15.0	27.6	3.03	3.4	1.8	3.7
BASE:	4 FLUOR. 40W, 2 CC BAL.	507	0.169	3000			0.0								
(7)	REPLACE W/34W LAMP	459	0.153	3000	48	0.016	4.4	0.00	0.0	6.7	4.4	0.85	1.8	0.2	1.3
(8)	REPLACE W/1 SS BAL.	372	0.124	3000	135	0.045	37.0	0.00	0.0	15.0	37.0	4.06	3.0	1.4	3.9
(9)	32W W/2 SS BAL.	405	0.135	3000	102	0.034	44.4	0.66	6.0	15.0	50.4	5.53	5.4	3.8	6.2
(10)	DELAMP W/REFLECTOR	264	0.088	3000	243	0.081	65.0	-0.30	-3.7	30.0	61.3	4.94	2.0	0.4	3.8
(11)	COMBO OF (4) & (10)	193	0.064	3000	314	0.105	85.0	-0.30	-2.7	15.0	82.3	9.03	2.9	1.3	3.9

Table A.5. Economics parameters for end-of-life replacement, incremental wholesale prices @ 4500 hrs/yr (best case)

BASE:	INCAND. CASE 75W BULB	338	0.075	4500			0.00								
(1)	REPLACE W/SL-18	81	0.018	4500	204	0.057	9.34	-2.67	-5.3	2.2	4.0	2.01	1.0	-0.4	0.7
BASE:	2 FLUOR. 40W, CC BAL.	428	0.095	4500			0.00								
(2)	REPLACE W/34W LAMP	356	0.079	4500	72	0.016	1.47	0.00	0.0	4.4	1.5	0.40	0.5	-0.5	0.3
(3)	REPLACE W/EFFIC. CC BAL.	392	0.087	4500	36	0.008	3.34	0.00	0.0	10.0	3.3	0.47	1.3	0.3	1.3
(4)	REPLACE W/SS BAL.	329	0.073	4500	99	0.022	13.34	0.00	0.0	10.0	13.3	1.90	1.9	0.9	1.9
(5)	COMBO OF (2) & (4)	284	0.063	4500	144	0.032	14.81	0.34	2.4	10.0	17.2	2.45	1.7	0.6	1.5
(6)	T-8s W/SS BAL.	293	0.065	4500	135	0.030	15.47	0.49	3.4	10.0	18.9	2.69	2.0	0.9	1.6
BASE:	4 FLUOR. 40W, 2 CC BAL.	761	0.169	4500											
(7)	REPLACE W/34W LAMP	689	0.153	4500	72	0.016	2.93	0.00	0.0	4.4	2.9	0.79	1.1	0.0	0.6
(8)	REPLACE W/1 SS BAL.	558	0.124	4500	203	0.045	24.68	0.00	0.0	10.0	24.7	3.51	1.7	0.7	1.7
(9)	32W W/2 SS BAL.	608	0.135	4500	153	0.034	29.61	0.66	4.6	10.0	34.3	4.88	3.2	2.1	2.8
(10)	DELAMP W/REFLECTOR	396	0.088	4500	365	0.081	43.36	-0.30	-3.2	20.0	40.2	3.79	1.0	-0.0	1.7
(11)	COMBO OF (4) & (10)	288	0.064	4500	473	0.105	56.70	-0.30	-2.1	10.0	54.6	7.77	1.6	0.6	1.7

Table A.6. Lumen Output versus CCEs

	A	Effic. (lm/W) C	Rel-ative Effic. D	Light Output (lm) E	Rel-ative Light Output F	Fixture Data: Light Output (lm) H	Fixture Data: Effic. (lm/W) I	Fixture Data: Rel-ative Effic-acy J	3kHrs, Retail $ Marginal CCE Energy (¢ kWh)	3kHrs, Retail $ Marginal CCE w/Pk$ (¢ kWh)	3kHrs, Retail $ Pay Back (7¢ kWh) (Yrs)	4.5 kHrs, 33% off$ Marginal CCE Energy (¢/ kWh)	4.5 kHrs, 33% off$ Marginal CCE wPk$ (¢/ kWh)	4.5 kHrs, 33% off$ Pay Back (7¢ kWh) (Yrs)	3 kHrs, Retail $ Marginal CCE Energy (¢ kWh)	3 kHrs, Retail $ Marginal CCE w/Pk$ (¢ kWh)	3 kHrs, Retail $ Pay Back (7¢ kWh) (Yrs)	4.5 kHrs, 33% off Inc. $ Marginal CCE Energy (¢/ kWh)	4.5 kHrs, 33% off Inc. $ Marginal CCE w/Pk$ (¢/ kWh)	4.5 kHrs, 33% off Inc. $ Pay Back (7¢ kWh) (Yrs)
BASE:	INCAND. CASE 75W BLUB	16	1.00	1190	1.00															
(1)	REPLACE W/SL-18	61	3.81	1100	0.92				0.7	-0.9	1.3	0.5	-0.8	0.7	0.5	-1.1	1.2	1.0	-0.4	0.7
BASE:	2 FLUOR. 40W, CC BAL.	63	1.00	5990	1.00															
(2)	REPLACE W/34W LAMP	61	0.97	4790	0.80				2.2	0.6	1.7	1.4	0.6	0.7	0.9	-0.7	0.7	0.5	-0.5	0.3
(3)	REPLACE W/EFFIC. CC BAL.	69	1.10	6003	1.00				6.6	5.0	8.6	3.8	3.9	3.8	2.3	0.7	3.0	1.3	0.3	1.3
(4)	REPLACE W/SS BAL.	78	1.24	5694	0.95				4.9	3.3	6.4	2.8	2.2	2.8	3.3	1.7	4.3	1.9	0.9	1.9
(5)	COMBO OF (2) & (4)	79	1.25	4977	0.83				4.4	2.8	5.2	2.6	1.8	2.3	2.9	1.3	3.3	1.7	0.6	1.5
(6)	T-8s W/SS BAL.	90	1.43	5820	0.97				4.9	3.3	5.7	2.3	2.2	2.5	3.4	1.8	3.7	2.0	0.9	1.6
BASE:	4 FLUOR. 40W, 2 CC BAL.	55	1.00	9340	1.00	6070	36	1.00												
(7)	REPLACE w/34W LAMP	57	1.04	8710	0.93				4.5	2.9	3.3	2.8	1.7	1.5	1.8	0.2	1.3	1.1	0.0	0.6
(8)	REPLACE W/1 SS BAL.	78	1.42	9672	1.04				4.2	2.6	5.4	2.4	1.3	2.4	3.0	1.4	3.9	1.7	0.7	1.7
(9)	32W W/2 SS BAL.	86	1.56	11650	1.25				8.2	6.6	9.8	4.8	3.7	4.4	5.4	3.8	6.2	3.2	2.1	2.8
(10)	DELAMP W/REFLECTOR	59	1.07	5210	0.56	3960	45	1.25	2.0	0.4	3.8	1.0	0.0	1.7	2.0	0.4	3.8	1.0	-0.0	1.7
(11)	COMBO OF (4) & (10)	79	1.44	5060	0.54	3846	60	1.67	3.0	1.4	4.1	1.7	0.7	1.8	3.0	1.7	3.9	1.7	-0.6	1.7

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