## Title
MUTUAL IMPACTS OF LIGHTING CONTROLS AND DAYLIGHTING APPLICATIONS



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ABSTRACT

Several types of lighting control strategies, techniques, and equipment are examined with respect to cost and performance. Daylighting is found to require the use of sophisticated equipment that can provide more than this one control strategy. Simple control systems can reduce the lighting load by 12 to 50%; implementing four control strategies provides savings of 60 to 79%. The four control strategies are scheduling, tuning, lumen depreciation, and daylighting. The use of daylighting, properly integrated with electric lighting, makes economic sense and will be more commonly practiced in the future.

## 1.0 INTRODUCTION

There is a resurgence of interest in using daylighting to illuminate the interiors of buildings in order to improve their energy performance. The reduced operating costs for electric lighting are the primary economic justification for the added structural costs of daylighting. There are now progressive lighting designers who can improve a building's energy performance by the dynamic control of illumination. A lighting management industry is developing based on dynamic design concepts [1]. It focuses on the use of daylighting, which is one of four or five strategies that designers can use to justify economically the lighting equipment costs incurred to improve energy performance. This report examines several lighting control scenarios to explore the combined economic impacts of lighting controls and daylighting.

It is essential that daylighting schemes and lighting control systems be acceptable to end-users. That is, the illumination provided by daylight and electric lighting must facilitate occupants' required visual tasks, be comfortable, and be aesthetically pleasing. If architects and lighting designers do not fulfill these goals, the growth of daylighting will be stymied regardless of its economic advantages.

In recently designed buildings that are illuminated with daylight, both manual and automatic lighting management systems have been used [2,3]. The results of informal surveys were mixed; occupants were not predictably responsive to the wall switches, and some automatic systems were not properly integrated with the daylight. Excessively high window luminances, on-off switching techniques, and lighting levels well below the prescribed design levels tended to be unacceptable. In fact, where multi-level switching was used so that the electric lights were changed by 30% steps, some occupants found it distracting, although the illumination level was above the specified level.

When occupants responded negatively to the use of controls, the controls were overridden or disabled, and predicted reductions in electric lighting loads were not realized (4).

The above shortcomings are evidence that the electrical illumination of buildings has not been a high priority for architects. To assure good lighting practice, they must become more familiar with the performances of light sources, lighting systems, and traditional lighting control strategies and techniques. This is important because many lighting innovations have been introduced in the past few years.

The above observations of occupant responses provide one philosophical basis for a lighting control design that minimizes occupants' responses. A formal study has been made of the interaction between the lighting system and occupants via manual switches [4]. In multi-person office spaces, lights will be switched on when needed and rarely switched off until the space is completely empty, i.e., lights are generally switched on or off at the beginning or end of the day. In school classrooms and intermittently occupied rooms, on-off switching occurs throughout the day. This information indicates manual light switches can be used for some spaces, e.g., intermittently used spaces and one- or two-person rooms. These data provide another basis for choosing a lighting control system aimed at maximizing the interaction between lighting and occupants.

The lighting designer who has been designing static systems must become more familiar with the concept of dynamic lighting design. This concept includes the use of lighting control techniques and daylight. From the lighting designer's viewpoint, daylight is a complex light source. It varies in intensity, distribution, color, and quality throughout the minutes, days, and months. It creates high contrast and glare conditions that are not generally considered good lighting practice in office spaces. It is the lighting designer's responsibility to integrate the electric lighting system with this dynamic daylight source.

The Lighting Systems Research group at Lawrence Berkeley Laboratory, under contract to the Department of Energy, has gathered evidence from field tests to show that building energy performance can be improved by dynamic management of the lighting system [5-7]. Demonstrations have included field tests of solid-state fluorescent ballasts [8,9], which promise to be most effective components for integrating electric and natural illumination.

This paper briefly reviews the various available lighting control strategies, techniques, and equipment. It then considers six different scenarios, incorporating one or more control strategies, for the same sample building. Commercially available control equipment has been selected for each scenario. The relative cost-effectiveness of each scenario is determined given the cost for the equipment and the reduced operating cost for the electric lighting. Based on these results, the economic impact of combining electric lighting controls with daylighting is discussed.

## 2.0 CONTROL SYSTEMS AND STRATEGIES

Table 1 lists lighting control strategies and techniques and gives generic descriptions of presently available equipment. It is possible to use one or more techniques or types of equipment to implement each control strategy. Load-shedding is a viable lighting control strategy and can reduce cost but is not energy-saving and is not considered in this report.

### 2.1 Scheduling

The scheduling strategy illuminates spaces according to their occupancy. For predictable schedules (working hours, lunch periods, weekends, holidays, evening maintenance), lighting patterns and illumination levels may be programmed on a microprocessor or computer. For unpredictable schedules, the designer can specify spring-loaded switches, such as those that control heat lamps in motel-hotel bathrooms, or personnel sensors that switch the lights on-off depending on whether a space is occupied.

Because it uses a costly computer, the predictable scheduling strategy is most cost-effective with large banks of lamps, i.e., centrally controlled systems and relay-type switches. The unpredictable scheduling techniques are best applied in small, one-person areas with few lamps, where modular control is the most appropriate technique.

### 2.2 Tuning

The tuning strategy adjusts the light output of individual fixtures based on local lighting needs. Tuning reduces the light output of fixtures that illuminate aisles and other less visually critical task spaces. A simple way to apply this strategy is to use lamps or circuits that provide less light and can be used with standard magnetic ballasts, for instance phantom-tube, 35-watt "Watt-Saver" lamps, "Thriftmate" lamps, and front-end circuits (capacitor-resistors) that reduce lamp current. Tuning techniques also include delamping--removing one or two lamps from three- and four-lamp fixtures. Also available are solid-state ballasts having accessible resistive potentiometers that can be adjusted to control the light level of the lamps in each fixture. The solid-state ballast permits each fixture's light output to be adjusted continuously down to 10% of full light output, and is the optimum device for implementing the tuning strategy.

### 2.3 Lumen Depreciation

Due to the poisoning of a lamp's phosphors over time and the accumulation of dirt, the illumination of a space declines with time. During a two-year period, the decrease in light level can exceed 30%. Thus, the installed lighting must provide an initial illumination well above the specified level. When the illumination falls below the minimum acceptable level, the fixtures must be cleaned and relamped.

Systems employing a photocell that can detect the illumination level and control the light level continuously over at least a 20% range can respond to declining light levels. Centrally controlled systems are suitable; these depend on voltage- and phase-control equipment. Modular equipment, front-end current limiters, and solid-state ballasts are also suitable.

## 2.4 Daylighting

Where daylight illuminates an interior space through windows and/or skylights, the electrical illumination can be reduced corrrespondingly. In offices, schools, and other spaces where critical visual tasks are performed and disturbances must be minimized, we have found continuous dimming to be preferable to step or on-off techniques. In warehouses and spaces housing less visually critical activities, on-off, one-step dimming techniques may be adequate and more cost-effective.

Because of the dynamic characteristics of daylight illumination, centrally controlled systems cannot be used optimally in large spaces. Independent (modular) control of smaller spaces has been found to be more appropriate. Solid-state ballasts and front-end current limiters that respond to photocell feedback are most suitable to meet the above conditions.

# 3.0 RELATIVE ENERGY SAVINGS

There are few data on the energy savings realized in buildings that employ one or more lighting control strategies. Table 2 lists the energy savings used in this report for each lighting strategy. These values are based on the average values measured in lighting demonstrations [5-9] as well as those estimated in a previous paper (for tuning and lumen depreciation) where no measured values could be obtained [1].

The first row in the table lists the energy savings for each control strategy. The next rows give estimated energy savings for more than one strategy, based on the equipment employed. The second row describes the front-end current limiter. This equipment decreases the system efficacy by 5%. The other rows describe the effect of solid-state ballasts that operate lamps at high frequency; these increase system efficacy by 25% [10].

The bottom four rows apply to use of all four strategies; solid-state ballasts are employed throughout the space. Each row applies to a different building, which can be daylighted effectively throughout only a portion of the floor--10,30,60, or 100%. Thus, the energy savings from daylighting change proportionally.

Note that the total cumulative savings for the multiple strategies are not the arithmetic sums of each energy-saving contribution.

# 4.0 BUILDING CHARACTERISTICS

Several lighting control scenarios will be examined for a commercial office building having the characteristics listed in Table 3. The initial and maintained light levels, power density, and energy density were calculated based on four-lamp troffers (0.5 coefficient of utilization) with F40 T-12, rapid-start, cool-white fluorescent lamps operated with standard two-lamp F40, Certified Ballast Manufacturer (CBM) ballasts. These components were selected to provide the base-line performance of the lighting system because their characteristics (input power, light output) conform to those of the only ballast system for four-foot lamps that is specified by American National Standards Institute (ANSI C78.1, C82.1) and certified by CBM. The standard argon-filled F40 rapid-start lamp is also preferable to the energy-saving krypton-filled lamps in dimming applications because it can be dimmed over a wider dynamic range.

The annual use of 3500 hours is based on a pattern of 14 hours a day, 5 days a week, 50 weeks per year. A lower limit might assume 10 hours a day for an annual total of 2500 hours. The lower use pattern would increase the cited payback by a factor of 1.4.

The number of solid-state ballasts in the table is half the number of magnetic ballasts because four-lamp F40 ballasts are used.

## 5.0 CONTROL SCHEMES AND EQUIPMENT

### 5.1 Scenarios

Six lighting control scenarios will be considered; these are listed in Table 4. The first three use single strategies. The tuning strategy, for instance, is accomplished by substituting one light-reducing lamp in each two-lamp fixture. The light-reducing lamp reduces the light output of the other lamp. Both lamps show power and light output reduced by 50%. To calculate the average energy savings per square meter, several office layouts were measured. It was found that 24% of the floor space consisted of aisles and less visually critical areas; by reducing the light output of fixtures in these areas by 50%, an average energy savings of 12% was obtained.

The daylighting strategy is not considered separately because the most reasonable equipment available can also perform one or more of the other strategies. Therefore it was assessed based on the energy savings of all strategies.

The last scenario uses all four strategies (scheduling, tuning, lumen depreciation, and daylighting); the selected equipment combines the relay-microprocessor and solid-state ballasts.

### 5.2 Equipment Cost

The equipment cost per unit, per floor, and per square meter is given in Table 4. The procedures used to determine the equipment costs for scheduling and all four strategies were given in a previous paper

[1].

To implement tuning (based on visually non-critical space comprising 24% of the floor space), 144 light-reducing lamps were installed per floor. The lamp and installation cost is $8 per lamp.

To implement the lumen maintenance strategy, a voltage-control system was selected which can control all the lamps on the floor by varying the supply voltage to each ballast. The power and current that must be supplied to each floor is (600 x 96 watts ≡ 57.6 kW) and (600 x 0.36 amps = 216 amps). For a three-phase system the load is 73 amps per phase. The selected voltage controller was rated at 277 volt/76 kW/100 amp (per phase). One controller per floor was required at a list cost of $12,500.

The front-end current limiter is placed in front of each magnetic ballast. This device uses a fiberoptic cable to transport the sensed ambient light level to a photocell. In response to the sensed light level, the device alters the operating current to the ballast to provide a constant illumination level. One unit is required per ballast at a list price of $35 per unit. Because the photocell senses the ambient and electrical illumination, the lumen depreciation strategy is also provided. As indicated in Table 2, however, the device dissipates an additional 5 W at full light output, and reduces the intrinsic system efficacy by 5%.

The solid-state ballast selected can operate four F40 lamps and will soon be available at a premium cost of $70 per ballast. The premium cost is the additional cost above the cost of two standard CBM core-coil ballasts. When used for daylighting, photocells are remotely positioned; only slight additional cost is required for the low-voltage wiring. The additional cost is estimated to be $11 per ballast. The total premium cost for a four-lamp solid-state ballast is $81. The photocell system also accomplishes the lumen depreciation strategy. These ballasts have a resistive potentiometer that enables the electric light level to be tuned, as discussed in section 2. Thus, these solid-state ballasts can provide three lighting strategies. In addition, the ballast-lamp system operated at high frequency with solid-state ballasts is intrinsically 25% more efficient than the standard F40 two-lamp ballast system [10].

For the scenario using all strategies, the cost of the relay-microprocessor system ($13 per ballast) is added to the cost of the solid-state system ($81 per ballast) for a total equipment cost of $94 per ballast.

### 5.3 Total Cost

#### 5.3.1 Simple Payback

Table 5 compiles the total cost of equipment per square meter for each scenario and the annual energy savings per square meter ($\$/m^2$) based on the conditions listed in tables 2 and 3. For example, the scheduling strategy reduces energy costs by 26%. The base energy density is 107.6 kWh/$m^2$; at an energy cost of \$0.10 per kWh, the annual saving is \$2.80/$m^2$. The simple payback period (initial cost divided by annual savings), is 0.74 years. For an annual use of 3500 hours, the payback is one year.

Except for the lumen depreciation strategy, provided by the supply voltage control system, the simple paybacks for all of the scenarios are attractive and within industry's acceptable decision criterion of two to three years [1]. When all strategies are employed, the payback depends on the relative area that can be daylighted. If 60% or more of the building can be daylighted, the simple payback period is less than two years.

#### 5.3.2 Discounted Costs

There is another method for comparing the relative cost-effectiveness of the scenarios. A more precise payback period can be determined by including the cost of financing the capital investment. The scenarios can be assessed by calculating the total savings based on the life of the equipment. In Table 6 the payback period and total savings (for up to 20 years) are listed for each scenario. These estimates are conservative because only the cost of capital is considered, and energy costs are assumed constant. Also, there is no allowance for interest gained on the return of capital after the equipment payback period.

The payback period increases when we include the cost of capital. The different equipment costs for the four-strategy scenario reflect the cost of financing for a longer period of time. In the long term, if one uses the energy savings to pay the equipment costs and totals the net return after 5, 10, 15, and 20 years, the most advantageous investments tend to be the ones that save the most energy.

## 6.0 IMPACTS

### 6.1 Lighting Controls

#### 6.1.1 Retrofit

In retrofits, the daylighting strategy will have little impact on the choice of lighting control system. Single control strategies that can be centrally applied and that require minimum wiring outside the electric closet will be the most attractive. This includes the scheduling strategy, with an on-off microprocessor, and the tuning strategy, in which the fixtures can be delamped or refitted with lamps having a lower light output. A voltage-reducing system that provides the lumen depreciation strategy gives a return too low to justify its expense.

#### 6.1.2 Renovations

For lighting renovations, where decision-makers are committed to replacing the entire lighting system, the applicability of the daylighting strategy will depend on the existing fenestration. This strategy could be considered for favorably positioned buildings that have large window areas. For example, the PG&E building in San Francisco has large windows and enclosed outer offices that are 3.7 m deep. Each floor is 30 m x 61 m (1830 $m^2$) in total area, and 33% (602 $m^2$) of this floor space is perimeter office space that can be daylighted. Based on costs and the shortest payback (Table 5), the scheduling strategy would be appropriate for the entire floor, with solid-state ballasts in the outer offices. After 20 years this would yield a total return of (54 x 100%) + (140 x 33%) = $100.2/$m^2$, (see Table 6).

6.1.3 New Construction

The daylighting strategy will have the greatest impact on the selection of controls for new buildings, especially those designed to exploit natural illumination. There are designs in which the daylighted space exceeds 50% [2,3]. For percentages above 50%, the total return is most attractive for equipment that can provide all four control strategies.

In our previous paper, estimates of the potential lighting controls market ranged from $1 to $4 billion by the year 2000 [1]. The lower estimate assumed that all new buildings would employ the simple control strategy, and the higher estimate was obtained by assuming the general use of solid-state ballasts and microprocessors that could perform all four strategies. The evidence in this report indicates that use of equipment that can provide multiple strategies makes most economic sense when one of the strategies is daylighting. In addition, only when daylighting can be used throughout a large portion of a floor does it make sense to install sophisticated equipment throughout the floor. Construction of well-daylighted buildings will foster the use of multiple control strategies and help produce the $4 billion controls market.

## 6.2 Daylighting Techniques

Office environments where critical visual tasks are performed require continuous dimming systems that control small areas. The equipment that meets the above criteria can also provide one or more lighting control strategies. Therefore, architects proposing building designs that exploit daylight can include in their economic justification the total savings in electric lighting energy for all the lighting strategies the equipment can employ. Based on the data in Table 2, the average energy savings for the entire space will range from 60 to 79%, rather than the 5 to 50% calculated by considering only daylighting. These greater savings can provide the incentive for daylighting techniques to become standard building design practice.

## 7.0 CONCLUSIONS

Daylighting is a major energy-saving lighting control strategy. In new buildings, the use of natural illumination to supplement electric lights for a large portion of floorspace will be a major incentive to select sophisticated control equipment.

Lighting control equipment that best integrates the electric lighting system with natural illumination can be used to perform additional lighting control strategies.

The use of sophisticated lighting controls in well-designed daylighted buildings can reduce the building's electric lighting load 60 to 79%, as compared to 12 to 26% from simpler controls dedicated to one control strategy (with no daylighting). The use of daylighting techniques makes economic sense and will become general practice if electrical and natural illumination are properly integrated.

## 8.0 ACKNOWLEDGEMENT

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# CONTROL SYSTEMS

| | |
|---|---|
| Control Strategies | Scheduling, Tuning, Daylighting, Lumen Depreciation, Load-Shedding |
| Control Techniques | Light Level (on-off, step, continuous)<br>Dynamic (manual, automatic)<br>Sensing (light, occupancy)<br>Area-Based (central, modular) |
| Control Equipment | Relays, Voltage Control, Phase Control, Solid-State Ballasts, Front-End Current Limiters, Clocks, Microprocessors, Computers, Photocells, Infrared, Ultrasonic, Phantom Tubes, F35 Lamps, Thrift-Mate Lamps, Delamping |

TABLE 1.

Lighting control strategies, techniques, and equipment.

# RELATIVE ENERGY SAVINGS OF SINGLE AND MULTIPLE CONTROL STRATEGIES

| Description | Strategy | | | | Equipment Energy Savings (%) | Cumulative Savings (%) |
|---|---|---|---|---|---|---|
| | Scheduling (%) | Lumen Depreciation (%) | Tuning (%) | Daylighting (%) | | |
| Single Strategy | 26 | 14 | 12 | 50 | 0 | |
| Two Strategies with Front-End Limiter | | 14 | | 50 | -5 | 55 |
| Three Strategies with Solid-State Ballasts in Daylit Area | | 14 | 12 | 50 | 25 | 72 |
| Four Strategies with Solid-State Ballasts throughout the Space: | | | | | | |
| floor 10% daylit | 26 | 14 | 12 | 5 | 25 | 60 |
| floor 30% daylit | 26 | 14 | 12 | 15 | 25 | 64 |
| floor 60% daylit | 26 | 14 | 12 | 30 | 25 | 71 |
| floor 100% daylit | 26 | 14 | 12 | 50 | 25 | 79 |

TABLE 2.

Energy savings from individual lighting control strategies and cumulative totals for several combinations.

# BUILDING CHARACTERISTICS

| | |
|---|---|
| Floor Area | 1830 $m^2$ (61 m × 30 m) |
| No. of Floors | 40 |
| Light Level | |
| Maintained | 750 lux (70 fc) |
| Initial | 1010 lux (94 fc) |
| No. of Fixtures per Floor | 300 |
| No. of Ballasts per Floor | 600 2-lamp ballasts *or* 300 4-lamp ballasts |
| No. of Lamps per Floor | 1200 |
| Annual Use | 3500 hours |
| Power Density | 30.8 $W/m^2$ (2.86 $W/ft^2$) |
| Annual Energy Density | 107.6 $kWh/m^2$ (10 $kWh/ft^2$) (34 $MBtu/ft^2/yr$) |
| Energy Cost | $0.10/kWh |

TABLE 3.

Characteristics of sample office building considered for the various lighting control scenarios.

# CONTROL SCHEMES AND EQUIPMENT COSTS

| Scenario | Equipment | Equipment Cost ($) | Equipment Cost per floor ($) | Equipment Cost per m² ($) |
|---|---|---|---|---|
| Scheduling | Relays, Transceivers, Microprocessor | Reference 3 | 3860 | 2.08 |
| Tuning | Lamp Change — 144 lamps per floor | 8 per tube | 1152 | 0.62 |
| Lumen Depreciation | Voltage Controller rated 277V/100A/67kW — one per floor | 12,500 | 12,500 | 6.73 |
| Lumen Depreciation, Daylighting | Front-End Current Limiter — one per ballast | 35 | 21,000 | 11.30 |
| Lumen Depreciation Tuning, Daylighting | Solid-State Ballast — one per fixture + Photocells | 81 | 24,300 | 13.08 |
| All Strategies | Relays-Microprocessor + Solid-State Ballasts | 94 | 28,170 | 15.18 |

TABLE 4.

Various control scenarios and types of equipment used to apply each strategy. The cost of equipment per floor and per square meter is listed.

## SIMPLE COSTS AND SAVINGS OF CONTROLS

| Strategy | Equipment Used | Cost ($1/m²) | | Payback Period (Yr.) |
|---|---|---|---|---|
| | | Equip. | Annual Savings | |
| Scheduling | Relay - Microprocessor | 2.08 | 2.80 | 0.74 |
| Tuning | Lamp Change | 0.62 | 1.29 | 0.48 |
| Lumen Depreciation | Voltage Amplitude Control | 6.73 | 1.51 | 4.46 |
| Lumen Depreciation, Daylighting | Front-End Current Limiter | 11.30 | 6.35 | 1.78 |
| Lumen Depreciation, Tuning, Day-lighting | Solid-State Ballasts | 13.02 | 7.75 | 1.68 |
| ALL STRATEGIES 10% Daylit | Relay - Microprocessor/ Solid-State Ballasts | 15.18 | 6.46 | 2.35 |
| 30% Daylit | | 15.18 | 6.89 | 2.20 |
| 60% Daylit | | 15.18 | 7.64 | 1.99 |
| 100% Daylit | | 15.18 | 8.50 | 1.78 |

TABLE 5.

Simple payback periods for the various lighting control scenarios.

## COSTS AND SAVINGS OF CONTROLS

| Strategy | Equip. Cost* ($1/m²) | Payback Period (Yr.) | TOTAL SAVINGS ($1/m²) | | | |
|---|---|---|---|---|---|---|
| | | | 5 Yrs. | 10 Yrs. | 15 Yrs. | 20 Yrs. |
| Scheduling | 2.26 | 0.81 | 12 | 26 | 40 | 54 |
| Tuning | 0.71 | 0.55 | 6 | 12 | 19 | 25 |
| Lumen Depreciation | 9.36 | 6.20 | (−2) | 6 | 13 | 21 |
| Lumen Depreciation, Daylighting | 13.02 | 2.16 | 19 | 50 | 82 | 114 |
| Lumen Depreciation, Tuning, Day-lighting | 14.96 | 1.93 | 24 | 63 | 101 | 140 |
| ALL STRATEGIES | | | | | | |
| 10% Daylit | 18.19 | 2.82 | 14 | 46 | 79 | 111 |
| 30% Daylit | 18.08 | 2.62 | 16 | 51 | 85 | 120 |
| 60% Daylit | 17.87 | 2.33 | 20 | 59 | 97 | 135 |
| 100% Daylit | 17.55 | 2.07 | 25 | 67 | 110 | 153 |

*The present worth of equipment at 10% interest rate.

TABLE 6.

Net return on each lighting control scenario considering a 10% rate of interest and a 20-year life of equipment.

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