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LIGHTING CONTROLS: SURVEY OF MARKET POTENTIAL†

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Abstract—This study describes the impact of lighting management systems that dynamically control lights in accordance with the needs of occupants. Various control strategies are described: scheduling, tuning, lumen depreciation, and daylighting. From initial experimental results, the energy savings provided by each of the above strategies are estimated to be 26, 12, 14, and 15%, respectively.

Based upon a cost of $0.05–0.10 per kWh for electric energy and a 2-, 3-, or 4-yr payback, target costs for a simple and a sophisticated lighting management system are found to be $0.24 and 1.89 per ft^2, respectively, for a cost-effective investment.

A growth model, based upon an extrapolation of the increase in building stock since 1975, indicates that the commercial and industrial (C & I) building stock will grow from 40×10^9 ft^2 in 1980 to about 67×10^9 ft^2 by the year 2000. Even with the use of more efficient lighting components, the energy required for this additional C & I stock will be 307×10^9 kWh compared to the 230×10^9 kWh used today. Adopting controls would reduce this requirement to 243×10^9 kWh, an increase of only 13×10^9 kWh above current use.

The specified information is used to analyze the economic impacts that using these systems will have on the lighting industry, end users, utility companies, and the nation's economy. A $\$1–4 \times 10^9$ annual lighting control industry can be generated, creating many jobs. The estimated return on investment (ROI) for controls for end users would be between 19 and 38%. Utilities will be able to make smaller additions to capacity and invest less captial at 7–10% ROI. Finally, the annual energy savings, up to $\$3.4 \times 10^9$ for end users and about $\$5 \times 10^9$ for utilities, representing unneeded generating capacity, will be available to capitalize other areas of our economy.

1. INTRODUCTION

This paper has been prepared to describe the need and the evidence for a future large lighting control industry and to provide a basis for estimating its size. Data are presented to describe the participants (manufacturers, designers, architects, distributors, and building operators and owners), the present stock of buildings, and projections of the growth of the building stock. Based upon the above, the impact of this new industry upon end users, utilities, and the nation's energy consumption is projected.

The small size of the present lighting control market (estimated to be less than $\$100 \times 10^6$) is due to the prevailing lighting design philosophy. Nearly all existing commercial and industrial buildings installed lighting systems based upon minimizing initial costs. Operating costs were ignored (although they generally exceed initial costs) due to the traditionally low cost of electrical energy. Furthermore, those who constructed a building were generally not the eventual owners; the builders did not consider that effective energy management would add to the value of the building. Thus, lighting controls in a building usually consist of a few manual switches that are centrally located on each floor and that operate large banks of lamps.

The present lighting control industry is a specialty industry that meets the demands of spaces that require dimmable lights (e.g., theaters, hotels, conference rooms, and ballrooms) or that represent an added luxury (e.g., executive offices and boardrooms). Many control systems are designed for incandescent lamps, which are simple to control but are inefficient light sources. Some control systems are available that can switch and dim gas-discharge lamps, but at a cost of about $2–4 per ft^2, or about $100–200 per fixture.

The soaring cost of electrical energy since 1970 has begun to impact the philosophy of lighting design. The lighting industry is introducing more efficient lighting components and systems, which cost more initially but have a lower total cost (operating plus initial). That is, end users are basing their purchasing decisions on the payback period, the return of investment (ROI), or the life-cycle cost. The continued use of these decision techniques should create a

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demand for cost-effective lighting management systems. When such a demand emerges, industry will move to satisfy it.

The market for this energy-conserving lighting product is unique because it is not a replacement product but represents a virgin market that provides a growth opportunity for the lighting industry.

The Department of Energy (DOE) has an interest in supporting the development of this new industry. Its growth can impact the nation's annual consumption of energy used for lighting ($\sim 450 \times 10^9$ kWh), while still providing the illumination to maintain productivity. This will reduce future requirements for electrical generating capacity, providing capital for other needs. To this end, DOE supported two major demonstrations of lighting control systems, one at the Pacific Gas and Electric (PG & E) office building in San Francisco, and another at the Port Authority of New York and New Jersey's World Trade Center in New York City. The systems were installed on one entire floor at each site to measure the energy savings from various control strategies and techniques. Honeywell Inc., and the General Electric Company were subcontracted to supply the control hardware. In addition to supplying the controls, each subcontractor submitted reports examining the industrial and commercial lighting market. The information presented in this report represents, in part, a review of their contributions as well as information gathered and analyzed by the Lawrence Berkeley Laboratory (LBL) staff.

The study consists of five sections. Section 2 contains general information about the building industry and lighting. It discusses the major buying influences, lighting use patterns, and barriers to introducing control systems into the marketplace. Section 3 describes advanced control strategies and estimates the energy savings they can provide. Based upon these energy savings, a range of target costs for control systems is determined assuming different decision criteria. In Section 4 future floorspace is estimated using two growth models. Considering the growth of floorspace and assuming a cost-effective price for control systems, the potential lighting control market is determined. Section 5 analyzes the impact of control systems upon the lighting industry, utilities, and national energy consumption. The final section summarizes the report.

2. ASPECTS OF MARKET PENETRATION

2.1 *Lighting use patterns*

Table 1 shows the estimated average lighting use patterns for buildings in the commercial sector. The values for the average efficiencies of light sources have been calculated by weighing frequency of use and the efficacy of the light sources used in various building types. The frequency of use has been determined from sales data. Values for power density are calculated in the relation below, assuming 0.50 to be an average coefficient of utilization (CU) for the fixtures:

$$\text{power density (W/ft}^2\text{)} = \frac{\text{light level (lumens/ft}^2\text{)}}{\text{CU} \times \text{source efficacy (lumens/W)}}. \tag{2.1}$$

The light level in lumens/ft^2 is equivalent to footcandles. The final column, energy density, is a

Table 1. Lighting energy use in various commercial building types.

Building type	Estimated lighting level (footcandles)	Source efficiency (lumens/W)	Power density (W/ft^2)	Annual operating hours	Annual lighting energy use (kWh/ft^2)
Stores	90	44	4.1	4500	18.5
Offices	70	54	2.6	3500	9.1
Public buildings	70	54	2.6	3500	9.1
School classrooms	70	44	3.2	2000	6.4
Educational labs	100	44	4.5	2000	9.0
Warehouses	30	54	1.1	3000	3.3

metric of particular interest for control systems because it considers the time of use as well as the power density of a lighting system.

A survey of building owners, contractors, and spokesmen for utilities and trade organizations in 10 major U.S. cities provided the following general lighting patterns for commercial buildings.

(i) Lighting is 30–50% of the electrical load in typical commercial buildings. (ii) In 1974 the average connected load of lamps in commercial buildings was 2.85 W/ft^2. (iii) Most U.S. commercial buildings have light levels between 100 and 150 footcandles, although newer buildings and energy-efficient older buildings typically have 75–100 footcandles. (iv) Nearly all the lighting for commercial applications is fluorescent, with the 2 × 4 ft fixture dominating. (v) More than half of all fluorescent lighting is operated at 277 V; the trend is toward 277 V. The other major supply voltage is 120 V. (vi) There are about 1.75×10^9 fluorescent ballasts in place in the commercial sector. In 1979, about 67×10^6 new ballasts were shipped. (vii) The cost of labor to replace an existing ballast is between \$6.30 and 9.52. (viii) Most wiring for lighting has been installed in large-block, minimum-wire-run patterns without regard to light-level zoning. In some newer buildings and progressive states, lighting wiring now includes switches for local light control. (ix) Group relamping is not commonly practiced. (x) Nearly all U.S. utilities charge their commercial customers a demand and consumption rate. (xi) It is estimated that in the next decade commercial electric utility rates will increase 10% faster than inflation.

Table 2 lists the lighting use patterns in three types of industrial buildings. The estimates of average lighting levels and source efficiencies have been obtained in the same manner as for Table 1.

Table 2. Lighting energy use in various industrial building types.

Building type	Estimated lighting level (footcandles)	Source efficiency (lumens/W)	Power density (W/ft^2)	Annual operating hours	Annual lighting energy use (kWh/ft^2)
Manufacturing plants	75	52	2.9	3500	10.2
Industrial labs	100	52	3.8	3450	13.1
Industrial warehouses	40	52	1.6	2500	4.0

2.2 *Buying influences in the construction market*

When a new building is being designed and built, a potential buyer/owner can turn to several sources for information and recommendations. Figure 1 shows the participants who influence the decision-making process and illustrates their relationship to the owner.

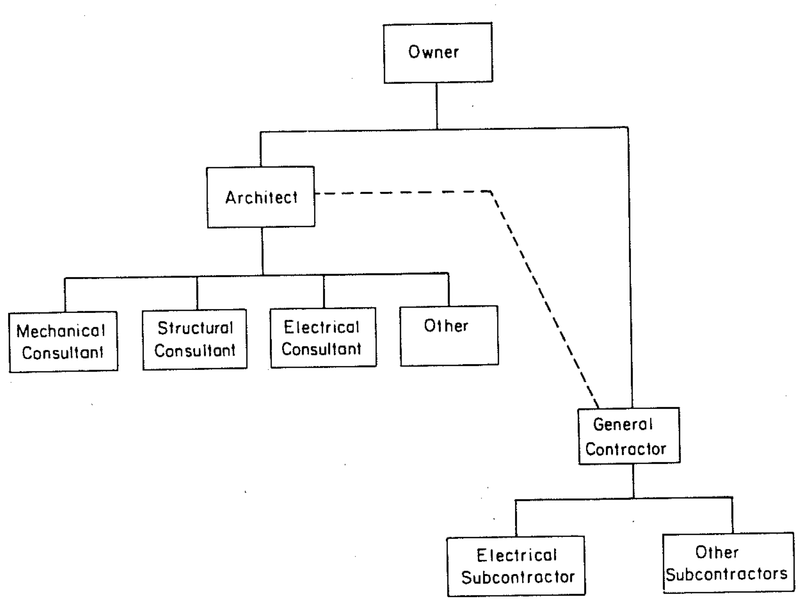

Fig. 1. Hierarchy of buying influences in the construction market.

In retrofit installations the roles of architect and electrical consultant are supplanted by an energy or facilities manager. These individuals are not specialists and lack the expertise to perform a completely effective job of application engineering. Therefore, in retrofit applications there is greater need for the electrical subcontractor or manufacturer to provide engineering services. Manufacturers with large service organizations supply this need; they sell the engineering as well as the hardware in what is called a turn-key job.

For lighting controls to effect a major penetration of the market, marketing efforts should be directed primarily at the individual with the greatest influence—i.e., the building owner, who controls project funding. Although this "top-down" marketing effort should be effective, such an effort will be expensive because building owners are a diverse group. A similar problem exists for controls manufacturers attempting to reach building tenants for retrofit orders.

Until a mature market for controls is developed, we would not expect most consultants to actively promote lighting controls. Consultants are concerned primarily with the design of a building and less with the long-range operating costs. Consequently, there is little financial incentive for consultants to promote energy-conserving lighting controls. Also, some consultants are overwhelmed with the complexities of modern building systems; lighting controls represent an additional building component with attendant questions of specification, engineering, and installation. Consultants will be receptive to using lighting controls if they are easy to install and if manufacturers assure the consultants that they involve no risk.

2.3 *Market survey*

A limited survey of 50 building owners and tenants was conducted to assess the marketability of lighting control systems, payback criteria, and influences on product selection. All regions of the country—Northeast, Midwest, South, and West—were represented. More than 50% of the respondents, however, were concentrated in the Northeast. No attempt was made to break down the data regionally. A summary of the results appears in Table 3.

Table 3. Summary of responses from owners and tenants.

Buy factors	Respondent percentage
Building size	
— Less than 50×10^3 ft^2	0%
— Greater than 50×10^3 ft^2	100%
Awareness of automated or semi-automated lighting control system	
— Has reviewed a lighting control system	10%
— Has heard of lighting control systems	40%
— Unaware of lighting control systems	50%
What would your payback criterion be for a lighting control system?	
— 2 years or less	80%
— 2 to 3 years	18%
— more than 3 years	2%
System service (after installation)	
— System should provide capability to be serviced in-house	40%
— Service contract	30%
— No response	30%

Specifying and selecting influences	Respondent percentage
Who specifies lighting systems applications?	
— Consultant/engineer	60%
— Owner	20%
— Electrical contractor	--
— Don't know	20%
Who selects lighting systems equipment?	
— Consultant/engineer	10%
— Owner	40%
— Electrical contractor	40%
— Don't know	10%
Purchase decision influenced by	
— Single manufacturer of all components	60%
— System components from several manufacturers	20%
— No perference	20%

2.4 *Barriers to market penetration*

The previous sections were presented to provide a basic understanding of the lighting market and of the complexity of purchasing and marketing new lighting products: no single person or department is solely responsible for their purchase.

A major barrier to the adaptation of centralized lighting control systems is that reduced operating costs are not considered an asset. Thus, if the original builder/owner does not intend to operate the building, he will not incur initial costs in order to reduce operating costs. The same reluctance will prevail if an operating owner passes energy costs to the tenants.

The mode of operation of a building is important. If the tenant pays the utilities, there is little incentive for the building operator to invest in energy-efficient practices. If the operators/owners can cost-effectively reduce their operating costs while maintaining income, they will invest in energy-efficient products that realize a good return.

The separation between the knowledge of lighting systems, the specification of the system, and the final selection is also a significant barrier. In regard to Table 3, note that 50% of the owners are unaware of lighting controls and another 40% are just aware of them, yet the owner makes the decision about their use. The consultant who is knowledgeable about these new products specifies the system but does not select the equipment. This lack of overall responsibility means that all participants hesitate to recommend new concepts. The owner is reluctant to spend extra funds on items he does not understand; the consultant's judgement is questioned if he specifies a technique and then the contractor purchases an inadequate system. This division of decision-making and split responsibility tends to support the use of traditionally accepted techniques.

The general purchasing criterion for a payback of two years or less (see Table 3) is a stringent requirement for a large-cost product at its initial introduction. A payback of two years or less is equivalent to a 50% or greater return on capital investment. Because a lighting control system will have a life of 20–30 yr, a life-cycle cost analysis would be a more realistic method for assessing its cost-effectiveness.

The lack of federal and/or state energy-saving tax incentives is another barrier to the use of these systems. In determining the decision criteria (payback period, return on investment, life-cycle costing), any gains (profits) that are realized will be taxed at a rate of 50%. This lowers the net return on investment.

Many current federal and state lighting codes give no credit for the use of lighting management systems. The connected load (W/ft^2) is used as the standard that a lighting system must meet. This is satisfactory for static lighting systems. The dynamic lighting capability offered by control systems may require a higher connected load to be optimally effective. However, by virtue of the dynamic control, less energy will be used, and the computer is programmed to limit the load in use at any time to meet government regulation. Thus, regulations that are based on connected load without providing for the use of control systems are another barrier to these products.

3. TARGET COSTS FOR CONTROL SYSTEMS

3.1 *Control strategies and their energy savings*

To estimate the energy savings of a lighting control system, we will consider the four control strategies listed in Table 4. The table also includes the type of control required and the response time of each system. For example, in order to use tuning, which provides a semipermanent lighting pattern that can be changed occasionally when the visual task or room

Table 4. Lighting control strategies.

Strategy	System performance	Response period
Scheduling	Central	Hourly
Lumen maintenance	Central	Monthly
Tuning	Modular	Occasional
Daylighting	Modular	Immediate

arrangement is altered, the system must have modular control (local independent control of one or a few fixtures).

Load-shedding is one strategy not considered in this report because it does not reduce energy use. However, it will reduce high demand charges and offers an additional monetary savings.

3.1.1 *Scheduling.* A control system can provide the necessary patterns of lighting in time to respond to the scheduled activities of a space. A typical office schedule might be: lights on at 7:00 a.m.; dim lamps for lunch from 12:00 p.m. to 1:00 p.m.; turn off lamps at 8:00 p.m. (leaving some stumble lighting); and in the evening provide one-third light levels for the cleaning crew. On weekends and holidays the lights are off all day. These systems must provide a suitable override for unscheduled activities.

Most workers (about 83%) work from 8:00 a.m. to 5:00 p.m. Their lighting needs can be supplied from 7:30 a.m. to 5:30 p.m., 10 hr per day. Neglecting holidays, this amounts to 2600 hr annually (10 hr per day, 5 days a week, 52 weeks per year). The lighting use patterns described in Section 2.1 showed that the average annual operating time in offices is 3500 hr. Scheduling could save 26% of that lighting. This is a conservative estimate because our experience in monitoring demonstrations involving manual lighting controls documents that the lights often are accidentally left on all night. Thus actual usage exceeds 3500 hr annually.

3.1.2 *Lumen depreciation.* Lighting systems are designed to maintain a particular level of illumination. Because of lumen depreciation, lighting systems must initially provide illumination in excess of the specified level. These recoverable light-loss factors include lamp lumen depreciation (the decreases in light output of lamps with operating time) and dirt lumen depreciation (the accumulation of dust on walls and fixtures, which decreases transmission and reflection of light from the source). They are designated recoverable light-loss factors because the initial illumination level can be recovered by washing the fixtures and walls and by relamping.

A continuously dimmable lighting system can provide a constant illumination level. A control system linked to a photocell that senses the illumination level can dim the lamps to the design level. As the lamps age and dirt accumulates, more power is applied to the lamps to maintain the required light level. When the lumen depreciation becomes too severe to compensate for, it is time to clean and relamp the area. This technique provides an incentive to maintain the lighting system: aged lamps and dirt accumulation require more power (consume more energy) and cost more to operate than a newly lamped, clean area. Thus, scheduled maintenance will lower operating costs. A static, dedicated lighting system cannot compensate for these recoverable light-loss factors.

In a previous paper, an estimate was made of the initial light levels for a room with a 2.3 room/cavity ratio, using open, semidirect luminaires category II[1] and a 2-yr maintenance period.[2] For a standard ballasted, dimmable lighting system the energy savings were determined to be 14%.

3.1.3 *Tuning.* After a lighting system is installed and the arrangement of the space is finalized, the lighting system can be "tuned" to the space if the light level from each fixture can be independently controlled. For example, the lamps can be dimmed above aisles and less visually critical work spaces. In areas where critical visual tasks are performed, light levels can be increased. Thus, the proper light can be provided throughout the space to maintain productivity and optimize energy use. The significance of this strategy is that when subsequent changes are made in floor arrangements, the illumination can be readily altered to accommodate them at virtually no cost.

Centralized control systems that operate large banks of lamps cannot employ tuning, so other means must be used to "tune" such a lighting system—delamping, low-output lamps, etc. However, these limit the range one can dim and incur added cost for the additional inventory of lighting products that must be maintained. Solid-state ballasts are available that permit each fixture's light level to be set over a wide range, enabling the optimum employment of this strategy.

It is difficult to estimate average energy savings. We have used the office layouts at the PG & E building and the World Trade Center to determine the amount of aisle space where the light level could be reduced by 50%. The aisle space in these demonstrations amounted to 24% of the total area; thus, the average savings for an entire floor from tuning the lights above the aisles is estimated at 12% (50 × 24%). This is a conservative estimate because illumination levels can also be lowered in work spaces designed for less visually critical tasks (reception areas, etc.).

3.1.4 *Daylighting*. In the perimeter area of a building, part of the required illumination can be supplied by natural daylight. In order to exploit this illumination one must be able to dim the electrical lights in proportion to the amount of available daylight. A dimmable lighting control system can respond to daylight by using a photocell that senses light levels. The design objective for such a system is to maintain the prescribed light level at all times. This daylighting strategy can greatly reduce the energy consumption of an electrical lighting system.

The energy savings that can be realized from daylighting in buildings depends upon many factors—climatic conditions. building form and design, and the activities within the building. Interest in the use of daylighting is just emerging, and there is little documented research in this field. The Civil Engineering Laboratory at Port Hueneme, California, has measured the energy reduction in a well-daylit office in Los Angeles, reporting a 70% reduction in energy consumption.[3] Considering the climatic conditions of other selected cities, they estimate a range in savings from a low of 57% in Indianapolis to a high of 70% in Los Angeles. Based upon the above and projected savings by others,[4,5] we will assume an average energy savings of 50% in those areas of a building that can employ daylighting.

Only a portion of a building can be daylit, however 30% of the floorspace for a building 10^4 ft^2 is sufficiently near the perimeter to be daylit; thus, the average energy savings from daylighting for an entire building that can save 50% in the daylit area will be (50 × 30%), or 15%.

3.1.5 *Summary of energy savings*. The total energy savings for a control system that can use one or some combination of the above strategies is listed in Table 5. Notice that total accumulated energy savings is not the arithmetic sum of the strategies.

The energy savings listed in Table 5 are based upon limited experimental data. Thus, we have attempted to use the most conservative values. The lack of sufficient data is precisely the reason we are carrying out the two switching and control demonstrations.

3.2 *Decision criteria*

Traditionally, first costs have been used to determine whether to purchase a lighting component or system that meets design specifications. Standard procedures required purchasing agents to obtain at least three bids for a set of specifications. If the lowest bid was not accepted, a detailed justification was required.

Because of the increased cost of energy, current criteria for purchase include the operating cost of the equipment. Analytical methods are used to determine and compare the payback, ROI, or life-cycle cost of different lighting products and techniques. Each of these methods considers initial cost, operating costs, and the rate of interest. Life-cycle costing also includes the life and salvage value of the equipment. Industries base their decisions on the payback period, which is inversely proportional to the ROI. From our market survey (Table 3), the

Table 5. Cumulative energy savings for one or more control strategies.

	I	I,II	I,II,III	I,IV	I,II,III,IV	II,III	II,IV	I,III
I Scheduling	26	26	26	26	26	-	-	26
II Lumen depreciation	14	14	14	-	14	14	14	-
III Tuning	12	-	12	-	12	12	-	12
IV Daylighting	15	-	-	15	15	-	15	-
Total	-	36	44	37	52	24	27	35

acceptable payback time is two years, which is equivalent to a 50% return on investment. This high rate of return describes an attractive investment and stringent guideline for many new products. Some building owners employ 3-yr payback periods[6] because lighting control systems have long lives. Federal agencies are required to base their decisions on a life-cycle cost analysis.

The use of paybacks and life-cycle costing are mandatory for purchasing decisions regarding retrofits. When one is replacing a functional lighting system with a system that will reduce operating costs, the only rationale for purchase is the reduced energy cost.

3.3 *Target costs for lighting systems*

One objective of this paper is to estimate an effective cost (equipment plus installation) an end user could be expected to pay for a lighting control system. The analysis will be based upon the control strategies the system can provide (scheduling, lumen depreciation, tuning, daylighting) and the energy savings that will be realized from each strategy or combination of strategies. The target cost of the system will be described in dollars per square foot. We will employ a simple payback analysis using the relation:

$$\text{payback period (yr)} = \frac{\text{initial investment (\$)}}{\text{annual savings (\$/yr)}}. \tag{3.1}$$

The number of lighting control strategies that can be employed depends upon the complexity of the control system. We will determine the effective total cost (equipment plus installation) of systems having different degrees of capability. Using the data listed in Tables 1 and 2 for annual energy consumption and in Table 5 for percent energy savings, we will calculate the annual energy savings for an energy cost of \$0.05 and 0.10 per kWh. A decision criteria of a 2-, 3-, or 4-yr payback period will be used.

3.3.1 *Scheduling.* This strategy requires the simplest control system and could consist of a clock and relays to turn large segments of lamps off or on. Such a system could be installed in the electric closet so that there would be virtually no difference in cost between new construction or a retrofit. In an office using 9.1 kWh/ft^2/yr annually,

$$\text{annual savings (\$/ft}^2) = \text{annual energy use (kWh/ft}^2\text{/yr)} \times \%\ \text{savings} \times \text{energy cost (\$/kWh)}, \tag{3.2}$$

which is \$0.118/ft^2 at \$0.05/kWh. The acceptable total cost of a system for a 3-yr payback is \$0.354/ft^2.

3.3.2 *Scheduling, lumen depreciation, and daylighting.* This control system is more complex than the first because the equipment must respond both to a photocell that senses the ambient light level and to a time clock. For the conditions used above, the annual savings for the three strategies is \$0.187/ft^2. The total cost of this system for a 3-yr payback is \$0.560/ft^2.

Table 6. Total cost of control system.

Strategy	Energy cost (\$/ft^2)					
	\$0.05/kWh			\$0.10/kWh		
	Payback (years)			Payback (years)		
	2	3	4	2	3	4
Sch	0.236	0.354	0.472	0.472	0.708	0.946
Sch, LD	0.328	0.491	0.655	0.656	0.982	1.310
Sch, LD, D	0.373	0.560	0.746	0.746	1.119	1.492
Sch, LD, D, T	0.473	0.710	0.946	0.946	1.420	1.893

Sch = Scheduling
LD = Lumen depreciation
D = Daylighting
T = Tuning

This type of control system is less costly in new construction than for retrofits because it entails considerable rewiring in the ceiling; new dimming ballasts or relays and photocells must be installed in the workspace.

3.3.3 *Scheduling, lumen depreciation, daylighting, and tuning.* The addition of the tuning strategy requires the capability of controlling each fixture. Each fixture can be controlled by using solid-state ballasts that enable light levels to be set by a potentiometer in the ballast. For the same general conditions as above, the annual savings is \$0.237/ft^2. For a 3-yr payback period, the total cost is \$0.710/ft^2.

As with the previous system, the payback period for new construction will be less than for a retrofit because installation of this system will require considerable rewiring.

Table 6 summarizes the results for 2-, 3-, and 4-yr payback periods and for energy costs of \$0.05 and 0.10 per kWh for four combinations of strategies.

4. POTENTIAL CONTROLS MARKET

4.1 *Building market structures*

4.1.1 *Commercial building stock.* The total square footage of in-place commercial building stock is listed in Table 7. The total area is broken down into the nine major categories of the commercial sector. Office space, retail stores, and educational buildings account for more than 50% of the total space.

The total commercial building space is plotted as a function of time in Fig. 2. The curve represents the net growth of commercial stock. Between 1960 and 1975 the rate of growth has been large and constant.

4.1.2 *Commercial growth potential.* The total in-place commercial floor stock given in Table 7 extends to 1975. We have extended this curve to 1978 by using gross construction data from the *Statistical Abstract of the United States.*[7] In order to employ the above data on yearly additions, we amended the values by considering a yearly stock removal rate of 1.1%. The above estimate of the growth rate between 1978 and 1983 is slightly less than the preceding five years, 680×10^6 ft^2 per yr vs 800×10^6 ft^2 per yr.

In 1978 Oak Ridge National Laboratory (ORNL) developed a model for predicting the growth of commercial stock.[8] This model estimates future commercial construction based on population data and per capita income. The model predicts that the average growth rate of in-place commercial buildings will be 4.3% annually through the year 2000. Considering a stock removal rate of 1.1%, total annual additions will be 5.4%.

The authors estimated an average growth rate by extrapolating the data between 1975 and

Table 7. In-place commercial building stock (10^6 ft^2).

Year	Office	Retail/ wholesale	Garage	Warehouse	Educational	Public	Hospital	Religious	Hotel/ motel	Miscellaneous	Total commercial
1925					2,136	273	531	450		782	7,640
1930					2,312	321	599	501		883	8,678
1935					2,282	384	608	494		889	8,662
1940	(††)	(††)	(††)	(††)	2,387	447	652	502		1,071	9,114
1945					2,406	488	732	506		1,498	9,957
1950					2,683	512	888	594		1,681	11,123
1955					3,359	585	1,028	795		2,049	13,071
1960					4,203	720	1,175	972	(†)	2,368	15,801
1965	2,851	3,163	375	1,381	5,049	870	1,413	1,185	1,273	2,650	20,269
1966	2,957	3,328	404	1,953	5,258	899	1,462	1,221	1,293	2,718	21,023
1967	3,037	3,496	433	1,526	5,961	928	1,516	1,254	1,313	2,782	21,777
1968	3,164	3,676	466	1,605	5,659	959	1,574	1,204	1,337	2,853	22,602
1969	3,313	3,891	501	1,700	5,833	985	1,648	1,306	1,306	1,306	2,936
1970	3,452	4,084	531	1,784	5,985	1,002	1,705	1,324	1,369	3,000	24,252
1971	3,614	4,278	554	1,869	6,126	1,034	1,771	1,339	1,378	3,071	25,061
1972	3,769	4,535	583	1,982	6,239	1,062	1,840	1,356	1,407	3,236	25,934
1973	3,940	4,837	601	2,114	6,339	1,100	1,900	1,372	1,425	3,225	26,883
1974	4,088	5,088	690	2,224	6,766	1,134	1,962	1,388	1,445	3,311	27,745
1975	4,180	5,241	618	2,291	6,564	1,168	2,010	1,405	1,468	3,383	28,328

†The figures prior to 1960 do not include hotel/motel floorspace.
††In-place stock estimates for these building types not available prior to 1965.

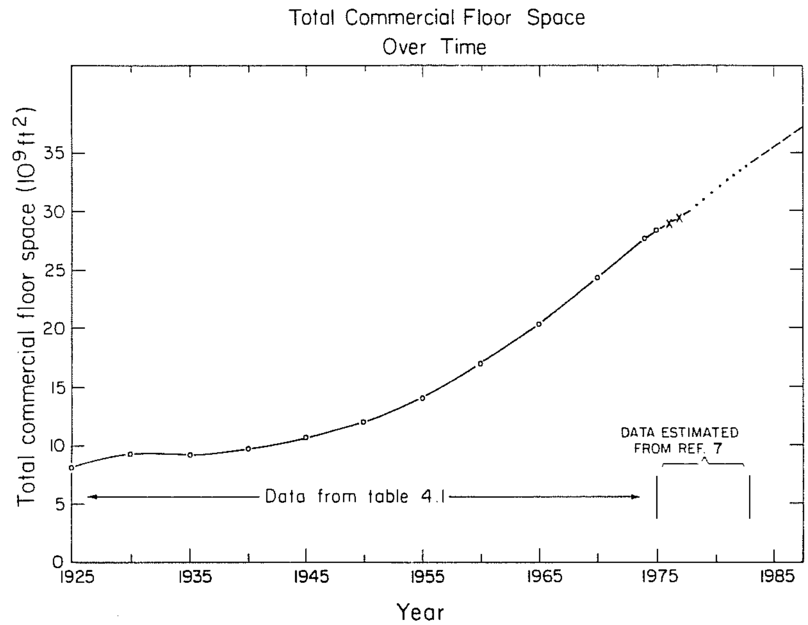

Fig. 2. Total commercial floor space over time.

1980 (2.3% annually) to the year 2000. Taking into account the 1.1% stock removal rate, yearly additions occur at a rate of 3.4%.

The ORNL model was amended;[8] Table 8 lists the results of a computer run of their model made in May 1979.

Figure 3 shows these estimates of growth rates from 1980 to the year 2000. By the years 1990, 1995, and 2000, the building stock added since 1980 will be 30–43, 43–59, and 54–72% of the total in-place stock, respectively. The annual additional floorspace for those three years is projected to be between 1.33 and 2.53×10^9 ft^2. The ORNL growth model as amended in 1979 predicts a considerably smaller growth rate and is slightly greater than the simple projections used by the authors.

4.1.3 *Industrial building stock.* Data on industrial floorspace are quite scarce. Discussions with realtors lead us to conclude that the in-place stock of industrial buildings in 1980 was about 8.2×10^9 ft^2 (estimate from T. Dale of Coldwell-Banker).[9] This estimate includes industrial warehouses as well as manufacturing floorspace.

Annual construction of manufacturing buildings appears closely correlated with the business cycle. Physical volume declined 50% between the growth year of 1973 and the recession of 1975. Additions to manufacturing buildings were probably about 200×10^9 ft^2 in 1979 and 1980.

There are few available data on the growth potential for industrial buildings during the next 15 yr. However, because growth of building space in a given sector is at least roughly correlated with the number of employees in that sector, the potential for growth in industrial buildings is probably much less than for commercial buildings. This conclusion is based on the fact that between 1948 and 1977 the number of workers employed in the manufacture of goods has only slowly increased, from 15.5×10^6 workers in 1948 to 19.1×10^6 in 1977.[10] This amounts to an average annual increase of only 0.72% between 1948 and 1977.

If the trend in manufacturing employment which began in 1948 continues throughout the next 15 yr, the net increase in industrial floorspace will average no more than 1% annually through 1995. Based on this assumption, the in-place inventory of industrial buildings will be no more than 9.5×10^9 ft^2 by 1995. Figure 4 plots this growth rate.

4.2 *Estimated market*

By combining target costs and predictions of new building stock, we can estimate a lighting controls market. The low estimate is based upon the use of a simple energy management system (scheduling strategy), which has a target cost of \$0.236/ft^2. If the investments during the 14

Table 8. ORNL commercial energy use simulation, 1970–2000: summary of energy-demand forecast.

Stock including additional total floorspace (10^6 ft^2).

	1970	1975	1980	1985	1990	1995	2000
Retail/wholesale	3,972	4,579	5,625	6,677	7,774	9,000	10,290
Office	3,266	3,956	5,272	6,658	8,179	10,010	12,031
Auto repair	485	511	535	566	596	621	645
Warehouse	1,782	2,117	2,732	3,368	4,052	4,852	5,718
Educational	5,983	6,581	7,470	8,356	9,240	10,140	11,048
Health	1,697	1,881	2,161	2,440	2,720	3,010	3,305
Public buildings	1,004	1,051	1,095	1,150	1,204	1,247	1,291
Religious	1,337	1,456	1,625	1,795	1,963	2,130	2,297
Hotel/motel	1,371	1,539	1,805	2,070	2,340	2,626	2,920
Miscellaneous	2,999	3,428	4,157	4,883	5,632	6,462	7,327
Total	23,896	27,100	32,476	37,961	43,700	50,099	56,872

Annual additions to floorspace (10^6 ft^2).

	1970	1975	1980	1985	1990	1995	2000
Retail/wholesale	195.1	120.6	258.0	265.5	284.1	324.8	358.2
Office	181.0	120.8	312.9	332.3	369.1	447.7	507.9
Auto repair	27.4	9.3	10.0	12.1	13.3	13.9	16.1
Warehouse	93.0	61.4	147.8	154.7	169.0	200.1	224.2
Educational	195.0	136.3	238.0	252.3	273.0	303.6	335.9
Health	75.0	42.1	76.1	80.7	86.4	94.1	101.5
Public buildings	29.0	20.6	22.6	26.3	27.8	28.1	31.7
Religious	27.0	29.0	47.2	50.9	55.8	62.1	69.0
Hotel/motel	47.0	40.6	73.0	75.2	78.8	85.7	92.4
Miscellaneous	89.0	89.6	191.3	202.5	217.2	241.3	256.3
Total	958.4	670.2	1376.9	1452.5	1574.5	1801.4	1993.1

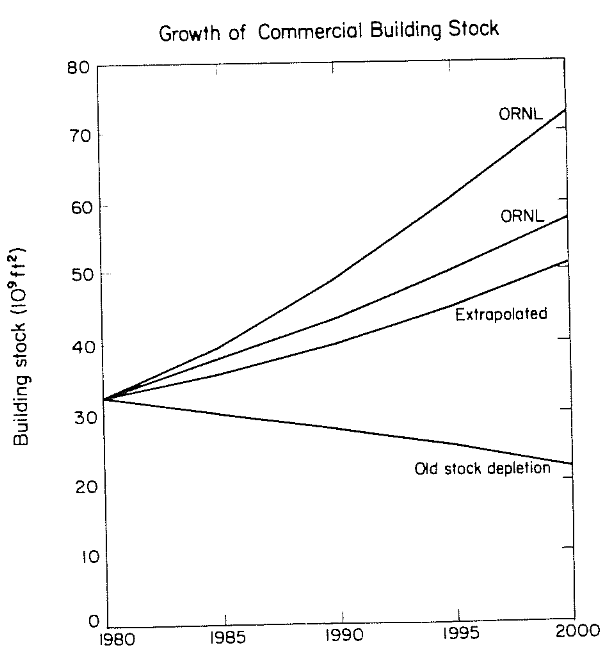

Fig. 3. Growth of commercial building stock.

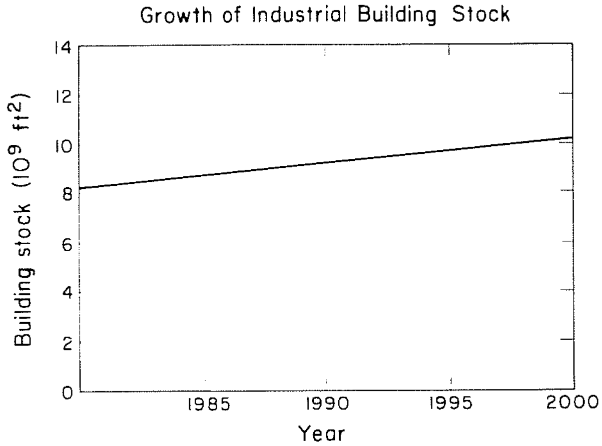

Fig. 4. Growth of industrial building stock.

years between 1986 and the year 2000 are in simple lighting management systems, the total market will be $\$5.2 \times 10^9$. In the year 2000, 4.5×10^9 ft^2 will be added and the annual market will be $\$1.1 \times 10^9$.

To estimate an upper limit we assume that all new systems will employ all four control strategies. At an energy cost of \$0.10/kWh, the target cost is \$0.946/ft^2. For the same new building stock (22×10^9 ft^2), the total market from 1986 to the year 2000 will be $\$21 \times 10^9$. In the year 2000 the annual market will be $\$4.2 \times 10^9$ (4.5 Bft^2 × \$0.946/ft^2).

The range determined above, a total market between \$5.2 and 20×10^9 and an annual market in the year 2000 of \$1.1 to 4.2×10^9, is based upon 100% penetration of control systems by the year 1986. While this may appear optimistic, the object of this paper is to estimate the potential market and its subsequent impact. We believe that a market in the above range can be realized because we did not include the potential sale of controls in the retrofit market. For example, in 1990 there will be more than 25×10^9 ft^2 of old building stock that will be candidate for a lighting management system.

5. ENERGY IMPACT

In the previous sections, information was presented on energy management systems, control strategies, and their relative energy savings. From these data the total cost of a system was determined based upon an energy cost of \$0.05–0.10 per kWh and a payback criteria of 2, 3, or 4 yr. Based upon the growth of floorspace in the industrial and commercial sectors, a potential controls market was calculated. In this section the energy impact of the lighting controls will be assessed. Table 9 shows the mix of floorspace in the year 2000 for buildings built after 1986.

5.1 *No-control scenario*

In the United States, approx. 450×10^9 kWh of electrical energy are consumed annually for lighting. Fifty-one per cent of this energy (230×10^9 kWh) is used in the indoor commercial and industrial (C & I) sector. Current C & I floorspace is estimated to be 40×10^9 ft^2 and has an average annual energy density of 5.8 kWh/ft^2. Average building usage is 2500 hr a year, from which one obtains the average installed power density of 2.32 W/ft^2.

Several of the energy-efficient lighting products on the market, such as energy-efficient core-coil ballasts and energy-saving fluorescent lamps, are based upon improvements made to

Table 9. Commercial and industrial floorspace mix in the year 2000 for buildings built after 1986.

Stock	Extrapolated model (10^9 ft^2)	ORNL model (10^9 ft^2)
New	29.1	35.7
Old	31.3	31.3
Total	60.4	67.0

old technologies. In addition, the Illuminating Engineering Society has reduced the recommended light levels for many visual tasks.[11] The above techniques save 9, 6, and 30% in lighting energy, respectively. The accumulated saving of all three is 40%. The incorporation of the above into new lighting systems will reduce a building's energy density and power density for lighting to 3.5 kWh/ft^2 and 1.4 W/ft^2, respectively. The particular products have been cited because they are on the market today; more efficient lighting systems using new technologies will be available in the mid-1980s.

The projected energy usage in the C & I sectors in the year 2000 will be between 284 and 307×10^9 kWh using the extrapolated or the ORNL growth model (60.5 or 67.0×10^9 ft^2). The above values are calculated using the lower energy density for new construction and 5.8 kWh for existing buildings.

5.2 *Use of energy management systems*

5.2.1 *Scheduling.* If all buildings constructed after 1986 employed the scheduling strategy, the energy consumed in the C & I sector would be reduced by 26% (see Table 5). The average energy density and power density of the new buildings would become 2.6 kWh/ft^2 and 1.0 W/ft^2, respectively. The total annual energy usage in the C & I sector would be between 258 and 275×10^9 kWh. The annual savings, at $0.10 per kWh, would be between $2.6 and 3.2×10^9. The above range is obtained by using the two building growth models.

The investment to install this control equipment in all buildings that are built after 1986, at $0.236/ft^2 (see Table 6 for a 2-yr payback), is between $6.9 and 8.4×10^9, for an annual investment of $0.5 to 0.6×10^9.

5.2.2 *All strategies.* If all buildings constructed after 1986 employed all four strategies—daylighting, scheduling, tuning, and lumen depreciation—the average reduction in energy would be 52% (see Table 5). In the year 2000 the energy density of these new buildings would be 1.7 kWh/ft^2 (3.5 kWh × 0.49). The average power density for a usage of 2500 hr is 0.7 W/ft^2. The energy use of the new building stock would be 49 or 61×10^9 kWh, for the extrapolated and ORNL models respectively. If these are added to the old stock, 31.3×10^9 ft^2 at 5.8 kWh/ft^2 (182×10^9 kWh), total energy consumption for C & I would be 231 to 243×10^9 kWh. The net energy reduction from the no-control scenario is 53 to 64×10^9 kWh annually. The annual savings at $0.10/kWh is between $5.3 and 6.4×10^9 annually.

The necessary total investment for employing these systems at $0.946/ft^2 (see Table 6) is $27.5 to 33.8×10^9, or a capital investment of $1.9 to 2.4×10^9 annually.

5.2.3 *Total cost of energy management system.* The arguments presented in the previous sections have been based upon a 100% market penetration, which assumes the manufactured price can meet the end user's purchasing criteria. Because the controls market is expected to be elastic, the rate of total market penetration depends upon the manufacturers' ability to produce controls below the limiting criteria. To provide some evidence that the cost of the lighting management systems can be expected to be below the limiting criteria (determined from the price of energy and a 2-, 3-, or 4-yr payback period), two examples of control installations will be described. The systems from which the prices were obtained are available today.

5.2.3.1 *Scheduling system.* One cost we wish to determine is the total cost of an energy management system based on the scheduling strategy. The characteristics of an example building are listed in Table 10.

A programmable control system is available which can send a prescribed schedule of lighting patterns to transceivers and can operate relays that switch groups of lamps on and off. The example system consists of a microprocessor with a memory capacity for 500 transceivers. Each transceiver can control 32 relays operating at 20 A.

The installed control system will employ 30 relays and one transceiver per floor. The entire building (40 floors) will require 1200 relays and 40 transceivers. To function as the central control system (with memory), one programmable microprocessor will be required for the 40 transceivers. Table 11 gives the estimated cost of the system.

5.2.3.2 *All strategies.* A control system for all strategies—scheduling, lumen depreciation, tuning, and daylighting—might consist of the above programmable control system with the addition of dimmable solid-state ballasts. Branches of lamps can be switched on or off according to a prescribed schedule; a photocell signals each ballast, varying the light output to

Table 10. Office building statistics.

Characteristic	Description
Floors	40
Floor area	200 ft × 100 ft (20,000 ft^2)
Lighting power density	2.6 W/ft^2
Light output	3150 lumens/lamp
Lamp type	F40 rapid-start, cool white
Ballast loss (core-coil CBM ballast)	8 W/ballast/lamp
Fixture	4 lamps/fixture
Coefficient of utilization (fixture)	0.50
Maintenance factor	0.75
Maintenance illumination	70 footcandles
Initial illumination	94 footcandles
Number of fixtures per floor	300
Number of ballasts per floor	600
Number of lamps per floor	1200
Supply voltage	277 volts
Current per ballast	0.34 amps
Power factor	0.92

Table 11. Total control costs.

	Equipment	
	Unit	Total
Microprocessor	$10,000	$10,000
40 transceivers	2,000	80,000
1200 relays	7.00	8,400
Total		$98,400

	Installation		
	Man-hours		Cost
	Each	Total	@$25/hr
Microprocessor	40 hr	40 hr	$ 1,000
40 transceivers	40 hr	1600 hr	40,000
1200 relays	0.5 hr	600 hr	15,000
Total			$56,000

Total cost	$154,400
Floorspace	800,000 ft^2
Cost per square foot	$0.193

maintain a constant illumination (lumen depreciation and daylighting strategies). The dimmable solid-state ballasts also have potentiometers (variable resistors) that can be used to manually adjust the light output of each lamp (tuning strategy). Thus, this energy management system consists of the central control system plus dimmable solid-state ballasts with photocells to monitor illumination levels. This example will employ 4-lamp solid-state ballasts at $90 per ballast. Each floor will require 40 photocells. The photocell control system requires 18-V d.c. power supplies and an electrical isolator for each ballast. There is an additional $5 per fixture cost for wiring each ballast in a fixture with the low-voltage wire from the photocell. There is no additional installation cost because the cost of installing a solid-state ballast is the same as that

Table 12. Total cost of control systems for all strategies.

	Unit	Total
Central control system		$154,400
12,000 solid-state ballasts	$70	840,000
1600 photocells	4	6,400
12,000 fixture wiring	5	60,000
400 DC supplies	10	4,000
12,000 isolators	5	60,000
		$1,124,800

Total cost	$1,124,800
Floorspace	800,000 ft^2
Cost per square foot	$1.406

for a core-coil ballast. That is, the solid-state ballasts will be installed at the factory by the fixture manufacturer. We will assume that energy-efficient 2-lamp, 40-W, core-coil ballasts made by a Certified Ballast Manufacturer (CBM) cost $10 each; thus, the premium cost for a 4-lamp solid-state ballast is $70. The total cost for this lighting management system is itemized in Table 12. The payback is less than calculated because we have not included the intrinsic 15% energy reduction achieved by using the solid-state ballasts[2] (solid-state ballasts are 25% more efficient than standard coil-core ballasts and 15% more efficient than the energy-efficient type).

5.2.4 *Summary of use of control systems.* This section argues that the use of lighting management systems will reduce national electrical energy consumption. For an estimated increase in floorspace of 151% (from 40 to $60.5 \times 10^9\,ft^2$), energy use will increase 123% (from 230 to 284×10^9 kWh). The impact upon energy is greater than the above projection indicates because we have not included the impact that reducing the lighting load has upon the HVAC load of a building. The importance of adopting lighting management systems is evidenced by the resulting financial benefits (see Sections 5.2.1 and 5.2.2). For an annual investment of \$0.5 to 1.9×10^9 in equipment, an annual energy saving of \$2.6 to 3.3×10^9 would be realized in the year 2000. The \$0.5 to 1.9×10^9 of investments represents real growth in the lighting industry (unit products, money, and jobs). The net savings in energy costs, minus equipment costs, is between \$2.1 and 3.4×10^9, representing capital that is available for investment in industrial growth.

Forecasting market penetration is a complex task. To provide confidence that lighting management systems will be employed in newly constructed buildings, we have determined the total cost of a control system for a large office building (Section 5.2.3). Based upon the target cost of control equipment that will be a sound investment (Table 5) and a 2- to 4-yr payback, we have shown that equipment available today can provide the scheduling strategy at a cost of $0.193/ft^2. This is well below the acceptable decision criteria of $0.236/ft^2 based upon a cost of energy of $0.05/kWh and a 2-yr payback period. The more sophisticated system, which employs all four control strategies, presently is limited to regions in which energy cost is $0.10/kWh and to end users who are willing to base investments on 3-yr paybacks.

Thus, there are energy management systems available today that could meet a payback criteria considered acceptable by some segment of the market at energy prices of $0.05–0.10 per kWh. By 1986 the costs of lighting products will be less (especially the solid-state ballast, which now accounts for the primary cost of the sophisticated system). In addition, the cost of electrical energy is expected to increase faster than the inflation rate, These factors will make these capital investments more attractive than estimated in this study, and are evidence that we can reasonably expect a near 100% penetration of controls in new buildings.

5.3 *Utilities*

In 1980 the connected load for lighting in the C & I sector was 93×10^9 kWh ($2.32\,W/ft^2 \times 40\,Bft^2$). Table 13 lists the connected load for the C & I sector for the extrapolated and ORNL estimates of in-place building stock in the year 2000. New building stock consists of buildings constructed after 1986. Table 13 shows that if no controls are used in new construction, the connected load for lighting in the C & I sector will increase by 30×10^9 W (30 gW).

Table 13. Total connected C & I building load (10^9 W).

Current		Year 200					
		No controls		Simple controls		Sophisticated controls	
		ORNL	Extrapolated	ORNL	Extrapolated	ORNL	Extrapolated
New		50.0	40.7	35.7	29.1	25.0	20.4
Old	92.8	72.6	72.6	72.6	72.6	72.6	72.6
Total	92.8	122.6	113.3	108.3	101.7	97.6	93.2

If no controls are used, utilities will have to increase their present capacity of 700 gW by 4.3%. A generating plant costs about \$3/W to build. Thus, utilities will have to expend about \$61.5 to 89.4×10^9 by the year 2000 to provide this new capacity, or an average annual investment (from 1986) of \$4.4 to 6.3×10^9. If only the simple control system is employed, 8.9–15.5 more gW will be required at \$26.7–46.5×10^9, for an average annual investment of \$1.9–3.3×10^9. If the sophisticated control system is used, 0.4–4.8 gW (at \$1.2–14.4×10^9) will be required, for an average annual investment of \$0.09–1.03×10^9. Thus, the use of lighting control systems could save utilities approx. \$4 to 5×10^9 annually in the year 2000. This is \$4–5×10^9 utilities would otherwise have to spend building generating capacity.

5.4 *Summary of impacts*

Table 14 summarizes the conclusions of this chapter and lists the energy saved under each scenario and the costs for controls to realize this energy savings. The various investments required by utilities to meet the projected commercial and industrial building load in the year 2000 are given.

From the above data, the return on investment has been determined for the end user, (B) ROI, and for the utilities based upon need since 1986 and with respect to the no-control scenario, (A) ROI. Each of the above ROIs is determined by summing the annual investment for 14 yr (1986–2000) and dividing into the return realized in the year 2000.

Table 14. Impacts in the year 2000.

Parameter	1980	2000		
		No controls	Simple controls	Sophisticated controls
Energy use (10^9 kWh)	230.0	284 - 307	258 - 275	231 - 243
Energy density (kWh/ft^2)	5.8	3.5	2.6	1.7
Power density (W/ft^2)	2.32	1.4	1.0	0.7
Increased energy cost (10^9 \$) @ \$0.10 per kWh		5.4 - 7.7	2.8 - 4.5	0.1 - 1.3
Decrease in energy cost by use of controls (10^9 \$)		-	2.6 - 3.2	5.3 - 6.4
Annual investment in controls (10^9 \$)		-	0.5 - 0.6	1.9 - 2.4
Connected load (10^9 W)	92.9	113 - 123	102 - 108	93 - 98
Total utility investment (10^9 \$) @ \$3 per W		62 - 89	27 - 47	1.2 - 14
Added connected load (10^9 W)		21 - 30	9 - 16	0.4 - 5.0
Average annual added load (10^9 W)		1.5 - 2.1	0.6 - 1.1	0.03 - 0.3
Average annual investment (10^9 \$)		4.5 - 6.3	1.8 - 3.3	0.09 - 0.9
Annual increased load (10^9 W)		1.5 - 1.8	0.6 - 0.8	-
Annual increased load (10^9 \$)		4.5 - 5.4	1.8 - 2.4	-
(A) Return on investment at year 2000 (%)		8.7	10.3 - 9.6	8.3 - 9.3
Total capital saved (by utilities) by use of controls (10^9 \$)			34.8 - 42.9	60.3 - 75.0
Annual energy saved (year 2000) by use of controls (10^9 \$)			2.6 - 3.2	5.3 - 6.4
Annual investment in controls (10^9 \$)			0.5 - 0.6	1.9 - 2.4
Annual reduced utility investments (10^9 \$)			2.7 - 3.0	4.5 - 5.4
(B) ROI of end users (%)			37 - 38	20 - 19

All of the ROIs for the utilities are between 8.7 and 10.3%. In the case of the ROI for the three scenarios, (A) ROI in Table 14, the adaptation of controls would minimize the need for new power plants, resulting in a low ROI. For end users, investing in controls would result in an attractive ROI (19–38%) by the year 2000.

6. SUMMARY

Information on various aspects of lighting management systems has been presented to reveal the energy savings of various control techniques, the barriers that inhibit their introduction, potential impacts on utilities, and the effect on our national energy consumption.

The major barriers that inhibit use of advanced control systems are the nature of the construction industry, the split responsibility for the recommendation and the purchase of control systems, and the fact that low operating costs are not considered a contribution to a building's value.

A credible data base is being compiled to substantiate the energy savings that can be realized by the use of one or more control strategies. A conservative estimate based upon some early measurements shows cumulative energy savings between 30 and 50%. Using this estimate, typical energy costs ($0.05–0.10 per kWh), and standard acceptable payback periods (2–4 yr), we have determined the target cost for an energy management system ($0.236–1.893 per ft^2) that should significantly penetrate the marketplace.

Two examples are presented for the cost of installing a lighting management system in a large building; one system employs a single control strategy, while the second system employs all four major strategies. The cost of the systems is $0.193/$ft^2$ and 1.406/ft^2, respectively. Even at today's costs these are both cost-effective conservation strategies.

Finally, the investment of capital in the development of lighting management systems can lead to a $1.1–4.2 $\times 10^9$ annual market by 2000 and will increase employment in the lighting industry. It will reduce the need for utilities to make large capital investments that have unattractive returns on investment (8.3–10.3%) compared to the ROI realized by the end user. The savings for both the utilities and end users represent capital that can be invested in other sectors of our economy.

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