Technical Approach

General Framework

Lighting energy requirements depend on the amount of floorspace lighted, the duration of lighting use, the illumination level, and the efficiency of lighting equipment in using energy to produce light. Thus, the analysis presented here focuses on four key components of indoor lighting energy consumption[1]:

1. **Floorspace**: the amount of floorspace lighted, broken down by type of equipment serving the space. (Floorspace is derived from CBECS only.)

2. **Hours**: the number of hours per week lighting is used. This measure is not just the reported operating hours, but also incorporates the lighting used during off-hours. (Hours are derived from CBECS only.)

3. **Illuminance:** the technical measure of how strongly lighted the space is. (Illuminance is obtained from the engineering literature, based on CBECS building activity.)

4. **Efficacy**: an energy efficiency measure. Technically, the amount of light produced per unit of energy consumed. (Efficacy is obtained from the engineering literature, based on CBECS lighting equipment categories.)

Statistics are presented on combinations, as well as on each factor individually. The principal combinations considered are:

- **Floorspace-Hours**: a measure of the total lighting service needed, in terms of duration and area of service. Together with the lighting power density, this determines the energy requirement.

- **Lighting Power Density**: the lighting energy requirement per square foot (during periods when the lighting is in use).

- **Lighting End-Use Intensity (EUI)**: the lighting energy requirement per unit of floorspace. The EUI is derived from the duration of use, illumination level, and equipment rating.

No data source completely specifies the four key components for each portion of commercial floorspace. However, the CBECS provides national estimates for closely related factors. The approach adopted here is to use these related factors as a basis for assigning assumed values for the unknown factors.

The assignments are made at the individual building level. Thus, various lighting-related quantities are derived for each building in the CBECS data set. Statistics on these derived quantities are presented, by principal building activity, by building size, by construction year, and by Census region. In addition, floorspace within each building is allocated among the different types of lighting equipment, so that lighting statistics are given also by equipment type. The statistics presented include both national aggregates, such as total floorspace, power, and energy use, and floorspace-weighted averages. Appendix A, "Methodology for Computing Aggregates and Averages," describes the computational procedures. Appendix D, "Motivation and Computation of Lighting Measures," gives the details of specific computations.

[1]Attention is restricted to indoor lighting, because the CBECS collects no data on the type, extent, presence, or use of outdoor lighting equipment. Some energy for outdoor lighting is included in the CBECS estimate of electricity consumption, to the extent that outdoor lighting is included in the electricity bills associated with CBECS buildings.

Formal Specification:
The end-use intensity (EUI) can be expressed as the product of the illumination level (brightness), the hours of lighting, and the amount of energy required per unit of illumination. Multiplying the **EUI** by the floorspace served gives the total lighting energy use for that floorspace. Summing over all floorspace gives total commercial lighting energy consumption.

Thus, the quantities of interest for this analysis are the illuminance **I**, the hours **H** of lighting use, the efficacy **Q** of the lighting equipment, and the floorspace **S** served by each combination of equipment, illuminance, and usage hours. Formally,

$$\begin{array}{llllll} \textbf{Energy} & = \Sigma & \textbf{floorspace x} & \textbf{hours x} & \textbf{illuminance /} & \textbf{efficacy} \\ \textbf{E (kWh)} & & \textbf{S (ksf)} & \textbf{H (h)} & \textbf{I (l/sf)} & \textbf{Q (l/w)} \end{array}$$

where the summation is over portions of commercial floorspace defined by lighting level (illuminance), equipment (efficacy), and usage (hours). The units ksf, h, l/sf, and l/w, respectively, indicate thousand square feet, hours per week, lumens per square foot, and lumens per watt.

Methodology for the Lighting Energy Profile

In the "Commercial Lighting Energy Profile," statistics are first presented on the factors that rely on the CBECS alone. These are the floorspace, hours, and their product, the overall floorspace-hours. The last quantity is not a conventional measure of lighting use, but is of interest as a complement to the lighting power density, which is commonly used. Total energy use is the product of the lighting power density and the overall floorspace-hours.

Illuminances are then assigned to CBECS buildings on the basis of the principal building activity, using engineering guidelines. These assignments (listed in Appendix B, "Illuminance Assignments for CBECS Buildings Activity Categories") are necessarily somewhat speculative. As a result, the statistics derived from these assignments have a lower degree of reliability than statistics obtained directly from the CBECS data. Nonetheless, these derived statistics are useful at least as qualitative indicators of the relationship among illuminance and factors such as building structural characteristics, hours of lighting use, and lighting equipment.

For each of the lighting categories identifiable from the CBECS data, efficacies are assigned from the technical literature. Deflation factors representing the effect of conservation features are similarly assigned. Details on these assignments are given in Appendix C, "Equipment Technical Characteristics."

These technical specifications complete the information necessary to estimate lighting energy consumption and end-use intensity for different equipment configurations and for different types of buildings. Because several assumptions and uncertainties underlie the assignment of technical specifications based on the CBECS characteristics, the sensitivity of the overall estimates to the assumptions is considered. Moreover, in comparisons among groups of buildings or types of equipment, attention is focused on less sensitive quantities, such as their relative contributions to total commercial lighting energy consumption.

Methodology for Estimating Potential Savings in Commercial Lighting Energy Use

Using the results of the "Commercial Lighting Energy Profile," the potential energy savings are estimated in the section on "Lighting Energy Conservation Potential." For these savings estimates, the existing lighting equipment is assumed to be replaced by other, more efficient equipment. Savings are estimated under various assumptions for the equipment replacements.

The conservation cases considered indicate the effects of immediate full penetration of specific groups of existing technologies. In practice, of course, replacements would occur gradually over a period of time. However, the purpose of this analysis is not to examine alternate forecasts for the future, but to estimate the potential for conservation in the current stock.

The replacements considered do not necessarily represent cost-effective strategies, nor are they intended to cover the full range of realistic options. The savings estimates are developed in such a way that estimates can easily be derived under alternate assumptions, using the elements presented here. The estimation method is detailed in Appendix E, "Savings Estimation Methodology."

Defining the Conservation Cases for Analysis

For this analysis, a *conservation case* is defined by three elements. First is the *equipment replacement scheme*, which specifies what combination of more energy-efficient equipment is assumed to be installed in place of each configuration of existing equipment. Second is the *conservation effect*, that is, the quantitative effect each conservation feature is assumed to have. Third is the extent of *delamping*, which is the assumed reduction in illumination level.

Equipment Replacement Schemes

The three equipment replacement schemes considered are:

(1) *Comprehensive*: replace all existing equipment by the most efficient for that lamp type (fluorescent, incandescent, or high-intensity discharge), together with lighting controls, high-efficiency ballasts, and reflectors where applicable.

(2) *Compact Fluorescent Conversion Only*: all incandescent bulbs are converted to compact fluorescent lamps, with reflectors. No other improvements are made.

(3) *Comprehensive Improvements Without Compact Fluorescent Conversions*: all the changes of the comprehensive scheme except conversion of incandescents to compact fluorescents.

Conservation Effects

The conservation features considered are high-efficiency ballasts, lighting controls, and reflectors. Each equipment replacement scheme is evaluated with the effects of all these features assumed at a *modest* level, and with all assumed at an *optimistic* level.

For each conservation feature, the *modest* and *optimistic* effects are the endpoints of a range of plausible effects suggested by a review of the literature and consultation with experts. *Modest* indicates a modest (low) level of conservation. Likewise, the *optimistic* effect is the high-conservation end of the range. The terms *modest* and *optimistic* are, thus, used to indicate the relative level of conservation. The quantitative effects assumed for the *modest* and *optimistic* levels are specified in Appendix C.

Delamping

With no delamping, it is assumed that existing illumination levels are maintained, so that the improved equipment is associated with fewer fixtures serving a given space. That is, more efficient equipment does not imply more brightly lit space, but a need for less equipment. Thus, efficiency improvements translate directly into energy savings, rather than serving to increase lighting service.

Delamping is defined here as a reduction in illumination level. The implicit assumption of the delamping cases is that commercial space is more strongly lit, on average, than necessary for comfort and function. (More generally, delamping refers to the removal of lamps.) Each combination of a basic replacement scheme with an assumed conservation effect (modest or optimistic) is evaluated also with delamping assumed at a modest and at an optimistic level, as well as with no delamping. The modest level represents a small reduction in lighting levels, the optimistic level a more extensive reduction. The quantitative levels corresponding to "modest" and "optimistic" are specified in Appendix C.

Error Estimation

The main source of uncertainty in the energy and savings estimates is the technical assumptions. This uncertainty is addressed by developing estimates under a range of plausible assumptions, testing the sensitivity of results to alternate assumptions, and providing the components of the analysis in a form that facilitates the incorporation of other assumptions.

An additional source of uncertainty is the random error from the CBECS sample. The CBECS data set does not include the entire stock of commercial buildings, but is a statistically selected sample. Estimates of population totals based on the CBECS have random errors due to the random selection of the sample. The magnitude of the random errors is estimated by the Relative Standard Errors (RSE's) given in Appendix F, "Relative Standard Errors for the Lighting Profile Tables." In general, the RSE's for the statistics presented here are sufficiently small that the random error can be ignored in comparison to the uncertainty in the technical assumptions.

For smaller population subsets, the RSE's would generally be larger, so that this component of error would not be as easily ignored. For this analysis, only a few population subsets are examined, each supported by a sufficiently large sample size to provide reliable estimates.

Data Sources

Building Characteristics Data

The CBECS is a nationally representative probability sample of commercial buildings. For purposes of this survey, commercial includes all buildings whose principal activity is not residential or industrial. The survey covers all commercial buildings over 1,000 square feet. For each of the roughly 6,000 buildings in the sample, the CBECS collects data on energy-related characteristics of the building as well as on the amount of energy consumed in the building.

The 1986 CBECS, which provides data for that calendar year, was used for the present analysis because this survey had more detail on lighting equipment and lighting conservation features than did the more recent 1989 survey. Previous reports have provided summary statistics on 1986 building characteristics,[5] on 1986 energy consumption and expenditures in relation to those characteristics,[6] and on 1989 building characteristics.[8]
The detail of the lighting questions was reduced on the 1989 CBECS for budget reasons. Because of the importance of this information, as evidenced by findings from this report, detailed lighting questions will be restored for the 1992 CBECS.

It is anticipated that the data for 1992 will reveal increased penetration of more efficient lighting technologies compared to the 1986. Nonetheless, given the general pace of change in the commercial building stock, the overall statistical profile has probably not shifted dramatically since 1986. For example, the estimated fraction of lighted floorspace served by fluorescent lamps increased from 76.2 percent in 1986 to 79.2 percent in 1989, but the change was not statistically significant. Thus, the qualitative relationships revealed by this analysis should still hold. Moreover, the approach developed here can be applied to the 1992 CBECS lighting data when they become available.

The data collected on the 1986 CBECS included the following:

- total floorspace
- the percent of floorspace lighted during usual operating hours
- the percent of floorspace lighted during off hours
- the percent of the floorspace lighted during usual operating hours that was lighted by each of several types of lamp
- the presence in the building of various lighting conservation features
- the number of operating hours per week
- the principal activity taking place in the building.

The CBECS data are collected for the building as a whole, not for separate portions of the building. It is therefore not known which conservation features are associated with which specific activities within the building, nor with which types of lamps or how much floorspace. Nor is it known which equipment is used for the space lighted during off-hours.

A further limitation of the CBECS data is the level of knowledge of the respondent. These data are collected not by a trained auditor, but by an interview with a respondent knowledgeable about the building. Respondents vary in their understanding of question terminology and knowledge about their buildings. For this reason, the CBECS questions are phrased to be meaningful to a broad set of respondents, rather than emphasizing precise technical distinctions.

Despite these limitations, the CBECS data provide a basis for characterizing the combinations of factors affecting commercial lighting requirements. This characterization requires that technical information from other sources be linked to the CBECS data.

Illuminance Data

The CBECS does not collect data on lighting levels, either in terms of power density (watts per square foot, or w/sf) or illuminance (lumens per square foot, or l/sf). However, the CBECS does identify the principal building activity, which is a strong determinant of lighting requirements.

The Illumination Engineering Society[11] publishes lighting guidelines by detailed space function. The guideline for each function consists of a low, medium, and high value, ranging from low to high by a factor of two or two and one-half. Actual levels in place may be outside this range. Nevertheless, the guidelines serve as an indicator of relative lighting requirements for different types of buildings. Appendix B describes how IES guidelines were used to assign illuminances to CBECS building activities.

Technology Specification Data

Technology specifications were drawn from a number of sources. A comprehensive review of lighting technologies has been performed by Piette et al.[15] A similar, somewhat less detailed, overview was prepared for the New York State Energy Research and Development Authority.[14] The Lighting Research Group at Lawrence Berkeley Laboratory (LBL) is conducting a life-cycle cost analysis for an extensive list of equipment combinations.[1] The California Energy Commission (CEC)[2] has issued a series of lighting technology guidelines with technical specifications for several types of equipment.

The CEC guidelines include efficacies, in lumens per watt (l/w) for the major lamp types considered here. Because this source offered a comprehensive and consistent set of specifications, efficacies for the broad lamp classes considered here were taken from the CEC guidelines whenever possible. Efficacies reported by other sources were similar. Some missing elements were filled in from other sources. Details are given in Appendix C, "Equipment Technical Characteristics."

Technical characteristics of different lamps and fixtures are given fairly consistently in the literature. For the effects of different conservation features, though, there is less agreement. For this reason, a high and low value were used for each effect, roughly covering the range of values suggested by the literature. Details on the particular values adopted are given in Appendix C.