Appendix D

Motivation and Computation of Lighting Measures

Floorspace by Lighting Equipment Configuration

As described in Appendix A, for each building **b**, the CBECS data set has the total floorspace, $\mathbf{S_b}$, the fraction $\mathbf{q_b}$ of that floorspace lighted during usual operating hours, and the fraction $\mathbf{q_{Lb}}$ of the lighted floorspace served by each type of lamp **L**. These are used to estimate the amount of floorspace lighted by each lamp type, for various population subgroups **G**.

A further step is to estimate the amount of floorspace lighted by lighting configurations, defined by a combination of a lamp type with a set of lighting conservation features. For this step, the CBECS buildings were partitioned according to the combination of lighting conservation features present and absent in the building. For a lighting configuration **c** defined by a lamp **L** together with a combination **f** of conservation features, the floorspace served by that lighting configuration was computed as:

$$\mathbf{S_{Lf} = \Sigma_{b\varepsilon GLf}\, s_b\, q_b\, q_{Lb}\, w_b}\ , \qquad \mathbf{(9)}$$

where **GLf** is the group of CBECS buildings that have the combination **f** of conservation features associated with lamps of type **L**. For each lamp type **L**, each building in the data set was assigned to only one group **GLf** of conservation features.

As indicated in Table 1 of the Detailed Tables, the lamp types identified by the CBECS include five of the seven considered in this analysis; compact fluorescents and very-high efficiency fluorescents are the two types not separately identified. These would have been reported as standard or energy-efficient fluorescents, or as "other," depending on the respondents' interpretation. The floorspace currently lighted by these types is assumed to be negligible and set at zero.

Floorspace currently under reflectors is similarly assumed to be zero; no CBECS data are available on reflectors. The 1986 CBECS does have data on the presence in the building of daylight sensors, other lighting controls, and high-efficiency ballasts, and on whether delamping has been performed in the building.

As noted, data were not collected on which lamps or how much floorspace each of these features was associated with. The configuration floorspace estimate $\mathbf{S_{Lf}}$ given above represents the total floorspace to which the collection of features **f** could be applied, in buildings where those features are present. For high-efficiency ballasts, that floorspace is the total floorspace lighted by fluorescent lamps in buildings that have high-efficiency ballasts. For controls and delamping, all lighted floorspace in buildings that have those features is included.

The fact that the penetration of a particular feature may be less than 100 percent even within a building where it is present is accounted for in the deflation factor assumed for each feature. This factor represents the average effect of the feature over all applicable floorspace in buildings where the feature is present. Higher penetration within those buildings is represented by a lower (more optimistic) deflation factor.

Effective Lighting Hours and Floorspace-Hours

One measure of the amount of use of the floorspace that is lighted during operating hours is the number of operating hours during a typical week. To account for the floorspace lighted during off hours, the "effective lighting hours" is computed. The effective lighting hours represents the number of hours per week the building would have to be open for the same amount of lighting use if no floorspace were lighted during off hours.

While the total hours of use of different types of equipment cannot be determined directly, the CBECS data do provide the floorspace $\mathbf{S^o}$ lighted during operating hours and the floorspace $\mathbf{S^n}$ lighted when closed, as indicated in Appendix A. Combining these with the typical operating hours $\mathbf{H^o}$ per week gives the total weekly lighted floorspace-hours $\mathbf{(SH)^T}$, as given in Table 3:

$$\mathbf{(SH)^T = S^o\, H^o + S^n(168 - H^o).} \tag{10}$$

Dividing this total by the floorspace lighted during operating hours gives the effective hours $\mathbf{H^e}$ of lighting for that floorspace:

$$\mathbf{H^e = (SH)^T/S^o.} \tag{11}$$

$$\mathbf{= H^o + (S^n/S^o)\, H^n.} \tag{12}$$

The floorspace-hours $\mathbf{(SH)^T}$ and effective hours $\mathbf{H^e}$ can be computed for each building **b** within a group. Summing floorspace-hours over buildings gives the total floorspace hours for the group. Dividing by the total lighted floorspace for the group gives the floorspace-weighted average effective hours for the group. An advantage of using the effective lighting hours is that this quantity incorporates the percent of floorspace lighted during off hours as an adjustment to the assumed hours of lighting. As a result, the remainder of the analysis only needs to consider the amount of floorspace lighted during operating hours.

With the floorspace lighted during off hours taken into account, the effective lighting hours are 13 percent higher on average than the usual operating hours, as indicated in the text. Thus, considering only operating-hours usage could result in substantial understatement of lighting demand.

The magnitude of the potential understatement varies considerably with building activity. For buildings that tend to be open almost all the time, including health care, lodging, and public order and safety buildings, the ratio of effective lighting to operating hours is close to 1.0. These buildings types have more than half as much floorspace lighted during off hours as during usual operating hours, but the off-hours are so few that the effective lighting hours are still only slightly large than the operating hours.

For office, mercantile, education, and vacant buildings, all of which have fewer than 60 operating hours per week, the effective lighting hours are 17 to 30 percent higher than the usual operating hours. For all these building types, the floorspace lighted during off hours was 15 percent or less of the floorspace lighted during usual operating hours.

In general, higher ratios of effective lighting to operating hours would be expected with higher ratios of floorspace lighted during off hours to floorspace lighted during usual operating hours. However, higher fractions of floorspace lighted off hours tend to go with fewer off hours; the trends in the two factors tend to balance out. For example, both weekly operating hours and the ratio of off-hours to operating-hours lighted floorspace tend to increase with building size, and also with building construction year. (See Table 3 of the Detailed Tables.) The net effect is that the ratio of effective lighting to operating hours shows little variation with building size or age.

Time-Averaged Illuminance

Multiplying the in-use illuminance (in lumens per square foot, l/sf) by the hours of use per week gives the weekly lighting service intensity, in lumen-hours per square foot. Dividing by 168 (the number of hours in a week) gives the time-averaged illuminance. For this analysis, the in-use illuminance is known only in terms of the assigned values based on activity, and the hours of use is approximated by the effective hours. Using these proxy measures, the time-averaged illuminance is given by :

$$\mathbf{T} = \mathbf{I\ H^e/168} \tag{13}$$

$$= \mathbf{U\ I.} \tag{14}$$

Thus, the time-averaged illuminance is affected both by the illuminance **I** and by the effective lighting hours $\mathbf{H^e}$. Reducing the lighting energy requirement by reducing the lighting service provided, either through the illuminance or the hours, reduces the time-averaged illuminance **T**.

The in-use illuminance **I** is assigned based on the principal building activity. The effective lighting hours are computed as described above. The resulting time-averaged illuminance is assumed to apply to all equipment and lighted floorspace in the building.

Usage and in-use illuminance are equally important in determining lighting energy consumption. The time-averaged illuminance measures their combined effect. For example, education buildings have twice the in-use illuminance of food sales buildings but a usage factor half as large. The two building types have about the same time-averaged illuminance, and about the same lighting end-use intensity.

Lodging buildings and mercantile buildings show the opposite effect. The two types have about the same in-use illuminance, but lodging buildings have twice the usage factor, hence about twice the time-averaged illuminance.

The value of examining the average combined illuminance and usage is that combining the separate averages does not always give an accurate measure of their combined effect for a group. For buildings over 500,000 square feet, the (floorspace-weighted) average time-averaged illuminance $\mathbf{T^\#}$ is 14 percent higher than the corresponding average in-use illuminance $\mathbf{I^\#}$ times the average usage factor $\mathbf{U^\#}$. This discrepancy could translate directly into a corresponding error in the energy estimate that would be obtained by combining average illuminance, average usage, and average efficiency.

Energy Intensity and Floorspace-Weighted Illuminance by Lamp Type

The end-use lighting intensity **EUI** depends on the illuminance **I**, the hours of use **H**, and the equipment efficacy **Q**. For a building **b**, the floorspace lighted by lighting configuration **c** has annual energy intensity

$$\mathbf{EUI_{bc}} = \mathbf{(8760/168)\ I_b\ H^e_b\ /\ Q_c.} \tag{15}$$

The factor 8760/168 is the ratio of the total hours in a year to the total hours in a week. The **EUI** can also be expressed as:

$$\mathbf{EUI_{bc}} = \mathbf{8760\ U_b\ I_b\ /\ Q_c} \tag{16}$$

$$= \mathbf{8760\ T_b\ /\ Q_c.} \tag{17}$$

In reality, illuminance **I** and hours $\mathbf{H_e}$ are likely to be different for different lighting configurations within building **b**. There being no way of estimating these differences, the building's overall value is assigned to all configurations **c**.

Multiplying the intensity $\mathbf{EUI_{bc}}$ by the floorspace $\mathbf{S_{bc}}$ served by configuration **c** in building **b** gives the energy consumed by that configuration in the building. Summing over buildings gives the total energy used by the configuration. Dividing by the total floorspace under the configuration gives the **EUI** for that configuration:

$$\mathbf{EUI_c} = 8760 \; \frac{\Sigma_b \, w_b \, S_{bc} \, T_b \, / \, Q_c}{\Sigma_b \, w_b \, S_{bc}} \qquad \textbf{(18)}$$

$$= 8760 \; T^{\#}_c \, / \, Q_c, \qquad \textbf{(19)}$$

where $\mathbf{T^{\#}_c}$ is the floorspace-weighted average of the time-averaged illuminance for configuration **c**.

Alternatively, the **EUI** for the configuration can be thought of as the floorspace-weighted average over buildings of the **EUI** for the floorspace lighted by that configuration within each building:

$$\mathbf{EUI_c} = \Sigma_b \, S_{bc} \, EUI_{bc} \, w_b \, / \, \Sigma_b \, S_{bc} \, w_b. \qquad \textbf{(20)}$$

Energy Estimate Incorporating Conservation Effects

The base case energy estimate assumes that the lighting conservation features currently present have negligible effect, as an average over all the floorspace in buildings where they are present. An alternate calculation was performed, assuming a modest effect for the features currently present.

The different classes of conservation features considered in this analysis affect different components of lighting energy. High-efficiency ballasts and reflectors increase the equipment efficacy **Q**. Delamping decreases the illuminance **I**. Lighting controls operate in various ways, some of which might be considered to affect the average hours of lighting use, others that are better thought of as affecting the electrically provided illuminance.

For the savings estimates, the deflation factors assumed for the different conservation features are combined into one overall deflation factor, which is applied to the base energy estimate. This procedure is described in Appendix E. This approach gives correct savings estimates under the given set of assumptions, but does not indicate the effect of the features on the different components.

For the alternate energy calculation, the conservation effects are applied separately to the corresponding components. The efficacy **Q** is divided by the deflation factor $\mathbf{d_{HEB}}$ for high-efficiency ballasts. Illuminance **I** is multiplied by the deflation factor $\mathbf{d_{DEL}}$ for delamping, and also by the deflation factor $\mathbf{d_{CTL}}$ for lighting controls (Tables D1 and D2). From the resulting alternate efficacy and illuminance, alternate lighting power density, end-use intensity, and energy use are derived. These are then aggregated by lighting configuration (Table D3) and by building characteristics (Table D4), just as the original base-case estimates are.

Table D1. Alternate Illuminance and Power Measures by Lighting Configuration

Lamp Type and Conservation Feature Present	Percent of Total Lighted Floorspace	Usage Factor (percent)	Illuminance (lumens per square foot) In-Use	Illuminance (lumens per square foot) Time-Averaged	Efficacy (lumens per watt)	In-Use Lighting Power Density (watts per square foot)
Standard Fluorescent	41.6	43.9	62.7	27.5	60.4	1.0
No Conservation Features	22.8	41.3	59.2	25.6	59.0	1.0
Ballast	6.6	43.6	61.5	27.3	64.1	1.0
Controls	3.3	48.1	62.7	26.5	59.0	1.1
Delamping	2.6	45.3	73.5	30.5	59.0	1.3
Ballast and Controls	2.7	54.5	61.0	30.7	64.1	1.0
Ballast and Delamping	1.5	40.5	67.6	24.8	64.1	1.1
Controls and Delamping	1.2	55.4	91.4	47.7	59.0	1.6
Ballast, Controls, and Delamping	0.9	51.2	87.2	39.9	64.1	1.4
Energy-Efficient Fluorescent	34.6	50.4	77.3	38.0	65.6	1.2
No Conservation Features	6.5	44.3	66.2	30.5	62.0	1.1
Ballast	9.5	46.7	76.8	38.0	67.4	1.1
Controls	2.6	46.2	65.9	27.8	62.0	1.1
Delamping	1.2	46.6	79.7	33.3	62.0	1.3
Ballast and Controls	4.1	62.1	83.5	49.1	67.4	1.2
Ballast and Delamping	4.2	49.5	85.4	40.1	67.4	1.3
Controls and Delamping	1.1	47.7	84.8	33.2	62.0	1.4
Ballast, Controls, and Delamping	5.4	59.8	84.0	44.0	67.4	1.3
Standard Incandescent	13.6	46.5	50.6	23.8	18.0	2.8
No Conservation Features	10.4	43.6	47.8	22.4	18.0	2.7
Controls	1.8	58.4	54.6	26.4	18.0	3.0
Delamping	0.9	45.5	63.4	26.4	18.0	3.5
Controls and Delamping	0.5	65.3	71.9	39.1	18.0	4.0
Energy-Efficient Incandescent	5.2	54.7	61.4	32.0	20.0	3.1
No Conservation Features	2.6	45.9	56.6	26.3	20.0	2.8
Controls	1.1	64.5	63.5	39.4	20.0	3.2
Delamping	0.6	52.9	70.6	32.7	20.0	3.5
Controls and Delamping	0.9	70.3	67.5	39.5	20.0	3.5
High-Intensity Discharge	6.3	56.1	51.9	28.5	69.0	0.8
No Conservation Features	3.2	52.0	42.3	20.9	69.0	0.6
Controls	1.5	65.6	62.3	40.5	69.0	0.9
Delamping	0.9	49.2	47.5	19.6	69.0	0.7
Controls and Delamping	0.7	64.1	80.7	50.5	69.0	1.2

Notes: • Ballast, Controls, and Delamping, respectively, indicate that high efficiency ballasts, any type or combination of lighting controls, and a delamping program were reported for the building containing the floorspace lighted by the indicated lamp. High-efficiency ballasts, when reported, were assumed to apply only to fluorescent lamps. • The illuminance and power density in this table are adjusted for conservation features present, assuming the modest effect for each feature. • The illuminance or power measure for each lighting equipment configuration is the (lighted-floorspace-weighted) average of that measure across buildings. A column that represents an average product is not equal to the product of the corresponding columns. For example, for a single building, the time-averaged illuminance is the product of the usage factor and the in-use illuminance; however, the average time-averaged illuminance is not the average usage factor times the average in-use illuminance. • Table of Relative Standard Errors can be found in Appendix F. • See the Glossary for explanations of abbreviations and definitions used in this report.

Sources: Percent of floorspace and usage factor from Energy Information Administration, Office of Energy Markets and End Use, Form EIA-871A, "Building Questionnaire" of the 1986 Nonresidential Buildings Energy Consumption Survey; Illuminance and efficacy derived from sources described in Appendices B and C. Lighting power density is derived from illuminance and efficacy.

Table D2. Alternate Illuminance and Power Measures by Building Characteristics

Building Characteristics	Percent of Total Lighted Floorspace 1986	Usage Factor (percent)	Illuminance (lumens per square foot) In-Use	Illuminance (lumens per square foot) Time-Averaged	In-Use Lighting Power Density (watts/square foot)
All Buildings	100.0	47.6	65.3	30.8	1.4
Principal Activity					
Assembly	11.9	36.2	46.9	16.1	1.4
Education	14.1	36.5	100.0	34.4	1.9
Food Sales	1.3	70.0	50.0	33.2	1.1
Food Service	2.3	58.8	20.0	11.2	0.7
Health Care	4.1	91.3	186.5	154.0	3.6
Lodging	4.9	96.1	50.0	45.4	2.0
Mercantile/Service	22.9	46.4	50.0	22.1	1.0
Office	17.7	41.1	91.0	35.0	1.8
Public Order and Safety	1.2	80.5	78.5	60.0	1.9
Warehouse	13.9	44.0	17.6	7.5	0.4
Vacant	2.8	28.0	5.0	1.4	0.1
Other	3.0	58.5	117.5	65.0	2.5
Building Size (square feet)					
1,001 to 5,000	10.1	40.0	55.0	21.4	1.3
5,001 to 10,000	11.2	40.2	54.8	20.8	1.3
10,001 to 25,000	14.9	42.3	59.5	24.2	1.4
25,001 to 50,000	15.0	43.3	61.8	26.6	1.3
50,001 to 100,000	14.8	49.7	62.7	29.3	1.4
100,001 to 200,000	12.7	50.7	69.9	35.5	1.4
200,001 to 500,000	12.5	55.6	75.3	40.3	1.6
Over 500,000	8.8	62.6	89.7	55.7	1.7
Year Constructed					
Before 1920	8.3	42.3	56.9	24.2	1.5
1920-1945	13.9	44.6	66.4	30.3	1.6
1946-1959	14.5	43.5	63.7	28.1	1.4
1960-1969	20.2	47.3	66.2	29.8	1.4
1970-1979	25.5	51.6	65.5	34.0	1.3
1980-1986	17.6	50.3	68.2	33.3	1.4
Census Region					
Northeast	20.1	49.9	64.7	31.2	1.4
Midwest	26.5	47.6	67.4	32.7	1.5
South	33.9	47.0	63.1	29.5	1.4
West	19.6	46.3	66.8	30.3	1.4

Notes: • The illuminance and power density in this table are adjusted for conservation features present, assuming the modest effect for each feature. • The illuminance or power measure for each building characteristic is the (lighted-floorspace-weighted) average of that measure across buildings. A column that represents an average product is not equal to the product of the corresponding columns. For example, for a single building, the time-averaged illuminance is the product of the usage factor and the in-use illuminance; however, the average time-averaged illuminance is not the average usage factor times the average in-use illuminance. • Table of Relative Standard Errors can be found in Appendix F. • See Appendices B, C, and D for derivations and the Glossary for explanations of abbreviations and definitions used in this report.

Sources: Percent of floorspace and usage factor from Energy Information Administration, Office of Energy Markets and End Use, Form EIA-871A, "Building Questionnaire" of the Nonresidential Buildings Energy Consumption Survey; Illuminance and efficacy derived from sources described in Appendices B and C. Lighting power density is derived from illuminance and efficacy.

Table D3. Alternate Lighting Energy and Intensity Estimates by Lighting Configuration

Lamp Type and Conservation Feature Present	Floorspace (million square feet) Total Lighted	Floorspace (million square feet) Percent of Total Lighted	Annual Lighting End-Use Intensity (kWh/square foot)	Annual Lighting Energy (billion kWh)
Standard Fluorescent	20,700	41.6	4.0	82.7
No Conservation Features	11,327	22.8	3.8	43.1
Ballast	3,286	6.6	3.7	12.2
Controls	1,654	3.3	3.9	6.5
Delamping	1,297	2.6	4.5	5.9
Ballast and Controls	1,322	2.7	4.2	5.6
Ballast and Delamping	739	1.5	3.4	2.5
Controls and Delamping	615	1.2	7.1	4.4
Ballast, Controls, and Delamping	460	0.9	5.5	2.5
Energy-Efficient Fluorescent	17,130	34.6	5.1	86.6
No Conservation Features	3,222	6.5	4.3	13.9
Ballast	4,702	9.5	4.9	23.2
Controls	1,286	2.6	3.9	5.1
Delamping	600	1.2	4.7	2.8
Ballast and Controls	2,042	4.1	6.4	13.0
Ballast and Delamping	2,098	4.2	5.2	10.9
Controls and Delamping	526	1.1	4.7	2.5
Ballast, Controls, and Delamping	2,654	5.4	5.7	15.2
Standard Incandescent	6,774	13.6	11.6	78.3
No Conservation Features	5,177	10.4	10.9	56.3
Controls	899	1.8	12.8	11.5
Delamping	455	0.9	12.9	5.9
Controls and Delamping	243	0.5	19.0	4.6
Energy-Efficient Incandescent	2,551	5.2	14.0	35.8
No Conservation Features	1,305	2.6	11.5	15.0
Controls	536	1.1	17.3	9.3
Delamping	279	0.6	14.3	4.0
Controls and Delamping	431	0.9	17.3	7.5
High-Intensity Discharge	3,064	6.3	3.6	11.1
No Conservation Features	1,570	3.2	2.7	4.2
Controls	722	1.5	5.1	3.7
Delamping	440	0.9	2.5	1.1
Controls and Delamping	332	0.7	6.4	Q

Q Data withheld because the Relative Standard Error (RSE) was greater than 50 percent.

Notes: • Ballast, Controls, and Delamping, respectively, indicate that high-efficiency ballasts, any type or combination of lighting controls, and a delamping program were reported for the building containing the floorspace lighted by the indicated lamp. High-efficiency ballasts, when reported, were assumed to apply only to fluorescent lamps. • The energy and intensity in this table are adjusted for conservation features present, assuming the modest effect for each feature. • Table of RSE's can be found in Appendix F. • See the Glossary for explanations of abbreviations and definitions used in this report.

Sources: Floorspace from Energy Information Administration, Office of Energy Markets and End Use, Form EIA-871A, "Building Questionnaire" of the 1986 Nonresidential Buildings Energy Consumption Survey; Illuminance and efficacy derived from sources described in Appendices B and C. Lighting end-use intensity and energy measures are derived from illuminance and efficacy.

Table D4. Alternate Lighting Energy and Intensity Estimates by Building Characteristics

Building Characteristics	Floorspace, 1986 (million square feet) Total	Total Lighted	Percent of Total Lighted	Annual Lighting End-Use Intensity (kWh/square foot) per Total Square Feet	per Total Lighted Square Feet	Annual Lighting Energy (billion kWh)
All Buildings	58,199	49,590	100.0	5.1	5.9	294.5
Principal Activity						
Assembly	7,339	5,918	11.9	3.0	3.7	22.2
Education	7,292	6,968	14.1	5.7	5.9	41.2
Food Sales	712	668	1.3	5.9	6.3	4.2
Food Service	1,281	1,133	2.3	3.1	3.5	3.9
Health Care	2,107	2,010	4.1	24.9	26.1	52.4
Lodging	2,785	2,423	4.9	13.6	15.6	37.8
Mercantile/Service	12,805	11,361	22.9	3.5	4.0	45.0
Office	9,546	8,763	17.7	5.5	6.0	52.9
Public Order and Safety	680	573	1.2	11.1	13.2	7.5
Warehouse	8,996	6,917	13.9	1.1	1.5	10.2
Vacant	2,931	1,392	2.8	0.1	0.3	0.4
Other	1,726	1,464	3.0	9.7	11.4	16.8
Building Size (square feet)						
1,001 to 5,000	6,209	5,023	10.1	3.7	4.6	23.0
5,001 to 10,000	6,861	5,545	11.2	3.5	4.4	24.2
10,001 to 25,000	9,119	7,405	14.9	4.2	5.2	38.4
25,001 to 50,000	8,661	7,451	15.0	4.4	5.1	38.1
50,001 to 100,000	8,559	7,350	14.8	4.9	5.7	41.9
100,001 to 200,000	7,161	6,275	12.7	5.8	6.6	41.5
200,001 to 500,000	6,737	6,198	12.5	6.9	7.5	46.4
Over 500,000	4,893	4,342	8.8	8.4	9.4	40.9
Year Constructed						
Before 1920	5,735	4,139	8.3	4.0	5.5	22.8
1920-1945	8,894	6,907	13.9	5.3	6.8	46.7
1946-1959	8,534	7,180	14.5	4.5	5.4	38.5
1960-1969	11,117	10,000	20.2	5.3	5.9	58.5
1970-1979	14,036	12,644	25.5	5.4	6.0	76.4
1980-1986	9,883	8,721	17.6	5.2	5.9	51.6
Census Region						
Northeast	11,830	9,963	20.1	5.2	6.2	61.5
Midwest	16,034	13,140	26.5	5.1	6.2	81.1
South	19,397	16,790	33.9	4.9	5.7	95.1
West	10,937	9,697	19.6	5.2	5.9	56.8

Notes: • The energy and intensity in this table are adjusted for conservation features present, assuming the modest effect for each feature. • Table of Relative Standard Errors can be found in Appendix F. • See the Glossary for explanations of abbreviations and definitions used in this report.

Sources: Floorspace from Energy Information Administration, Office of Energy Markets and End Use, Form EIA-871A, "Building Questionnaire" of the 1986 Nonresidential Buildings Energy Consumption Survey; Illuminance and efficacy derived from sources described in Appendices B and C. Lighting end-use intensity and energy measures are derived from illuminance and efficacy.