Title

Lighting Market Sourcebook for the U.S.

Authors

Vorsatz, Diana
Shown, Leslie
Koomey, Jonathan
et al.

Publication Date

1997-12-01

LBNL-39102
UC-1600

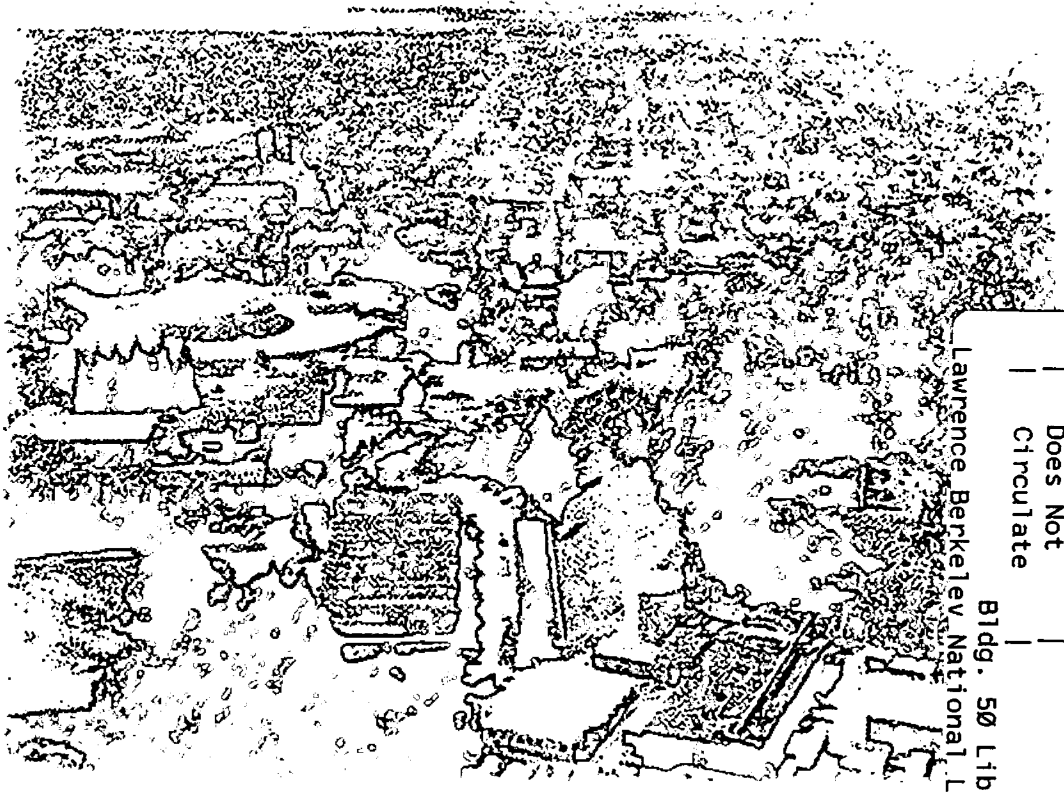
ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Lighting Market Sourcebook for the U.S.

Diana Vorsatz, Leslie Shown,
Jonathan Koomey, Mithra Moezzi,
Andrea Denver, and Barbara Atkinson

**Environmental Energy
Technologies Division**

December 1997



DISCLAIMER

LBNL-39102
UC-1600

LIGHTING MARKET SOURCEBOOK FOR THE U.S.

Diana Vorsatz, Leslie Shown, Jonathan Koomey,
Mithra Moezzi, Andrea Denver, and Barbara Atkinson

December 1997

Energy Analysis Program
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
1 Cyclotron Road, Building 90-4000
Berkeley, CA 94720

http://enduse.lbl.gov/projects/LMS.html

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, State, and Community Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

Throughout the United States, in every sector and building type, lighting is a significant electrical end-use. Based on the many and varied studies of lighting technologies, and experience with programs that promote lighting energy-efficiency, there is a significant amount of cost-effective energy savings to be achieved in the lighting end use. Because of such potential savings, and because consumers most often do not adopt cost-effective lighting technologies on their own, programs and policies are needed to promote their adoption.

Characteristics of lighting energy use, as well as the attributes of the lighting marketplace, can significantly affect the national pattern of lighting equipment choice and ownership. Consequently, policy makers who wish to promote energy-efficient lighting technologies and practices must understand the lighting technologies that people use, the ways in which they use them, and marketplace characteristics such as key actors, product mix and availability, price spectrum, and product distribution channels. The purpose of this report is to provide policy-makers with a sourcebook that addresses patterns of lighting energy use as well as data characterizing the marketplace in which lighting technologies are distributed, promoted, and sold. We examine residential and commercial lighting in the U.S. in order to answer important market-related questions such as:

- Who uses which lighting technologies and how much do they use them?
- What market shares do various technologies represent and how have these market shares changed over time?
- Who are the key participants in the lighting marketplace?
- Which distribution channels do these key participants use?

In addition, we discuss the policy implications of lighting energy use and current market characteristics. The lighting products we address in this report include lamps, ballasts, fixtures, and lighting controls.

In Appendix A, we introduce and define some of the most important terms that are used to compare lamps, ballasts, and fixtures and provide summary information on lighting technologies including lighting controls. In Appendix B, we provide a list of valuable references for learning about the technical as well as market characteristics of lighting technologies.

ACKNOWLEDGMENTS

We are extremely grateful to Robert Clear (Lawrence Berkeley National Laboratory) for his attention to, and enthusiasm for, the technical characteristics of lighting technologies as well as his willingness to review many drafts of this report.

We offer special thanks to Kathryn Conway (Lighting Research Center, Rensselaer Polytechnic Institute) for her careful review of numerous drafts of this report and insightful suggestions for improving it.

We would also like to thank others who reviewed the report in its final stages: Steve Johnson (who graciously served as our designated division reviewer), Francis Rubinstein, Judy Jennings, Jim McMahon, and Evan Mills (Lawrence Berkeley National Laboratory); and Chris Calwell (ECOS Consulting).

In addition, we are grateful for the contributions of Jiang Lin and Osman Sezgen (Lawrence Berkeley National Laboratory), Miriam Goldberg (Xenergy, Inc.), and Lisa Heschong (Heschong Mahone Group).

We also wish to thank Dick Jones and Bill Raup of the U.S. Department of Energy, Office of Building Technologies, State, and Community Programs, who funded the preparation of this report.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, State, and Community Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

TABLE OF CONTENTS

1. INTRODUCTION TO THE SOURCEBOOK

Throughout the United States, in every sector and building type, lighting is a significant electrical end-use. Based on data from the Energy Information Administration (EIA), lighting accounted for approximately 9% of residential and 36% of commercial electricity consumption in 1995 (EIA 1996a). Although energy use for lighting has been increasing in all sectors, this growth in consumption has been slowed by utility-sponsored demand-side management (DSM) programs, state and national building codes, federal efficiency standards for lighting equipment, and government-sponsored market-pull programs.

We take as axiomatic that there are large reservoirs of cost-effective energy savings to be achieved in the lighting end use, based on the many and varied studies of lighting technologies and real program experience that have accumulated over the years (e.g., Atkinson et al. 1995a, Atkinson et al. 1992, Audin et al. 1994, Eley Associates 1993, Eto et al. 1996b). Because of such potential savings, and because consumers most often do not adopt cost-effective lighting technologies on their own, programs and policies are needed to promote their adoption.

Characteristics of lighting energy use, as well as the attributes of the lighting marketplace, can significantly affect the national pattern of lighting equipment choice and ownership. Consequently, policy makers who wish to promote energy-efficient lighting technologies and practices must understand the lighting technologies that people use, the ways in which they use them, and marketplace characteristics such as key actors, product mix and availability, price spectrum, and product distribution channels. The purpose of this report is to provide policy-makers with a sourcebook that addresses patterns of lighting energy use as well as data characterizing the marketplace in which lighting technologies are distributed, promoted, and sold. We examine residential and commercial lighting in the U.S. in order to answer important market-related questions such as:

- Who uses which lighting technologies and how much do they use them?
- What market shares do various technologies represent and how have these market shares changed over time?
- Who are the key participants in the lighting marketplace?
- Which distribution channels do these key participants use?

In addition, we discuss the policy implications of lighting energy use and current market characteristics. The lighting products we address in this report include lamps, ballasts, fixtures, and lighting controls.

In Appendix A, we introduce and define some of the most important terms that are used to compare lamps, ballasts, and fixtures and provide summary information on lighting technologies including lighting controls. In Appendix B, we provide a list of valuable references for learning about the technical as well as market characteristics of lighting technologies.[1]

---

[1] Any post-publication corrections to this report, as well as related data that we compile after the report's publication, will be listed at the project website: http://enduse.lbl.gov/projects/LMS.html.

2. LIGHTING END-USE DATA FOR THE U.S. RESIDENTIAL AND COMMERCIAL SECTORS

Estimates of the amount of electricity used by any end-use are never precise, and vary with equipment ownership, equipment efficiency, operating hours, and other factors. For lighting in the U.S., the uncertainties in such estimates are larger than for most other end-uses. Estimates of the total electricity used for U.S. lighting can differ by as much as a factor of two, depending on the methodology used to derive them. Such uncertainty should prompt the reader to use the data with utmost care. In this section, we rely on data from many sources and, when we know them, identify limitations of those sources to help readers use the information in a responsible way.

Based on the *Annual Energy Outlook 1996* published by the Energy Information Administration (EIA), approximately 9% of residential and 36% of commercial electricity consumption was attributable to lighting in 1995 (**Table 2.1**) (EIA 1996a). The majority of electricity used for lighting in the United States is consumed in commercial buildings; Atkinson et al. (1995) estimate that, in 1990, commercial-sector consumption accounted for 60% of total lighting electricity consumption while consumption in the residential and industrial sectors accounted for 20% and 16%, respectively.[2]

Although electricity use for lighting is steadily increasing, lighting represents a decreasing share of total electricity demand, due to the more accelerated growth in other electricity end uses such as office equipment and electric home appliances. Energy use trends in the residential and commercial sectors are discussed in the following sections. In addition, we describe the regulations and standards that affect the lighting product mix in the U.S.

Table 2.1. On-Site Lighting Electricity Consumption in the United States, 1995[3]

Sector	Lighting Electricity Use (terawatt-hours)	Total Electricity Use (terawatt-hours)	Lighting as Percent of Sectoral Total
Residential	94	1034	9.1%
Commercial	340	938	36.3%

Note: Industrial and "Other" lighting consumption are not reported by EIA; a rough estimate of the lighting electricity consumption in these additional sectors is ≈100 TWh (Atkinson et al. 1995a).
Source: EIA (1996a)

---

[2] Illuminating buildings has indirect energy effects as well. For example, the indirect costs of illumination can include the cost of extra cooling energy to deal with the excess heat created by lighting technologies. Additionally, the decrease in heat output as a result of more efficient lighting can require an increase in space heating requirements. Due to the complex interactions with cooling and heating, indirect energy consumption or benefits vary widely by building type, operating characteristics, and climate (Franconi and Rubinstein 1992, Sezgen and Huang 1994). A recent study of lighting-HVAC interactions in commercial buildings indicates that, although these interactions induce monetary savings in warm climates and monetary penalties in cold climates, the monetary savings and penalties resulting from a reduction in lighting energy use that is well distributed geographically across the U.S. commercial building stock will balance each other out and, on average, cause no change in primary energy use or energy expenditures (Sezgen and Koomey 1997). To date, there has been no comprehensive study of total indirect lighting energy impacts for the residential sector. In this report, we discuss only direct lighting energy consumption.

[3] The bulk of energy use by residential and commercial buildings is for interior lighting. Both the Residential Energy Consumption Survey (RECS) and Commercial Buildings Energy Consumption Survey (CBECS), upon which EIA lighting data are based, use customers' monthly utility bills to calculate building energy consumption. Thus, to the extent that exterior lights are billed to the building's meter, exterior lighting will be included. There are often special rates for automatic dusk-to-dawn pole lighting; in some cases, residential and commercial customers may be able to use these rates which may be billed separately (billing practices vary) and thus excluded from RECS and CBECS (Wade 1997). Most residential exterior lighting is controlled from indoors and so will be included in a home's monthly electricity bill. It is likely that a larger portion of commercial exterior lighting is billed separately and thus is unaccounted for in EIA data.

2.1. Residential Lighting Energy Use and Equipment Ownership

2.1.1. Sources and Limitations of Residential Lighting Data

Currently, there is no comprehensive database for U.S. residential lighting energy use data. Because of the inadequacy of the existing data, we feel it is important that readers understand the residential data sources used in this chapter as well as some of their limitations. The most reliable lighting data sets for the residential sector are the result of numerous small studies that focus on regional, rather than national, lighting energy use; however, because data were collected from small, diverse geographic areas (e.g., utility service territories), numerical results for the same lighting energy parameter can vary significantly.

Summary data on national lighting hours and the number of lamps in households in 1993 are based on an Energy Information Administration report (1996b) entitled *Residential Lighting: Use and Potential Savings*. The EIA report is based on two questionnaires administered through the Residential Energy Consumption Survey (RECS), the Household Questionnaire answered by 7111 households and the more detailed Lighting Supplement answered by a subset of 474 households across the United States.

The results of the Electric Power Research Institute (EPRI) study on consumer perceptions of compact fluorescent lamps (Weiner and Campbell 1992) are based on focus group discussions with residential consumers in San Francisco and Boston, and telephone interviews with retailers and consumers in San Francisco, Boston, Chicago, New York, and Milwaukee.

Both Moezzi (1996-97) and most of Jennings et al. (1996) are based on a data set compiled in the Baseline Residential Lighting Energy Use Study, funded by the Bonneville Power Administration. Tacoma Public Utilities (TPU) was the lead utility in the study, which metered 82% of fixtures in 161 single-family homes in the Pacific Northwest from 1993 to 1995, in seven different utility service territories, in order to establish lighting energy use and actual hours of use for household lamps and fixtures (Tribwell and Lerman 1996). Because only 82% of household fixtures were monitored for the TPU project, estimates of aggregate lighting hours and energy use may be somewhat low; in addition, estimates are more biased for some categories than for others (e.g., based on a fixture inventory of the households included in the TPU study, relatively low proportions of outdoor-hardwired and bedroom-portable fixtures were logged for the study) (Moezzi 1996-97). See Tribwell and Lerman (1996) for an overview of the TPU project and its results.[4]

The residential data from Leslie and Conway (1993) were collected by researchers at the Lighting Research Center at Rennselaer Polytechnic Institute (RPI) in Troy, New York. The RPI data we refer to include the results of a telephone survey of approximately 2500 homes in Albany, New York, as well as lighting equipment prices that are based on information from national manufacturers as well as local price checks.

---

[4] The Heschong Mahone Group has also analyzed the TPU data - see Heschong Mahone Group (1997).

2.1.2. Residential Lighting Energy Use

According to EIA (1995a), on average, lighting accounted for approximately 9% of total electricity use in U.S. households in 1993. Based on EIA's statistical analysis of utility billing data as well as household survey data, each U.S. household consumed an average of 940 kWh of electricity for lighting in 1993 (EIA 1995a) and paid about $83 in lighting electricity costs (EIA 1996b).[5] Estimates of residential energy use, however, vary significantly depending upon the source. As seen in **Table 2.2**, estimates of household lighting energy use that are based on measured data tend to be much higher than EIA's estimate. Although studies based on measured data are more likely to be reliable indicators of actual household lighting energy use, the studies summarized in Table 2.2 resulted in very different estimates of household lighting energy use. Clearly, further studies are needed – particularly a monitoring study of at least several hundred households that are distributed across the U.S. and that represent a true cross-section of household types in each part of the country.

U.S. residential lighting electricity consumption is expected to increase as a result of the growing number of households as well as increased lighting energy use per household. The extent to which residential lighting energy use will increase in the coming decades will largely depend on the introduction and success of lighting efficiency policies and programs. As can be seen in **Figure 2.1**, both EIA and Lawrence Berkeley National Laboratory (LBNL) forecast an increase in lighting electricity use through the year 2010 (EIA 1996a, Koomey et al. 1997).

The LBNL and EIA forecasts, however, predict notably different levels of energy consumption in any given year. The variations in energy forecasts such as these are attributable to differences in assumptions. For example, Figure 2.1 shows clearly that the LBNL and EIA estimates of baseline energy use differ substantially; this is largely attributable to differing estimates of household lighting energy use.

In general, EIA's analysis results are based on surveys combined with conditional demand techniques while the results of analyses at energy research institutions such as LBNL are based upon detailed bottom-up end-use models. Because of the different methods used in their calculations, estimates of the same energy parameter by EIA and other institutions such as LBNL can vary substantially; currently, there is no independent check as to which procedure is producing the most accurate estimates.

---

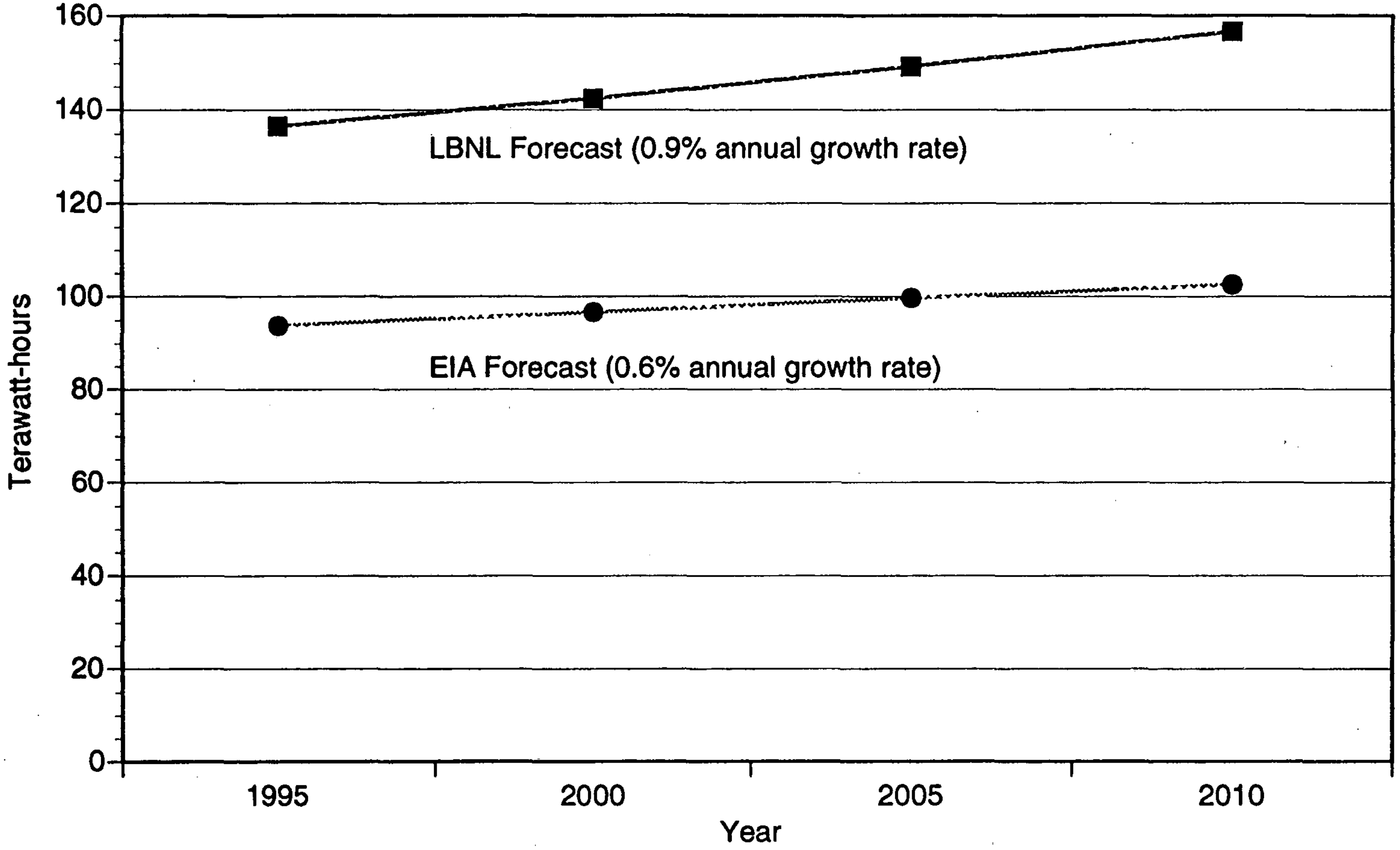
[5] It is important to recognize, when considering aggregated data, that household lighting energy consumption varies based on Census region, income level, number of household members, housing size, and housing type. For example, EIA's (1996b) regression allocation estimates of average annual lighting energy consumption in 1993 indicate that, for households paying from 7.5-12.29¢/kWh for electricity, single-family homes consumed 1,051 kWh, mobile homes consumed 869 kWh, and households in apartment buildings consumed 584 kWh.

Table 2.2. Estimates of Annual Household Energy Use for Lighting

Annual Household Energy Use for Lighting	Source	Notes
940 kWh*	EIA (1996b)	Average for all U.S. households in 1993. Based on RECS national survey of 7000 households; analysis used conditional demand techniques to extract lighting energy use from survey data. Average heated floorspace of all U.S. households in 1993 was estimated to be 1630 sq ft (EIA 1995b).
1313 kWh*, for *incandescent* lamps only	Hanford (1994)	Average for all U.S. households in 1990. Based on metered wattage and lighting energy use data for the service territory of Pacific Gas & Electric; scaled by floor area to approximate a national average for all housing types. Average heated floorspace for U.S. homes was estimated to be 1570 sq ft.
1704 kWh	Heschong Mahone Group (1997)	Average for all households in California (average for single-family homes was 2076 kWh). Based on survey of homeowners regarding hours of use for 16,000 fixtures in 697 homes in Southern CA; in order to correct for an assumed self-reporting error on hours of use, survey data were correlated to monitored data from Tacoma Public Utilities (see below) for 2600 fixtures (Heschong 1997).
1818 kWh	Tribwell and Lerman (1996)	Average for selected homes in Pacific Northwest. Based on metering of 161 *single-family* homes in the Pacific Northwest from 1993 to 1995, in seven different utility service territories (the study was led by Tacoma Public Utilities). Average floorspace of metered households was estimated to be ≈1750 sq ft, based on Moezzi (1996-97).
2418 kWh	Manclark et al. (1992)	Average for selected homes in Yakima, WA (service territory of Pacific Power and Light). Based on surveys and metering of 53 homes for three months. Information regarding home type and square footage was unavailable.
2517 kWh	Manclark et al. (1992) and Manclark and Nelson (1992)	Average for selected homes in Grays Harbor County in the state of Washington. Based on surveys of 20 homes (18 *single-family*, 1 duplex), six of which were metered from November 1991 to July 1992. Average floorspace (excluding garage) of the 20 homes was 1594 sq ft.

* The total number of households in the U.S. in 1993 was 96.6 million according to EIA (1995a). Thus, the EIA (1996b) estimate of annual lighting energy use per household translates to a total residential lighting energy consumption of about 91 TWh; the Hanford (1994) estimate translates to residential lighting energy consumption of about 127 TWh (for incandescent lamps only).

FIGURE 2.1. FORECASTED ELECTRICITY USE FOR RESIDENTIAL LIGHTING, 1995 - 2010 (TWh)



Source: LBNL forecast adapted from Koomey et al. (1997); EIA forecast data obtained from EIA (1996a)

2.1.3. Distribution of Household Energy Consumption by Room Type

Based on the studies of residential lighting examined in Jennings et al. (1996), approximately three billion lighting fixtures illuminate U.S. homes, with an average of 35–50 lamps operating in 20–30 lighting fixtures in each home.[6] On average, there are 2–3 fixtures per room and the lamps within these fixtures have an installed lighting wattage intensity of 1.4–1.8 watts per square foot (15–19 watts per square meter).

Figure 2.2 is based on data obtained from the TPU analysis and indicates, for household room types, the percentage of total installed lighting wattage and percentage of annual household energy use for lighting. Of the rooms in an average household, the highest installed wattage as well as the highest annual lighting energy consumption is found in kitchens, living rooms, bathrooms, and bedrooms. Together, these four room types account for more than 50% of household installed wattage and lighting energy use. It should be noted that, because there are multiple bathrooms and bedrooms in most homes, the installed wattage and energy use percentages reported in Figure 2.2 do not apply to a single bathroom or bedroom as they do for a living room and kitchen. Bathrooms and bedrooms have high installed wattages and lighting energy use when considered as a room *type* (e.g., data for all bathrooms in a home are aggregated into a single category); wattages and energy use are considerably less when rooms are considered on an individual basis. Consequently, on an individual room-by-room basis, kitchens and living rooms are the household rooms with both the highest installed wattages and highest lighting energy consumption.

The trends reported for U.S. households in EIA (1996b) are consistent with TPU's data for installed wattage and energy use: the room types with the most lights are kitchens, living rooms, bathrooms, and bedrooms; in addition, the lights within these four room types are illuminated for more hours per day than the lights in other types of rooms.[7] As with the TPU data, the EIA report points out that one reason bedrooms have the largest number of lights is that an average home has 2.6 bedrooms.

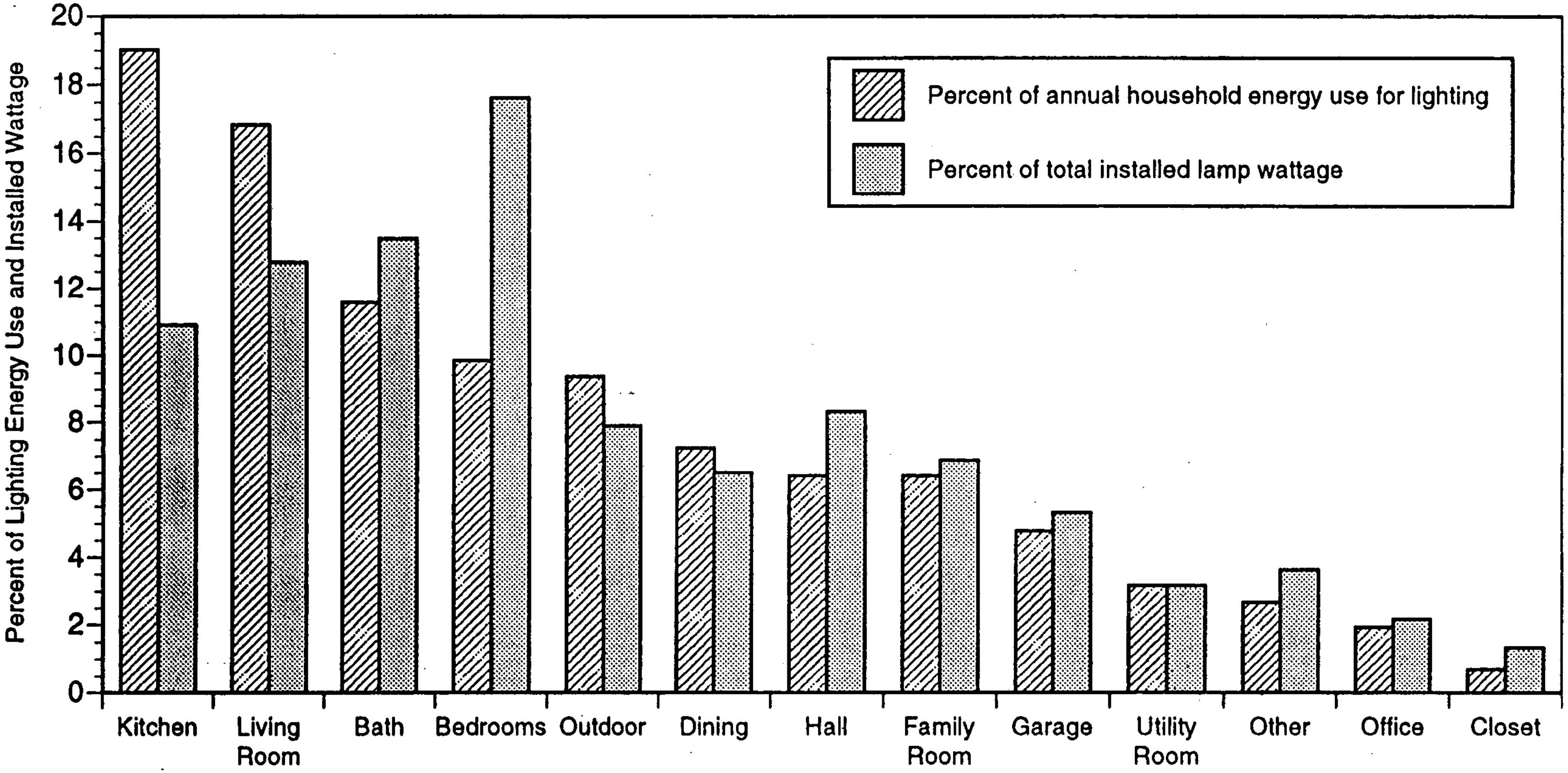
As seen in Figure 2.2, for most household room types, relative energy consumption corresponds closely to installed wattage – for example, dining rooms have approximately 7% of the installed household wattage and also use about 7% of total household lighting energy; this correspondence indicates that, throughout many parts of the household, the lamps in each room are turned on for about the same total number of hours. However, energy use and installed wattage do not correspond so closely for kitchens and living rooms (the two rooms in the household that have the highest lighting energy use as well as the highest installed wattage on a room-by-room basis). In both the kitchen and the living room, the percentage of total lighting energy use is considerably higher than the percentage of total installed wattage. This indicates that the lights in the kitchen and living room are typically turned on for more hours than the lights in other rooms of the house.

---

[6] While a "lamp" refers to an individual light bulb, a "fixture" may house one or more lamps.

[7] In EIA (1996b), a "light" is defined as every light bulb turned on by a single switch. If a light has only one switch, it is counted as one light, even if it has more than one bulb. A fixture or lamp with two switches controlling different bulbs is counted as two lights. If two switches control the same light, it is counted as one light.

FIGURE 2.2. ANNUAL LIGHTING ENERGY CONSUMPTION AND INSTALLED LAMP WATTAGE IN HOUSEHOLDS, BY ROOM TYPE



Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995. Rooms are listed in order of decreasing energy consumption.
Source: Adapted from Jennings et al. (1996); TPU data updated based on Moezzi (1996-97)

2.1.4. Residential Lamp Types

The majority of lamps used in the residential sector are incandescent lamps and tubular fluorescent lamps (often referred to as "standard fluorescent" lamps).[8] According to EIA (1996b), about 87% of household lights in use for more than fifteen minutes per day are incandescent. Similarly, based on the TPU analysis, incandescent lamps account for about 78% of lighting hours and consume about 86% of household lighting energy, while tubular fluorescent lamps account for about 22% of household lighting hours and consume about 13% of household lighting energy (Moezzi 1996-97). In addition, compact fluorescent lamps (CFLs) and high-intensity discharge (HID) lamps are found in some homes.

In 1992, researchers at the Lighting Research Center at Rennselaer Polytechnic Institute (RPI) conducted a telephone survey in approximately 2500 homes in Albany, New York, asking household residents what type of lamps they used in the primary fixture of different room types (Leslie and Conway 1993). The results of the RPI survey are summarized in **Table 2.3.** Clearly, incandescent lamps are the most commonly used in the primary fixture of every room type; however, in kitchens and bathrooms, tubular fluorescents are also quite popular.

Table 2.3. Percentage of Homes with Lamp Type in Room's Primary Fixture

Room Type	Incandescent	Tubular Fluorescent	CFL	Other
Kitchen w/only one primary fixture	57%	41%	<2%	<1%
Kitchen w/primary fixtures in both the cooking & dining areas:				
Cooking area	60%	38%	<2%	<1%
Dining area	79%	19%	<2%	<1%
Main Bathroom	77%	22%	<1%	<1%
Main Living/Family Room	96%	2%	2%	<1%
Main Bedroom	98%	<2%	<1%	<1%
Front Porch	98%	<1%	<1%	<1%
Back Porch	97%	<2%	<1%	<2%

Source: Leslie and Conway (1993) based on a 1992 telephone survey of approximately 2500 households in Albany, New York.

Generally, the lamp types identified in the RPI survey correspond to the data collected for the TPU analysis. **Table 2.4** summarizes the percent of homes with a lamp type in a given room type, based on data from the TPU study (Moezzi 1997). When comparing the tables, it should be noted that the RPI survey focused on the *primary* fixture in each room type; in contrast, the TPU data indicates whether there was a certain lamp type in *any* fixture in the room. Again, incandescent lamps are by far the most common lamps found in all room types and tubular fluorescent lamps are far more likely to be used in the kitchen than in any other room. In addition, many of the homes metered for the TPU analysis use tubular fluorescents in the garage.

---

[8] Refer to Appendix A for summary descriptions of different lamp types. The tubular fluorescent lamp category includes circline lamps as well as linear lamps.

Table 2.4. Percent of Homes with Lamp Type in Room

Room Type	Standard Incandescent Lamps	Incandescent Reflector Lamps (non-halogen)	Tungsten-Halogen Lamps (incl. reflectors)	Tubular Fluorescents	CFLs	Other (incl. HID and quartz)
Kitchen	88%	24%	2%	52%	7%	1%
Bathroom	96%	17%	0%	12%	2%	<1%
Living Room	98%	9%	6%	4%	8%	1%
Family Room	50%	6%	3%	13%	4%	2%
Bedroom	100%	6%	2%	9%	5%	2%
Dining Room	80%	4%	0%	4%	0%	1%
Utility Room	65%	3%	0%	16%	4%	<1%
Outdoor	80%	35%	7%	1%	5%	11.2%
Garage	49%	3%	1%	34%	1%	0%

Notes: These percentages are based on surveys of 161 single-family homes in the Pacific Northwest. Data indicate the percent of homes surveyed that have at least one of a particular lamp type in at least one of a particular room type. In any home, a single room type may contain more than one lamp type. These percentages do not take into account whether or not a house has a certain type of room. For most room types listed, this is not an issue (e.g., most homes have kitchens, bathrooms, bedrooms, and living rooms). However, some homes may not have family rooms, utility rooms, or garages. It should thus be noted that the percentage of homes surveyed (161) that use fluorescents in the garage is 34%; the percent of garage-possessing homes that use fluorescents in their garages will be higher than 34%.

Source: Based on TPU data obtained from Moezzi (1996-97)

Figure 2.3, which is based on TPU data, shows the percentage of annual household energy consumption for standard fluorescent lamps, CFLs, and incandescent lamps by room type. As mentioned above, incandescents account for more than 85% of household lighting energy consumption. The only room in which standard fluorescents consume more energy than incandescents is the garage. Overall, standard fluorescents consume about 13% of total household lighting energy while CFLs account for less than 1%.

Table 2.5, which is based on EIA (1996b), reports the percentage of lights found in 474 homes in terms of both lamp type and the room type in which the lights are located. The EIA data support the trends identified by both RPI and TPU: incandescent lamps dominate in every room type (accounting for 88% of all lights in the homes surveyed) and tubular fluorescents (accounting for only 8% of the lights in the homes) are most commonly found in kitchens, bathrooms, and utility areas. In addition, the EIA report (1996b) points out that fluorescent lights tend to have longer lighting hours than incandescents; for example, about 21% of household lamps used daily for more than 12 hours are fluorescent.

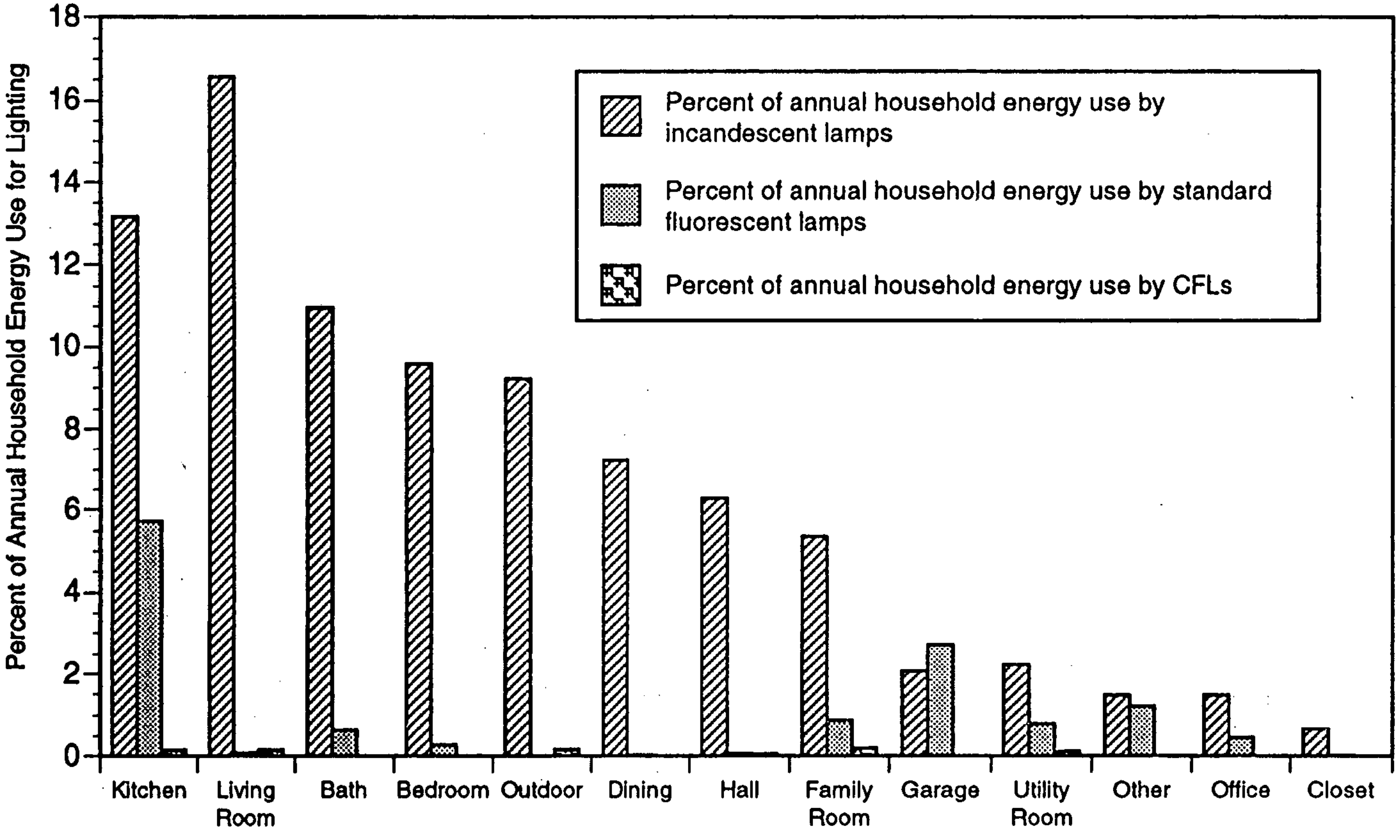
Table 2.5. Percentage of Household Lights by Lamp and Room Type

Room Type	Incandescent	Tubular Fluorescent	CFL	Other/ Unknown	TOTAL
Bathroom	88%	8%	<1%	4%	100%
Bedroom	95%	1%	<1%	3%	100%
Dining Room	93%	<1%	<1%	6%	100%
Den/Family Room	88%	7%	<1%	5%	100%
Hallway/Stairs	95%	2%	0%	3%	100%
Kitchen	72%	23%	1%	3%	100%
Living Room	93%	3%	1%	3%	100%
Laundry Room/Other	81%	16%	0%	3%	100%

Note: See footnote in Section 2.1.3 for the definition of a "light" as used in EIA (1996). These data were obtained from the 474 households surveyed using the RECS Lighting Supplement. Of the incandescent lights reported, fewer than 1% were halogen lamps.
Source: Based on data obtained from EIA (1996b)

The TPU study found that CFLs are most commonly located in living rooms, kitchens, bedrooms, hallways, and outdoors (Moezzi 1996-97). As seen in Table 2.5, based on EIA data, CFLs are most commonly found in kitchens and living rooms. Similarly, an EPRI survey of 178 CFL users in San Francisco, Chicago, Milwaukee, New York City, and Boston (Weiner and Campbell 1992) determined that CFLs are most frequently found in living rooms, bedrooms, kitchens, hallways, and bathrooms. The results of the EPRI survey are summarized in **Table 2.6**.

FIGURE 2.3. ANNUAL LIGHTING ENERGY CONSUMPTION IN HOUSEHOLDS, BY LAMP AND ROOM TYPE



Note: The data for incandescent lamps also includes other lamp types including quartz and some HID lamps; these "other" lamp types, however, account for less than 1% of the energy consumption represented by the "incandescent" category in the figure. Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995. Rooms are listed in order of decreasing energy consumption.
Source: Adapted from Jennings et al. (1996); TPU data updated based on Moezzi (1996-97)

Table 2.6. Distribution of CFLs in CFL-Using Homes

Room Type	Percentage of CFLs Found in Room Type
Living Room	21%
Master Bedroom	13%
Kitchen	11%
Other Bedroom	11%
Hallway	8%
Master Bathroom	8%
Outside	6%
Laundry	6%
Dining Room	5%
Garage	4%
Other Bathroom	3%
Other Room	4%
TOTAL	100%

Source: Weiner and Campbell (1992)

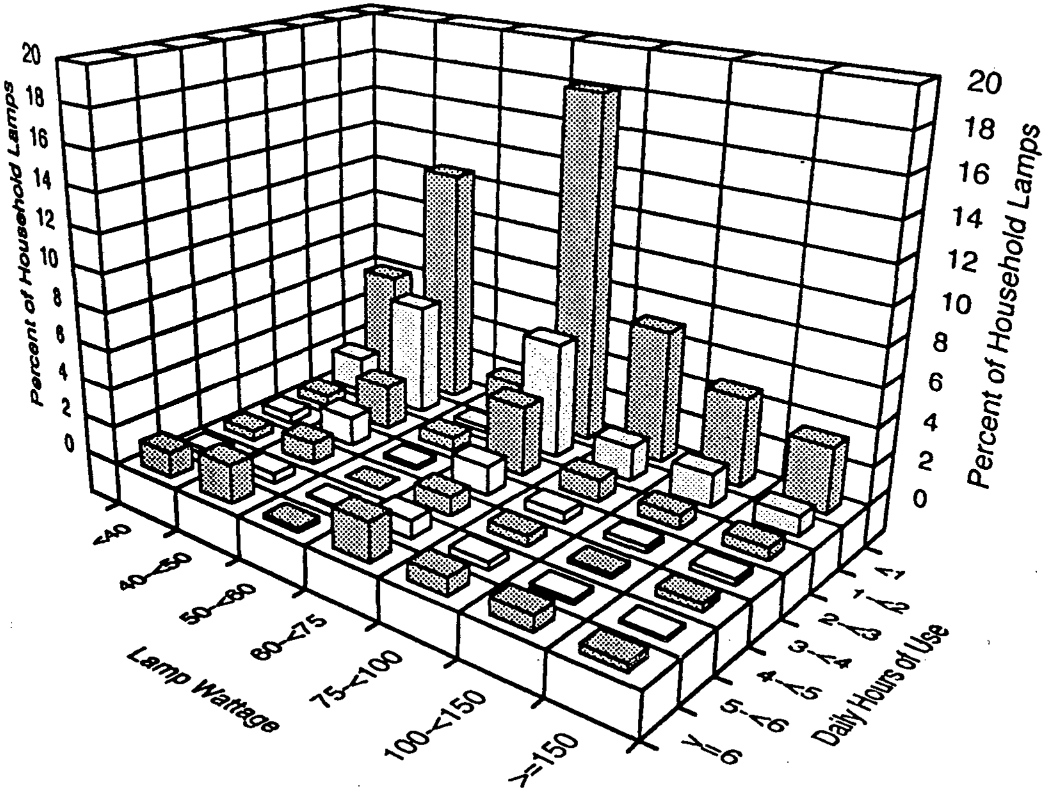
2.1.5. Wattage, Hours of Use, and Relative Energy Use of Residential Lamps and Fixtures

Figure 2.4 and **Figure 2.5** show the percentage of household lamps and fixtures that fall into various wattage and daily hours-of-use categories, based on the TPU analysis. **Figure 2.6** and **Figure 2.7** show the percentage of household lighting energy consumption that is accounted for by lamps and fixtures with different wattages and hours of use. **Table 2.7** and **Table 2.8** summarize the data presented for lamps in Figures 2.4 and 2.6. It can be seen in these figures and tables that the majority of household lamps and fixtures tend to be concentrated in the low-wattage and low-usage categories.

About three-quarters of lamps have wattages of less than 75, and three-quarters of fixtures have total wattages of less than 150. In addition, more than half of both lamps and fixtures are used for less than one hour per day, and more than 70% of both lamps and fixtures are used for less than two hours per day. Based on Table 2.7, only 28% of household lamps are used for more than two hours per day, but these lamps account for more than 75% of lighting energy use. Although less than 4% of lamps are used for more than ten hours per day, these lamps account for almost 25% of lighting energy use. In Table 2.8, we can see that about 95% of lighting energy is consumed by lamps of less than 200 watts. Lamps with wattages from 50-<75 watts consume approximately 32% of lighting energy. Note that almost all residential fluorescent lamps are included in the <50 watt category; the average hours of use for these fluorescent lamps (3 hours per day) are much higher than the hours of use for the incandescents in the same wattage category as well as the average hours of use for all lamp types (mostly incandescent) in all other wattage categories.

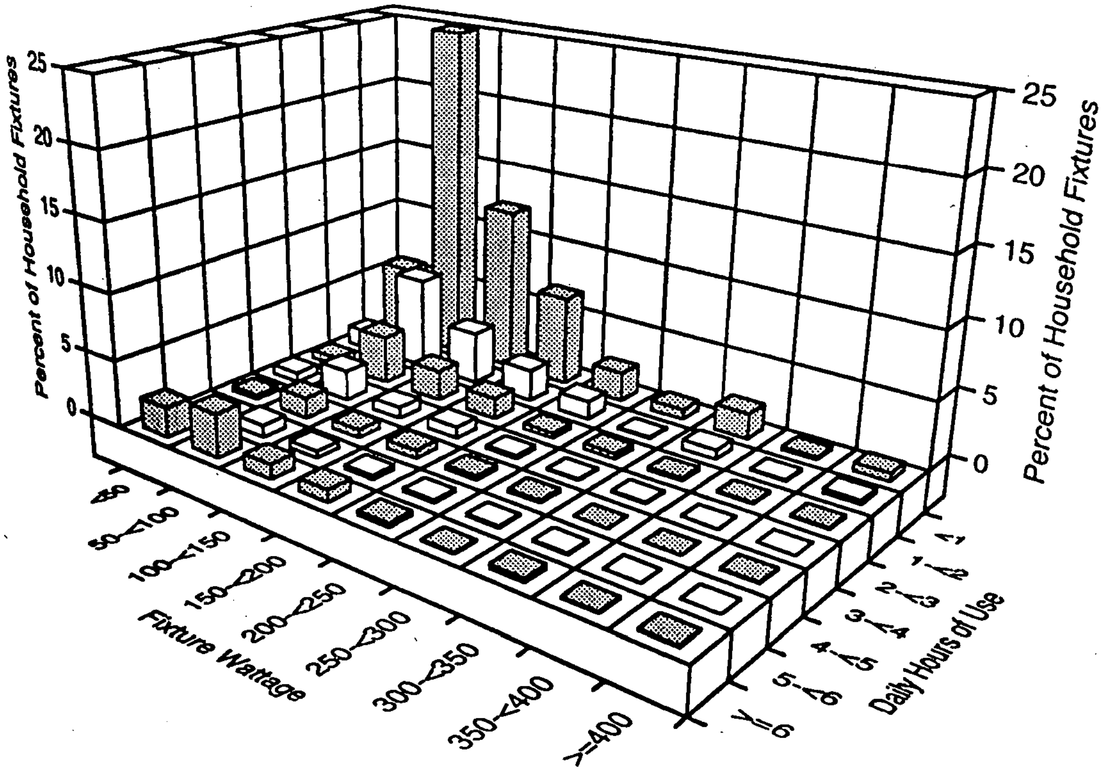
Figure 2.8 indicates, for fixture types, the percent of total installed wattage in the household and the percent of annual household energy consumption for lighting. With respect to different types of fixtures, wall and closed ceiling fixtures account for both the highest installed wattage and highest energy consumption. Fluorescent lamps are most commonly found in closed ceiling fixtures, but are also relatively common in bare bulb, open ceiling, recessed, and pendant fixtures as well as desk lamps (Moezzi 1996-97).

FIGURE 2.4. LAMP WATTAGE AND DAILY HOURS OF USE IN HOUSEHOLDS



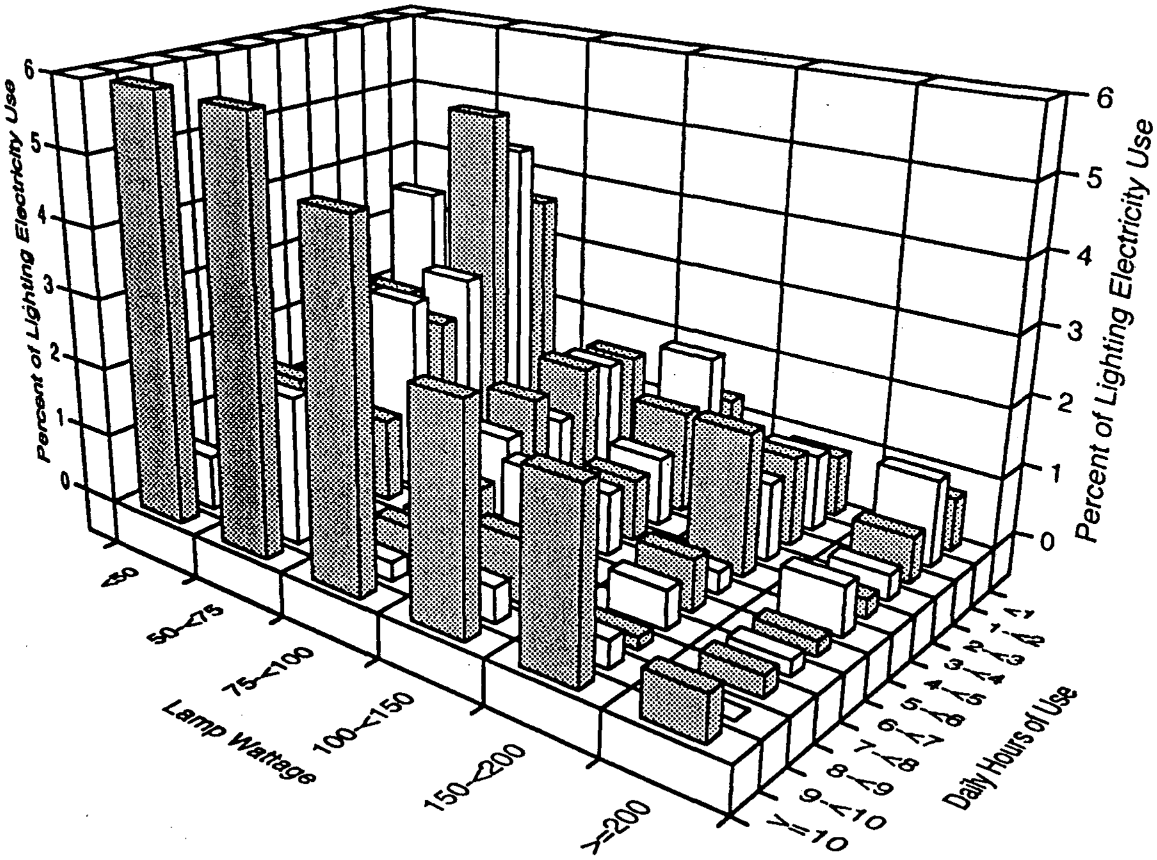
Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995.
Source: Adapted from Jennings et al. (1996); TPU data updated based on Moezzi (1996-97)

FIGURE 2.5. FIXTURE WATTAGE AND DAILY HOURS OF USE IN HOUSEHOLDS



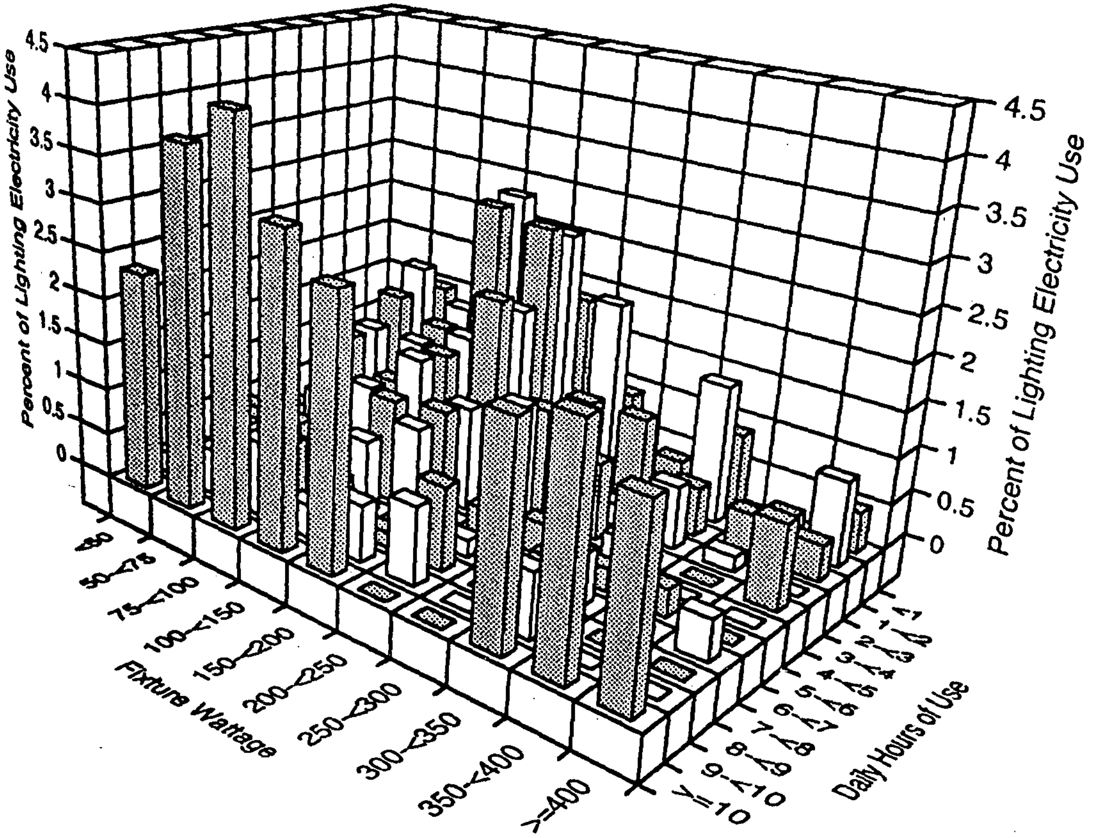
Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995.
Source: TPU data obtained from Moezzi (1996-97)

FIGURE 2.6. HOUSEHOLD USE OF LIGHTING ENERGY BY LAMP WATTAGE AND DAILY HOURS OF USE



Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995.
Source: TPU data obtained from Moezzi (1996-97)

FIGURE 2.7. HOUSEHOLD USE OF LIGHTING ENERGY BY FIXTURE WATTAGE AND DAILY HOURS OF USE



Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995.
Source: TPU data obtained from Moezzi (1996-97)

Table 2.7. Percent of Household Lamps and Lighting Energy Use in Terms of Daily Hours of Use

Hours of Use Per Day	Percent of Household Lamps	Percent of Household Lighting Energy Use
<1	53.2%	9.9%
1-<2	18.6%	13.9%
2-<3	9.5%	12.2%
3-<4	4.8%	8.2%
4-<5	3.8%	8.9%
5-<6	2.5%	7.0%
6-<7	1.6%	4.7%
7-<8	1.0%	4.2%
8-<9	0.9%	3.7%
9-<10	0.9%	4.0%
≥10	3.4%	23.3%
TOTAL:	100%	100%

Note: Average lamp wattages for each of the hours-of-use categories shown in this table fall into a narrow range (≈58-66 watts), indicating that lamp wattage does not typically correlate with hours of use.

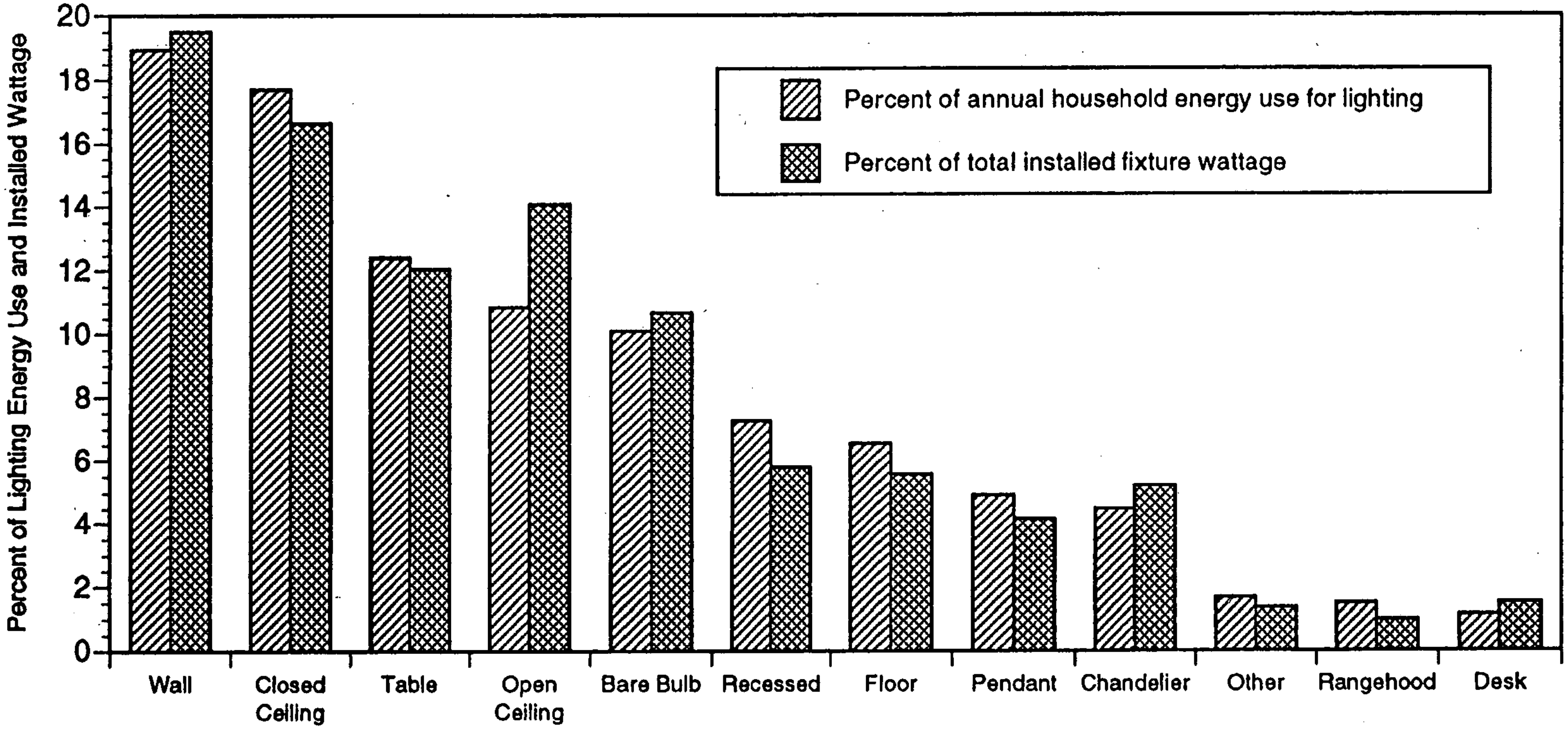
Source: Moezzi (1996-97), based on data obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest

Table 2.8. Percent of Household Lamps and Lighting Energy Use in Terms of Lamp Wattage

Lamp Wattages	Percent of Total Household Lamps	Percent of Total Household Lighting Energy Use	Average Hours of Use in Wattage Category (hours per day)
<50 (all lamp types)	36.8%	22.1%	2.2
<50 (fluorescent)	*14.0% of total* *93.3% of fluor.*	*11.3% of total* *82.9% of fluor.*	*3.0*
<50 (incandescent)	*22.2% of total* *26.3% of incand.*	*10.5% of total* *12.3% of incand.*	*1.7*
50-<75	36.5%	32.4%	1.8
75-<100	12.0%	15.3%	2.0
100-<150	8.6%	14.0%	2.0
150-<200	4.5%	10.9%	2.0
200-<250	0.3%	0.3%	0.6
250-<300	0.7%	2.6%	1.9
300-<350	0.6%	1.5%	1.0
350-<400	<0.1%	<0.1%	0.9
≥400	0.1%	0.8%	2.1
TOTAL	100%	100%	NA

Source: Moezzi (1996-97), based on data obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest.

FIGURE 2.8. ANNUAL LIGHTING ENERGY CONSUMPTION AND INSTALLED FIXTURE WATTAGE IN HOUSEHOLDS



Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest between 1993 and 1995.
Source: Adapted from Jennings et al. (1996); TPU data updated based on Moezzi (1996-97)

Table 2.9 indicates, for lamps in all hours-of-use categories, the room/fixture combinations that have the highest annual energy use. The room/fixture combinations listed account for about 34% of all household fixtures in the TPU analysis and, as noted in the table, about 50% of the total lighting energy. On average, table and floor lamps located in living rooms account for about 13% of lighting energy use in homes; recessed and closed ceiling fixtures in kitchens also account for about 13% of household lighting energy use; and wall fixtures and bare bulbs located outdoors account for about 8%. In the room/fixture combinations noted in Table 2.9, the highest energy-using fixture type is the wall-mounted fixture; the wall fixtures noted (in bathrooms and outdoors) together consume about 14% of household lighting energy.

Table 2.9. Location and Type of Highest Energy-Consuming Fixtures

Room Type	Fixture Type	Percentage of total household annual lighting energy consumed by the specified room/fixture combination
Kitchen	Closed Ceiling	8.0%
Living Room	Table	7.6%
Bath	Wall	7.5%
Outdoor	Wall	6.9%
Living Room	Floor	5.3%
Kitchen	Recessed	4.8%
Dining Room	Chandeliers	3.2%
Garage	Bare Bulb	3.4%
Family Room	Table	1.9%
Outdoor	Bare Bulb	1.3%
TOTAL		49.9%

Note: Data were obtained from TPU analysis of lighting energy use in 161 single-family homes in the Pacific Northwest. Only fixture types for which there were more than 50 fixtures in aggregate are included in this table.
Source: TPU data were updated based on Moezzi (1996-97)

Based on the TPU data, there tend to be a few fixtures in each home that use the bulk of household lighting energy. For example, based on the logged fixtures only, the highest energy-consuming fixture in a home consumes an average of 27% of household lighting energy; the top three energy-consuming fixtures in a home account for 53% of lighting energy use; and the top five account for almost 70% of household lighting energy use (Moezzi 1996-97). Among all fixtures included in the "top three per household", 22% were located in the kitchen, 19% were located in the living room, and 15% were located in the bathroom; in terms of fixture type for the top three per household, 21% were wall fixtures, 18% were closed ceiling fixtures, and 16% were table lamps (Moezzi 1996-97).

Because the bulk of residential lighting is incandescent, there are many opportunities for energy savings. Based on the TPU analysis, 27% of household fixtures account for about 80% of lighting energy use (Jennings et al. 1996, Moezzi 1996-97). Consequently, if we can identify these high-use fixtures, programs and policies can focus on promoting energy-efficient alternatives for specific fixtures in specific locations. As discussed above, there tend to be only a few high-use fixtures in an average home; thus, it may be easier and less expensive to design a strategy that focuses on the fixtures that consume the most energy. Based on the TPU data, the types of household fixtures that consume the most energy are wall and closed ceiling fixtures; in addition, high-use fixtures are most likely to be located in the kitchen and the living room. The policy implications of available residential lighting data are discussed further in Chapter 5.

2.2. Commercial Lighting Energy Use and Equipment Ownership

2.2.1. Sources and Limitations of Commercial Lighting Data

In recent years, the most comprehensive source of lighting data for the commercial sector has been EIA's "Lighting in Commercial Buildings" (1992). Because the EIA report is based on 1986 CBECS (Commercial Buildings Energy Consumption Survey) data, several trends noted in that report may no longer be valid. In addition, we have some concerns regarding both the illuminance levels and operating hours used by EIA in their report.

In EIA's "Lighting In Commercial Buildings," calculation of lighting power density, energy intensity, and annual lighting energy use are based on the illuminance levels *at the workplane* recommended by the Illuminating Engineering Society of North America (IES). However, in the EIA report, these illuminance levels are used to represent *source lumens*. EIA's calculations of lighting power density, energy intensity, and annual lighting energy use based on footcandles at the workplane are thus lower than they would be if calculated based on source lumens. In addition, the method that the report authors used to calculate illuminance levels based on IES was not always reliable. For example, the EIA report uses 187 lumens per square foot as the average illuminance level for health care facilities; although hospitals may require 187 lumens per square foot over surgery tables, they do not need this very high illuminance level throughout the entire hospital. In this case, EIA's assumptions led to an energy use estimate that was much too high.

Researchers at the Lawrence Berkeley National Laboratory (LBNL) believe that, for some building types, the lighting hours in the EIA report may be overestimated for a number of reasons: (1) the calculation of these lighting hours assumed that lighting equipment was in use during *all* the hours that a building was operating while, in reality, some lights may have been turned off during those hours, and (2) floorspace classified as lit during off-hours was considered to be lit during *all* off-hours – in fact, lights may have been operating for less than the entire period (Atkinson et al. 1992). For example, EIA's lighting hours for lodging facilities are likely to be so high (≈160 hours per week) because many hotels and motels are open to the public round the clock and the lamps in the hallways and reception areas of these buildings are almost always illuminated. However, one would not expect the long lighting hours for lodging to apply to the lamps located in guest rooms – typically, these lamps are not in use when the room is unoccupied and are also extinguished during the night when most guests are sleeping.

Because of these concerns, we present instead a lighting data set for commercial buildings that was developed for the Commercial End-Use Planning System (COMMEND) ballast analysis at LBNL. These data are being developed as part of an assessment of possible modifications to current efficiency standards for ballasts (1997a, 1997b). Although the COMMEND data set is still being finalized, we believe these data to be more reliable than EIA's lighting data. Both the lighting hours and shares of delivered lumens by lamp type that we present in this chapter were calculated by LBNL researchers based on data obtained from Xenergy's XENCAP database of lighting equipment and lighting hours of operation for more than 24,000 commercial and industrial buildings for the years 1990-1995. The data we present for illuminated interior floorspace, energy intensity, and annual on-site lighting energy use were obtained by LBNL from Regional Economic Research, Inc. (RER) and are based on 1992 CBECS data. Lighting power densities were calculated for this report based on the lighting hours and energy intensities specified in the COMMEND database.

2.2.2. Commercial Lighting Energy Use

According to EIA (1996a), commercial buildings in the U.S. consumed 340 TWh of electricity for lighting in 1995, accounting for more than one-third (36.5%) of total commercial electricity consumption and a 16% share of total commercial energy consumption. Based on a reported 7.9¢/kWh average commercial electricity tariff, EIA estimates that lighting cost U.S. businesses $26 billion in 1995.

There is significant variability, however, in estimates of national commercial lighting electricity use. In contrast to the EIA estimate for 1995, Vorsatz and Koomey (1997) estimate 1995 commercial lighting energy use to be about 240 TWh (**Figure 2.9**). In general, EIA's analysis results are based on surveys combined with conditional demand techniques while the results of analyses at energy research institutions such as LBNL are based upon detailed bottom-up end-use models. Because of the different methods used in their calculations, estimates of the same energy parameter by EIA and other institutions such as LBNL can vary substantially; currently, there is no independent check as to which procedure is producing the most accurate estimates.

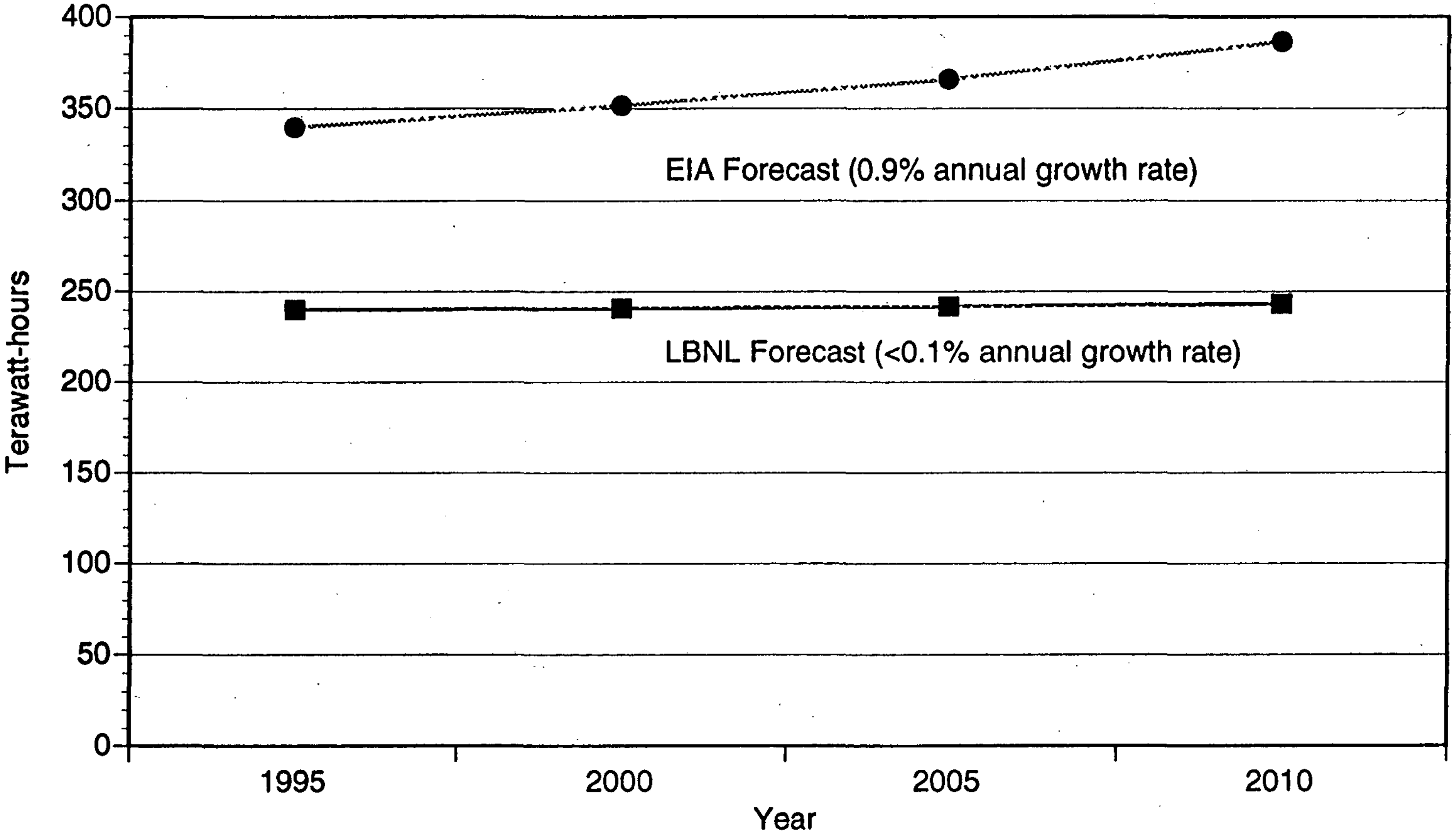
Trends in commercial lighting electricity use will be significantly affected by the future of federal lighting equipment and building performance standards, EPA Green Lights and Energy Star Buildings programs (see Section 4.2.3), the DOE Federal Energy Management Program (FEMP), utility DSM programs, state building codes, and market-pull programs. However, even if no efficiency improvements are made beyond the average efficiency of new lighting equipment in 1995, Vorsatz and Koomey (1997) forecast little growth in national commercial electricity use for lighting through 2010 (<0.1% annual growth rate). The EIA forecast also indicates that lighting electricity use (0.9% annual growth rate) will grow less quickly than floorspace in the commercial sector; commercial floor space is expected to increase from 71 billion square feet to 83.3 billion square feet between 1995 and 2010 (1.1% annual growth rate) (EIA 1996a). The federal efficiency standards for lamps and ballasts that took effect prior to 1996 are to some degree responsible for this leveling trend (see Section 2.3 for a summary of regulations affecting lighting equipment). In addition, as older spaces are upgraded, they use proportionally less energy.

2.2.3. Distribution of Commercial Energy Consumption by Building Type

Commercial lighting energy analyses typically disaggregate energy use by building type. Often, 10-12 building types are distinguished. **Figure 2.10** shows the average annual energy consumption for indoor lighting in common categories of commercial building types; as mentioned above, the energy consumption data were obtained by LBNL from Regional Economic Research, Inc. and are based on 1992 CBECS data. **Table 2.10** presents data for commercial lighting energy consumption, illuminated floorspace, weekly lighting hours, lighting power density, and lighting energy intensity for different commercial building types.

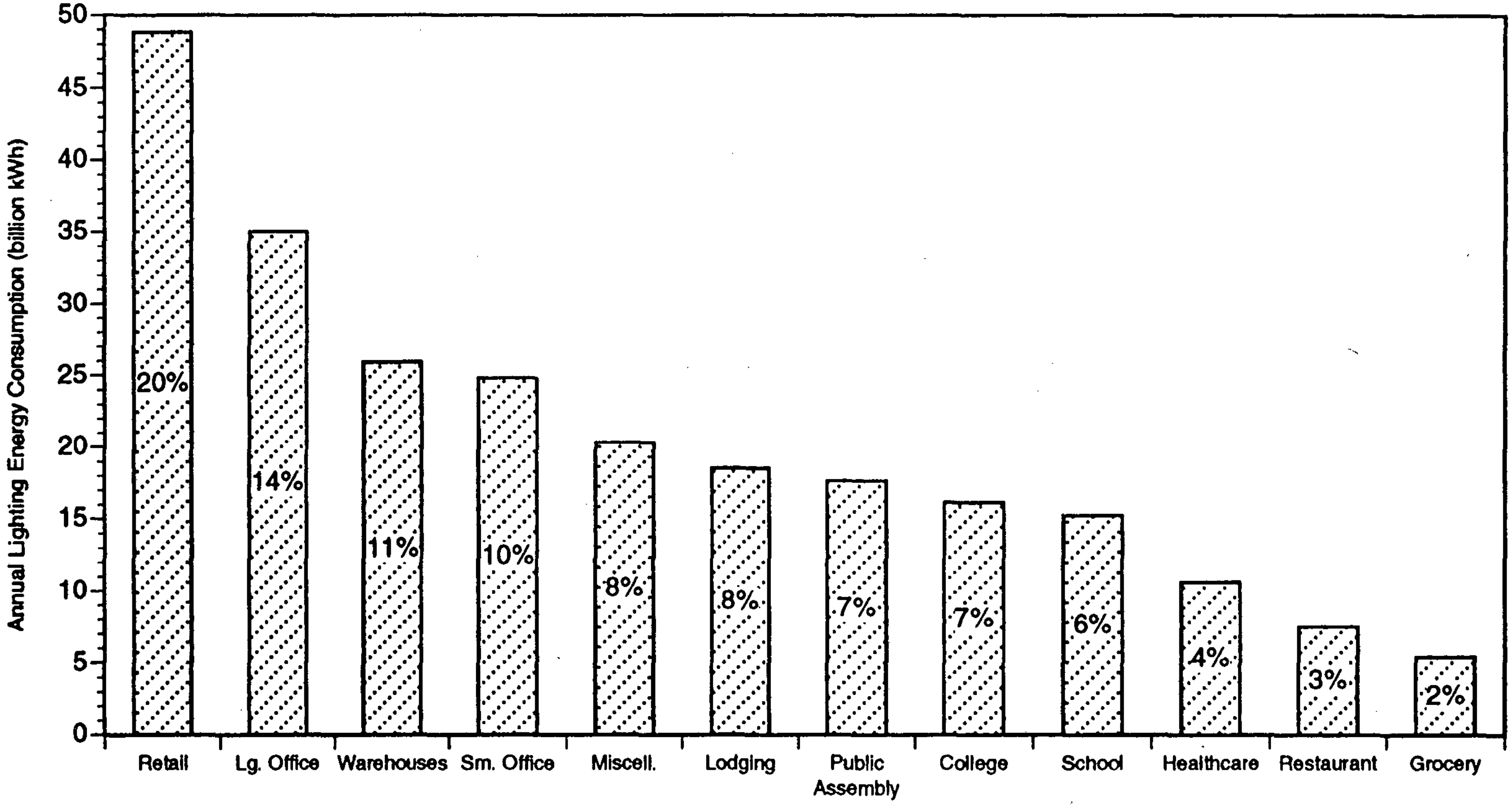
As seen in Figure 2.10, energy consumption in different building types varies dramatically. For example, retail buildings consume about 20% of all commercial lighting energy, while restaurants and groceries together consume only about 5% of total commercial lighting energy. Lighting energy consumption in commercial buildings depends on many factors, including: (1) the amount of floorspace to be illuminated, (2) the illuminance level within the building, (3) the number of hours the lights are on, and (4) the energy-efficiency of the lighting equipment. These factors are discussed below for various building types.

FIGURE 2.9. FORECASTED ELECTRICITY USE FOR COMMERCIAL LIGHTING, 1995 - 2010, (TWh)



<u>Source:</u> LBNL forecast adapted from Vorsatz and Koomey (1997); EIA forecast data obtained from EIA (1996a)

FIGURE 2.10. ANNUAL ENERGY CONSUMPTION FOR INDOOR LIGHTING IN U.S. COMMERCIAL BUILDINGS



Source: Based on data obtained from LBNL's Technology and Market Assessment Group (1997b), presentation material for DOE Public Workshop on Fluorescent Ballasts, March 18th 1997, Washington D.C.

Table 2.10. Characteristics of 1992 Commercial Lighting Energy Consumption, Based on COMMEND Database

Building Type	Annual on-site interior lighting energy use (billion kWh)	Illuminated interior floorspace (billion sq ft)	Lighting hours (hours/week)	Lighting power density* (watts/sq ft)	Lighting energy intensity (kWh/sq ft/year)
Data Source	LBNL obtained data from RER; the data are based on 1992 CBECS	LBNL obtained data from RER; the data are based on 1992 CBECS	Based on Xenergy data (1990-1995) adapted by LBNL	Calculated by authors based on lighting hours and energy intensities specified in this table	LBNL obtained data from RER; the data are based on 1992 CBECS
Retail	48.8	12.5	74	1.0	3.9
Large Office	35.0	6.8	80	1.2	5.2
Warehouses	25.9	11.5	68	0.6	2.3
Small Office	24.8	5.6	58	1.5	4.4
Miscellaneous	20.3	8.0	66**	0.7	2.5
Lodging	18.5	2.9	82	1.5	6.4
Public Assembly	17.6	8.3	32	1.3	2.1
College	16.1	3.1	72	1.4	5.3
School	15.2	5.4	49	1.1	2.8
Healthcare	10.6	1.8	104	1.1	6.0
Restaurant	7.5	1.5	80	1.2	5.0
Grocery	5.4	0.8	116	1.2	7.1
TOTAL	245.7	68.1	average lighting hours, wtd by floorspace: 66	average power density, wtd by floorspace: 1.1	average energy intensity, wtd by floorspace: 3.6

* A low power density in a given building type should not be equated with lighting energy efficiency. The lighting power densities presented in this table represent averages across all the different types of space within a given building type (e.g., the "retail" building category includes not only areas in which merchandise is displayed but also areas for merchandise storage and administrative offices). Even in building types with low power densities, there can be significant potential for cost-effective energy savings. For example, while department stores use a large percentage of fluorescent lamps, and shopping malls often illuminate common spaces with HID lamps, small retail stores frequently use incandescent lamps and thus provide a significant opportunity for energy savings. Consequently, if you are trying to infer the potential for energy savings within a given building type, you need to look not at the average energy consumption characteristics of the building type, but at the different types of space that make up the building type, the technologies used to illuminate the individual space types, and the lighting levels and lighting hours within them.

** Because Xenergy data did not include a "miscellaneous" building type, we assume the lighting hours for the miscellaneous building type to be the average lighting hours for all other commercial building types weighted by the square footage of each building type as reported in 1992 CBECS.

Source: Primary data sources are noted within table. Energy use, floorspace, lighting hours, and energy intensity data were obtained from LBNL's Technology and Market Assessment Group (1997b) presentation material for a DOE Public Workshop on Fluorescent Ballasts, March 18th 1997, Washington D.C.

Illuminated Floorspace

The amount of lighting energy required for a given building type depends upon the amount of illuminated floorspace. **Figure 2.11** shows the total amount of illuminated interior floorspace for different commercial building types; the data were obtained by LBNL from Regional Economic Research, Inc. and are based on 1992 CBECS data. Illuminated floorspace by building type is also presented in Table 2.10.

The building types with the greatest amount of illuminated floorspace include retail stores, warehouses, assembly halls, and offices. Together, these building types account for two-thirds of all commercial-sector illuminated floorspace.

Illuminance Levels

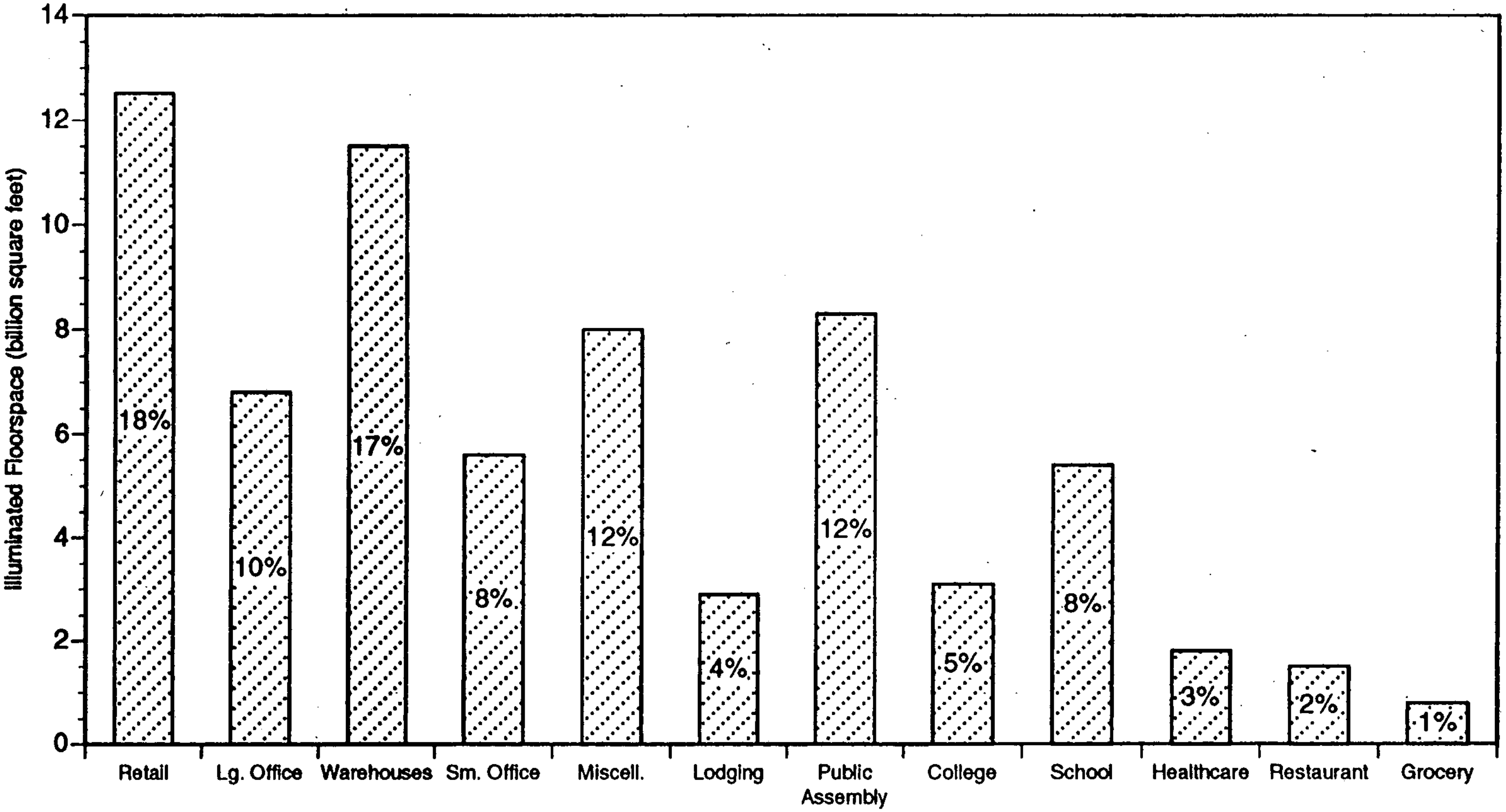
Energy consumption for lighting also depends on the illuminance level used within the building. According to the Illuminating Engineering Society of North America (IES) (1993), the appropriate illuminance level in a given space depends on a number of factors including the following: the type of activity within the space and the degree to which it depends on visual performance; the characteristics of the visual task; the age of the occupant (older people generally require more light to see); the importance of visual performance in terms of speed and accuracy; and the reflectance of the room surfaces (ceiling, walls, floor). Because of changes in building codes over time, the age of an existing building can also be a factor in its lighting level. For example, between the early 1970s and late 1980s, the lighting levels recommended by IES decreased by 34% for retail buildings, 21% for office buildings, 17% for schools, and 15% for hospitals (Mills et al. 1993). For a discussion of trends in recommended lighting levels internationally, see Mills and Borg (1993).

Table 2.11 presents building illuminance levels that were calculated indirectly, as a part of the COMMEND model calibration process; these calculations were based on lighting hours, energy intensities, and estimated technology characteristics and market shares in COMMEND. If the illuminance levels resulting from the model calibration were very different from illuminance values computed by averaging IES light levels over the different task areas for a building type, it would indicate a probable error. When compared to average IES light levels in a rough check calculation, some of the calibration results do differ somewhat and may warrant future analysis (e.g., groceries seem low, restaurants may be high); however, none of the deviations indicate a major error.

Table 2.11. Illuminance Levels Calculated as Part of the COMMEND Model Calibration Process

Building Type	Illuminance level at the workplane (footcandles)
Retail	34
Large Office	42
Warehouses	21
Small Office	48
Miscellaneous	21
Lodging	36
Public Assembly	30
College	45
School	35
Healthcare	35
Restaurant	29
Grocery	39

FIGURE 2.11. ILLUMINATED FLOORSPACE IN U.S. COMMERCIAL BUILDINGS



Note: The building types indicated in this figure are arranged in order of descending lighting energy consumption.
Source: Based on data obtained from LBNL's Technology and Market Assessment Group (1997b), presentation material for DOE Public Workshop on Fluorescent Ballasts, March 18th 1997, Washington D.C.

The illuminance levels calculated in the COMMEND calibration process range from 21 footcandles for both warehouses and miscellaneous buildings to about 48 footcandles for small offices.[9] The highest illuminance levels were found in office buildings, colleges, and groceries. It should be noted that these illuminance levels represent footcandle levels "at the workplane". Because of losses in the luminaire and at room surfaces, not all lumens emitted by a lamp will reach the work plane. Consequently, the quantity of lumens emitted by a lamp is multiplied by a "coefficient of utilization" (CU) which represents the ratio of the lumens from a luminaire that fall on a room's workplane to the total number of lumens produced by the lamps within the luminaire. The CUs used in COMMEND are unique to each lighting system type.

Lighting Hours

The amount of lighting energy consumed in a given building type depends on how many hours the lights are in use. Lighting hours vary significantly by building type. Table 2.10 and **Figure 2.12** provide weekly lighting hours for different commercial building types; these lighting hours were calculated by LBNL researchers based on data obtained from Xenergy's XENCAP database. Xenergy's commercial data were obtained from energy audits and interviews with building managers.

Based on Sezgen et al. (1994), HID lamps have longer lighting hours than fluorescent and incandescent lamps in almost all building types. Because of their long warm-up and restrike times, HID lamps are most often used in areas where they will not be turned off and on more than once a day.

Lighting Equipment

The energy efficiency of the lighting equipment used in a building can have a large impact on the amount of energy consumed. Lighting efficiency is referred to as "efficacy," and is calculated by dividing the quantity of the light emitted by the lamp (in lumens) by the power input (in watts) to the system (lamp/ballast). **Table 2.12** indicates typical ranges of initial system efficacy for incandescent, fluorescent, and HID lamps. The especially wide range in efficacy shown for HID lamps is due to the three different types of HID lamps that are most commonly used for general lighting.[10] Mercury vapor (MV) lamps have the lowest efficacy (36 lumens/watt for the most commonly used lamps); metal halide (MH) efficacies are mid-range; and high-pressure sodium (HPS) lamps are the most efficacious. (See Appendix A, Tables A.3 - A.6, for efficacies of specific incandescent, fluorescent, and HID lamp types.)

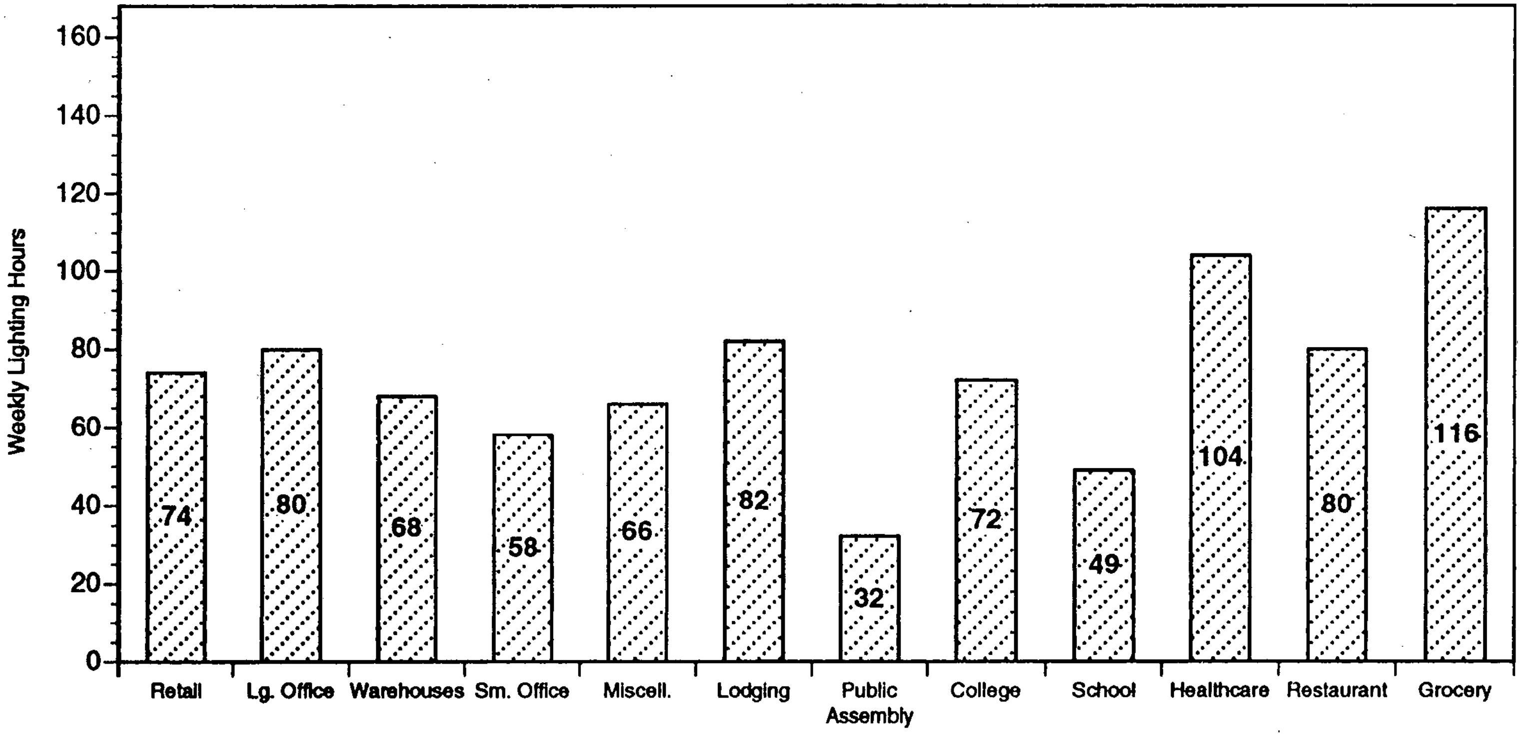
As indicated in Table 2.12, HID and fluorescent lamps are typically far more efficient than incandescent lamps. Consequently, buildings that are predominantly lit by fluorescent and HID lamps generally use less energy for light production than similar buildings that use mostly incandescent lamps.

---

[9] One footcandle is equal to one lumen per square foot.

[10] Low-pressure sodium (LPS) lamps are another type of HID lamp, but are not used for general lighting. Although LPS lamps are the most efficacious light source on the market, we do not cover them in this report. The use of LPS lamps is limited because their light is monochromatic (yellow), making them inappropriate for situations in which even moderate color rendition is needed. In addition, LPS lamps are very large and thus hard to control optically.

FIGURE 2.12. WEEKLY LIGHTING HOURS IN U.S. COMMERCIAL BUILDINGS



Note: The building types indicated in this figure are arranged in order of descending lighting energy consumption. Because the Xenergy data did not include a "miscellaneous" building type, the miscellaneous lighting hours included in this figure represent the average lighting hours across all other commercial building types weighted by the square footage of each building type as reported in 1992 CBECS.

Source: Based on data obtained from LBNL's Technology and Market Assessment Group (1997b), presentation material for DOE Public Workshop on Fluorescent Ballasts, March 18th 1997, Washington D.C. Data were adapted from extract of Xenergy, Inc.'s XENCAP database showing lighting equipment and lighting hours of operation for more than 24,000 commercial and industrial buildings for the years 1990-1995. Xenergy's commercial data were obtained from nationwide energy audits and interviews with building managers.

Table 2.12. Typical Ranges of Initial System Efficacy for Commonly Used Lamp Types

Lamp Type	Efficacy (lumens per watt)
Incandescent	10–20
Compact Fluorescent (including ballast losses)*	50-60
Fluorescent (including ballast losses)*	55-90
High-Intensity Discharge: MV, MH, and HPS (including ballast losses)*	32-124

* As discussed in Appendix A, fluorescent and HID lamps must be operated using a ballast to supply the correct voltage and control the current. Ballast losses typically reduce system efficacy below lamp efficacy (using nominal lamp watts) by 10-20%.

Table 2.13 provides the percentages of delivered lumens by lamp type for indoor lighting in existing commercial buildings in 1992 (see LBNL Technology Market and Assessment Group (1997a) for a lighting technology breakdown in *new* commercial buildings); these shares of delivered lumens were calculated by LBNL researchers based on data obtained from Xenergy's XENCAP database. In contrast to the residential sector, where almost all lamps are incandescent, we can see in Table 2.13 that almost all of the lumens delivered in commercial buildings are provided by fluorescent lamps. In terms of the lumens delivered to all commercial building types in 1992, fluorescent lamps accounted for about 80%, HID lamps accounted for about 15%, and incandescents accounted for about 5%. The three building types which rely most heavily on incandescent lighting are public assembly (15.5% of delivered lumens), lodging (14.3% of delivered lumens), and restaurants (12.5% of delivered lumens). At least in part, incandescents are common in lodging facilities and restaurants because the proprietors wish to make their customers feel "at home". Of all commercial building types, warehouses use the largest share of HID lamps by far; HIDs account for about 44% of delivered lumens in warehouses.

Lighting Power Density

Power density is an energy use characteristic commonly used by energy analysts to compare installed wattage in various building types. Lighting power density (measured in watts per square foot) is defined as the total wattage installed per square foot of floorspace. The wattage required depends on both the illuminance level in the building and the efficacy of the lighting equipment used. Table 2.10 and **Figure 2.13** provide lighting power densities for different commercial building types; these power densities were calculated for this report based on the lighting hours and energy intensities specified in the COMMEND database. Lighting power density is highest for lodging facilities, small offices, and colleges and lowest for warehouse facilities.

It should be emphasized that a low power density in a given building type should not be equated with lighting energy efficiency. The lighting power densities presented in Table 2.10 represent averages across all the different types of space within a given building type (e.g., the "retail" building category includes not only areas in which merchandise is displayed but also areas for merchandise storage and administrative offices). Even in building types with low power densities, there can be significant potential for cost-effective energy savings. For example, while department stores use a large percentage of fluorescent lamps, and shopping malls often illuminate common spaces with HID lamps, small retail stores frequently use incandescent lamps and thus provide a significant opportunity for energy savings. Consequently, if you are trying to infer the potential for energy savings within a given building type, you need to look not at the average energy consumption characteristics of the building type, but at the different types of space that make up the building type, the technologies used to illuminate the individual space types, and the lighting levels and lighting hours within them.

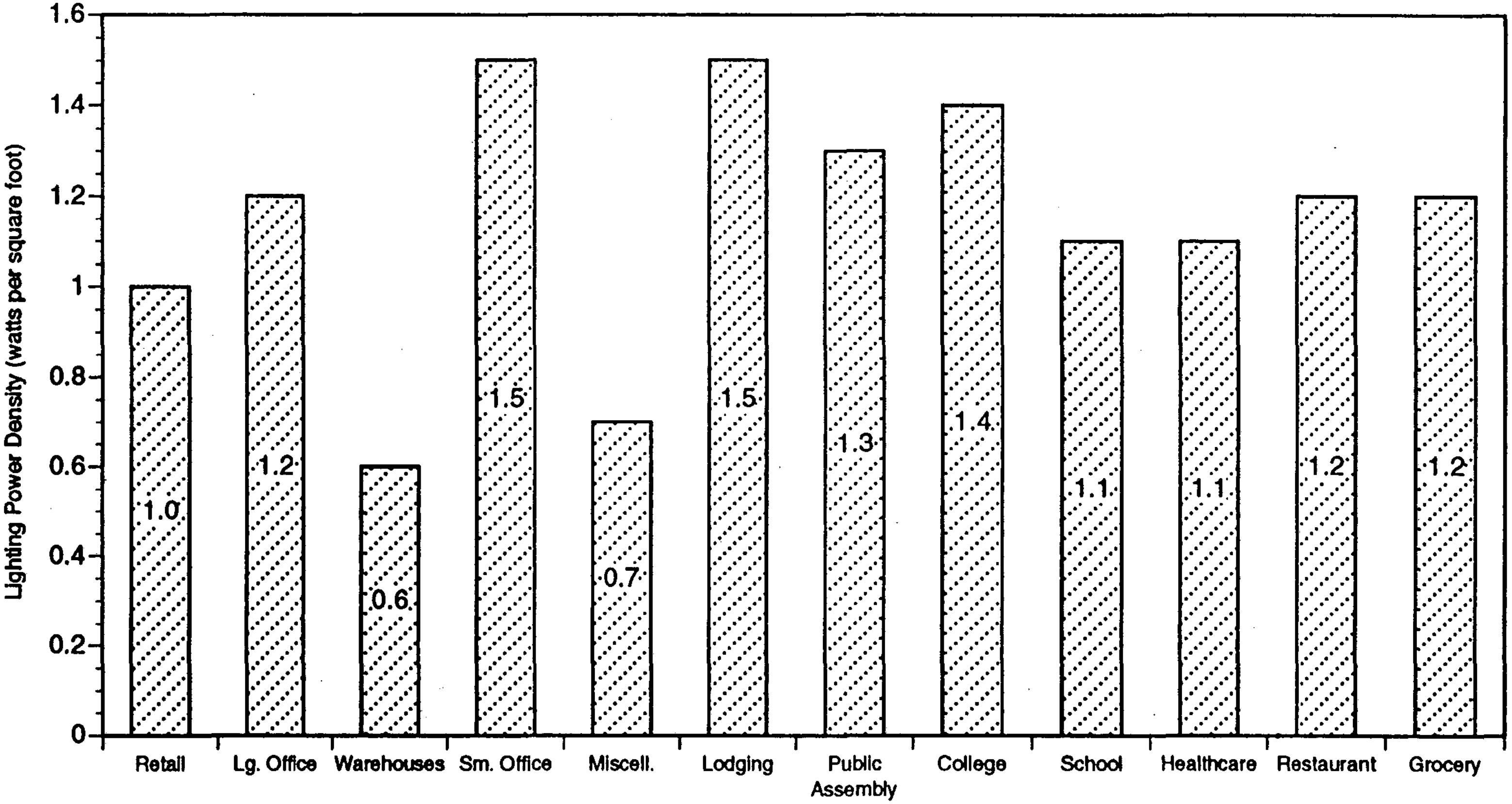
Table 2.13. Percent of Delivered Lumens by Lamp Type for Interior Lighting in Commercial Buildings, 1992

Building Type	Incand. non-refl.	Incand. reflector	**All incand.**	4-foot fluor.	8-foot fluor.	CFLs	Fluor. - other	**All Fluor.**	HPS	MH	MV	**All HID**	TOTAL
Retail	2.5%	0.7%	3.2%	44.6%	36.6%	0.1%	3.5%	84.8%	1.8%	7.0%	3.1%	11.9%	100%
Large Office	1.6%	0.2%	1.8%	84.2%	5.9%	0.2%	1.9%	92.2%	1.4%	1.4%	3.4%	6.2%	100%
Warehouses	1.9%	0.6%	2.5%	18.7%	26.9%	0.0%	7.7%	53.3%	21.6%	19%	3.8%	44.4%	100%
Small Office	2.4%	0.3%	2.7%	80.0%	12.5%	0.2%	2.0%	94.7%	0.8%	1.5%	0.6%	2.9%	100%
Miscellaneous	4.7%	0.6%	5.2%	56.8%	19.0%	0.2%	3.8%	79.8%	5.3%	6.7%	3.0%	15.1%	100%
Lodging	13.7%	0.6%	14.3%	71.2%	5.4%	1.0%	4.6%	82.2%	1.0%	1.3%	1.3%	3.6%	100%
Public Assembly	14.3%	1.2%	15.5%	60.4%	14.8%	0.2%	2.9%	78.3%	0.7%	3.4%	2.2%	6.3%	100%
College	2.6%	0.5%	3.1%	75.8%	4.7%	0.3%	3.9%	84.7%	1.3%	3.2%	7.8%	12.3%	100%
School	2.9%	0.2%	3.1%	74.2%	8.2%	0.1%	2.0%	84.5%	3.4%	5.0%	4.1%	12.5%	100%
Healthcare	1.7%	0.4%	2.1%	92.7%	2.0%	0.4%	1.6%	96.7%	0.5%	0.4%	0.3%	1.2%	100%
Restaurant	11.3%	1.2%	12.5%	63.1%	16.4%	0.2%	3.2%	82.9%	1.4%	2.0%	1.2%	4.6%	100%
Grocery	0.6%	0.1%	0.7%	25.1%	55.3%	0.0%	3.8%	84.2%	2.5%	10.2%	2.3%	15.0%	100%
AVERAGE, weighted by floorspace	4.7%	0.6%	5.2%	56.8%	19.0%	0.2%	3.8%	79.8%	5.3%	6.7%	3.0%	15.1%	100%

Note: Overall average shares of delivered lumens, by lamp type, are based on the average percentage of delivered lumens for all commercial building types weighted by CBECS square footage for 1992. Because Xenergy data did not include a "miscellaneous" building type, we assume that the delivered lumens for the miscellaneous category are the same as the total shares of delivered lumens. The building types indicated in this figure are arranged in order of descending lighting energy consumption.

Source: LBNL (1997a), Appendix B, Tables B.3 and B.8. Adapted from extract of Xenergy, Inc.'s XENCAP database showing lighting equipment and lighting hours of operation for more than 24,000 commercial and industrial buildings for the years 1990-1995. Xenergy's commercial data were obtained from nationwide energy audits and interviews with building managers. Weighted averages were calculated by authors based on commercial-sector floor area.

FIGURE 2.13. LIGHTING POWER DENSITY IN U.S. COMMERCIAL BUILDINGS



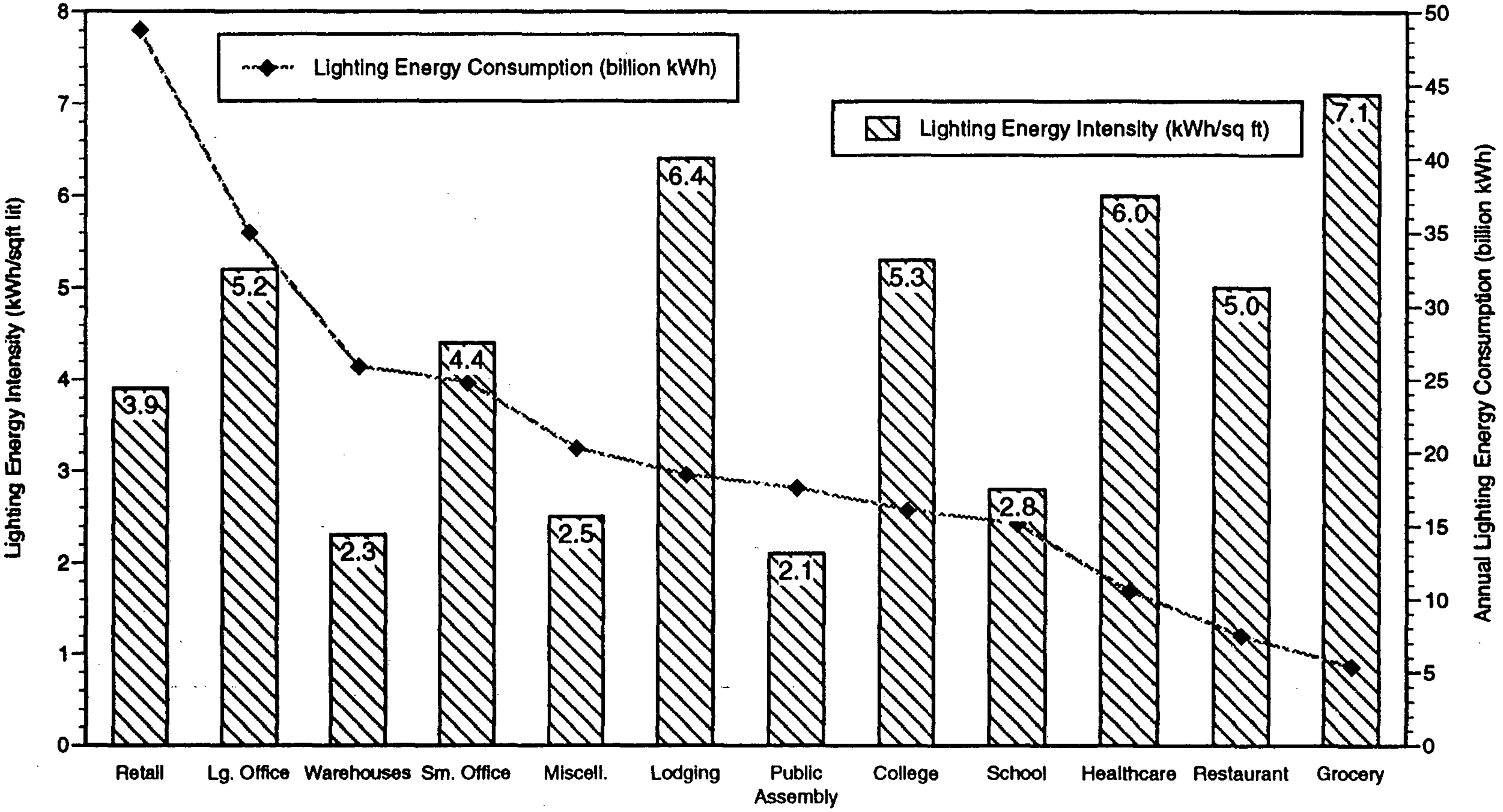
<u>Note:</u> The building types indicated in this figure are arranged in order of descending lighting energy consumption.
<u>Source:</u> Calculated for this report based on the lighting hours and energy intensities specified in the COMMEND database.

Energy Intensity

Energy intensity is an energy use characteristic commonly used by energy analysts to compare energy consumption in various building types. Lighting energy intensity, measured in kilowatt-hours per square foot, is defined as the amount of electricity consumed annually to illuminate one square foot of floorspace. Like power density, energy intensity depends on the illuminance level in the building and the efficacy of the lighting equipment used – energy intensity, however, also takes into account the annual lighting hours. Energy intensities by building type are presented in Table 2.10; the energy intensity data were obtained by LBNL from Regional Economic Research, Inc. and are based on 1992 CBECS data.

When we know the lighting energy intensity in a building as well as the amount of illuminated floorspace, we can then multiply these two quantities to calculate the total annual lighting energy consumption for the building. **Figure 2.14** indicates both the lighting energy intensity and annual energy consumption for various commercial building types. In Figure 2.14, we see that lighting energy intensity is highest for groceries, lodging facilities, and healthcare facilities. The high energy consumption but low energy intensity for retail, warehouses, public assembly, and miscellaneous building types indicates that a large amount of floorspace is illuminated in each of these four building types (as depicted in Figure 2.11).

FIGURE 2.14. LIGHTING ENERGY INTENSITIES AND ANNUAL ENERGY USE IN U.S. COMMERCIAL BUILDINGS



__Source:__ Based on data obtained from LBNL's Technology and Market Assessment Group (1997b), presentation material for DOE Public Workshop on Fluorescent Ballasts, March 18th 1997, Washington D.C.

2.3. Regulations Affecting Lighting Product Mix and Consumer Choice

As discussed in Atkinson et al. (1995c), the history of U.S. lighting regulations is complicated. Lighting regulations have been established by the U.S. Department of Energy and also by many state governments. Since the 1970s, guidelines for lighting have been included in national voluntary building energy standards; in addition, numerous states have established mandatory lighting standards. Mandatory federal ballast standards were established under an amendment to the National Appliance Energy Conservation Act in 1988 and took effect in 1990.

When the Energy Policy Act of 1992 (EPAct) was enacted in October 1992, regulations affecting lighting energy efficiency became much more comprehensive; the provisions of EPAct include both voluntary and mandatory programs including energy-efficiency standards for lamps, specifications for lamp testing procedures and lamp labeling, a luminaire testing and information program, and state building standards (Atkinson et al. 1995b).[11] The primary parties involved in negotiating the lighting efficiency provisions of EPAct were the American Council for an Energy-Efficient Economy (ACEEE) and the National Electrical Manufacturers Association (Atkinson et al. 1995c).

In this section, we summarize the regulations affecting lighting products that are available on the market today. In addition, we briefly describe the different types of building codes that may influence consumer choices of lighting products. All of the standards, guidelines, and codes described below are likely to be reassessed over time and are thus subject to change.

2.3.1. Lamp Standards

Incandescent Lamp Standards:
The incandescent lamp standards in EPAct pertain only to incandescent reflector lamps, and their purpose is to convert the majority of the reflector lamp market from traditional incandescent to the more efficient tungsten-halogen technology. EPAct's minimum efficacy standards for incandescent reflector lamps, which took effect in November 1995, banned the sale or import of most conventional incandescent floodlights and spotlights. Most standard-wattage and reduced-wattage reflector lamps do not meet the efficacy standards; halogen reflector lamps are the least expensive compliance option. The standards for incandescent reflector lamps are summarized in **Table 2.14.**

Exempted from the standards are ER (elliptical reflector) and BR lamps (specially shaped variants of the "R" lamp that are designed to deliver more usable light from recessed fixtures); several other categories of reflector lamps are also exempted, including colored lamps, rough or vibration service lamps, and lamps with a rated wattage of less than 40 watts (Brown and Atkinson 1994). In general, the exempted lamps are specialty lamps for which there are no energy-efficient substitutes and comprise only a small market share.

---

[11] EPAct standards apply to lamps that are distributed for sale within the U.S. Lamps imported to the U.S. must meet EPAct standards; however, lamps produced for export by manufacturers within the U.S. are not required to meet the standards.

Table 2.14. EPAct Minimum Efficacy Standards for Incandescent Reflector Lamps*

Lamp Wattage	Minimum Efficacy (lm/W)
40-50	10.5
51-66	11.0
67-85	12.5
86-115	14.0
116-155	14.5
156-205	15.0

* Standards effective as of November 1995
Source: U.S. House of Representatives (1992)

Fluorescent Lamp Standards
EPAct contains energy-efficiency standards and other regulations that prohibit certain fluorescent lamps from being manufactured or imported into the U.S. The lamps must meet both efficacy (lumens/watt) and CRI levels to comply.[12] The EPAct lamp standards for fluorescent lamps are indicated in **Table 2.15.**

As a result of these standards, the full-wattage (40 W), 4-foot, T12 lamps with standard (calcium) halophosphors have been eliminated from the lighting market. Reduced-wattage lamps with standard phosphors, however, meet the EPAct standards. Other more efficacious lamps, such as T8s and T12s with rare earth phosphors, also meet the standards. Similar restrictions apply to 8-foot T12 and T12 high-output lamps. Lamps that were in compliance with the law when they were manufactured may still be sold after the effective date.

Table 2.15. EPAct Standards for Fluorescent Lamps

Lamp Group	Wattage	Minimum Efficacy (lm/W)*	Minimum CRI	Effective Date
4-ft medium bipin	>35	75	69	11/1/95
	≤35	75	45	11/1/95
2-ft U-shaped	>35	68	69	11/1/95
	≤35	64	45	11/1/95
8-ft Slimline	>65	80	69	5/1/94
	≤65	80	45	5/1/94
8-ft high-output	>100	80	69	5/1/94
	≤100	80	45	5/1/94

* Efficacy values are calculated excluding ballast losses.
Source: U.S. House of Representatives (1992)

Several categories of fluorescent lamps are exempted from the standards. In general, the exempted lamps are specialty lamps for which there are no energy-efficient substitutes and comprise only a small market share.

---

[12] "CRI" refers to a lamp's color rendering index; CRI is defined in Appendix A.

Incandescent and Fluorescent Lamp Labeling

According to Atkinson et al. (1995b), EPAct required the U.S. Federal Trade Commission (FTC) to create a labeling program for the following lamp types: full-size fluorescents; medium-base self-ballasted (integral screw-in) CFLs; medium-base general service incandescents with a wattage of 30 or higher; and medium-base incandescent reflector lamps with a wattage of 40 or more. Packages for incandescent lamps and CFLs must specify lumen output, lamp wattage, rated lifetime, and advice to the consumer regarding how to use this information. Packages for full-size fluorescent lamps are not required to be labeled, but the lamp itself must have a special symbol etched upon it, indicating that the lamp meets EPAct efficacy requirements. The labeling requirements specified by EPAct took effect in 1995.

High-Intensity Discharge (HID) Lamp Testing, Standards, and Labels

The U.S. Department of Energy (DOE) will conduct an analysis to determine whether to proceed with testing requirements for those HID lamps for which standards are technologically feasible and economically justified, and for which there are determined to be significant energy savings (Logee 1997). If testing requirements are established, based on EPAct (U.S. House of Representatives 1992), DOE will prescribe standards for HID lamps; the standards would take effect three years after the standard is published. If efficiency standards are established, DOE will also prescribe labeling requirements for HID lamps.

2.3.2. Ballast Standards

In 1982, California adopted an energy-efficiency standard for fluorescent lamp ballasts having a power factor exceeding 0.6. The standard affected approximately 80% of ballasts manufactured at that time and essentially banned the manufacture and sale of "standard" magnetic ballasts within California. Over the next five years, four more states (New York, Massachusetts, Connecticut, and Florida) followed California's lead and adopted efficiency standards that banned the manufacture and sale of standard magnetic ballasts. A federal standard for fluorescent ballasts was added to the National Appliance Energy Conservation Act (NAECA) in 1988 and became effective in January 1990 (Geller and Miller 1988, Koomey et al. 1995).

The federal standard for ballast efficiency was established to avoid the complications associated with different states having different standards and because it appeared that the demand for efficient magnetic ballasts had leveled off. The regulations are based upon the Ballast Efficacy Factor (BEF), in order to allow meaningful comparison between different ballasts operating the same type and number of fluorescent lamps.[13] The BEF requirements could not be met by standard magnetic ballasts. "Energy-efficient" magnetic ballasts and electronic ballasts could meet the standard.[14] **Figure 2.15** indicates shipments of ballasts produced in the U.S. from 1977 through 1996 as well as the years in which the various state standards and the federal standard took effect.

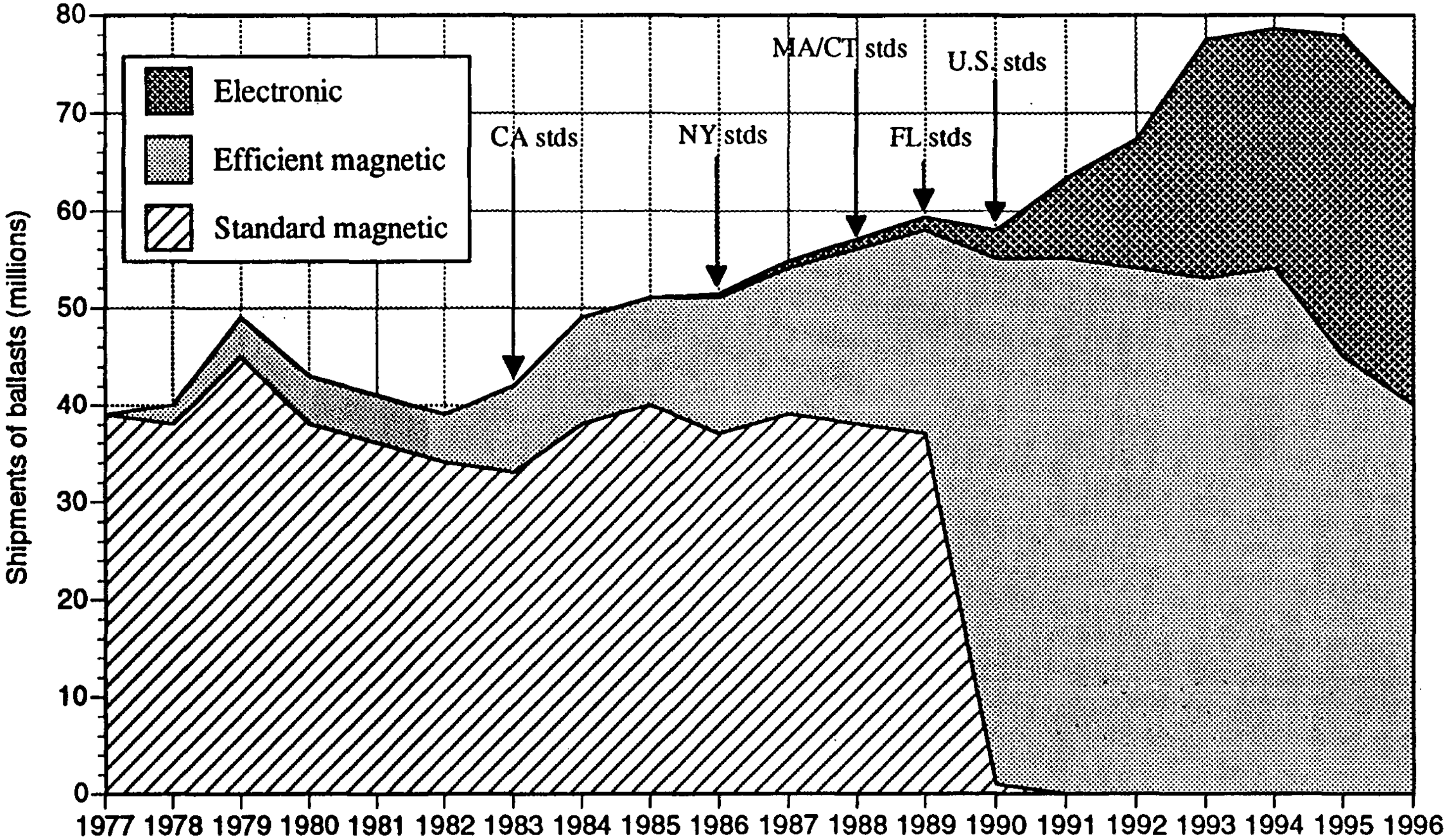
Minimum ballast efficacy standards are summarized in **Table 2.16**. The standards do not apply to dimming ballasts, ballasts designed to operate at a low temperature, or ballasts with a power factor less than 0.9 that are designed for residential use (Atkinson et al. 1995c).

---

[13] BEF is defined in Appendix A.

[14] "Energy-efficient" magnetic ballasts have low-loss metal cores and denser windings and are 10-15% more efficient than the banned standard magnetic ballasts. Their name is somewhat of a misnomer, however, since of the ballasts available for fluorescent lamps today, they are the *least* energy-efficient. Both electronic and cathode-cutout (hybrid) ballasts are more efficient than the "energy-efficient" magnetic ballasts.

FIGURE 2.15. U.S. SHIPMENTS OF FLUORESCENT BALLASTS FOR THE U.S. COMMERCIAL SECTOR



Note: Because they are not typically used in the commercial sector, the following ballast types are omitted from the data presented in this figure: low power-factor ballasts (shipments of 24.2 million in 1996), 1500 MA high power-factor ballasts (0.2 million in 1996), and ballasts included in the "All other corrected power" category of the Census Bureau data. Ballast imports are not included because they were not disaggregated by ballast type in the Census data. Arrows indicate the years in which state and, finally, federal standards took effect, preventing the sale of standard magnetic ballasts.

Sources: Koomey et al. (1995); Census Bureau MQ36C(94)-5, Table 3; Census Bureau MQ36C(96)-5, Tables 3 and 4

Table 2.16. NAECA Minimum Efficacy Standards for Fluorescent Ballasts

Ballast Application	**Total Nominal Lamp Wattage**	**Ballast Efficacy Factor**
One F40 T12	40	1.805
Two F40 T12 (120 V)	80	1.060
Two F40 T12 (277 V)	80	1.050
Two F96 T12	150	0.570
Two F96 T12 HO	220	0.390

Source: Geller and Miller (1988)

In 1994, DOE proposed updated efficiency standards for fluorescent lamp ballasts that could only have been met with electronic ballasts. These ballast standards were not implemented and, after many meetings and discussions with manufacturers and other stakeholders, the analysis was revised and a draft report was published in early 1996 (Lawrence Berkeley National Laboratory (LBNL) Technology and Market Assessment Group 1996). Several energy-efficiency levels were again studied in this draft analysis, including levels corresponding to cathode-cutout and electronic ballasts. DOE has not yet determined whether or when new standards for fluorescent lamp ballasts will be reproposed.

At the present time, ballast standards apply only to ballasts for T12 lamps; if implemented, updated standards may apply to ballasts for additional product classes.

2.3.3. Luminaire Standards[15]

EPAct called for a voluntary national testing and information program for luminaires. A program has been created jointly by a stakeholders' working group called the National Lighting Collaborative (National Lighting Collaborative 1996). Members of the Collaborative include the National Electrical Manufacturers Association, the American Lighting Association, and other interested parties. The working group has introduced a new tool for comparing luminaires, the "Luminaire Efficacy Rating (LER)", which is based on NEMA's LE5 standard for fluorescent luminaires. The LER is a single number expressing luminaire efficacy, and is calculated using the following equation:

$$\text{LER} = \frac{\text{luminaire efficiency} * \text{total rated lamp lumens} * \text{ballast factor}}{\text{luminaire input watts}}$$

Currently, the program focuses on fluorescent luminaires for commercial and industrial use, but is being expanded to include downlights and industrial HID luminaires. The luminaire testing and rating program received provisional approval from the U.S. Department of Energy in March, 1996. DOE determined that, in its beginning stages, the program is well-positioned to achieve its objectives. By the end of 1998, DOE will make a final determination on whether the program has continued its progress and outstanding issues have been resolved.

---

[15] Although the term "luminaire" is sometimes used interchangably with the term "fixture", "luminaire" more often refers to a complete lighting system including lamp(s), ballast(s), and fixture. In this report, "luminaire " is always used to refer to a complete lighting system.

2.3.4. Building Codes

Legislation such as building codes can affect design and purchase decisions regarding lighting systems. In some cases, homeowners may be influenced by the codes; more often, the codes provide guidelines for the people who are responsible for designing and installing lighting systems in new commercial and residential buildings (such as developers, contractors, and lighting designers). Residential and commercial building codes that have been recommended or mandated include the following:

Voluntary Building Energy Codes (Johnson 1997): As mandated by EPAct, DOE in consultation with other agencies and organizations supports the upgrading of voluntary building energy codes for new residential and commercial buildings. Consultations with the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), the International Codes Council, other national model code organizations, state governments, and others have facilitated the energy code change process. These code and standard upgrades represent the results of engineering and economic analyses that were introduced into a process that involved private industry, states, and other stakeholders. This process has produced a set of voluntary standards for public review that are cost-effective and technologically feasible. State and local governments must review and take action to put any of these codes or standards into regulation. At that point, they have the force of law and are no longer voluntary.

State Commercial Building Codes: EPAct requires that each state adopt a mandatory building code with provisions as least as strict as those in the voluntary building energy code for commercial buildings (as described in the previous paragraph). As of mid-1997, more than half the states had complied. DOE is conducting programs that help the remaining states to achieve compliance, including compliance software and training. The voluntary building code for commercial buildings in the U.S. was developed by ASHRAE and the Illuminating Engineering Society of North America (IESNA); the current version is called ASHRAE/IES 90.1-1989. The lighting section uses "lighting power density" levels, in watts per square foot, to limit the connected lighting load in a building or space type.

The revision of the code, ASHRAE/IES 90.1-R, is undergoing public review. This process will take several years, after which DOE will decide whether to accept the revised code as part of the EPAct requirements. The new lighting section contains updated lighting power density values as well as mandatory controls requirements.

State Residential Building Codes: Although each state must review its residential building codes, most state codes do not include any lighting provisions at this time. California's Title 24 standard does include lighting provisions that require the use of fluorescent lamps for providing the major lighting in bathrooms and kitchens.

Energy-Efficiency Standards for Federal Buildings: According to EPAct, DOE in consultation with other institutions would establish mandatory energy standards for new federal buildings that are technologically feasible and economically justified. The pending rule for federal commercial buildings effectively adopts the existing ASHRAE 90.1 code with adjusted (stricter) lighting levels. These commercial standards, which are likely to be issued by the end of 1997, should take effect within a year of the issue date (Majette 1997). The pending rule for federal residential buildings is based on the 1995 California Association of Building Officials' Model Energy Code (CABO MEC); this rule is currently being reviewed in response to public comment and will be issued in 1998 (Johnson 1997).

3. PRODUCT CHARACTERISTICS IN THE RESIDENTIAL AND COMMERCIAL LIGHTING MARKETPLACE

In order to design an effective lighting policy or efficiency program, one must be familiar with the lighting products that are manufactured, promoted, and sold in the lighting marketplace. In this chapter, we describe the volume and value of U.S. lighting product shipments, shipment trends, product mix, and product costs for the residential and commercial sectors.

3.1. Sources and Limitations of the Shipment and Product Mix Data

For the most part, the data presented in this chapter for lamps and ballasts were obtained from the *Current Industrial Reports* published by the U.S. Department of Commerce's Census Bureau. The Census Bureau has recorded data on U.S. manufacturing since 1943, and the lighting market data published by the Census are used widely in the research community. Unfortunately, the Census Bureau no longer publishes disaggregated market data for lamps; the most recent year for which detailed lamp data are available through the *Current Industrial Reports* is 1994. The Census Bureau continues to publish *Current Industrial Reports* containing ballast and fixture data quarterly.[16]

The fixture data in this chapter were obtained primarily from Sardinsky (1995). In his research, Sardinsky also relied on information from the Census Bureau, including data from *Current Industrial Reports* for lighting fixtures, the Census of Manufacturers, and the Foreign Trade Division. Fixture data were also obtained from Economic Industry Reports, Inc. (EIRI) (1995). The EIRI data presented in this chapter were compiled by EIRI based on data obtained from the U.S. Department of Commerce.

The Census Bureau maintains detailed data for the production and shipments of manufacturers located within the U.S. Products manufactured by U.S.-owned firms located overseas are counted as imports in the Census data rather than as part of U.S. production (Census Bureau 1996b). Information is scarce regarding what percentage of imports are in fact produced by U.S. companies owning plants abroad (Census Bureau 1997d). Similarly, lighting products manufactured by foreign-owned firms located within the U.S. are counted as U.S. shipments.

Far less detailed export and import data are recorded by the Census Bureau's Foreign Trade Division. Because import and export numbers are not available for many specific product types, it is not possible to completely identify domestic consumption (total sales within the U.S.) of specific lighting products. While imports of some product types are relatively low, other types of lighting equipment are often imported. For example, lighting fixtures containing brass work are almost exclusively imported because of strict U.S. environmental regulations and labor cost differences. Less restrictive environmental regulations and significantly lower labor costs outside the U.S. result in a preference for imports over U.S. products for several other lighting products as well.

Within this report, our comparisons of imports, exports, and U.S. shipments, are intended to give the reader a sense of the relative scales within the lighting market. For numerous reasons, these data comparisons should be considered only as approximations (see "Comparison of Export, Import, and Domestic Output Data" in Census Bureau (1993)). For example, the Standard Industrial Classification (SIC) system used to track U.S. production and shipments was developed independently of the Harmonized Tariff System that is used to classify exports and imports; the

---

[16] In most cases, the Census Bureau data that we provide in this report for lamps, ballasts, and fixtures are from 1993 and 1994. As noted, more recent data are available; unfortunately, resource constraints prevented us from updating our data.

level of detail provided by the different systems varies substantially and different categorical definitions and subsets make data difficult to compare accurately across the two systems. In addition, the valuations of U.S. shipments, imports, and exports differ.[17] According to the Census Bureau (1993), valuations of the three data sets differ in the following ways:

> Domestic output is valued at the point of production. It includes the net sales price, f.o.b. [freight on board] plant, after discounts and allowances, and excludes freight charges and excise taxes. Exports are valued at the point of exportation. Export value includes the net sales price or value, and inland freight, insurance and other charges to the export point. Imports are valued at the first port of entry in the United States. They include the cost, insurance, freight, duty, and other charges to the import point.

Although reliable market data for individual product types and sectors is essential to the development of effective lighting policies, only small portions of scattered raw data can be found and a comprehensive analysis is not currently available. Any such assessment can be only as comprehensive and systematic as the available data. Unfortunately, much of the data that would be necessary for a thorough analysis has not been collected or reported, or is protected as manufacturing trade secrets. Although we attempt to focus on the specific attributes of the residential and commercial markets, much of our analysis could only be performed at the level of the national lighting market because the data were available only in aggregate form.

3.2. Volume and Value of Lighting Product Shipments

Table 3.1 summarizes lamp, ballast, and fixture shipment data for 1993. At the wholesale level, shipments of lamps produced in the U.S. in 1993 were valued at about $3 billion, shipments of fluorescent ballasts were valued at about $1 billion, and shipments of lighting fixtures at about $5.7 billion. It can be seen in Table 3.1 that exports account for a relatively small fraction of U.S. lamp, ballast, and fixture shipments; in contrast, imports of lamps, ballasts, and fixtures represent a substantial portion of domestic consumption.

Typically, imported lamps are less expensive than those that are manufactured in the U.S. Table 3.1 indicates that, in terms of *units*, imported lamps accounted for about 30% of domestic lamp consumption in 1993; in terms of *value*, however, imported lamps accounted for only about 22%. **Figure 3.1** compares the number of lamps imported, exported, and domestically consumed by lamp type in 1993; **Figure 3.2** makes the same comparison in terms of lamp value.[18] Comparing Figures 3.1 and 3.2, it is clear that the relationship between the share of units and the share of value varies by lamp type.

---

[17] EIRI adjusted their estimates of fixture import, export, and U.S. shipment value in order to make the values more comparable; the data obtained from Sardinsky and the Census Bureau's *Current Industrial Reports* have not been adjusted.

[18] In the Census-based text and figures throughout this chapter, unless otherwise noted, photographic incandescent lamps are included in the "large incandescent" lamp category (in 1993, photo lamps accounted for less than 2% of large incandescent shipments). Tungsten-halogen lamps are treated separately from other large incandescents where disaggregated data are available. In addition, the "fluorescent" lamp category refers to hot-cathode fluorescent lamps; cold-cathode fluorescent lamps, of which very few are manufactured, are included in the "other electrical discharge" category. Both incandescent and fluorescent Christmas tree lamps are excluded from the data.

Table 3.1. Lamp, Ballast, and Fixture Shipments in 1993[19]

	Units	Total U.S. shipments	U.S. exports	U.S. shipments for domestic consumption ("domestic production")	U.S. imports	Total shipments for domestic consumption
Lamps (excludes Christmas tree lights)						
Number	*billions*	3.56	0.16	3.40	1.37	4.78
Value	*billions of 1993$*	2.91	0.46	2.45	0.70	3.15
Fluorescent Ballasts						
Number	*millions*	107.4	8.1	99.3	62.7	162.0
Value	*millions of 1993$*	969.5	64.0	905.5	385.1	1290.6
Fixtures (excludes vehicular lamp fixtures)						
Number	*NA*	NA	NA	NA	NA	NA
Value	*billions of 1993$*	5.7	0.4	5.3	1.2	6.5

Sources: Total U.S. shipments data for lamps were obtained from Table 2a in Census Bureau (1994a); import and export data for lamps were obtained from Table 4 in Census Bureau (1994a). Shipment, import, and export data for fluorescent ballasts were obtained from Table 2 in Census Bureau (1994b). Census data for other types of ballasts are not available. Fixture data were obtained from EIRI (1995) (data on the number of units shipped, imported, and exported were unavailable).

As with lamps, far more fluorescent ballasts are imported than exported and the imported ballasts tend to be less expensive than ballasts that are domestically manufactured. In Table 3.1, we see that in 1993 more than seven times as many fluorescent ballasts were imported as exported. While these imported ballasts accounted for about 40% of total domestic consumption, they accounted for only 30% of the value of fluorescent ballasts shipped for domestic consumption.[20]

Table 3.1 indicates that the value of fixture imports exceeded the value of fixture exports by a factor of three in 1993. **Figure 3.3** compares U.S. fixture exports, imports, and domestic production for 1991 through 1994.[21]

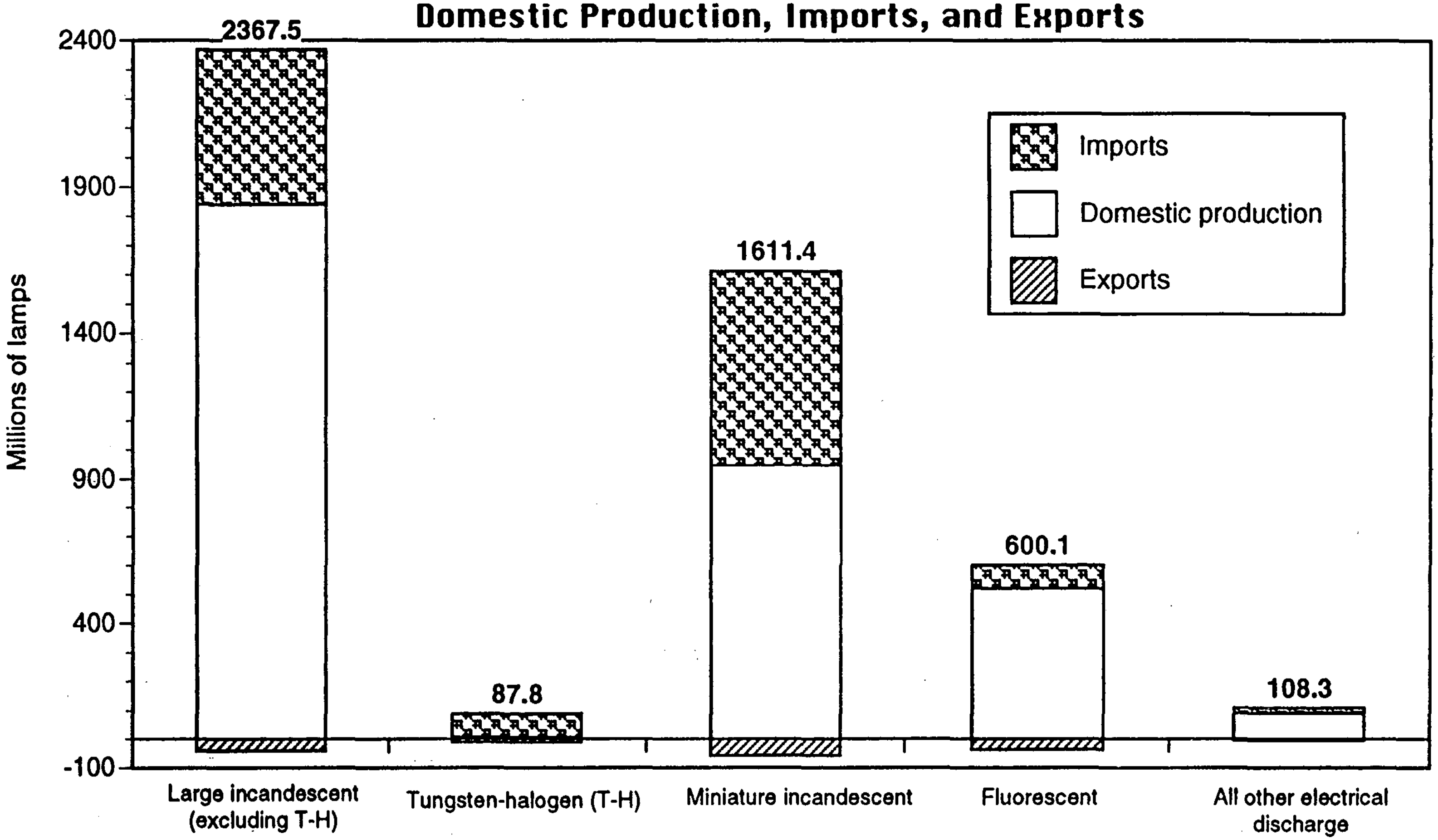
---

[19] Throughout this report, we use the term "U.S. shipments" to refer to total shipments by manufacturers located within the U.S. (including units to be exported). We use the term "domestic production" to refer to those units that are shipped in the U.S. for use within the U.S. (thus excluding both imports and exports). We use the term "domestic consumption" to refer to the units consumed in the U.S., which equals U.S. shipments minus exports plus imports.

[20] In our discussion of ballasts, we provide market characteristics only for *fluorescent* ballasts. Unfortunately, the Census Bureau does not publish data on ballasts for high-intensity discharge lamps and other sources of ballast market data were not available. Because far more fluorescent lamps are used than HID lamps, fluorescent ballasts do account for the bulk of the ballast market. In 1993, U.S. shipments of HID lamps totalled only 25.2 million while shipments of fluorescent lamps were about 560 million (Census Bureau 1994a).

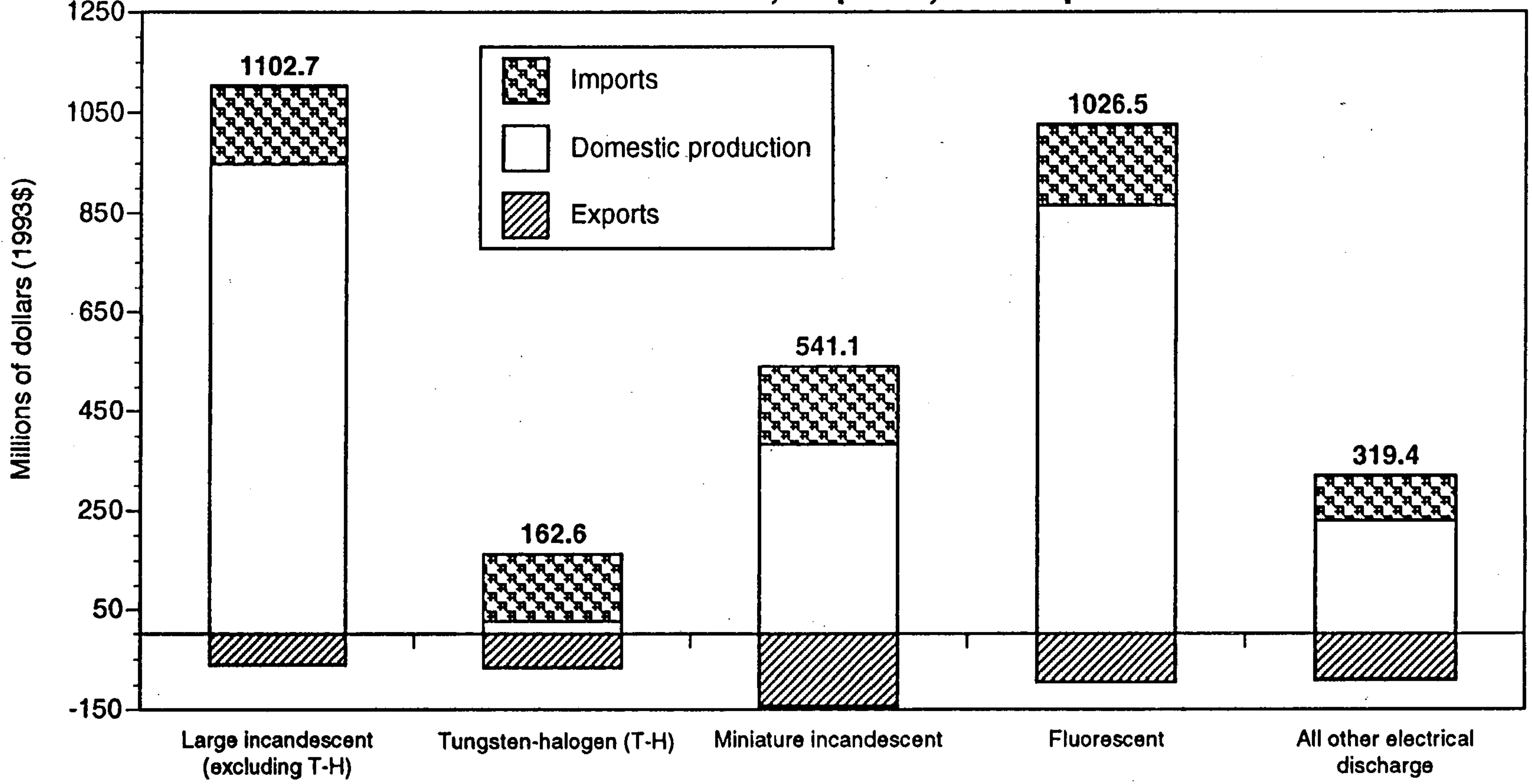
[21] Throughout this report, adjustments from current to 1993$ are based on the fixed-weight price indexes for personal consumption expenditures reported in Census Bureau (1995b). The indexes used are as follows: 1983: 86.7; 1984: 89.9; 1985: 93.3; 1986: 96.1; 1987: 100.0; 1988: 104.3; 1989: 109.5; 1990: 115.2; 1991: 120.3; 1992: 124.6; 1993: 128.1; 1994: 131.2.

FIGURE 3.1. LAMP SHIPMENTS IN THE U.S., 1993
Domestic Production, Imports, and Exports



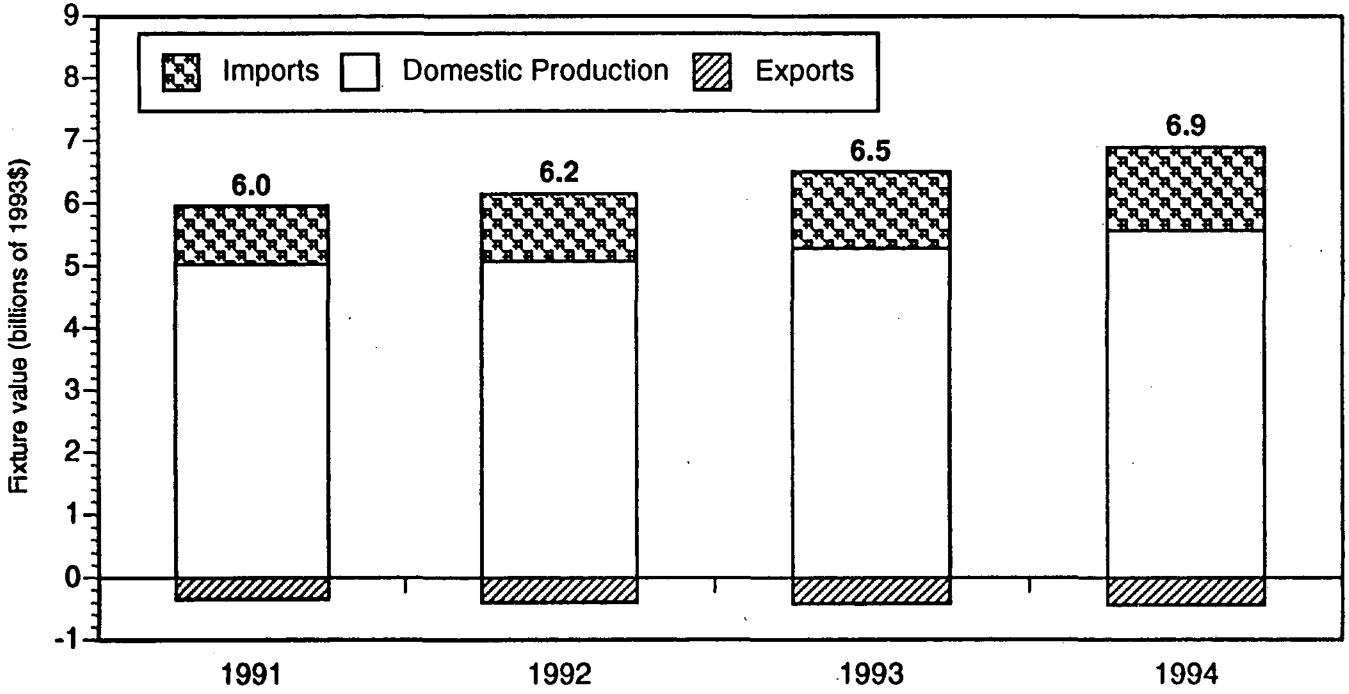
Note: Christmas tree lamps are not included in these data; cold-cathode fluorescent lamps (of which very few are manufactured) are included in the "Other Electrical Discharge" category. The number in bold above each column indicates total domestic consumption, which is equal to U.S. shipments minus exports plus imports. Domestic production is equal to U.S. shipments minus exports.
Source: U.S. shipment data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a); export and import data obtained from Census Bureau MQ36B (93)-5, Table 4 (1994a).

FIGURE 3.2. VALUE OF LAMP SHIPMENTS IN THE U.S., 1993
Domestic Production, Imports, and Exports



Note: As discussed in Section 3.1, domestic production is valued at the point of production; exports are valued at the point of exportation; and imports are valued at the first point of entry to the U.S. Christmas tree lamps are not included in these data; cold-cathode fluorescent lamps (of which very few are manufactured) are included the "Other Electrical Discharge" category. The number in bold above each column indicates total value of domestic consumption, which is equal to the value of U.S. shipments minus export value plus import value. The value of domestic production is equal to the value of U.S. shipments minus export value.
Source: U.S. shipment data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a); export and import data obtained from Census Bureau MQ36B (93)-5, Table 4 (1994a).

FIGURE 3.3. VALUE OF FIXTURE SHIPMENTS IN THE U.S., 1991-1994
Domestic Production, Imports and Exports (1993$)



Note: Vehicular lamp fixtures are not included in these data. The number in bold above each column indicates the total value of domestic fixture consumption, which is equal to domestic production plus imports.
Source: Data in current dollars were obtained from EIRI (1995); adjustments from current to 1993$ are based on the fixed-weight price indexes for personal consumption expenditures reported in Census Bureau (1995b)

In 1994, Canada was the primary consumer of U.S. fixture exports, followed by Mexico – in terms of fixture value, these two countries received almost 60% of 1994 U.S. fixture exports (EIRI 1995). Between 1991 and 1994, the value of fixtures imported relative to the value of fixtures domestically consumed increased from 15% to 19%. Based on EIRI (1995), China has increased its market penetration in the U.S. lighting fixture market remarkably in recent years. In 1990, in terms of fixture value, China provided only 7% of U.S. fixture imports; however, by 1994, China had captured 38% of the market and become the leading source of U.S. fixture imports. During this same time period, Taiwan's market share of fixtures imported to the U.S decreased from 51% to 27%.

Figure 3.4 and **Figure 3.5** compare exports, imports, and domestic production for hardwired and portable residential fixtures.[22] It is apparent from these figures that residential fixture imports far exceed exports; of the residential fixtures consumed in the U.S. in 1993, about 40% of hardwired fixtures and 65% of portable fixtures were imported.

3.3. Shipment Trends

Although the U.S. population has been increasing, as well as the number of homes and commercial buildings, U.S. shipments of lighting equipment have not necessarily increased at the same pace. As seen in **Figure 3.6**, U.S. shipments of lamps were relatively stable from 1983 through 1994 (the last year for which Census data on lamps is available). **Table 3.2** presents the data used to create Figure 3.6 as well as the available import data for the same years. Table 3.2 shows that lamp imports have increased steadily over the years, almost tripling between 1983 and 1994; based on these data, it appears that most of the increased demand for domestic consumption of lamps has been met by imported lamps. Part of the reason for the stabilization of U.S. lamp shipments could be the growing trend for U.S.-owned firms to locate their manufacturing facilities outside of the U.S.; as mentioned above, products manufactured by U.S.-owned firms located overseas are counted as imports in the Census data rather than as part of U.S. production.

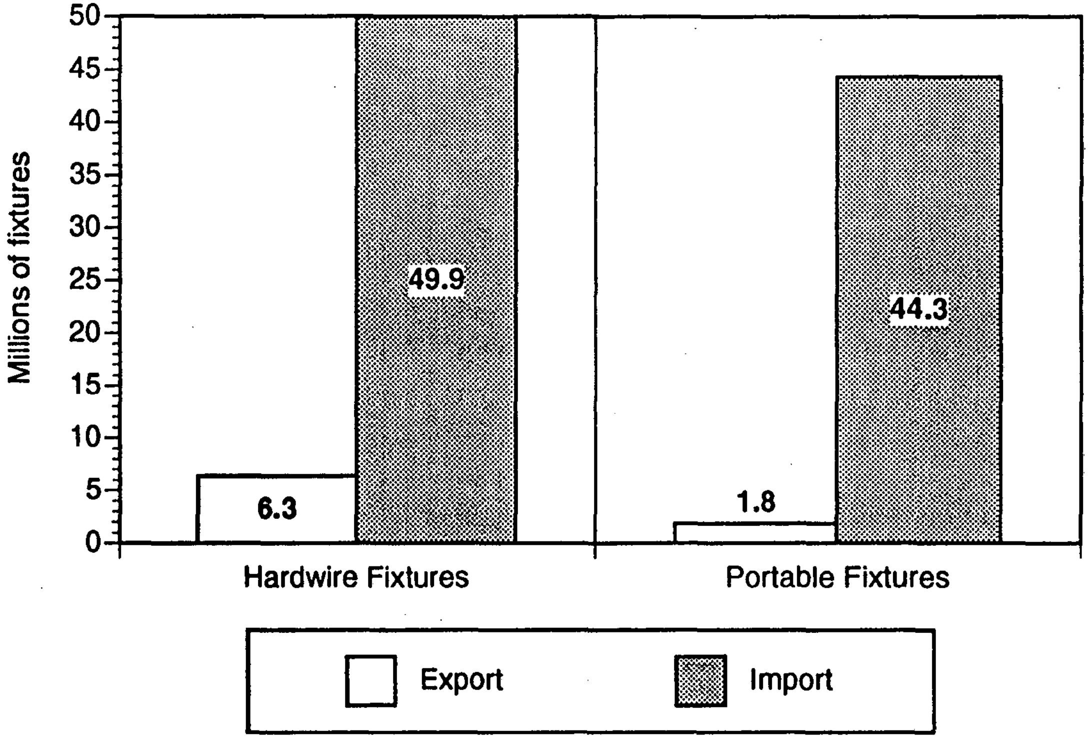
In recent years, U.S. shipments of magnetic ballasts for fluorescent lamps have remained fairly steady, and shipments of electronic fluorescent ballasts have increased significantly (see Figure 2.15 and **Figure 3.7**). While electronic ballasts accounted for less than 2% of U.S. shipments of fluorescent ballasts in 1989, they accounted for more than 30% in 1996 (Census Bureau 1996a, Census Bureau 1997b).

The value of U.S. shipments of lighting fixtures remained relatively stable in real terms through 1989; since then, however, the value of shipments has dropped off (**Figure 3.8**). As shown in **Figure 3.9**, between 1983 and 1993, the relative values of the fixture types produced in the U.S. for domestic consumption changed very little; the greatest shift was seen in residential portable fixtures, which accounted for 18% of total fixture value in 1983 but only 11% in 1993.

---

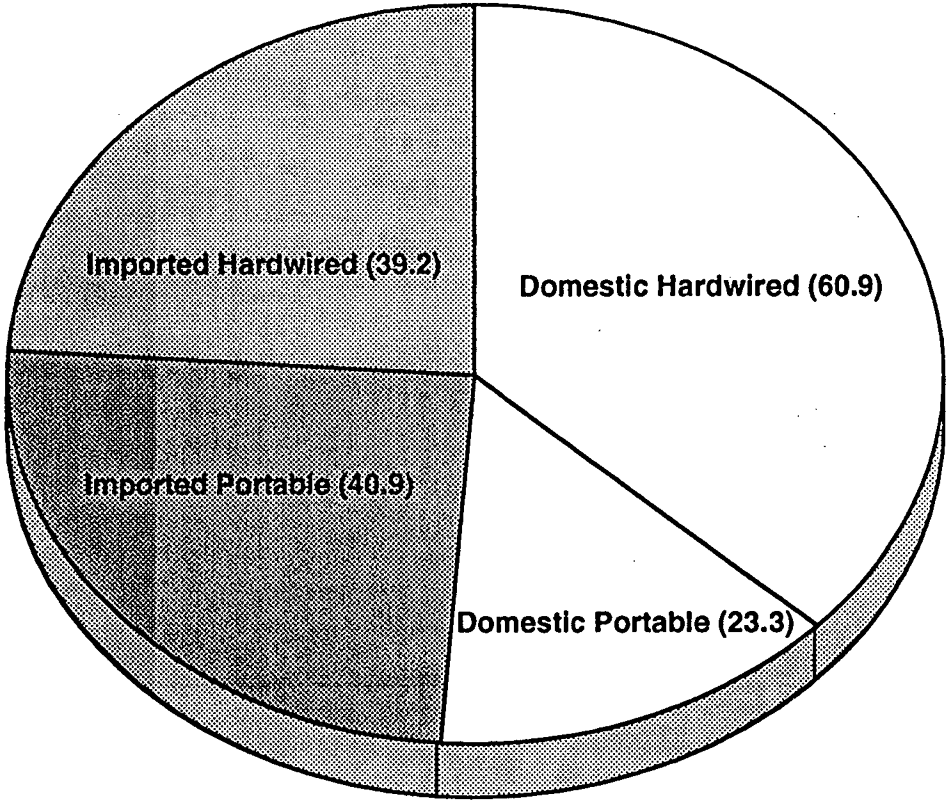
[22] "Portable" fixtures plug into an ordinary electrical socket and, consequently, can be moved easily from one place to another (e.g., floor and table lamps); "hardwired" fixtures are wired permanantly in one place, usually into the ceiling or a wall (e.g., overhead lights).

FIGURE 3.4. U.S. IMPORTS AND EXPORTS OF RESIDENTIAL HARDWIRED AND PORTABLE FIXTURES, 1994



Source: Adapted from Sardinsky (1995)

FIGURE 3.5. DOMESTIC CONSUMPTION OF RESIDENTIAL FIXTURES, IMPORTS AND DOMESTIC PRODUCTION, 1993 (millions of units)



Total: 164.3 million

Source: Adapted from Sardinsky (1995)

FIGURE 3.6. U.S. LAMP SHIPMENTS, 1983-1994

Note: These data include all U.S. lamp shipments except for Christmas tree lamps and cold-cathode fluorescent lamps. U.S. shipments include both exports and U.S. production for domestic consumption.
Source: Data obtained from Census Bureau MQ36B (94)-5, Table 1 (1995a), Census Bureau MQ36B (93)-5, Table 1 (1994a), and Census Bureau MQ36B (92)-5, Table 4 (1993).

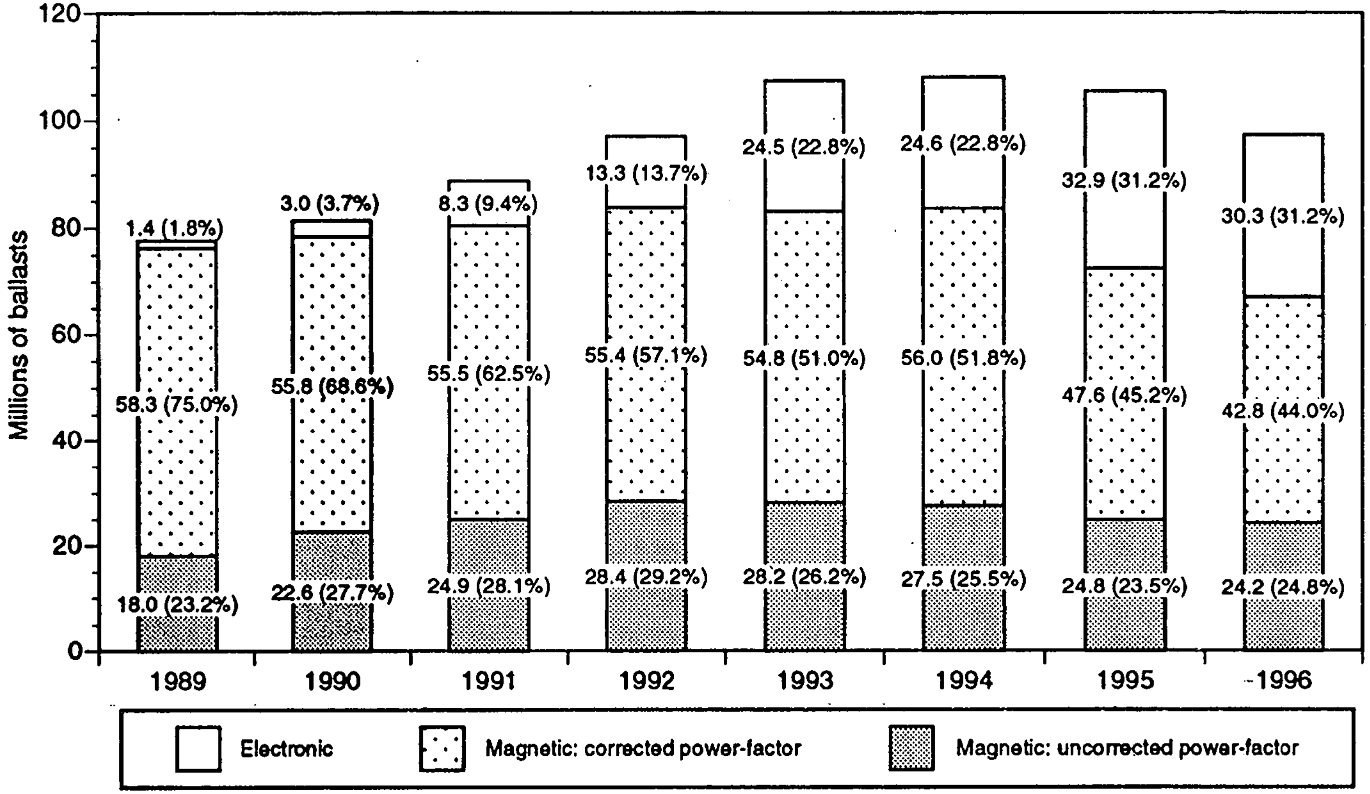
Table 3.2. U.S. Shipments and Imports of Lamps, 1983-1994

Year	U.S. Shipments (millions of lamps)	Imports (millions of lamps)
1983	3615.9	560.9
1984	3723.4	748.7
1985	3472.0	862.7
1986	3421.3	920.6
1987	3399.4	999.8
1988	3510.2	1130.8
1989	3429.5	1024.0
1990	3318.5	1051.0
1991	3297.5	Data unavailable from Census Bureau
1992	3422.1	Data unavailable from Census Bureau
1993	3564.3	1372.6
1994	3563.3	1577.8

Note: "U.S. shipments" refers to total shipments by manufacturers located within the U.S., including units to be exported. Cold-cathode fluorescent lamps are excluded from the U.S. shipment data; Christmas tree lamps are excluded from U.S. shipments as well as imports.

Sources: Census Bureau MQ36B (94)-5, Table 1 and Table 4 (1995a); Census Bureau MQ36B (93)-5, Table 1 and Table 4 (1994a); Census Bureau MQ36B (92)-5, Table 4 (1993); Census Bureau MQ36B (90)-5, Table 5 and Table 6 (1991); Census Bureau MQ36B (88)-5, Table 5 (1989); Census Bureau MQ36B (87)-5, Table 5 and Table 6 (1988); Census Bureau MQ36B (85)-5, Table 5 and Table 6 (1986); Census Bureau MQ36B (83)-5, Table 6 (1984)

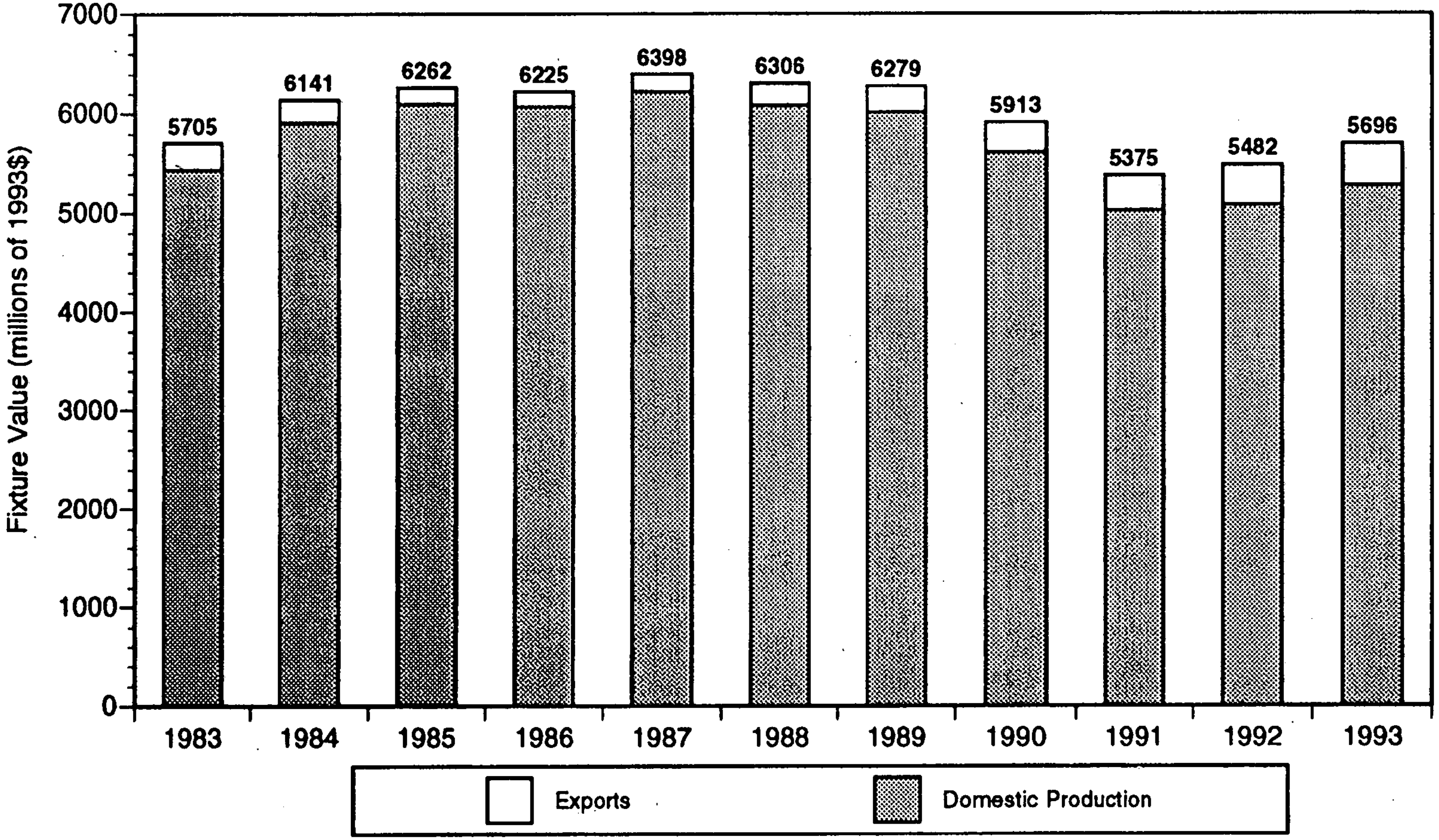
FIGURE 3.7. U.S. SHIPMENTS OF FLUORESCENT BALLASTS, 1989-1996



Note: Data include exports but not imports. "Corrected power-factor" indicates a high power-factor (typically, exceeding 0.95). In low power-factor ballasts, the phase shift between the current and voltage is substantial. Most ballasts used in the residential sector are low power-factor; ballasts used in the commercial and industrial sectors tend to be high power-factor. Cathode-cut-out (hybrid) ballasts account for a very small fraction of the corrected power-factor category (Coulson 1997).

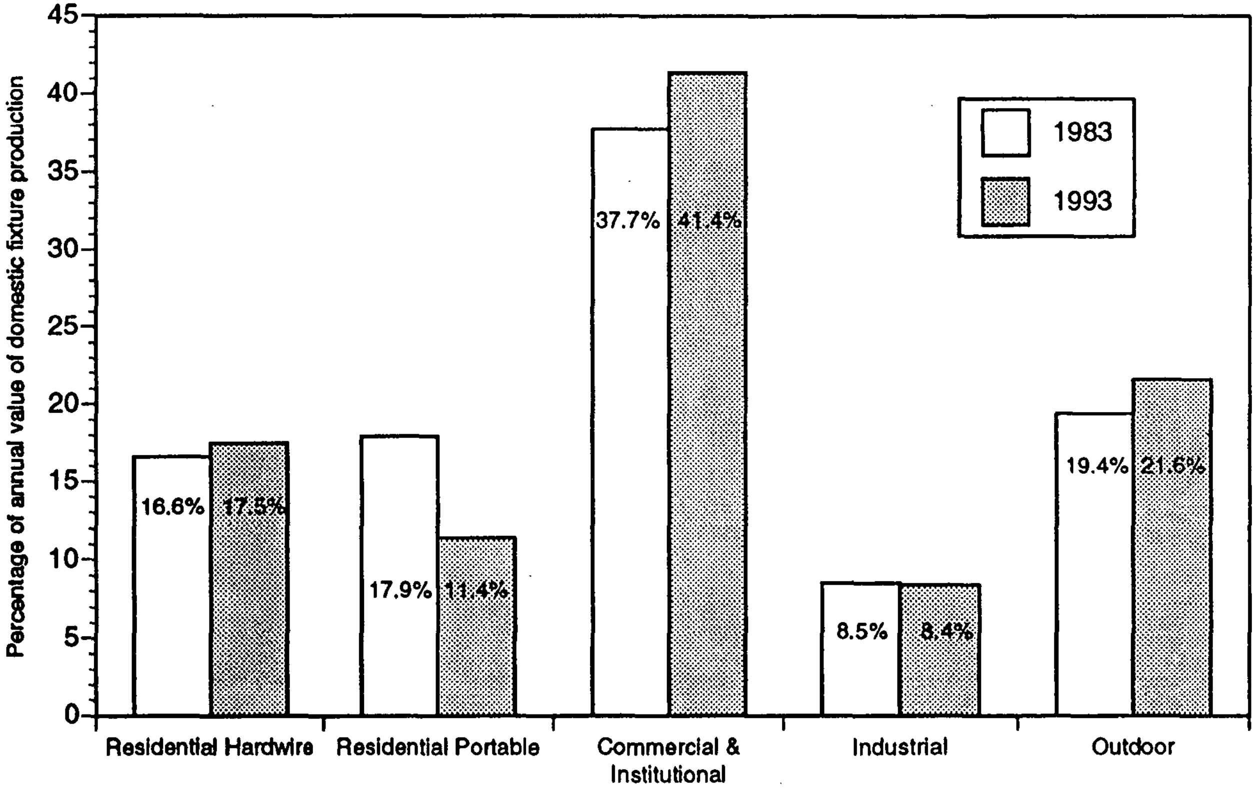
Source: Based on data obtained from Census Bureau MQ36C (95)-5, Table 1 (1996a) and MQ36C (96)-5, Table 1 (1997b)

FIGURE 3.8. VALUE OF U.S. FIXTURE SHIPMENTS, 1983-1993 (1993$)



Note: Vehicular lamp fixtures are not included.
Source: Data in current dollars were obtained from EIRI (1995); adjustments from current to 1993$ are based on the fixed-weight price indexes for personal consumption expenditures reported in Census Bureau (1995b)

FIGURE 3.9. DOMESTIC PRODUCTION OF FIXTURES,
PERCENTAGE OF TOTAL VALUE BY FIXTURE TYPE, 1983 AND 1993



Note: Vehicular lamp fixtures are not included in this data. Domestic fixture production is equal to U.S. shipments minus exports.
Source: EIRI (1995)

3.4. Lighting Product Mix

The U.S. lighting market offers a wide variety of products. Many different types of incandescent, fluorescent, and high-intensity discharge lamps, as well as a variety of ballasts and fixtures, are available.

3.4.1. Lamps

Large and miniature incandescent lamps accounted for more than 80% of U.S. lamp shipments in 1993 (**Figure 3.10**).[23] Fluorescent lamps represented 16% of U.S. shipments. All other lamp types, including HID lamps, accounted for less than 5% of U.S. shipments. In part, the predominance of incandescent lamps is attributable to their popularity in the residential sector, but it should be noted that the large number of incandescent lamps manufactured annually is also the result of the very short lamp lives of incandescents relative to other lamp types. The rated lifetimes of linear fluorescent lamps are 15-20 times longer than the rated lifetimes of most general service incandescents; consequently, for lamp replacements in existing fixtures, only 5-7% as many fluorescent lamps need to be manufactured per fixture.

As seen in **Figure 3.11**, general service lamps accounted for more than three quarters of U.S. shipments of large incandescent lamps in 1993.[24] The next largest shipment category was reflector lamps at 6%. The product mix of incandescent reflector lamps is expected to transform as a result of the Energy Policy Act of 1992 (EPAct) that took effect in November 1995. EPAct banned the production of most standard and reduced-wattage incandescent R and PAR type floodlights and spotlights; consequently, the shares of tungsten-halogen and halogen infrared-reflecting incandescents are expected to increase (see Section 2.3.1 for more information on lamp standards).

Figure 3.12 presents U.S. shipments of fluorescent lamps in 1993. The category "Other >30 W" accounted for about 60% of shipments in 1993 and is comprised of tubular fluorescents from four to eight feet (the majority of which are 32-, 34-, and 40-watt T12s) (Clear 1997). Linear T8 lamps have gained a larger share among linear fluorescent sources in recent years: compared to 1992 shipments, U.S. shipments of linear T8s increased by about 60% in 1993 and nearly doubled by 1994 (Census Bureau 1993, 1994a, 1995a). CFL shipments increased by about 10% between 1992 and 1993, accounting for about 6% of total fluorescent lamp shipments in 1993. Sales of CFLs in the U.S. totaled approximately 38 million in 1992, accounting for about 28% of total world CFL sales (Haddad 1994); however, only 1% as many CFLs are sold in the U.S. annually as incandescent lamps (Rasky 1993).[25]

As can be seen in **Figure 3.13**, high-pressure sodium lamps account for almost half of the general lighting HID lamps produced in the U.S.

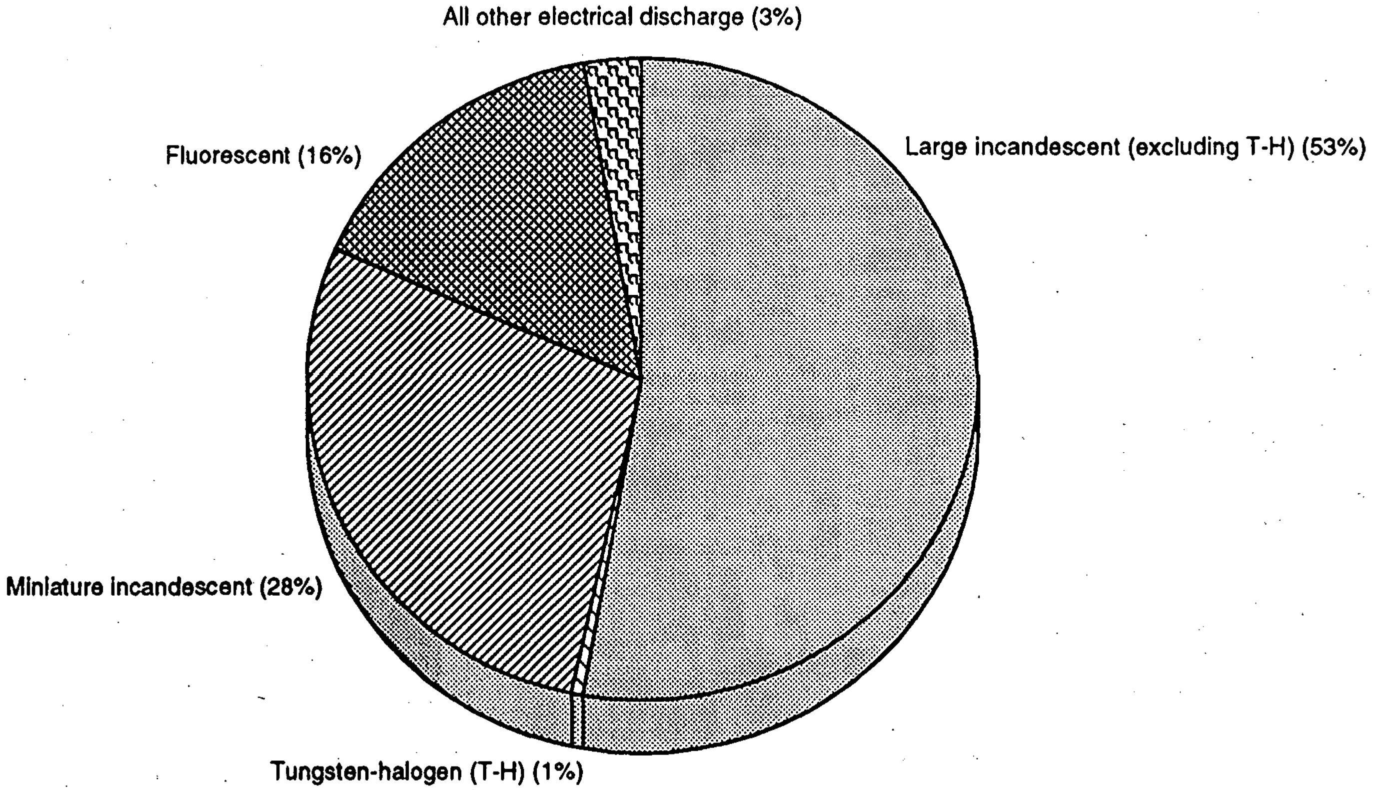
---

[23] In the Census Bureau data set, "miniature" incandescent lamps are small lamps that are used in automobiles (e.g., in headlights and glove compartments), flashlights, and radio panels.

[24] According to the Census Bureau, "general service" lamps include all large incandescent lamps used for general lighting purposes, 15 watts and above, 100-130 volts (including tinted lamps) (Census Bureau 1993).

[25] For information on global CFL sales, see Borg (1994).

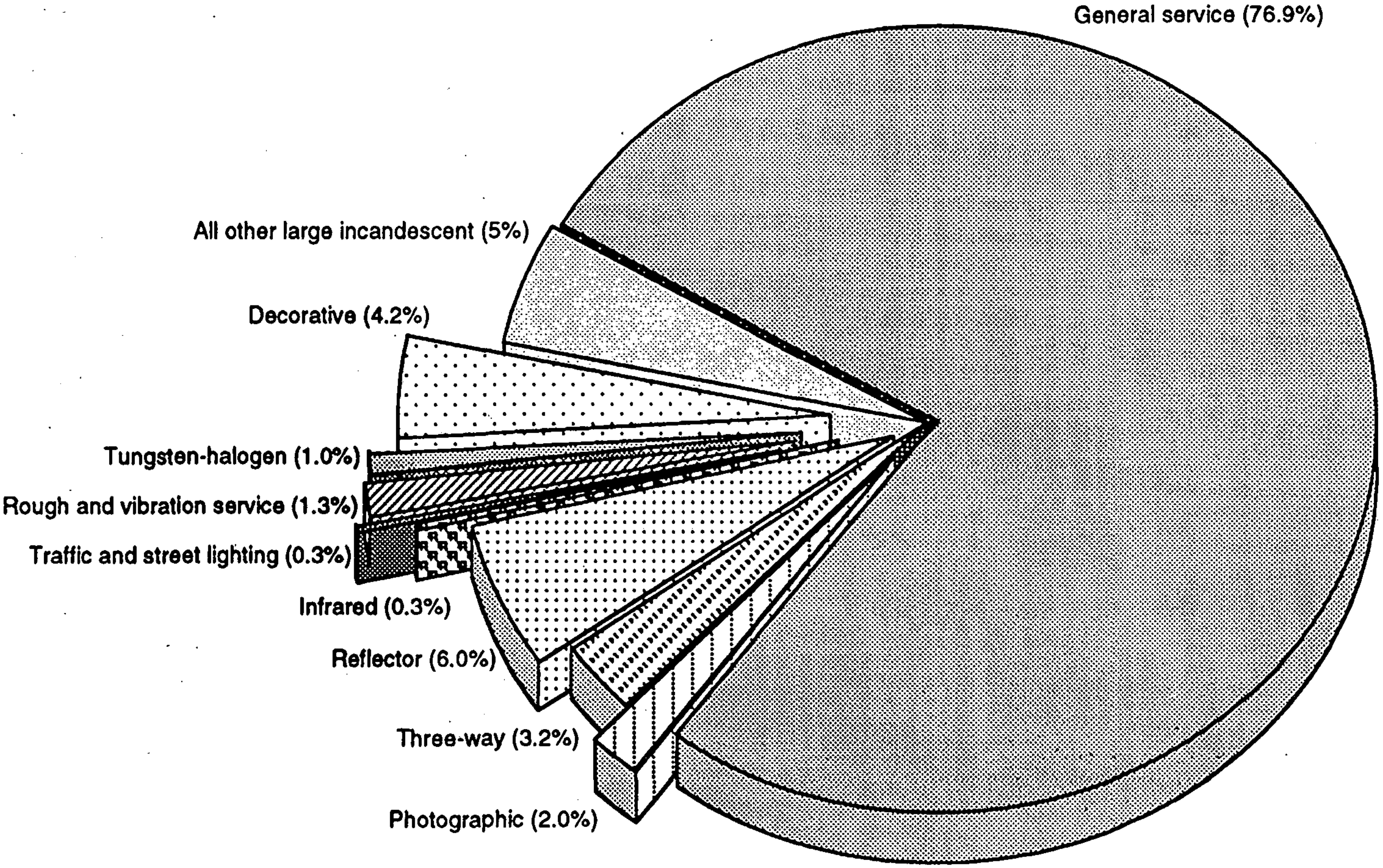
FIGURE 3.10. U.S. SHIPMENTS OF LAMPS, 1993



Total: 3563 million lamps

Note: Christmas tree lamps are excluded. U.S. shipments include both exports and U.S. production for domestic consumption.
Source: Based on data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a)

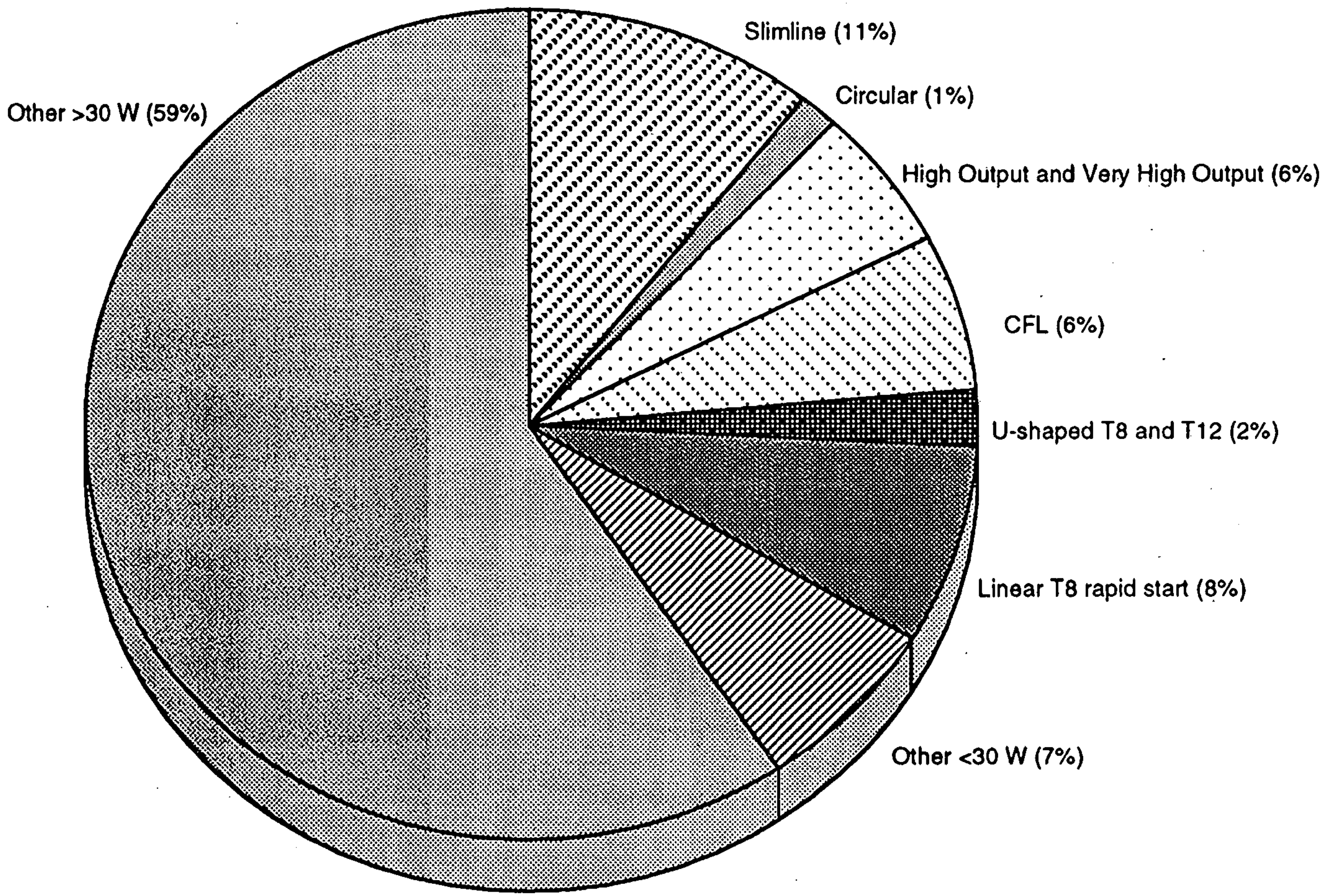
FIGURE 3.11. U.S. SHIPMENTS OF LARGE INCANDESCENT LAMPS, 1993



Total: 1899 million lamps

__Note:__ Christmas tree lamps are excluded. U.S. shipments include both exports and U.S. production for domestic consumption.
__Source:__ Based on data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a)

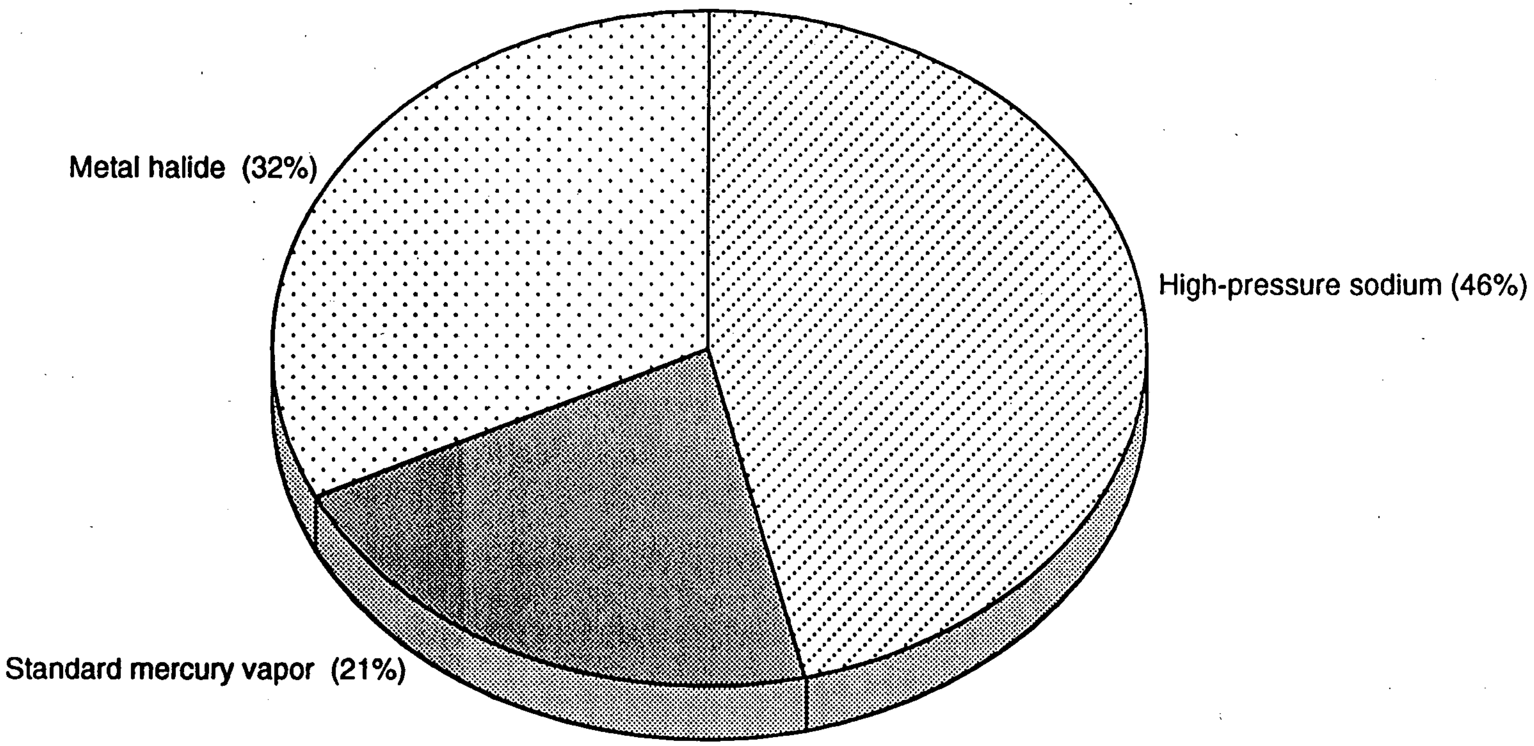
FIGURE 3.12. U.S. SHIPMENTS OF FLUORESCENT LAMPS, 1993



Total: 559.6 million lamps

Note: The category "Other >30W" is comprised of tubular fluorescents from four to eight feet; the bulk of these lamps are 32-, 34-, and 40-watt T12s (Clear 1997). Christmas tree lamps are excluded. U.S. shipments include both exports and U.S. production for domestic consumption.
Source: Based on data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a)

FIGURE 3.13. U.S. SHIPMENTS OF GENERAL LIGHTING HIGH-INTENSITY DISCHARGE LAMPS, 1993



Total: 25.2 million lamps

Note: Shipment data include U.S. production for domestic consumption as well as exports.
Source: Based on data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a)

3.4.2. Ballasts

Fluorescent ballasts show a well-mixed product marketplace (**Figure 3.14**), with the share of electronic ballasts rapidly increasing in recent years (Figure 3.7). As seen in Figure 2.15, the production of regular ("energy-efficient") magnetic ballasts rapidly replaced the production of the older standard magnetic ballasts because of the federal efficiency standard banning the manufacture and sale of standard ballasts starting in 1990 (Koomey et al. 1995). "Energy-efficient" magnetic ballasts and electronic ballasts meet the 1990 standard. (See Section 2.3.2 for more information on ballast standards.)

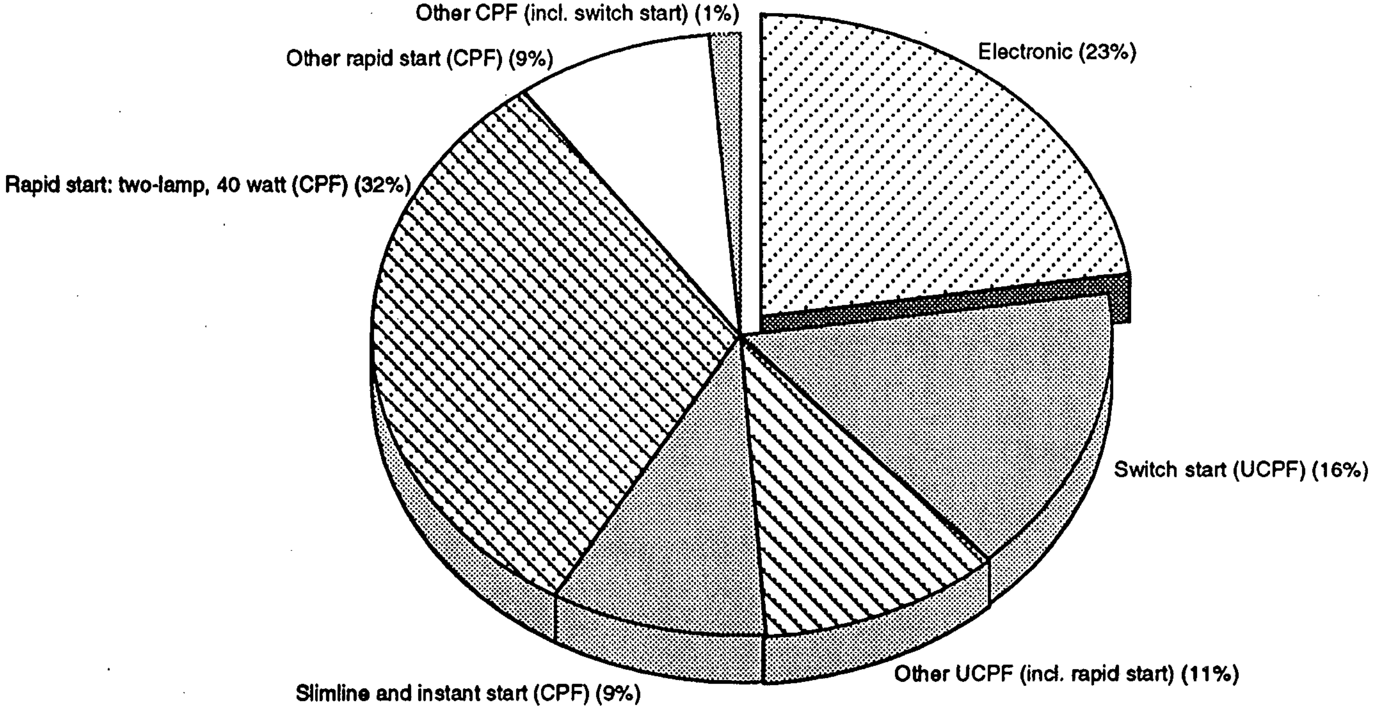
3.4.3. Fixtures

Fixtures can be classified in several ways. For policy makers focusing on residential lighting, it is useful to separate fixtures into two categories: hardwired fixtures and portable fixtures. This distinction is valuable because of the different channels through which these two fixture types are specified and distributed. Hardwired fixtures are integrated into a home, and thus usually specified and supplied by the developer or builder; when a home is sold, hardwired fixtures most often remain in place. In contrast, portable fixtures are typically selected by a home's occupant or a lighting designer; when a home is sold, portable fixtures are usually moved to the new home or are discarded (Sardinsky 1995). In 1993, about 40% of residential-sector fixture sales were portable and about 60% were hardwired (Figure 3.5). **Figure 3.15** and **Figure 3.16** depict the 1993 distribution of residential portable and hardwired fixture shipments by fixture type.

The majority of fixtures in commercial buildings are hardwired, and builders and developers make most of the decisions regarding the type of hardwired fixtures that are installed. As seen in **Figure 3.17**, fluorescent sources accounted for about 60% of the value of commercial-sector shipments of hardwired fixtures in 1993. Facility managers and lighting designers make most of the decisions regarding the types of task lighting used in commercial buildings. Overall, the share of incandescent fixtures in commercial and institutional buildings has declined significantly over time. **Figure 3.18** shows that, in terms of fixture value, the incandescent share of fixtures sales for commercial and institutional buildings fell from 27% to 15% between 1986 and 1995; at the same time, the fluorescent share increased from 57% to 66%.

For more information on both the residential and commercial fixture product mix over time, see EIRI (1995) and the Census Bureau's *Current Industrial Reports* for electric lighting fixtures.

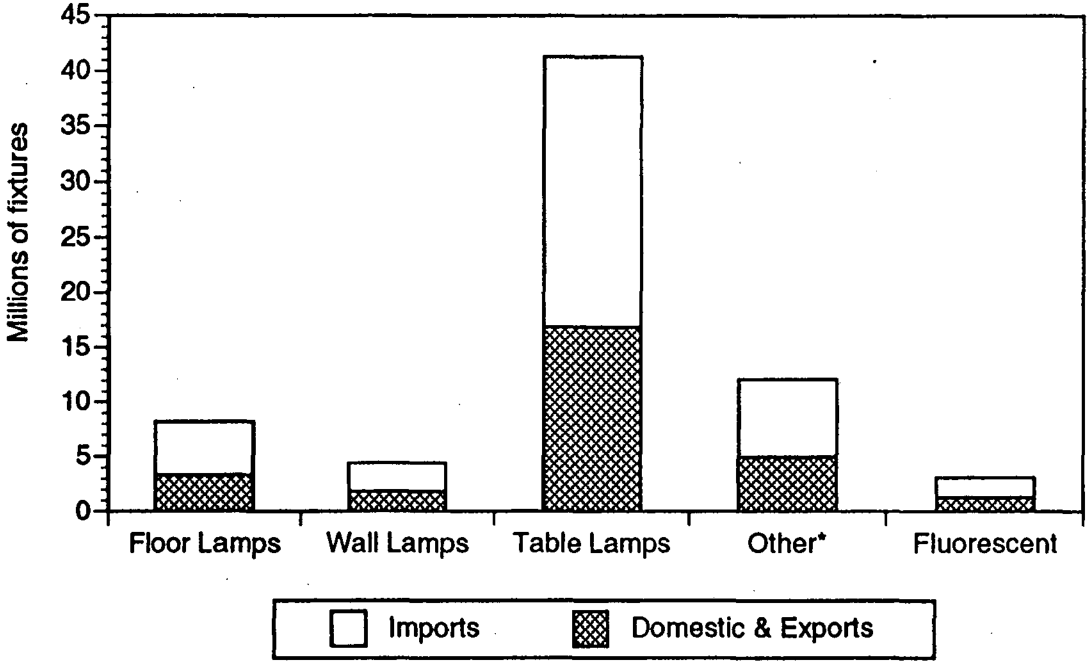
FIGURE 3.14. U.S. SHIPMENTS OF FLUORESCENT BALLASTS, BY BALLAST TYPE, 1993



Total: 107.43 million ballasts

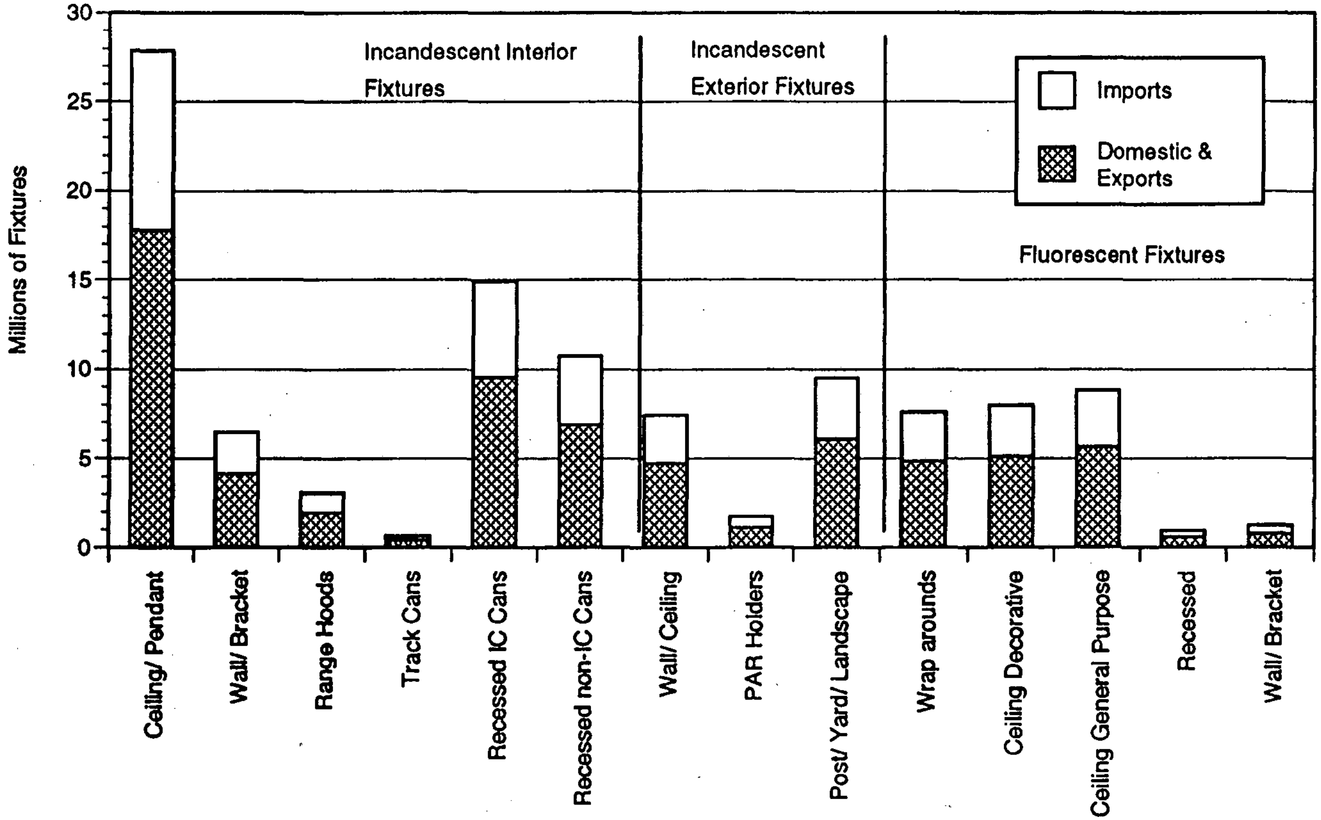
Note: Corrected Power Factor (CPF) and Uncorrected Power Factor (UCPF) type ballasts are magnetic ballasts. Cathode-cut-out (hybrid) ballasts account for a very small fraction of the corrected power-factor category (Coulson 1997). U.S. shipments include both exports and U.S. production for domestic consumption.
Source: Based on data obtained from Census Bureau MQ36C (93)-5, Table 3 (1994b)

FIGURE 3.15. RESIDENTIAL PORTABLE FIXTURE SHIPMENTS IN THE U.S., 1993



Note: "Other" includes fixtures for boudoir and desk lamps.
Source: Adapted from Sardinsky (1995)

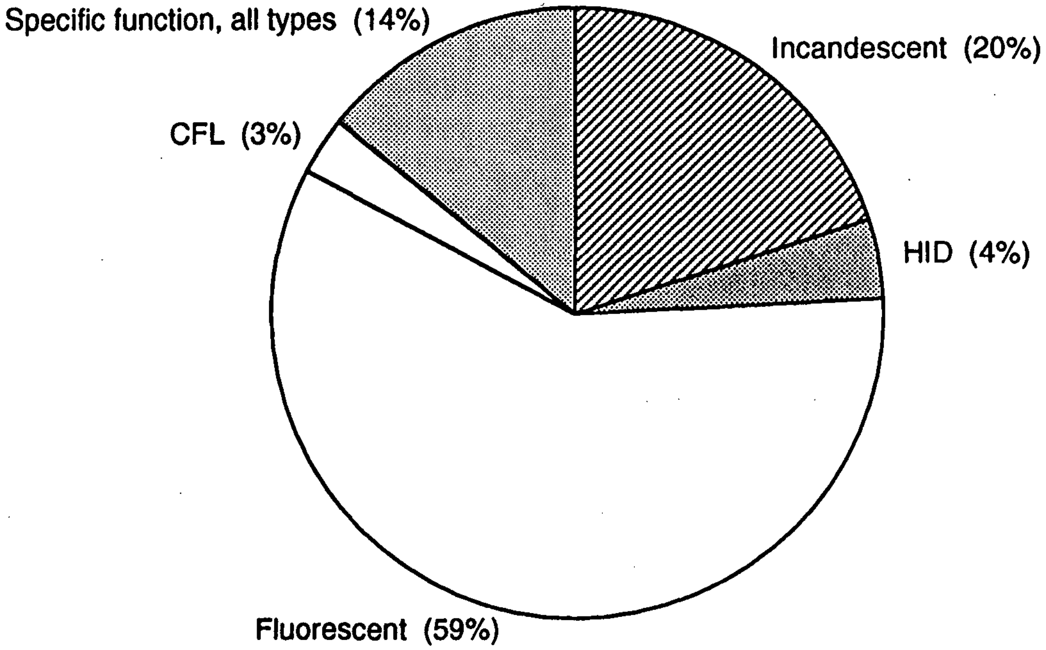
FIGURE 3.16. RESIDENTIAL HARDWIRED FIXTURE SHIPMENTS IN THE U.S., 1993



Source: Adapted from Sardinsky (1995)

FIGURE 3.17. VALUE OF U.S. SHIPMENTS OF COMMERCIAL AND INSTITUTIONAL HARDWIRE LIGHTING FIXTURES, 1993

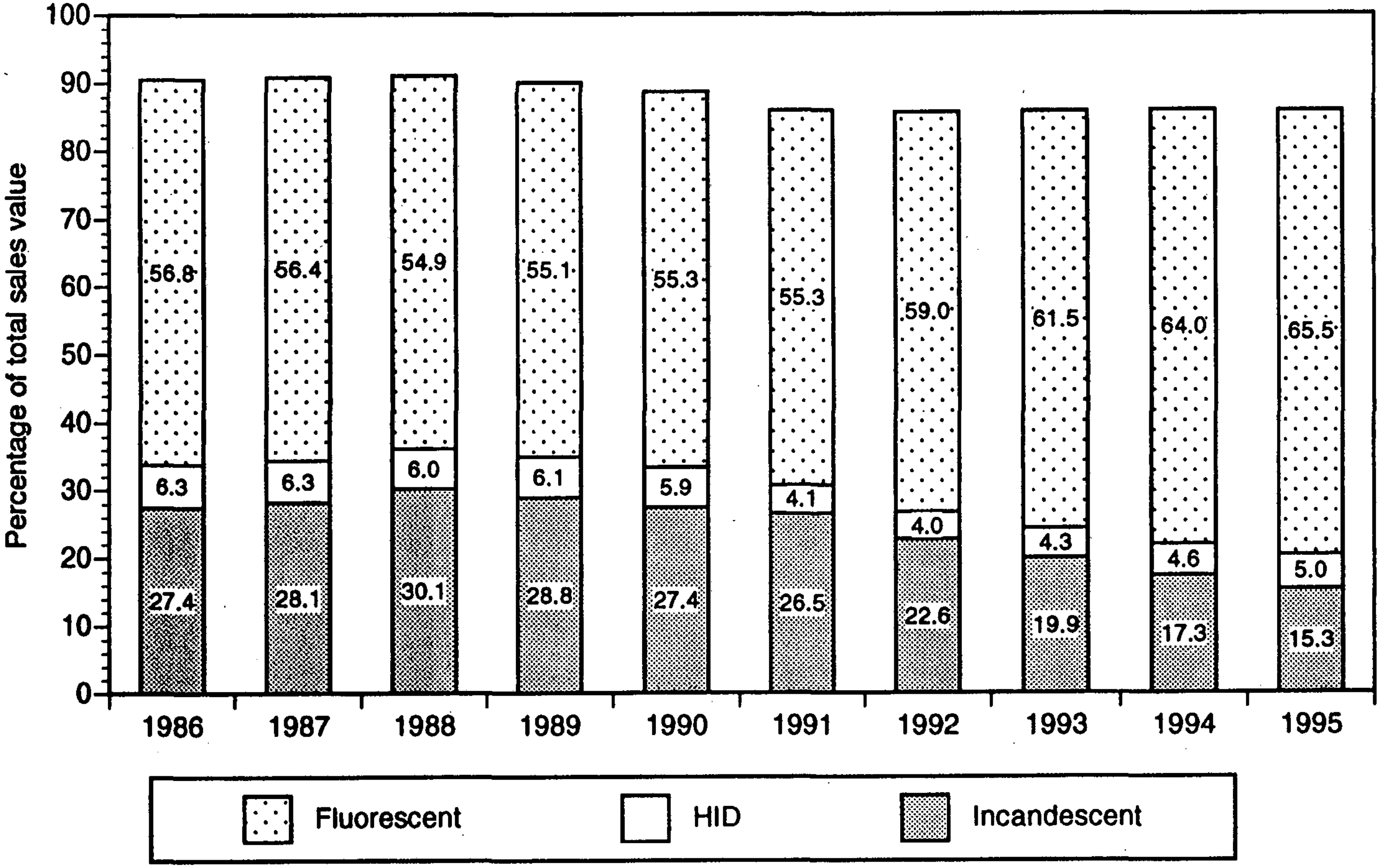
(millions of 1993$)



Total: $2340

Note: Portable and spotlight fixtures are not included.
Source: Adapted from Sardinsky (1995)

FIGURE 3.18. COMMERCIAL AND INSTITUTIONAL LIGHTING FIXTURE SALES: PERCENTAGE OF TOTAL SALES VALUE BY FIXTURE TYPE, 1986-1995



Note: Percentages for a given year do not add to 100% because the data for "Specific Function Lighting, All Sources" and "Components & Renewal Parts" were not included in the figure.
Source: EIRI (1995)

3.5. Product Costs

Lighting equipment costs vary significantly based on circumstances such as the location of the purchase, the number of units purchased, product distribution channels, and special promotions; there are especially wide ranges of costs for fixtures and lighting controls because of the variation in the quality and style of these products (Leslie and Conway 1993). In general, because they are purchasing lighting equipment in small quantities through "consumer channels," residential customers pay far more for a piece of comparable lighting equipment than commercial customers. Large commercial and government consumers typically purchase lighting products directly from distributors, while most residential and some commercial customers purchase from consumer channels such as retail stores and home improvement warehouses (Brown and Atkinson 1994).

3.5.1. Sources and Limitations of the Product Cost Data

We used data from the Census Bureau to estimate *wholesale costs* for lamps, ballasts, and fixtures in **Figures 3.19 – 3.24.** These data are not based on surveys of product prices at the cash register, but were obtained by dividing the total of shipments of a given product type by the number of those units shipped. The shipment values reported by the Census represent approximate wholesale costs. As discussed in Section 3.1, U.S. shipments are valued at the point of production while imports are valued at the first port of entry to the U.S. Typically, imported lamps, ballasts, and fixtures cost considerably less than their domestically manufactured counterparts.

There is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market. When assessing the ways in which particular markets function, however, it is important to understand the relative market shares of various distribution channels and their associated price mark-ups. Koomey et al. (1995) estimated mark-ups in ballast prices in order to calculate the retail price of ballasts in the commercial sector. While mark-up factors ranged from 1.8 to 3.5, the average mark-up factor for F40 magnetic ballasts was 2.3; for F96 magnetic ballasts, the average mark-up factor was 1.8. Similarly, a report from The Results Center (1995a) asserted that the mark-up factor from wholesale to retail prices for lighting products is typically 1.7. These factors are to be multiplied by the Census Bureau's reported costs per unit to derive a rough estimate of the actual retail price to consumers.

In addition to the wholesale costs shown in the following sections, we also provide estimates of typical 1993 residential-sector *retail prices* for lamps, ballasts, fixtures, and lighting controls. These prices are based on Leslie and Conway (1993). Estimates of commercial-sector *retail prices* for fluorescent lamps and ballasts are based on LBNL's Technology and Market Assessment Group (1997a).

See Footnote #21 for fixed-weight price indexes that can be used to convert the prices presented in tables below to 1993$ for comparison purposes.

3.5.2. Lamp Costs

Estimates of average 1993 wholesale costs for lamps are shown in Figure 3.19. There is large variability in the lamp prices: while the average wholesale cost of most incandescent lamps is less than $1, some types of HID lamps have an average wholesale cost of more than $10. Figure 3.20 provides estimates of average 1993 wholesale costs for imported lamps.

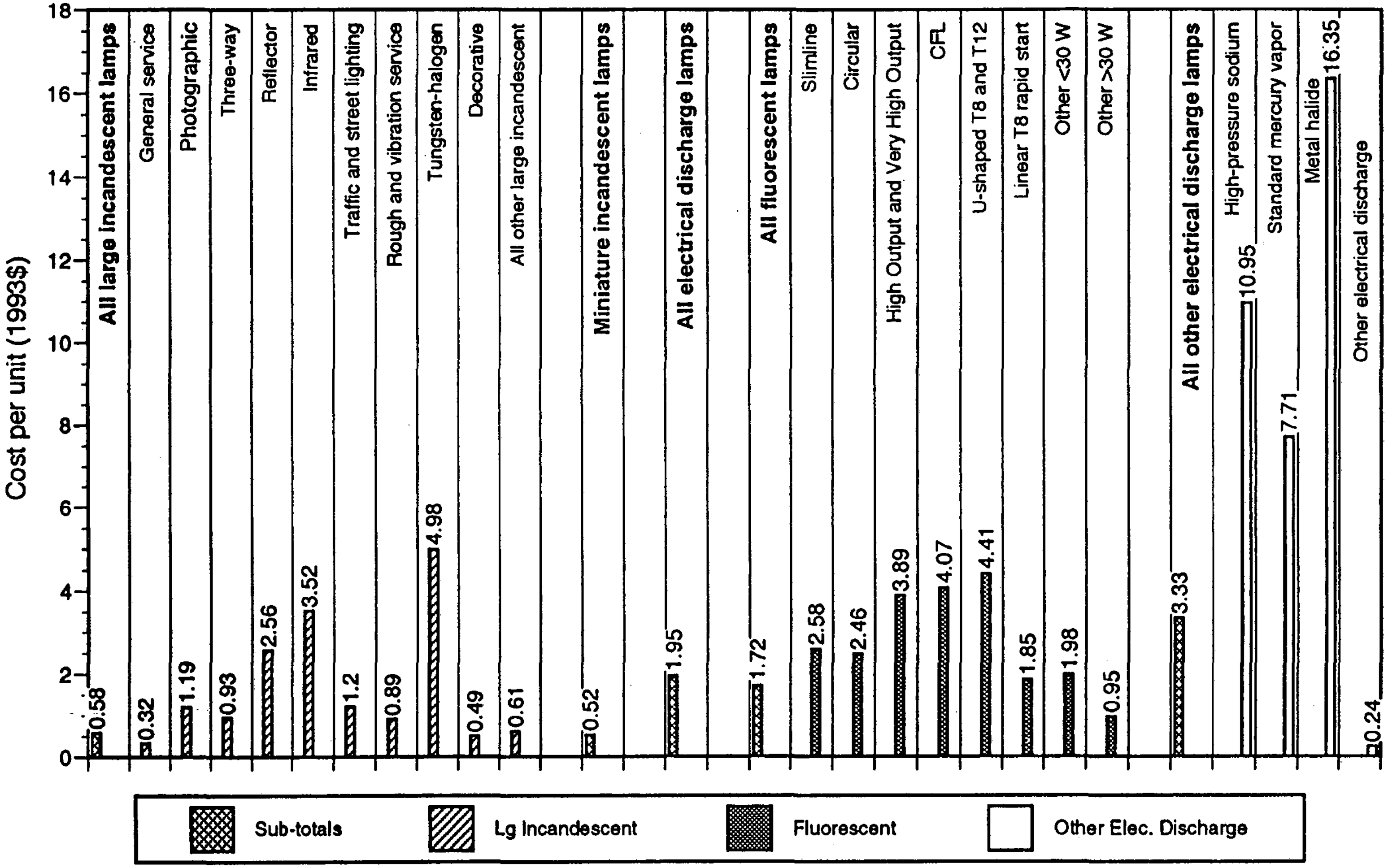
Table 3.3 provides estimates of typical lamp prices for a residential customer purchasing lamps in small quantities. These prices were obtained from Leslie and Conway (1993) and are based on prices listed by three major lamp manufacturers and a catalog of energy-efficient products as well as a survey of shelf prices at numerous retail establishments.

Table 3.3. Estimates of Typical Residential-Sector Retail Lamp Prices, 1993

Lamp Type	Rated Wattage (watts)	Rated Lifetime (hours)	Light Output (lumens)	Typical Price (1993$)
Incandescent lamps				
Common A-lamp	75	750	1190-1220	0.75
Common A-lamp	100	750	1750	0.75
Three-way A-lamp	50-100-150	1200-1500	580-2220	2.00
Reduced-wattage A-lamp	67	750	1130	1.00
Reduced-wattage A-lamp	90	750	1620	1.00
Incandescent reflector lamps				
R20	50	2000	410-420	5.00
R30 Flood	75	2000	830-900	4.50
R40 Flood	150	2000	1900	5.50
PAR38 Flood	75	2000	750-765	5.00
PAR38 Flood	150	2000	1740	5.00
Halogen PAR38 Flood	45	2000	540	10.00
Halogen PAR38 Flood	90	2000-2500	1270	10.00
Halogen IR PAR38 Flood	60	2000-2500	1150	12.00
Fluorescent lamps				
48" T12 Cool White, reduced wattage	34, excl. ballast	20,000	2650	3.00
48" T8 RE830	32, excl. ballast	20,000	3050	7.00
Modular CFL - CFQ18W	18, excl. ballast	10,000	1200	13.00
Self-ballasted CFL (with electronic ballast)	18, excl. ballast (20, incl. ballast)	10,000	1200	20.00
HID lamps				
High-pressure sodium	50, excl. ballast	24,000	4000	18.00
Metal halide	70, excl. ballast	10,000	5000-5200	27.00
Mercury vapor	100, excl. ballast	24,000	3850-4300	17.00

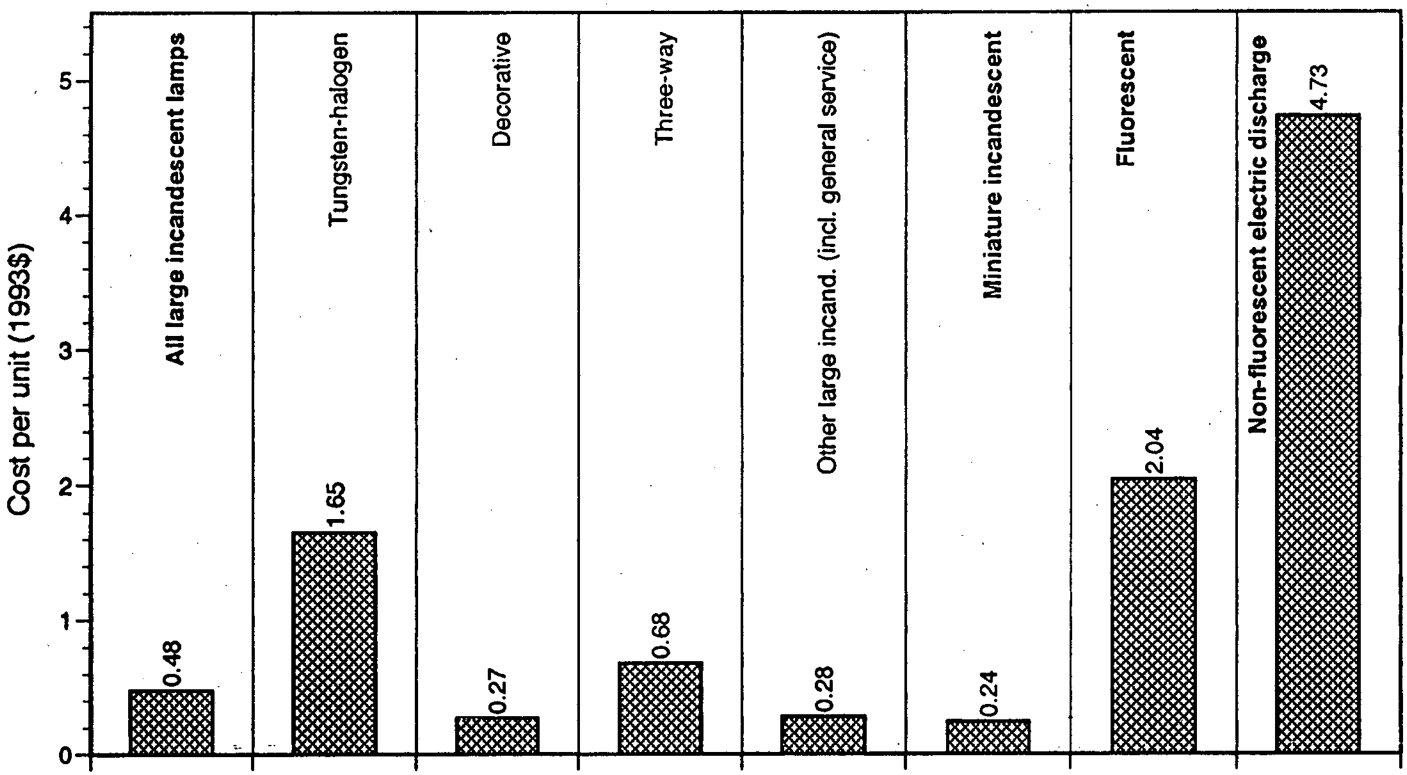
Source: Leslie and Conway (1993); rated lamp wattages (ballast excluded) for HID lamps and self-ballasted CFL were obtained from lamp manufacturer catalogs. These price estimates are based on prices obtained from three major lamp manufacturers as well as surveys of shelf prices at numerous retail establishments and prices listed in a catalog of energy-efficient products.

FIGURE 3.19. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR U.S. LAMP SHIPMENTS, 1993



Note: These average unit cost data are not based on surveys of product prices at the cash register, but were obtained from Census data by dividing the value of U.S. shipments for a given lamp type by the number of units shipped. U.S. shipments are valued at the point of production; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market.
Source: Based on data obtained from Census Bureau MQ36B (93)-5, Table 2a (1994a)

FIGURE 3.20. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR IMPORTED LAMPS, 1993



Note: These average unit cost data are not based on surveys of product prices at the cash register, but were obtained from Census data by dividing the value of U.S. imports of a given lamp type by the number of units imported. As discussed in Section 3.1, imports are valued at the first port of entry in the U.S.; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market.
Source: Based on data obtained from Census Bureau MQ36B (93)-5, Table 4 (1994a)

Table 3.4 provides estimates of typical fluorescent lamp prices for commercial and industrial customers purchasing lamps in large quantities.

Table 3.4. Estimates of Typical Commercial- and Industrial-Sector Retail Prices for Fluorescent Lamps, 1994

Fluorescent Lamp Type	Typical Price per Lamp (1995$)
F40T12/ES (energy saver)	$1.50
F40T12/RE70 (rare earth)	$3.00
F32T8	$2.50
F96T12/ES (energy saver)	$3.00
F96T12/RE70 (rare earth)	$7.00
F96T12HO/ES (high-output/energy saver)	$7.00
F96T12HO/RE70 (high-output/rare earth)	$9.00

Source: These prices are based on LBNL's Technology and Market Assessment Group (1997a) and have been rounded off to the nearest $0.50. LBNL based their prices on the General Electric Commercial and Industrial Lamp Price Schedule and the February 1994 Defense General Supply Center/Defense Logistics Agency price catalog.

3.5.3. Ballast Costs

Estimates of average wholesale costs for fluorescent ballasts are shown in Figure 3.21. Typically, magnetic ballasts are less expensive than electronic ballasts. **Table 3.5** provides estimates of ballast retail price ranges for residential customers. **Table 3.6** provides estimates of commercial retail prices for two-lamp fluorescent ballasts.

Table 3.5. Estimates of Typical Residential-Sector Ballast Retail Prices, 1993

Ballast Type	Typical Price per Ballast (1993$)
Magnetic	$15-25
Electronic	$25-65
Electronic Dimming	$30-90

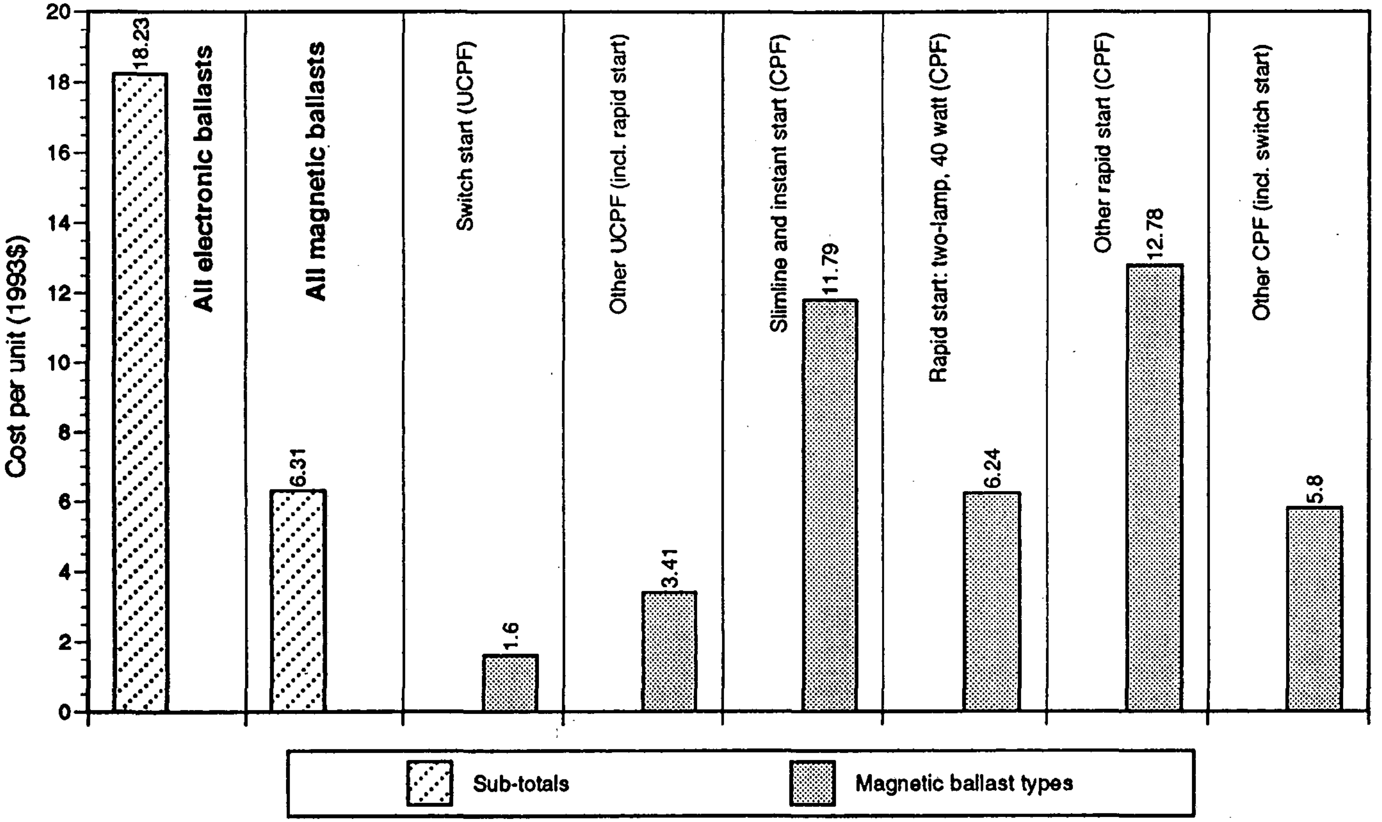
Source: Leslie and Conway (1993); the price ranges were developed by lighting application specialists and were spot checked at several lighting stores.

Table 3.6. Estimates of Typical Commercial-Sector Retail Prices for Two-Lamp Fluorescent Ballasts, 1996

Ballast/Lamp Type	Typical Price per Ballast (1996$)
Magnetic Ballasts	
2F40T12	$11.50
2F96T12	$20.00
2F96T12HO	$33.00
2F32T8	$15.50
Cathode Cut-Out (Hybrid) Ballasts	
2F40T12	$16.50
2F96T12HO	$38.00
2F32T8	$19.50
Electronic Ballasts	
2F40T12	$22.50
2F96T12	$30.50
2F96T12HO	$46.50
2F32T8 (rapid-start)	$20.00
2F32T8 (instant-start)	$19.00

Source: These prices are based on LBNL's Technology and Market Assessment Group (1997a) and have been rounded off to the nearest $0.50. LBNL based their prices on a price survey of luminaire manufacturers, ballast manufacturers, and lighting management companies.

FIGURE 3.21. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR U.S. SHIPMENTS OF FLUORESCENT BALLASTS, 1993



Note: These average unit cost data are not based on surveys of product prices at the cash register, but were obtained from Census data by dividing the value of U.S. shipments for a given ballast type by the number of units shipped. U.S. shipments are valued at the point of production; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market. "Corrected power-factor" (CPF) indicates a high power-factor (typically, exceeding 0.95). In low power-factor ballasts ("uncorrected," UCPF), the phase shift between the current and voltage is substantial. Most ballasts used in the residential sector are low power-factor; ballasts used in the commercial and industrial sectors tend to be high power-factor. Cathode cut-out (hybrid) ballasts account for a very small fraction of the corrected power-factor category (Coulson 1997).

Source: Based on data obtained from Census Bureau MQ36C (93)-5, Table 3 (1994b)

3.5.4. Fixture Costs

Figure 3.22 shows estimated average wholesale costs for various residential-sector hardwired fixture categories. Because lighting fixtures are perceived more as an element of home decor than as an appliance, there is large variability in their prices. **Table 3.7** shows the wide range in the retail prices of typical residential fixture types.

Table 3.7. Typical Retail Prices for Residential Fixtures, 1993

Fixture Type	Typical Price per Fixture (1993$)
Recessed with incandescent lamp	$20–75
Recessed with CFL	$45–100
Track lights, per head	$10–50
Wall- or ceiling mounted with fluorescent or incandescent lamp	$100–200
Linear fluorescent strips	$10–30
Wall-mounted exterior with incandescent lamp	$15–200
Wall-mounted exterior with HPS lamp	$70–150
Exterior floodlight with PAR lamp	$10–20
Exterior with HID lamp	$40–90

Note: For fluorescent fixtures, the price of a magnetic ballast is usually included in the price range (Leslie 1997).

Source: Leslie and Conway (1993); the price ranges were developed by lighting application specialists and were spot checked at several lighting stores.

Figure 3.23 provides estimates of average wholesale costs for commercial and institutional hardwired fixtures. Figure 3.24 provides estimates of average wholesale costs for imported hardwired and portable fixtures for all sectors.

3.5.5. Controls Costs

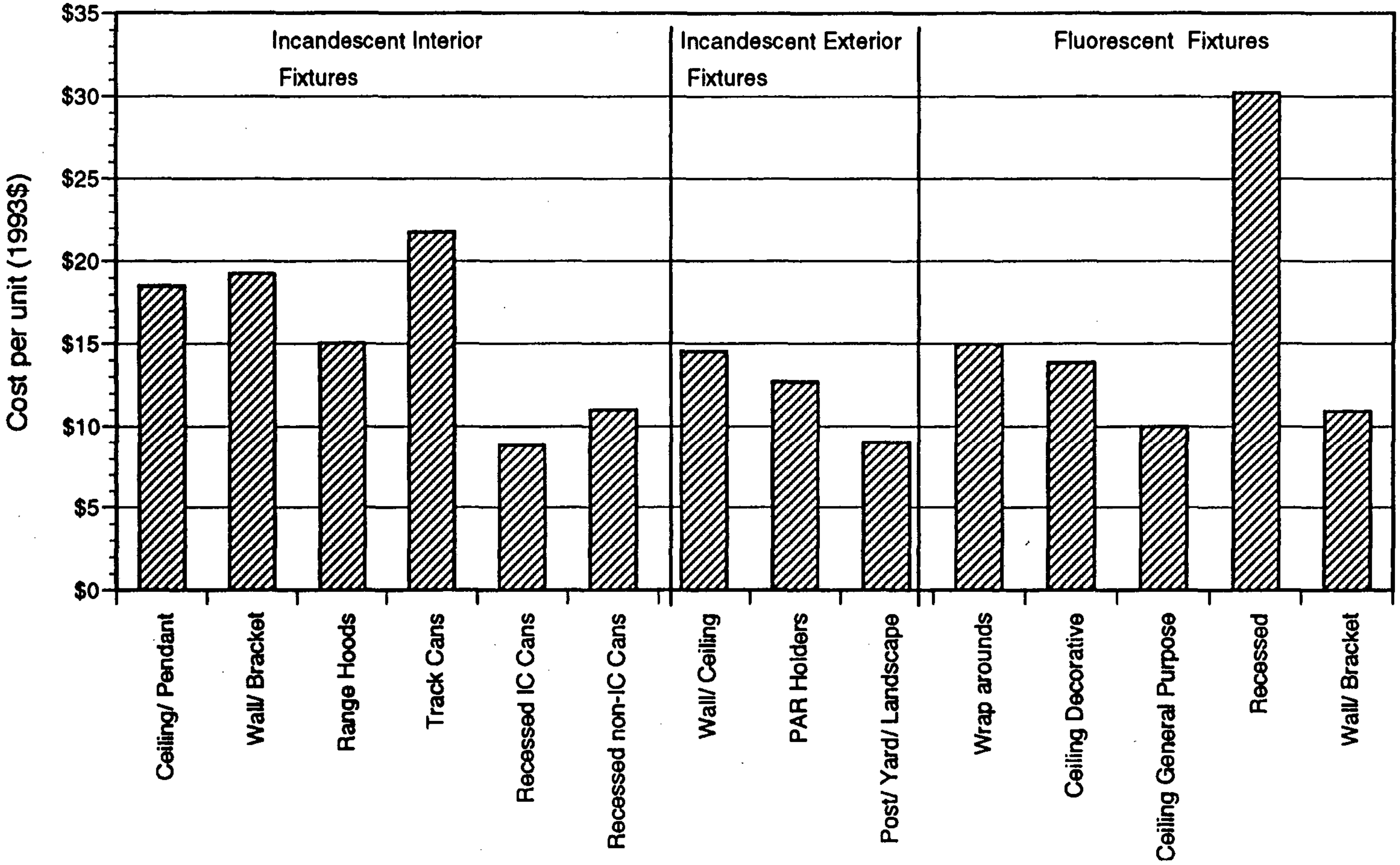
The Census Bureau does not collect data on lighting controls, and other sources of control data are scarce. **Table 3.8** provides prices for some of the commonly used controls in the residential sector.

Table 3.8. Typical Retail Prices for Residential Controls, 1993

Control Type	Typical Price (1993$)
Switches	$1-10
Door Switches	$10-20
Dimmers for Incandescent Lamps	$5-30
Dimmers for Fluorescent Lamps	$30-150
Motion Detectors	$40-100
Interval Timers	$5-25
Plug and Socket Timers	$10-20

Source: Leslie and Conway (1993); the price ranges were developed by lighting application specialists and were spot checked at several lighting stores.

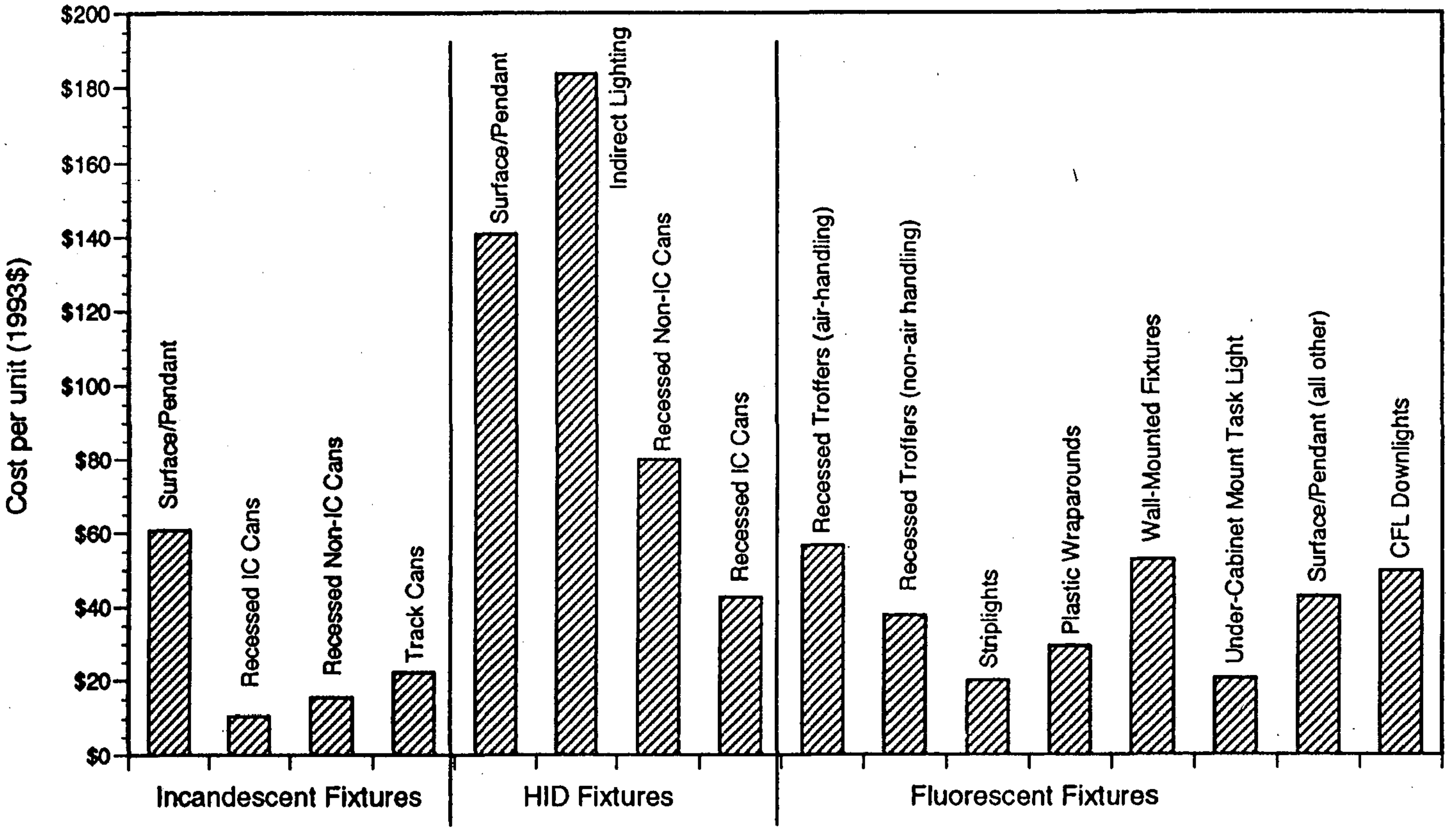
FIGURE 3.22. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR U.S. SHIPMENTS OF RESIDENTIAL HARDWIRED FIXTURES, 1993



Note: Average unit cost data were derived from Census data. These data are not based on surveys of product prices at the cash register, but were obtained by dividing the value of shipments of a given fixture type by the number of units shipped. As discussed in Section 3.1, U.S. shipments are valued at the point of production; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market.

Source: Adapted from Sardinsky (1995)

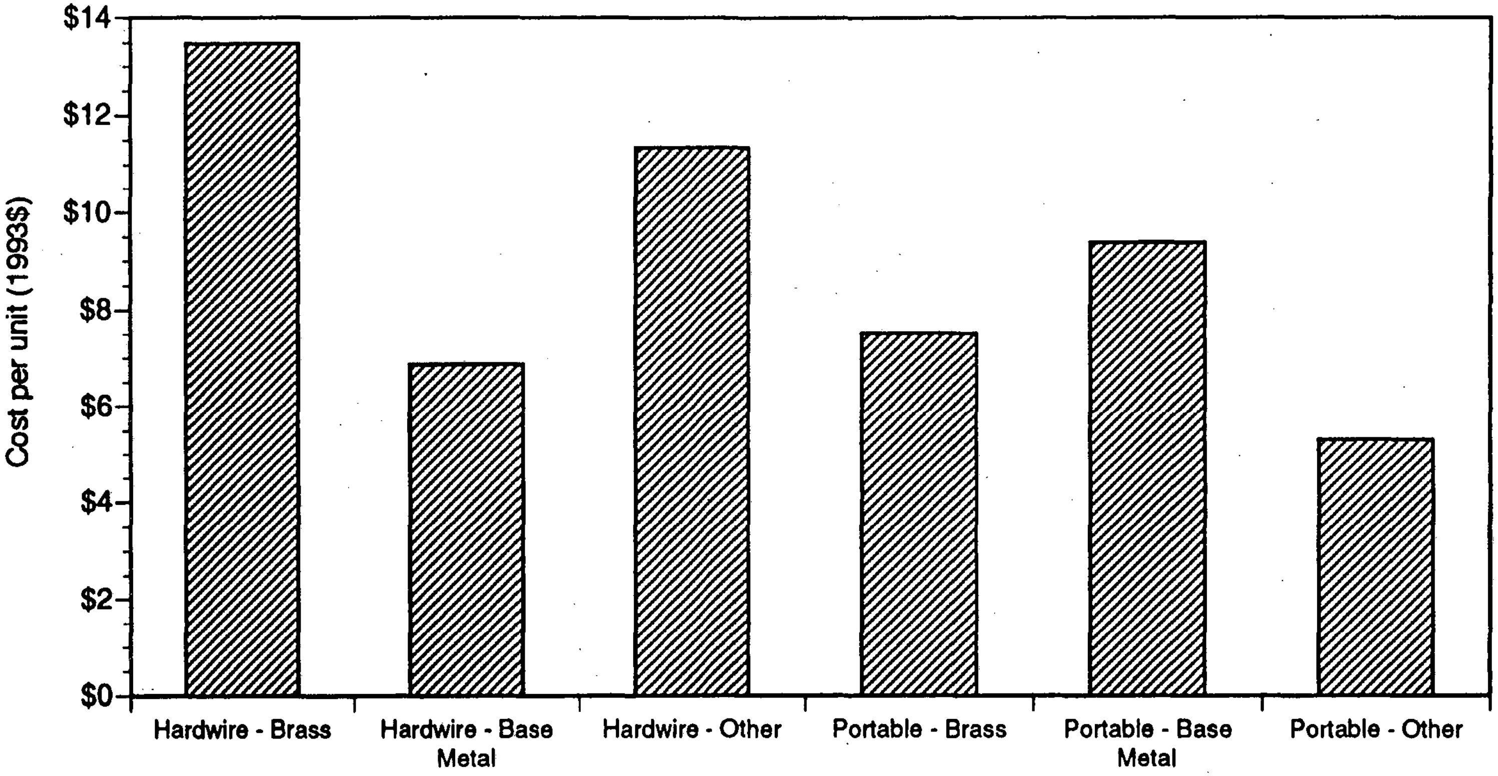
FIGURE 3.23. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR U.S. SHIPMENTS OF COMMERCIAL AND INSTITUTIONAL HARDWIRED FIXTURES



Note: Excludes portable fixtures and spotlights. Average unit cost data were derived from Census data. These data are not based on surveys of product prices at the cash register, but were obtained by dividing the value of shipments of a given fixture type by the number of units shipped. As discussed in Section 3.1, U.S. shipments are valued at the point of production; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market.

Source: Based on data obtained from Census Bureau MQ36L (93)-1, Table 2 (1994c)

FIGURE 3.24. ESTIMATED AVERAGE WHOLESALE COST/UNIT FOR IMPORTS OF HARDWIRED AND PORTABLE FIXTURES



Note: Average unit cost data were derived from Census data. These data are not based on surveys of product prices at the cash register, but were obtained by dividing the value of U.S. imports of a given fixture type by the number of units imported. As discussed in Section 3.1, imports are valued at the first point of entry to the U.S.; there is little information available regarding wholesale-to-retail price mark-ups for particular segments of the lighting market.

Source: Adapted from Sardinsky (1995)

4. THE STRUCTURE OF THE LIGHTING MARKETPLACE

In this chapter, we describe the roles and general characteristics of some of the major participants in the lighting marketplace. In addition, we discuss the various distribution channels by which lighting equipment can reach the consumer and the importance of moving energy efficiency up the distribution ladder.

4.1. Market Participants

4.1.1. Manufacturers

Manufacturer Data Sources
Numbers of manufacturers for different types of lighting products were obtained from the U.S. Census Bureau.[26] Manufacturer data for fixtures were also obtained from a report entitled *The U.S. Lighting Fixtures Industry: An Economic and Market Study, 1995-96 Edition* (EIRI 1995). The EIRI report relies on data from various sources, including the U.S. Department of Commerce. In some cases, the data reported by EIRI reflects the inconsistencies that are common among lighting market data: for example, based on Census data, EIRI reports that the number of companies manufacturing non-portable residential fixtures in 1992 was 117, but that the number of these companies with shipments of $100,000 or more was 132.

Market Shares and Competition
The extent to which an industry's market share is dominated by relatively larger firms is referred to as "market concentration." Market share can represent financial power in the marketplace; typically, the mark-ups that firms pass on to consumers increase as the concentration of the market increases (Atkinson et al. 1992). Generally, the lamp, ballast, and fixture markets are highly concentrated, while the lighting controls market is less so. Below, we discuss the number of manufacturers, as well as market share, for lamps, ballasts, fixtures, and controls.

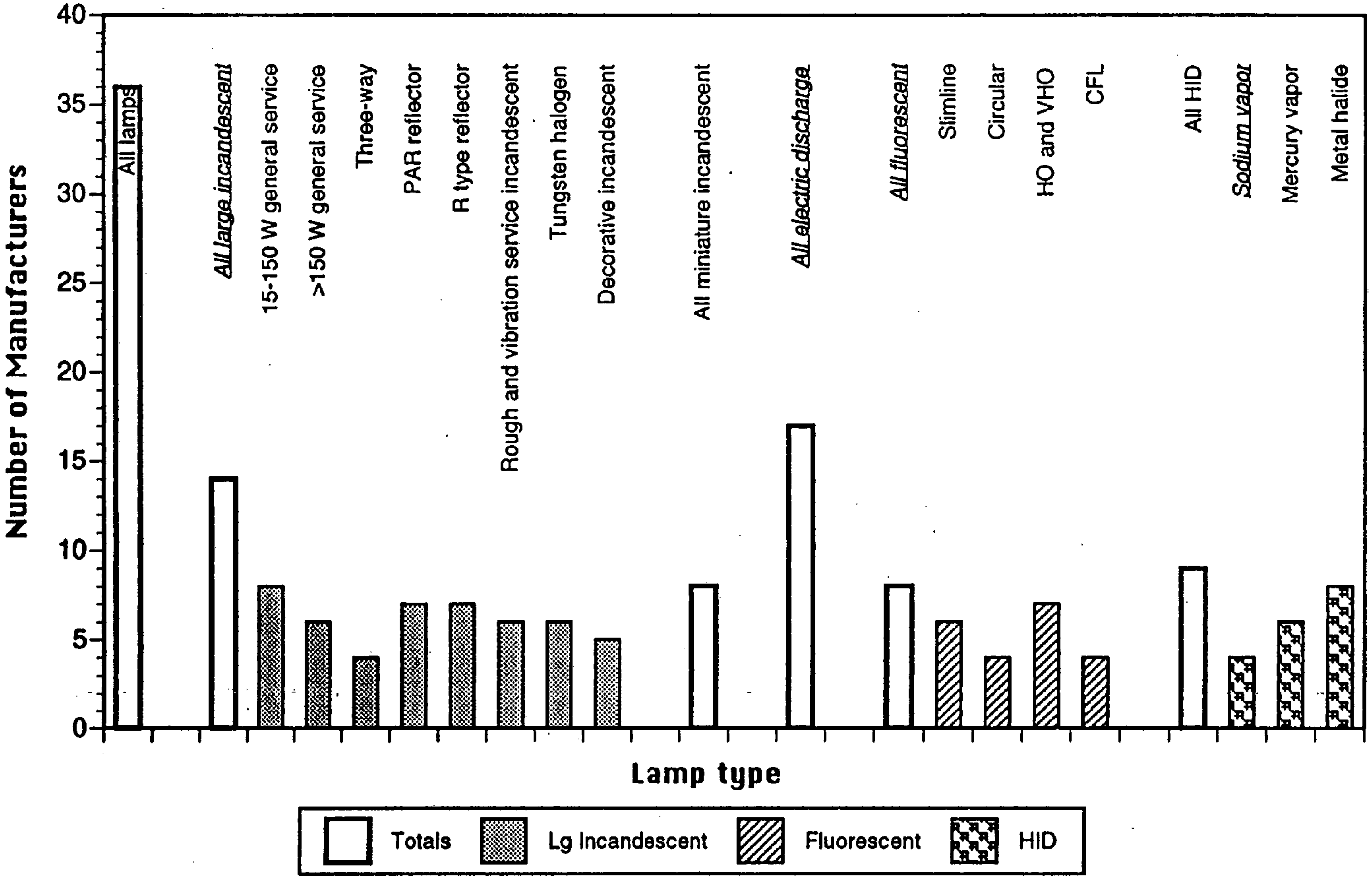
Lamps: **Figure 4.1** shows the number of U.S. lamp manufacturers for a variety of lamp types listed by the Census Bureau. The Census Bureau (1995a) reported that, in 1994, there were 36 U.S. manufacturers of electric lamps (as discussed in Section 3.1, the most recent year for which detailed lamp data are available from the Census Bureau is 1994). Typically, lamp manufacturers are multi-national corporations serving international markets. The U.S. lamp market is highly concentrated and the volume of lamp shipments is largely dominated by three large companies: General Electric (GE), Philips, and Osram Sylvania.[27] It is estimated that these three companies control 90% or more of the U.S. lamp market share (Atkinson et al. 1992, Lewis 1997).

---

[26] We believe that the most reliable data regarding numbers of lighting product manufacturers is published by the Census Bureau; however, based on which data source one consults, the number of U.S. manufacturers producing a certain type of lighting equipment can vary dramatically. For example, according to Census Bureau data, there were approximately 9 U.S. manufacturers of electronic ballasts for fluorescent lamps in 1996 (Census Bureau 1997c); in contrast, *Lighting Design + Application* (LD+A), a publication of the Illuminating Engineering Society of North America (IES), lists more than 80 U.S. manufacturers of electronic ballasts in 1996 (IES 1996). One explanation for this discrepancy is that some of the manufacturers listed by trade journals may simply use a private label to market products that were in fact manufactured to their specifications by a large manufacturing company. In phone surveys carried out using manufacturer lists from LD+A, Lighting Research Center researchers found the list to contain a mixture of original equipment manufacturers, assemblers, manufacturers, and retailers; some companies, especially the multi-nationals, were listed twice or more in the same category (Conway 1997).

[27] Osram and Sylvania were separate companies until Osram purchased Sylvania in 1993 (Osram Sylvania 1997).

FIGURE 4.1. NUMBER OF LAMP MANUFACTURERS IN THE U.S.,1994



Note: Manufacturers of christmas tree lamps are excluded from the data in this figure; in addition, the "large incandescent" category excludes photographic incandescent lamps.
Source: Based on data obtained from Table 2.a in Census Bureau MQ36B (94)-5 (1995a)

Figure 4.2 shows the results of interviews with lamp retailers asked to identify their best selling brands for residential customers. GE was named as the biggest selling brand by 40% of all retailers interviewed; 60% of chain store lighting managers named GE as the best selling brand (Campbell et al. 1993). GE's dominance of the residential market is most likely the result of exclusivity agreements between supermarket chains and lamp manufacturers, most often GE; as a result, GE dominates the U.S. residential lamp market with well over 50% market share (Polsby 1994). Fewer than 30% of residential consumers surveyed by Weiner and Campbell (1992) recognized any lighting brands other than GE, Philips, and Osram Sylvania.

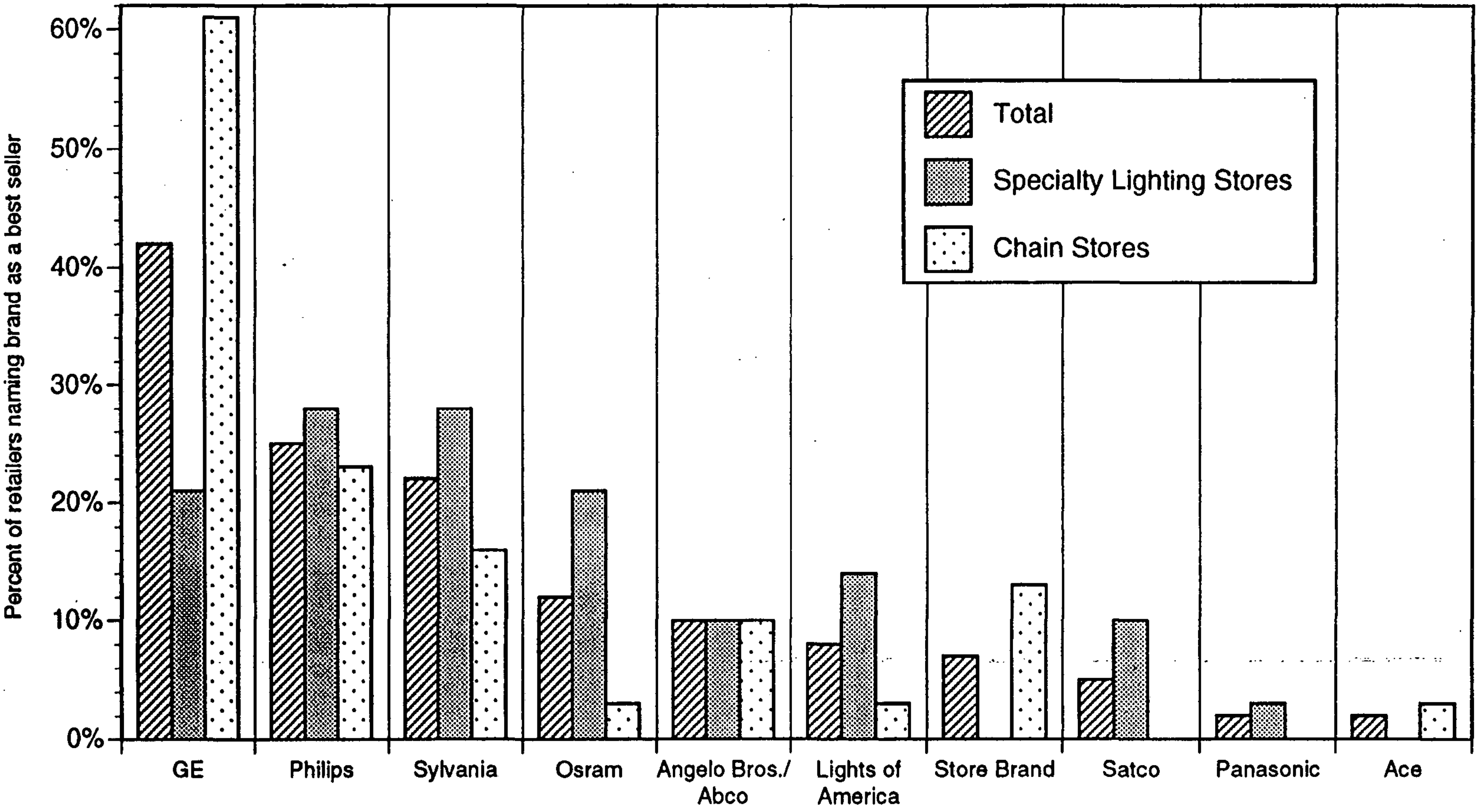
Ballasts: Like the lamp industry, the U.S. ballast industry is highly concentrated and almost all ballasts are produced by only a few manufacturers. It should be noted that these ballast manufacturers are not the same firms that dominate the lamp market. Most ballast-producing companies do not produce lamps, although some lamp-producing companies have now begun to produce ballasts. The Census Bureau (1997c) reported that there were approximately 12 manufacturers of fluorescent ballasts located in the U.S. as of March 1997. With respect to manufacturers of specific ballast types, the Census reported nine manufacturers of magnetic ballasts as well as nine manufacturers of electronic ballasts – indicating that many manufacturers produce both magnetic and electronic ballasts. Currently, the primary U.S. ballast manufacturers are Advance, Magnetek, Lighting Power Products (formerly Valmont), Motorola, Howard, and Robertson.

Fixtures: While there are relatively few U.S. lamp and ballast manufacturers, there are far more companies that manufacture fixtures. The Census Bureau reported 109 manufacturers of residential non-portable fixtures and 159 manufacturers of commercial and institutional non-portable fixtures for 1996 (Census Bureau 1997a). In spite of the large number of fixture manufacturers, however, the fixture market – like the lamp and ballast markets – is highly concentrated and a few large companies dominate sales.

In 1987, the four largest companies accounted for 54%, and the 50 largest companies accounted for almost 90%, of total commercial fixture shipments (EIRI 1995). The residential fixture industry is less concentrated than the commercial, with the four largest companies accounting for about one quarter, and the 50 largest manufacturers accounting for about two-thirds, of 1987 shipments (EIRI 1995). According to Ron Lewis, Director of Information Resources for the Lighting Corporation of America, the two largest manufacturers of fixtures for the commercial and industrial sectors are Lithonia and Cooper Lighting Group; behind these two mass producers comes the Lighting Corporation of America (Lewis 1997). Smaller still, but major players, are Thomas Industries, Hubbell Lighting, The Genlyte Group, and General Electric. In terms of sales, these seven companies are likely to account for 60-70% of the 1997 commercial market share (Lewis 1997). Generally, the major players in the commercial fixture market also manufacture residential fixtures; Lithonia and GE are exceptions – Lithonia primarily produces commercial fixtures, and almost all fixtures produced by GE are used for industrial and outdoor lighting (Mezger 1997).

As of 1992, five states hosted more than 50% of all U.S. lighting fixture manufacturing plants: California, New York, Pennsylvania, Illinois, and New Jersey (EIRI 1995). The fixture market's concentration in terms of both manufacturers and geography can make it easier for program designers to concentrate efficiency efforts on a small number of manufacturers or in a small number of states. For example, the New York State Energy Research and Development Authority sponsors competitive programs that encourage lighting product manufacturers in New York to develop new high-efficiency products (see Section 4.2.3 for further discussion of this program). The Lighting Research Center at Rensselaer Polytechnic Institute in Troy, New York also offers a technical assistance program for lighting manufacturers in the state of New York.

FIGURE 4.2. LAMP BRANDS PREFERRED BY RESIDENTIAL CUSTOMERS IN THE U.S.
Portion of Retailers Naming Brand(s) as Best Seller(s), 1992



Note: These data are based on telephone interviews with 60 lighting managers, 29 from lighting specialty stores and 31 from the lighting departments of chain stores. Although the survey was conducted to assess preferred residential brands, figures include portions of other market segments that purchase lamps from surveyed retailer types.
Source: Based on data obtained from Campbell et al. (1993)

Although the larger producers of fixtures dominate the market, based on the EIRI report (1995), the large majority of companies that manufacture fixtures are small. In 1992, about 28% of fixture manufacturing plants employed fewer than five people, and another 50% employ between five and 49 people. Residential fixture companies are somewhat smaller than commercial ones: 48% of residential fixture plants employ fewer than 10 people, compared to about 37% of commercial fixture manufacturing plants. Generally, the smaller manufacturers produce less efficient fixtures.

Controls: In contrast to the highly concentrated markets for lamps, ballasts, and fixtures, the lighting controls market is more disaggregated in terms of market share. According to Atkinson et al. (1992), there are 50 to 100 players in the lighting controls market, including Honeywell, General Electric, Johnson Controls, Robertshaw Controls Co., Allen-Bradley Co., Cutler-Hammer Products, Conservolite, Hubbell Inc., Lightolier (a Genlyte subsidiary), and Lutron. This market covers a wide spectrum of products, from simple timers to elaborate whole-building systems that can integrate controls for lighting, space conditioning, security, and more. The Census Bureau does not collect data on lighting controls.

The Different Market Roles of Large and Small Manufacturers

In terms of market roles, there is an important difference between small and large manufacturers of lighting products. Both the lamp and ballast industries in the U.S. have historically been dominated by a few large, well established manufacturers operating with a relatively rigid distribution network (Davis 1991). For example, GE, Philips, and Osram Sylvania not only account for approximately 90% of domestic lamp production, but also supply 60% of the world lamp market; the remaining 10% of domestic production is dominated by a handful of small companies, including Duro-Test and Supreme Corporation (Brown and Atkinson 1994).

Small manufacturers, however, do play several important roles in the lighting marketplace. In general, small manufacturers do not compete directly with large companies, but instead specialize in niche markets to distinguish their products. For example, in the reflector lamp market, small manufacturers have managed to remain in business by concentrating their production on long-life or vibration-resistant lamps that are purchased primarily by a small group of commercial and industrial customers with special demands (Brown and Atkinson 1994).

According to Davis (1991), small companies often possess characteristics with regard to technology innovation that challenge the "mature" lighting industry. Small companies are often less afraid of risk-taking, more in tune with market opportunities and conditions, and flexible enough to react quickly to new, emerging demands; consequently, they have been responsible for many innovations in the U.S. lighting marketplace. (See Davis (1991) for a description of the roles played by small U.S. manufacturers in the introduction of innovative lighting products.) On the other hand, some smaller companies offer less expensive, lower quality products, and thus go out of business after a relatively short time.

4.1.2. Consumers

In order to design a program promoting energy-efficient lighting, it is important to understand which consumer groups are purchasing which types of lighting products and in what quantities. It is also important to understand the preferences on which consumers base their lighting decisions. Unfortunately, except for research on a few market segments or products (e.g., the residential applications of CFLs), the extent of market research on consumers of lighting products is very limited.

The Preferences of Residential Consumers

Typically, the preferences of residential consumers for lighting products are more influenced by aesthetics, first cost, and availability than by the energy efficiency of a product. Especially in the case of lighting fixtures, a consumer is unlikely to make a purchase decision based on energy-conservation benefits (Jennings et al. 1996).

Asked about the preferences of their customers in a 1992 EPRI survey (Campbell et al. 1993), 60 lighting retailers indicated that incandescent lamps are the most suitable for the largest number of residential applications and that linear fluorescent lamps fill a niche in home work environments such as offices, garages, kitchens, and laundry rooms. Asked to choose among CFLs, linear fluorescents, and incandescents based on a variety of lamp characteristics, the retailers considered incandescent lamps to be the most attractive and most widely applicable, but also the most expensive to operate. Fluorescent lamps were considered to be the least attractive and most difficult to install. CFLs were considered to be the most efficient and the most environmentally friendly, but the most expensive to purchase. CFLs were expected to become the energy-efficient and cost-effective replacement for incandescent lamps and yet still play only a niche role in the residential sector (see box for a discussion of consumer perceptions of CFLs). In Chapter 2, Section 2.1.4, we provide detailed information regarding the types of lamps that are installed in U.S. households.

When asked to identify lighting types gaining popularity among consumers, CFLs were mentioned by 60% of the retailers interviewed in the 1992 EPRI survey (Campbell et al. 1993). Fifty percent of retailers mentioned halogen lamps and 25% mentioned fluorescent lamps as increasingly popular. It is interesting to note that, of the retailers interviewed who were managers of lighting departments in chain stores, almost one-third believed that incandescent lamps are continuing to gain popularity; in contrast, none of the retailers from lighting specialty stores indicated an increase in the popularity of incandescent lamps.

Although the owner or occupant of a household is most often the person to select the portable fixtures for the household, many other parties are potentially involved in the choice of hardwired fixtures in the residential sector. These additional decision makers are discussed in Section 4.2 on distribution channels.

Perceptions of Compact Fluorescent Lamps by Residential Customers

A great deal of research has been conducted on consumer attitudes towards CFLs. Although CFLs were expected to become the energy-efficient and cost-effective replacement for incandescents, CFLs still play only a niche role more than a decade after their introduction to the market. For a better understanding of the lighting market, it is interesting to explore the reasons behind this slow adoption rate.* Distribution issues affecting consumer adoption of CFLs are discussed below in Section 4.2.1.

The most comprehensive CFL consumer survey to date was carried out by EPRI in 1991 (Weiner and Campbell 1992) and updated in 1994 (Campbell 1994). The most significant barrier to a broad residential success of CFLs was found to be the high first-cost. Although many residential consumers are willing to try CFLs, especially with a rebate or at discounted prices, very few consumers repurchase CFLs or install them widely in their households. Most customers who have tried CFLs claim that they are not worth the full price. Manufacturers, consumers, and retailers seem to agree that "there will not be a consumer market for CFLs until they are available for less than $10 through regular retail stores"; in 1993, two-thirds of retailers surveyed thought that less than half of their customers paid full price (e.g., not using any rebates or discounts) for CFLs (Campbell et al. 1993).

In the updated EPRI survey, Campbell (1994) found that, in addition to the high first-cost barrier, CFLs possess four main deficiencies compared to incandescent lamps: (1) they are incompatible with many standard fittings; (2) they cannot be used with dimmer switches**; (3) they are perceived as unattractive; and (4) users are still unclear about where, or why, to use them. In addition, the survey found that broken lamps are considered difficult to clean up as well as potentially hazardous and that customers are unable to detect savings in their energy bill as a result of CFL installation. Other reasons offered by consumers for the unpopularity of CFLs include their bulkiness because of ballast size, their lack of versatility, and switch-on delays. In no known market research have CFLs achieved a product satisfaction level higher than 60%; manufacturers acknowledge performance problems related to light output and rated lifetime but tend to blame these problems on "cheap imports" (Campbell et al. 1993).

According to the 1991 EPRI survey, even among CFL-owning homes, CFLs are used on average in fewer than two rooms (Weiner and Campbell 1992). CFLs are most often installed in living rooms (21% of them); but are also often used in bedrooms and kitchens (see Table 2.6). Most CFLs (44%) are used in overhead lamps and table lamps (27%), but they are also often used in wall fixtures, floor lamps, and outdoor fixtures.

In the 1992 EPRI survey, several of the manufacturers interviewed asserted that the CFL market will not expand significantly until dedicated fixtures are more widespread; these manufacturers suggested that, instead of providing direct rebates for CFL users, efficiency efforts should focus on providing incentives to fixture and fittings manufacturers (Campbell et al. 1993).*** Retailers suggest that the driving motivation to buy CFLs for some consumers is the reduced need for replacements in hard-to-access fixtures such as ceiling cans, and that the marketing rhetoric should thus concentrate on long life rather than energy savings. Consumers are often more concerned about immediate cash outlays than long-term costs, or consider the long-term investment in CFLs risky.

Another important requirement for the wide residential success of CFLs is consumer education. For example, according to Weiner and Campbell (1992), the unit "watt" is not understood by about 45% of consumers surveyed. There is a widespread impression that watts measure light output levels, and this misconception obviously impedes informed consumer decisions related to efficient lighting technologies. It is often unclear to the average consumer how the $9-20 CFL could be "cheaper" than an incandescent lamp costing 50¢ or a dollar (Polsby 1994). As mentioned above, consumers are also uncertain about the toxicity and dangers associated with broken CFLs, and whether "it is safe to touch the white stuff" (Campbell 1994). It is not only consumers who lack sufficient education to make a rational market choice; often, the managers of chain store lighting departments are found to be almost as technically uninformed about CFLs as the average residential customer (Weiner and Campbell 1992).

* Although research indicates that CFL use in Europe is limited by a number of the same factors that limit use in the U.S. (e.g., first-cost, lack of dedicated fixtures), CFLs are more broadly accepted in Europe; for example, in the Netherlands, Germany, and Denmark, CFLs are installed in approximately half of all households (Kofod 1996). For more information on CFL use in European households, see Kofod (1996) and Mills (1993).

** One manufacturer is now producing dimmable CFLs for the residential sector (Clear and Rubinstein 1997).

*** See Mills et al. (1996) for a detailed discussion of the importance of dedicated CFL fixtures in the residential sector.

Compact Fluorescent Lamps: An Improving Technology

The characteristics of CFLs have improved each year since their introduction in the 1980s. In recent years, we have seen a steady reduction in the overall length and weight of CFLs. Generally, we see a continued trend towards an increased variety, with well over 100 types of CFLs available today when variations in size, color temperature, lamp shape, and base type are taken into consideration. New lamp designs even make it possible to use CFLs to replace halogen lamps in the pervasive and energy-wasting halogen torchieres (see Calwell (1996) and (1997a)). The new generation of electrodeless fluorescents (e.g., Genura and QL) are especially small compact fluorescent sources. In the past year, GE introduced the innovative "Helix" CFL, which has a tight spiral tube design. Unfortunately, GE has encountered manufacturing difficulties and the product is currently on hold.

Lamp performance has improved as well, including improvements in power quality (power factor and total harmonic distortion) and reduced sensitivity to high air temperatures around the lamp. Although dimming is still not a common option in consumer products, an increasing variety of CFLs are dimmable and special dimmable ballasts are increasingly available.

Beyond the lamp itself, there has been a steady trend towards fixtures more suitable for the CFL. This includes a new generation of "dedicated fixtures" for pin-based lamps, in which incandescents cannot be used. The most important of these has been the very recent appearance of CFL torchieres from about five manufacturers. There is also a positive trend towards fixture designs that better manage the high glare that a bare CFL lamp produces.

For more information, see McGowan (1997).

Source: Mills (1997)

The Preferences of Commercial Consumers

The occupants of the many types of commercial buildings are far less likely to choose their own lighting products than are the occupants of homes. Most often, a network of people is involved in making decisions about the types of lighting equipment installed within a commercial building. This network may include the building owner and manager, an electrical contractor, design and engineering professionals, and manufacturer representatives (Conway 1991). See Section 4.2 below for a brief discussion of commercial distribution channels and the network of lighting decision makers.

4.1.3. Additional Market Participants

Building Contractors, Lighting Management Companies, Energy Service Companies, etc.: Market participants such as construction companies and other building contractors, lighting management companies, and energy service companies can play an important role in shaping the lighting market by influencing the selection of lighting components used by their clients. Building owners or occupants can establish an ongoing lighting service contract with a lighting management company that will address lighting needs within the building such as the replacement of faulty lighting equipment and lamps that have reached the end of their lamp life. An energy service company (ESCO) can be hired by a building owner or occupant to develop, install, and finance comprehensive performance-based lighting retrofit projects; typically, the goal of ESCO projects is to improve energy efficiency or reduce the lighting load of facilities owned or operated by the customer. Most often, the ESCO covers the cost of the new equipment and installation while the client agrees to pay the financial benefits of their calculated energy savings to the ESCO for an agreed upon number of years.

Market Intermediaries: As lighting products travel from the manufacturer to the consumer, they can go through the hands of several levels of traders such as wholesalers and retailers. It is important to understand these 'invisible' intermediate stations between the manufacturer and the consumer, because the attitudes and behavior of these market participants play a major role in a technology's market failure or success.

For the residential market, it is especially important to understand the last link in the sales chain – the retailers who are at the consumer-market interface. Especially in the residential retrofit market, the point of lighting product purchase is usually the point at which a consumer acquires all his or her information for making a purchase decision. Thus, retailers are particularly important from a program design perspective, as they represent the group with the widest range of opportunities to communicate the energy savings, environmental benefits, and other benefits of efficient lighting technologies to the consumer (Campbell et al. 1993). Market intermediaries are an integrated part of product flow and market infrastructure, and are discussed further in Section 4.2 on distribution channels.

Utilities: Although utilities do not always represent an integral part of the lighting product flow, they often play a role in shaping the marketplace. Utility interests related to the lighting market include issues such as power quality, peak load reduction, demand management, energy conservation, and environmental regulations. Utilities can exert their influence on the market in several ways.

The most common way for utilities to influence the market is through demand-side management (DSM) or market transformation programs, which may include rebate programs, discounts, leasing programs, and free dissemination of products. Although there is uncertainty about the future role of utilities in DSM programs because of the impending deregulation of the industry, utilities are expected to play an increasing role in the education of both consumers and retailers. For a discussion of utility-sponsored energy-efficiency programs in a restructured utility industry, see Eto et al. (1996a) and Eto and Hirst (1996).

Less prevalent, but important, utility activities include education and product quality evaluations. In the 1992 EPRI survey, manufacturers suggested that a consortium of utilities should play the primary role in determining product performance standards such as power factor and total harmonic distortion standards; in addition, manufacturers asserted that utilities should monitor the lighting industry in terms of product quality, and include only high-performance products in their rebate and discount programs (Campbell et al. 1993). Some utilities, however, have expressed their discomfort about being “drawn into the lighting business” or conducting campaigns that target the environmental conscience of their consumers (Campbell et al. 1993).

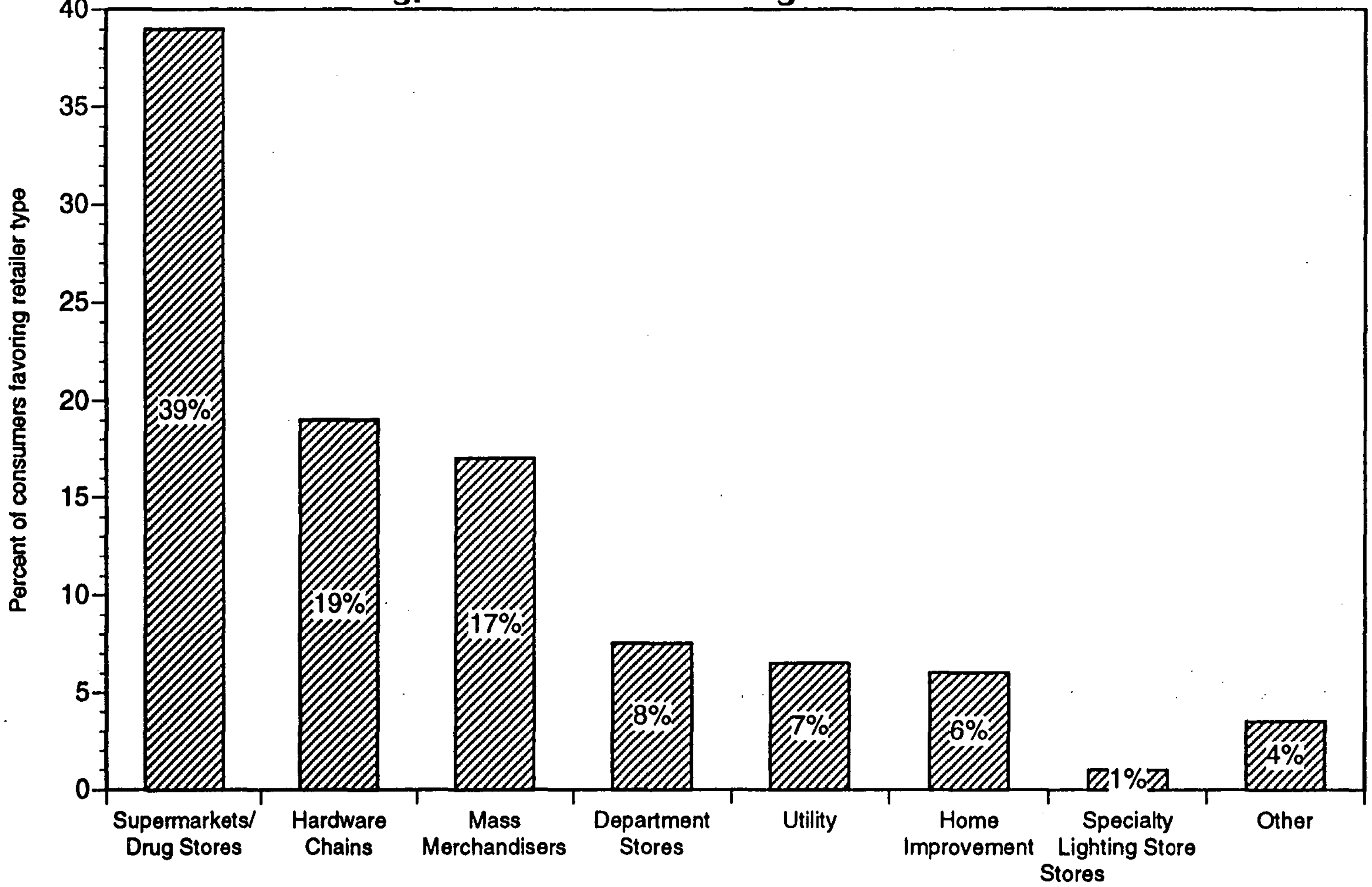
4.2. Distribution Channels

In order to successfully influence the types of lighting systems that are installed in U.S. homes and businesses, we must understand how lighting products find their ways into U.S. buildings. As discussed above, in addition to the lighting manufacturers and building occupants, a number of other players may be involved and there are various market channels through which lighting equipment can reach the end-user.

4.2.1. Residential-Sector Distribution Channels

The owner or occupant of a household is most often the person to select portable fixtures, and most residential customers purchase their lighting equipment through "consumer" channels such as retail stores and home improvement warehouses. Residential lamp purchasing behaviors are summarized in **Figure 4.3**. Clearly, many residential consumers (38%) purchase their lamps at supermarkets and drug stores (Weiner and Campbell 1992).

FIGURE 4.3. LAMP PURCHASING BEHAVIOR
Retailer Type Most Often Used by Residential Consumers



Note: These percentages are based on interviews with 178 people who use CFLs and 150 people who are aware of CFLs but choose not to use them. The retailer preference percentages for CFL users and non-users were averaged to produce the data in this figure; the differences for users and non-users, however, were slight: percentages for users and non-users were within 3% of each other in all cases.
Source: Weiner and Campbell (1992)

As mentioned above, many additional parties can be involved in the choice of hardwired fixtures for households. **Table 4.1**, which is taken from Calwell et al. (1996), provides a breakdown of who specifies the type of hardwired lighting technologies that are installed in various types of homes.

Table 4.1. Who Specifies Hardwired Lighting Technologies for Homes?

Specifier	Multi-Family Housing	Tract Home	Semi-Custom Tract Home	Custom Home
Commercial Architect	✔			
Electrical Engineer	✔			
Builder	✔	✔	✔	Possibly
Electrical Contractor	✔	Possibly	✔	Possibly
Lighting Showroom /Electrical Distributor	✔	Possibly	✔	✔
Homeowner/Renter			✔	✔
Interior Decorator	Possibly		Possibly	✔
Lighting Designer	Possibly		Possibly	✔
Residential Architect				✔

Source: Calwell et al. (1996), based on Sardinsky (1995)

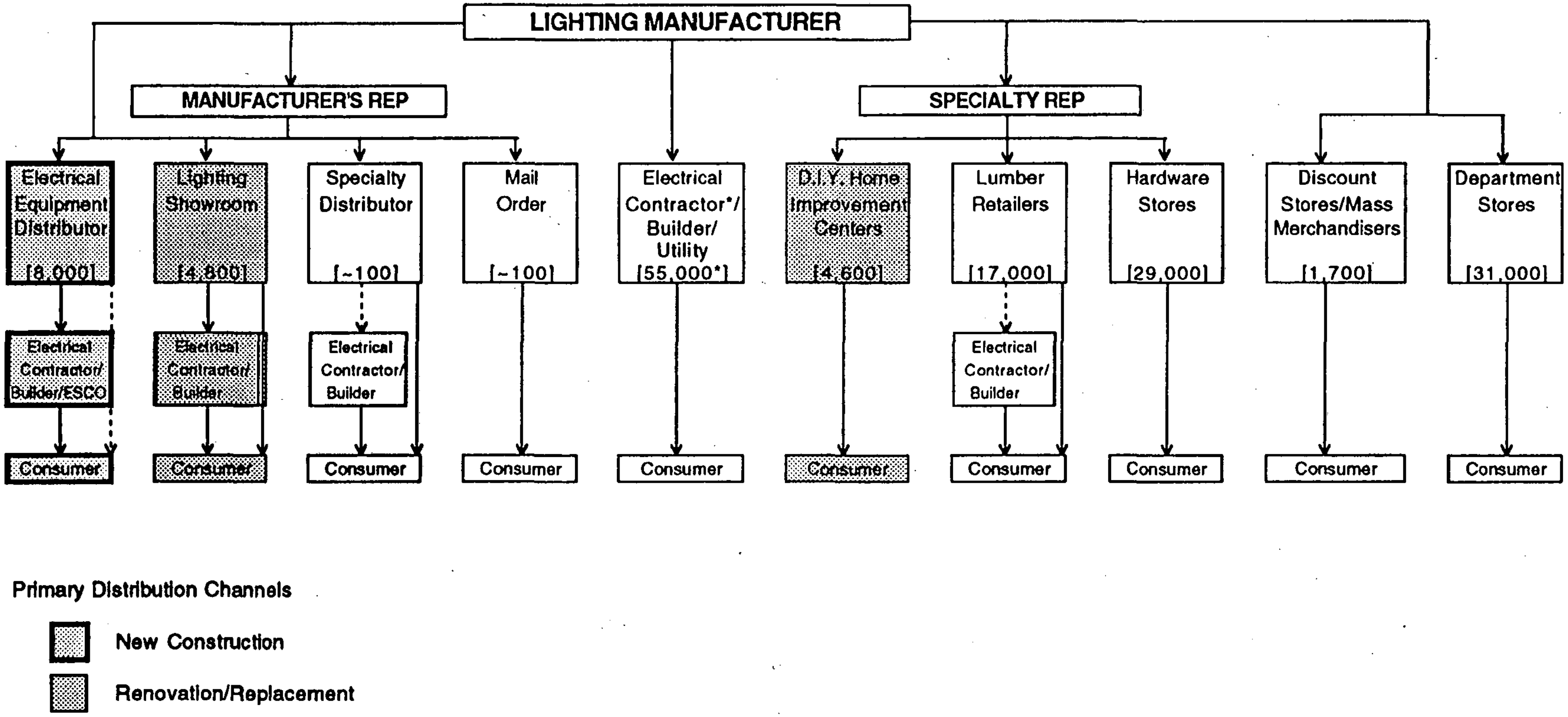
The horizontal axis of Table 4.1 is arranged in order of increasing home cost, and the vertical axis is arranged to approximate the chronological order of outsider involvement in a lighting project relative to the household resident. The specifiers indicated above the "Homeowner/Renter" tend to make decisions either before or apart from the ultimate resident; the specifiers indicated below the "Homeowner/Renter" are generally hired by the resident to assist in lighting design and/or product selection. Calwell et al. (1996) point out that the diagonal trend from upper left to lower right indicates the increasing resident involvement in lighting selection as income rises (that is, as the homes types become more expensive). Based on the table, the specifiers most often involved in residential-sector lighting decisions are builders, electrical contractors, electrical distributors, and lighting showrooms. For further discussion of this table, as well as additional information on residential-sector market transformation, see Calwell et al. (1996).

In the residential market, retrofit lighting purchases often differ from those in new construction. As seen in Table 4.1, for new construction, builders and contractors more often make decisions about lighting systems than household residents. In contrast, retrofit lighting purchases are often made by the building occupants. In addition to the split incentives between building occupants and building contractors regarding energy efficiency (e.g., occupants are more likely to consider energy efficiency a priority because they are often responsible for paying the electricity bill), occupants and contractors also use different channels for purchasing products. Builders and contractors predominantly use "high-end designer" distribution channels. These lighting specialty stores include lighting showrooms and electrical equipment or specialty distributors. Lighting product manufacturers or their representatives play important roles in these distribution channels. Building occupants, on the other hand, more often purchase through commodity channels or chain stores. Chain stores include home improvement stores such as Lowes, Home Depot, and Home Base; mass merchandisers such as K-Mart and Wal-Mart; chain hardware stores such as ACE; department stores such as J.C. Penney or Sears; and supermarkets and drug stores.

According to an EPRI study (Campbell et al. 1993), from a policy-making perspective there are important distinctions between lighting specialty stores and chain stores as market-consumer interfaces. These differences affect available technologies, product mix, brand mix, knowledge of products, awareness of energy efficiency and environmental issues, and sales attitudes. For example, lighting specialty stores are more likely to sell HID products than chain stores. While chain stores carry more GE and Lights of America products, specialty stores show a strong bias towards Osram Sylvania and Panasonic merchandise; Philips is represented about equally in both distribution channels (Figure 4.2). The study also concluded that lighting specialty store personnel are more knowledgeable than personnel in chain stores, about issues related to both energy use and lighting technologies. This has important implications for product sales and consumer education. For example, managers of lighting specialty stores were found to be more inclined than lighting department managers in chain stores to believe that CFLs are easy to explain and offer a better value than incandescent lamps. According to the EPRI study, such lack of knowledge can result in little or no support from a major portion of the retail distribution system which sees energy-efficient lighting technologies as expensive, hard-to-sell alternatives to the incandescent lamp.

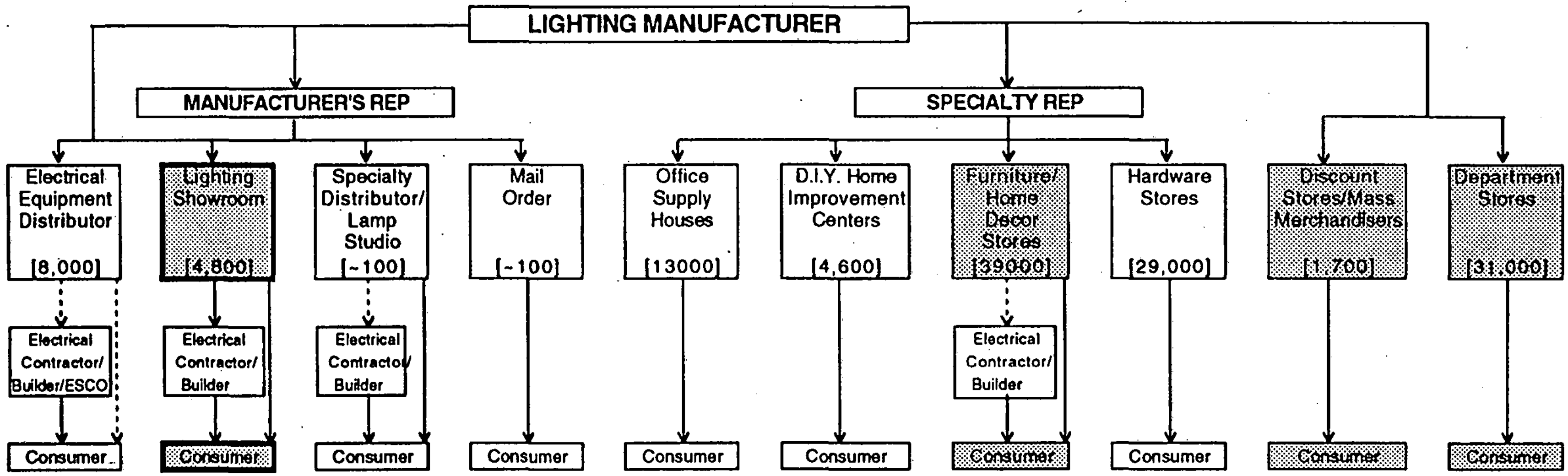
Figure 4.4 and **Figure 4.5** show the primary residential-sector distribution channels for hardwired and portable lighting fixtures, respectively (Sardinsky 1995). As mentioned above, portable fixtures are generally selected by the occupant, while hardwired fixtures are much more frequently specified by a design professional, builder, electrical contractor, or lighting showroom. Based on Figure 4.4, the primary sources of hardwired fixtures for new residential construction are electrical contractors, builders, and energy service companies; some owners of new homes also obtain lighting equipment directly from the distributor. Hardwired fixtures for renovation or replacement are most often obtained through electrical contractors or builders, or directly from lighting showrooms and do-it-yourself (D.I.Y.) home improvement centers such as Home Depot or Lowes. Based on Figure 4.5, consumers seeking high-end portable fixtures generally purchase from lighting showrooms. Commodity portables are primarily bought from furniture/home decor stores and department or discount stores.

FIGURE 4.4. RESIDENTIAL LIGHTING DISTRIBUTION CHANNELS
HARDWIRE FIXTURES



Note: Primary distribution channels are indicated by solid-line arrows, while secondary channels are indicated by dotted-line arrows.
The numbers in brackets indicate the approximate number of U.S. outlets for each type of distribution center.
Source: Sardinsky (1995)

FIGURE 4.5. RESIDENTIAL LIGHTING DISTRIBUTION CHANNELS PORTABLE FIXTURES



Primary Distribution Channels

- ▣ "High End" Designer
- ▨ Commodity

Note: Primary distribution channels are indicated by solid-line arrows, while secondary channels are indicated by dotted-line arrows. The numbers in brackets indicate the approximate number of U.S. outlets for each type of distribution center.
Source: Sardinsky (1995)

Distribution Issues Affecting Residential Consumer Adoption of CFLs

Consumer perceptions of CFL technology limitations were discussed above; however, a further barrier to CFL adoption is that the distribution systems that have evolved for incandescent lamps are not always well-suited to the characteristics of CFLs. The distribution channels by which a lighting technology is disseminated can play an important role in a product's market success. Consequently, policy makers who understand the channels through which incandescent lamps are distributed will be better prepared to both encourage the distribution of CFLs though standard incandescent channels and encourage consumers to explore new distribution channels in order to obtain a more efficient and more cost-effective lamp.

Most residential consumers purchase their light bulbs in supermarkets or drug stores, and many people in the lighting field believe that CFLs will not be a ubiquitous lighting product until they are as widely available in these chain stores as incandescent lamps. CFLs are reported to have become increasingly common in hardware chains and specialty outlets in recent years, but are still not widely available in supermarkets (Campbell 1994). Although CFLs are intended as replacements for incandescents, it will be a challenge to increase their availability in supermarkets for the reasons discussed below.

Many consumers may not be willing to purchase a product in a supermarket that is significantly more expensive than the other products that they are accustomed to purchasing in that environment. While the average price of a supermarket product is about \$3–5, buying a CFL for \$15–20 can suddenly transform an inexpensive grocery shopping trip into an expensive one (Haddad 1994). In addition, consumers are unaccustomed to making long-term purchases when they go to the grocery store, and the higher price of CFLs can make their purchase a complex decision. With CFLs, it becomes important to choose the most appropriate lamp and ballast for the fixture/lighting situation – both because of the high lamp price and the fact that the lamp choice will determine light quality for the next 3–10 years.

From the perspective of the supermarket, an attempt to sell CFLs may represent too great of a business risk. Typically, supermarkets are risk-averse: they are very cautious about introducing products that may not sell quickly or products that have narrow profit margins (McDougall and Snetsinger 1993). While most of the products sold in supermarkets last less than six months (Haddad 1994), CFLs need to be replaced only once or twice in a decade and are thus unlikely to sell as quickly as other products. If one assumes a CFL-incandescent lifetime ratio of 10:1, a supermarket loses nine incentives for a customer to return to the store when it sells a CFL rather than an incandescent light bulb. In addition, there has also been concern regarding the altered shelf space requirements associated with the different sizes and shapes of CFLs compared to incandescents (Haddad 1994), but a Canadian chain, Loblaws, has found that the shelf problem can be managed with some minor alterations to the existing shelf configuration (McDougall and Snetsinger 1993).

Affecting both supermarkets and consumers is the necessity for supermarkets, if they are going to sell CFLs, to develop an infrastructure for handling lamp returns. This is an important distinction between incandescents and CFLs as a result of the huge price difference between the two lamp types: if an incandescent lamp fails, it is inexpensive enough so that very few people will bother to return it – in contrast, consumers pay so much for a single CFL that they will want to return a lamp that has malfunctioned. From this perspective, the CFL market requires an infrastructure for handling lamp returns that has never been necessary for the incandescent lamp market. Generally, a shopper does not save the receipt from the supermarket in case a product needs to be returned, and grocery stores are not accustomed to handling returns of such fragile items.*

It may be that only the significant shift of consumer purchasing patterns from chain stores towards specialty outlets can trigger the widespread application of innovative lighting technologies in the residential market (Campbell et al. 1993). As light bulbs come to be considered less as a commodity such as milk and bread, and more as a home improvement investment, it is hoped that consumer sensitivity to lamp price will go down (Polsby 1994).

*One option for reducing the worries of consumers concerned that CFLs will not last long enough to justify their high cost may be for CFL manufacturers to provide a warranty guaranteeing the life of a CFL, assuming proper use. Such warranties have been successful in Germany (Kofod 1996).

4.2.2. Commercial-Sector Distribution Channels

Although some commercial customers purchase lamps through the typical residential "consumer" channels (e.g., commercial contractors are increasingly purchasing lamps from home improvement warehouses), large commercial and government consumers typically purchase lamps directly from distributors (Brown and Atkinson 1994). While purchase price plays the primary role in the lamp decisions made in the consumer market, larger commercial customers are more inclined to consider additional factors such as light quality and the costs of energy and lamp maintenance in their purchase decisions.

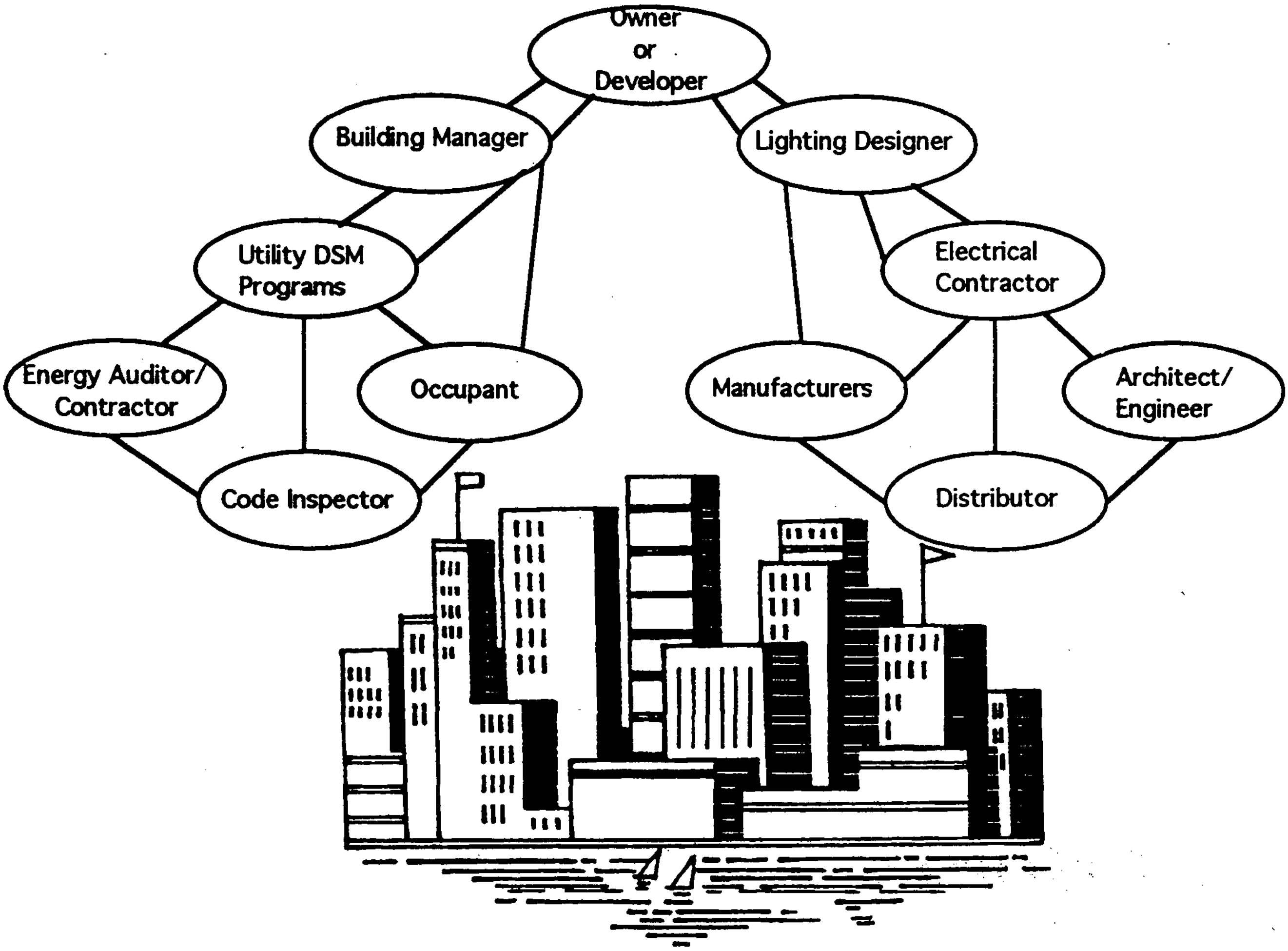
In a study of the market for energy-efficient lighting in commercial buildings in downstate New York, researchers at the Lighting Research Center found the decision-making process for commercial lighting to be highly complex and to involve at least eleven groups of people (Conway et al. 1990). **Figure 4.6** shows the web of decision makers for commercial lighting. The three most influential groups of decision makers were found to be the building owners, lighting designers, and building managers.

Conway et al. (1990) point out that, in spite of the diversity among the groups of lighting decision makers, these groups share three primary concerns regarding the installation of efficient lighting systems:

> First, the initial costs of efficient lighting (including design, installation and hardware) are perceived as being higher than conventional lighting and therefore less acceptable financially. These costs raise concerns about the length of the payback period for an investment. Most decision makers demand a short, one- to two-year payback on lighting installations. Developers are most sensitive to the initial cost issue. Lighting is often the last item specified in a building and therefore is subject to a limited budget and frequently subject to last-minute cost cutting measures.
>
> Second, decision makers are concerned that building occupants may not accept efficient lighting, for a variety of reasons, such as fear of lower visibility, unfamiliarity with products, aesthetics, resistance to change, maintenance requirements, availability, and costs of replacement components. Lack of current and/or accurate information perpetuates this concern.
>
> Third, decision makers express concerns about the reliability of efficient technologies. During most of the site visits, anecdotes regarding the failure of efficient lighting were voiced. There were also questions about energy saving performance and cost-effectiveness of energy-efficient lighting. Again, lack of unbiased, detailed information about lighting technologies, systems, and the impact of lighting on whole building performance clearly slows the implementation of efficient lighting.

See Conway (1991) and Conway et al. (1990) for a discussion of potential strategies for promoting the installation of efficient lighting systems through commercial distribution channels.

Figure 4.6. Commercial Lighting Decision Makers



Source: Based on Conway (1991), p. 3-2.

4.2.3. Moving Efficiency Up the Distribution Ladder

To accelerate the adoption of efficient lighting technologies, it is important to educate consumers about energy-efficiency products; however, it must also be a priority for manufacturers to produce efficient products, distributors to distribute them, and non-consumer lighting decision makers to promote their installation. Although most energy-efficiency programs and policies focus on end-users (consumers), some programs have focused instead on manufacturers and market transformation. These programs have taken a number of forms, including the establishment of a certification program for lighting professionals, procurement policies favoring energy-efficient equipment, manufacturer competitions, and manufacturer "buydowns". Below, we provide brief overviews of a few important consumer information programs as well market transformation programs.

Consumer Information Programs

Green Lights/ENERGY STAR (EPA 1997): The Green Lights Program, launched by the U.S. EPA in 1991, is a voluntary energy-efficiency program that encourages the use of energy-efficient lighting systems in both large and small commercial, industrial, and institutional buildings (e.g., Fortune 500 companies, small businesses, manufacturing facilities, hospitals, universities, and state and local governments). When they join Green Lights, organizations agree to survey all domestic facilities and to upgrade their lighting systems, where it is profitable and also maintains or improves lighting quality, within five years. The program provides member organizations with technical information and software that can assist them in making decisions regarding their lighting upgrades. On average, as a result of lighting upgrades implemented through the program, Green Lights participants reduce their lighting energy use by 40%; from 1991-1996, Green Lights was responsible for the installation of 26.6 million energy-efficient lamps and 10.9 million energy-efficient ballasts. In addition to being a stand-alone program, Green Lights is also the first step in the EPA's ENERGY STAR Buildings program, a comprehensive energy-efficiency program for commercial and industrial buildings

EPA has also recently introduced an ENERGY STAR product labeling program for residential lighting fixtures. Partnership agreements have been signed with leading fixture manufacturers to recognize the most energy-efficient models. ENERGY STAR lighting fixtures include both indoor and outdoor hardwired and portable fixtures designed to operate only energy-efficient lamps. Fixtures that carry the ENERGY STAR label meet energy-efficiency criteria as well as quality criteria to assure that consumers do not sacrifice performance in order to save energy. In addition, the fixtures start immediately, operate quietly, and some models are dimmable. The outdoor fixtures automatically shut off during daylight hours and some models have motion sensors. Manufacturers began sales of lighting fixtures with the ENERGY STAR label in June 1997. ENERGY STAR also has a labeling program for exit signs.

Green Seal: Another organization involved in labeling of lighting products is Green Seal, an independent, non-profit organization dedicated to protecting the environment by promoting the manufacture and sale of environmentally responsible consumer products (Ton 1997). Green Seal sets environmental standards and awards a "Green Seal of Approval" to products that cause less harm to the environment than other similar products. To date, Green Seal has set standards for CFLs and CFL-fixtures, and has certified several CFL products. The Green Seal CFL standard was adopted by the California Compact in its initial efforts, and the Green Seal draft Luminaire Standard served as the basis for the current U.S. EPA Energy Star Residential Fixtures requirements.

As discussed below, while product labeling programs help consumers choose high-quality and high-efficiency lighting products, product labels are also very useful for non-consumer lighting decision makers.

Certification and Education of Non-Consumer Lighting Decision Makers

Professionals who specify lighting products to be installed in buildings (electrical contractors, electrical distributors, lighting designers, etc.) need to be encouraged to install efficient lighting equipment. Often, the people who end up choosing the exact products that are actually installed in a building are contractors who are meeting a specification given in a contract document (Conway 1997). These contractors will substitute the least expensive products they can find, while (hopefully) staying within the requirements of the specification. Thus, it is very important that the person who draws up the final documents includes precise language and requirements concerning energy-efficient products.

Lighting efficiency is more likely to be encouraged or required by specifiers who are educated with respect to energy-efficient lighting equipment and design as well as other important aspects of lighting. To promote the education of lighting professionals, the National Council on Qualifications for the Lighting Professions (NCQLP) has established an LC ("Lighting Certified") Credential that can be obtained by passing the NCQLP lighting certification exam.[28] These

---

[28] For more information on this certification program, contact the National Council on Qualifications for the Lighting Professions, 4401 East West Highway, Suite 305, Bethesda, MD 20814.

qualified lighting professionals will have the motivation and professional responsibility to respond to lighting efficiency policy/education programs. For example, these professionals can be encouraged to make use of EPA's ENERGY STAR labeling program in order to reduce the amount of time and effort that they spend seeking out and specifying energy-efficient products. The ENERGY STAR label assures the specifier and the client of a high level of performance for visibility and for energy use.

Procurement Policies

The establishment of procurement policies that favor energy-efficient products can be an effective strategy for moving efficiency up the distribution ladder and encouraging manufacturers to produce more efficient lighting products. Large-scale buyers of lighting equipment, such as the government and large corporations, can significantly influence the lighting market via their purchasing policies. These large buyers can increase the availability and penetration of efficient lighting products by creating a coordinated market-pull that communicates to manufacturers the demand for efficient products.

One example of this type of program is the Energy Efficiency and Resource Conservation Challenge; the Challenge has been developed by the Federal Energy Management Program (FEMP) to help U.S. government agencies comply with federal energy-efficiency procurement mandates established by both EPAct and numerous Executive Orders. As described in McKane and Harris (1996), the federal sector in the U.S. is the largest purchaser of energy-using equipment in the world and the goals of the Challenge program are to use the purchasing power of the U.S government to achieve the following: "support and expand markets for today's 'best practice' energy efficient, renewable, and water conserving products; create new entry markets for advanced energy saving technologies and products; and lower the cost of efficient products for all consumers by providing a large reliable market." An additional, and very important, goal of Challenge is to provide a model of purchasing guidelines and programmatic support that could be adopted by state and local governments as well as corporate and institutional purchasers. In order to promote federal spending on efficient products, the Challenge program is developing product recommendations that can be consulted by federal agencies when making purchase decisions (see Johnson et al. (1996)) and promoting active leadership by federal supply agencies in identifying efficient products through product catalogs and on-line systems (McKane and Harris 1996).

Additionally, the Energy-Efficiency Procurement Collaborative, Inc. provides federal, state, and local government agencies and other large purchasers with easily accessible and accurate information regarding energy-efficient equipment and appliances that can be incorporated into their purchasing practices (Energy-Efficient Procurement Collaborative Inc. 1996). The ultimate goal of the Collaborative is to transform the market by stimulating increased demand for energy-efficient equipment to make it more widely available and at a lower cost. The New York State Energy Research and Development Authority (NYSERDA) currently manages the daily operations of the Collaborative.

Manufacturer Competitions

Manufacturer competitions are essentially incentive programs directed towards manufacturers rather than consumers. Offering incentives to manufacturers for the design and production of more energy-efficient products can accelerate the development and commercialization of new efficient products.

One of the best known manufacturer competitions was the Super Efficient Refrigerator Program (SERP), in which a group of 24 utilities offered a $30 million winner-takes-all prize to the manufacturer that could design the most efficient CFC-free refrigerator, manufacture and distribute the new refrigerator, and track its sales (The Results Center 1995b). The winning refrigerator was required to be at least 25% more efficient than those meeting 1993 efficiency standards and the wholesale price could not exceed that of standard CFC refrigerators with similar features. Whirlpool won the competition with a CFC-free model that was 30% more efficient than required by 1993 standards. As a result of SERP, other manufacturers have been encouraged to develop super-efficient refrigerators – a good indication of the program's positive influence on the market.

On a smaller scale, these sorts of competitions are being established for lighting products as well. In 1996, NYSERDA implemented a competitive grant program to encourage lighting product manufacturers to develop, demonstrate, and commercialize innovative, high-efficiency lighting products, systems, and components in the state of New York. Grants of up to $250,000 are available and those who receive grants must cover 50% or more of project costs.

Outside the U.S., the International Energy Agency (IEA) is coordinating "The Technology Procurement Competition," launched in April 1997 (NUTEK 1997). The competition is based on the need for an inexpensive lamp with a performance somewhere between a CFL and a standard incandescent for those sockets in homes where CFLs are not cost-effective or don't fit. A European buying group has issued functional specifications for a replacement incandescent lamp that is at least 30% more efficient than standard general lighting service (GLS) lamps and lasts three times as long; manufacturers can now compete for orders of several million lamps to make their potential entry into this new market more attractive. If the competition is successful, program coordinators believe that the new lamp could be on the market in late 1998 or early 1999.

In the United States, the U.S. Department of Defense (DOD) attempted to implement a similar A-lamp replacement program as a means to replace incandescent lamps in military barracks and homes nationwide. Two subsequent "Request for Proposals" (RFPs) for the production of several million improved efficiency lamps meeting a stringent set of performance criteria failed to garner significant manufacturer response.. Researchers at LBNL and the Natural Resources Defense Council are now trying to revitalize the DOD effort by producing revised specifications for future RFPs that can be more easily achieved by manufacturers. By relaxing the efficiency requirements for the new lamp and talking to manufacturers before issuing any RFPs, researchers hope to entice manufacturers into producing more energy-efficient and long-lived replacement for the screw-in A-lamp at a reasonable first cost. Lamp purchasers will include the DOD as well as other institutional and commercial bulk purchasers.

Manufacturer Buydowns

In a manufacturer buydown, a rebate is moved upstream from the consumer to the manufacturer. Given typical mark-ups between the manufacturer and the wholesaler, and then between the wholesaler and the retailer, a dollar paid to a manufacturer can often yield $1.50 to $2.50 of savings at the retail level (Calwell 1997b). Consequently, providing a manufacturer with an incentive for energy efficiency can be much more cost-effective than distributing individual rebate checks to individual consumers. A successful example of a manufacturer buydown is the "Compact Fluorescent Bulb" program operated by Southern California Edison (SCE) from 1992 through 1994. As described in a report by The Results Center (1995), SCE's incentives to CFL manufacturers succeeded in reducing the consumer cost of a CFL to less than $12 and moving more than two million CFLs into the residential sector. The administrative cost represented only 10% of the program's total cost; in contrast, the overhead cost had been about 70% for two of SCE's earlier CFL programs that distributed rebate coupons to consumers. For the duration of the program, CFL distribution within SCE's service territory increased eight-fold; according to the program manager, the CFL market in that territory has been completely redefined as a result of the program. SCE has had similar success when using this program model for commercial customers and with other efficient technologies. See The Results Center (1995a) for a more detailed description of the program.

5. POLICY ISSUES AND IMPLICATIONS

In this report, we provide lighting energy use and market data for the residential and commercial sectors. Such data can be useful to policy makers who wish to promote the use of energy-efficient lighting technologies and strategies in residential and commercial buildings. As discussed in the preceding chapters, however, comprehensive and reliable databases for lighting energy use and lighting market transactions are not available at this time. From a policy-making perspective, it would be highly valuable if such lighting data for the U.S. were collected and reported on a regular basis; this data collection issue is discussed further below.

In spite of some gaps and inconsistencies in the data, the information we *do* have access to can provide some clues as to viable policy options. Below, we describe a few of the lighting policy implications of the residential and commercial data provided in this report as well as some general policy issues such as the importance of whom a program targets and the need for policy makers to understand the technical characteristics of the technologies they promote.

5.1. Energy-Saving Policies for the Residential Sector

Because of the predominance of incandescent lighting in households, there is significant energy savings potential in the residential sector. Approximately 85% of household lighting energy is consumed by incandescents, and about 30% of household lamps account for approximately 80% of household lighting energy use. Consequently, if we could identify the fixture and room types in which these primary energy-using lamps are located, lighting programs and policies could promote energy-efficient alternatives for specific fixtures in specific locations.

As discussed in Chapter 2, based on the TPU data, there tend to be only a few fixtures in each home that use the bulk of household lighting energy. For example, based on the logged fixtures only, the highest energy-consuming fixture in a home consumes an average of 27% of household lighting energy; the top three energy-consuming fixtures in a home account for 53% of lighting energy use; and the top five account for almost 70% of household lighting energy use (Moezzi 1996-97). It is thus important for regulators to avoid over-regulating a very fragmented end-use. It may be easier and less expensive to design a strategy that focuses on the fixtures that consume the most energy. Based on the TPU data, the types of household fixtures that consume the most energy are wall and closed ceiling fixtures; in addition, high-use fixtures are most likely to be located in the kitchen and the living room.

Based on the TPU data, information regarding the number of household lamps in a given wattage bin and the number of lamps or fixtures of a given type is less useful for policy-making than the data on hours of use. As indicated in Table 2.7, fewer than 4% of lamps are used for more than 10 hours per day, but these lamps account for almost one-quarter of residential lighting energy use. This high energy use by a relatively small number of lamps makes high-usage lamps a potentially valuable target for lighting efficiency programs. The value of targeting high-usage lamps is also noted in Vorsatz (1996): in her conservation potential analysis of U.S. residential lighting, Vorsatz estimates that energy consumption of household lamps used for more than four hours per day could be reduced by 67% (50 TWh) by the year 2010, for a cost of conserved energy of only 2.7¢/kWh.

Although the identification of fixtures with high hours of use and energy consumption is an important component of residential energy conservation, it is essential that the energy-efficient lamps used to replace the incandescents in these locations provide all the benefits of incandescent lighting. As discussed in Atkinson et al. (1995a), aside from energy-efficiency, the characteristics of incandescent lamps are hard to match:

> Although the prevalence of incandescent lamps in the residential sector may be partially due to historical precedence and inertia, these lamps do have advantages that, to some extent, counterbalance their relatively poor efficacies: they have excellent CRIs and a warm color; they are easily dimmed, inexpensive, small, lightweight, and can be used with inexpensive fixtures; and, in a properly designed fixture, they permit excellent optical control...[In addition], they are simple to install, maintain, and dispose of.

Certainly, full penetration of an alternative lamp type will not be possible until there is a superior replacement technology – possibly a less expensive and technically improved CFL or halogen IR lamp. In the meantime, policy makers need to be aware of the limitations of the lamps they suggest as replacements for incandescents.[29]

So far, CFLs are the lamps most often promoted as replacements for incandescents. In order to increase the penetration of CFLs in homes, it is important to increase the number of dedicated hardwired fixtures for CFLs in homes – a goal that could be promoted by energy policies or programs. However, it is also necessary for policy makers to be aware of the barriers to CFL use in the U.S. today and to develop programs and policies that promote consumer acceptance of CFLs. As described above, when CFLs were developed, they were expected to become the energy-efficient and cost-effective replacement of incandescent lamps. More than a decade after their introduction to the market, however, CFLs still play only a niche role. Studies indicate that the most significant barrier to a broad residential success of CFLs is the high first-cost. In addition to their high purchase price, compared to incandescent lamps, CFLs are incompatible with many standard fittings, are not so easily used with dimmer switches, and are perceived as unattractive. Moreover, users are still unclear about where, or why, to use CFLs.

In addition, policy makers need to know that there is untapped potential for installing more standard fluorescent fixtures in homes. Many homeowners are using standard fluorescent lamps effectively in kitchens, dens, and garages. These lamps are inexpensive, readily available in retail stores, dimmable (with an electronic ballast or dual-switching), and have good color characteristics.

5.2. Energy-Saving Policies for the Commercial Sector

Energy consumption varies significantly by commercial building type; consequently, any policy or program for reducing the energy consumption of commercial lighting should take into account the building type in which energy savings is desired. As discussed in Chapter 2, energy consumption is the result of illuminance level, lighting hours, illuminated floorspace, and equipment type. In terms of energy-saving options for commercial buildings, good lighting design that includes effective use of lighting controls is essential. In buildings where major lighting retrofits (including redesign) are not feasible, lighting energy use can be reduced by retrofitting the existing lighting equipment with more efficient equipment.

Although the proportion of incandescent lamps used in the commercial sector (≈5% of all commercial lamps) is not nearly as high as in the residential sector, replacing incandescent lamps in building types where they are commonly used can be an effective lighting efficiency strategy. As seen in Table 2.13, in terms of delivered lumens, the use of incandescent lamps is highest in public assembly (15.5%) and lodging (14.3%) facilities and in restaurants (12.5%). In her conservation potential analysis of U.S. commercial lighting, Vorsatz (1996) found that, compared to baseline

---

[29] It should be noted that the lamps used in some of the high-use fixtures are not incandescent A-lamps, but are decorative incandescent lamps (e.g., chandelier lamps) for which there are no economical energy-efficient alternatives at this time.

energy consumption, the proportions of potential cost-effective energy savings were highest for incandescent-using building types: 35% of energy could be conserved in lodging facilities, 33% in restaurants, and 41% in miscellaneous building types (which includes public assembly) by the year 2010. The primary reason for the profitability of these incandescent retrofits is the labor savings associated with the longer lamp lives of the efficient replacement lamps (Vorsatz 1996).

It is also important to look at the commercial building types that consume the most energy and try to figure out ways to conserve lighting energy within them. For example, based on Table 2.10, retail stores and large and small office buildings account for about 44% of commercial lighting energy use in the U.S. In Vorsatz's analysis, conservation measures in retail establishments and office buildings account for about half of the energy savings potential (Vorsatz 1996).

5.3. Deciding Whom Lighting Efficiency Policies Should Target

To accelerate the adoption of efficient lighting technologies, energy-efficiency programs need to move up the distribution chain. While the education of consumers is important, it should also be a priority for manufacturers to produce efficient products, distributors to distribute them, and non-consumer lighting decision makers to promote their installation. Although the majority of efficiency programs and policies focus on end-users, innovative market transformation programs can take a number of other forms such as the certification and education of intermediary, non-consumer lighting decision makers, the establishment of procurement policies favoring the purchase of energy-efficient equipment, manufacturer competitions, and manufacturer buydowns. As described above for the case of a manufacturer buydown, because of the significant price mark-ups between the manufacturer and the wholesaler, and then between the wholesaler and the retailer, a dollar paid to a manufacturer can often yield $1.50 to $2.50 of savings at the retail level. It will be wise for policy makers to educate themselves about these different program types and decide carefully which strategy will work best for them in terms of their policy goals.

See Appendix B for a list of useful references relating to market transformation.

5.4. The Importance of Technical Understanding

While is it essential for policy makers to understand lighting energy use patterns as well as the marketplace in which lighting products are distributed, promoted, and sold, it is also important for policy makers to understand the basic technical characteristics of the lighting technologies that they promote through efficiency policies and programs. Many opportunities for energy savings exist, and excellent energy-saving lighting technologies are available on the market today; however, in order for these technologies to operate optimally and to produce the expected energy and cost savings, they must be used correctly. For example, the energy-efficient operation of a lamp depends not only on the lamp itself but can also depend on a variety of other factors such as the lamp's burning position, the ambient temperature in which the lamp is used, the lamp-ballast combination, the amount of times the lamp is turned off and on in a given day, system configuration, and power quality. If a lamp's optimal operating conditions are not considered, lumen output, lamp life, and other technology characteristics can be compromised. By learning about the optimal operating conditions of a given lighting product, policy makers enable themselves to make decisions regarding the situations in which that technology can best be used for energy conservation. In Appendix A, we briefly introduce the general categories of lamps, ballasts, fixtures, and lighting controls; we also define the technical characteristics by which these lighting products are most often assessed and compared. In Appendix B, we provide a list of references that discuss in great detail the technical aspects of various lighting technologies.

Many lighting policy makers do not have the time to become experts on all the technical characteristics of lighting products; consequently, it is important for policy makers to have access to experts who can help them make practical and strategic technology-based policy decisions. For this reason, it is important for policy makers to support the establishment of more lighting education and demonstration centers and to support ongoing funding for lighting research.

5.5. Future Research Needs

As discussed above, it would be very useful from a policy-making perspective if reliable and comprehensive data were regularly gathered on U.S. lighting energy use and related parameters. A comprehensive residential data set would include collected (and not derived) household data for the following parameters as a function of lamp, fixture, and room type:

- installed wattage,
- lighting electricity use,
- floorspace,
- illuminance level,
- lighting hours of use, and
- occupant characteristics and behavior (e.g., age, income, use patterns).

A comprehensive data set for the commercial sector would include the same types of collected data, as a function of lamp, ballast, fixture, and building type, as well as by room type within a given commercial building (e.g., lighting in guest rooms and reception areas should be distinguished for lodging facilities).

Most assessments of the national lighting market have relied primarily on data obtained from the Census Bureau. However, in order to understand the full potential of reducing lighting energy use through market transformation, it will be necessary to have sales or purchase data for specific lighting products. Based on our inquiries regarding the availability of detailed sales data, this type of data has not been collected by any group so far. Manufacturers do have sales data for their own products, and the National Electrical Manufacturers Association (NEMA) collects some data as well, but these data are not released to the public. It is our hope that, in the future, sales data for individual types of lighting products will be recorded and made available in a form that will be useful to lighting policy makers. Some lighting purchase data is collected in surveys by market research firms; however, these surveys are proprietary and cover only data requested by the paying clients.[30]

---

[30] As mentioned above, related lighting data that we compile after this report's publication as well as post-publication corrections to the report will be listed at the project website: http://enduse.lbl.gov/projects/LMS.html.

6. CONCLUSIONS

Lighting is a significant electrical end-use in every sector and building type throughout the United States. Because of a lighting system's many components (e.g., lamps, ballasts, fixtures, controls), the numerous options within each component type (e.g., incandescent, fluorescent , or HID lamps), and the aesthetic value of lighting in our lives, lighting is a highly complex end use. As we have discussed throughout this report, the characteristics of lighting energy use, as well as the attributes of the lighting marketplace, can significantly affect national patterns of lighting equipment choice and ownership. Consequently, it is important for policy makers promoting energy-efficient lighting technologies to understand the lighting technologies that people use, the ways in which they use them, and marketplace characteristics such as key actors and their behaviors, product mix and availability, price spectrum, and product distribution channels.

In this report, we have provided an overview of lighting energy use patterns in the United States as well as the marketplace in which lighting products are distributed, promoted, and sold. In general, reliable lighting energy use and market data at the national level are difficult to obtain, and policy makers would be able to design more effective lighting policies and programs if comprehensive data on U.S. lighting energy use and related parameters were regularly gathered and appropriately analyzed.

With respect to lighting policy, there is significant energy savings potential in the residential sector because of the predominance of incandescent lighting in households. While it is important for lighting programs to promote the use of CFLs where they can adequately replace incandescents, it is also clear that CFLs are not at this time an ideal replacement for many incandescents and manufacturers should continue to work on improving CFLs and also focus on the development of additional light sources. In terms of energy-saving options for commercial buildings, good lighting design that includes effective use of lighting controls is essential. In buildings where major lighting retrofits (including redesign) are not feasible, lighting energy use can be reduced by retrofitting the existing lighting equipment with more efficient equipment. The replacement of incandescent lamps in the commercial sector can be highly cost-effective as a result of tremendous savings in the labor cost of lamp replacement.

Distribution channels play an important role in what type of lighting is found in a given building; consequently, policy makers should focus their efforts on intermediaries as well as end-users. We must increase our understanding of distribution channels in order to identify the points in the chain at which efficiency can be promoted most effectively by innovative strategies such as labeling programs, manufacturer buy-downs, competitions, and procurement policies.

7. REFERENCES

Atkinson, Barbara, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear. 1995a. *Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors.* Boca Raton, FL: CRC Press, pp. 399-427.

Atkinson, Barbara, James E. McMahon, Terrence Logee, Carol Jones, and Joanne Lindsley. 1995b. *U.S. Lighting Regulations: 1995 Update.* In Proceedings of the Right Light Three Conference, Newcastle Upon Tyne, England.

Atkinson, Barbara, James E. McMahon, and Steve Nadel. 1995c. " U.S. Lighting Standards: A Review of Federal and State Lighting Efficiency Regulations." *Light & Engineering* 3(1).

Atkinson, Barbara, James E. McMahon, Evan Mills, Peter Chan, Terry Chan, Joseph H. Eto, Judith D. Jennings, Jonathan G. Koomey, Kenny W. Lo, Matthew Lecar, Lynn Price, Francis Rubinstein, Osman Sezgen, and Tom Wenzel. 1992. *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-31469. December.

Audin, L., D. Houghton, M. Shephard, and W. Hawthorne. 1994. *Lighting Technology Atlas.* Boulder, Colorado: E Source, Inc.

Borg, Nils. 1994. " Global CFL Sales." *IAEEL (International Association for Energy-Efficient Lighting) Newsletter* 4/94: 9-10.

Brown, Richard, and Barbara Atkinson. 1994. *Incandescent Reflector Lamp Energy Efficiency Standard Analysis: Draft Report.* Berkeley, CA: Lawrence Berkeley National Laboratory. Draft LBL-36223. September.

Calwell, Chris. 1996. *Halogen Torchieres: Cold Facts and Hot Ceilings.* Boulder, CO: E-Source. September.

Calwell, Chris. 1997a. " Bright Prospects for CFL Torchieres." *Home Energy* January/February: 13.

Calwell, Chris. 1997b. *Personal Communication:* E-mail to Leslie Shown regarding efficiency incentives to manufacturers. February 25.

Calwell, Chris, Chris Granda, Charlie Stephens, and My Ton. 1996. *Energy Efficient Residential Luminaires: Technologies and Strategies for Market Transformation, Final Report.* Washington, DC: U.S. Environmental Protection Agency. Prepared for the Natural Resources Defense Council. May 13.

Campbell, C. J. 1994. *Perceptions of Compact Fluorescent Lamps in the Residential Market: Update 1994.* Palo Alto, CA: Electric Power Research Institute. TR-104807. November 1994.

Campbell, C. J., J. Weiner, and R. Cannedy. 1993. *Market Infrastructure and Compact Fluorescent Lamps.* Palo Alto, CA: Electric Power Research Institute. TR-102120. March 1993.

Census Bureau. 1984. *Current Industrial Reports: Electric Lamps - MQ36B (83)-5, Summary for 1983.* Washington, DC: U.S. Department of Commerce. August.

Census Bureau. 1986. *Current Industrial Reports: Electric Lamps - MQ36B (85)-5, Summary for 1985.* Washington, DC: U.S. Department of Commerce. June.

Census Bureau. 1988. *Current Industrial Reports: Electric Lamps - MQ36B (87)-5, Summary for 1987*. Washington, DC: U.S. Department of Commerce. June.

Census Bureau. 1989. *Current Industrial Reports: Electric Lamps - MQ36B (88)-5, Summary for 1988*. Washington, DC: U.S. Department of Commerce. August.

Census Bureau. 1991. *Current Industrial Reports: Electric Lamps - MQ36B (90)-5, Summary for 1990*. Washington, DC: U.S. Department of Commerce. August.

Census Bureau. 1993. *Current Industrial Reports: Electric Lamps - MQ36B (92)-5, Summary for 1992*. Washington, DC: U.S. Department of Commerce. September.

Census Bureau. 1994a. *Current Industrial Reports: Electric Lamps - MQ36B (93)-5, Summary 1993*. Washington, DC: U.S. Department of Commerce. November.

Census Bureau. 1994b. *Current Industrial Reports: Fluorescent Lamp Ballasts - MQ36C (93)-5, Summary 1993*. Washington, DC: U.S. Department of Commerce. August.

Census Bureau. 1994c. *Current Industrial Reports: Electric Lighting Fixtures - MQ36L (93)-1*. Washington, DC: U.S. Department of Commerce.

Census Bureau. 1995a. *Current Industrial Reports: Electric Lamps - MQ36B (94)-5, Summary 1994*. Washington, DC: U.S. Department of Commerce. July.

Census Bureau. 1995b. *Statistical Abstract of the United States 1995: The National Data Book*. Washington, DC: U.S. Department of Commerce.

Census Bureau. 1996a. *Current Industrial Reports: Fluorescent Lamp Ballasts - MQ36C (95)-5, Summary 1995*. Washington, DC: U.S. Department of Commerce.

Census Bureau. 1996b. *Personal Communication:* Telephone conversation between Leslie Shown and Chris Blackburn (survey statitician for the Manufacturing and Construction Division of the Census Bureau) regarding Census Bureau documentation of U.S. production and import of lighting equipment. February 7.

Census Bureau. 1997a. *Current Industrial Reports: Electric Lighting Fixtures - MA36L (96)-1*. Washington, DC: U.S. Department of Commerce. September.

Census Bureau. 1997b. *Current Industrial Reports: Fluorescent Lamp Ballasts - MQ36C (96)-5, Summary 1996*. Washington, DC: U.S. Department of Commerce. July.

Census Bureau. 1997c. *Current Industrial Reports: Fluorescent Lamp Ballasts - MQ36C (97)-1, First Quarter 1997*. Washington, DC: U.S. Department of Commerce. May.

Census Bureau. 1997d. *Personal Communication:* Telephone conversation between Leslie Shown and Trade Data Office staff person regarding percentage of imports produced by U.S.-owned manufacturing facilities located overseas. February 7.

Clear, Robert. 1997. *Personal Communication:* Written comments provided to Leslie Shown regarding review of April 3, 1997 DRAFT Sourcebook. April.

Clear, Robert, and Francis Rubinstein. 1997. *Personal Communication:* Conversation with Leslie Shown regarding the dimmability of fluorescent lamps. March 10.

Conway, Kathryn. 1997. *Personal Communication:* Written notes to Leslie Shown regarding review of April 1997 DRAFT Lighting Sourcebook. June.

Conway, Kathryn, Russell Leslie, Marcia Ward, and Suzanne Hartleb. 1990. *Commercial Lighting Efficiency Program, Phase 1: Feasibility Study*. Troy, New York: Lighting Research Center, Rensselaer Polytechnic Institute. Prepared for the New York State Energy Research and Development Authority. August 20.

Conway, Kathryn (editor). 1991. *Commercial Lighting Efficiency Resource Book.* Troy, New York: Lighting Research Center, Rensselaer Polytechnic Institute. Prepared for Electric Power Research Institute. Report No. CU-7427. September.

Davis, Fred. 1991. *Engines of Energy Innovation: The Role of Smaller Manufacturers of Efficient Lighting Products.* In Proceedings of the Right Light Bright Light, Stockholm, Sweden, pp. 239-247.

Energy Information Administration (EIA). 1992. *Lighting in Commercial Buildings.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0555(92)/1. March.

Energy Information Administration (EIA). 1995a. *Household Energy Consumption and Expenditures 1993.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0321(93). October.

Energy Information Administration (EIA). 1995b. *Housing Characteristics 1993.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0314(93). June.

Energy Information Administration (EIA). 1996a. *Annual Energy Outlook, with Projections to 2015.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0383(96). January.

Energy Information Administration (EIA). 1996b. *Residential Lighting: Use and Potential Savings.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0555(96)/2. September.

Economic Industry Reports, Inc. (EIRI). 1995. *The U.S. Lighting Fixtures Industry: An Economic and Market Study, 1995-96 Edition, Volumes I and II.* Raleigh, North Carolina: EIRI.

Eley Associates. 1993. *Advanced Lighting Guidelines: 1993.* San Francisco, CA: Eley Associates. Prepared for the U.S. Department of Energy, California Energy Commission, Electric Power Research Institute by Eley Associates, Luminae Souter Lighting Design, and Lawrence Berkeley National Laboratory. DOE/EE-0008.

Energy-Efficient Procurement Collaborative Inc. 1996. *Data Sources Directory for Purchasing Officials: Energy-Efficient and Environmentally Preferred Products.* Albany, NY: New York State Energy Research and Development Authority. July.

U.S. Environmental Protection Agency (EPA). 1997. *Building on Our Success: Green Lights and ENERGY STAR Buildings 1996 Year in Review.* Washington, DC: EPA. EPA 430-R-97-002. May.

Eto, J., C. Goldman, and M.S. Kito. 1996a. " Ratepayer-Funded Energy Efficiency Programs in a Restructured Electricity Industry." *The Electricity Journal* August/September: 71-81.

Eto, Joseph, and Eric Hirst. 1996. " What Kind of Future for Energy Efficiency?" *The Electricity Journal* June: 76-82.

Eto, Joseph, Edward Vine, Leslie Shown, Richard Sonnenblick, and Chris Payne. 1996b. " The Total Cost and Measured Performance of Utility-Sponsored Energy Efficiency Programs." *The Energy Journal* 17(1): 31-51.

Franconi, Ellen, and Francis Rubinstein. 1992. *Considering Lighting System Performance and HVAC Interactions in Lighting Retrofit Analyses.* In Proceedings of the 1992 IEEE Industry Applications Society Annual Meeting, Houston, Texas, October 4-9, 1992, pp. 1858-1867.

Geller, H. S., and P. M. Miller. 1988. *1988 Lighting Ballast Efficiency Standards: Analysis of Electricity and Economic Savings.* Washington, DC: American Council for an Energy-Efficient Economy.

Haddad, Brent M. 1994. *Why Compact Fluorescent Lamps Are Not Ubiquitous: Industrial Organization, Incentives, and Social Convention.* In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, California, pp. 10.77-10.83.

Hanford, James W., Jonathan G. Koomey, Lisa E. Stewart, Matthew E. Lecar, Richard E. Brown, Francis X. Johnson, Roland J. Hwang, and Lynn Price. 1994. *Baseline Data for the Residential Sector and Development of a Residential Forecasting Database.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-33717. May.

Heschong, Lisa. 1997. *Personal Communication:* E-mail regarding source of household energy use estimate. May 19.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume I, California Baseline Report.* Fair Oaks, CA: Heschong Mahone Group. California Energy Commission, Sacramento. CEC Contract #400-95-012. May 30.

Illuminating Engineering Society of North America (IES). 1993. *Lighting Handbook: Reference & Application.* 8th Edition. New York, NY: IES.

Illuminating Engineering Society of North America (IES). 1996. " 1996 Lighting Equipment & Accessories Directory." *Lighting Design + Application* 26(3): March.

Jennings, J., R. Brown, M. Moezzi, E. Mills, R. Sardinsky, B. Heckendorn, D. Lerman, and L. Tribwell. 1996. *Residential Lighting: The Data to Date.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL Report # 35484. Also presented at IESNA Annual Conference in Cleveland, Ohio, August 1996. March.

Johnson, Francis, Aimee McKane, and Jeffrey Harris. 1996. *Development of Federal Energy Efficiency Product Recommendations.* In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA, Washington, DC, pp. 107-117.

Johnson, Jeffrey (Pacific Northwest National Laboratory). 1997. *Personal Communication:* E-mail to Barbara Atkinson regarding building codes and standards. September.

Kofod, Casper. 1996. " Large CFL Potential in European Homes." *IAEEL (International Association for Energy-Efficient Lighting) Newsletter* 3/96.

Koomey, J.G., A. H. Sanstad, and L. J. Shown. 1995. *Magnetic Fluorescent Ballasts: Market Data, Market Imperfections, and Policy Success.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-37702. December.

Koomey, Jonathan G., Diana Vorsatz, Richard E. Brown, and Celina S. Atkinson. 1997. *Updated Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley National Laboratory. DRAFT LBNL-38894. In process.

Lawrence Berkeley National Laboratory (LBNL) Technology and Market Assessment Group. 1996. *Draft Report on Potential Impact of Possible Energy Efficiency Levels for Fluorescent Lamp Ballasts*. Berkeley, CA: LBNL. Prepared for DOE's Office of Codes and Standards. February.

Lawrence Berkeley National Laboratory (LBNL) Technology and Market Assessment Group. 1997a. *Draft Report on Potential Impact of Possible Energy Efficiency Levels for Fluorescent Lamp Ballasts*. Berkeley, CA: LBNL. Prepared for DOE's Office of Codes and Standards. July.

Lawrence Berkeley National Laboratory (LBNL) Technology and Market Assessment Group. 1997b. *Personal Communication:* Presentation material for DOE Public Workshop on Fluorescent Ballasts (Washington, DC, March 18, 1997).

Leslie, Russell. 1997. *Personal Communication:* E-mail to Leslie Shown regarding lamp product prices reported in *Research for 'The Lighting Pattern Book for Homes'*. September 19.

Leslie, Russell, and Kathryn Conway. 1993. *Research for "The Lighting Pattern Book for Homes", Final Report*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Lewis, Ron (Director of Information Resources at the Lighting Corporation of America). 1997. *Personal Communication:* Telephone conversation with Leslie Shown regarding commercial fixture manufacturers. February 26.

Logee, Terry (U.S. DOE). 1997. *Personal Communication:* E-mail to Andrea Denver regarding EPAct standards for HID lamps. March 5.

Majette, Ronald (U.S. DOE). 1997. *Personal Communication:* E-mail regarding the implementation of federal energy-efficiency standards for buildings. September 3.

Manclark, Bruce, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study*. Eugene, OR: Delta-T. April.

Manclark, Bruce, Howard Reichmuch, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study: Lighting Use and Economic Supplement*. Eugene, OR: Delta-T. BPA DE-AI79-91BP58689. September.

McDougall, G. H. G., and D. Snetsinger. 1993. *Loblaws*. New York: McGraw-Hill, pp. 169-185.

McGowan, T. 1997. *New Efficient Lighting Technologies for the Home*. In Proceedings of the International Conference on Energy-Efficient Appliances, Florence, Italy, November 9-11, 1997.

McKane, Aimee, and Jeffrey Harris. 1996. *Changing Government Purchasing Practices: Promoting Energy Efficiency on a Budget*. In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Washington, DC, pp. 159-168.

Mezger, Bernie. 1997. *Personal Communication:* Telephone conversation regarding fixture manufacturers. February 27.

Mills, Evan. 1993. " Efficient Lighting Programs in Europe: Cost Effectiveness, Consumer Response, and Market Dynamics." *Energy* 18(2): 131-144.

Mills, Evan. 1997. *Personal Communication:* E-mail to Leslie Shown regarding technical improvements to CFLs over time. November 13.

Mills, Evan, and Nils Borg. 1993. *Trends in Recommended Lighting Levels: An International Comparison.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34565.

Mills, Evan, and Mary Ann Piette (Lawrence Berkeley National Laboratory Center for Building Science). 1993. " Advanced Energy-Efficient Lighting Systems: Progress and Potential." *Energy* 18(2): 75-97.

Mills, Evan, Michael Siminovitch, Erik Page, and Robert Sardinsky. 1996. " Dedicated Compact Fluorescent Fixtures: The Next Generation for Residential Lighting." *Svetotechnika (Light and Engineering)* 1/2: pp. 29-33 (in Russian). Prevously published in the Proceedings of the 3rd European Conference on Energy-Efficient Lighting, Newcastle, 1993, UK, pp. 207-216. Lawrence Berkeley Laboratory Report No. 36835.

Moezzi, Mithra. 1996-97. *Personal Communication:* Memos to Diana Vorsatz and Leslie Shown regarding statistical distribution of residential lighting fixtures and lamps based on data obtained from the TPU analysis.

National Lighting Collaborative. 1996. *What is LER?: Announcing the New Luminaire Energy Information Program.* Rosslyn, VA: National Lighting Collaborative. July.

NUTEK. 1997. *Website description of The Technology Procurement Competition (http://eff.nutek.se/engelsk.html).*

Osram Sylvania. 1997. *Personal Communication:* Telephone conversation between Leslie Shown and Leah Gaines (Osram Sylvania customer service agent) regarding history of corporate ownership. February 20.

Polsby, Emily. 1994. " Putting Energy-Efficient Lighting in Its Place." *Home Energy* 11(6): 41-44.

Rasky, L. 1993. " Consumers and Compact Fluorescents." *Home Enegy* 10(6): 11-13.

Sardinsky, Robert. 1995. *U.S. Residential Lighting Fixture Marketplace: Accelerating the Penetration of Dedicated Energy Efficient Light Fixtures (including a large set of electronic spreadsheets).* Basalt, CO: Rising Sun Enterprises. June.

Sezgen, A. Osman, Y. Joe Huang, Barbara A. Atkinson, and Jonathan G. Koomey. 1994. *Technology Data Characterizing Lighting in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34243. May.

Sezgen, Osman, and Y. Joe Huang. 1994. *Lighting/HVAC Interactions and Their Effects on Annual and Peak HVAC Requirements in Commercial Buildings.* In Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, Asilomar, CA,

Sezgen, Osman, and Jonathan Koomey. 1997. *Interactions Between Lighting and Space Conditioning Energy Use in U.S. Commercial Buildings.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-39795. November.

The Results Center. 1995a. *Southern California Edison: CFB & CFL Manufacturers' Rebates.* Aspen, CO: IRT Environment, Inc.

The Results Center. 1995b. *Super Efficient Refrigerator Program.* Aspen, CO: IRT Environment, Inc.

Ton, My (Green Seal). 1997. *Personal Communication:* E-mail to Leslie Sown regarding the activities of Green Seal. October 3.

Tribwell, Lyle S., and David I. Lerman. 1996. *Baseline Residential Lighting Energy Use Study.* In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, CA, Washington, DC, pp. 153-160.

U.S. House of Representatives. 1992. *Energy Policy Act of 1992.* Washington DC: U.S. Government Printing Office.

Vorsatz, Diana. 1996. *Exploring U.S. Residential and Commercial Electricity Potentials: Analysis of the Lighting Sector.* Doctoral Dissertation. University of California, Los Angeles.

Vorsatz, Diana, and Jonathan G. Koomey. 1997. *The Potential for Efficiency Improvements in the U.S. Commercial Lighting Sector.* Berkeley, CA: Lawrence Berkeley National Laboratory. DRAFT LBNL-38895. In Process.

Wade, Steven (Energy Information Administration). 1997. *Personal Communication:* E-mail to Barbara Atkinson regarding CBECS and RECS data. October 10.

Weiner, J., and C. J. Campbell. 1992. *Perceptions of Compact Fluorescent Lamps in the Residential Market.* by Macro Consulting for the Electric Power Research Institute. EPRI-TR-100734. July 1992.

APPENDIX A

Introduction to the Technical Characteristics of Lighting Products

LAMPS

Defining The Technical Characteristics of Lamps

Various types of lamps differ from one another in numerous ways such as how energy-efficient they are, what color of light they produce, whether or not the level of light they produce dims over time, and whether or not they can be dimmed by the user. Below, we define some of the important characteristics by which lamps are often assessed and compared.

Lamp Wattage:
Lamp wattage is a measure of the power input to a lamp, measured in watts (W).

Efficacy:
The energy efficiency of lighting is referred to as "efficacy". Efficacy is calculated by dividing the quantity of the light emitted by the lamp (in lumens) by the power input to the lamp (in watts):

$$\text{luminous efficacy of a light source}\left[\frac{\textit{lumens}}{\textit{watt}}\right] = \frac{\text{total luminous flux}}{\text{total lamp power input}}$$

Different lighting mechanisms have different efficacies. The theoretical maximum efficacy is 683 lumens/watt (lm/W) for a yellowish-green light. The efficacy of a "pure" white light with equal energy at every wavelength of the visible spectrum is about 220 lm/W, but a light that is white in appearance can have efficacies of over 350 lm/W. The lighting technologies available today have maximum efficacies over 100 lm/W for white lights, and up to 140 or 150 lm/W for yellow lights.

Rated Lifetime:
The average rated lamp life of a given lamp type is the number of operating hours after which only half of a large group of lamps are still operating; this definition allows for the lifetimes of individual lamps to vary significantly from the average (IES 1993). Commonly used incandescent lamps have relatively short rated lifetimes (≈750-3000 hrs); compact fluorescent lamps have rated lifetimes of about 10,000 hours; full-size fluorescents have rated lifetimes ranging from 12,000-20,000 hours; and general-use high-intensity discharge lamps have rated lifetimes ranging from 3500-29,000 hours.

Color Temperature:
A lamp's color temperature is a measure of the color appearance of the lamp's light, expressed in degrees Kelvin (K). Conceptually, color temperature is based on the fact that the emitted radiation spectrum of a blackbody radiator depends only on temperature. A given lamp's "correlated" color temperature is the temperature of the blackbody closest in temperature to the light source. "Warm" white light that appears yellowish or reddish in color is emitted by lamps with low color temperatures (3000 K and below). "Cool" white light appearing bluish in color is emitted by lamps with high color temperatures (4000 K and above). **Table A.1** provides the approximate color temperature of common light sources.

Color Rendering:
Color rendering refers to the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference or standard light source of the same correlated color temperature. The color rendering properties of a lamp are expressed in terms of a *color rendering index (CRI)*, which has a value of up to one hundred. The higher a lamp's CRI (the closer to 100), the less a color shift occurs compared to the reference source. In general, lamps with CRIs of 70–100 are considered to render color excellently, a CRI of 60–75 is considered good, 50–60 is considered fair, and less than 50 is considered poor (Ontario Hydro

1992). Some lamp types, such as low-pressure sodium, have CRIs of less than zero (Clear 1996). **Table A.2** provides approximate CRIs for common light sources.

Lumen Maintenance:
Typically, lamps continue to draw approximately the same amount of power and yet produce fewer lumens as they age.[1] A lamp's lumen maintenance refers to the extent to which the lamp maintains its lumen output, and therefore efficacy, over time.

Dimmability:
Whether or not a lamp is dimmable refers to the user's ability to vary the lumens that it emits. Lamp dimming is important for two reasons: aesthetic lighting effects and energy conservation. Incandescent lamps can be easily dimmed using a simple device to lower the voltage across the lamp filament. Fluorescent lamps can be dimmed using dimming ballasts; almost all dimming ballasts used today are electronic. An electronic dimming ballast alters the output power to a lamp by sending a low-voltage signal to the output circuit (Eley Associates 1993). Some high-intensity discharge (HID) lamps are dimmable with specialized ballasts.

Table A.1. The Color Temperature of Common Light Sources

Source of Light	**Color Temp. (K)**	**Description**
Sky - extremely blue	≈25,000	cool
Sky - overcast	≈6500	cool
Sunlight at noon	≈5000	cool
Rare earth fluorescent	2700-5000	warm/cool
Cool-white fluorescent	≈4300	cool
Metal halide	3000-4200	warm/cool
Warm-white fluorescent	≈3000	warm
Incandescent (100 W)	≈2900	warm
High-pressure sodium	1900-2100	warm
Candle flame	≈1800	warm
Low-pressure sodium	≈1740	warm

Source: Ontario Hydro (1992) and lamp manufacturers catalogs for General Electric (1995), Osram Sylvania (1996), and Philips (1996)

---

[1] There are some exceptions to this generalization: for example, some HID lamps draw increasing amounts of power as they age (Clear 1996) and some low-pressure sodium lamps maintain constant lumen output over time (Philips Lighting Company 1996)

Table A.2. The Color Rendering Indexes of Common Light Sources

Source of Light	CRI	Color Rendering
Tungsten-halogen	≈99	excellent
Standard incandescent	≈97	excellent
Rare-earth fluorescent	72-84	good/excellent
Compact Fluorescent	≈82	excellent
Metal halide (400 W, clear)	≈65	good
Cool-white fluorescent	≈62	good
Warm-white fluorescent	≈52	fair
Mercury vapor (phosphor-coated)	45-50	poor
High-pressure sodium (400 W, diffuse-coated)	≈22	poor
Mercury Vapor (clear)	≈15	poor

Source: Ontario Hydro (1992) and lamp manufacturer catalogs for General Electric (1995), Osram Sylvania (1996), and Philips (1996)

Introduction to Incandescent, Fluorescent, and High-Intensity Discharge Lamps

The primary categories of lamps that we address in this report include incandescent, fluorescent, and high-intensity discharge. We describe the basic operating principles of these different lamp types briefly below. **Tables A.3-A.6** present primary physical characteristics for the lamp types discussed below.

In addition to physical lamp characteristics, we also include lamp price in Tables A.3 through A.6. Lamp prices are sensitive to demand; lamps in higher demand tend to be less expensive. In general, commercial customers buy lighting products in large quantities and thus pay the prices at the lower end of the price ranges provided in this report; residential customers typically buy lamps one or two at a time and thus pay prices at the higher end of the range. Lamp prices also vary depending on where they are purchased - for example, lamps purchased from lighting design stores are likely to be more expensive than those purchased from a do-it-yourself store such as Home Depot.

Incandescent Filament Lamps

In the late 1800s, the incandescent lamp was invented independently by Thomas Edison in the United States and Joseph Swan in England (Atkinson et al. 1995). Today, incandescent lamps provide most of the light in households and are also used widely for lighting commercial buildings. Because about 90-95% of an incandescent lamp's emissions are in the infrared (thermal), rather than visible, range of the electromagnetic spectrum, incandescent lamps are much less efficacious than other lamp types. However, as discussed in Atkinson et al. (1995), aside from energy-efficiency, incandescent lamps have many advantages:

> Although the prevalence of incandescent lamps in the residential sector may be partially due to historical precedence and inertia, these lamps do have advantages that, to some extent, counterbalance their relatively poor efficacies: they have excellent CRIs and a warm color; they are easily dimmed, inexpensive, small, lightweight, and can be used with inexpensive fixtures; and, in a properly designed fixture, they permit excellent optical control...They are simple to install, maintain, and dispose of.

General service and reflector/PAR (parabolic aluminized reflector) lamps are the most common types of incandescents. General service lamps (also called "A-lamps") are the pear-shaped light bulbs that are regularly used in households. Reflector lamps are typically used to highlight indoor retail displays and artwork and to illuminate outdoor areas.

Modern incandescent lamps use filaments that are made of tungsten. When electricity is used to heat a lamp filament to the point of incandescence, light is produced. The efficacy of the light production depends on the filament temperature. The higher the filament temperature, the greater the portion of radiated energy that falls into the visible part of the irradiated spectrum.[2] Consequently, when designing an incandescent filament lamp, it is important to keep the temperature of the filament as high as possible while still maintaining a satisfactory lamp life. See Table A.3 for more information on standard incandescent lamps.

A *tungsten-halogen lamp*, which uses the halogen regenerative cycle, is a variation of an incandescent filament lamp. The tungsten-halogen bulb has a quartz envelope that is located close to the filament so that the envelope can reach temperatures of 260° C or more in normal operation. At this temperature, the halogen gas fill in the lamp reacts with any tungsten that evaporates from the filament and deposits on the lamp wall. The resulting gaseous tungsten-halogen compound circulates inside the bulb until it comes in contact with the incandescent filament. Here, sufficient heat breaks down the compound into tungsten and redeposits it on the filament.

Tungsten-halogen lamps improve on regular incandescent sources because of their excellent lumen maintenance, long lifetime, and compactness. Although they are not as efficacious or long-lived as fluorescent or HID lamps, tungsten-halogens offer excellent color, brilliance, and control characteristics at a relatively low unit price (Eley Associates 1993). These lamps are most often combined with a reflector housing, and are available in a wide variety of tubular forms, and in spotlights and floodlights.

The *tungsten-halogen infrared-reflecting (HIR) lamp* is even more efficacious than the standard tungsten-halogen lamp. As mentioned above, 90-95% of the energy radiated by incandescent lamps, including tungsten-halogen lamps, is in the form of heat In an HIR lamp, a multi-layer interference film-coating technology is applied to a tungsten-halogen lamp to reflect the emitted heat back to the filament; consequently, the required power input to reach the operating temperature for the tungsten-halogen cycle is reduced.

HIR lamps have been available for a number of years as high-wattage double-ended quartz lamps, and HIR PAR lamps only recently (1994) became widely available (Atkinson et al. 1995). HIR lamps have been promoted to residential- and commercial-sector customers primarily as low-wattage reflector lamps; general service HIR lamps have been developed as prototypes but are not yet commercially available (Atkinson et al. 1995).

See Table A.3 and Table A.4 for more information on different types of tungsten-halogen lamps.

Reflector lamps are standard incandescent or tungsten-halogen lamps made in special or standard bulb shapes and with a reflective coating applied to part of the bulb surface. Both silver and aluminum coatings are used. In reflector lamps, better optical control directs the illuminance to a

---

[2] An incandescent source that emits the theoretical maximum amount of energy is called a "blackbody" radiator. A blackbody radiator emits energy at all wavelengths, but the amount and proportion of the energy that is potentially visible increases rapidly with temperature. A blackbody at 600° C will probably be visible under normal lighting. Objects below about 300° C are not visibly brighter than their surroundings even for the dark adapted eye.

specific area; thus, reflector lamps can be energy-efficient alternatives to general service incandescents in applications where illumination requirements are direction-specific. In spotlight and floodlight applications, the filaments are concentrated and are accurately positioned with respect to the base. When the filament is placed at the focal point of a reflector or lens system, a precisely controlled beam is obtained. See Table A.4 for more information on reflector lamps.

Fluorescent Lamps

The first practical fluorescent lamps were produced in the United States in the late 1930s, and fluorescent lamps came into general use in the 1950s (Atkinson et al. 1995). Fluorescent lamps are used to illuminate most commercial buildings, and are also common in the industrial sector. Only a small amount of fluorescent lighting is found in homes, primarily in kitchens, bathrooms, and utility areas.

The most common fluorescent lamps are tubular and have a length of four feet. Tubular lamps that have a diameter of 1.5 inches (38 mm) are called T12s and tubes that have a diameter of one inch (26 mm) are called T8s; the "8" and "12" refer to the number of eighths of an inch in the diameter of the lamp tube. Lamp tubes are available in other diameters as well.

Like most discharge lamps, fluorescent lamps must be operated using a "ballast" to limit the current to the value for which each lamp is designed and provide the starting and operating lamp voltages. Typically, the ballast adds another 10-20% to the power draw, thus decreasing system efficacy. A fluorescent lamp system's efficacy depends on lamp length and diameter; the type of phosphor used to coat the lamp; the type of ballast used with the lamp; the number of lamps per ballast; the temperature of the lamp (which depends on the fixture and its environment); as well as a number of lesser factors (Atkinson et al. 1995). Ballasts are discussed in greater detail below.

Technically, a fluorescent lamp is a low-pressure gas discharge source in which light is produced when UV energy generated by a mercury arc activates fluorescent powders that coat the inside of the lamp tube. Fluorescent lamps are usually long and tubular with an electrode sealed into each end; they contain mercury vapor at low pressure and a small amount of inert gas for starting. Standard fluorescent lamps are filled with argon gas. The interior of the bulb wall is coated with fluorescent powders that are usually referred to as 'phosphors'. When a suitably high voltage is applied across the electrodes, an electric arc discharge is initiated and the resulting current ionizes the vaporized mercury in the tube. The ionized mercury emits mostly invisible UV radiation, which strikes and excites the phosphor tube coating, causing a glow or 'fluorescence' and producing visible light.

The blend of phosphors used to coat a fluorescent lamp's inner wall determines the color of light produced by the lamp. In the past, the most frequently used lamps have been the halophosphate ("standard phosphor") cool-white and warm-white lamps. In a newer type of fluorescent lamp, the inside of the lamp tube is coated with a combination of rare-earth (RE) phosphors that produce visible light at wavelengths to which the red, green, and blue retinal sensors of the human eye are most sensitive. Lamps using RE phosphors can withstand a higher loading (arc power per unit of phosphor area) and thus provide better lumen maintenance than standard-phosphor lamps. The arc power per unit of phosphor area increases as lamp diameter decreases, and lumen degradation in standard-phosphor lamps of small diameter is too severe to make lamp production practical. The introduction of RE phosphor coatings for lamp tubes, however, has made it possible to develop fluorescent lamps with smaller diameters such as the T-8 and T-5. All fluorescent lamps with diameters of one-inch or less use the new RE phosphors. Rare earth coatings can also be used for lamps of larger diameter. Although the use of RE phosphors increases the price of a lamp, RE phosphor lamps provide improved lumen maintenance, color rendering, and lamp efficacy.

See Table A.5 for more information on T12 and T8 fluorescent lamps.

Compact fluorescent lamps (CFLs), which are significantly smaller than standard fluorescent lamps, were introduced in the early 1980s as an energy-efficient alternative to incandescent lamps. As mentioned above, the introduction of RE phosphor coatings for fluorescent lamps made it possible to develop fluorescents with smaller diameters. In a CFL, the small-diameter tube (T4 or T5) is bent into two to six sections. Originally, CFLs were designed to be interchangeable with conventional 25–100 W incandescent lamps, but they are now available in various sizes, colors, wattages, and bases.

Typically, a CFL produces three to four times more lumens per watt than an incandescent A-lamp; efficiency increases with lamp wattage. In addition, the rated lifetime of a CFL is about 10 times longer than that of an incandescent A-lamp. However, factors such as ambient temperature, switching, mounting position, lumen depreciation, and fixture size may alter the laboratory-determined efficacies and lifetimes of CFLs. For example, a CFL operating in a base-down position may produce 15-20% fewer lumens than a CFL operating in a base-up position (Siminovitch and Mills 1994).

There are three different types of compact fluorescent lamp-ballast systems (Eley Associates 1993):

- *Integral systems* are self-ballasted packages and are made up of a one-piece, disposable lamp, ballast, and socket adapter combination. Integral systems are designed to replace incandescent lamps in fixtures fitted for incandescents. A disadvantage of the integral system is that the ballast (which would otherwise have a life of ≈45,000 hours) must be disposed of when the lamp fails (normally, CFL lamp life is about 10,000 hours).

- *Modular systems* are self-ballasted packages as described for integral systems except that the lamp is replaceable. Like integral systems, modular systems are designed for incandescent retrofit situations, but are more cost-effective in the long run because the ballast does not need to be replaced every time a lamp fails.

- *Dedicated (hardwired) systems* are new or retrofitted fixtures that are hardwired for CFL ballasts. These systems do not use socket adaptors; instead, they use a pin socket for the lamp.

See Table A.5 for more information on compact fluorescent lamps.

High-Intensity Discharge Lamps

HID lamps are most widely used in the commercial and industrial sectors and, for many commercial and industrial applications, provide the most-cost-effective illumination. Low-wattage HID lamps can be used effectively for outdoor security, corridor, and landscape lighting in the residential sector, particularly in timer-controlled functions.

Like fluorescent lamps, HID lamps produce light by discharging a well-stabilized arc discharge through a mixture of gases in a refractory envelope. Unlike fluorescent lamps, HID lamps use a compact "arc tube" in which the pressure and temperature are very high. Because the arc tube is small, it permits compact reflector designs with good optical controllability. Like fluorescent lamps, HID lamps require a ballast to supply the correct voltage and control the current.

The three primary types of HID lamps in use today are mercury vapor (MV), metal halide (MH), and high-pressure sodium (HPS). Mercury vapor lamps were the first HID lamps to be developed. In MV lamps, light is produced by the passage of an electric current through an arc tube filled with mercury vapor; a small amount of argon is added to facilitate starting IES (1993). Metal halide lamps are similar in construction to MV lamps, and produce light by passing a current through an arc tube containing various metallic halides in addition to mercury and argon (IES 1993); compared to MV lamps, metal halide lamps have shorter rated lamp lives, but offer improved efficacy, color rendering, and lumen maintenance In high-pressure sodium lamps, light is produced by the passage of current through an arc tube containing sodium vapor (IES 1993); HPS lamps are even more efficacious and have better lumen maintenance than MH lamps.

HID lamps are most effectively used for applications in which switching (turning lamps off and on) is limited. One reason for this is the amount of time they require for starting (cold start) and restriking (hot start). A mercury vapor lamp, once started, requires several minutes to achieve full light output; restrike time (cooling time required before the lamp will restart) is 3-7 minutes, depending on lamp type (IES 1993). A metal halide lamp, once started, requires about 2-10 minutes to achieve full light output and equilibrium color, depending on the lamp type; restrike time can be as long as 15 minutes because of the high operating temperature (IES 1993). A high-pressure sodium lamp, once started, requires about 10 minutes to achieve full light output, during which time the color of the light changes; restrike time is less than a minute and full warm-up takes 3-4 minutes (IES 1993).

For industrial and outdoor applications where color was not a priority, MV lamps were the most efficient lamp type for many years. With the introduction of higher-efficacy HPS and MH lamps, MV lamps are now the least efficacious of the three primary HID lamp types and have lost a significant portion of their original market share. However, although many building owners have now replaced MV lamps with more efficient MH and HPS lamps, many MV lamps are still in use because they are relatively inexpensive and conversion to MH and HPS often requires installation of new ballasts and sometimes requires installation of new fixtures (Atkinson et al. 1995, Clear 1997a).

See Table A.6 for additional information on HID lamps.

Table A.3. The General Characteristics of Incandescent Lamps (non-reflectors)

	Standard Incandescent A-Lamps	**Tungsten-Halogen (T-H) A-Lamps**	**A-LAMP PROTOTYPE: Tungsten-Halogen Infrared-Reflecting (HIR) A-Lamps***	**Tungsten-Halogen (T-H): Double-Ended (DE) & Single-Ended (SE)**
Available Wattages	Typically, 15-250 watts (3)	42-150 watts (12)	PROJECTED: 13-73 watts (wattages necessary to match lumen output of 25-100 watt standard incandescents)	DE: 45-2000 watts (6) (lamps for halogen torchieres are included in this category) SE: 5-10,000 watts (6)
Initial Lamp Efficacy	10-19 l/W, for lamps with wattages from 40-250 (efficacy increases with wattage) (3)	14-20 l/W (12)	PROJECTED: 15-22 l/W, efficacy increases with wattage (depending on lamp wattage, efficacy is 30-70% improved over standard incand. A-lamps)	DE: 10-25 l/W**; with IR coating 26-38 l/W (6, 16) SE: 20-25 l/W; higher with IR coating (6)
Rated Lifetime	750-2500 h; however, when a standard incandescent lamp is dimmed even slightly, lifetime increases significantly (3)	2000-3500 h (12)	5000 hours*	≈2000 hours (6)
CRI & Color Temperature	CRI: ≈97 (2) CT: 2500-3000 K (3)	CRI: 99 (12); CT: 3000 K (6); T-H lamps often produce a whiter light than standard incandescents (2)	CRI and color temperature characteristics are assumed to be similar to those of the tungsten-halogen A-lamp.	CRI: 99 (12); CT: 3000-3100 K (6); T-H lamps often produce a whiter light than standard incandescents (2)
Lumen Maintenance	Lumen output typically declines by ≈20% over rated lamp life (1)	T-H lamps have better lumen maintenance than standard incandescents because of the regenerative cycle that removes evaporated tungsten from the bulb and redeposits it on the filament. Typically, lumen output declines by ≈7% over rated lamp life. (1)	Lumen maintenance characteristics are assumed to be similar to those of the tungsten-halogen A-lamp.	T-H lamps have better lumen maintenance than standard incandescents because of the regenerative cycle that removes evaporated tungsten from the bulb and redeposits it on the filament. Typically, lumen output declines by ≈7% over rated lamp life. (1)
Dimmability	Fully dimmable	Fully dimmable - but halogen cycle ceases to operate when lamps are dimmed substantially. Lamps should be operated at full power periodically to restore the halogen cycle and thus clean the tungsten from the bulb wall.	Dimming characteristics are assumed to be similar to those of the tungsten-halogen A-lamp.	Fully dimmable - but halogen cycle ceases to operate when lamps are dimmed substantially. Lamps should be operated at full power periodically to restore the halogen cycle and thus clean the tungsten from the bulb wall.
Advantages	Economical in low wattages and for applications involving low use per day (13), low first-cost, excellent optical controllability (point source), excellent color rendering, easy to install	Excellent optical controllability (point source), excellent color rendering, slightly more efficacious than standard incandescents, easy to install	PROJECTED: With the exception of low first-cost, this lamp has all the advantages of a standard incandescent as well as a longer lamp life and lower life-cycle cost.	Very compact with high lumen output; more efficacious than standard incandescents, especially with IR coating; excellent optical controllability (point source); excellent color rendering

Table A.3, cont.	Standard Incandescent A-Lamps	Tungsten-Halogen (T-H) A-Lamps	A-LAMP PROTOTYPE: Tungsten-Halogen Infrared-Reflecting (HIR) A-Lamps*	Tungsten-Halogen (T-H): Double-Ended (DE) & Single-Ended (SE)
Limitations	Very low efficacy, relatively short rated lamp lives	More expensive than standard incandescents; although somewhat more efficacious than standard incandescents, much less so than fluorescent and HID sources	PROJECTED: Low efficacy and moderate first-cost.	Although these lamps are somewhat more efficacious than standard incandescents, they are much less so than fluorescent and HID sources. Although the very popular halogen torchieres are attractive because of their low price, tall elegant fixtures, and warm indirect light, their operating cost and the risk of fire they pose are significant drawbacks (14).
Applications:	Standard incandescent lamps are widely used in homes, accounting for more than 85% of household energy use (4). In the commercial sector, incandescents are widely used for task lighting in many building types, and are especially common in restaurants and lodging facilities.	Tungsten-halogen A-lamps can be used to replace the slightly less efficacious standard incandescents where the qualities of the incandescent (e.g., optical controllability, good color) are desired	Use to replace high-wattage standard incandescents that receive low to moderate use and all low-wattage standard incandescents except those that are used very little	DE: commonly used in chandeliers, wall sconces, and torchieres (6) SE: commonly used in sconces, downlights, and wall washers (6)
Lamp Price	25¢-$1 for general service A-lamps; $1-3 for an extended or vibration service 100 W A-lamp, (1996$) (7)	$4-6 for 90 W tungsten-halogen A-lamp, (1996$) (7)	Target price of $3-6; lamps will not generally be cost-effective if their price exceeds ≈$6 (1997$)	$4-50, with even higher prices for lamps with highly specialized applications (1997$) (17)
Primary Manufacturers	General Electric, Philips, Osram Sylvania	General Electric, Philips, Osram Sylvania	Not applicable at this time	General Electric, Philips, Osram Sylvania

* The theoretical information presented for the HIR A-lamp prototype is based on an assumed lamp life of 5000 hours for lamps with mean lumen outputs that will allow them to replace 25-100 watt standard incandescents; data were obtained from researchers at Lawrence Berkeley National Laboratory (Clear and Rubinstein (1996), Clear (1994), Clear (1997b)).

** Halogen lamps for torchieres manufactured in the U.S. and Europe have efficacies toward the higher end of this range, while torchiere lamps manufactured elsewhere tend to have efficacies toward the lower end of the range. The halogen lamps included in most of the torchiere fixtures sold within the U.S. are lower efficacy lamps (Page 1997).

Sources: 1: IES (1993); 2: Ontario Hydro (1992); 3: Atkinson et al. (1995); 4: Moezzi (1996-97); 5: Leslie and Conway (1993); 6: Eley Associates (1993); 7: Denver (1996) 8: EPRI (1993a); 9: National Lighting Product Information Program (1993); 10: U.S. House of Representatives (1992); 11: Clear and Rubinstein (1997); 12: Lamp Manufacturer Catalogs for General Electric, Osram Sylvania, and Philips; 13: Clear (1996); 14: Calwell (1996); 15: Brown and Atkinson (1994); 16: Calwell (1997); 17: Clear (1997a)

Table A.4. The General Characteristics of Incandescent Reflector Lamps*

	Tungsten-Halogen Parabolic Aluminum Reflector (PAR) Lamps	**MR Reflector Lamps**	**Standard Incandescent Reflector R-Lamps***
Available Wattages	Halogen PAR: 35-150 watts (12) HIR PAR: 50-100 watts (3)	20-75 watts (12)	Typically, 30-120 (12)
Initial Lamp Efficacy	Based on EPAct standards, incandescent reflector lamps must have a minimum efficacy ranging from 10.5 l/W for lamps with wattages of 40-50 to 15.0 for lamps with wattages from 156-205 (10). The HIR PAR lamp is the most efficacious PAR lamp available. Halogen PAR: 11-17 l/W (12) HIR PAR: ≈20 l/W for 50 & 60 W lamps (3)	Lumen efficacy is not normally listed for MR reflector lamps. Based on an estimated 30% optical loss due to the reflector assembly, lamp efficacy is estimated to be 10.5-14 l/W (17)	8-12 l/W, for lamps of 50-75 watts (3)
Rated Lifetime	Halogen PAR: 2000-5000 hours HIR PAR: ≈3000-6000 hours The high end of the lifetime range for both lamp types is for a 130 volt lamp operated on a standard 120 volt circuit (12)	2000-5000 hours (12)	Typically, 2000 hours; as with all standard incandescents, when dimmed even slightly, lifetime increases significantly (3)
CRI & Color Temperature	CRI: 99 (12); CT: 2800-3000 (12) Tungsten-halogen lamps often produce a whiter light than standard incandescents (2)	CRI: ≈99 (12) CT: 2900-3050 (12)	CRI: ≈97 (2) CT: 2500-3000 K (3)
Lumen Maintenance	Halogen lamps have better lumen maintenance than standard incandescents because of the regenerative cycle that removes evaporated tungsten from the bulb and redeposits it on the filament. Typically, lumen output declines by ≈7% over the rated life of the lamp. (1)	Similar to other halogen lamps	Lumen output typically declines by ≈20% over rated lamp life (1)
Dimmability	Fully dimmable - but halogen cycle ceases to operate when lamps are dimmed substantially. Lamps should be operated at full power periodically to restore the halogen cycle and thus clean the tungsten from the bulb wall.	Similar to other halogen lamps	Fully dimmable

Table A.4, cont.	Tungsten-Halogen Parabolic Aluminum Reflector (PAR) Lamps	MR Reflector Lamps	Standard Incandescent Reflector R-Lamps*
Advantages	More efficacious than standard incandescents, excellent optical controllability (point source), very compact, excellent color rendering. Reflector lamps can be energy-efficient alternatives to general service incandescents in applications where illumination requirements are direction-specific.	Small size (easily hidden), very good optical controllability (point source), low-voltage wiring increases ease of changing layout	Excellent optical controllability (point source), excellent color rendering
Limitations	More expensive than standard incandescents	Relatively expensive compared to standard incandescents; requires a low-voltage transformer	Very low efficacy
Applications	PAR lamps are typically used for illuminating outdoor areas and for accent and display lighting. They are often used in restaurants and retail stores as well as for illuminating commercial displays and artwork. They are also commonly used to improve the optical efficiency of downlights (3).	MR reflector lamps are most often used in retail establishments for display and accent lighting.	These specialty lamps include ER (elliptical reflector) lamps, BR lamps (specially shaped variants of the "R" lamp which are designed to deliver more usable light from recessed fixtures), colored lamps, rough or vibration service lamps, and lamps with a rated wattage of less than 40 watts (15).
Lamp Price	Typically, the prices of halogen reflector lamps range from $7-14 (1996$) (7)	$7.50-11 (1996$) (12)	Typically, the prices of standard incandescent reflector lamps range from $2-10 (1996$) (7)
Primary Manufacturers	Halogen PAR: General Electric, Philips, Osram Sylvania HIR PAR: General Electric	General Electric, Philips, Osram Sylvania, Ushio	General Electric, Philips, Osram Sylvania

* As a result of EPAct, the majority of the incandescent reflector lamp market was converted from traditional incandescent to the more efficient tungsten-halogen technology; EPAct standards banned production of most traditional incandescent floodlights and spotlights. Standard-wattage and reduced-wattage non-halogen reflector lamps could not meet EPAct's minimum efficacy standards, which took effect in November 1995; halogen reflector lamps are now the least expensive compliance option. The remaining standard incandescent reflector lamps are specialty lamps for which there are no energy-efficient substitutes; these lamps comprise only a small market share.

Sources: 1: IES (1993); 2: Ontario Hydro (1992); 3: Atkinson et al. (1995); 4: Moezzi (1996-97); 5: Leslie and Conway (1993); 6: Eley Associates (1993); 7: Denver (1996) 8: EPRI (1993a); 9: National Lighting Product Information Program (1993); 10: U.S. House of Representatives (1992); 11: Clear and Rubinstein (1997); 12: Lamp Manufacturer Catalogs for General Electric, Osram Sylvania, and Philips; 13: Clear (1996); 14: Calwell (1996); 15: Brown and Atkinson (1994); 16: Calwell (1997); 17: Clear (1997a)

Table A.5. The General Characteristics of Fluorescent Lamps*

	Four-Foot Tubular Fluorescent: T12 Lamps	Four-Foot Tubular Fluorescent: T8 Lamps	Compact Fluorescent Lamps (CFLs)
Available Wattages	Typically, 32, 34, and 40 watts; As a result of EPAct standards that took effect in November 1995, the lamp type most commonly used in the commercial sector (the 40-watt, 4-foot, T12 with standard phosphors) was eliminated from the lighting market. Reduced-wattage T12 lamps with standard phosphors are still permitted. All 40-watt T12s sold today use the more efficacious rare earth phosphors.	32 watts (9)	5-55 watts (1)
Lamp Efficacy	Based on EPAct standards, all 4-foot T12 lamps must have a minimum efficacy of 75 l/W, excluding ballast losses (10). Combined with a magnetic ballast, T12s typically have an efficacy of 60-70 l/W, including ballast losses (3). For two 34-watt T12s (RE-70) and a single electronic ballast, efficacy including ballast losses is about 73-79 l/W (6).	The rare-earth coating on the T8 lamp improves its efficacy compared to standard-phosphor fluorescents. For two 32-watt T8s (RE-70) and a single ballast, efficacy including ballast losses is as follows: magnetic ballast - 78 l/W rapid-start electronic ballast - 82 l/W instant-start electronic ballast - 87 l/W (6)	With magnetic ballast, 40-55 l/W; with electronic ballast, 50-70 l/W (6). Efficacy improves with lamp size.
Rated Lifetime	Typically, 20,000 hours (2)	Typically, based on three hours of operation per start, 20,000 hours with rapid-start magnetic ballast and 15,000 with electronic ballast. Lamp life increases with increased burning period. (9)	≈10,000 hours, based on three hours of operation per start (8)
CRI & Color Temperature	Based on EPAct standards, all 4-foot T12 lamps with wattages >35 must have a minimum CRI of 69 and all 4-foot T12 lamps with wattages ≤35 must have a minimum CRI of 45 (10). CRI: 50-90 (50-60 for 32- and 34-watt cool-white and warm-white lamps) (3) CT: 3000-7500 K (≈3000-4150 K for 32- and 34-watt cool-white and warm-white lamps) (3) For rare-earth 40-watt T12s, CRI is ≈70-80 and CT is ≈3000-6500 (12)	In T8s, as well as all other fluorescent lamps with diameters of ≤1 inch, the lamp tube is coated with rare-earth phosphors that produce visible light at wavelengths to which the red, green, and blue retinal sensors of the human eye are most sensitive. Thus, color rendering is improved. CRI: 70-90, some T8s now have CRIs greater than 90 - however , they are less efficacious (3). CT: T8s are available in a variety of color temperatures, including warm (3000 K), neutral (3500 K), cool (4100 K), and very cool (5000 K) (9)	CRI: ≈82 (2) CT: 2700-5000 (6)

Table A.5, cont.	**Four-Foot Tubular Fluorescent: T12 Lamps**	**Four-Foot Tubular Fluorescent: T8 Lamps**	**Compact Fluorescent Lamps (CFLs)**
Lumen Maintenance	Lumen output typically declines by about 20-25% over rated lamp life (3)	Lamps using RE phosphors can withstand a higher loading (arc power per unit of phosphor area) and thus provide better lumen maintenance than standard-phosphor lamps (1). Lumen output typically declines by about 10-12% over rated lamp life (3)	Typically, lumen output is reduced by 10-30% over the rated life; lumen maintenance improves with lamp size (3)
Dimmability	Dimmable when used with dimming ballast (1). Almost all dimming ballasts used today are electronic.	Dimmable when used with dimming ballast. (1) Almost all dimming ballasts used today are electronic.	Some CFLs are dimmable. In commercial buildings, the use of dimming CFLs is not uncommon; dimmable CFLs for homes are much less common. One manufacturer is now producing dimmable CFLs for the residential sector. (11)
Advantages	More efficacious than incandescent lamps, very long lifetimes	T8s are more efficacious and have better color rendition and lumen maintenance than standard-phosphor T12s. T8 lamps operating with electronic ballasts are the most efficacious of the fluorescent lamps available today (3).	Excellent color rendition; long rated lifetime compared to incandescents; very efficacious compared to incandescents; large variety of available sizes, shapes, and wattages (8)
Limitations	Not suitable for applications in which lamps are often turned off and on; not a point source; sensitivity to ambient (room) temperature - efficacy varies with temperature	In almost all cases, when T8s are used to replace T12s, the ballasts must also be replaced (9). Not suitable for applications in which lamps are often turned off and on; sensitivity to ambient temperature; not a point source; more expensive than standard-phosphor T12s.	Very high first-cost compared to incandescents; larger size than incandescents; limited dimming capabilities; not a point source; laboratory-determined lumen output and lamp life are sensitive to factors such as operating position, operating temperature of the lamp within the fixture, frequency of switching
Applications	Most of the lamps used in the commercial sector are fluorescent; in homes, fluorescents are often used in kitchens and bathrooms as well as utility areas such as garages and laundry rooms. The introduction of rare earth coatings for lamps has improved color rendering and is thus expanding the number of potential uses of tubular fluorescents in homes.	These lamps are most often used as replacements for conventional T12s.	In homes and commercial buildings, screw-in CFLs can be used to replace incandescents. Commercial buildings have more fixtures that are hardwired for CFLs and they are used for down lights, wall sconces, exit signs, and also in two-foot by two-foot troffers (3)

Table A.5, cont.	**Four-Foot Tubular Fluorescent: T12 Lamps**	**Four-Foot Tubular Fluorescent: T8 Lamps**	**Compact Fluorescent Lamps (CFLs)**
Lamp Price	$3-6 for 32 & 34 W T12s; $7-13 for a 40 W T12 with rare-earth phosphors (1996$) (7)	$1.75-5.00 for a 32 W T8 (1996$) (7)	CFL prices vary based on design and ballast type. Typically, the price of a CFL without a ballast ranges from $4-12. The price of a self-ballasted CFL ranges from $8-30. CFLs with electronic ballasts are usually more expensive than those with magnetic ballasts. (1996$) (7) Promotional prices and rebates are often available for CFLs, particularly in the residential sector, and can reduce lamp price significantly.
Primary Manufacturers	General Electric, Philips, Osram Sylvania	General Electric, Philips, Osram Sylvania	General Electric, Philips, Osram Sylvania, Panasonic, Mitsubishi, Lights of America

* Four-foot T12 and T8 fluorescent lamps account for the bulk of fluorescent lighting in the U.S.: based on Sezgen et al. (1994), four-foot T12s and T8s are used to illuminate approximately 80% of the commercial floorspace that is lit by fluorescent lamps. High Output (HO) and Very High Output (VHO) lamps are not covered in this table; based on Census data, HO and VHO lamps accounted for less than 6% of fluorescent lamp shipments in 1993 (Census Bureau MQ36B (93)-5, Table 2a (1994)).

Sources: 1: IES (1993); 2: Ontario Hydro (1992); 3: Atkinson et al. (1995); 4: Moezzi (1996-97); 5: Leslie and Conway (1993); 6: Eley Associates (1993); 7: Denver (1996) 8: EPRI (1993a); 9: National Lighting Product Information Program (1993); 10: U.S. House of Representatives (1992); 11: Clear and Rubinstein (1997); 12: Lamp Manufacturer Catalogs for General Electric, Osram Sylvania, and Philips; 13: Clear (1996); 14: Calwell (1996); 15: Brown and Atkinson (1994); 16: Calwell (1997); 17: Clear (1997a)

Table A.6. The General Characteristics of High-Intensity Discharge Lamps

	Mercury Vapor Lamps	Metal Halide Lamps	High-Pressure Sodium Lamps
Available Wattages	40-1000 watts (2)	32-1500 watts (2)	35-1000 (2)
Initial Lamp Efficacy	Including ballast losses, from 25 l/W in smaller lamps (50-100 W) to 50 l/W for larger lamps (400-1000W) (3)	Including ballast losses, from 46-100 l/W; the 1000-watt lamp is most efficacious (3)	Including ballast losses, from 50-124 l/W. Efficacy increases with wattage. (3)
Rated Lifetime	29,000 hours for most lamps of 50 watts or more, based on a ten-hour burning cycle; however, economic lifetime is shorter (see lumen maintenance) (12)	3500 hours for compact arc lamps; 5000-10,000 hours for the smallest and largest lamps; up to 20,000 hours for the 400-watt lamps (3)	29,000 hours for most lamps of 50 watts or more, based on a ten-hour burning cycle (12)
CRI & Color Temperature	Both clear and phosphor-coated MV lamps are available. Clear lamps produce bluish-green light; phosphor coating improves color properties. (1) CRI: 50 for coated lamps, 15 for uncoated lamps (3) CT: 4000 K for coated lamps, 5900-7000 K for uncoated lamps (2)	Both clear and phosphor-coated MH lamps are available; clear lamps produce bluish-white light while coated lamps produce warmer light and have a higher CRI. (2) CRI: typically, 65-70; a few recently developed MH lamps have higher CRIs (6) CT: 3000-4400 K (3)	Both clear and coated lamps are available (1); lamps emit a yellowish light (3). CRI: ≈22 (1) CT: 1900-2200 K (1) New higher-pressure HPS lamps are now available with CRIs of more than 65 and CTs ranging from 2200-2800 K; however, efficacy and rated lifetime are drastically reduced. (3)
Lumen Maintenance	Poor: in spite of long rated lamp life, lumen output typically declines by 25-40% after only 12,000 hours (3)	Lumen output typically declines up to 20% after 12,000 hours (3)	Lumen output typically declines by 20% after 18,000 hours (3)
Dimmability	Some lamps are dimmable with specialized ballasts; lamp efficacy decreases with dimming. Clear lamps are dimmable down to 25% without change in color, coated lamps down to 30% (1)	Some lamps are dimmable with specialized ballasts; lamp efficacy decreases with dimming. Some clear, low-wattage lamps are dimmable only to 80% without change in color; for higher wattages, color changes begin at about 60%. Dimmability in coated lamps is slightly better. (1)	Some lamps are dimmable with specialized ballasts; lamp efficacy decreases with dimming. HPS lamps are dimmable down to 50% without a significant change in color; below 50%, light becomes intensely yellow. (1)
Advantages	Low cost compared to other HID sources; high-wattage available in compact size; good optical controllability	More efficient than MV lamps; better color rendition than other HID sources; high-wattage available in compact size; good optical controllability	Of the HID lamps, HPS lamps are the most efficacious and have the best lumen maintenance; high-wattage available in compact size; good optical controllability; operate effectively in almost any position (1)
Limitations	Poor color rendition; poor lumen maintenance; limited dimming capabilities; slightly less efficacious when operated in horizontal position (1)	Limited dimming capabilities; color temperature may vary with operating position and some lamps have restricted burning positions (1); potential for explosion if arc tube ruptures	Poor color rendition, limited dimming capabilities

Table A.6, cont.	**Mercury Vapor Lamps**	**Metal Halide Lamps**	**High-Pressure Sodium Lamps**
Applications	Because of their poor color rendition, these lamps are only used where good color is not a priority. MV lamps are used mostly in the commercial and industrial sectors and are rarely used for new lighting systems (2). For industrial and outdoor applications where color was not a priority, MV lamps were the most efficient lamp type for many years. Many building owners have now replaced MV lamps with more efficient MH and HPS lamps; however, many MV lamps are still in use because they are relatively inexpensive and conversion to MH and HPS usually requires installation of new ballasts and sometimes requires installation of new fixtures. MV lamps are useful for replacing incandescents in landscape lighting because they bring out the greens in foliage. (3)	MH lamps are effective replacements for MV lamps. Higher-wattage lamps are used for floodlights, are increasingly used for streetlights, and are also used in large industrial areas and sports arenas. Smaller-wattage lamps are used in assembly spaces, schools, public buildings, and merchandising areas. (2) Reduced maintenance costs, good lumen maintenance, longer lamp lives, and the fact that they blend more naturally with fluorescent sources has made MH lamps a very good replacement for 300-watt and 500-watt PAR lamps in commercial spaces. New fixtures utilizing these lamps, particularly one-foot by one-foot recessed lensed troffers (downlights), are becoming common in lobbies, shopping malls, and retail stores.(3)	HPS lamps are effective replacements for MV lamps. These lamps are very useful in the industrial sector and outdoors, where high light levels are often required and good color rendition is not a priority. Most street lighting in the U.S. today is done with HPS lamps. (3)
Lamp Price	$22-30 for a coated 250 W MV lamp; prices are insensitive to wattage (1996$) (7)	$26-40 for a coated 250 W MH lamp; prices are insensitive to wattage (1996$) (7)	$25-35 for a clear HPS 250 W lamp; $60-85 for a coated 250 W HPS lamp (1996$). Prices are insensitive to wattage. (7)
Primary Manufacturers	General Electric, Philips, Osram Sylvania	General Electric, Philips, Osram Sylvania, Venture Lighting International (6)	General Electric, Philips, Osram Sylvania, Iwasaki, Venture Lighting International (6)

Sources: 1: IES (1993); 2: Ontario Hydro (1992); 3: Atkinson et al. (1995); 4: Moezzi (1996-97); 5: Leslie and Conway (1993); 6: Eley Associates (1993); 7: Denver (1996) 8: EPRI (1993a); 9: National Lighting Product Information Program (1993); 10: U.S. House of Representatives (1992); 11: Clear and Rubinstein (1997); 12: Lamp Manufacturer Catalogs for General Electric, Osram Sylvania, and Philips; 13: Clear (1996); 14: Calwell (1996); 15: Brown and Atkinson (1994); 16: Calwell (1997); 17: Clear (1997a)

BALLASTS

Defining The Technical Characteristics of Ballasts

All discharge lamps must be operated with a current-limiting device referred to as a "ballast". A lamp ballast is an electrical device that controls the current provided to the lamp and provides the high voltage necessary to start most discharge lamps. In addition, ballasts can provide power quality correction and control features such as dimming or compensation for lumen depreciation. Ballasts differ from one another in numerous ways such as how energy-efficient they are, how much distortion they cause in a power wave, and how much light a lamp produces when using them. Below, we define the primary physical characteristics by which ballasts are most often assessed and compared.

Ballast Factor (BF):
The ballast factor provides a relative measure of how much light is produced using a specific ballast. A meaningful comparison can only be made between ballasts that are used to operate the same type of lamps.

$$BF = \frac{\text{actual lumen output of lamp operated by ballast}}{\text{rated lumen output of the lamp}}$$

For most ballasts, the BF is less than one; for some of the new electronic ballasts, however, the BF is greater than one (Koomey et al. 1994).

Ballast Efficacy Factor (BEF):
The ballast efficacy factor is used to determine which ballast supplies more light for a given wattage.

$$BEF = \frac{BF \times 100}{\text{lamp + ballast input power}}.$$

As with BF, BEF can be used to meaningfully compare different ballasts only when they operate the same number and type of lamps.

System Efficacy:
Like lamps, ballasts consume power. Consequently, the only meaningful measure of the efficiency of a lighting system is the efficacy of the lamp-ballast system. Typically, a fluorescent ballast consumes from a few to a dozen watts. HID ballasts consume from 10–20% of nominal lamp watts; this percentage is usually higher for lower-wattage lamps. System efficacy refers to the efficacy of the lamp-ballast combination, and is calculated as follows:

$$\text{System Efficacy} \left(\text{lm}/\text{W}\right) = \frac{\text{rated lamp lumens}}{\text{input power (W)}} * \text{number of lamps} * \text{BF}$$

Power Factor (PF) Ratio:
The power factor ratio represents, for a given ballast, the amount of power that a customer is actually using as a fraction of what the utility must supply. This ratio is used to determine how efficiently a ballast uses total input power. To calculate the PF ratio, the power (watts) is divided by the root mean square of the ballast volt-amps (Eley Associates 1993). Utilities may penalize customers whose electric load has a low PF. Ideally, lighting equipment should have a PF greater than 0.9 and as close to 1.0 as possible. PFs of less than 1.0 occur when the voltage and current are out of phase or when the sinusoidal shape is distorted.

Total Harmonic Distortion (THD):
Ballasts, especially electronic ones, affect power quality by generating harmonic distortion. Total harmonic distortion refers to the amount of distortion that a ballast causes in the power wave form. Utilities often require a THD of less than 20%, but the electric industry is considering a standard that permits a THD up to 32% (Audin et al. 1994). High THD can disrupt powerline carrier controls and create unacceptably high currents in three-phase systems. THD values are typically calculated for ballasts based on their operation of a 4-foot fluorescent lamp.

Introduction to Ballasts for Fluorescent and High-Intensity Discharge Lamps

The light output of a lamp depends on the ballast that operates the lamp. Ballasts are often designed to operate a unique lamp type; some ballasts, however, can be used to operate more than one type of lamp. It is important to use the ballast specified by the manufacturers because improper lamp-ballast combinations can result in reduced light output, efficacy, and lifetime.

For all types of ballasts, rated lifetimes are in the range of 45,000 hours. Ballast life is rated for 12 hours of use per day. Ballast life is very dependent on operating temperature – an increase of 10°C over the rated ballast operating temperature of 90°C can translate into as much as a 50% reduction in ballast life (National Lighting Product Information Program 1994). Because manufacturers who specify longer-than-usual ballast lifetimes may also prescribe lower operating temperatures, it is advisable to check the ballast specifications for the temperature to which a specific ballast lifetime corresponds.

Typically, fluorescent lamps are operated using magnetic core-coil or electronic high-frequency ballasts; both magnetic and electronic ballasts are available for most types of fluorescent lamps. Hybrid ballasts are also available for rapid-start lamps. Typically, HID lamps cannot be operated using fluorescent ballasts. The three primary types of HID ballasts are magnetic ballasts: reactor ballasts, high-reactance autotransformers, and constant-wattage autotransformers (Audin et al. 1994). We briefly describe these different ballast types below.

Ballasts for Fluorescent Lamps

Magnetic core-coil ballasts use a capacitor and a transformer with a magnetic core coiled in copper or aluminum wire in order to control the current provided to a lamp. A thermal cutoff switch protects the ballast from overheating. Magnetic ballasts operate at an input frequency of 60 hertz (Hz) and also operate lamps at 60 Hz.

Electronic ballasts use integrated electronic circuitry rather than magnetic components to control voltage and current. Like magnetic ballasts, electronic ballasts use standard 60 Hz power; however, electronic ballasts operate lamps at a much higher frequency (20,000–60,000 Hz), which increases lamp efficacy. Lamp efficacy is also improved because electronic ballasts are less sensitive to ambient (room) temperature than magnetic ballasts. Although dimming magnetic ballasts are available, almost all dimming fluorescent ballasts are electronic (IES 1993).

A third type of fluorescent ballast is the *hybrid ballast*, which is also referred to as a cathode cut-out or heater cut-out ballast. In the hybrid ballast, which is a modified version of the magnetic ballast and operates at a low frequency, electronic circuitry is used to control power to the lamp's cathodes and magnetic components drive the main arc (Audin et al. 1994). Energy consumption is reduced because the electronic circuitry removes the power that is used to heat the lamp filaments once the lamp has started. Typically, hybrid ballasts use 5–10% less energy than energy-efficient magnetic ballasts; however, they can only be used with rapid-start lamps and are not dimmable. Hybrid ballasts account for only a small share of the ballast market.

Table A.7 provides a comparison of magnetic, hybrid, and electronic ballasts.

Ballasts for HID Lamps

Typically, HID lamps cannot be operated using fluorescent ballasts. The three primary types of HID ballasts are magnetic ballasts: reactor ballasts, high-reactance autotransformers, and constant-wattage autotransformers (Audin et al. 1994):

- *Reactor ballasts* consist mainly of an inductor coil. They are small, inexpensive, simple, and have low losses; however, their use leads to more rapid lumen depreciation than the use of other ballast types. Reactor ballasts have a low power factor, and can cause flicker or turn-off if power is unstable.

- *High-reactance autotransformers* are more expensive and consume more power than reactor ballasts, but also have a more sophisticated design. Although they are similar to reactor ballasts, they are capable of boosting line voltage when it is insufficient to start a lamp.

- *Constant-wattage autotransformers* are the most expensive of these three ballast types, but are also the most commonly used. Of these ballast types, constant-wattage autotransformers regulate power the best and their use thus reduces flicker and shutoffs when power is unstable.

There are several disadvantages associated with magnetic HID ballasts, such as high internal losses (an especially high percentage in the case of low-wattage lamps), audible noise, and bulkiness.

Electronic ballasts are now available for some low-wattage MH and HPS lamps, but they are uncommon. Electronic ballasts for HID lamps do not operate on the same principles as those for fluorescent lamps. The primary benefits of an electronic HID ballast are reduced size and weight, quieter operation, and increased control of the arc tube wattage during the lamp's life. More precise arc tube wattage management improves the color consistency over the lamp life, and can lengthen expected life. Unlike electronic fluorescent ballasts, with few exceptions, electronic HID ballasts do not significantly improve lamp efficacy.

Table A.7. Comparison of Magnetic, Hybrid, and Electronic Ballasts for Four-Foot Fluorescent Lamps

	High-Efficiency Magnetic*	**Hybrid**	**Electronic**
Operation	Low-Frequency (60 Hz)	Low-Frequency (60 Hz)	High-Frequency (20,000–60,000 Hz)
Compatible Lamp Types	Standard fluorescents	Rapid-start standard fluorescents	Many types of standard fluorescents
Ballast Factor (BF)	>0.925 (5)	0.79–0.95 (5)	0.73–1.3 (5)
Ballast Efficiency Factor (BEF)	1.1, for a 2-lamp system (5)	1.1–1.37, for a 2-lamp system (5)	1.15–1.56, for a 2-lamp system (5)
Power Factor (PF)	>0.9 (5)	>0.9 (5)	>0.9 (5)
Total Harmonic Distortion (%)	20–35 (5)	11–20 (5)	mostly <20, some <5, some >20 (5)
Energy-Efficiency Attributes	Because of their low-loss metals and denser windings, high-efficiency magnetic ballasts are 10-15% more efficient than the older standard magnetic ballasts that they have now replaced (3)	Because they disconnect the electrode-heating circuit after the lamp is in operation, hybrid ballasts are 5-10% more efficient than high-efficiency magnetic ballasts (3)	Improved efficiency because, when used with electronic ballasts, lamps are operated at a higher frequency (20,000-60,000 Hz) and a lower temperature; lamp-ballast systems using electronic ballasts are approximately 15% more efficient than systems using high-efficiency magnetic ballasts (6)
Additional Benefits	• Least expensive ballast type	• Less expensive than electronic ballasts • More efficacious than high-efficiency magnetic ballasts • Produce less audible noise than high-efficiency magnetic ballasts (5)	• Can operate 1-4 lamps (5) • Reduced weight compared to magnetic, thus reduced shipping costs and easier installation (4) • Audible noise reduced by ≈75% compared to high-efficiency magnetic ballasts (4) • Reduced flicker (5) • Dimmable
Limitations	• Operates only 1-3 lamps (5) • Audible hum (5) • Flicker (5)	• Operates only 2-3 lamps (5) • More expensive than high-efficiency magnetic ballasts • Less efficacious than electronic ballasts • Not dimmable	• Generally more expensive than magnetic ballasts • Can generate radio-frequency noise (5)
Lifetime	45,000 hrs, based on 12 hours of use per day (1)	45,000 hrs, based on 12 hours of use per day (1)	45,000 hrs, based on 12 hours of use per day (1)

Table A.7, cont.	**High-Efficiency Magnetic***	**Hybrid**	**Electronic**
Price	$10-15 (1994$) (5)	$12–17 (1994$) (5)	$20-80, the higher prices are for dimming ballasts (1994$) (6)
Primary Manufacturers	Advance Transformer Co., MagneTek, Valmont Electric	Advance Transformer Co., MagneTek, Valmont Electric (2)	Advance Transformer Co./EBT (Electronic Ballast Technology); MagneTek; Motorola Lighting; Osram Sylvania; Toshiba; Valmont, Lutron (dimming only) (2)

* Federal standards banning the manufacture and sale of "standard" magnetic ballasts became effective in January 1990. They were replaced by "high-efficiency" magnetic ballasts. The "high-efficiency" magnetic ballasts have low-loss metals and denser windings and are 10–15% more efficient than the banned standard ballasts. Their name is somewhat of a misnomer, however – of the ballasts available for fluorescent lamps, they are the *least* energy-efficient. See Koomey et al. (1995) for further discussion of this issue.

Sources: 1: IES (1993); 2: Eley Associates (1993); 3: Atkinson et al. (1995); 4: EPRI (1993b); 5: National Lighting Product Information Program (1994); 6: Koomey et al. (1994)

FIXTURES

A lighting fixture provides physical support for lamp(s), ballast(s), and wiring. The function of the fixture is to efficiently direct and distribute light to the desired area without causing glare or discomfort. The geometric design of a fixture, as well as the material of which the reflector and/or lens is made, determines how the light of a lamp is distributed as well as the overall efficiency of the lighting system.

We use the term "fixture" to refer to the physical housing for a lamp, including: sockets, lamp holders, and fittings to attach the lamp to the fixture; reflectors to direct light in the desired direction; shielding and diffusion components (such as lenses, diffusers, and louvers) to shield the light from non-desired directions, reduce visual discomfort, prevent glare, and distribute light evenly; and, for certain types of lamps, ballasts to start lamp and control electric characteristics during lamp operation. An efficient fixture optimizes the system performance of each of its components.

If installed in the wrong fixture, even the most efficacious lamp can be inefficient and provide light of poor quality. There are more fixtures on the market today than any other type of lighting equipment. Consequently, it is important that fixtures be selected carefully, based on factors including the user's specific lighting needs, lamp requirements, and environmental conditions.

Various types of fixtures differ from one another in numerous ways such as reflector design, operating position of the lamp, ease of lamp insertion and removal, thermal characteristics, and fixture life time. Fixtures also differ from one another in terms of their energy use and light distribution characteristics.

The performance of a fixture is assessed by evaluating its performance as part of a "luminaire"; in this appendix, the term "luminaire" refers to a complete lighting system including lamp(s), ballast(s), and fixture. Below, we define some of the energy-efficiency and light distribution characteristics by which fixture performance can be assessed and compared.

Luminaire Efficiency:
Luminaire efficiency is the ratio of the lumens leaving a luminaire to the total number of lumens produced by a lamp (IES 1993).

Luminaire Efficacy Rating (LER):
As mentioned in the main body of this report, in response to EPAct's call for a voluntary national testing and information program for luminaires, a program has been created by the National Lighting Collaborative (1996). Members of the Collaborative include the National Electrical Manufacturers Association, the American Lighting Association, and other interested parties. The working group has introduced a new tool for comparing luminaires, the LER, which is based on NEMA's LE5 standard for fluorescent luminaires. The LER is a single number expressing luminaire efficacy in lumens per watt, and is calculated using the following equation:

$$\text{LER} = \frac{\text{luminaire efficiency} * \text{total rated lamp lumens} * \text{ballast factor}}{\text{luminaire input watts}}$$

Coefficient of Utilization (CU):
The coefficient of utilization expresses the ratio of the lumens from a luminaire that are received on a room's workplane to the total number of lumens produced by the lamps within the luminaire (IES 1993).

LIGHTING CONTROLS

A large variety of technologies are available for controlling the way that lights are used in a building. These technologies can be mechanical and/or electronic and range from a basic timer that turns the lights off or on at a given hour of the day to a complex energy management system (EMS) that controls not only the lighting in a building but also the space conditioning system. Both simple and highly complex lighting control systems are used in commercial buildings. In homes, lighting control systems tend to be simple; however, the control systems installed in the recently introduced "smart houses" are quite complicated.

Common lighting control strategies and tools are summarized in **Table A.8** and **Table A.9**, respectively. The choice of a lighting control strategy and tools, which can be a combination of the options described in Tables A.8 and A.9, depends on numerous factors – including the type of lamp one wishes to control. Not all lighting controls are appropriate for all lamp types. For example, HID and fluorescent lamps may not be ideal for applications where a motion sensor frequently switches the lights on and off, because the lifetime of these lamps is very sensitive to frequent switching. In addition, HID lamps may take too long to start up. HID and fluorescent lamps are the ideal choice in time-controlled applications where relatively long burning cycles are needed.

The type of controls one selects will also depend on whether they are being installed as a retrofit, renovation, or for new construction. As described in Koomey et al. (1994), the electrical wiring configuration is the major constraint in installing controls in buildings. Most often, it is not cost-effective to substantially re-wire the ceiling electric lighting system in an existing building in order to install lighting controls. Consequently, lighting control systems for retrofits in existing buildings tend to be simpler than the lighting control systems designed for new buildings.

In new construction, it can be cost-effective to install more advanced lighting control systems. As described in Atkinson et al. (1995), integrated workstation sensors and energy management systems are two highly promising efficiency options:

> Of the control systems available today, integrated workstation sensors and energy management systems are two of the most promising efficiency options. An *integrated workstation sensor* allows users to control lighting, electric heating and cooling equipment, and other electrical equipment (such as plug loads) for individual workstations or spaces. For example, user lighting controls might include dimmer switches for area and task lighting as well as daylight sensors. From their workspace, users can adjust lighting and HVAC controls according to their preference. Occupancy sensors automatically shut down electrical equipment when the space is unoccupied, and system memory allows the equipment to come back on at the same level when the occupant returns. Comprehensive, automated, *building energy management systems* are user-programmable and can control equipment for several energy end-uses including lighting, HVAC, security, and safety systems. A well-designed energy management system may offer greater energy savings than individual controls for single end uses; the "systems approach" is becoming more common in both new construction and retrofits of existing buildings.

For a clear and practical guide to the strategies and tools used in designing lighting control systems for commercial buildings, see Rundquist et al. (1996).

Table A.8. Common Lighting Control Strategies

Scheduling	Scheduling is a lighting control strategy based on turning lamps off and on according to the need for illumination. *Predictable scheduling* regulates illumination levels in a predetermined way, with the use of equipment such as timed controls, and can be effective for buildings in which activities follow a similar routine from day to day. *Unpredictable scheduling* controls lighting levels based on whether or not someone is present; for example, occupancy/motion sensors extinguish or dim the lights when a space is unoccupied and turn the lights back on when someone enters the space.
Task-Tuning	Normally, spaces are illuminated uniformly. Using a *task-tuning* control strategy and dimming devices, however, the lighting levels of different spaces can be adjusted to meet the needs of the different people using those spaces. For example, workers performing visually detailed tasks are likely to require more illumination than workers who are primarily looking at their computer monitors throughout the day. Additionally, lighting levels can be reduced in spaces that are not oriented towards visual tasks (e.g., hallways and reception areas).
Daylighting	In many buildings, the daylight coming in through windows and skylights can provide a significant amount of the light necessary for many visual tasks. After decades of overdependence on artificial light, many lighting designers are once again thinking in terms of using sunlight to illuminate interior spaces. For designers, the challenge of *daylighting* is to admit only the required amount of daylight, distribute the light evenly, and avoid glare. When daylight is used within a building, the electric lighting levels can be reduced. Using a control photocell, a dimmable lighting system can be connected to the ambient light levels within a room; in this way, electric light levels can be reduced during the times when natural light is available and supply most or all of the light needed when natural light levels are low and when it is dark outside.
Lumen Maintenance	Typically, electric lighting systems are designed to produce light levels that are 20-35% higher than the design minimum so that, as lamps age and the amount of light delivered by the lamp-luminaire system diminishes, the illuminance level will always meet or exceed the minimum light requirement. Light losses over time are the result of lamp lumen depreciation as well as the accumulation of dirt on the luminaire and room surfaces. *Lumen maintenance* is a control strategy that uses photocells and dimmers to sense the actual illuminance level in a space and reduce system power input to maintain only the desired light level. In this way, a lighting system can be designed with lower initial lighting power densities and design-specified illuminance levels are maintained at all times, rather than only at the end of the maintenance cycle.
Load Shedding	In order to avoid brownouts and blackouts, many utilities charge their larger customers based on peak power demand. Selective reduction of lighting levels in less critical areas of a building is an effective way of reducing lighting power demand for short periods of time. Typically, lighting levels can be reduced by 10% or more with only minimal impact on the occupant's visual performance or productivity. Automatic dimming controls allow the reduction in light level to occur without occupant awareness.
Adaptation Compensation	In places that are illuminated both during the day and throughout the night (e.g., 24-hour supermarkets or entry foyers), the level of electric lighting needs to be higher during the daytime because a person whose eyes are adapted to daylight will need more light to see in areas that are less bright. When a person's eyes are adapted to the lack of light at night, however, they do not require as much light to see indoors. An adaptation compensation control strategy uses dimming devices or switching relays in combination with automatic timers to vary the lighting level accordingly.

Sources: IES (1993), Eley Associates (1993)

Table A.9. Common Lighting Control Tools*

Programmable Timers	Programmable timers are used to implement time-based control of electric lights. The usual method of implementation is a system of low-voltage controlled relays that are controlled by a programmable time clock. These systems are primarily used to efficiently schedule the operation of a lighting system in areas where the occupant schedule is relatively predictable. To accommodate lighting needs during off-hours, these systems are typically equipped with overrides so that building occupants can control the lights using a low-voltage switch or a telephone override system.
Occupancy Sensors	Occupancy sensors are switches that are activated by detecting the presence or absence of people in the sensor's field of view. There are two basic types of occupant sensor: passive infrared sensing and ultrasonic (some sensors combine these two methods). These sensors are most effective in locations where occupancy is not easily predicted (e.g., conference rooms, restrooms, and storerooms).
Photo-Switches	Photo-switches are photo-electrically controlled switches that can be used to switch off lights in building zones receiving daylight from adjacent windows. These devices are usually installed in one of three ways: on each fixture; on groups of fixtures using intermediate relays; or as inputs to low-voltage programmable relay systems.
Dynamic Controls	Dynamic controls are devices that allow standard lighting equipment (including both fluorescent and HID sources) to be continuously dimmed to an intermediate level. These systems can control a single lamp or entire branch circuits. Although these controls can typically provide any light level within the control range, they rarely permit dimming below 40% of maximum. They generally accept an input from a photocell and/or an input from an energy management system.
Static Controls	Static controls are devices that allow the light output of standard lighting equipment to be reduced to one intermediate level. These systems can control a single lamp or entire branch circuits. The larger systems generally accept an input from an EMS system for scheduling control. The smaller systems generally control only a single lamp or ballast - their sole function is to reduce input power (and light output). The primary application of these systems is in areas that are overlit.
Dimmable Ballasts	With the use of dimmable ballasts, fluorescent lamps can be dimmed over a wide range, and represent the state-of-the-art in controllable lighting. Although dimming magnetic ballasts are also available, almost all dimming ballasts in use today are electronic (Clear and Rubinstein 1997). Typically, electronic ballasts can be controlled using a low-voltage wiring network that allows them to respond to inputs from a photocell, occupancy sensor, or input from an energy management system.

* Except where otherwise noted, the descriptions of these lighting control tools were obtained from Koomey et al. (1994).

APPENDIX A REFERENCES

Atkinson, Barbara, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear. 1995. "Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors" in the *CRC Handbook of Energy Efficiency*. Boca Raton, FL: CRC Press, pp. 399-427.

Audin, L., D. Houghton, M. Shephard, and W. Hawthorne. 1994. *Lighting Technology Atlas*. Boulder, Colorado: E Source, Inc.

Brown, Richard, and Barbara Atkinson. 1994. *Incandescent Reflector Lamp Energy Efficiency Standard Analysis: Draft Report*. Berkeley, CA: Lawrence Berkeley National Laboratory. Draft LBL-36223. September.

Calwell, Chris. 1996. *Halogen Torchieres: Cold Facts and Hot Ceilings*. Boulder, CO: E-Source. September.

Calwell, Chris. 1997. *Personal Communication:* Telephone conversation with Jonathan Koomey regarding review of April 1997 DRAFT Sourcebook. May.

Census Bureau. 1994. *Current Industrial Reports: Electric Lamps - MQ36B (93)-5, Summary 1993*. Washington, D.C.: U.S. Department of Commerce. November.

Clear, Robert (Lawrence Berkeley National Laboratory). 1994. *Personal Communication:* Memo to co-workers entitled "Summary Statement on Economics of IR-Halogen Lamps." May.

Clear, Robert (Lawrence Berkeley National Laboratory). 1996. *Personal Communication:* E-mail to Jonathan Koomey regarding review of October 1996 DRAFT Sourcebook. October 21.

Clear, Robert (Lawrence Berkeley National Laboratory). 1997a. *Personal Communication:* Written comments provided to Leslie Shown regarding review of April 3, 1997 DRAFT Sourcebook. April.

Clear, Robert (Lawrence Berkeley National Laboratory). 1997b. *Personal Communication:* E-mail to Leslie Shown regarding technical characteristics of an HIR A-lamp. March 17.

Clear, Robert, and Francis Rubinstein (Lawrence Berkeley National Laboratory). 1996. *Evaluating the Relative Efficacy of Incandescent Lamp Technologies*. Unpublished report.

Clear, Robert, and Francis Rubinstein (Lawrence Berkeley National Laboratory). 1997. *Personal Communication:* Conversation with Leslie Shown regarding the dimmability of fluorescent lamps. March 10.

Denver, Andrea (Lawrence Berkeley National Laboratory). 1996. *Personal Communication:* Conversation with Leslie Shown regarding lamp prices (based on catalogs and survey of shelf prices at Bay Area stores).

Electric Power Research Institute (EPRI). 1993a. *Compact Fluorescent Lamps: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Electric Power Research Institute (EPRI). 1993b. *Electronic Ballasts: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Eley Associates. 1993. *Advanced Lighting Guidelines: 1993.* San Francisco, CA: Eley Associates. Prepared by Eley Associates, Luminae Souter Lighting Design, and Lawrence Berkeley National Laboratory for the U.S. Department of Energy, California Energy Commission, and Electric Power Research Institute. DOE/EE-0008.

General Electric Company. 1995. *GE Lighting: Spectrum 9200 Lamp Catalog.* U.S.: General Electric Company.

Illuminating Engineering Society of North America (IES). 1993.*Lighting Handbook: Reference & Application* . 8th Edition. New York, NY: IES.

Koomey, J.G., A.H. Sanstad, and L.J. Shown. 1995. *Magnetic Fluorescent Ballasts: Market Data, Market Imperfections, and Policy Success.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-37702. December.

Koomey, Jonathan G., Francis X. Johnson, Jennifer Schuman, Ellen Franconi, Steve Greenberg, Jim D. Lutz, Brent T. Griffith, Dariush Aresteh, Celina Atkinson, Kristin Heinemeier, Y. Joe Huang, Lynn Price, Greg Rosenquist, Francis M. Rubinstein, Steve Selkowitz, Haider Taha, and Isaac Turiel. 1994. *Buildings Sector Demand-Side Efficiency Technology Summaries.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-33887. March.

Lamp Manufacturer Catalogs for General Electric (1995), Osram Sylvania (1996), and Philips (1996).

Leslie, Russell, and Kathryn Conway. 1993. *Research for "The Lighting Pattern Book for Homes", Final Report.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Moezzi, Mithra. 1996-97. *Personal Communication:* Memos to Diana Vorsatz and Leslie Shown regarding statistical distribution of residential lighting fixtures and lamps based on data obtained from the TPU analysis.

National Lighting Collaborative. 1996. *What is LER?: Announcing the New Luminaire Energy Information Program.* Rosslyn, VA: National Lighting Collaborative. July.

National Lighting Product Information Program. 1993. *Lighting Answers: T8 Fluorescent Lamps.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. April.

National Lighting Product Information Program. 1994. *Specifier Reports: Electronic Ballasts.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. May.

Ontario Hydro. 1992. *Lighting Reference Guide, 5th Edition.* Ontario, Canada: Ontario Hydro.

Osram Sylvania Inc. 1996. *Osram Sylvania Product Catalog: 1996 Lighting Technology in the Age of EPAct.* Danvers, MA: Osram Sylvania Inc.

Page, Erik (Lawrence Berkeley National Laboratory). 1997. *Personal Communication:* Conversation with Leslie Shown regarding efficacies of halogen torchieres.

Philips Lighting Company. 1996. *Lamp Specification and Application Guide.* Somerset, NJ: Philips Lighting Company.

Rundquist, R.A., T. McDougal, and J. Benya. 1996. *Lighting Controls: Patterns for Design*. Palo Alto, CA: Electric Power Research Institute. Prepared by R.A. Rundquist Associates for Empire State Electric Energy Research Corporation and the Electric Power Research Institute. EPRI TR-107230. December.

Sezgen, A. Osman, Y. Joe Huang, Barbara A. Atkinson, and Jonathan G. Koomey. 1994. *Technology Data Characterizing Lighting in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34243. May.

Siminovitch, Michael, and Evan Mills. 1994. " Fixing the Fixtures." *Home Energy* 11(6): 47-49.

U.S. House of Representatives. 1992. *Energy Policy Act of 1992*. Washington DC: U.S. Government Printing Office.

APPENDIX B

Useful Lighting References

General Lighting Overviews

Atkinson, Barbara, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear. 1995. "Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors". In *CRC Handbook of Energy Efficiency*. Boca Raton, FL: CRC Press, pp. 399-427.

Audin, L., D. Houghton, M. Shephard, and W. Hawthorne. 1994. *Lighting Technology Atlas*. Boulder, Colorado: E Source, Inc.

Berman S, M. Horowitz, C. Blumstein, V. Adams, K. Anderson, P. Caesar, R. Clear, D. Goldstein, B. Greene, D. Gustafson, E. Kahn, L. King, and R. Weisenmiller. 1976. *Electrical Energy Consumption in California: Data Collection and Analysis*. Berkeley, CA: Lawrence Berkeley National Laboratory. Report # UC-3847. July.

Eley Associates. 1993. *Advanced Lighting Guidelines: 1993*. San Francisco, CA: Eley Associates. Prepared by Eley Associates, Luminae Souter Lighting Design, and Lawrence Berkeley National Laboratory for the U.S. Department of Energy, California Energy Commission, and Electric Power Research Institute. DOE/EE-0008.

Energy Information Administration (EIA). 1996. *Annual Energy Outlook 1997, with Projections to 2015*. Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0383(97). December.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume I, California Baseline Report*. Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume IV, Recommendations Report*. Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Illuminating Engineering Society of North America (IES). 1993. *Lighting Handbook: Reference & Application*. New York, NY: IES.

Lighting Research Center. 1994. *Research Results: A Summary of Lighting Research Center Research Projects*. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Mills, Evan and Mary Ann Piette. 1993. "Advanced Energy-Efficient Lighting Systems: Progress and Potential." *Energy* 18(2): 75-97.

Mills, Evan, and Nils Borg. 1993. *Trends in Recommended Lighting Levels: An International Comparison*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34565.

Office of Technology Assessment (OTA). 1992. *Building Energy Efficiency*. Washington, DC: U.S. Government Printing Office.

Ontario Hydro. 1992. *Lighting Reference Guide, 5th Edition*. Ontario, Canada: Ontario Hydro. August.

Vorsatz, Diana. 1996. *Exploring U.S. Residential and Commercial Electricity Potentials: Analysis of the Lighting Sector*. Doctoral Dissertation Thesis, University of California, Los Angeles.

Technical Aspects of Specific Lighting Technologies[1]

Atkinson, Barbara, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear. 1995. "Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors". In *CRC Handbook of Energy Efficiency*. Boca Raton, FL: CRC Press, pp. 399-427.

Audin, L., D. Houghton, M. Shephard, and W. Hawthorne. 1994. *Lighting Technology Atlas*. Boulder, Colorado: E Source, Inc.

Calwell, Chris. 1996. *Halogen Torchieres: Cold Facts and Hot Ceilings,*. Boulder, CO: E-Source. September.

Calwell, Chris. 1997. "Bright Prospects for CFL Torchieres." *Home Energy* January/February: 13.

Conway, Kathryn (editor). 1991. *Commercial Lighting Efficiency Resource Book*. Troy, New York: Lighting Research Center, Rensselaer Polytechnic Institute. Prepared for Electric Power Research Institute. Report No. CU-7427. September.

Electric Power Research Institute (EPRI). 1992. *Occupancy Sensors: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Electric Power Research Institute (EPRI). 1992. *Specular Retrofit Reflectors: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Electric Power Research Institute (EPRI). 1993. *Compact Fluorescent Lamps: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Electric Power Research Institute (EPRI). 1993. *Electronic Ballasts: High-Efficiency Electric Technology Fact Sheet*. Palo Alto, CA: EPRI.

Electric Power Research Institute (EPRI). 1993. *High-Intensity Discharge Lighting: Efficient Solutions for Commercial and Industrial Interior Applications*. Palo Alto, CA: EPRI.

Eley Associates. 1993. *Advanced Lighting Guidelines: 1993*. San Francisco, CA: Eley Associates. Prepared by Eley Associates, Luminae Souter Lighting Design, and Lawrence Berkeley National Laboratory for the U.S. Department of Energy, California Energy Commission, and Electric Power Research Institute. DOE/EE-0008.

Franconi, Ellen, and Francis Rubinstein. 1992. *Considering Lighting System Performance and HVAC Interactions in Lighting Retrofit Analyses*. In Proceedings of the 1992 IEEE Industry Applications Society Annual Meeting, Houston, Texas, October 4-9, 1992, Volume II: pp. 1858-1867.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume IV, Recommendations Report*. Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

---

[1] For a complete list of the lighting-related publications of the Building Technologies Program at the Lawrence Berkeley National Laboratory, contact Pat Ross: phone: (510) 486-6845, fax: (510) 486-4089, e-mail: plross@lbl.gov.

Illuminating Engineering Society of North America (IES). 1993. *Lighting Handbook: Reference & Application.* New York, NY: IES.

Ji, Y., and R. Davis. 1996. "Toward More Accurate Predictions of Energy Use and Light Output for 2 by 4 Luminaires." *Journal of the Illuminating Engineering Society* (Winter 1996): 60-67.

Kofod, Casper. 1996. " Large CFL Potential in European Homes." *IAEEL (International Association for Energy-Efficient Lighting) Newsletter* 3/96.

Koomey, Jonathan G., Francis X. Johnson, Jennifer Schuman, Ellen Franconi, Steve Greenberg, Jim D. Lutz, Brent T. Griffith, Dariush Aresteh, Celina Atkinson, Kristin Heinemeier, Y. Joe Huang, Lynn Price, Greg Rosenquist, Francis M. Rubinstein, Steve Selkowitz, Haider Taha, and Isaac Turiel. 1994. *Buildings Sector Demand-Side Efficiency Technology Summaries.* Prepared for the Technology Characterization Database of the Intergovernmental Panel on Climate Change. Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-33887. March.

Lamp Manufacturer Catalogs (the largest manufacturers are General Electric, Osram Sylvania, and Philips).

Manclark, Bruce, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study.* Eugene, OR: Delta-T. April.

Manclark, Bruce, Howard Reichmuch, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study: Lighting Use and Economic Supplement.* Eugene, OR: Delta-T. BPA DE-AI79-91BP58689. September.

Mills, Evan and Mary Ann Piette. 1993. "Advanced Energy-Efficient Lighting Systems: Progress and Potential." *Energy* 18(2): 75-97.

Mills, Evan, Michael Siminovitch, Erik Page, and Robert Sardinsky. 1996. *Dedicated Compact Fluorescent Fixtures: The Next Generation for Residential Lighting.* In Proceedings of the 3rd European Conference on Energy-Efficient Lighting, Newcastle, UK, pp. 207-216, also Lawrence Berkeley National Laboratory Report No. 3683.

National Lighting Product Information Program. 1992. *Specifier Reports Supplements: Power Reducers.* Volume 1, Issue 2. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March, Revised in August.

National Lighting Product Information Program. 1993. *Lighting Answers: Multilayer Polarizer Panels.* Volume 1, Number 2. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. August.

National Lighting Product Information Program. 1993. *Lighting Answers: T8 Fluorescent Lamps.* Volume 1, Issue 1. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. April.

National Lighting Product Information Program. 1993. *Specifier Reports: Parking Lot Luminaires.* Volume 1, Issue 4. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

National Lighting Product Information Program. 1994. *Lighting Answers: Task Lighting for Offices.* Volume 1, Number 3. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. April.

National Lighting Product Information Program. 1994. *Specifier Reports: Electronic Ballasts.* Volume 2, Number 3. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. May.

National Lighting Product Information Program. 1994. *Specifier Reports: Exit Signs.* Volume 2, Number 2. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. November.

National Lighting Product Information Program. 1995. *Lighting Answers: Electromagnetic Interference Involving Fluorescent Lighting Systems.* Volume 2, Number 1. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

National Lighting Product Information Program. 1995. *Lighting Answers: Power Quality.* Volume 2, Number 2. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. February.

National Lighting Product Information Program. 1995. *Lighting Answers: Thermal Effects in 2' X 4' Fluorescent Lighting Systems.* Volume 2, Number 3. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

National Lighting Product Information Program. 1995. *Specifier Reports Supplements: Electronic Ballasts.* Volume 2, Number 3, Supplement 1. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

National Lighting Product Information Program. 1995. *Specifier Reports Supplements: Exit Signs.* Volume 2, Number 2, Supplement 1. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

National Lighting Product Information Program. 1996. *Specifier Reports Supplements: Electronic Ballasts.* Volume 2, Number 3, Supplement 2. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. March.

Ontario Hydro. 1992. *Lighting Reference Guide, 5th Edition.* Ontario, Canada: Ontario Hydro. August.

Page, E. and M. Siminovitch. 1997. *Photometric Assessment of Energy Efficient Torchieres.*, Berkeley, CA: Lighting System Research Group, Lawrence Berkeley National Laboratory, Draft Pub # 40507. To be presented to Right Light Four in November 1997, Copenhagen, Denmark.

Page, E. and M. Siminovitch. 1997. *The Energy Case Against Halogen Torchieres.* Berkeley, CA: Lighting System Research Group, Lawrence Berkeley National Laboratory. Proceedings of Globalcon'97, AEE. April.

Piette, Mary Ann, Florentin Krause, and Rudy Verderber. 1988. *Technology Assessment: Energy-Efficient Commercial Lighting.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-27032. March.

Rea, Mark, and Dorene Maniccia. 1994. *Lighting Controls Scoping Study Annotated Bibliography: Lighting Controls.* Prepared for California Institute of Energy Efficiency, New York State Energy Research and Development Authority, Pacific Gas and Electric, Bonneville Power Administration. Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute. February.

Rundquist, R.A., T. McDougal, and J. Benya. 1996. *Lighting Controls: Patterns for Design.* Prepared for Empire State Electric Energy Research Corporation and the Electric Power Research Institute. Palo Alto, CA: Electric Power Research Institute. EPRI TR-107230. December.

Sezgen, A. Osman, Y. Joe Huang, Barbara A. Atkinson, and Jonathan G. Koomey. 1994. *Technology Data Characterizing Lighting in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34243. May.

Siminovitch, M., L. Marr, J. Mitchell, and E. Page. 1997. *Energy Efficiency Alternatives to Halogen Torchieres.* Berkeley, CA: Lighting System Research Group, Lawrence Berkeley National Laboratory, Pub # 40243. Presented to IESNA in August 1997, Seattle, WA.

Summers, K., M. Ungs, and J. Radde. 1995. *Information on the Fate of Mercury from Fluorescent Lamps Disposed in Landfills.* Palo Alto: Electric Power Research Institute. EPRI TR-104953.

Vorsatz, Diana. 1996. *Exploring U.S. Residential and Commercial Electricity Potentials: Analysis of the Lighting Sector.* Doctoral Dissertation Thesis, University of California, Los Angeles.

Sector-Specific Lighting Energy Use and Technology Assessment

Residential

Atkinson, Barbara, James E. McMahon, Evan Mills, Peter Chan, Terry Chan, Joseph H. Eto, Judith D. Jennings, Jonathan G. Koomey, Kenny W. Lo, Matthew Lecar, Lynn Price, Francis Rubinstein, Osman Sezgen, and Tom Wenzel. 1992. *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings.* Lawrence Berkeley National Laboratory. LBL-31469. December.

Calwell, Chris, Chris Granda, Charlie Stephens, and My Ton. 1996. *Energy Efficient Residential Luminaires: Technologies and Strategies for Market Transformation, Final Report.* Washington, DC: U.S. Environmental Protection Agency. Prepared for the Natural Resources Defense Council. May 13.

Campbell, C.J. 1994. *Perceptions of Compact Fluorescent Lamps in the Residential Market: Update 1994.* Palo Alto: Electric Power Research Institute. TR-104807. November.

Energy Information Administration (EIA). 1995. *Household Energy Consumption and Expenditures 1993.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0321(93). October.

Energy Information Administration (EIA). 1996. *Residential Lighting: Use and Potential Savings.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0555(96)/2. September.

Hanford, James W., Jonathan G. Koomey, Lisa E. Stewart, Matthew E. Lecar, Richard E. Brown, Francis X. Johnson, Roland J. Hwang, and Lynn Price. 1994. *Baseline Data for the Residential Sector and Development of a Residential Forecasting Database.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-33717. May.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume I, California Baseline Report.* Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume II, Scenarios Report.* Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Jennings, J., R. Brown, M. Moezzi, E. Mills, R. Sardinsky, B. Heckendorn, D. Lerman, and L. Tribwell. 1996. *Residential Lighting: The Data to Date.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-35484. March. (Also presented at annual conference of the Illuminating Engineering Society of North America in Cleveland, Ohio, August 1996.)

Kofod, Casper. 1996. " Large CFL Potential in European Homes." *IAEEL (International Association for Energy-Efficient Lighting) Newsletter* 3/96.

Kofod, Casper, Ali Rahbar, and Laila Naser. 1996. *Market Research on the Use of Energy Saving Lamps in the Domestic Sector.* Lyngby: DEFU (Research Institute of Danish Electric Utilities). DEFU TR 366. June.

Leslie, Russell, and Kathryn Conway. 1993. *Research for "The Lighting Pattern Book for Homes", Final Report.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Leslie, Russell, and Kathryn Conway. 1996. *The Lighting Pattern Book for Homes, 2nd Edition.* New York, NY: McGraw Hill.

Manclark, Bruce, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study.* Eugene, OR: Delta-T. April.

Manclark, Bruce, Howard Reichmuch, and Mike Nelson. 1992. *The Grays Harbor PUD Compact Fluorescent Maximization Study: Lighting Use and Economic Supplement.* Eugene, OR: Delta-T. BPA DE-AI79-91BP58689. September.

Manclark, Bruce. 1991. "Of Sockets, Housecalls, and Hardware." *Home Energy* November/December: 22-26.

Mills, Evan, Michael Siminovitch, Erik Page, and Robert Sardinsky. 1996. *Dedicated Compact Fluorescent Fixtures: The Next Generation for Residential Lighting.* In Proceedings of the 3rd European Conference on Energy-Efficient Lighting, Newcastle, UK, pp. 207-216, also Lawrence Berkeley Laboratory Report No. 3683.

Pacific Energy Associates Inc. 1996. *A Market Transformation Study for the Residential Lighting Market.* Portland, OR: Pacific Energy Associates, Inc.

Polsby, Emily. 1994. "Putting Energy-Efficient Lighting in Its Place." *Home Energy* 11(6): 41-44.

Rasky, L. 1993. "Consumers and Compact Fluorescents." *Home Energy* 10(6): 11-13.

Siminovitch, Michael, and Evan Mills. 1994. "Fixing the Fixtures." *Home Energy* 11(6): 47-49.

Tribwell, Lyle S., and David I. Lerman. 1996. *Baseline Residential Lighting Energy Use Study* in 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 3. Washington, DC: American Council for an Energy Efficiency Economy.

Weiner, J., and C. J. Campbell. 1992. *Perceptions of Compact Fluorescent Lamps in the Residential Market.* Prepared by Macro Consulting for the Electric Power Research Institute. EPRI-TR-100734. July 1992.

Non-Residential

Atkinson, Barbara, James E. McMahon, Evan Mills, Peter Chan, Terry Chan, Joseph H. Eto, Judith D. Jennings, Jonathan G. Koomey, Kenny W. Lo, Matthew Lecar, Lynn Price, Francis Rubinstein, Osman Sezgen, and Tom Wenzel. 1992. *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings.* Lawrence Berkeley National Laboratory. LBL-31469. December.

Conway, Kathryn (editor). 1991. *Commercial Lighting Efficiency Resource Book.* Troy, New York: Lighting Research Center, Rensselaer Polytechnic Institute. Prepared for Electric Power Research Institute. Report No. CU-7427. September.

Conway, Kathryn, Russell Leslie, Marcia Ward, and Suzanne Hartleb. 1990. *Commercial Lighting Efficiency Program, Phase 1: Feasibility Study.* Troy, New York: Lighting Research Center, Rensselaer Polytechnic Institute. Prepared for the New York State Energy Research and Development Authority. August 20.

Energy Information Administration (EIA). 1992. *Lighting in Commercial Buildings.* Washington, DC: U.S. Department of Energy, EIA. DOE/EIA-0555(92)/1. March.

Goldstein, D. B., and R. K. Watson. 1988. *Deriving and Testing Power Budgets for Energy Efficient Lighting in Nonresidential Buildings* in the Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 3. Washington, DC: American Council for an Energy Efficiency Economy.

Gordon, Fred, and Les Tumidaj. 1995. *Opportunities for Market Transformation for Commercial Lighting Remodeling.* Portland, OR: Pacific Energy Associates, Inc.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume I, California Baseline Report.* Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume II, Scenarios Report.* Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Piette, Mary Ann, Florentin Krause, and Rudy Verderber. 1988. *Technology Assessment: Energy-Efficient Commercial Lighting.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-27032. March.

Sezgen, A. Osman, Y. Joe Huang, Barbara A. Atkinson, and Jonathan G. Koomey. 1994. *Technology Data Characterizing Lighting in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-34243. May.

Sezgen, Osman, and Jonathan Koomey. 1997. *Interactions Between Lighting and Space Conditioning Energy Use in U.S. Commercial Buildings.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-39795. November.

Market-Related Lighting Information

Borg, Nils. 1994. " Global CFL Sales." *IAEEL (International Association for Energy-Efficient Lighting) Newsletter* 4/94: 9-10.

Campbell, C.J. 1994. *Perceptions of Compact Fluorescent Lamps in the Residential Market: Update 1994.* Palo Alto: Electric Power Research Institute. TR-104807. November.

Campbell, C.J., J. Weiner, and R. Cannedy. 1993. *Market Infrastructure and Compact Fluorescent Lamps.* Palo Alto: Electric Power Research Institute. TR-102120. March.

Census Bureau. *Current Industrial Reports* for electric lamps (published through 1994), electric lighting fixtures (published quarterly), and fluorescent lamp ballasts (published quarterly). Washington, DC: U.S. Department of Commerce.

Davis, Fred. 1991. *Engines of Energy Innovation: The Role of Smaller Manufacturers of Efficient Lighting Products* in Proceedings of the 1991 Right Light Bright Light Conference, Stockholm, Sweden, pp. 239-247.

Economic Industry Reports, Inc. (EIRI). 1995. *The U.S. Lighting Fixtures Industry: An Economic and Market Study, 1995-96 Edition, Volumes I and II.* Raleigh, North Carolina: EIRI.

Electric Power Research Institute (EPRI). 1993. *Drivers of Electricity Growth and the Role of Utility Demand-Side Management.* Palo Alto: EPRI. TR-102639. August.

Eto, J., C. Goldman, and M.S. Kito. 1996. " Ratepayer-Funded Energy Efficiency Programs in a Restructured Electricity Industry." *The Electricity Journal* August/September: 71-81.

Eto, Joseph, and Eric Hirst. 1996. " What Kind of Future for Energy Efficiency?" *The Electricity Journal* June: 76-82.

Gough, A., and R. Blevins. 1992. *Survey and Forecast of Marketplace Supply and Demand for Energy-Efficient Lighting Products: Final Report.* Prepared for California Institute for Energy Efficiency, U.S. EPA - Global Change Division, U.S. DOE - Federal Energy Management Program, and Electric Power Research Institute. Palo Alto, CA: Electric Power Research Institute. EPRI TR-100288. December.

Haddad, Brent M. 1994. *Why Compact Fluorescent Lamps Are Not Ubiquitous: Industrial Organization, Incentives, and Social Convention* in Proceedings of 1994 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 10. Washington, DC: American Council for an Energy-Efficient Economy.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume III, Market Barriers Report.* Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Illuminating Engineering Society of North America (IES). 1996. "1996 Lighting Equipment & Accessories Directory." *Lighting Design + Application* 26(3): March.

Kofod, Casper, Ali Rahbar, and Laila Naser. 1996. *Market Research on the Use of Energy Saving Lamps in the Domestic Sector.* Lyngby: DEFU (Research Institute of Danish Electric Utilities). DEFU TR 366. June.

Koomey, J.G., A. H. Sanstad, and L. J. Shown. 1995. *Magnetic Fluorescent Ballasts: Market Data, Market Imperfections, and Policy Success.* Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-37702. December.

Leslie, Russell, and Kathryn Conway. 1993. *Research for "The Lighting Pattern Book for Homes", Final Report.* Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

McDougall, G. H. G., and D. Snetsinger. 1993. "Loblaws". In *Marketing Challenges: Cases and Exercises.* C. H. Lovelock and C. B. Weinberg, eds. New York: McGraw-Hill.

Rasky, L. 1993. "Consumers and Compact Fluorescents." *Home Energy* 10(6):11-13.

Vorsatz, Diana. 1996. *Exploring U.S. Residential and Commercial Electricity Potentials: Analysis of the Lighting Sector.* Doctoral Dissertation Thesis, University of California, Los Angeles.

Weiner, J., and C. J. Campbell. 1992. *Perceptions of Compact Fluorescent Lamps in the Residential Market.* Prepared by Macro Consulting for the Electric Power Research Institute. EPRI-TR-100734. July 1992.

Lighting Policy, Innovative Efficiency Programs, and Market Transformation

Atkinson, Barbara, James E. McMahon, and Steve Nadel. 1995. "U.S. Lighting Standards: A Review of Federal and State Lighting Efficiency Regulations." *Light & Engineering* 3(1).

Atkinson, Barbara, James E. McMahon, Evan Mills, Peter Chan, Terry Chan, Joseph H. Eto, Judith D. Jennings, Jonathan G. Koomey, Kenny W. Lo, Matthew Lecar, Lynn Price, Francis Rubinstein, Osman Sezgen, and Tom Wenzel. 1992. *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings.* Lawrence Berkeley National Laboratory. LBL-31469. December.

Atkinson, Barbara, James E. McMahon, Terrence Logee, Carol Jones, and Joanne Lindsley. 1995.*U.S. Lighting Regulations: 1995 Update* in Proceedings of the Right Light Three Conference, Newcastle Upon Tyne, England.

Bonneville Power Administration (BPA). 1995. *Market Transformation Guide.* Portland, OR: BPA.

Brown, Richard, and Barbara Atkinson. 1994. *Incandescent Reflector Lamp Energy Efficiency Standard Analysis: Draft Report.* Berkeley, CA: Lawrence Berkeley National Laboratory. Draft LBL-36223. September.

California Energy Commission (CEC). 1995. *Energy Efficiency Standards for Residential and Nonresidential Buildings.* Sacramento, CA: CEC. Report No. P400-95-001. July.

Calwell, Chris, Chris Granda, Charlie Stephens, and My Ton. 1996. *Energy Efficient Residential Luminaires: Technologies and Strategies for Market Transformation, Final Report.* Washington, DC: U.S. Environmental Protection Agency. Prepared for the Natural Resources Defense Council. May 13.

Conway, Kathryn. 1995. "Procuring Energy Efficient Technologies: A Review of Works by Hans Westling." *Energy Services Journal* 1(2): 159-163.

Energy-Efficient Procurement Collaborative Inc. 1996. *Data Sources Directory for Purchasing Officials: Energy-Efficient and Environmentally Preferred Products*. Albany, NY: New York State Energy Research and Development Authority. July.

Eto, Joseph, and Eric Hirst. 1996. " What Kind of Future for Energy Efficiency?" *The Electricity Journal* June: 76-82.

Eto, Joseph, Edward Vine, Leslie Shown, Richard Sonnenblick, and Chris Payne. 1996. "The Total Cost and Measured Performance of Utility-Sponsored Energy Efficiency Programs." *The Energy Journal* 17(1): 31-51.

Eto, Joseph, Suzie Kito, Leslie Shown, and Richard Sonnenblick. 1995. *Where Did the Money Go? The Cost and Performance of the Largest Commercial Sector DSM Programs*. Berkeley, CA: Lawrence Berkeley National Laboratory. Report No. LBL-38201. December.

Feldman, Shel. 1994. *Market Transformation: Hot Topic or Hot Air?* In Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, Asilomar, CA, pp. 8-37-8.47.

Geller, H. S., and P. M. Miller. 1988. *1988 Lighting Ballast Efficiency Standards: Analysis of Electricity and Economic Savings*. Washington, DC: American Council for an Energy-Efficient Economy.

Geller, Howard, and Steve Nadel. 1994. *Market Transformation Strategies to Promote End-Use Efficiency*. Washington, DC: American Council for an Energy-Efficient Economy.

Gordon, Fred, and Les Tumidaj. 1995. *Opportunities for Market Transformation for Commercial Lighting Remodeling*. Portland, OR: Pacific Energy Associates, Inc.

Harrigan, Merrilee. 1994. " Can We Transform the Market Without Transforming the Customer?" *Home Energy* January/February: 17-23.

Hastie, Steve, et al. 1996. *Market Transformation In a Changing Utility Environment*. Bala Cynwyd, PA: Synergic Resources Corporation.

Heschong Mahone Group. 1997. *Lighting Efficiency Technology Report: Volume IV, Recommendations Report*. Prepared for California Energy Commission, Sacramento. Fair Oaks, CA: Heschong Mahone Group. CEC Contract #400-95-012. May 30.

Johnson, Francis, Aimee McKane, and Jeffrey Harris. 1996. *Development of Federal Energy Efficiency Product Recommendations* in 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 2. Washington, DC: American Council for an Energy Efficiency Economy.

Koomey, J.G., A. H. Sanstad, and L. J. Shown. 1995. *Magnetic Fluorescent Ballasts: Market Data, Market Imperfections, and Policy Success*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBL-37702. December.

McKane, Aimee, and Jeffrey Harris. 1996. *Changing Government Purchasing Practices: Promoting Energy Efficiency on a Budget* in the Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 5. Washington, DC: American Council for an Energy Efficiency Economy.

Meyers, Edward, Stephen Hastie, and Grace Hu. 1997. " The Next Steps for Market Transformation." The Electricity Journal 10(4): 34-41.

Mills, Evan. 1993. " Efficient Lighting Programs in Europe: Cost Effectiveness, Consumer Response, and Market Dynamics." *Energy* 18(2): 131-144.

National Lighting Collaborative. 1996. *What is LER?: Announcing the New Luminaire Energy Information Program.* Rosslyn, VA: National Lighting Collaborative. July.

Office of Technology Assessment (OTA). 1992. *Building Energy Efficiency.* Washington, DC: U.S. Government Printing Office.

Pacific Energy Associates Inc. 1996. *A Market Transformation Study for the Residential Lighting Market.* Portland, OR: Pacific Energy Associates, Inc.

The Results Center. 1995. *Southern California Edison: CFB & CFL Manufacturers' Rebates.* Publication no. 113. Aspen, CO: IRT Environment, Inc.

The Results Center. 1995. *Super Efficient Refrigerator Program.* Publication no. 106. Aspen, CO: IRT Environment, Inc.

U.S. Environmental Protection Agency (EPA). 1997. *Building on Our Success: Green Lights and ENERGY STAR Buildings 1996 Year in Review.* Washington, DC: EPA. EPA 430-R-97-002. May.

U.S. House of Representatives. 1992. *Energy Policy Act of 1992.* Washington DC: U.S. Government Printing Office.

Vorsatz, Diana. 1996. *Exploring U.S. Residential and Commercial Electricity Potentials: Analysis of the Lighting Sector.* Doctoral Dissertation Thesis, University of California, Los Angeles.

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098