# Lighting energy consumption trends and conservation opportunities in U.S. buildings

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**KEYWORDS**

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**ABSTRACT**

Electric lighting of buildings in the United States consumes nearly 20% of the nation's primary electricity and is second only in magnitude to heating, ventilation and air conditioning systems. This installed lighting base is generally inefficient and is characterized by relatively low performance especially when compared to other building systems. While substantial opportunities for improving overall lighting system efficiency exist, the pathway to achievement of this goal is less clear. Lighting research and development conducted by the US Department of Energy's (DOE), Office of Energy Efficiency and Renewable Energy's (EERE), Office of Building Technology, State and Community (BTS) addresses this national issue and aggressively pursues a number of broad research areas that promise to yield significant increases in overall lighting system efficiency.

Implementation of a successful program in lighting energy conservation depends upon a detailed assessment of energy consumption trends by lighting technology. The results of several years of research are presented that describe electricity consumption by market sector, application and lamp type. Following this lighting market assessment and identified energy conservation opportunities, an overview of the DOE's ongoing lighting research and development (LR&D) program portfolio linked to the market assessments is provided. Individual program contributions toward achieving ambitious lighting energy conservation goals are described. The BTS portfolio includes research in three broad areas: (1) lighting source research, (2) electronics, fixtures and controls and (3) human factors. An overview of each technical objective is provided, as well as a timeline for achieving specific energy conservation goals.

## INTRODUCTION

The mission of the United States Department of Energy's (DOE) Office of Building Technology, State and Community (BTS) is to work in partnership with industry and government to develop, promote and integrate energy technologies and practices to make buildings more efficient and affordable, and communities more livable. Worldwide, the buildings in which we live and work have changed in many important ways over the years and will continue to change as new, energy efficient technologies become available. Within BTS, an Office of Building Research and Standards (BRS) was formed by the DOE to manage and facilitate these changes and serve as a catalyst for the development of new technologies for the buildings sector.

For over twelve years, BRS has supported a program in Lighting Research and Development (LR&D). The mission of this program is to develop viable technologies that have the technical potential to conserve 50% of lighting consumption by 2010. Like most companion BRS programs, the LR&D program partners and leverages the BRS investment with industry, utilities, universities, and re-

**Figure 1 – Total US Energy Consumption of Electricity 2000, PEC (BTS, 2001)**

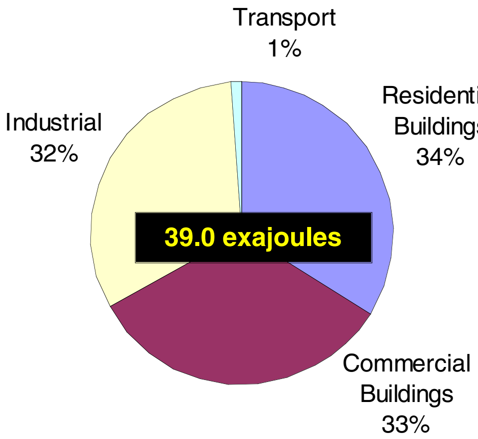
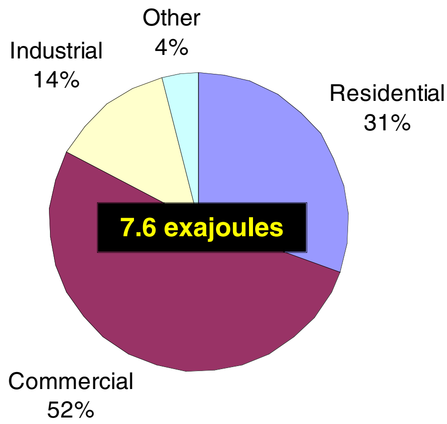



**Figure 2 –Energy Consumption for Lighting by Sector 2000, PEC (DOE, 2002)**




search institutions to help create new, energy-efficient lighting solutions.

The rationale for the LR&D program is clear. In the United States, total energy consumption in 2000 was approximately 103.9 exajoules (EIA, 2000). Figure 1 shows the electricity portion of this energy consumption - more than a third of the total energy consumption in the US (BTS, 2001). This energy consumed in buildings powers – among other things – the lights in our homes, offices and factories. Across all sectors, the DOE estimates that the national primary energy consumption dedicated to lighting our homes, offices and other metered applications around the US is approximately 7.6 exajoules – or nearly 20% of the total electricity consumed in all US buildings (DOE, 2002).

Figure 2 suggests that the lion's share of energy consumption for lighting is in the Commercial sector (DOE, 2002). Indeed, this is one of the principle markets that the LR&D program has targeted to develop more efficient technologies. This is especially important given what happened in California last year, as lighting is an important contributor to peak electricity demand and contributes to a building's internal heat load and subsequent air-conditioning requirements.

Across four sectors, the DOE has estimated energy consumption by the three main electric lighting technologies. In Figure 3, the red areas correspond to energy consumed by incandescent lamps, blue corresponds to fluorescent sources, and silver to high intensity discharge (HID) lamps. The bar chart on the left illustrates the magnitude of energy consumption by lighting technology. The bar chart on the right shows the annual lumen service provided, again by technology and sector.

In Figure 3, the end-use energy consumption chart on the left shows that fluorescent sources in the commercial sector are the single largest energy-consuming segment in the U.S., slightly higher than residential incandescent. However, across all sectors, incandescent is the leading energy consumer in the U.S. with nearly 300 terawatt-hours per year (TWh/yr) consumption. Fluorescent lighting is second with about 270 TWh/yr and HID is third with approximately 90 TWh/yr (DOE, 2002).

The annual lumen service chart on the right estimates the quantity of light produced by each of the major technologies in the various sectors. The units in this chart are teralumen hours per year (Tlm-hr/yr), a measure of the annual lighting service. Teralumen (10E+12) hours is an infrequently used but highly descriptive measure of the number of lumen hours delivered by a light source in one year. Comparing the two charts in Figure 3, it becomes clear that the incandescent light production per unit energy consumption is considerably lower than that of fluorescent or HID.

Findings such as these enable the US Department of Energy to garner a better understanding of the nature of the installed lighting technologies, their energy consumption and what segments of the market they are servicing. The following section discusses in more detail some of the findings of the US Market Characterization, which has completed its first phase.

## ASSESSMENT OF US LIGHTING MARKET

The US Department of Energy initiated a Lighting Market Characterization Study to collect and present an inventory of lighting technologies installed in the United States. This study provides essential information for planning and running an effective program in stationary light research and development. The final report of the Assessment will be made available on the DOE website.

The study classified the lighting market into four sectors made up of three building categories (residential, commercial and industrial) and one category that contains major stationary lighting applications (e.g., roadway lighting) that are not related to buildings ("other" stationary lighting). In terms of sources, the study reviewed the four light sources (incandescent, fluorescent, high intensity discharge and solid state). Within each, the market analysis evaluated subgroups of commonly available products, as listed in Table 1 (DOE 2002).

**Figure 3.**

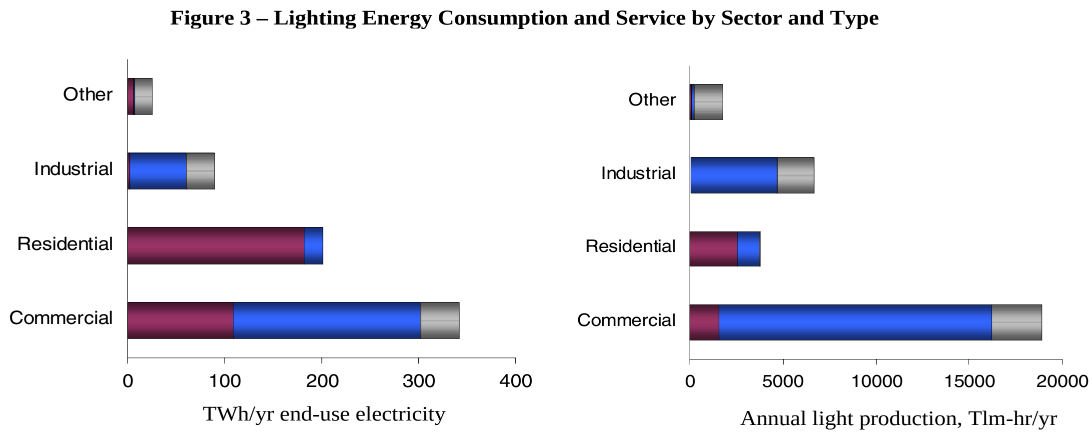



**Table 1. Lamp and Source Classification in the US Lighting Market Characterization**

| Lamps | |
|---|---|
| **Fluorescent** | **Incandescent** |
| T5 | Standard |
| T8 – less than 4’ | Standard – integral reflector |
| T8 – 4’ | Halogen |
| T8 – greater than 4’ | Halogen – integral reflector |
| T8 – U-bent | Halogen – integral reflector – low voltage |
| T12 – less than 4’ | Low wattage (less than 25W) |
| T12 – 4’ | Miscellaneous incandescent[2] |
| T12 – greater than 4’ | **High Intensity Discharge** |
| T12 – U-bent | Mercury vapor |
| Compact – Pin-base | Metal halide |
| Compact – Screw base | High pressure sodium |
| Compact – Pin-base – integral reflector | Low pressure sodium[1] |
| Compact – Screw base – integral reflector | **Solid State** |
| Circline | Light Emitting Diode |
| Miscellaneous fluorescent[2] | Electroluminescent |

*1 Low pressure sodium is a discharge lamp, but is not high intensity. It is included in this category for convenience of presentation.*
*2 "Miscellaneous" means that the light source cannot be categorized elsewhere either because it is of a different type (e.g. T4 fluorescent) or because it is undesignated in the database.*

Table 2 summarizes the most recent data available (2001) estimating lighting energy consumption for the four lighting market sectors in terms of both delivered (end-use) and primary (source) energy (DOE, 2002). The primary energy term is the total energy required to supply the required energy and includes generation and transmission losses.[1] Total lighting consumption is estimated to be 659 TWh, or 2.37 exajoules (7.61 exajoules primary). Commercial buildings were the largest share of lighting energy use (52 percent), followed by residential (31 percent), Industrial (14 percent) and other stationary (4 percent)

Table 3 compares energy use data for the three buildings sectors (not including Other stationary) based on illuminance[2] and lighting energy intensity (DOE, 2002). Installed wattage per square foot remains generally uniform across the sectors, however lighting energy intensities in the commercial and industrial sectors exceed residential by a factor of 4 to 5. Efficacies are generally higher in the commercial and industrial sectors, approximately 3 times higher than residential. Hours of operation in the commercial and industrial sectors are considerably higher than resi-

1. The factor used to convert the site-use electrical energy to primary energy consumed at the generating power plant is 10,958 BTU/kWh, from the BTS Core Databook 2001 for the year 2000. Please note that the conversion efficiency varies from year to year, depending on the mix of electrical generating power plants used in a given year.

2. For calculation purposes, we assumed that half of all light produced reaches the work plane (Coefficient of Utilization (CU) equals 0.5, which is a standard assumption). Applying a CU of 0.5 yields illuminance levels corresponding to IESNA categories C-D in the residential sector and D-E in the industrial and commercial sectors. These agree with the IESNA recommendations for the bulk of tasks carried on in those sectors, lending support to our wattage and efficacy estimates.

**Table 2. US National Lighting Energy Use Summary**

| Building Use | Electricity Use per Building (kWh/yr) | Population | Delivered Energy (TWh/yr) | Delivered Energy (exajoules/yr) | Primary Energy (exajoules) | Percent of Total |
|---|---|---|---|---|---|---|
| Residential | 1,988 | 101,481,171 | 202 | 0.73 | 2.33 | 31% |
| Commercial | 74,704 | 4,578,748 | 342 | 1.23 | 3.95 | 52% |
| Industrial | 359,980 | 247,199 | 89 | 0.32 | 1.03 | 14% |
| Other stationary | n/a | n/a | 26 | 0.09 | 0.30 | 4% |
| Totals | | | 659 | 2.37 | 7.61 | 100% |

**Table 3. Lighting Usage per square foot**

| Building Use | Installed Wattage (W/sq meter) | Mean Efficacy (lm/W) | Illuminance (fc) (CU=0.5) | Operating Hours (hr/day) | Energy Intensity (kWh/yr/m_) |
|---|---|---|---|---|---|
| Residential | 15.1 | 19 | 18 | 2.0 | 15.1 |
| Commercial | 17.9 | 55 | 45 | 9.8 | 62.4 |
| Industrial | 14.0 | 75 | 48 | 13.9 | 71.0 |

**Table 4. Distribution of Lighting Electricity Consumed by building by lamp type**

| Technologies | Residential (%) | Commercial (%) | Industrial (%) | Other (%) | All Sectors (%) | Exajoules PEC | Technology (%) |
|---|---|---|---|---|---|---|---|
| Incandescent | 90% | 32% | 2% | 22% | 46% | 3.5 | 100% |
| Standard - General Service | 76% | 18% | 1% | 17% | 34% | 2.5 | 74% |
| Standard - Reflector | 11% | 8% | 1% | 3% | 8% | 0.6 | 17% |
| Halogen - General Service | 1% | - | - | - | - | - | 1% |
| Halogen - Reflector | 1% | 3% | - | 2% | 2% | 0.2 | 5% |
| Halogen - refl. - low volt | - | 2% | - | - | 1% | 0.1 | 2% |
| Low wattage (less than 25W) | - | 1% | 1% | - | 1% | - | 1% |
| Miscellaneous incandescent | - | - | - | - | - | - | - |
| Fluorescent | 10% | 56% | 66% | 7% | 43% | 3.2 | 100% |
| T5 | - | - | - | - | - | - | - |
| T8 – less than 4’ | - | 1% | 1% | - | - | - | 1% |
| T8 – 4’ | - | 12% | 19% | 1% | 9% | 0.7 | 21% |
| T8 – More than 4’ | - | - | - | - | - | - | - |
| T8 – U-bent | - | - | - | - | - | - | 1% |
| T12 – less than 4’ | - | 1% | - | - | - | - | 1% |
| T12 – 4’ | - | 28% | 15% | 2% | 17% | 1.3 | 40% |
| T12 – More than 4’ | - | 10% | 30% | 3% | 10% | 0.7 | 22% |
| T12 – U-bent | - | 1% | - | - | 1% | 0.1 | 2% |
| Compact – Plug-in | - | 2% | - | - | 1% | 0.1 | 2% |
| Compact – Screw-in | 1% | 1% | - | - | 1% | - | 1% |
| Compact – Plug-in – reflr | - | - | - | - | - | - | - |
| Compact – Screw-in – reflr | - | - | - | - | - | - | - |
| Circline | - | 1% | - | - | - | - | 1% |
| Miscellaneous fluorescent | 9% | - | - | 1% | 3% | 0.2 | 7% |
| High Intensity Discharge | - | 12% | 31% | 71% | 11% | 1.0 | 100% |
| Mercury vapor | - | 2% | 3% | 18% | 1% | 0.2 | 16% |
| Metal halide | - | 9% | 24% | 14% | 8% | 0.6 | 62% |
| High pressure sodium | - | 1% | 5% | 34% | 1% | 0.2 | 21% |
| Low pressure sodium | - | - | - | 5% | - | - | 2% |
| Solid State | - | - | - | - | - | - | - |
| LED | - | - | - | - | - | - | - |
| Electroluminescent | - | - | - | - | - | - | - |
| Total | 100 | 100 | 100 | 100 | 100 | 7.61 | n/a |

dential – a factor of 5 to 7 greater – resulting in the calculated higher energy intensities.

Table 4 provides the contribution of each lamp type to the lighting electricity consumption in each building sector (DOE, 2002). In the Residential sector, incandescent light sources were responsible for 90% of the electricity consumption. In the Commercial and Industrial sectors, fluorescent lighting was the dominant energy consumer.

**Table 5. Distribution of Lumens delivered by building sector by lamp type**

| Technologies | Residential (%) | Commercial (%) | Industrial (%) | Other (%) | All Sectors (%) | All Sectors (Tlmhr/yr)[1] |
|---|---|---|---|---|---|---|
| Incandescent | 69% | 8% | - | 5% | 14% | 4,285 |
| Standard - General Service | 60% | 5% | - | 4% | 11% | 3,373 |
| Standard - Reflector | 5% | 1% | - | - | 1% | 453 |
| Halogen - General Service | 1% | - | - | - | - | 54 |
| Halogen - Reflector | 1% | 1% | - | 1% | 1% | 303 |
| Halogen - refl. - low volt | - | - | - | - | - | 68 |
| Low wattage (less than 25W) | - | - | - | - | - | 34 |
| Miscellaneous incandescent | - | - | - | - | - | - |
| Fluorescent | 31% | 78% | 70% | 8% | 66% | 20,636 |
| T5 | - | - | - | - | - | 11 |
| T8 – less than 4’ | - | 1% | 1% | - | 1% | 208 |
| T8 – 4’ | - | 18% | 22% | 1% | 16% | 4,836 |
| T8 – More than 4’ | - | - | - | - | - | 25 |
| T8 – U-bent | - | - | - | - | - | 118 |
| T12 – less than 4’ | - | 1% | - | - | 1% | 185 |
| T12 – 4’ | - | 38% | 15% | 2% | 26% | 8,155 |
| T12 – More than 4’ | - | 14% | 32% | 3% | 16% | 4,853 |
| T12 – U-bent | - | 2% | - | - | 1% | 368 |
| Compact – Plug-in | - | 2% | - | - | 1% | 357 |
| Compact – Screw-in | 1% | 1% | - | - | 1% | 204 |
| Compact – Plug-in – reflr | - | - | - | - | - | - |
| Compact – Screw-in – reflr | - | - | - | - | - | 17 |
| Circline | - | 1% | - | - | - | 155 |
| Miscellaneous fluorescent | 29% | - | - | 1% | 4% | 1,144 |
| High Intensity Discharge | 1% | 14% | 29% | 87% | 20% | 6,199 |
| Mercury vapor | 1% | 1% | 2% | 13% | 2% | 601 |
| Metal halide | - | 10% | 21% | 10% | 11% | 3,451 |
| High pressure sodium | - | 3% | 7% | 54% | 6% | 1,939 |
| Low pressure sodium | - | - | - | 11% | 1% | 208 |
| Solid State | - | - | - | - | - | 1 |
| LED | - | - | - | - | - | 1 |
| Electroluminescent | - | - | - | - | - | 0 |
| Total | 100% | 100% | 100% | 100% | 100% | 31,122 |

*[1] Tlmhr/yr - Teralumen (10E+12) hours is a descriptive measure of the number of lumen hours delivered by a light source in one year.*

HID light sources were found to consume the most electricity (over 70%) in the Other Stationary sector.

Table 5 provides a distribution of lighting service (lumens delivered) over a one-year period for each of the categories by lamp type (DOE, 2002). Within each sector, this table identifies the light sources providing the majority of light service. It should be noted that some sectors may register as zero in this table, however this does not mean the light source is not in service, rather it could be a reflection of the light source providing less than one-half of one percent of lumens in that sector.

Comparing the All Sectors (%) columns in Table 4 and Table 5, it becomes clear which light sources are more efficacious. In Table 4, incandescent sources consume 46% of the electricity used for lighting in the US, while only producing 14% of its lumens. Contrasting with that, fluorescent sources consume slightly less energy (43%), while providing more than four times the light (66%). The far right column in Table 5 presents a measure of the annual light service provided by that source in the inventory year. The units in this column are teralumen-hours per year.

## LIGHTING RESEARCH AND DEVELOPMENT PORTFOLIO OVERVIEW

The Department of Energy’s LR&D program goal is to develop technologies that if successfully deployed into the marketplace, could reduce lighting energy use by 50% by 2010 through the development of a new generation of advanced lighting equipment and design. The program’s activities are focused in three areas: (1) advanced light sources; (2) lighting fixtures, controls and distribution systems; and (3) human factors and vision science. The DOE also strives to coordinate its lighting research efforts with other public and private efforts at the local, state and national levels to avoid duplication, but more importantly, to leverage the relative strengths and support of all participants. Finally, the DOE is also developing its LR&D program in consultation with the lighting industry, through its lighting technology roadmap, Vision 2020.

### U.S. Lighting Market Characterization Priority Areas

Having completed the US Lighting Market Characterization national inventory and energy consumption estimate, the Department is reviewing the results and identifying priority areas. This includes a review of lighting technologies, energy savings potentials, and other opportunities for energy savings.

Residential electricity consumption for lighting is primarily (90%) incandescent. For the commercial and industrial sectors, fluorescent dominates, contributing 56% and 66% respectively to electricity demand. For the "other" stationary category, high intensity discharge lighting dominates, constituting 71% of the electricity used for lighting. Due to the high level of market penetration of these technologies, targeting lighting research to improve the energy performance of these technologies has the potential for the greatest energy savings impact.

From a lamp technology standpoint, further review of Tables 4 and 5 generate several observations about energy consumption and technology:

- For incandescent sources, general service lamps account for 74% of the electricity consumed across all building sectors. The second highest incandescent energy user is the standard-reflector lamp, estimated at 17% of the electricity consumed by incandescent sources.
- For fluorescents, four-foot linear lamps account for 61% (T-8 and T-12 together). The second highest energy consumer in the fluorescent category includes the greater than four foot tubes, accounting for 22%. Of these, most are used in industrial building installations.
- For high intensity discharge lamps, metal halide is the primary consumer, constituting 62% of energy consumed by HID sources in the U.S. This is followed by high pressure sodium at 21%, and mercury vapor at 16%. HID sources, while both used in commercial and industrial applications, consume over 70% of the energy in the "other" stationary sources, delivering 87% of the lumens for that sector.

Findings such as these provide guidance to the DOE's LR&D program, and help to identify areas where new technologies should be developed, and where incremental improvements in existing technologies should be made. This study provides information for sound decision-making and resource allocation in the DOE LR&D program.

### BTS Lighting R&D Portfolio Areas

In 1999, industry representatives and the DOE completed a lighting roadmap called Vision 2020. This document provides guidance to the DOE and the lighting industry towards their common goal of improving lighting technologies. For the DOE, energy efficiency is the primary driver; for industry, other important criteria may enter the picture. Using this roadmap, the LR&D program focuses on three areas:

- Advanced Light Sources and Electronics
- Luminaries, Controls, Ballasts and Distribution Systems
- Human Factors and Vision Science

#### Light Sources and Electronics

Lighting energy consumption can be reduced significantly by increasing the efficiency of light production at the source. To increase the installed base of lamp efficiency or source efficacy, the LR&D program seeks a better understanding of the basic science of light production and of the physical processes that limit electric lighting energy efficiency. Projects include basic studies and engineering improvements in light source types, materials, processes, components, electronics, and systems. Research priority areas include: electrodeless fluorescent lamps; molecular radiators; multi-photon or quantum splitting phosphors; high color rendering and high efficiency phosphors; novel phosphor systems; integration of advanced electronics; and solid state light sources.

#### Luminaires, Controls, Ballasts and Distribution Systems

Delivering and controlling light efficiently to facilitate the performance of tasks dependant upon visual information is the role of luminaires in general illumination applications. However, the installed base (in U.S. commercial buildings) of luminaires, controls, ballasts and distribution systems is generally outdated and inefficient. Only recently have reflectors begun to reach high optical performance levels but other physical factors such as dirt, UV degradation of surfaces, etc. continue to adversely affect the performance of luminaires over time. Numerous studies conducted by the DOE and others have suggested that maximizing the use of day lighting in buildings can conserve nearly half the energy currently consumed for electric lighting representing one of the most significant opportunities for wholesale conservation of US building energy consumption. With approximately 60% of the commercial and industrial lighting energy budgets consumed by fluorescent lighting, the opportunity to significantly reduce energy use in his segment is clear. Since every fluorescent lamp requires a ballast to function, the role the ballast may play in reducing energy consumption is correspondingly clear. Moreover, the opportunity to network ballasts together into an advanced and efficient lighting system complete with integrated controls and performance-oriented intelligence is now penetrating the marketplace. Continuing research priority areas include: materials and coatings; light collection, management, and distribution; and advanced lighting controls that integrate building systems and power management functions.

#### Human Factors

Energy conservation in general illumination applications may also arise from optimizing the amount and type of delivered light for the purposes required. However, optimizing delivered light is difficult since lighting impacts the way users interact with their environment in many complicated and incompletely understood ways. The DOE is supporting projects that address opportunities to reduce lighting energy requirements by taking advantage of this complicated relationship to achieve better vision, reduced glare, increased comfort, or improved task performance, etc. with simultaneous reductions in lighting power. Current priority areas in include research in basic and applied vision science and light metrology.

## CONCLUSION

The DOE continues to be actively engaged in the research and development of energy efficient technologies including lighting in US buildings for decades. Through this interaction with industry, academia and our national laboratories, the LR&D team has amassed considerable expertise. Studies such as the U.S. Lighting Market Characterization have provided the information to guide the DOE's investment strategy towards projects that meet the portfolio needs of the LR&D program and the American public.

The energy consumption trends and conservation opportunities described here have considerable utility to managers of research portfolios but are also of great value to anyone interested in managing electric lighting loads in buildings or who may be considering investing in energy conserving technologies. The partners of the LR&D program know that energy efficient priorities create demand for better lighting systems, and by aggressively seeking new and efficient lighting solutions, everyone benefits.

## REFERENCES

(BTS, 2001) *BTS Core Databook 2001*; U.S. Department of Energy, Washington DC. The percentages are from Table 1.1.3, page 1-1 and are estimates of the 2000 breakdown.

(DOE, 2002) U.S. *Lighting Market Characterization Volume I – National Lighting Inventory and Energy Consumption Estimate, internal draft.* Prepared for the US Department of Energy by Arthur D. Little and XENERGY Inc., January 20, 2002. Primary energy for lighting in the US: 7.23 quads (7.63 exajoules).

(EIA, 2000) Energy Information Administration, Annual Energy Review 2000. *Preliminary estimate of energy consumption for the year 2000: 98.5 quadrillion BTUs*, August 2001, Washington DC. <www.eia.doe.gov>