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**A Technology Assessment of Light Emitting Diode (LED)
Solid-State Lighting for General Illumination**

Amanda Slocum

Working Paper Series

Working Paper # 05-04
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Abstract

Innovative technologies can play a major role in curbing emissions of GHG that contribute to global climate change. Solid-state lighting (SSL) is one recent example of an innovative technology, which has received considerable attention in the last several years. This emerging lighting technology has tremendous potential to become significantly more energy-efficient than lighting technologies that are currently used, such as incandescent and fluorescent lighting.

The purpose of this report is to provide an overview on SSL technology for the U.S. Environmental Protection Agency (EPA) and to serve as a reference for future work in this technology area. This report was prepared using the methodological approach of a "technology assessment". An overview of SSL is provided, and the drivers and barriers to its use as general illumination lighting are discussed. The report also highlights both potential environmental benefits and negative impacts, which might accompany the development and use of this emerging technology.

Keywords

Solid-state lighting; LEDs; energy-efficiency; technology assessment

Subject Area Classification

Energy (#33); Climate Change (#45)

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ACRONYMS & ABBREVIATIONS

ATP	Advanced Technology Program (NIST)
CCT	Color correlated temperature
CFL	Compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage
CO_2	Carbon dioxide
CRI	Color rendering index
DARPA	Defense Advanced Research Projects Agency (DOD)
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy (DOE)
EIA	Energy Information Administration (DOE)
EH&S	Environmental health and safety
EPA	Environmental Protection Agency
GaAs	Gallium Arsenic
GHG	Greenhouse gases
HB LED	High-brightness light emitting diodes
HID	High-intensity discharge
HPS	High-pressure sodium
IESNA	Illuminating Engineering Society of North America
InAs	Indium Arsenic
InP	Indium Phosphide
IRIS	Integrated Risk Information System
LCA	Life cycle assessment
LED	Light-emitting diodes
LED-SSL	Light-emitting diode solid-state lighting
LRC	Lighting Research Center
MBE	Molecular beam epitaxy
MMTCE	Million metric tons of carbon equivalent
MOCVD	Metal organic chemical vapor deposition
MSDS	Materials Safety Data Sheets
NAICS	North American Industrial Classification System
NEMS	National Energy Modeling System
NIST	National Institute of Standards and Technology
OEM	Original equipment manufacture
OIDA	Optoelectronics Industry Development Association
OLED	Organic light emitting diodes
MV	Mercury vapor
MH	Metal halide
RGB	Red-green-blue
SSL	Solid-state lighting
USGS	United States Geological Survey
YAG	Yttrium aluminum garnet

I. INTRODUCTION

Global climate change is one of the most serious environmental problems facing this generation. Average global temperatures have risen by approximately 0.6°C (1.1°F) in the last century, and this trend is expected to continue and even accelerate over the 21st century (IPCC, 2001). As the warming continues, the effects of climate change are likely to have adverse impacts on environmental and socio-economic systems throughout the world, although the extent of these impacts is highly sensitive upon the rate and the magnitude of the climate change over the next century (IPCC, 2001).

There is growing consensus in the scientific community that the warming trend is a result of rising atmospheric concentrations of greenhouse gases (GHGs) (NRC, 2001). These GHG are accumulating in the atmosphere as a result of human, or anthropogenic, activities such as fossil-fuel combustion. Currently in the United States, fossil fuel energy sources (including coal, natural gas, and oil) are used to generate approximately 70% of U.S. electricity (EIA, 2004). When fossil fuels are burned to extract energy, carbon dioxide (CO_2), one of the primary GHG is released into the atmosphere. Atmospheric concentration levels of CO_2 have been extracted from ice core samples taken in Antarctica and Greenland. These samples show that CO_2 concentration levels today are higher than those of pre-industrial times, and have followed an upward trend over the last 43 years. A 2001 report from the National Academies conclusively attributed the rising concentration of CO_2 to anthropogenic activities (NRC, 2001). Of these anthropogenic activities, fossil fuel burning has been, and is projected to be, the most significant source of CO_2 emissions.

Innovative technologies can play a major role in curbing emissions of GHG that contribute to global climate change. Solid-state lighting (SSL) is one recent example of an innovative technology, which has received considerable attention in the last several years. This emerging lighting technology has tremendous potential to become significantly more energy-efficient than lighting technologies that are currently used, such as incandescent and fluorescent lighting.

Currently in the U.S., approximately 22% of the electricity generated is used for lighting. Put into a broader context, the DOE estimates that 8.3% of U.S. primary energy consumption goes to lighting (DOE, 2002). Solid-state lighting has the potential to significantly reduce the electricity needed for lighting. Estimates for lighting energy savings potential have been as optimistic as a 50% reduction by 2025, which would in turn decrease total electricity consumption by about 10% (Tsao, 2004). In the U.S., a recent analysis using a SSL market penetration model found that by 2025, SSL in general illumination applications could reduce the amount of electricity needed for lighting by 33% (DOE, 2003b).

Policies that promote technological innovation are an important strategy for reducing GHG emissions. Well-designed policies to develop and diffuse new environmentally benign technologies have the potential to play an important role in reducing the emission of GHG and mitigating the impacts of climate change. These technological advancements can be realized by (1) increasing the efficiency of technologies in order to reduce the energy demanded, (2) substituting old high-carbon energy technologies with low- or zero-carbon technologies, (3) capturing the carbon either before or after it enters the atmosphere, and (4) developing technology which reduces the emissions of GHG other than CO_2 (Alic, Mowery, & Rubin, 2003).

Solid-state lighting is an emerging energy-efficient technology, with high potential to fulfill the first of these four technology pathways identified above. Research and development is underway worldwide to develop SSL suitable for general illumination. In the U.S., the Department of Energy (DOE) and industry have recognized this opportunity and are pushing for a national initiative to accelerate the development of this promising technology (Haitz, Kish, Tsao, & Nelson, 2000). Solid-state lighting is eventually expected to become approximately twice as efficient as fluorescent lighting, and up to ten times as efficient at incandescent lighting.

The purpose of this report is to provide an overview on SSL technology for the U.S. Environmental Protection Agency (EPA) and to serve as a reference for future work in this technology area. It should be noted that the term “solid-state lighting” encompasses two distinct, yet both promising, technologies: organic light-emitting diodes (OLEDs) and inorganic light-emitting diode (LEDs). It is the latter of these technologies that this report is explicitly focused on, although both are expected to play important roles in future lighting applications. The scope of this report is predominantly limited to only LED-SSL technology; although some SSL energy estimates from the DOE that will be discussed have combined the potential of LED and OLED technology.

This report was prepared using the methodological approach of a "technology assessment" similar to those that were once performed by the now defunct, U.S. Office of Technology Assessment. While all efforts were made to be as comprehensive as possible, complete technology assessments traverse a wide terrain and only limited time was available to prepare the report. There is a considerable amount of literature available on LED-SSL, but none directly focused on the environmental impacts from a product life cycle perspective. Hence, special consideration was given to highlighting both potential environmental benefits and negative impacts, which might accompany the development and use of this emerging technology. The scope of the report is predominately limited to LED-SSL used within the U.S., although Section IV does describe work being done by a humanitarian organization, *Light Up the Work Foundation*, which is bringing LED-SSL technology to developing nations. The remainder of the report is structured as follows:

Section II provides an overview of lighting technologies that are currently used, including some basic information on how they work, their applications, and particular characteristics. The most current data available on the energy consumed by lighting is presented, broken down by lighting technology and market sector (residential, commercial, industrial and outdoor stationary).

Section III is an overview on LED-SSL technology including the history of the development of the underlying technology – lighting-emitting diodes (LEDs), the basic science of LEDs, and the materials and processes used to manufacture them. The focus will be on the newest generation of LEDs, the so-called high-bright LEDs (HB LEDS). These have already begun to penetrate and gain significant market share in a number of niche applications, and rapid pace technology development indicates that these niche applications will continue to grow. This section will provide an introduction to the exciting challenge of developing and deploying white LED-SSL in general illumination applications, a challenge dubbed by industry as the “holy grail”. Finally, the energy-savings estimates on the potential of LED-SSL in both niche and general illumination applications will be reviewed.

Section IV describes the major drivers that are propelling forward the development LED-SSL technology for general illumination. These drivers are grouped into the following six categories: environmental, performance and human interaction, safety, economic, energy, and potential technology spin-offs.

Section V will present an overview of technical, infrastructure-related, and market barriers which could hinder the development and adoption of LED-SSL for general illumination.

Section VI provides a high-level scoping assessment of potential life cycle impacts from this new technology. To date, most work has been concentrated on the environmental benefits to be gained from the expected energy-efficiency advantage of solid-state lighting. However, there has been little to no work holistically assessing the environmental issues during entire life cycle – from natural resource extraction through to final disposal.

Section VII focuses on the nexus between SSL and public policy. Current U.S. efforts as well as initiatives in other countries to develop this technology are reviewed. The role of the U.S. EPA in the development and adoption of LED-SSL is discussed in context of (1) the potential of LED-SSL to potentially provide substantial energy-efficiency savings thereby helping to mitigate global climate change and (2) the life-cycle implications of LED-SSL.

Section VIII contains concluding remarks and recommendations for future EPA research.

II. LIGHTING TECHNOLOGIES & ENERGY CONSUMPTION

Today, artificial lighting is an essential service in the modern world, providing the light people require for performing a wide variety of visual tasks. Solid-state lighting (SSL) has tremendous potential to become a revolutionary lighting technology by ushering in an entirely new lighting paradigm. One major benefit that is propelling this transition forward is the potential for significant energy savings from the development and adoption of highly efficient SSL. However, in addition to the energy-efficiency potential of SSL, there are a number of other attributes of lighting technologies that are important determinants for widespread market adoption. These include aesthetics (lamp design as well as the color of light emitted), purchasing convenience and distribution channels, ease of use, safety considerations, disposal requirements, maintenance requirements, and the initial capital cost.

In order to assess the energy efficiency potential of SSL, it is important to understand the structure of the current lighting market and key attributes that drive lighting technology purchasing decisions. This is by no means a simple task; the lighting market is a complex and diverse entity (DOE, 2002).[1] Furthermore, the amount of energy consumed by lighting (and hence the potential for greater energy conservation) also depends on a variety of other factors besides the technology that is used. For example, the lighting intensity level, the number of hours that the equipment is in use in a given time period, and the design of the lighting system are also important determinants in final lighting energy consumption (Atkinson et al., 1995).

The following section will first include a brief overview of the three main categories of lighting technologies that are currently used: incandescent, fluorescent and high-intensity discharge (HID). Next, the energy consumption of lighting, and its significance as an end-use consumer of energy in the U.S. will be discussed.

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[1] In this report, resource limitations inhibit an exhaustive overview of the lighting market, however the *Lighting Market Sourcebook* (1997) provides a much more in-depth look at lighting technologies, energy consumption, market structure, distribution channels, and policy issues (Vorsatz et al., 1997).

CONVENTIONAL LIGHTING TECHNOLOGIES

Today, a large and diverse portfolio of technologies is used to provide lighting service. These lighting technologies can be broadly classified into four main groups of light sources: incandescent, fluorescent, high-intensity discharge (HID), and most recently, SSL. Below are brief overviews of the four groups of lighting technologies.[2] Solid-state lighting is discussed in much greater detail in Section III of this report. Definitions of lighting terminology used throughout this report can be found in Appendix 2.

1. Incandescent

Invented in the late 1800s by Thomas Edison in America and simultaneously by Joseph Swan in England, today these lamps provide most of the light used by households. They are also widely used throughout commercial buildings (Vorsatz et al., 1997). Incandescent lamps are very inefficient because 90-95% of the emissions are in the infrared (thermal) rather than the visible range of the electromagnetic spectrum. Incandescent lamps today have efficiencies or "efficacies," ranging from 13-25 lumens per Watt (lm/W) (DOE, 2003b).[3] These lamps operate by passing electrical current through a metal filament, which heats the filament to the point of incandescence. Today, these metal filaments are most commonly made of tungsten. Recent technological advancements have shown that with further research, a nanotube filament composed of carbon nanotubes might one day be used as more energy-efficient filament for incandescent lamps (Wei, Zhu, & Wu, 2004). An author of the study, Bingquiq Wei, cited that more work needs to be done in this area, but thought that such bulbs could be available within three to five years.

[2] These four classifications of lighting technologies all include a number of different sub-classifications of lamp types. These sub-classifications are found in Appendix 1.
[3] "Efficacy" is the terminology used for the energy efficiency of lighting, and is calculated by dividing the quantity of light emitted from the lamp (in lumens) by the power input to the lamp (in watts).

Despite the current inefficiency of incandescent lamps, they provide several important advantages over the other light sources. These advantages include: an excellent color rendering index (CRI)[4] and warm color, their ability to be easily dimmed, inexpensiveness, small and lightweight, their ability to be used with inexpensive fixtures, and the simplicity of purchasing, installation, maintenance, and disposal (Atkinson et al., 1995). These lamps are the most prevalent in the residential sector, accounting for an estimated 86% of the lamps used by households and consuming 90% of the electricity used for household lighting (DOE, 2002). They are also widely used in the commercial sector, representing approximately 22% of the installed lamps and consuming 32% of the electricity used for lighting in the commercial sector (DOE, 2002).

2. Fluorescent

Fluorescent lamps were first produced in the U.S. in the late 1930s, and came into general use by the 1950s (Atkinson et al., 1995). Fluorescent lamps produce light by applying a high voltage across two electrodes, initiating an electric arc discharge that ionizes the evaporated mercury in the lamp. The ionized mercury emits mostly UV radiation, which strikes and excites the phosphorus coating on the tube causing fluorescence and producing visible light. These lamps must operate in conjunction with a ballast. The purpose of the ballast is to limit the incoming current to a certain value, and to provide the needed start-up and operating lamp voltages. The most common fluorescent lamps are tubular and four-feet in length. The efficacies of fluorescent lamps – including ballast losses – range between 60-90 lm/W (Atkinson et al., 1995). The efficacies of fluorescent lighting also depend on the type of ballast used: efficiencies are higher with electronic ballasts than with magnetic ballasts. A significantly smaller version of the fluorescent lamp – the compact fluorescent lamp (CFL) – was introduced

[4] The color rendering index (CRI) of a lamp is a measure of how surface colors appear when illuminated by the lamp, compared to the same surface color appears when it is illuminated by a reference light source of the same temperature.

in the early 1980s as a more energy-efficient and longer lasting alternative to incandescent lamps. These CFLs have efficacies of approximately 55 lm/W.

Fluorescent lamps are most commonly used in the commercial and industrial sectors. In the commercial sector they account for 77% of the installed lamps and consume 56% of the total electricity for lighting used in the commercial sector. In the industrial sector they account for 93% of the installed lamps and consume 67% of the electricity that goes to lighting (DOE, 2002). On the other hand, in the residential sector the use of fluorescent lighting is limited, and when it is used it is generally restricted to kitchens, bathrooms and utility areas (Vorsatz et al., 1997). Compact fluorescent lamps have been on the market since the 1980s but initially saw very slow adoption rates. In recent years CFLs have begun to gain greater market share within market of retail screw-based lamps, with national sales reaching 2.1% of this market by the end of 2001(Calwell, & Zugel, 2003).

3. High-Intensity Discharge

High-intensity discharge (HID) lamps operate similarly to fluorescent lamps in that they initiate an arc discharge though a mixture of gases, and they require a ballast to regulate their voltage and current. However, HID lamps differ from fluorescent light sources in that they operate at very high temperatures and pressures. The three primary types of HID lamps are mercury vapor (MV), metal halide (MH), and high-pressure sodium (HPS). These lamps are the most effective when used in applications with limited start-ups and shut-downs because of the time they require for starting, which can vary from 2-15 minutes depending on the lamp type and whether it starting (cold start) or restriking (hot start). Including ballast losses, the efficacies of these three HID technologies are: mercury vapor lamps (25-50 lm/W), metal halide lamps (46-100 lm/W), and high-pressure sodium (50-124 lm/W) (Atkinson et al., 1995). Generally HID lamps are used where the color of the light is not a high priority.

HID lamps are most widely used in the outdoor stationary sector, as well as in commercial and industrial sectors.[5] In the outdoor stationary sector, they account for 75% of lamp installations, and consume 87% of the electricity used for lighting in this sector (DOE, 2002). In the commercial and industrial sectors, HID lamps account for 2% and 5% of lamp installations. They consume 11% and 30%, respectively, of the electricity used for lighting in the commercial and industrial sectors (DOE, 2002).

4. Solid-State

Solid-state lighting is a relatively new and extremely promising emerging lighting technology, which uses either light-emitting diodes (LEDs) or organic light emitting diodes (OLEDs) as a light source. To date, LED technology is further advanced than OLED technology, and thus is expected to be the first to enter into the market for general illumination (Tsao, 2004). However both are expected to eventually play a role in the lighting market. The advantages of LED-SSL over more conventional lighting technologies include their low energy consumption, longer lifetime, ruggedness and durability, compactness, safety from a low operating current, fast "on" time, operability in low temperature applications, dimmability, easy installation, and directionality.

Many of these inherent advantages of LEDs over conventional lighting sources have already allowed them to penetrate into the market for niche application lighting. For instance, LEDs inherently produce monochromatic light and hence are a natural choice for indication applications such as traffic lights and exit signs, which require colored light. In these cases, the need to use an incandescent light coupled with a filter to convert white light to colored light (an inefficient process), is eliminated. Niche lighting applications in which the compactness, ruggedness, and longevity of LEDs provide a

[5] This "stationary outdoor" sector was used in the 2002 U.S. Lighting Market Characterization report commissioned by the Department of Energy. This sector includes lighting installations such as street lighting, airport runway systems, traffic signals and billboard lighting. Outdoor lighting from mobile sources such as automobiles is not included.

comparative advantage have also been penetrated by LEDs. Creating truly a white LED-SSL to be used as general illumination is the greatest challenge of all, but experts are optimistic that in time it will be accomplished. Currently the efficacy of most commercially available white LED-SSL is between 25 and 40 lm/W, while laboratory prototypes demonstrate efficiencies of 70 to 80 lm/W (Karlicek, Steele, & Walker, 2004). However, white LED-SSL has the technical potential to become significantly more efficiency, reaching efficacies of 150-200 lm/W. The efficiencies of the four groups of lighting technologies are shown in Table II-1 for comparison.

Table II-1. Lighting Technology Efficacies

Lighting Technology		Efficacy (lm/W)
Incandescent		13-25
Fluorescent		55-90
HID		25-124
SSL	Current	25-40
	Potential	150-200

Table II-2 provides a summary on these four classifications of lighting technologies and how they are distributed throughout the residential, commercial, industrial, and outdoor stationary sectors of the economy. The lighting consumed in these sectors is referred to as lighting for general illumination purposes.

Incandescent lamps represent an estimated 63% of installed lamps in the U.S. and consume 42% of the electricity for lighting. However, they produce only approximately 12% of the luminous output.[6] This is largely because while incandescent lamps dominate by sheer number of installations, in the residential sector where they are most widely used, lamps are only used an average of 2 hours per day. Meanwhile, the average operating hours of lamps in the commercial, industrial and outdoor stationary sectors are much longer, estimated at 9.9, 13.5 and 10.5 hours per day, respectively (DOE, 2002). Furthermore, incandescent lamps are comparatively very inefficient, providing the fewest lumens per unit energy of any of the lighting technologies.

[6] All data presented here was taken from the US Lighting Market Characterization (2002).

Table II-2. Distribution of Lamps, Lighting Electricity Consumed, and Lamp Output - per Sector by Lamp Type[1]

	Residential	Commercial	Industrial	Outdoor Stationary	All
Distribution of Lamps per Sector by Lamp Type					
Incandescent	86%	22%	2%	22%	63%
Fluorescent	14%	77%	93%	3%	35%
HID	-	2%	5%	75%	2%
Solid State	-	-	-	-	-
Distribution of Lighting Electricity Consumed per Sector by Lamp Type					
Incandescent	90%	32%	2%	11%	42%
Fluorescent	10%	56%	67%	2%	41%
HID	0.3%	12%	31%	87%	17%
Solid State	-	0.02%	-	0.01%	0.01%
Distribution of Lamp Output (Tlm h) per Year, per Sector by Lamp Type					
Incandescent	2,693	1,777	36	111	4,614
Fluorescent	1,188	16,733	5,744	68	23,732
HID	31	3,068	2,320	4,677	10,097
Solid State	-	-	-	-	2

[1]Not all categories may add to 100% due to rounding.
Source: DOE (2002): Tables 5-3, 5-7 and 5-8

LIGHTING ENERGY CONSUMPTION

A recent report commissioned by the Department of Energy (DOE) involved a multiyear study to evaluate lighting in the U.S. and identify opportunities for energy savings (DOE, 2002). This DOE report contains the most up-to-date data on the U.S. lighting patterns and consumption. The first phase of the study, *U.S. Lighting Market Characterization: Volume 1- National Lighting Inventory and Consumption Estimate* found that lighting for general illumination in the U.S. (taking into account generation and transmission losses) consumed a total of 8.2 quads of primary energy in 2001, which is equivalent to 765 Terawatt-hours (TWh) at the building, or end-use, site (DOE, 2002). [7]

To understand the significance of lighting as an end-use consumer of electricity and identify energy-efficiency opportunities, it is helpful to put this figure into a broader context. In 2001, the total amount of energy consumed by the U.S. was approximately 98.3 quads of energy – more

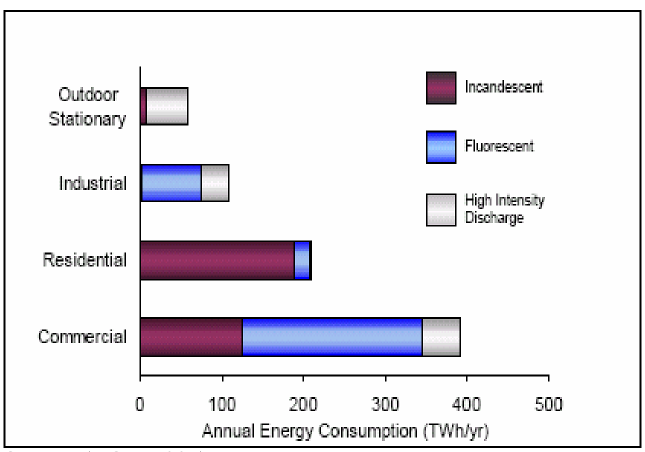
[7] The conversion factor (incorporating generation, transmission and conversion losses) used for site-use energy to primary energy consumed at the generating power plant was 10,768 BTU/kWh for the year 2000. See Appendix 3 for a list of conversion factors used in this report.

than a third of which, 37 quads – was used to generate electricity. Of this electricity generated, lighting as an end-use accounted for approximately 22% of electricity consumption.[8] This translates into lighting consuming approximately 8.3% of the national primary energy consumption in 2001.

Figure II-1 indicates that the commercial sector is by far the largest consumer of electricity for lighting, with substantial energy consumption by incandescent, fluorescent and HID. The commercial sector's 391Tera-watt hours per year (TWh/yr) accounts for just over 50% of the total electricity consumed for lighting in the U.S.[9] The residential sector is the second largest lighting energy consumer, consuming 27% or 208 TWh/yr. The industrial and outdoor stationary sectors consume 14% and 8%, respectively, of the electricity used for lighting. The DOE (2002) found that incandescent light sources are the most common in terms of number of installations (63%), as well as the largest consumer of electricity (42%). However, they provide only 12% of the nation's light due to their comparatively poor efficiency. This makes them an important target for replacement with a more energy-efficient technology.

Figure II-1. U.S. Energy Consumption for Lighting in 2001

(Per Sector by Lamp Type)



Source: (DOE, 2002)

[8] In addition, the excess heat given of by lighting systems leads to additional electricity consumption. Researchers have estimated that 3-4% of national electricity can be indirectly attributed to lighting systems, due to the air conditioning electricity consumption that is needed to cool off the buildings from the heat generated from lighting. See: (Atkinson et al., 1995)

[9] The prefix "tera" denotes 10^12, and hence 1 TWh = 1,000,000,000 kWh.

Energy consumption data for lighting is an essential component for planning effective lighting research and development activities. There is a high potential for electricity savings through the use of more energy-efficient lighting technologies, as well as more advanced lighting designs and control strategies (Atkinson et al., 1995). Despite the rapid pace of technology advancement in LED-SSL, the technology today is too immature for use in general illumination applications. However, a recent DOE model was created to estimate future market penetration of SSL between 2005 through 2025, and the energy savings generated through SSL market penetration (DOE, 2003b). It was found that under an accelerated SSL investment scenario, 3.51 quads of primary energy could be saved by 2025 (DOE, 2003b). This would represent a 33% reduction from 10.47 quads, the projected baseline of energy required for lighting in 2025. The energy savings would translate into a cumulative $130 billion dollars in savings for consumers on electricity costs, between 2005 and 2025.[10] These findings, as well as some of the assumptions made to create this model will be more fully explored in the next section.

Despite the highly promising energy savings potential of SSL, it is important to keep in mind that there are a number of efficient and cost-effective lighting technologies as well as energy-savings lighting designs and controls, currently available on the market. If adopted, these too could result in significant energy savings. Atkinson et al. (1992) determined that if cost-effective lighting technologies already on the market were installed, electricity consumption for commercial interior lighting could be reduced as much as 50-60%, and residential interior and exterior electricity consumption could be reduced by as much as 20-35%. Hence, while a SSL efficacy of 200 lm/W has the technical potential to be twice as efficient as fluorescent lighting and up to ten times as efficient as incandescent lighting, there is reason to be cautious of highly optimistic estimates of national energy-savings. To understand the energy-efficiency potential of SSL, one needs to take into account things such as: the gradual diffusion of all new technologies,

[10] Note that this electricity savings is undiscounted, and was found by multiplying the electricity energy savings by the Energy Information Administrations Annual Energy Outlook (AEO) 2003 forecasted electricity prices.

barriers which are often common to energy-efficient technologies, as well as the drivers and challenges that will shape the development and market penetration of LED-SSL.

III. SOLID-STATE LIGHTING

BASIC LED SCIENCE

Solid-state lighting includes both organic and inorganic light-emitting diodes (LEDs). For the purpose of this report, the discussion will be limited to only inorganic LEDs, but both are projected to play a role in the future lighting market.[11] Light-emitting diodes are based upon the scientific principles of injection luminescence, in which in electrons and holes combine (also known as radiative recombination) within the active region of semiconductor materials, and emit photons (packets of light).[12] When these photons are released they typically have very similar energies to one another, and hence the emitted light falls within a narrow bandwidth. This gives LEDs their monochromatic characteristic. This band can be engineered to fall anywhere across the visible electromagnetic spectrum, as well as in the infrared and ultraviolet.

The most basic structure of an LED is that of a semiconductor diode, which functions essentially like a valve, allowing current to pass in one direction and not the other. In LEDs, the active region where the electrons and holes recombine is the junction between the n-type and the p-type semiconductor materials. Light-emitting diodes are made up of compound semiconductors, typically two to four elements. By varying the types of semiconductor materials used, a particular wavelength (color) of light can be achieved.

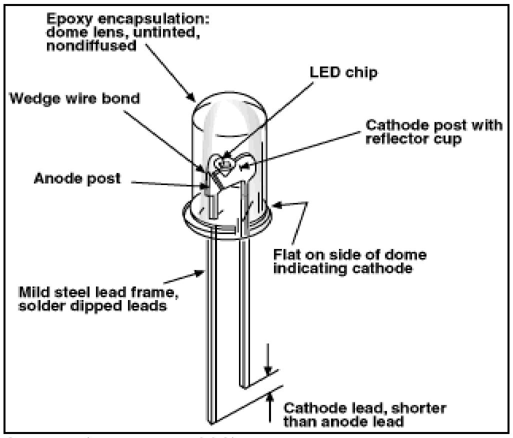
In the basic LED, electrodes are fixed to the semiconductor chip, and it is and encapsulated within a dome shaped lens. The small semiconductor chip is the "light engine" of the LED. The

[11] Organic lighting emitting diodes (OLEDs), which are based upon flexible plastic materials (polymers) have their own set of technical challenges, but are also expected to be a player in the general illumination market, albeit further in the future than LEDs. One particular advantage OLEDs have over LEDs is that they don't need to be manufactured in (costly) semiconductor fabrication facilities. The DOE is currently funding both technologies in an effort to develop energy-efficient SSL.

[12] While electrons are negatively charged subatomic particles, holes can be thought of as a vacancy of an electron, which carries a positive charge.

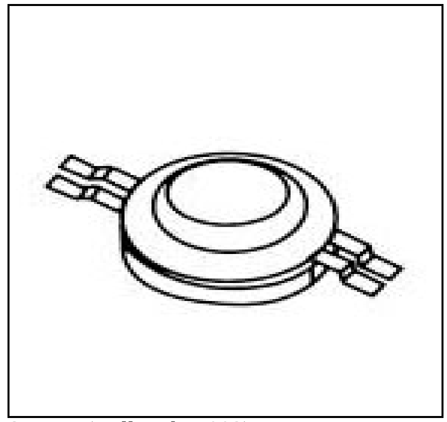
basic LED used for indication is show below in Figure III-1, and an LED commonly used in illumination applications is shown in Figure III-2.

Figure III-1. Basic Indication LED



Source: (Bierman, 1998)
Note: Drawing not to scale

Figure III-2. Illumination LED



Source: (Bullough, 2003)
Note: Drawing not to scale

Using semiconductor materials to generate light is not a novel concept – it was first demonstrated over forty years ago. The first LED was invented in 1962 by Nick Holonyak Jr. at General Electric (NRC, 2002). Six years later, LEDs were commercially introduced by Monsanto and Hewlett-Packard (Haitz et al., 2000). Light-emitting diodes were first used as indicator lights on electronics devic es, and later applications expanded to the dots and bars seen on alphanumeric displays in the first electronic watches and calculators (Zukauskas et al., 2002). Subsequent improvements in the last decade have improved the efficiency of LEDs. A technological breakthrough occurred in the mid-1990s when a blue LED was finally demonstrated. Today, LED technology can be used to generate monochromatic light spanning the entire visible spectrum. This has made a future with "white" solid-state lighting used in general illumination applications, a reality. High-power, or high-brightness LEDs (HB LEDs) can operate on higher currents, thus enabling greater luminous output. The HB LEDs have extended the use of LEDs from small indicator lights, to applications requiring greater luminous output such as traffic signals and displays. Today, LEDs are rapidly moving even beyond these brighter indication applications.[13] In the last year HB LEDS have begun to move rapidly into niche illumination applications, such as architectural accent lighting, vehicle headlights, and outdoor stationary lighting.

THE "WHITE" LED

Today the "white" LED lamps most widely mass-produced, operate by combining a blue LED chip with a phosphorus coating. The phosphor absorbs some of the blue light and re-emits it is yellow: the combination of the yellow and blue light make a rough approximation of white light. The human eye, however, perceives this combination of yellow and blue light as more of a "dirty" white, than the familiar warm glow of an incandescent light bulb (Martin, 2001).

The quest is ongoing to produce the next generation of white LEDs with improved efficiency, lower cost and with an appealing white glow is ongoing. There are a number of potential ways to achieve this; one is to develop an ultra violet (UV) emitting LED whose light could be fine-tuned to white by selecting the appropriate phosphor(s). At least early on in the research process, there are many appropriate phosphors to choose from which work with UV light because they are currently used in fluorescent lighting. However, due to the different requirements of LEDs, in the later stages of research the phosphors used for LEDs will likely diverge from those which are used for fluorescent lighting (Tsao, 2002).

A second option involves a tri-chip system, placing red, green and blue (RGB) LEDs close together so that the light from these primary colors mixes and produces white light. Both techniques offer advantages and disadvantages, and research is currently underway on both of these strategies for developing the next generation of white LEDs. A downfall of the first option is that combining a LED and a phosphor is less efficient than the RGB system. However, the second option, which uses the RGB system, also is at a disadvantage because the different degradation rates of LEDs would create the need for more complex control circuitry to maintain a

[13] Indication and illumination lighting are distinct, in that the first can be thought of a light that you look directly at, while the second is light which illuminates objects that are seen, by casting light on them.

constant white luminous output (DOE, & OIDA, 2001). However, ultimately with time it is expected that the second option employing the RGB system, will dominate. Nevertheless, the technology is developing at a rapid pace and new methods to create a “white” LED are still being explored. Recent technology advancements made have yielded yet another option to create a white LED, which involves engineering nanosized quantum dots to act as phosphors, emitting visible light when excited by a near UV LED (Sandia National Laboratory, 2004).

Ambitious performance and cost targets were established for LED-SSL technology during a SSL industry roadmapping meeting, attended by SSL experts and interested parties from industry, government and academia. The report of this meeting, *Light Emitting Diodes (LEDs) for General Ilumination: An OIDA Technology* Roadmap, contains the established technology targets (Tsao, 2002). These roadmap targets, with updated modifications from Tsao (2004) are shown below in Table III-1. On the right hand of the graph, performance attributes and costs of conventional lighting technologies are provided for comparison. The performance improvements and cost reductions necessary for LED-SSL to be competitive with traditional technologies are far from trivial, yet industry experts are optimistic that they are feasible. However, it should be noted that these scenarios below were established with the expectation that a significant national investment in SSL would begin in 2002; the scenario could play out differently under an alternate investment scenario (Tsao, 2004). Section VII will provide an overview on the current status of public policy initiatives in the U.S. and abroad, for accelerating the development of SSL.

Table III-1. Roadmap Targets for SSL-LED Technology in Comparison to Conventional Lighting Technologies

Lamp Targets	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incandescent	Fluorescent	HID
Luminous Efficiency (lm/W)	20	75	150	200	16	85	90
Lifetime (hr)	20,000	20,000	100,000	100,000	1,000	10,000	20,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400	36,000
Input Power (W/lamp)	1.3	2.7	6.7	7.5	75.0	40.0	400.0
Lamp Cost[1] (U.S. $/klm)	200.0	20.0	5.0	2.0	0.4	1.5	1.0
Lamp Cost[1] (U.S. $/lamp)	5.0	4.0	5.0	3.0	0.5	5.0	35.0
Color Rendering Index (CRI)	70	80	80	80	100	75	80
Lighting Markets Penetrated	Low-Flux	Incandescent	Fluorescent	All			

Source: Data from (Tsao, 2004, 2002)
[1] The costs are in "street costs," estimated approximately 2 times higher than the original equipment manufacture costs. The lamp cost represents the cost of the SSL lamp, not including any fixture costs which would be necessary to complete a lighting system.

In a 2001 report by Sandia National Laboratory, it was observed that the luminous output ("flux" which is measured in lumens per lamp) and efficiency of LEDs roughly doubles every 18 to 24 months over the last 30 years, and that the future trends are likely follow a similar pace (Drenner, 2001). This LED performance trend has been dubbed Haitz's Law, similar to the well-know Moore's Law that applies to the number of transistors which can fit onto a semiconductor chip (Ton, Foster, Calwell, & Conway, 2003). This trend of Haitz's Law however, applies mainly to monochromatic LEDs rather than to white LEDs which are more complex to design (Ton et al., 2003).

Early in the development of LED-SSL for general illumination, it was recognized that one of the primary impediments for developing and deploying white LED-SSL, would be its initial cost when compared to the initial cost of other conventional lamps (Haitz et al., 2000). A white-paper by Haitz et al. (2000), laid out the case for a national investment in solid-state lighting, and optimistically predicted that the "cross over points" (the point at which LEDs would transition from signally applications to general illumination applications) would occur in 2002. After this point, they argued that LEDs would be able to gradually replace incandescent bulbs. While today in 2004 "white" LEDs are penetrating low-flux and outdoor illumination applications, they have not yet reached performance or cost targets, which would allow them to become viable contenders for replacing the incandescent lighting that is primarily used in the residential and commercial sectors. In fact, Aprad Bergh, the current President for the Optoelectronics Industrial Development Association stated in the May/June 2004 issue of *IEEE Circuits & Devices Magazine* that "in retrospect, indoor illumination will be the most difficult to retrofit and will probably not happen for another 15-20 years. In the meantime, however, solid-state lighting will penetrate other markets such as signaling, signage, displays, and illumination of mobile appliances and platforms such as mobile phones and automobiles" (Tsao, 2004).

For LED-SSL to break into general illumination market, not only must there be significant performance improvements and cost reductions, but LEDs must also be successfully incorporated into lighting systems. In striving to create a highly energy-efficient lighting source, it will also be important to fully optimize the design of the entire LED-SSL lighting systems to maximize light output (Ton et al., 2003).

MANUFACTURING PROCESS[14]

The light engine of an LED is a small semiconductor chip, composed of very thin layers (each typically under a micron) of crystalline materials that are typically compounds consisting of two to four different elements. These layers are either grown onto or later transferred to, a different more durable material known as the substrate. Light-emitting diode substrates are made of materials that are chosen to be compatible with their overlying compound semiconductor layers. These substrates are grown in long cylindrical pieces called boucles and then sliced into wafers and polished to ensure their surface is defect free. While in the computer industry, semiconductor substrates of silicon can be grown as large diameter wafers of approximately 12 inches, the substrate materials required for LEDs are more difficult to grow (while maintaining a

[14] The information from this section was largely based on: Ton, Foster et al. (2003) and (Zukauskas et al., 2002).

low defect density). Thus, most typical LED wafers are approximately four to six inches, and some are even limited to two inches.

Creating the thin semiconductor layers that comprise an LED requires multiple highly controlled steps. Impurities, or dopants (typically elements such as magnesium and zinc) are intentionally introduced to alter the electrical properties of the semiconducting materials. The newest generations of LEDs are manufactured using techniques known as molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD). The epitaxial growth of LEDs in MOCVD reactors is currently the most demanding and costly processing steps, with much lower yields (~60%) than in the more mature silicon-chip industry (DOE, 2004). Since manufacturing economics of processing at the wafer level scales with respect to the size of the wafer, developing larger wafers for HB LEDs will reduce their cost.

Following the deposition of the semiconductor layers, the wafer's luminescence is tested. Typically, there are some areas on the wafer that have superior performance to other areas. To create the necessary circuits, a multi-step process is used that involves depositing conductive metals and applying photoresist to selectively etch the necessary circuitry patters onto the wafer. The wafer itself then holds a grid of tiny chips, and the next step is to separate wafer into individual LED chips. While the typical chips used in conventional indication LEDs were about 0.25 millimeters square (mm^2), today HB LED chips are up to 1.0 mm^2. Very fine circular blades or laser scribing is used to dice the wafer and produce the tiny individual chips known as die. These LED die are then often coated with a highly reflective coating or placed in a reflective cup, and metal contacts (typically gold) are attached to one or more side of the die. The material encasing the LED die can be molded into a certain preferential optical shape to improve the extraction efficiency (the rate at which photons that are created exit the LED package).

While LEDs are the light engines of SSL, they are not the only necessary component. They must be incorporated into a lighting system which includes a thermal heat sink, a circuit, a driver/power supply that connects the circuit to the LED and modifies the electricity to meet the

LED's operational needs, and a control device. Thermal heat sinks, typically composed of aluminum, copper or a ceramic material are essential components of the high power LEDs on the market today. These heat sinks siphon away the heat that is generated at the p-n junction, where high temperatures can adversely affect the LED performance. Because LEDs operate on direct current, they require a driver to convert the alternating current from the electricity grid, to direct current. The input power that LEDs use varies from just a few milliwatts for the older LEDs used as small indication lights, up to five to ten watts, that now supply the HB and ultra HB LEDs.

THE INDUSTRY

In the last few years, the market for HB LEDs has been expanding into niche applications found in a number of different industries. Today, the end-use market for HB LEDs is diverse, including for instance: brake lights in the automotive sector,[15] traffic lights, cell phone backlighting, large video screens including the eight-story Nasdaq display in Times Square New York, and retail displays. Although LED technology has been in commercial application since the 1960s, HB LEDs are a much newer technology. The performance of HB LEDS has been rapidly improving since the 1990s, and costs have been falling. The market for HB LEDs has been growing strongly as these performance and cost trends allow HB LEDs to penetrate into new markets.

In 2003, the market research firm Strategies Unlimited, placed the worldwide market for HB LEDs at $1.84 billion dollars in 2002 (Steele, 2003). This $1.84 billion dollars was the result of a brisk 54% growth in the industry during 2002. The HB LED market is broken down by application in Table III-2 below. In 2003, only 5% of the HB LED market went to what was termed "illumination" applications. However, this category of "illumination" applications is still just niche markets, such as architectural lighting, specialty lighting, and signage. Strategies

[15] The use of LEDs as brake lights improves automobile safety because they are able to turn on an order of magnitude faster (less than a millisecond, as compared with over ten milliseconds) than the tungsten lamps.

Unlimited forecasted that this "illumination" market for HB LEDs will rise to $522 million dollars in 2007, at which time it would account for approximately 12% of the HB LED market (Steele, 2003).

Table III-2. Applications of High Brightness LEDs in 2002		
Application	*Market Value & Share*	*Typical Uses*
Mobile applications	$716 m (40%)	Cell phone screen and keypad backlights, PDAs, digital cameras
Signs	$422 m (23%)	Single-color (highways VMS, moving message panels), full color large video screens
Automotive	$322 m (18%)	Car interior (instrument panel lighting, map lights), car exterior (CHMSL, stop, turn, tail), truck and bus exterior (marker, stop, turn, tail)
Illumination	$85 m (5%)	Machine vision, architectural lighting, specially lighting, channel letters, contour lighting, flashlights, marker lights, etc.
Signals	$44 m (2%)	Traffic signals, pedestrian crossings, railroad, aviation
Other	$331 m (12%)	Indicator lamps in commercial, industrial and consumer electronics, entertainment, indoor displays, miscellaneous

Source: Strategies Unlimited data from (Steele, 2003)

The companies that are pioneering the "revolution" in SSL are by and large, smaller companies currently focused on niche markets. Robert Steele, a leading market analyst for LEDs with Strategies Unlimited describes these niche applications as being filled by lighting systems companies who manufacture the lighting fixtures, including control electronics and options, using LED devices provided by another manufacturer, to fulfill a specific task (Steele, 2003). Currently, most LEDs are sold as components and relatively few companies have come into the market offering to provide complete lighting systems (Ton et al., 2003). Many of these companies are smaller in size, although there is some participation by the larger companies from the tradition lighting industry.

The U.S. lighting industry encompasses lamps (light bulbs), fixtures, ballasts, and lighting controls. The U.S. Census North American Industrial Classification Code (NAICS) for the "Electric Lighting Equipment Manufacturing" industry is 3351. This industry covers a myriad of products including lamps, lighting fixtures, electrical outlets, switches, fuses, and similar devices and hardware for commercial and residential electrical service. According the latest available bicentennial U.S. Economic Census data, this industry was $12.6 billion in 1997(U.S. Census, 1999). The industry is broken down in the U.S. Economic Census data by light bulbs, parts and components, and light fixtures. These two sub-sectors were worth $3.3 billion and $9.6 billion respectively in 1997. There is a high degree of market concentration in the lamp, ballast and fixture market, but somewhat less in the lighting controls market (Vorsatz et al., 1997). For example, three large multinational companies dominate the U.S. lamp market: General Electric, Philips and Osram Sylvania, and they control approximately 90% of the market. However small manufactures also play an important role in the lighting market by specializing in niche applications and challenging the "mature" lighting industry with their flexibility and innovativeness (Davis, 1991).

LED APPLICATIONS & ENERGY-EFFICIENCY POTENTIAL

While there is no single commonly accepted definition of energy-efficiency, for the purposes of this paper a more technical definition will be adopted which was used by the U.S. Energy Information Agency (EIA). In general, greater energy-efficiency is thought of as decreasing energy inputs while retaining a given level of service, or providing increased or enhanced services for a given amount of energy inputs (Battles, & Burns, 1998). An important question to remember when considering energy-efficiency is, "efficient with respect to what?"

In this section the energy-efficiency potential of solid-state lighting will be considered in (1) niche lighting applications, and (2) general illumination lighting, based on the findings in two recent DOE reports (DOE, 2003a, 2003b). For niche applications, the energy-efficiency potential will be considered based on the hypothetical case in which lighting for applications was instantaneously replaced with LEDs.

For general illumination, the results of a DOE report which modeled SSL market penetration between 2005 and 2025 are discussed (DOE, 2003b). The energy-efficiency potential of SSL is estimated as the difference between the lighting energy projected to be consumed in the absence of SSL, and the energy consumed assuming that solid-state lighting is developed and penetrates the market.[16] The future energy-efficiency potential for SSL in general illumination depends not only on future R&D developments to improve performance and reduce costs of LED-SSL, but also on quickly this technology penetrates the market and replaces less efficient conventional lighting technologies.

Niche Applications for LEDs

In additional to the lighting that is used in general illumination applications; there is also a significantly sized lighting market for niche lighting. This niche market includes not only certain illumination applications but also many indication lighting applications, such as in traffic lights and automobile signaling. A recent report *LED Lighting Technologies and Potential for Near-Term Applications* prepared for the Northwest Energy Efficiency Alliance, focused on assessing the energy-efficiency potential of LEDs in niche, near-term (1-4 years) applications (Ton et al., 2003).

Today, LEDs are commercially available for a number of different niche applications. Some of the portable and off-grid applications include headlights and safety signals for cars, trucks and buses, portable messaging systems (many of which are powered by photovoltaics), flashlights and other portable lighting applications such as those used for bicycles and headlamps, backlighting in cell phones and other portable electronic devices such as personal digital assistants, emerging signals and beacons such as those used for docks, landscape and pathway lanterns, and clothing and footwear (Ton et al., 2003).

[16] It is important to note that in this model, SSL represents both LED and OLED technology.

Also in the near term (1-3 years) Ton et al. (2003) cite that it likely LEDs will become more efficient and replace fluorescent lights as backlighting in liquid crystal displays (LCDs). Today, these LCDs are used in a number of applications including computer monitors, TVs, office and home appliance displays and large-screen displays. Liquid crystal displays (LCDs) have typically used fluorescent lights as backlighting. However LEDs have the potential to become a more energy-efficient alternative to fluorescent lighting, and at the same time provide important performance enhancements (Ton et al., 2003). Ton et al. (2003) estimate that at the 2001 annual shipment volume of the LCD monitor market (3.9 million units), there is the potential to save over 38 gigawatt hours (GWh) annually if every monitor where to incorporate LED technology.[17] LED penetration into the TV market could yield even greater energy savings: an estimated 25% market penetration could save up to 800 GWh per year. Additional environmental benefits of using LED backlights are possible because of the longer (50,000 hr) lifetime than conventional backlights, thus generating less waste. Furthermore, LEDs contain no mercury, a toxic substance found in trace amounts in fluorescent lighting. However, toxicity issues from materials used in LED have yet to be adequately addressed and the potential environmental concerns will be discussed in greater length in Section VI.

In addition to LCDs, there are a large number of other grid-connected industrial, commercial and residential niche lighting applications. Some of these applications, such as traffic lights and exit signs, have already seen significant market penetration by LEDs. In a 2003 report prepared for the DOE entitled *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*, an overview of the current applications for LEDs in twelve niche markets is presented. The "overnight" technical potential for energy savings if these markets were to be fully penetrated is also quantified. The twelve markets considered in this report are listed below,

[17] The 2001 LCD annual sale estimate was for the North American market, and was based on (Poor, 2002). A Gigawatt hour is equivalent to 10^6 kWh.

grouped into three primary categories: mobile transportation applications, stationary transportation activities, and other stationary activities.

Mobile Transportation Applications
- Automobile Safety and Signal Lighting
- Large Truck and Bus Safety and Signal Lighting
- Aircraft Passenger Reading Lighting
- Lighted Navigational Aids (Water Buoys)

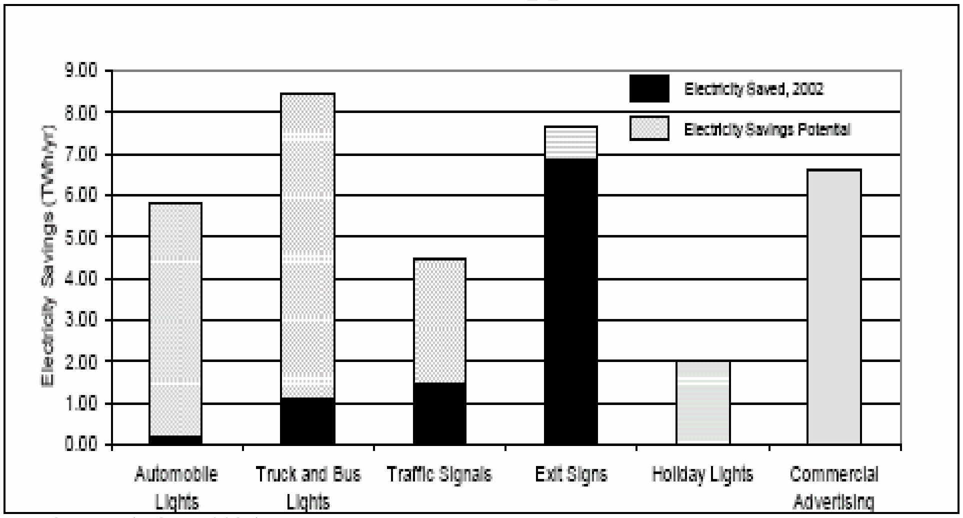
Stationary Transportation Applications
- Traffic Signal Heads
- Railway Signal Heads
- Airport Taxiway Edge Lights
- Navigational Bridge Lights

Other Stationary Applications
- Exit Signs
- Holiday Lights
- Commercial Refrigerated Display Cases and Advertising Signs

The DOE (2003a) focused on six niche applications that were found to have the greatest energy savings potential: automobile lights, truck and bus lights, traffic signals, exit signs, holiday lights and commercial advertising. Figure III-3 shows these six applications and the chart shows the energy that has already been saved through market penetration of LEDs, and the potential energy savings possible. It was found that 9.6 TWh (of approximately 35.0 TWh), of electricity had been saved in 2002 through the use of LEDs (DOE, 2003a). However, when considering only electricity grid applications this number falls slightly to 8.3 TWh. All stationary niche applications considered in this report were classified under the commercial sector. To put the energy savings from these niche applications in perspective, the DOE estimated that the commercial sector in 2001 consumed 391 TWh (2002) for lighting end use, while all sectors in the U.S. combined consumed a total of 765 TWh for lighting.[18]

[18] This report did not consider mobile sources although they were included in the niche applications.

Figure III-3. U.S. Electricity Saved and Potential Savings of Selected Niche Applications



Source: (DOE, 2003a)

According to the DOE (2003a), LEDs have had an 80% market penetration in the exit sign market. In addition, LEDs have become relatively commonplace in traffic signals, where they have captured roughly 30% of the market. In fact, traffic signals were the first mass application of high-brightness LEDs (Zukauskas et al., 2002). While the first LED traffic lights contained hundreds of chips arranged onto a visually dotted pattern, advanced traffic lights today might contain just a dozen efficient LEDs combined with the necessary optics to provide a smooth radiation field. The economic advantages of LED traffic lights include their extended lifetime (reducing maintenance repair costs) and their lower power consumption. While conventional traffic lights are equipped with either a 70 or 135 watt incandescent lamp, an LED module consumes 10 watts or less. Hence, each LED traffic signal can reduce electricity consumption by 82-93% (Suozzo, 2001). The DOE/EPA have developed energy-performance specifications for LED traffic lights and exit signs. Manufactures that meet the specifications can use the ENERGY STAR label on their products, which then enables purchasers to more easily identify energy-saving products (Suozzo, 2001).[19]

[19] For more information see www.energystar.gov

Other niche markets for LEDs have seen only limited market penetration. It is estimated that large truck lights have had roughly a 5-7% LED market penetration; automobiles 1-2%; and bus lights have by far the highest penetration, of around 41%. According to the DOE (2003a), applications such as commercial signage and holiday lights were not shown to have penetrated the market in 2002. Nevertheless, the market for LED niche applications is extremely dynamic and rapidly expanding. Currently, Christmas lights and commercial signage using LED technology are commercially available. The DOE estimated no market penetration in had occurred by 2002 in these niche areas, although because LEDs are a rapidly growing market it is possible the market share could be higher in 2004.[20]

There have been a number of applications for LEDs in specialty outdoor illumination. For example, a mix of 17,000 white and yellow LEDs now illuminate the Jefferson Memorial on the mall in Washington, D.C. creating a hue that matches the marble wall (Tsao, 2002). Recently, 360 LED arrays were used to create a unique illumination system, lighting an entire London apartment – this system consumes less electricity than four 100-watt incandescent lamps (Austen, 2004). While installation costs for this apartment ran approximately $50,000 making it a luxury that few can afford in their residential homes, it illustrates the impressive energy savings that one day might be commonplace in the residential sector.

In addition to the energy savings possible from replacing conventional lighting technologies with LEDs in niche applications, there are a number of additional positive externalities to be gained. As demand grows for this technology in niche applications, both manufacturers and consumers will benefit from using these early opportunities as a learning period. For instance, manufactures will benefit from learning-by-doing, during which they can increase throughputs, improve the characteristics of the technology, achieve higher economies of scale and lower costs, and receive feedback from customers allowing them to continuously improve their product.

[20] For instance, Forever Bright has Christmas Lights available at http://www.holidaycreations.com/Consumers/Consumer_IndexForeverbright.htm .

Consumers simultaneously, will benefit from learning-by-using, becoming familiar with, and aware of the energy-savings and innovative designs available with LEDs.

General Illumination LED SSL

While niche applications certainly offer important opportunities for energy savings using LED technology, much greater energy-efficiency savings could be gained if the full potential of white LED-SSL technology is realized. A report entitled *Energy Savings Potential of Solid State Lighting in General Illumination Applications,* was prepared for the DOE (2003b) by Navigant Consulting, Inc. In this report, an overview is given of the energy-savings potential of SSL in general illumination applications in the U.S. between 2005 and 2025. This analysis was based on a spreadsheet model, which simulated consumer lighting purchasing decisions over this twenty year time period in order to estimate the market penetration of SSL and the subsequent energy savings.[21]

A short description of the model, the results of this analysis, and some of the critical assumptions made, are detailed below. For a complete overview of the methodology used in constructing the model, the report is available from the DOE website.[22]

Model Description: the projected lighting demand is based on new construction estimates used in the National Energy Modeling System (NEMS) and the Annual Energy Outlook (2003). The DOE *U.S. Lighting Market Characterization* report (2002) is used to provide thebaseline inventory of installed lighting technologies and their characteristics. The market includes four sectors: residential, commercial, industrial and outdoor stationary. The inventory of the lighting stock is broken down into four bins by

[21] There are several other models and reports what have estimated the energy savings potential of solid-state lighting (see Drenner, 2001 and DOE, 2001). The DOE (2003b) model is the most recent and detailed model available, and has been used as the basis for the energy-savings and carbon emission reduction estimates cited throughout this report.

[22] This report is found on the DOE Office of Energy Efficiency and Renewable Energy, Building Technologies Program, accessible at http://www.netl.doe.gov/ssl/

color rendering index (CRI) value.[23] The CRI is used as a proxy for the lighting quality required for a certain application and the four bins created include: low, medium, high and very high CRI.

The model is constructed to simulate the purchasing decision of new lighting technologies. When purchasing decisions are made, there is market turnover in which SSL has the potential to be adopted. The market turnover occurs via three different routes: new installation (new construction), replacement lamps, and retrofit fixtures. The performance and costs of conventional technologies were projected to improve minimally, on a linear basis. The SSL performance improvements (efficacy and lifetime) and cost reductions were developed in consultation with industry experts for two scenarios: an accelerated scenario ($100 million annual national investment) and a moderate scenario ($50 million annual national investment). The SSL technology improvements over time followed an "s-shaped" curve, in which first exponential progress gives way to linear improvements, and finally the curve levels off as the technology asymptotically reaches its maturity. It is important to note that for simplification purposes an aggregate set of SSL curves, which encompass both LEDs and OLEDs for SSL, were developed and used in the model.

Due to the competition from SSL, the conventional lighting technologies are assumed to improve modestly, despite the fact that they are relatively mature. Three different conventional technology improvement scenarios are given: low, medium and high baseline, although the medium baseline scenario is used as the default throughout the analysis.

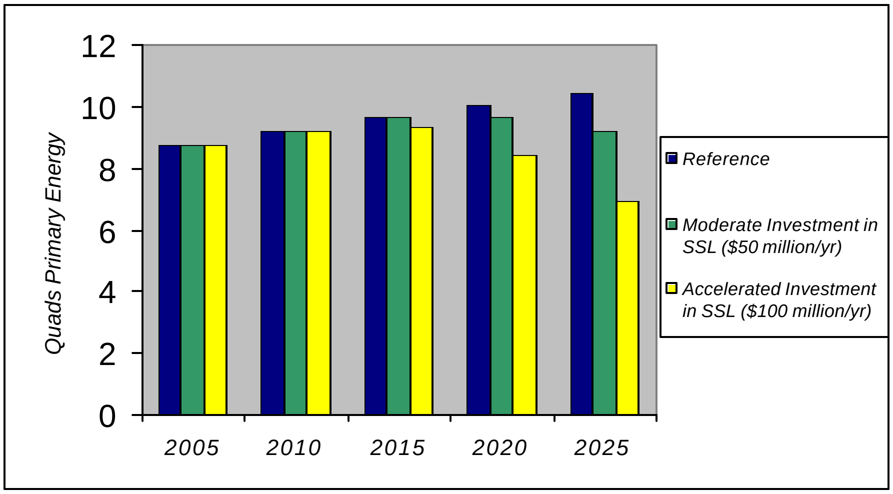
The SSL compete against the conventional lighting technologies, and the model awards market share to various technologies based on simple-payback. Simple payback is the ratio of the first year incremental capital cost to the first year incremental savings, expressed in years. Using market penetration curves for simple payback developed by Arthur D. Little,

[23] The CRI of a lamp is a measure of how surface colors appear when illuminated by the lamp, in comparison to how they appear when they are illuminated by some reference light source of the same color temperature.

the number of year's payback determines the percentage market share awarded to SSL. For instance, in the commercial sector if the payback period is two years SSL will gain a 30% market penetration, while if instead the payback period is four years, the market penetration will only be about 8%.

Figure III-4 captures the results of the aggregate energy-saving possible between 2005 and 2025, from the scenarios used in the model. In the reference scenario, energy consumption for lighting is projected out to 2025 assuming that there is no SSL market penetration. The conventional lighting technologies are assumed to improve only modestly; the performance improvements and cost reductions are minimal because it is assumed that these technologies are relatively mature. The modest investment assumes that industry and government work together to develop SSL, but with only a modest investment ($50 million per year), the technology is not developed quickly enough to yield significant energy savings. In the accelerated scenario, the national investment is twice that of the modest investment ($100 million per year). This higher level of R&D is able to achieve better performance (efficacy and lifetime) and lower costs, and thus this scenario yields the most significant energy savings.

Figure III-4. U.S. Primary Energy Consumption for Lighting: Three Scenarios



Source: Data from (DOE, 2003b)

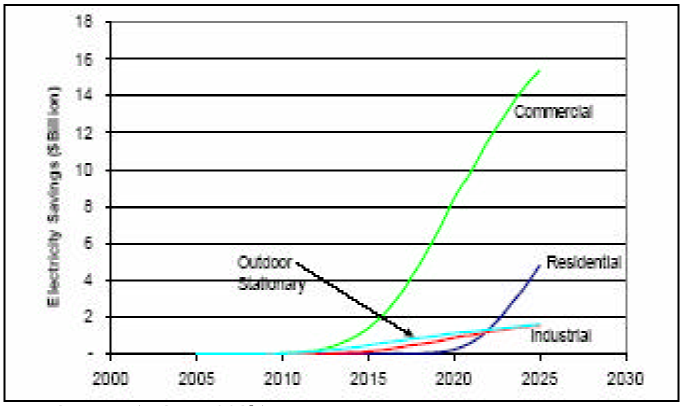
In the reference scenario from Figure III-4, lighting consumes 10.47 quads of primary energy in 2025. The moderate investment scenario saves 1.23 quads, or approximately 12% from the reference scenario. The accelerated investment scenario yields a higher energy savings of 3.51 quads, or approximately 33%.[24] Cumulatively between 2005 and 2025, the modest investment scenario saves 5.44 quads of primary energy, while the accelerated investment scenario saves 19.9 quads.

The total undiscounted savings across all sectors of the economy for the accelerated investment scenario is approximately $130 billion dollars. When these savings are broken down by sector as depicted below in Figure III-5, it can be seen that the commercial sector would see the bulk (72%) of these savings. In this analysis, by 2025 SSL has penetrated into all four of the lighting sectors. However, the majority of the energy savings accrue from replacing inefficient incandescent lighting in the residential and commercial sectors. It is also interesting to note that the commercial and the outdoor stationary sectors are shown to be the earliest adopter of this SSL

[24] The uncertainly given for the moderate investment scenario is +/- 0.2 quads, and for the accelerated investment scenario is +/- 0.5 quads.

technology, with adoption beginning in roughly 2012. Penetration into the residential sector does not begin until considerably later in 2019.

Figure III-5. Electricity Savings from SSL by Sector



Source: (DOE, 2003b)

A critical environmental benefit resulting from the penetration of SSL will be the reductions in carbon dioxide (CO_2) emissions. Assuming that the current mix of energy sources used to produce electricity remains static, the emissions factor for CO_2 can be held constant and applied to the projected energy savings in order to estimate reductions in CO_2. Applying this methodology to the SSL market penetration analysis, it is found that CO_2 emissions would be reduced by 19.2 million metric tons of carbon equivalent (MMTCE) in 2025 under the moderate investment scenario, and by 54.7 MMTCE under the accelerated investment scenario.[25] Cumulatively between 2005 and 2025, the moderate and accelerated investment scenarios have the potential to save nearly 85 and 310 MMTCE, respectively.

To examine the potential of SSL in a broader context, it is important to ask: What is the significance of these CO_2 reductions in light of CO_2 emissions projections in the U.S.? The Energy Information Administration (EIA) of the DOE estimates that in 2002 the U.S. released a total of approximately 5,680 million metric tons of CO_2 (equivalent to 1,548 MMTCE), from

[25] This is employing the emissions factor of 15.58 million metric tons of carbon per quad of primary energy which was used in (DOE, 2001).

energy-related activities (EIA, 2003).[26] These energy-related CO_2 were by far the most significant source (82.3%) of GHG emissions in the U.S.

The electric power sector was responsible for about 39% of these energy-related CO_2 emissions.[27] Since 1990, the emissions of CO_2 have increased on annually on average about 1.2%. In the EIA Annual Energy Outlook 2004, energy-related CO_2 emissions are projected to grow 1.5% annually between 2002 and 2025, to reach approximately 2,220 MMTCE in 2025 (EIA, 2004).[28] Hence, the accelerated technology scenario for SSL has the potential to achieve a 2.5% reduction of total U.S. energy-related CO_2 emissions from projected 2025 emissions levels. In the case of a moderate investment scenario, the reduction in these emissions would be 0.9%.[29]

Another useful way to consider the potential of SSL is to compare it to the results of current programs that promote energy-efficiency to reduce CO_2 emission. For example, in 1992 the EPA began the ENERGY STAR program, to identify and promote energy-efficient products in order to reduce greenhouse gas emissions (R. Brown, Webber, & Koomey, 2000). Today, this program is run through a partnership between the DOE and EPA, and spans across 35 product categories. The annual report entitled, *ENERGY STAR and Other Voluntary Programs 2002 Annual Report*, cited that the combination of these program prevented more than 43 MMTCE in 2002 (EPA, 2002).[30] The ENERGY STAR program alone was estimated to save 25.2 MMTCE in 2002. Hence, the CO_2 reductions possible by 2025 under a SSL accelerated investment scenario are over twice the reduction achieved by the ENERGY STAR program in 2002. In the case of a medium SSL investment scenario, the CO_2 emissions are slightly less than those achieved in 2002 through the ENERGY STAR program.

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[26] The conversion here is: C / CO_2 = 1 / 3.67

[27] In the EIA report the "electric utility sector" is defined as: all utilities, nonutilities, and combined heat and power (CHP) facilities whose primary business is the production of electric power.

[28] There is of course a number of uncertainties with forecasting carbon emissions out to 2025.

[29] Calculated by dividing 19.2 MMT CE and 54.7 MMTCE, by 2218.0 MMTCE.

[30] In addition to ENERGY STAR, this estimate includes the: Clean Energy, Methane, and Environmental Stewardship programs.

However, there are at least four important caveats to keep in mind when estimating the GHG emissions reductions out to the year 2025. First, the mix of energy sources to produce electricity has in recent years shown a trend towards cleaner generation technologies (Webber, & Brown, 1998). In the 2004 Annual Energy Outlook, the EIA projects that the average CO_2 per kWh of electricity generated by utilities will decline by about 2% between 2002 and 2010 and then remain relatively flat through 2025 (EIA, 2004). This trend will change the carbon emissions factor, which will then have an effect on the future "dent" that SSL will take out of the overall CO_2 emissions in the U.S..

Second, the CO_2 emissions from electric utilities per unit of lighting service provided is affected by the thermal efficiency of power plants, as well as distribution losses as electricity is transported over the grid. Third, the energy-savings estimates from SSL only took into account the energy consumed directly for lighting. Inefficient lighting generates excess heat that leads to further energy-requirements for space conditioning. Therefore, using more efficient lighting could reduce the amount of energy required for air-conditioning. Finally, the possibility of a carbon emissions cap-and-trade scheme could in effect set a cap on the amount of CO_2 emitted – and hence greater energy-efficiency would only ultimately serve to make these carbon permits less expensive and would not have an affect on the quantity of CO_2 emitted.

As in all models, critical assumptions have to be made in order to build a model. To gain a richer appreciative of the energy-efficiency potential of SSL, it is necessary to understand the assumptions and simplified parameters that are used in the model. Below, some of the assumptions and simplifying parameters used in the DOE (2003) SSL market penetration model are discussed:

- The CRI is used to divide the national lighting inventory into four bins. The competition between SSL and conventional technologies can only occur within a single bin and it is assumed that the end-users who require, for example, applications with very high CRI lighting today will only use very high CRI lighting in the future. However Naredran et al.(2002) tested human preferences for LED readings lights with different CRI values and found there was no coloration between preference and CRI for LEDs. From this study, they concluded that the CRI metric should not be used to determine the color rendering properties of LEDs. Hence, dividing the market into CRI bins might not accurately represent how LEDs will compete in the lighting market. The metric problem for LEDs will be discussed in greater length in Section V, as one of the challenges for LED-SSL.

- The SSL performance curves are constructed based on expert opinion, however forecasting the future of technology performance improvements and cost reductions (particularly through a 20 year timeframe) are inherently fraught with uncertainty.

- The model assumes that SSL lamps produced will be readily able to fit into the existing fixtures or sockets. Currently there are a few SSL lamps available on the market, which are compatible for example, with the traditional incandescent Edison (E-26) sockets.[31] While this might be technologically feasible, the development of a new SSL lighting paradigm might also focus on more radical designs, which might not be compatible with the existing physical lighting infrastructure. In fact, some in the industry believe that SSL should be introduced not as a simple drop-in replacement for current lighting technologies, but instead as an entirely new infrastructure for lighting (DOE, 2004). For example, Kevin Dowling, vice president for strategy and technology at the LED technology company Color Kinetics remarked “The bulb culture might give way to a new culture of lighting” (Dowling, 2003).

[31] For examples of some of the SSL lamps, see http://www.bocaflasher.com/

If this is the case, it is important to recognize the energy-efficiency gains from SSL lamps will be different. Overall, the market penetration of LED-SSL would proceed at a slower rate, and hence the energy-efficiency benefits would likely be smaller over the 2005-2025 time frame used in the market penetration model.

- The “rebound effect” could occur in which a new SSL lighting paradigm actually promotes more lighting installations, potentially even increasing lighting energy consumption. Nonetheless, because of the significant energy-efficiency potential of SSL, it seems highly unlikely this would occur even supposing the number of lighting installations does grow.

- In the model, the future lighting demand was estimated by multiplying the NEMS annual growth estimates of floor-space by a constant lumen hour demand per square foot. However, the directional nature of LEDs might also make task lighting more prevalent in the future. In this case, the lumen hour demand per square foot would be less than it is today and the future lighting demand would be lower than today (DOE, 2003a).

- The actually efficacy of SSL will not only depend on properties of the LED or OLED “light engine” which is used to generate the lighting, but also on the efficiency of the drive electronics and the design of the entire lighting system. It will also be important to maximize the energy-efficiency potential of SSL by taking a “systems approach” as using SSL in conjunction with other known energy-efficient practices such as optimal fixture designs, energy-management lighting controls, and daylighting.

The future market penetration potential of SSL in this model is driven largely by economics: initial price, efficiency, lifetime, and operational and maintenance costs (DOE, 2003b).

However, while economics will be a very important factor in the penetration of SSL into the lighting market, it is critical to remember that it is not the only factor. As mentioned earlier in this paper, the lighting market is an incredibly complex entity. Whether or not consumers purchase SSL will also depend on their awareness of this new technology and its advantages, the aesthetics of this new lighting, and if they are able to conveniently purchase it.

It is also important to keep in mind that oftentimes cost-effective energy-efficient technologies are not quickly adopted in the market. Substantial amounts of literature have been devoted to this so-called energy "efficiency-gap." In part, this "gap" can be attributed to the gradual diffusion of that all new technologies experience (Jaffe, & Stavins, 1994).

Brown (2001) provides a recent review on the market barriers and failures that are believed to account for the efficiency gap, and articulates a number of the market failures and barriers which inhibit consumer investment in energy-efficient technologies. Market failures occur when there are flaws in the way the market operates. Brown cites examples of market failures including misplaced incentives; distorted fiscal and regulatory policies; unpriced benefits; unpriced goods including education, training and technological advances; and insufficient and inaccurate information. Brown then goes on to differentiate between market barriers from market failures. The market barriers are not based market failures per se, but nevertheless contribute to the slow diffusion and adoption of energy-efficient innovations. Market barriers include the low priority of energy issues, capital market barriers and incomplete markets for energy-efficiency. The future path of SSL diffusion is likely to be influenced by these market barriers and failures, which limit the diffusion of currently available clean-energy technologies.

IV. DRIVERS

There are a number of important drivers behind the development and diffusion of LED-SSL into the general illumination market. These drivers discussed below have been grouped into six broad categories: environmental, performance and human interaction, safety, economic, energy, and potential spin-offs.

ENVIRONMENTAL

Energy Savings

Perhaps the most important environmental benefit of SSL is its potential to provide substantial energy savings (DOE, & OIDA, 2001; Tsao, 2002).[32] The energy savings from SSL will reduce CO_2 emissions, a significant contributor to global warming. As was shown earlier in Section III, the two SSL investment scenarios have the potential to deliver a 0.9% or 2.5% reduction from the EIA's projection of CO_2 emissions in 2025.

Furthermore, the inherent nature of LEDs to be point sources of light will allow them to deliver light more efficiently to small areas. Because of this, they are particularly well suited to task-lighting applications. In addition, the directional nature of LEDs means that using LED-SSL outdoors could reduce the "overglow" created by outdoor light pollution in urban areas (Ton et al., 2003). Light pollution is an unwanted by-product of outdoor lighting which results from using inefficient lamps and luminaires, or excessive levels of lighting during the night time (McColgan, 2003).

Mercury Elimination

In addition to the energy-related benefits, LED-SSL contains no mercury; a toxic component used in trace quantities within some conventional lighting technologies such as fluorescent and HID lighting. When mercury-containing lamps are disposed of, the mercury has the potential to end up in landfills or incinerators, becoming a hazard to the environment and human health. Mercury is a known toxic that will cause kidney, nerve and brain damage in adults, children and developing fetuses, upon prolonged exposure.

[32] There are also a number of other environmental impacts, or externalities, associated with the use of energy including natural resource extraction and refinement, distribution, and the impacts associated with building additional electricity generation capacity, but those have not been discussed in this analysis.

Since 1999, EPA has classified mercury-containing lamps as Universal Waste. This classification streamlines their end-of-life handing in an effort to ensure that these lamps are safely recycled and managed.[33] In addition to the federal guidelines, a number of states have promulgated their own (more stringent) hazardous and universal waste requirements for spent lamps. Despite these mercury regulations over lamps, the EPA estimated in 2002 that only 20% of the mercury-containing lamps were recycled. Under an outreach program begun in 2002, the goal was to bring that figure to 40% by 2005, and 80% by 2009 (EPA, 2004).

As SSL gradually replaces fluorescent and other mercury-containing lighting, this will also eventually cut down on the purchase of the mercury-containing lamps. However, it should be noted that in the short-term, the turnover of fluorescent lighting might increase; particularly if the benefits of SSL prove sufficiently enticing that more lighting retrofit projects are undertaken to replace the fluorescent with SSL. This could potentially increase the waste stream of mercury-containing lamps over the short-term.

Despite the toxicity concerns of mercury-containing lamps, it is important to understand their place in the larger context of the mercury cycle. The EPA estimated that only 1% of the 158 tons of mercury released into the environment by human activities came from mercury-contain lamps (fossil fuel combustion sources accounted for 87%) (EPA, 1997). Furthermore, manufactures in the last decade have made significant strides to reduce the quantity of mercury contained in lamps. Fluorescent lamps contained as much as 48 milligrams (mg) of mercury in the early 1990s, but by the end of the decade that amount had decreased to about 23 mg and some cases as low as 10 mg (Daly, 2000). Despite this, mercury is an essential component for fluorescent lamps to operate and will never be completely eliminated.

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[33] For information specifically on the federal regulation classifying spent lamps as Universal Waste see, http://www.epa.gov/epaoswer/hazwaste/id/merc-emi/merc-pgs/fedreg.pdf

Waste Stream Reductions

A benefit of developing LED-SSL luminaries that are thin and compact is that the physical product will contain less raw materials. Furthermore, LEDs used in SSL are projected to have significantly longer lifetimes than traditional lighting technologies. (See Table III-1 for SSL lifetime targets, in comparison to the lifetime of conventional lighting). An extended lifetime could significantly reduce the number of lamps disposed of each year, thereby cutting down on the municipal waste stream. For example, consider comparing two average households, each that uses a lamp (one light bulb) seven hours a day. Family One uses an incandescent lamp (with a lifetime of 1,000 hr), and would need to replace that lamp approximately every five months. On the other hand, Family Two uses a SSL lamp (with a conservative estimate placing the lifetime at 20,000 hr) and would only theoretically only need to replace the lamp just under every 8 years! Thus in this eight year time span, while Family One uses and discards roughly 18 incandescent lamps, Family Two will have used just one SSL lamp.[34]

Despite many of the environmental benefits, hidden-materials flows and potential toxic concerns are among the important environmental issues that are important to consider when analyzing the environmental sustainability of LED-SSL. To date, there have been no full environmental life cycle assessments of this new technology. Section VI of this report will provide a scoping life cycle assessment to address some of these potential environmental concerns.

[34] Based on SSL Roadmap 2002 targets, 100,000 hr was given as a target lifetime of the LED. However it is important to remember that all of the possible components (e.g.,circuitry, power converters, phosphors) must also last just as long or longer- and therefore a more conservative estimate of 20,000 yrs has been adopted in this example.

PERFORMANCE & HUMAN INTERACTION

Performance

The quality of the light provided by SSL will be an important factor in the adoption of this new technology. Solid-state lighting has significant potential to create a new lighting culture, significantly changing how we use and interact with light (Tsao, 2002). This technology offers an array of exciting and new innovative architectural possibilities such as the ability to continuously vary the color of light, the ability to dim the lighting without reducing efficiency, and the potential to design unobtrusive and architecturally blended luminaires and fixtures. In addition, SSL could be easily integrated into advanced building controls, offering a high level of control and programmability. The physical ruggedness of LEDs will also enable them to be more easily integrated into building architectures and materials. Solid-state lighting could also provide companies with unique and innovative ways to establish a "mood" – creating exciting new visual effects and a particular ambience that sets them apart from their competitors.

Innovative Possibilities

The characteristics of SSL have the potential to create a very innovative way to think about lighting. Instead of building in "backwards compatibility" with the existing lighting infrastructure, SSL could be creatively integrated into entirely radical and creative lighting systems. For example, at a National Academies workshop held in 2001, researcher and architect Sheila Kennedy offered several examples of innovative lighting applications with LEDs including: networks of LED lighting loaded into movable housing or office partitions; user controlled colors and patterns of light; and perhaps the most radical – recycled light provided by embedding LEDs in curtains that absorb ultraviolet light from the sun and re-emit it at night into the room as white or colored light (NRC, 2002).

Advantages in Current Applications

Currently, the use of LED-SSL in the commercial sector is expanding from niche applications to providing a larger portion of the lighting in spaces such as retail stores, bars, hotels, casinos, museums, concert halls, churches, building facades, and restaurants (Dowling, 2003). Research has been ongoing to identify opportunities for new applications were LED-SSL could provide improved performance, energy-efficiency advantages, and enhance the human-light interaction. In recent laboratory research by the Lighting Research Center (LRC) of Rensellaer Polytechnic Institute, it was found that study participants strongly preferred the refrigerated display cases lit with a prototype LED system to one lit with traditional fluorescent lighting (Raghavan, & Naredran, 2002).

Human Interaction

The human experience and interaction with artificial lighting is very complex (Tsao, 2002). While the properties of the light emitted by LEDs is fairly well understood, there has been little work on the human physiological impacts of LEDs (Zukauskas et al., 2002). However, Zukauskas et al. (2002) cite that an investigation in 1999 was performed in which laboratory animals were exposed to LED-SSL. This study compared an LED light source to a cool white fluorescent lamp and found that a normal wake-sleep period was maintained and that there was no statistically significant difference between these two light sources in maintaining normal retinal physiology. This research provides early support for the physiological well being of mammals under LED light sources (Zukauskas et al., 2002).

It has been hypothesized that SSL might have positive impact on the level of human comfort and productivity in the workplace, which, in it and of itself, could provide significant economic benefits (Tsao, 2002). For example, a dynamic SSL system could allow the intensity and color of the light to change to suit the particular user and/or their mood or level of activity. Balancing the ratio between task (direct) lighting and diffuse (indirect) lighting could also be a significant factor in the human interaction. In this case, with SSL the individual user could potentially have the opportunity to tailor their own workspace to meet their personal preferences. Accordingly, impacts of SSL on human comfort and productivity in the workplace, in particular could be significant. However, to date there have been no definitive studies to verify this (DOE, 2004).

SAFETY

Safety is an important consideration for new technologies. One inherent advantage of LEDs is that they are low power devices. Since they operate at low voltages, they can provide simpler installation and a higher level of safety for the installer (Ton et al., 2003). The long lifetime of LEDs can be particularly advantageous in applications such as traffic signals, where replacing lighting disrupts traffic flows and poses a potential safety hazard for maintenance crews. When LEDs are used in automobiles they provide a safety advantage because they are able to turn-on an order of magnitude faster (less than a millisecond, compared with over ten milliseconds) than tungsten lamps.

However, despite these safety advantages of LED-SSL, there is some concern because of the high lumen output of a single lamp could create a brightness that might be dangerous for humans to look directly into.(Tsao, 2002) Optics that appropriately diffuse the light from LEDs throughout the room or workspace, will be necessary.

ECONOMIC

Consumer Savings on Electricity Bills

The energy-savings potential estimated by the DOE market penetration model reveals that end-use customers will save approximately $130 billion dollars cumulatively between 2005 and 2025 on their electricity bills from the development and adoption of efficient SSL. By 2025 it was determined that the largest electricity savings will have accrued in the commercial sector. In the commercial sector, approximately $92 billion dollars will have been saved, or about 72% of the total projected savings. Approximately a $13 billion dollar savings was estimated for each the residential and outdoor stationary sectors, along with a $10 billion dollar savings for the industrial sector.[35]

One way to compare the economic case for SSL is based on its lamp ownership cost. Tsao (2004; 2002) derived estimates for future lamp costs based on the scenario laid out in SSL Roadmap 2002 (see Table III-1 in Section III for SSL performance and cost targets). Table IV-1 shows the capital cost, operating cost and ownership costs over the development time period of SSL, compared with average costs for conventional lighting technologies. The capital cost includes the cost ($ per Mlm) to purchase the lamp and the labor cost to replace it when it burns out, both amortized over its lifetime (up to 20,000 hr). The relevant figures for these calculations are based on the SSL Roadmap 2002 and found earlier in the report in Table III-1.[36] The operating cost is the cost ($ per Mlm) to run the lamp – a figure that depends on the cost of electricity (assumed to be $0.07/kWh here) and the luminous efficiency of the lamp. The ownership cost, is then simply the sum of the capital and operating costs. Please note that these costs only include the lamp, and do not take into account associated fixtures.

Table IV-1. Projections of LED Solid-State Lighting Lamp Costs vs. Conventional Lamp Costs

	LED-SSL 2002	LED-SSL 2007	LED-SSL 2012	LED-SSL 2020	Incandescent	Fluorescent	HID
Capital Cost ($/Mlmh)	12.00	1.25	0.30	0.13	1.25	0.18	0.05
Operating Cost ($/Mlmh)	3.50	0.93	0.47	0.35	4.38	0.82	0.78
Ownership Cost ($/Mlmh)	15.50	2.18	0.77	0.48	5.63	1.00	0.83

Source: (Tsao, 2004)
Note: All cost projects are shown in 2002 dollars.

This table indicates that between 2002 and 2007, LED-SSL will cross over the threshold to become competitive with incandescent lighting on an ownership cost basis. On a capital cost

[35] It is important to note that these savings were not discounted in the original report. Using a net present value calculation would substantially lower total savings, particularly because the bulk of the savings don't accrue until after roughly 2018.
[36] Note that a (conservative) LED-SSL lifetime of 20,000 used in the capital calculation.

basis, SSL becomes equivalent with incandescent lighting in 2007. Due to the higher comparative efficiencies and lower capital cost of fluorescent and HID lighting, LED-SSL would not surpass these lighting technologies on an ownership cost basis until roughly 2012. It should be noted also the main expense of incandescent, fluorescent and HID are their operating costs, whereas the main cost of LED-SSL is its capital outlay. Hence, reducing the capital cost will be critical for LED-SSL (Tsao, 2002). It is critical to remember that the targets established by the SSL Roadmap 2002 were aggressive, and hence these calculations that have been derived from those targets represent an aggressive scenario.

One caveat of this calculation is that it does not include the disposal costs for certain lamps. For example, most fluorescent and other mercury-containing lamps must be sent to a recycling facility at the end of life. Incorporating this into the analysis would raise the cost of ownership for mercury-containing lamps and allow SSL to compete with these lamps at an earlier point in time.

ENERGY

Solid-state lighting has the potential to deliver improved lighting service, at a fraction of the energy required by conventional lighting technologies. In the U.S. as well as other developed countries throughout the world, artificial lighting has become an essential component of modern life. The transition from conventional technologies to SSL offers the potential to dramatically reduce the energy consumed for lighting. One important benefit of SSL is that its greater efficiency can lessen the strain on the electricity grid during peak hours of demand, because lighting is a peak-load consumer of electricity.

Perhaps even more significant is the impact that SSL could have in the developing world. The World Bank estimates that 67% of rural populations in developing nations have no access to electricity (Robertson, Craine, Irvine-Halliday, & Stone, 2003). The high cost of establishing an electricity generation, transmission and distribution infrastructure in these parts of the worlds has been prohibitive; thus many of these people in developing nations are left relying on fuel-based lighting. Analysts believe that using SSL in developing countries will be similar to the leap to wireless communications technology that has been made in areas that lack a wired communications infrastructure (Strassberg, 2004).

One of the pioneering organizations devoted to using SSL technologies to enhance the quality of life in developing countries is the *Light up the World Foundation*.[37] This humanitarian organization was established by Dr. David Irvine-Halliday from University of Calgary. The organization uses donor and local social entrepreneurial means to bring clean, reliable, safe and affordable home lighting to villages in developing countries that lack electricity. This has been accomplished in over a dozen countries so far, by coupling low power-consuming high brightness LEDs with complementary renewable energy technologies such as solar photovoltaic (Robertson et al., 2003).

SPIN-OFFS

The materials science and engineering that forms LED chips are compound semiconductor materials such as aluminum gallium indium nitride (AlGaInN). These materials systems are also used in a number of technologies critical to national security (Tsao, 2002). For instance, they are used in high-powered electronics for wireless and radar applications, solar-blind detectors used to detect missile launches, and as UV light sources for detecting biological and chemical agents. The SSL-LED technology is also well suited to be a source of lighting for military personnel in extreme environmental conditions because of its high resistance to impact and vibrations, its compactness, and its low power consumption.

V. CHALLENGES

There are a number of challenges to be overcome before SSL expands from niche applications into being widely used for general illumination. These challenges, sometimes also

[37] More information on the Light Up the World Foundation can be accessed at: http://www.lutw.org/

referred to as "barriers," have been identified and grouped into three categories: technical, infrastructure and market barriers.

The challenges discussed below are predominantly based on reports from meeting and workshop, which have been held between government, industry and academia experts to discuss the challenges facings SSL. These sources include: two SSL industry roadmaps (DOE, & OIDA, 2001; Tsao, 2002), a SSL program planning workshop hosted in Fall 2003 by the DOE (DOE, 2004), and a National Academies workshop in 2001 (NRC, 2002).

TECHNICAL

There are a host of technical barriers that must be surmounted before a new lighting "paradigm" based on SSL comes to fruition. The SSL research and development (R&D) initiative by the DOE is currently focused in six critical technical areas: quantum efficiency, packaging, longevity, infrastructure, stability and control, and cost reduction (DOE, 2004). The funding for SSL R&D through 2003 totaled $31 million (DOE, 2003c); which represents a very small fraction of the estimated $500 million government dollars needed to develop SSL. This government investment, combined with a matching investment from the private sector of a $500 million dollars over the next ten years is expected to reach the performance and cost objectives which have been established for SSL (see Table 3-1).

In this section, these technical challenges have been further broken down into three areas: performance, cost, and packaging. The level of detail has been held to a minimum, but a more technical discussion of these challenges can be found in the 2002 SSL Roadmap (Tsao, 2002).

Performance

Luminous Efficiency: The energy-efficiency of white LED-SSL must improve substantially. The overall luminous efficacy measured in lumens per watt (lm/W), of the device is technically a product of the efficiencies of a multi-step process. This process takes the electricity from the power grid, converts the electricity into the current and voltage required by the LED device, feeds the current into the chip, creates photons, extracts photons from the chip, transforms these photons into broadband white light, and finally, delivers this white light to the viewer. While each stage of this process could theoretically be 100% efficient, in practice there are difficulties associated with every stage of the process that reduce efficiency. A 100% power conversion efficiency for a SSL system is about 400 lm/W, and the DOE is targeting a system efficiency of 50%, or 200 lm/W (Tsao, 2002).[38] Quantum efficiency is one of the six critical technical areas the DOE is concentrating on. The quantum efficiency encompasses the internal quantum efficiency of converting electrons and holes into photons, and the external quantum efficiency of extracting those photons out of the chip.

Currently, white LED products on the market have efficiencies of approximately 25-40 lm/W, with laboratory prototypes as high as 60-70 lm/W. The target goal established through the 2002 SSL Roadmap was ambitiously set at 200 lm/W for 2020. In contrast, Arpad Bergh, the president of the Optoelectronics Industry Development Association (OIDA) has suggested that an end goal of 120 lm/W might be more realistic (Tsao, 2004).[39] The SSL market penetration model (DOE, 2003b) differentiated SSL efficiency improvements in the accelerated investment scenario, based on the CRI value of the light: the highest quality light (termed "very high CRI") reached 140 lm/W by 2025, while the lowest quality light ("low CRI") reached 225 lm/W in 2025.[40] These differentiation by CRI is because R&D on SSL in the low CRI range has been underway for longer than R&D on higher CRI SSL, and also because of the technological hurdles are greater in creating higher CRI SSL (DOE, 2003b). A significant barrier to creating the RGB white LED light is the relative inefficiency of the green LEDs. Currently the efficiency of green LEDs is lagging red LEDs by a factor of 6-8 (Tsao, 2004).

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[38] This 400 lm/W efficacy corresponds to a RGB LED white light source with a moderate CRI of 80 and a relatively warm CCT of 3900 K.
[39] The goal of 120 lm/W is consistent with the goal of the Japanese Akari Project to develop SSL, however they established 2010 as the year to reach this target.
[40] However, in the moderate investment scenario the low CRI SSL reached only 160 lm/W and the very high CRI reached only 65 lm/W, by 2025.

Lifetime: Solid-state lighting is expected to achieve impressively high lifetimes of 100,000 hours, far exceeding the lifetimes of conventional lighting technologies (that range from 1,000 hr for incandescent, 10,000 hr for fluorescent, and 20,000 hr for HID) (Tsao, 2002). The DOE market penetration report estimates that in an accelerated investment scenario, SLL in all CRI quality bins will reach 100,000 hours by roughly 2020 (DOE, 2003b).[41] It is important to realize that "lifetime" has been defined in different ways, depending on the light source. For example, in the case of incandescent lamps the lifetime was taken to be the point at which 50% of the lamps would fail by burning out. However LEDs operate very differently; instead of suddenly burning out, their luminous output gradually depreciates over time. Therefore, a more commonly accepted definition of "lifetime" for LEDs has been to consider it to a 50% depreciation in the lumen level (Tsao, 2002). However this definition is not universal: Lumileds for example, one of the leading LED manufactures specifies that its Luxeon LEDs as having an average lumen maintenance of 70% at 50,000 hr (Whitaker, 2004).

The longevity of SSL is also one of the current focus areas for R&D the DOE has funded between 2000 and 2004. Some of this research is to explore materials science issues related to impurities, defects, and crystal structures of different materials systems. One crucial element that underpins the longevity of a LED chip is efficient thermal management. Despite the high efficacies that LED-SSL are expected to reach, it will not be 100% efficient and there will be some waste heat generated (Tsao, 2002). The small size of an LED chip (on the order of .25 - 2.5 mm^2) means that the heat generated is concentrated in an extremely small area. There must be some kind of heat sink to siphon away this excess heat so that the high temperatures don't adversely affect the P-N junction where photons are created. Furthermore, if the intensity and color of light from the LEDs drift over time, then the system will need to be equipped with the necessary controls to compensate and retain a consistent white light output over the lifetime of

[41] In the case of the moderate investment scenario, the SSL lifetime improvements by 2025 reach only 65,000 and 80,000 hr for very high and low CRI SSL, respectively.

lighting system. An additional current challenge is that the lumen depreciation over time is a function of a number of factors, including operating conditions and the manufacturer (Whitaker, 2004).

Despite the potential longevity of LED chips, it is important to realize that a SSL lamp will be a system of components. A system is only as strong as its weakest link. While the LED itself might be the "light engine" of this system, the longevity of the system's components such as the drive electronics, the encapsulant, and potentially the phosphorus coating, are examples of necessary SSL components that will require equally, if not longer, lifetimes.

Color Quality: The quality of lighting is a difficult metric to capture because it not only relies on the lighting technology in question, but also on the properties of human vision. The color quality of lighting has conventionally been measured using two metrics: color correlated temperature (CCT) and the color rendering index (CRI). These two metrics are summarized below.[42]

Color correlated temperature (CCT)

One attribute of a light source is the color it appears when viewed directly, or when it is illuminating a perfectly white object. The color correlated temperature (CCT) is a metric that represents the temperature of a blackbody whose perceived color most resembles the light source in question. This metric is expressed in degrees Kelvin (K). Lamps with low CCT (3,000 K and below) emit "warm" white light that has yellowish or reddish hues. Lamps with high CCT (3,500 K and above) emit "cool" white light that appear bluish in color (Atkinson et al., 1995).

Color rendering index (CRI)

The color rendering of a light source represents how faithfully it renders the color of non-white objects it illuminates. The comparison of how faithfully it renders this object is

[42] For more information on lighting metrics, see the Commission Internationale de l'Eclairage (CIE), at http://www.cie.co.at/cie/

compared to a “perfect” reference light source with the same CCT. The CRI is a scale and it ranges from 0 to 100, in which 100 the “best.” The higher the CRI, the smaller the difference is in the perceived color of the test objects, between the source and a reference.

Unfortunately neither of these metrics is perfect and furthermore, these metrics have been deemed unsuitable for characterizing light from LED-SSL because of the inherent narrow broadband emission of LEDs. For instance in recent research, the LRC performed a human subjects experiment using several white LED reading lights compared side-by-side with halogen and incandescent reading lights.[43] The study found that RGB white LED lights were preferred over both the halogen and incandescent lights. However, of the two RGB white LED lights, human participants had no preference between the CRI of 23 and the CRI of 63, indicating that CRI is not a good predicator of color preference (Narendran, & Deng, 2002). Ton et al.(2003) suggest that the use of these conventionally used metrics could actually hinder the adoption of LED-SSL. Therefore, an important challenge for the development of LED-SSL will not only be to improve the quality of the LED-SSL light, but to be sure that appropriate metrics are in places that accurately convey the quality of LED-SSL light to the purchasers in the market.

When lighting designers use LEDs, one problem they currently face is the high degree of color variation within batches of white LEDs. This can be particularly problematic in applications requiring large number of white LEDs that are viewed side-by-side (Whitaker, 2004). Furthermore, penetration of LED-SSL into the general illumination will require that this lighting not only have acceptable light quality, but is also able to meet the stringent requirements for color rendering stability, color temperature stability, and brightness uniformity.

[43] For more information on the experiment see: http://www.lrc.rpi.edu/programs/solidstate/completedProjects.asp?ID=54

Cost

The cost of white LED-SSL needs to be significantly reduced in order to be competitive with traditional lighting technologies in general illumination applications. The cost reduction estimated in the 2002 SSL Roadmap went from $200 per klm in 2002, to $20 per klm in 2007, $5 per klm in 2012 and finally, $2 per klm in 2020; a 100X total reduction (Tsao, 2002).[44] Estimates are given in the 2002 SSL Roadmap on three ways these cost reductions can be accomplished – they include increases in power-conversion efficiency, increasing the power density to the chip while improving its thermal management, and decreasing costs of chip manufacturing.

Packaging

Packaging is a very important aspect of the white LED-SSL system because of the large impact it has on the efficiency, life and cost of the LED-SSL devices. However, to date this area has received less attention and the R&D focus has predominately concentrated on new materials and lowering the costs of manufacturing (Ton et al., 2003).

The LED chip(s) must be packaged into some form of a lamp, which will include an encapsulant, a heat sink, and possibly phosphors for light conversion. The lamp then will be inserted into a luminaire, or fixture, which directs the light into the appropriate area. The drive electronics can either be incorporated into the lamp itself or a separate module. Currently, there is no consistent approach to creating this type of system. However, packaging will be an important consideration particularly for maximizing the energy-savings potential of LED-SSL.

INFASTRUCTURE

As performance of white LED-SSL improves and costs are reduced, they will be able to compete for market share in the general illumination market. However, because the technology is still very young, to date there has been more of a focus on materials and manufacturing R&D areas, and relatively less R&D on LED systems. Hence, issues of socket compatibility and other

[44] All prices are in "street prices" and it can be inferred that the OEM price would be roughly less, by roughly 2X.

codes and standards will still need to be addressed down the road, before the widespread adoption of LED-SSL will occur.

Compatability

The question still looms of whether the future of LED-SSL will be direct replacements for existing lighting sockets, or whether a new lighting infrastructure will be created, independent of the “bulb culture” (Tsao, 2002). On one hand, accelerating near-term adoption could be accomplished by making LED-SSL devices that come with the necessary circuitry and are able to fit into existing sockets. In fact a few such Edison-socket LED bulbs are commercially available today.[45] In addition, many of the energy-savings estimates have been predicated on the assumption that SSL will be able to be used in existing sockets (DOE, 2001, 2003b; Drenner, 2001). Energy-savings in general illumination lighting over the next two decades would be significantly reduced if LED-SSL is only available for new building construction or large lighting retrofit projects.

But on the other hand, creating a new lighting infrastructure based on the unique and innovative characteristics of SSL could be a critical driver in its success in the general illumination market. The innovativeness is currently driving LEDs into specially niche applications such as the façade of a building and accent lighting in retail stores. For instance, according to Kevin Dowling, the vice-president of strategy and technology at the LED company Color Kinetics “Most Color Kinetics installations are not driven by energy savings, although the benefits are still there” (Whitaker, 2004). Rather, Dowling cited in a recent article that customers using LED-products are more focused on the achieving unique visual effects and ambiance (Dowling, 2003). In conclusion, it remains unknown how LED-SSL devices will compete in the general illumination market.

[45] See http://ledmuseum.home.att.net/ for a wide overview and review of currently available LED products.

Codes and Standards

The revolutionary nature of LED-SSL in the lighting market will necessitate that accompanying codes and standards be developed alongside this new technology. New guidelines for installation, and product certifications (for instance the UL provided by the Underwriters Laboratory) must be developed.[46] There are number of standards setting bodies for lighting, such as the Illuminating Engineering Society of North America (IESNA), the Commission Internationale de l'Eclairage (CIE), and the National Electrical Manufactures Association (NEMA). Common "sockets," allowing for lamp interchangeability will be necessary if consumers are feel confident that the LED-SSL lamp they purchase will fit into an existing fixture.

Unless new metrics are developed and embraced by the lighting community, it is likely that final users will compare LEDs to conventional lighting technologies as well to other LEDs, using CRI and CCT. Because these metrics are not well suited for LEDs, it is possible that using them could actually impede the diffusion of LED-SSL. Standardizing the metrics (such as the rated lifetime of the LED-SSL device) will be important so that end-users can comparatively evaluate using LED-SSL from different manufactures, as well as compare LED-SSL against traditional lighting technologies.

MARKET

Existing Lighting Market Structure

Since LED-SSL promises to be a highly innovative and energy-efficient way of providing lighting service, it will likely be a disruptive technology in the existing general illumination market that is dominated by incandescent, fluorescent and HID lamps. However, displacing older lighting technologies is likely to be challenging, in part because the vertically integrated structure of the mature lamp industry. Many of these industries are not set up to buy their

[46] The Underwriters Laboratory has evaluated LED lighting systems and components for applications such as exit signs, traffic lights, and general lighting. For more information see: http://www.ul.com/lighting/led.html

components from third parties, but none of them currently manufacture the LED chips that are the heart of LED-SSL. Furthermore, many end-users now require highly specialized lighting products; this has resulted in a highly fragmentized lighting industry.

A January 2004 conference titled "LEDs: Meeting the Design and Performance Challenges" was slated towards lighting designers and end-users in the industry, but also brought in some LED manufactures. The meeting highlighted a disconnect between these two communities, revealing that more communication between them will be important for realizing the potential of LED-SSL. While manufactures of LEDs are working feverishly to increase the brightness and efficiency of their devices, many members of the broader lighting community remain unsure of how to use this new technology in their products and designs (Whitaker, 2004). Meeting participants also identified standardization as a significant problem for companies that are looking to evaluate the costs and benefits of using LEDs over traditional lighting technologies. Even comparing LEDs from different manufactures is difficult because the industry is relatively new and common standards have not yet been established (Ton et al., 2003).

Consumer Acceptance

There is a substantial body of literature that has concentrated on explaining the so-called energy "efficiency-gap." That is, while technologies appear to be economically cost effective on a life cycle cost basis, consumers fail to adopt them. Thus there is a gap between the level of cost-effective energy-efficiency possible, and the actual level of energy-efficiency that exists. Jaffe et al. (1994) provide an overview of this efficiency-gap.

For instance, a major prerequisite for consumer acceptance of LED-SSL will be education. While many consumers are familiar with small LED indicator lights found on electronic equipment, they are likely to be much less familiar with LED-based lighting used for illumination purposes. This unfamiliarity applies to many end-users of lighting, including lighting designers, installers, building inspectors, government officials, and residential and commercial users (Ton et al., 2003).

VI. SOLID-STATE LIGHTING: SCOPING LIFE-CYCLE ASSESSMENT

Solid-state lighting using LED technology has the potential to create an entirely new lighting culture, as well as provide substantial energy-savings. Despite this, a holistic assessment of the potential environmental impacts from LED-SSL has not been performed. This type of holistic assessment would take into account the environmental impacts extending throughout the LED-SSL product's life cycle, from "cradle-to-grave."[47] The potential environmental benefits from highly efficient LED-SSL are important. Nevertheless, the energy-efficiency of LED-SSL while it is used to provide lighting service is only one aspect of the impact this lighting technology will have on the environment throughout the course of its life cycle.

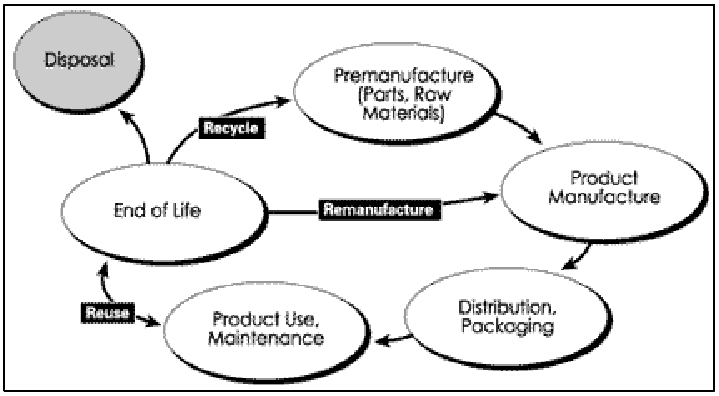
Life cycle assessment (LCA) is a methodological framework for estimating a product's environmental impact throughout its life cycle (Rebitzer et al., 2004).[48] Environmental impacts such as climate change, ozone creation, toxicological stress on human heath, the depletion of resources, and may other impacts, can be estimated using LCA. The LCA framework can serve as a decision tool, allowing practitioners to comparatively assess alternative products, to determine which one has less environmental impact. It can also support the identification of pollution prevention opportunities and resource reduction opportunities.

Figure VI-1 shows the stages in a typical product's life cycle, from raw materials extraction through final end-of-life.

[47] "Cradle-to-grave" refers holistically to all stages of a products life cycle, from raw material extraction all the way through end-of-life.

[48] For recent review on the methodology of LCA, see (Rebitzer et al., 2004). The EPA LCA website also provides valuable information on LCA: http://www.epa.gov/ORD/NRMRL/lcaccess/index.htm

Figure VI-1. Simplified Flow of a Product's Life Cycle



Source: (Yarwood, & Eagan, 2001)

While LED-SSL has tremendous potential, the technology is still in its infancy and there still are basic lamp, chip and design choices being actively debated (Tsao, 2004). There are no publicly available studies, which address life cycle or disposal issues explicitly for LED-SSL. A complete life cycle assessment was deemed to be inappropriate for this report due to time constraints, a lack of publicly available data, and finally but perhaps most importantly, the multitude of possible materials choices and design strategies still being debated. Hence, the purpose of this scoping life cycle assessment is to assess potential significant environmental impacts of LED-SSL throughout its life cycle. This scoping life cycle assessment is primarily qualitative, but will include some quantitative estimates where possible. It focuses on (1) the material systems commonly used in LEDs today and potential toxicity concerns, and (2) energy consumed throughout the life cycle of LED-SSL.

MATERIALS

Currently there is no consistent way to make a "white" LED, and R&D pursing a number of different technology pathways is ongoing (see Section III). Consequently, this section will explore the materials and material systems commonly used to create LEDs, but will not focus on a single device. Future LED-SSL will come as a system of components in addition to the LED light source, but these components have not been considered here. The chemicals used to manufacture LEDs are used throughout the semiconductor industry. Many of these chemicals are highly toxic substances; however they too have been excluded from the scope of this analysis.

The LED

The current generation of “white” light LEDs generally resembles those seen in Figure 3-2 (Section III). The components of this type of LED package typically include: [49]

Substrate: The substrates on which LEDs are grown, or are transferred to can be geranium (Ge), sapphire (Al_2O_3), silicon carbide (SiC), silicon (Si), zinc oxide (ZnO), gallium phosphide (GaP) or gallium arsenic (GaAs). Gallium nitride (GaN) or aluminum nitride (AlN) could also be used, but the growth of these materials is in its infancy.

Epitaxial layers and dopants: Ternary and quaternary alloys make up the materials systems used HB LEDs. These alloys typically contain a mixture of aluminum (Al), gallium (Ga), and indium (In) cations, and a mixture of arsenic (As), phorphorus (P) or nitrogen (N) anions. The three materials systems commonly used to make the HB LEDs include:

Aluminum gallium arsenide (AlGaAs): Emits in the red end of the spectrum.

Aluminum gallium indium phosphide (AlGaInP): Emits in the red-orange-amber yellow end of the visible spectrum.

Aluminum indium gallium nitride (AlInGaN): Emits in the green and blue parts of the visible spectrum as well as in the ultra violet (UV). However, it theoretically spans the entire visible spectrum.

The latter two systems of materials are known as III-V compounds, because they include elements from the third and fifth columns in the periodic table of elements. The 2002 SSL Roadmap cited that these two materials systems are the primary focus for

[49] Information on materials systems and elements used in LEDs was gathered primarily from (Zukauskas et al., 2002); and (Tsao, 2002).

creating SSL, because they have the ability to span wide portions of the spectrum, can be easily tailored into nanostructures, and are sufficiently robust to withstand manufacturing and operation conditions (Tsao, 2002). Dopants are added to change the electrical properties of these materials. Commonly used dopants include tin (Sn), tellurium (Te), silicon (Si), magnesium (Mg), and zinc (Zn).

Contacts: The contacts (or electrodes) form the pathway through which the current is fed. Gold (Au) in combination with Ge or Zn, is often used for AlGaAs and AlGaInP based LEDs. Electrodes for AlInGaN LED can be either be Au and Al, titanium (Ti)/Al, or Au/nickel (Ni).

Encapsulants: To maximize the light that is extracted from the LED die; clear materials with higher refractive index are used. Typical encapsulates are acrylics, epoxies and silicones. These encapsulants also function to protect the chip from mechanical handling and various environmental conditions.

Thermal heat sink: The thermal heat sinks are vital to maintaining the performance of HB LEDS, and can be made of aluminum, copper or a conductive ceramic material.

Phosphors: These materials can be used in conjunction with a blue or UV emitting LED, the phosphors absorbing part of the light from the LED and re-emitting it at longer wavelengths such as yellow, blue, green or red. Early commercial "white" LEDs used a blue LED and YAG (yttrium aluminum garnet) activated with trivalent cerium ($YAG{:}Ce^{+3}$).

To further limit the scope of a materials toxicity analysis, it was decided that toxicity information would only be gathered on the elements commonly used in the epitaxial layers of the LED chip.

Constituent Toxicity

The potential toxicity of the metals and selected compounds used in LEDs was assessed using several sources of environmental chemical/materials information. These sources include:

the EPA Integrated Risk Information System (IRIS); Scorecard – an online environmental information portal provided by Environmental Defense;[50] and Materials Safety Data Sheets (MSDS). It was also noted when one of the elements and/or compounds was cited on a list as subject to a particular regulation. Data was gathered from the U.S. Geological Survey (USGS) Materials Commodity Summaries and Mineral Yearbook, to determine the quantity of each element that is used in electronics applications, and if possible, LEDs specifically. Below the results of preliminary data gathering are shown for each element considered, and select compounds. The Chemical Abstract Service (CAS) registry numbers are also provided.

Arsenic (7440-38-2): According to Scorecard, arsenic is ranked as one of the most hazardous materials, and is a known carcinogen and developmental toxin. It appears on multiple federal regulatory lists. It is federally regulated as an air contaminant under the Occupational Health and Safety Act (OHSA); a hazardous air pollutant under the Clean Air Act (CAA); a hazardous constituent under Resource Conservation and Recovery Act (RCRA); a hazardous substance under Superfund; the Clean Water Act (CWA), the Safe Water Drinking Act (SWDA) and the Toxic Release Inventory (TRI). It is also subject to specific regulations in the state of California.

Gallium arsenic (GaAs) and indium arsenic (InAs) electronics applications require high purity (99.9999%-pure) arsenic metal. The USGS estimates that the U.S. consumed 19,600 metric tons of arsenic in 2002, of which 88% was used as wood preservatives (Brooks, 2003). Only about 3%, (650 metric tons) of arsenic was used as nonferrous alloys and electronic applications. Arsenic is also used in agricultural chemicals (insecticides, fertilizers and herbicides), as a pigment, and in glassmaking. The U.S. is the largest consumer of arsenic in the world and 100% of its demand is met by foreign imports. Arsenic is not recovered from consumer end-product scrap, but the GaAs scrap in

[50] The Scorecard database of chemicals is available at http://www.scorecard.org/chemical-profiles/

semiconductor manufacturing was reprocessed for gallium and arsenic recovery (Brooks, 2004).

Aluminum (7429-90-5): Aluminum is a high volume material that is used in a number of different industries. Aluminum powder causes irritation to eyes and the respiratory tract, and may affect the lungs and skin. It is not considered toxic by ingestion.[51] It is federally regulated as an air contaminant under OHSA, a registered pesticide under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), and is listed on the TRI.

In 2003 the U.S. consumed 6,500 million metric tons of aluminum. According the USGS, the transportation industry accounted for 35% of domestic consumption of aluminum, and the packaging and container industry accounted for 24% (Plunkert, 2003). While 8% of aluminum was used in electrical equipment, no estimate was given for the percent used specifically as an element in semiconductor compounds. However, it is quite likely almost negligible in comparison to overall domestic consumption.

Gallium (7440-55-3): The MSDS sheets consulted cited that the toxicology of gallium has not been fully investigated. It is regarded as a potential skin, eye, and respiratory irritant, may cause nausea and vomiting upon digestion and may cause chronic bone marrow abnormalities.[52] Gallium is not in the IRIS database and is not listed by Scorecard as being on any regulatory lists.

Semiconductor applications which use GaAs and gallium nitride (GaN) consume about 98% of U.S. domestic gallium consumption (Kramer, 2004). According to the USGS, 42% of gallium was used in optoelectronic devices (including LEDs, lasers, photodetectors and solar cells), 49% was used in microcircuits and the remaining 9% was used in R&D, specialty alloys and other applications (Kramer, 2004). The U.S. consumed a reported 26,000 million kilograms of gallium in 2003, a demand that was met almost entirely by

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[51] Toxicity information obtained from Aluminum MSDA http://www.jtbaker.com/msds/englishhtml/a2712.htm

[52] The MSDS was found at: http://www.acialloys.com/msds/ga.html

imports. While no old scrap was reported to be recycled, "substantial quantities" of new scrap generated during GaAs manufacturing was recycled (Kramer, 2004).

Indium (7440-74-6): Like gallium, the toxicology data on indium is incomplete. A MSDS cites that indium is a skin irritant, may cause respiratory irritation and may be harmful if swallowed.[53] According to Scorecard, indium is listed on one regulator list as an air containment regulated by California Occupational Heath and Safety. Indium is not listed in the IRIS database.

The U.S. consumed 115 metric tons of indium in 2003, all of which were imported (Jorgenson, 2004). Currently, the largest end-use of indium is for thin film coatings found on liquid crystal displays (LCD) displays and electroluminescent lamps, accounting for about 65% of U.S. consumption in 2003. Of the remainder that was consumed by the U.S. in that year, 15% was for solders and alloys, 10% for semiconductors and electrical components, and 10% for R&D and other uses (Jorgenson, 2004).

Select Compounds

GaAs (1303-00-0): Although quantitative data was not found comparing GaAs and silicon (Si) explicitly, it is estimated that there are higher economic and environmental costs associated with the use of GaAs than with Si. According to Swartzbaugh et al. (1998), GaAs is not a waste that is specifically regulated except in California. While arsenic is a low cost metal and offers very little incentive itself for reclaiming and recycling, gallium and indium are relatively scarce, more costly, and obtained almost entirely through imports. Hence, these metals provide an incentive for the waste minimization and recycling of compounds such as GaAs and InAs.

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[53] The MSDS was found at: http://www.kester.com/MSDS/USA%20and%20Canada/English/Bar%20Solder%20and%20Metals/MSDS%20Indium%20US%20(26Sep03).PDF

Flora (2000) reviews the health risks posed by these III-V compounds and cites that it is now well known that GaAs produces a definitive adverse effect on the pulmonary, haematopoietic, and immune systems.

InP (22398-80-7): This compound was added to in February 2001 to California's proposition 65 list of chemicals that are recognized carcinogens. A MSDS reveals that InP is a toxic upon inhalation and if swallowed.[54]

While silicon remains the dominant material used in the semiconductor industry, in the last ten to twenty years there has been a significant expansion in the popularity of compound semiconductors. The potential environmental health and safety (EH&S) issues from the compound materials used in LED-SSL need to be comprehensively addressed. In the last twenty years, similar concerns have been raised over the toxicity of constituent materials and chemicals used in the manufacturing for photovoltaics.[55] While both LEDs and photovoltaic use compound semiconductors, much of the photovoltaic technology is based on II-VI semiconductors (from the second and sixth columns of the periodic table), whereas many of the LED materials are III-V semiconductors (Swartzbaugh, & Sturgill, 1998).

Flora (2000) reviews the possible occupational health hazards in the semiconductor industries that use toxic metals such as GaAs, InAs and InP. These intermetalic compounds are viewed as possible health risks to semiconductor manufacturing workers who are exposed to their airborne particles. Toxic effects appear to be due to inhalation or oral exposure and may result in poisoning, although the degree of risk has not been quantified. According to Flora (2000), a risk assessment of these compounds is difficult because of the lack of data on the toxicology of these compounds. Most toxicity is currently estimated based on the knowledge that these compounds

[54] The MSDS was found at: http://www.wafertech.co.uk/msds/msds_InP.html

[55] The National Renewable Energy Lab's National Center for Photovoltaics has a bibliography if EH&S issues related to photovoltaics: http://www.nrel.gov/ncpv/eshbib.html

will dissociate into their constituent elements (both *in vitro* and *in vivo*), and on the toxicity data of inorganic arsenic.

Despite the toxicity concerns, it should be recognized that opportunities for materials substitutions are oftentimes limited in the semiconductor industry. Swartzbaugh et al. (1998) cite that while significant strides have been made in developing cleaner substitutions for materials used in manufacturing processes, the replacement of the "toxic" semiconductor materials (e.g., lead, cadmium, mercury, or selenium) would be far more time-consuming.

Pollution Prevention

Previous research analyzed the technical and economic potential of reducing arsenic wastes in the semiconductor industry, under a grant funded by the EPA Office of Research and Development (Swartzbaugh, & Sturgill, 1998). As a result of this research, Swartzbaugh et al. (1998) recommended that two processes for arsenic and gallium recovery (one from GaAs solid waste and a second from GaAs polishing wastes) be implemented as in-plant pollution prevention techniques. They found that these techniques would be economically advantageous in both the short term (by minimizing or eliminating the amount of toxic arsenic that is disposed of from facilities) and the long term (by reducing future liability costs associated with environmental cleanup). Furthermore, they determined that because of the similarity of chemistry and physics that underlie III-V semiconductors, with slight modification these recovery techniques could be expanded beyond GaAs to other III-V materials systems. Currently, no estimation could be found on the percentage of new scap recovery that is occurring in the U.S. semiconductor facilities.

No Mercury

One important benefit of LED-SSL is that it contains no mercury, a highly toxic substance that is found in all fluorescent and many HID lamps (see Section IV). Despite containing no mercury, it is too early to conclude that there are no environmental risks posed by the disposal or incineration of LEDs. Ton et al.(2003) cite that materials researchers claim that any toxins in the devices are tightly bonded chemical molecules, or are encapsulated in epoxy. Therefore, they conclude that disposing of LEDs in a landfill is not anticipated to be a problem. The EPA procedure for waste classification (e.g., hazardous or non-hazardous) under the Resource Conservation and Recovery Act (RCRA) is the toxic characteristic leaching procedure (TCLP). This procedure attempts to simulate the conditions of waste as if it was in a landfill. Samples that are tested using this procedure are then analyzed to determine if certain chemical or metal constituents are present above the threshold TCLP concentration level, in which case it would classify as a hazardous waste. The details of this procedure are outlined n the EPA publication SW-846 entitled *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods.*[56]

No studies or tests were found that explicitly address the disposal issues of LEDs.[57] Uryu et al. (2003) assessed the environmental fate of GaAs contained in mobile phones, and determined that a greater amount of arsenic is emitted from air and leached from the ash residue when these devices are incinerated and then the ash is disposed of in a landfill, in comparison to the discarded phones being placed directly in the landfill. They therefore suggest that the phones be directly placed in landfills rather than incinerated.

Because of the costs associated with the handling of spent mercury-containing lamps, it appears to be an issue that is on the radar of those in the SSL industry. In the 2002 SSL Roadmap, it is stated:

> The materials from which luminaires are constructed are a final critical area…The second [key area] is related to the life cycle of the luminaire, especially its end-of-life disposal. For traditional mercury-containing fluorescent lamps, disposal costs are significant. For solid-state lighting, one important challenge will be to ensure that there are no similar end-of-life disposal costs. This means the use of non-toxic materials (e.g., lead-free solders) throughout the chip, lamp and luminaire. It also means assessing disposal issues related to materials that are mildly

[56] The guidelines for the TCLP can be found in the SW-86 manual which is found online at: http://www.epa.gov/epaoswer/hazwaste/test/sw846.htm

[57] Ton et al. (2003) also addressed some of the potential environmental life cycle concerns and also found no studies focused on the disposal of LEDs.

toxic, such as the GaAs substrate used in AlGaInP-based red LEDs. We note that in this example, it would not be difficult to switch to a non-toxic Ge substrate if necessary (Tsao, 2002). p.90

Impact on Waste Stream

LEDs are made from chips on the order of 0.5-2.5 mm^2 and are compact sources of light. Accordingly, a benefit of developing LED-SSL is that the physical product will be comprised of fewer raw materials. Although the technology is still in its infancy and final lamp/luminaire designs have yet to evolve, it is likely LED-SSL will reduce waste stream of spent lamps. Furthermore, the projected longevity of LEDs (up to 100,000 hours) would significantly extend the lifetime of the lighting technology and would reduce the quantity of spent lamps that enter the waste stream.

Recycling in the semiconductor industry runs up against unique constraints, because of the extremely high purity standards (oftentimes purity less than 99.999% can't be tolerated), in contrast with typical manufacturing industries that generally consider a purity of 90% to be acceptable (Swartzbaugh, & Sturgill, 1998).

ENERGY

The energy-efficiency potential of LED-SSL has been a critical driver in the push to accelerate the development of this emerging technology. However from a life cycle perspective, it is important to take into account how much energy is consumed through all stages of the product's life cycle, and not only during it's use-phase. In particular, semiconductor manufacturing which is used to produce LEDs is a highly energy intensive process and therefore could potentially reduce the overall energy-savings of LED-SSL over conventional lighting technologies.

Ideally, a LCA would determine the energy consumed for a LED-SSL device over its entire life cycle (including raw materials extraction and processes, manufacturing, packaging, use, end-of-life, and transportation between all of these stages). This energy requirement could then be compared to the energy required over the life cycle for a traditional lighting technology.

Gydesen et al. (1991) performed a LCA, comparing a compact fluorescent lamp (CFL) to an incandescent lamp. This assessment focused on energy consumption and emissions. The CFL was a 15 W lamp with an integrated ballast,[58] a luminous intensity of 900 lm, and a lifetime of 8000 hr. The incandescent lamp was an ordinary 60 W lamp, with a luminous intensity of 730 lm, and a lifetime of 1000 hr (no ballast required for incandescent lamps). The total energy requirements for producing, operating, and scrapping each lamp is shown in Table IV-1.

Table VI-1. Energy Life Cycle Assessment of Two Lamps: Incandescent vs. CFL[1]

Product Stage	Incandescent Lamp	Compact Fluorescent Lamp
Production	0.21 kWh	0.19 kWh
Use	82.2 kWh	16.7 kWh
Scapping[2]	-	-
Total	**82.4 kWh**	**16.9 kWh**

Source: (Gydesen, & Maimann, 1991)
[1] Energy requirements for each stage were normalized to assume that both technologies would be required to produce 10^6 lm-hr.
[2] The energy requirement during the scrapping phase was deemed to be negligible.

Based on this analysis, a CFL would consume only 21% of the energy consumed by an incandescent lamp over a defined period of lighting service.[59] It is also evident that the vast majority (approximately 99%) of the energy consumed over the lifetimes of both lamps is done so during the use-stage.

How would an LED-SSL lamp compare to the incandescent and CFL? Currently, several LED-SSL lamps are available on the market as direct screw-in replacements for incandescent lamps.[60] The basic form of these lamps looks very much like an incandescent lamp, however LEDs are used as the light source, as opposed to a the filament used in incandescent lamps.

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[58] CFLs come either as integrated ballast (the lamp and the ballast are one unit) or as a modular unit (the lamp and the ballast are separate).
[59] Gydesen et al. (1991) based their energy consumption requirement for production of these two light sources on a previous analysis, which was cited as paper written in German. Hence, it was not possible to track this reference.
[60] For an example of these lamps see: www.bocaflasher.com

Hence, the production energy of a LED-SSL replacement lamp could be very roughly approximated by adding the production energy of a typical incandescent lamp, to the production energy of an LED.

For the purposes of this analysis, a hypothetical LED-SSL "lamp" is used, which can screw directly into an Edison socket.[61] This LED-SSL will take on the shape of an incandescent lamp, but will use just one LED chip as its light engine.[62] Future LED-SSL performance targets for 2020 are adopted from the 2002 SSL Roadmap for this analysis.

Very little data could be found on the energy consumed for particular semiconductor-manufacturing processes, and none was found for processes that involved compound materials such as GaAs or AlInGaP. Because LEDs are manufactured in a semiconductor fabrication facility, it was decided that an alternative semiconductor product would be selected to serve as a "proxy" for the LED chip. A 32MB DRAM chip was selected as this proxy, with necessary data provided from a LCA analysis performed by Williams et al.(2002). It should be stressed that this is an extremely rough estimation for an LED chip. Compound semiconductor materials such as AlGaInP are used to produce an LED, while silicon is used in 32MB DRAM chip. Production of these two chips is similar in that they both take place in a semiconductor fabrication facility. However the actual processing steps vary between the two (e.g., LEDs require epitexial growth using MOCVD or MBE).

There are a number of other discrepancies between the LED and the 32MB DRAM chip, for instance – the size (in mm^2) of the chip used. While LED chips are on the order of 0.5-2.5 mm^2, the 32 MB DRAM chip used in the analysis was 1.6 cm^2 (larger by a factor of ten). However, for several reasons it was decided that no adjustment would be made based on chip size. First, the 32

[61] This assumption is made for the purposes of this life cycle energy analysis, however it remains uncertain whether future SSL products will resemble current technologies or if they will usher in radically different designs.
[62] One chip per bulb was selected because the future performance targets would allow one chip to provide sufficient light. However, the current models of LED screw-in bulbs contain multiple chips to fulfill the needed luminous output.

MB DRAM chip is fabricated on a larger wafer than LEDs, and hence one would expect the energy consumed per square area to be higher for the LED chip than for the 32MB DRAM chip. Second, the processing yields can vary considerably in semiconductor manufacturing, from between 16 and 94% depending on the maturity and complexity of the particular technology (Williams et al., 2002). Low processing yields are likely for LEDs because the technology is still in its infancy, and hence the energy consumed per square area is likely to be considerably higher than silicon technology. At this point in time it seems likely that the production energy per square area could be both shifted up and down – and hence it was decided that no adjustment should be made at this time without further investigation. Despite quite significant differences between the two chips, it was reasoned that a 32 MB DRAM chip was best available proxy for a LED chip.

Williams et al.(2002) found that 41 mega joules (MJ) were required to produce one chip. Converting this production energy to kWh, and adding it to the production energy for the incandescent lamp, the total energy consumed in production of one LED-SSL lamp is found to be 11.5 kWh.[63]

For comparison purpose, all three lighting technologies (CFL, incandescent and LED-SSL) have been converted to a fixed luminous service (10^6 lm-hr). The energy consumption estimates (including production and use) for these three lamps is show in Table VI-2 below.

[63] This calculation used 11.4 kWh for the chip production (conversion factor of 1 MJ = 0.278 kWh), and 0.15 kWh for the lamp production. Note that this 0.15 kWh is different from Table 6-1, because data in Table 6-1 was normalized to a certain lighting service.

Table VI-2. Comparison of Energy Consumption by 3 Lamps (Production & Use)			
	CFL	**Incandescent**	**LED-SSL**
Input Power (W/lamp)	15.0	60.0	7.5
Flux (lm/lamp)	900	730	1500
Luminous Efficacy (lm/W)	60	12	200
Lifetime (hr)	8,000	1,000	20,000[1]
Required luminous service (lm-hr)	1,000,000	1,000,000	1,000,000
Number of hours lamp is used to provide required service (hr/lamp)	1,11	1,370	667
Number of lamps used to provide required service	0.14	1.37	0.03
Energy consumed in use, based on required service (kWh)	**16.67**	**82.19**	**5.00**
Production energy for 1 lamp unit (kWh)	1.4	0.15	11.5
Production energy of lamp, based on required service (kWh)	**0.19**	**0.21**	**0.38**
Total Energy (kWh)[2]	**16.86**	**82.40**	**5.38**

Source: (Gydesen, & Maimann, 1991); Author's calculations.
[1]A conservative estimate for the lifetime of SSL device is assumed, because of the uncertainty regarding the lifetime of lamp and luminaire components, besides the LED chip.
[2] The energy estimates do not imply these values are accurate to four significant digits. As discussed in the text, values should be considered to be order-of-magnitude only.

The production energy required to make one SSL-LED "lamp" is significantly higher than the energy required to manufacture an incandescent or fluorescent lamp. This is not surprising, because of the highly controlled production processes and high purity materials required in semiconductor processing. However, the significance of this energy requirement for "LED" production is diminished rapidly when it is based on an established required lighting service (lm-hr). This is in part due the expected longevity of LED-SSL lamps (20,000 hr).[64] The diminished energy required for an LED-SSL lamp on a per lighting service basis, is also a result of the performance assumption that LED lamps will provide 1,500 lm/lamp, which is significantly more than the CFL and incandescent lamp.

The energy consumed in manufacturing an LED-SSL lamp (0.38 kWh) is a higher portion of its total energy requirement (5.35 kWh). Despite this, the total energy consumption per lighting

[64] It should be noted that this lifetime estimate is a conservative one, and the 2002 SSL Roadmap projects that devices will have lifetimes of over 100,000 in 2020 (Tsao, 2002).

service is significantly lower for the LED-SSL lamp on a life cycle basis than either of the two other lamps. It is of course important to remember that these are very rough calculations. The actual energy consumption of manufacturing a LED chip to be used in a future SSL product is impossible to determine, due to very limited data availability, uncertainty over materials and lamp designs which will comprise LED-SSL lamps, likely efficiency improvements in the production processes, as well as additional factors. However, based on this preliminary life cycle analysis, the energy consumption over the life cycle of an LEDs is still significantly smaller than the life cycle energy of the incandescent and CFL. However, additional work to examine the life-cycle energy issues for LED-SSL seems warranted given the energy-intensive nature of semiconductor manufacturing and the extremely limited data that was available for this analysis.

PRELIMINARY CONCLUSIONS

Based on this scoping LCA, several preliminary conclusions on the life cycle impact of future LED-SSL can be drawn. There are gaps in the research of toxicity of, and the risk posed, by the elements and compound that comprise LEDs and other devices which rely upon compound semiconductors. These materials are a potential risk for occupational heath and safety in semiconductor fabrication facilities. Moreover, the presence of toxic substances might pose a problem once these lighting technologies reach the end of their useful life. The ecological and human heath risks posed by disposal into municipal landfills, or incinerations are not known. Furthermore, the technical or economic feasibility of collecting and recycling LED-SSL technology in the future has not been explored.

The energy-efficiency potential of LED-SSL is significant. Based on the energy analysis performed, the SSL-LED "lamp" consumes approximately one-third the energy of a CFL, and sixteen times less energy than an incandescent lamp, over their life cycle to provide the same lighting service. Semiconductor manufacturing was found to be a comparatively small component of the total energy consumed over the life cycle of an LED-SSL "lamp." Hence the significant energy-efficiency potential of LED-SSL, overshadows the comparatively small increase in the production energy requirement. However, it is again emphasized that the energy production estimate for LED-SSL is based on a very rough estimation.

Because LED-SSL technology is still in an early stage of development, there is opportunity to shape this transition into a new lighting "paradigm" into one that is truly sustainable. Rebitzer et al. (2004) estimates that 70% of a product's environmental impact are (pre)determined during the design/development stage. Accordingly, if the aim of an LCA is to reduce the environmental impact of a product, the study should be carried out as early in the design phase as possible (Rebitzer et al., 2004).

As will be discussed in the next section, public policy is currently accelerating the development of SSL. Based on this life cycle assessment, future directions the EPA might take with regards to LED-SSL will be addressed in Section VIII.

VII. PUBLIC POLICY

BACKGROUND ON U.S. EFFORTS

In 2001, interest for a government-industry partnership to accelerate the development of SSL was catalyzed by a white paper written by researchers from Sandia National Laboratories, and Hewlett-Packard (Haitz et al., 2000). In this paper, the authors proposed that the high risk of developing SSL coupled with significant potential economic and environmental benefits; provide a compelling case for a coordinated national effort to accelerate the development of this technology. They suggested that this effort should involve a $500 million dollar government investment over a ten-year time frame. A SSL workshop report from the National Academies as well as a previous report by the National Academies Committee on Optical Sciences and Engineering, have also recommended a cooperative, cost-shared approach for a public-private R&D support to develop SSL (NRC, 1998, 2002).

To date, several market penetration models and reports have been commissioned by the DOE Building Technologies Program to evaluate the energy and monetary savings from the diffusion of SSL2005 and 2025 (DOE, 2001, 2003b). Despite the uncertainties of modeling the market penetration of a new technology, these models helped to validate the economic and energy-savings potential of SSL. On Capitol Hill, the Senate bill S.1166 first introduced in to Congress in 2001 encompasses the "Next Generation Lighting Initiative" (NGLI), a public-private effort that would authorize the funding of $500 million dollars over ten years, to accelerate the development of SSL.[65] This bill was then included in the 2003 Energy Bill which has not successfully gone through Congress. However, in anticipation, eight companies have formed an alliance: "The Next Generation Lighting Industry Alliance" (NGLIA) to keep the legislation a priority in Congress. The NGLIA also serves as a forum for collaboration between companies, provides "reasonable" access to intellectual property that is generated under R&D funded by the DOE, and interfaces with the DOE to provide feedback on R&D and roadmapping strategies (Becker, 2003).

Despite a legislative stagnation on the 2003 Energy Bill; there has been continued R&D funding for SSL and related technologies. According to the Department of Energy, Energy Efficiency and Renewable Energy Building Technologies Program's *Project Portfolio for Solid State Lighting*, approximately $31 million dollars in contracts have been issued since 2000 to develop SSL (with approximately $25 million contributed by the DOE) (DOE, 2003c). This cumulative funding up to 2003 has composed only 5% of the expected total cost ($500 million) of government investment that has been estimated necessary to develop SSL (DOE, 2004). However, there has been additional government research funding for R&D related to SSL technology that is not included in this $25 million. This funding comes through the Defense Advanced Research Project Agency (DARPA), the Basic Energy Sciences (BES) of DOE, the National Science Foundation (NSF), and the National Institute of Standards (NIST) Advanced Technology Program (ATP). A SSL program-planning workshop held in November 2003

[65] The text of this bill can be accessed at a Sandia National Laboratories website, devoted to solid-state lighting: http://lighting.sandia.gov/

presented the framework of a long-term strategy for technology development, illustrated in the shape of a pyramid. The stage of applied research occupies the bottom of the pyramid, which has been the focus between 2000 and 2004. The subsequent stages include product development and systems integration, demonstration, and market conditioning to meet the final goal of commercialization.

To date, the Building Technologies Program, housed within the DOE Office of Energy Efficiency and Renewable Energy (EERE) has been the federal government program most active in developing SSL. EPA involvement up to this point has been limited to work within the EPA/DOE ENERGY STAR program, which has developed certification guidelines for energy-efficient LED traffic signals and exit signs.

SUMMARY OF FOREIGN EFFORTS

Governments in other countries have been more aggressive in promoting SSL through cooperative partnerships with industry. In Japan, public-private cooperative efforts have been underway since 1998 to promote SSL, under a project named "Lighting for the 21st Century." Programs to accelerate the development of SSL are also underway in China, Taiwan, and Korea (Steele, 2003). The basic argument that government should fund high-risk and long-term research has been an argument put forth to justify R&D funding for SSL. Furthermore, expectations of significant energy savings (electricity accounts for approximately 20% of end use electricity in the U.S., and a similar figure is found worldwide), a reduction in GHG emissions, the benefits of reduced oil importation, as well as an monetary savings for electricity customers could be cited as appropriate rational for public investment in developing this new technology (Steele, 2003).

VIII. RECOMMENDATIONS & FUTURE RESEARCH

This technology assessment report has covered a wide terrain of topics and literature, in an effort to better understand the future potential of LED-SSL and the environmental impacts (both beneficial and negative) that could accompany the widespread use of this technology.

EPA'S POTENTIAL ROLE IN SOLID-STATE LIGHTING

Although LED-SSL technology is developing rapidly, there are still hurdles before it can displace currently used lighting technologies in general lighting applications. The EPA has not yet participated in the SSL workshops and meetings, which have brought together, interested industry, government, and trade association representatives. However, in light of the environmental impacts that SSL could have – both positive and negative – EPA participation in future SSL meetings between industry and government representatives should be considered to ensure all environmental impacts are given adequate attention while this technology is still in its infancy. Although this report had raised some issues of potential environmental impacts – particularly relating to use of hazardous materials in LED-SSL – the potential need for environmental regulation warrants a future analysis.

As a result of this research, recommendations for future research involvement of EPA have been developed. These recommendations have been organized along three main thrusts: toxicological impacts, pollution prevention and product sustainability, and finally, energy-efficiency.

First, as a result of the scoping life cycle assessment included in this report, it is recommended that further toxicological and risk-assessment work be done to determine the environmental impacts of the widespread use of compound semiconductors. While there has been some research on the environmental impacts of these metals and their compounds, the actual risk that these materials pose on ecosystems and human health has not been assessed. This could be particularly important because of the likelihood that LED-SSL will become widely used.

Current production of these compound semiconductors has very low yields and thus there is an opportunity to encourage pollution prevention and recycling during manufacturing.

Second, SSL is a technology that is rapidly improving; but still remains in its infancy with respect to general lighting applications (Tsao, 2004). Hence, while the development and design of LED-SSL is still in its infancy, there is the opportunity to ensure that these future lighting technologies are truly sustainable. This might involve developing alternatives to the use of arsenic in the LED-SSL products. Also, different options (and the economic and technical feasibility) for end-of-life collection, and reuse or recycling have not fully been explored, but are likely to become increasingly important as countries around the world mandate that producers take-back and provide for the safe recycling and/or final disposal of their electronic products.

The last major thrust concerns the potential of SSL to create significant energy savings. Under several scenarios, these energy-savings could reduce CO_2 emissions from projected 2025 levels either by 0.9% or 2.5%. Programs such as the EPA/DOE ENERGY STAR program have proved to be a successful platform for accelerating the development and diffusion of new energy-efficient technologies. Developing labels for cost-effective white LED-SSL for general illumination in the future could likewise, increase and accelerate the market penetration of energy-efficient SSL.

APPENDIX 1. LIGHTING TECHNOLOGY TABLE

Lamp and Ballast Classification

	Lamps
Fluorescent	**Incandescent**
T5	Standard – general service
T8 – less than 4′	Standard – integral reflector
T8 – 4′	Halogen – general service
T8 – greater than 4′	Quartz Halogen
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	Xenon[1]
Circline	Electrodeless (e.g. mercury)[1]
Induction discharge	**Solid State**
Miscellaneous fluorescent[2]	LED
	Electroluminescent

[1] Low pressure sodium, xenon, and electrodeless lamps are discharge lamps, but are not high intensity. They are included in this category for convenience of presentation. Electrodeless lamps consist primarily of mercury vapor lamps excited by radio frequencies, but this category also includes the sulfur lamp.

[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.

Source: Table 2-3 of (DOE, 2002)

APPENDIX 2. LIGHTING GLOSSARY

Ballast: An electrical device that controls the current provided to the lamp, and provides the necessary voltage to start up the lamp. A ballast must be used in conjunction with all discharge lamps.

Color Correlated Temperature (CCT): A measure of a lamp's color appearance, expressed in degrees Kelvin (K).

Color Rendering Index (CRI): A measure of a lamp's ability to render the color of the object it illuminates, accurately. The scale ranges from 1 (low pressure sodium) to 100 (the sun). A CRI of 85 is considered to be very good.

Efficacy: The energy-efficiency of light. Efficacy is calculated by dividing the amount of light emitted (lumens) to the power (watts) drawn by the lamp.

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

Fixture: A lighting fixture is the "housing" which provides support for a lamp, its ballast and the necessary wiring.

Illumination: Light which is incident on a unit area, generally illuminating an object.

Indication: Light which is generally viewed directly, commonly used in signaling applications.

Lumen (lm): A measurement of the light output (luminous flux) from a light source.

APPENDIX 3. UNITS & CONVERSION FACTORS

Units

Gwh	gigawatt hour
Kwh	kilowatt hour
lm	lumen
lm-h	lumen hour
MJ	mega joule
Mlm	million lumen
Quads	quadrillion British thermal units (BTUs)
Tlm-h	teralumen hour
TWh	terawatt hour
W	watt

Conversion Factors Used

Site energy to primary energy	1kWh / 10,768 BTU
Carbon emissions from primary energy	15.58 MMTCE/ 1 quad
Carbon emissions to carbon dioxide emissions	1 / 3.67

1 MJ	=	0.278 kWh
1 TWh	=	1,000,000,000 kWh or 10^{12} Wh
1 GWh	=	1,000,000 kWh or 10^{6} kWh

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