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Assessing the Economic and Environmental Impacts associated with Current Street Lighting Technologies

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ASSESSING THE ECONOMIC AND ENVIRONMENTAL IMPACTS ASSOCIATED WITH CURRENTLY AVAILABLE STREET LIGHTING TECHNOLOGIES

THESIS

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AFIT/GEM/ENV/10-M01

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Abstract

Rising global energy demand and natural disasters continuously threaten energy supplies and prices. As a result, the U.S. government has mandated all government agencies to reduce energy consumption in order to minimize dependence on foreign energy supply and reduce costs. Concern over carbon emissions and environmental impacts has also been expressed in these mandates. One solution may be to invest in newer lighting technologies, such as light-emitting diode (LED) and electrodeless induction, in order to reduce the energy consumption, environmental impact, and costs required for both exterior roadway and parking lot lighting applications. This research compared these lighting technologies with high-pressure sodium (HPS) lighting technology at 56 Air Force installations to assess the economic and environmental consequences associated with each technology over the product life-cycle. This study utilized *Building Life-Cycle Cost 5* and *Economic Input-Output Life Cycle Assessment* software packages to perform the analysis. Both the LED and electrodeless induction technologies showed moderate economic savings and less environmental impact when compared to HPS technology. The overall economic life-cycle costs for LED and induction lighting were 21% and 23% less, respectively, than HPS lighting. Environmental life-cycle assessment showed reductions of 55% and 45% for LED and induction technologies, respectively, compared to HPS lighting.

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Dedication

To my family and friends

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Acknowledgements

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Carlos J. Colon Jr.

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ASSESSING THE ECONOMIC AND ENVIRONMETAL IMPACTS ASSOCIATED WITH CURRENTLY AVAILABLE STREET LIGHTING TECHNOLOGIES

I. Introduction

Today's energy markets are unstable due to high global demand and natural disasters, which combine to threaten energy supplies and prices. The rate at which the world is consuming energy overall is on the rise; in the United States (U.S.), the demand has long been greater than production capacity. Renewable resources may help alleviate energy concerns; however, the current renewable energy infrastructure is not strong or robust enough to meet the energy demands needed to sustain current needs. In response, the U.S. government has mandated that all government agencies reduce their energy consumption to minimize dependence on foreign energy supplies and decrease environmental pollution. One way to minimize energy usage is to invest in new technologies for exterior lighting, such as roadways and parking lots. Upgrading the street lighting infrastructure would not only improve energy efficiency, but it could also reduce costs over time and improve driver and pedestrian visibility.

Background

There are many areas within the lighting industry for potential energy savings; however, this research specifically targets outdoor street lighting for roadways and parking lots on Air Force installations. According to the Air Force Civil Engineering Support Agency (AFCESA), the Air Force spent over $1.06 billion dollars in facility energy in FY 2007, with $707 million being spent on electricity alone (Department of Defense, 2007). Figure 1 shows how facility energy in the Air Force was distributed in FY 2007. With over 79,000 street lights identified across the Air Force, a reduction in power consumption for street lighting could lead to a significant cost savings.

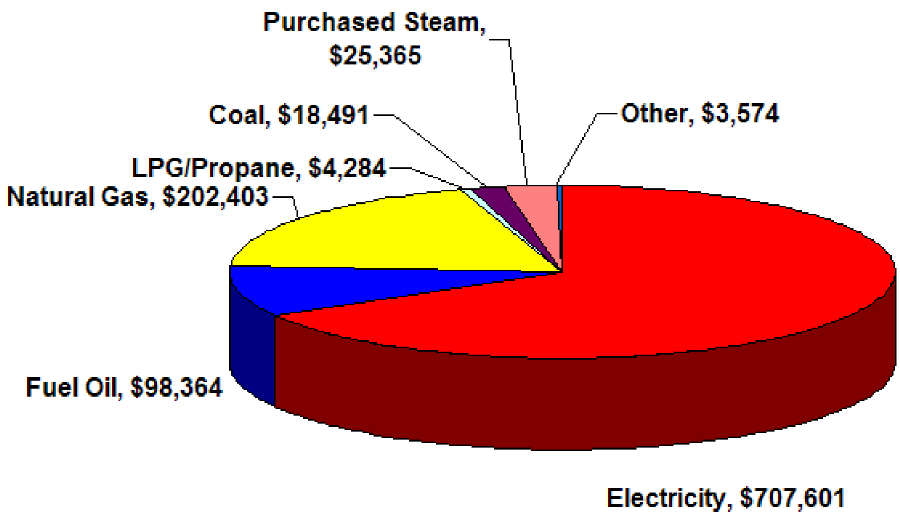


Figure 1. Fiscal Year 2007 Facility Energy Costs ($000) (Department of Defense, 2007)

Street lighting is mostly used as a deterrent to crime and for increasing night time visibility of both automobile drivers and pedestrians. Lighting can come from a number of sources; however, most roadway and parking lot lighting comes from overhead shoe box or cobra head fixtures 30 feet above the pavement surface. The most common technologies used for the lighting of roadways and parking lots are High Pressure Sodium (HPS) lamps and Metal Halide (MH) lamps. Both of these technologies provide sufficient lighting for their assigned task by focusing their lighting downward onto the road surface and allowing light to spill over sidewalks and in between the other light posts in a parking lot or along the roadway. These technologies have been in use for a long time and are popular due to their efficiency compared to older lighting technologies, such as mercury vapor fixtures.

With a focus on more energy-efficient infrastructure, newer lighting technologies have emerged on the market. Two of these technologies are light-emitting diodes (LEDs) and electrodeless induction lighting. These technologies claim to last longer and reduce energy consumption by up to 60%, which would create a significant savings to both the Air Force and the American taxpayer. These fixtures also have reduced mercury content which reduces hazardous waste disposal fees. However, there is some reluctance to introduce these new types of technologies as they require a complete replacement of current lighting fixtures at a significant initial cost. There has also been a reluctance to pursue these technologies because there have not been enough studies and tests performed to determine the viability and the accuracy of manufacturers' claims. However, with rising energy prices and a call for all government organizations to reduce energy consumption, these lighting technologies need to be explored in more detail.

Lighting Technology Overview

The high pressure sodium (HPS) and metal halide (MH) fixtures currently being used by the Air Force have been around since the 1970s. These technologies, considered energy efficient at the time, are antiquated compared with the technological advancements in electronics over the past three decades. There are newer technologies that may be able to perform the essential tasks of street lighting while being more energy efficient. These newer technologies also come with significant maintenance reductions and increased flexibility for the user. The following sections thus provide a quick synopsis of the LED and electrodeless induction technologies.

LED Street Lamp Technology

LED street lamps are the most modern technology on the market. LEDs are an electronic light source which produce light when excited by an electrical voltage. These voltages must be carefully regulated for the lamps to work properly. This technology is popular for its high energy efficiency, maintainability, and flexibility. The more recent LED models can produce over 100 lumens of light per watt and are expected to work at greater than 70% of their initial light output past 50,000 hours; under certain conditions, they may last up to 117,000 hours (BetaLED, 2009). These lighting fixtures are also vibration and impact resistant as a result of their solid-state construction, making them more resistant to damage from outdoor elements. These fixtures are also capable of being turned on and off instantaneously without delay, a capability not available with current light fixtures. Finally, LED fixtures are a point-source lighting technology, which allows greater control of the light being distributed.

Electrodeless Induction Lighting

Electrodeless induction lamps are similar to indoor fluorescent lighting. They use electromagnetic fields instead of electrodes to create light. Because electrodes are the point of failure in most conventional lighting technologies, their life span is limited to the durability of the wire or filament being used. Electrodeless lamps, as a result, have a much longer extended lamp life than standard street lamps. These lamps have been rated to last up to 100,000 hours (US Lighting Tech, 2009). These lamps can also use high efficiency light-generating substances that would normally react with electrodes in standard lamps (Rea, 2000). These lamps also have a very high lumen-per-watt efficiency that rivals the HPS fixture while providing a whiter light.

Problem Statement

The Air Force, through government legislation, has been forced to reduce energy consumption by 3% each year through the end of FY 2015 relative to the FY 2003 baseline while reducing environmental pollution (Bush, 2007). The Air Force must comply with these energy reduction requirements. There needs to be a concrete study that compares current outdoor lighting fixtures with newer technologies from both an economical and environmental standpoint. Most studies only focus on power consumption or environmental pollution resulting from that power consumption, but no studies have been conducted to determine the environmental impact of newer technologies. There are many reports that claim one technology is better than another for various reasons, yet it is difficult to determine truth versus bias as most of these studies come from the manufacturers themselves. Therefore, a study using data from a non-biased source would help not only the Air Force decide which technology to use but could also provide insight to other local municipalities and government branches across the United States.

Research Objectives

The main objective of this research was to conduct a study comparing HPS, LED, and electrodeless induction street lighting fixtures and determine which technology is not only the most economically advantageous but also the most environmentally friendly.

The baseline used for comparison was the HPS lighting currently used by the Air Force.

To address this objective, the following investigative questions were posed.

1. Do new lighting technologies offer enough of an economic and environmental benefit for the Air Force to change its current outdoor lighting technology?

2. How does energy use between lighting technologies compare?

3. What would be the economic and environmental impact Air Force wide if a new lighting technology were implemented?

4. How significant would the addition of a carbon emission offset cost be on the economic viability of different lighting technologies?

Methodology

This research effort implemented a two-part methodology based on the estimated energy use of different lighting technologies along with actual utility and labor rates for 56 Air Force bases around the world. The methodologies of Economic Input-Output Life-Cycle Assessment (EIO-LCA) and Life-Cycle Cost Analysis (LCCA) were used to analyze the data. The EIO-LCA methodology allows for a life-cycle assessment through all phases of product life, from raw material extraction required to make the product to its disposal, by analyzing the interaction between economic sectors. This tool was used to measure the environmental impacts associated with the life-cycle of each product. The assessment was performed using the EIO-LCA online tool available through Carnegie-Mellon University. The LCCA focuses on economic analysis tools such as net present worth to determine the costs associated with each technology over a set period of time. The Department of Energy's Building Life-Cycle Cost 5 (BLCC5) software was used to perform the LCCA. BLCC5 also provided environmental data that was used to determine the environmental impact of these technologies throughout their use phase, thereby contributing to the EIO-LCA methodology.

Assumptions/Limitations

Several assumptions were required for this comparison to be feasible and sensible. One primary assumption was that all newer technology street lamps were designed as a direct replacement for the current HPS fixtures. As a direct replacement, the LED and electrodeless induction technologies would provide approximately the same level of lighting service as the HPS technology while requiring no additional modifications to the current infrastructure for their operation. Any additional hardware, such as surge protection or additional wiring, is assumed to have been included with the purchase of the fixture and any additional time required for installation has already been factored into the labor hours. Another assumption was that all the lighting technologies in this study would perform similarly at all Air Force bases and provide approximately the same level of lighting service currently being experienced. Due to the different line voltages used for roadway and parking lot lighting across the Air Force, the assumption of similar performance across varying infrastructure layouts and geographical locations is important for this study to be relevant. A third assumption was the durability of each of these lighting technologies. There were no definitive studies to show whether these lighting technologies were capable of lasting their claimed maximum service life. Therefore, reduced service lives were assumed for each technology to simulate more real-world scenarios. The data collected was for outdoor roadway and parking lot lighting only. Although the same technologies can be used for interior lighting, the differences in environment between indoor and outdoor lighting are significant enough that this analysis would not be generalizable to interior lighting.

Implications

This study provides the data and analysis necessary to evaluate whether changing street lighting technologies is a worthwhile investment, not only economically but environmentally as well. The adoption of newer technologies could save the Air Force millions of dollars each year in both energy and environmental costs while freeing up resources to invest in other infrastructure upgrades. This study can also assist other municipalities and government agencies in determining which type of lighting system makes the most economic and environmental sense.

Preview

This work consists of four additional chapters including the literature review, methodology, results and analysis, and discussion. The literature review explains the basics behind street lighting, the different types of lighting technologies, how they work, how they affect the environment, and how they meet current lighting requirements along with their advantages and disadvantages. The methodology chapter explains how the study was conducted with a detailed explanation of both methodologies and why they are relevant to this study. How the data was applied to these methodologies will also be explained. The results and analysis chapter covers the results from the study to include their sensitivity to changes in costs associated with power production, carbon emissions offset costs, fixture costs, and service life. Environmental costs and impacts were also calculated and discussed with regards to the different lighting technologies. The discussion chapter reviews the findings of this study and recommends the course of action that should be taken by the Air Force along with areas for future research.

II. Literature Review

The intent of this chapter is to present the context from which street lighting will be discussed and understood. It starts with a discussion of U.S. energy policy and electrical power production. Next, environmental issues are discussed along with how U.S. environmental policy attempts to address these issues. A more in-depth description of streetlight components and construction for high pressure sodium (HPS), electrodeless induction, and light-emitting diode (LED) street lighting technologies will be used to compare the differences between the technologies and build a strong foundation for this study. The current requirements for outdoor lighting will be discussed, along with developing guidance as a result of these new technologies. Finally, some lighting case studies are discussed to further establish a sound foundation regarding lighting technologies.

Energy Policy

The U.S. government has been actively seeking ways to reduce energy consumption since the energy crisis of the 1970s. Lighting is one avenue by which energy savings can be realized. According to the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE), lighting in the United States is projected to consume nearly 10 quadrillion British Thermal Units (BTUs) of primary energy by 2012 (Navigant Consulting Inc., 2006). In 2007, President George W. Bush signed Executive Order (EO) 13423, "Strengthening Federal Environmental, Energy and Transportation Management." Section 2 of EO 13423 outlines the goals for all government agencies, requiring improvement in energy efficiency and a reduction of greenhouse gas (GHG) emissions for all federal agencies through the reduction of energy intensity by 3 percent annually or 30 percent by FY 2015 using FY 2003 as the baseline. Section 3 establishes agency objectives and targets through collection, analysis, and reporting of information to measure performance and accountability in congruence with the executive order (Bush, 2007).

Later in 2007, President Bush signed into law the Energy Independence and Security Act (EISA). According to Congressman Nick Rahall (2007), the stated purpose of this act is "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes." This act revises lighting and energy saving standards, requiring 25% greater efficiency for light bulbs by 2014 and 200% greater efficiency by 2020 (Bush, 2007). All federal buildings are required to use Energy Star products and all new and renovated federal buildings must reduce fossil fuel use by 55% by 2010 and 80% by 2020, with all new federal buildings being "carbon-neutral" by 2030. With current energy legislation and the continuing emphasis on reducing dependence on foreign energy, finding ways of reducing energy usage in compliance with these government mandates without adverse affects will be an important challenge over the next decade.

Electrical Energy Production

With energy policy defined, a brief overview of electricity production and how it is priced is appropriate. The volatility of electricity supplies can have a significant effect on its cost. Having an understanding of how most electricity is produced helps understand where vulnerabilities can occur, as these factors affect the long-term cost benefits and environmental impacts associated with each lighting technology. Long-term forecasting of costs can be extremely difficult; however, an understanding of these cost factors ensures these values are as unbiased and accurate as possible. One way to understand energy is to examine how it is produced. Therefore, Figure 2 identifies all of the energy sources used in the U.S. to produce electricity.

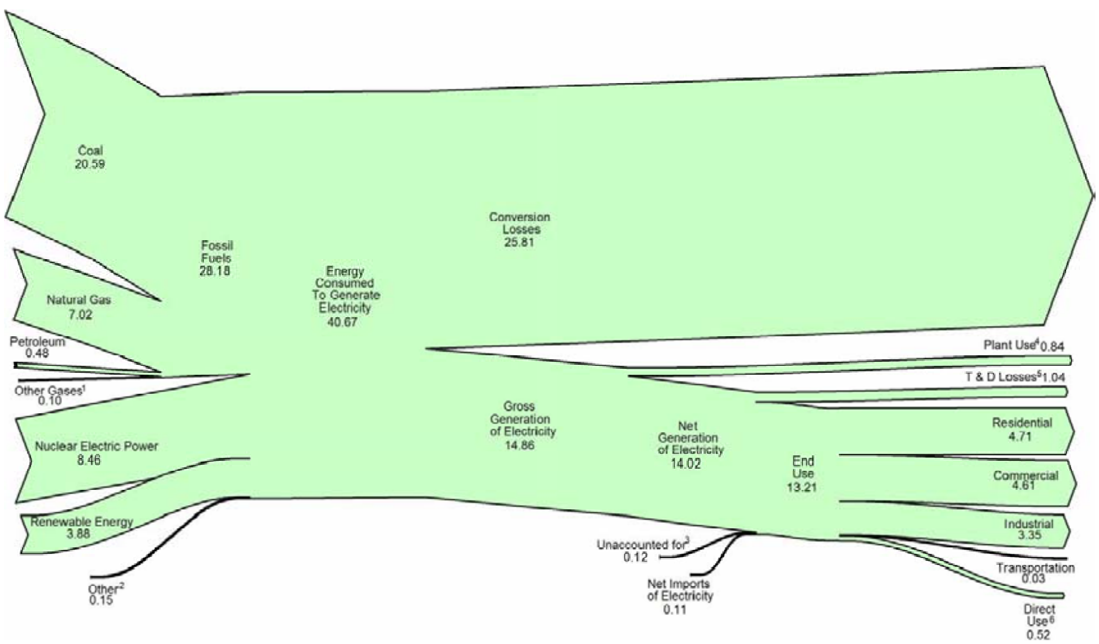


Figure 2. Electricity Flow, Quadrillion BTUs (EIA, 2008)

The figure shows that electricity production is dominated by fossil fuels at 28.18 quadrillion British Thermal Units (BTUs), with coal being the primary energy source at 20.59 quadrillion BTUs, which means that coal represents 50.6% of all energy consumed to create electricity. Nuclear power is the second most used energy source at 8.46 quadrillion BTUs or 21% of the total. Natural gas comes in third at 7.02 quadrillion BTUs, which represents 17.3% of total energy consumption. Renewable resources are the last major source for electricity generation at 3.88 quadrillion BTUs, which is 9.5% of the total. Petroleum is an insignificant portion of electricity production, contributing only 0.48 quadrillion BTUs or 1.1% of the total amount.

Looking across all energy sources, the U.S. relies heavily on fossil fuels; however, there is room for improvement in this area while reducing environmental implications. Fossil fuels are only 35% efficient on average, resulting in significant conversion losses that are unavoidable (EIA, 2008). These conversion losses result in 25.81 quadrillion BTUs of energy lost, not including losses occurring from plant use, transmission, and delivery. An increase in renewable energy technology, such as solar and wind, can significantly reduce not only the reliance on fossil fuels but also the conversion losses currently being experienced. While the conversion of solar or wind power is not 100% efficient, the loss in conversion has no effect on the environment because it is an emission-free process. Hydroelectricity is not being overlooked as a renewable energy source; it is simply limited in growth potential due to the ecological issues associated with this type of power production and the limited areas in which it can be used. The U.S. has much more potential in wind and solar power generation resulting from the availability of land for these technologies. The emissions that can be offset by the use of renewable energy are huge; however, it is often difficult getting renewable resources approved from an economic standpoint as their payback periods are not always the most desirable.

Because power production plants lack the flexibility to change energy sources, any fluctuation in the price of the natural resources required to produce electricity will directly affect the end-user. Also, certain regions of the U.S. use different primary energy sources for electricity production, creating a greater cost sensitivity towards the dominant primary energy sources in that area. For example, an increase in the cost of coal extraction would create a more significant end-user price increase in Pennsylvania because of the higher percentage of coal-fired electricity production there compared to Nevada which uses mostly hydroelectric power. These price concerns are typically of much more concern to the end-user than are the environmental impacts.

Environmental Issues

Although energy use is necessary for our current standard of living and provides many benefits, there are issues of environmental waste and pollution that need to be addressed. This section will discuss some of the environmental issues caused by energy use and describe a few of the harmful pollutants that exist in both power production and street lighting. Light pollution associated with current street lighting designs will also be discussed.

Greenhouse Gases

According to the Intergovernmental Panel on Climate Change (IPCC), greenhouse gases (GHG) are “those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds” (IPCC, 2007). The IPCC recognizes gases such as carbon dioxide (CO_2), nitrous oxide (NO_2), methane (CH_4) and ozone (O_3) as primary greenhouse gases. Greenhouse gases are necessary for maintaining the earth’s temperature by trapping the heat from the sun’s rays. The trapping of heat allows the earth to maintain a warmer temperature, allowing ecosystems and life to survive. However, if the concentration of greenhouse gases becomes too great, the earth’s temperature may begin to rise and thereby disrupt current ecosystems. According to the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), the earth's average surface temperature has increased by about 1.2 to 1.4ºF in the last 100 years, with the eight warmest years on record (since 1850) having occurred since 1998 (EPA, 2009). As shown in Figure 3, there has been an increase in anthropogenic activity over the past 200 years, which scientists believe has attributed to the phenomenon known as global climate change (EPA, 2009).

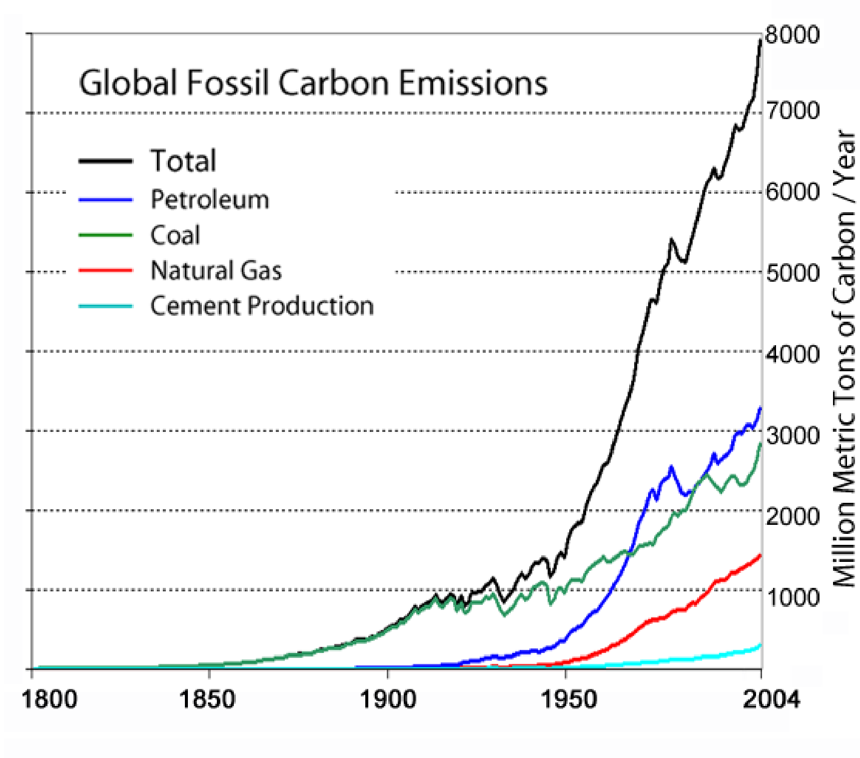


Figure 3. Anthropogenic Carbon Emissions 1800 - 2004 (Thorpe, 2008)

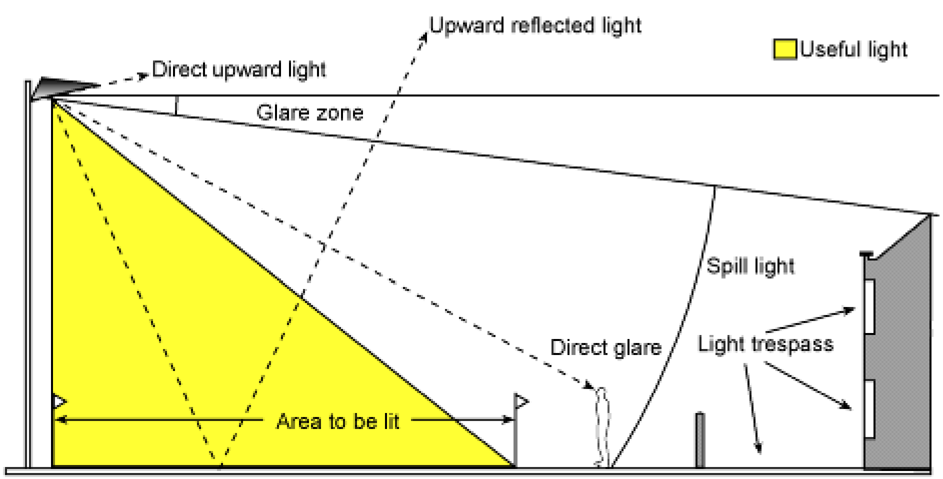
Mercury

Mercury (Hg) is "a naturally occurring element that is found in air, water and soil. It exists in several forms: elemental or metallic mercury, inorganic mercury compounds, and organic mercury compounds" (EPA, 2009). Mercury is an odorless, tasteless substance that can be difficult to detect, so special care needs to be taken to minimize exposure and contamination. Although it is a natural element found in the environment, human activities such as mining and manufacturing have increased the amount of mercury being distributed throughout the environment. The effects of mercury on humans and the environment can be drastic. Mercury exposure at high levels can harm the brain, heart, kidneys, lungs, and immune system of people of all ages, while high level exposure to animals can cause death, reduced reproduction, slower growth and development, and abnormal behavior (EPA, 2009). These effects vary depending on the type of mercury present; however, all forms of mercury are considered toxic and should therefore be handled and disposed of properly. In 1979, the U.S. Food and Drug Administration (FDA) ruled that bottled water could contain no more than 2 parts per billion (ppb) or about .000002 grams of mercury per liter of water for safe consumption (Divison of Environmental and Occupational Health, 1998).

Light Pollution

Dust, water vapor, and other particles reflect and scatter light that is emitted into the atmosphere, resulting in the sky glow found over most urban areas (Rea, 2000). Light pollution is an unwanted consequence of outdoor lighting. Figure 4 illustrates various types of light pollution and how they occur. Glare is a condition caused by stray light scattered within the eye, which reduces the contrast of the retinal image (Rea, 2000). Glare occurs when there is high contrast between the light and the environment or a non-uniform distribution of luminance in the field of view. Direct glare is caused by light aimed directly at the eye, whereas reflected glare is the result of light bouncing off of a surface and toward the eye. Glare can be very distracting to drivers and can cause temporary loss of vision as a result.

Light trespass occurs when light is unintentionally cast where it is not wanted (Rensselaer Polytechnic Institute, 2007). Most cases of light trespass involve streetlights that unintentionally illuminate windows and indoor areas of homes and businesses that did not request it. This is usually caused by poor aiming of the light fixture or lack of shielding on the light fixture itself. Sky glow is the illumination of the sky by both natural and man-made lighting. Examples of naturally occurring sky glow come from the moon, stars, and zodiacal light (Rensselaer Polytechnic Institute, 2007). Outdoor lighting adds to sky glow when light is emitted directly upward by luminaires or reflected from the ground, especially when moisture is present on the ground (Rensselaer Polytechnic Institute, 2007). Sky glow makes it difficult for astronomers and others interested in viewing the night sky to see stars and planets clearly. While sky glow may not have a direct environmental effect, it shows that areas may be overlit, causing wasted light to escape into the atmosphere.



Light pollution is often caused by the way light is emitted from lighting equipment. Choosing proper equipment and carefully mounting and aiming it can make a significant difference.

Figure 4. General Lighting Issues Associated with Street Lighting (Rensselaer Polytechnic Institute, 2007)

Power Production

Most environmental waste associated with power production is in the form of air pollutants, such as carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). The Energy Information Administration (EIA) has tracked the amount of air pollution associated with power production, as shown in Table 1. As the table shows, the amounts of SO_2 and NO_X have steadily declined over the years, while the amount of CO_2 has increased. This is of concern to most environmentalists, as CO_2 is a major contributor to global climate change.

Table 1. Emissions from Conventional Power Plants and Combined Heat-and-Power Plants (EIA, 2009)

(Thousand Metric Tons)

Emission	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998	1997	1996
Carbon Dioxide (CO_2)…..	2,516,580	2,459,800	2,513,609	2,456,934	2,415,680	2,395,048	2,389,745	2,441,722	2,338,660	2,324,139	2,232,709	2,161,258
Sulfur Dioxide (SO_2) ………	9,042	9,524	10,340	10,309	10,646	10,881	11,174	11,963^R	12,843^R	13,464^R	13,480^R	12,991^R
Nitrogen Oxides (NO_x) ……	3,650	3,799	3,961	4,143	4,532	5,194	5,290	5,638^R	5,955^R	6,459^R	6,500^R	6,474^R

R = Revised.
Notes: • See Appendix A, Technical Notes, for a description of the sources and methodology used to develop the emissions estimates. • CO2 emissions for 1995 - 2000 have been revised to reflect the emission factors shown in Table A3.
Source: Calculations made by the Electric Power Division, Einergy Information Administration.

Another air pollutant associated with power production is mercury. In 1999, the EPA estimated that approximately 75 tons of mercury were found in the coal being delivered to power plants each year and about two thirds of this mercury (50 tons) was emitted into the air (EPA, 2009). Coal-burning power plants are thus the largest human sources of mercury emissions in the United States, accounting for over 40 percent of all domestic human-caused mercury emissions (EPA, 2009). These airborne mercury emissions circulate around the environment and eventually settle on land and in waterways, creating higher levels of mercury exposure than would normally be present. The EPA has instituted regulations such as the Clean Air Mercury rule to reduce mercury emissions and the environmental effects associated with power production.

Street Lighting

Energy is required for the production, use, and disposal of street lights, with the bulk of the energy use being in the use phase. The amount of energy used by a street light is directly related to the type and power rating of the street light. The higher the amount of power consumed by street lighting, the more power that needs to be produced by the power plants, which in turn produce the emissions discussed earlier. Electrodeless induction and HPS street lighting technologies use mercury to aid in the lighting process. Mercury is typically contained within the bulb during use; however, when the light bulbs reach the end of their life, special care must be taken with disposal. The amount of mercury contained within the bulbs can vary from 1mg to 15mg (Harder, 2007). As a result, the EPA classified all hazardous waste lamps as universal waste in 40 CFR Part 273, requiring specialized disposal to minimize the opportunities for environmental damage as a result from mercury contamination.

Light pollution is a major issue concerning street lighting. Issues such as glare, light trespass, and sky glow have gotten the attention of many states. As a result, some states have adopted legislation controlling light pollution, with other states pending legislation (Rensselaer Polytechnic Institute, 2007). Figure 5 shows which states have adopted or are pending statewide legislation. According to IESNA, the methods to best control light pollution are to limit flux above the horizontal plane, minimize non-target illumination, and turn off lighting during times of low use (Rea, 2000).

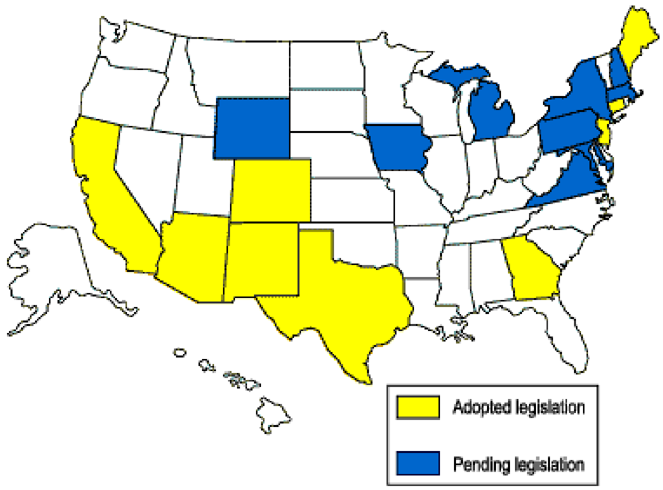


Figure 5. States adopting Light Pollution Legislation (Rensselaer Polytechnic Institute, 2007)

Environmental Policy

As a result of these and many other environmental issues, environmental policy has become an important aspect of U.S. legislation. Since the 1970s, there have been significant achievements in environmental regulation regarding air quality, water quality, and hazardous waste. The Clean Air Act of 1970, which was amended in 1990, called for air pollution prevention and reduction, emissions standards for all vehicles, acid rain reduction, and ozone layer protection (EPA, 2009). President Bush also pushed for better environmental stewardship through Executive Order 13423, calling for the use of sustainable environmental practices through the acquisition of environmentally preferable, energy-efficient products while reducing the quantity of toxic and hazardous chemicals and materials acquired, used, or disposed of by the government (Bush, 2007).

Global climate change has also been a topic of concern and legislative debate as it is most commonly associated with anthropogenic activity via carbon emission. Discussion over this topic resulted in the creation of the Kyoto Protocol in 1997. The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCC) and designed to combat global climate change. This environmental treaty attempts to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” by setting binding targets for reducing greenhouse gas emissions in industrialized countries (UNFCC, 2009). The protocol was initially adopted on 11 December 1997 in Kyoto, Japan, but was not entered into force until 16 February 2005. As of December 2009, 187 countries have signed and ratified the Kyoto Protocol; however, the United States is not one of them. The U.S. has signed the protocol but is unwilling to ratify the treaty, with reasons ranging from lack of representation from developing countries (CNN, 1997) to the exemption of China (Bush, 2001). Because the U.S. has not ratified the Kyoto Protocol, they are not required to abide by it, which has concerned advocates of global climate change.

In an effort to create awareness for global climate change, twelve states and several U.S. cities, along with other activist groups, brought a lawsuit against the EPA in an effort to force the agency to regulate carbon dioxide and other greenhouse gases as pollutants in the court case Massachusetts vs. the EPA (Massachusetts vs Environmental Protection Agency, 2007). In the case, the plaintiff claimed that global climate change resulted in significant damage, creating land loss and endangering public health and welfare. The Supreme Court directed the EPA to explain its position as to why carbon emissions are not currently regulated. In a 5-4 ruling, the court decided that greenhouse gases were air pollutants based upon the definitions stated in the Clean Air Act. The ruling suggests that the EPA should regulate CO_2 emission, but is not required to do so, given the uncertainties surrounding global climate change.

The latest effort in environmental policy comes from the Lieberman-Warner Climate Security Act of 2008. This bill would require the administrator of the EPA to establish a federal greenhouse gas (GHG) registry for which companies must report fossil fuel and GHG activity (U.S. Senate, 2009). The administrator would also need to establish a GHG emission allowance transfer system (also known as cap and trade). Under the cap and trade system, companies can produce emissions up to their allowance without penalty; however, if more emissions production is required, those companies must purchase excess emissions from companies who have produced fewer emissions than they are allowed. While this legislation did not pass, it is clearly visible that steps are being made to try and control GHG emissions on an industrial scale.

The U.S. government and other activist groups continue to work on solutions for promoting environmentally friendly behaviors and practices. With a continued focus on the reduction of greenhouse gas emissions and fossil fuel usage, while promoting an increase in renewable energy sources, it is clear that the U.S. government is, at the very least, considering the environmental effects associated with current energy consumption. However, the government must also be careful of other consequences relating to these emission measurements, such as the cost to the end-user. Instituting a cap and trade program, or a carbon tax (paying a certain amount for each metric ton of carbon produced), could have a significant cost impact on both businesses and end-consumers.

The Importance of Street Lighting

"The purposes of street illumination are: first to reveal, and second to embellish. Protection against the hazard of criminal violence and collision; security in avoiding obstacles and inequalities in roadway; facility in finding one's way about, all require that the light which is provided shall reveal what it is important to see on or about the street. No system of street lighting is effective which fails to achieve this purpose" (Millar, 1924). In the Air Force, the primary purpose of outdoor lighting is to provide lighting for exterior facilities, which require some degree of lighting during times of reduced visibility for safety or for observation (Department of the Air Force, 1996). Aspects such as security and safety are of significant importance to the government, especially for the protection of military and intelligence assets (humans, equipment, information, communication, and financial assets). "Darkness induces a sense of insecurity because it cuts down visibility and recognition at a distance. Dark or dimly lit streets create a limitless source of blind spots, shadows, and potential places of entrapment" (Painter, 1996). It is thus important that exterior lighting be improved, as "improved lighting is an immediate means of cost effectively creating a sense of public safety, enhancing the quality of the built environment and increasing the number of people on the streets after dark" (Painter, 1996). Painter and Farrington (2001) show the cost-benefit of improved street lighting based on crime reduction. The study found that for crimes such as burglary, vandalism, vehicle crime, cycle theft, rob/snatch, assault, and threat/pest, there was a significant decrease in crime after improved lighting had been introduced, resulting in a savings of £558,415 over the course of one year (Painter & Farrington, 2001).

While the elimination of blind spots and dark spots is important when evaluating street lights, there are also other factors that contribute to the effectiveness of street lighting. "Effectiveness in a street lighting system, like personal charm, is recognized when encountered, but it is difficult to define. The effectiveness of the lighting system depends upon the right combination of several qualities, some of which are perhaps intangible" (Millar, 1924). Factors such as location of the lamps, mounting height, characteristics of lighting, and illumination affect the ability of street lamps to perform effectively and efficiently. With the importance of street lighting defined, the next section describes some of lighting characteristics that need to be understood when comparing lighting technologies.

Lighting Characteristics

Before lighting technologies can be compared, a few terms regarding lighting characteristics need to be defined in order for the comparisons to make sense. The Color Rendering Index (CRI) is understood to be a measure of how well light sources render the colors of objects, materials, and skin tones. The CRI is measured by comparing the appearance of eight color samples under the light in question and a reference light source. The average measured differences are subtracted from 100 to get the CRI (EERE, 2008). A CRI of 100 suggests that the colors rendered under that particular light source are the same as the color rendering properties of daylight. The CRI is a good measure for showing how well colors are perceived by the human eye, which can help with the identification of objects under artificial light. Having a lighting system with a high CRI is useful in areas that require faster reaction times or better recognition of objects and people, such as security checkpoints. Color temperature is a description of the color reproduced by the light source, typically classified in degrees Kelvin (K). Lights with color temperatures above 5000K have a blue-white color, while lights with a color temperature below 3000K are more yellowish-red in appearance.

Efficacy refers to the amount of light produced by a light source as a ratio to the power needed to produce that light (EERE, 2009). This term is typically defined as lumens per watt. This is different from illuminance, which is the total amount of light over a given area and is typically expressed in foot-candles or lux (lumens per square meter). Vertical illuminance is the amount of light density measured on a vertical plane, while horizontal illuminance is the amount of light density measured on the horizontal plane.

Types of Street Lighting

This section will discuss both current and emergent technologies in the street lighting industry. The history of each lighting application will be explained, along with its construction, how it works, and its perceived benefits and drawbacks.

High Pressure Sodium

High pressure sodium lamps have been around since the 1970s. They are considered part of the high-intensity discharge (HID) family of lights. This means that the lamp produces light by using an electrical arc discharge contained inside an arc tube inside a bulb. The arc tubes typically contain tungsten electrodes that terminate the arc discharge at each end of the arc tube. There are typically starting gases (e.g., neon, xenon, argon) inside the arc tube that ionize easily at low pressure and normal ambient temperatures. The arc tube is contained inside a glass outer bulb built to protect the arc tube and internal electrical connections from the elements. The outer glass bulb can be coated with a diffusing material to reduce or increase the source brightness of the lamp. The gas in between the inner and outer bulb is typically a low pressure gas or vacuum. These lamps are known for emitting UV energy that is typically captured by the outer bulb; however, if the outer bulb were to break, the UV energy emitted can produce skin reddening or eye damage (Rea, 2000).

Light in a HPS bulb is produced by electric current passing through sodium vapor. The arc tubes are made out of polycrystalline alumina to prevent sodium attack at high temperatures. The arc tube also contains both xenon as a starting gas and a small quantity of sodium-mercury amalgam, which is in liquid form at startup and partially vaporized as the bulb reaches operating temperature. The mercury acts as a buffer gas to raise the gas pressure and operating voltage of the lamp. The amount of mercury in the bulb varies depending on the rated power of the bulb and can range from 0 to 50mg depending on manufacturer and type (Keith, 2003) with an average of 15mg being the standard for 250-watt bulbs (Harder, 2007). The outer glass prevents chemical attack of the electrodes and also maintains arc tube temperature by isolating the metal from ambient temperature effects. These lamps can operate in any position or orientation without any significant effects on light output. A picture of a HPS bulb detailing its construction can be seen in Figure 6.

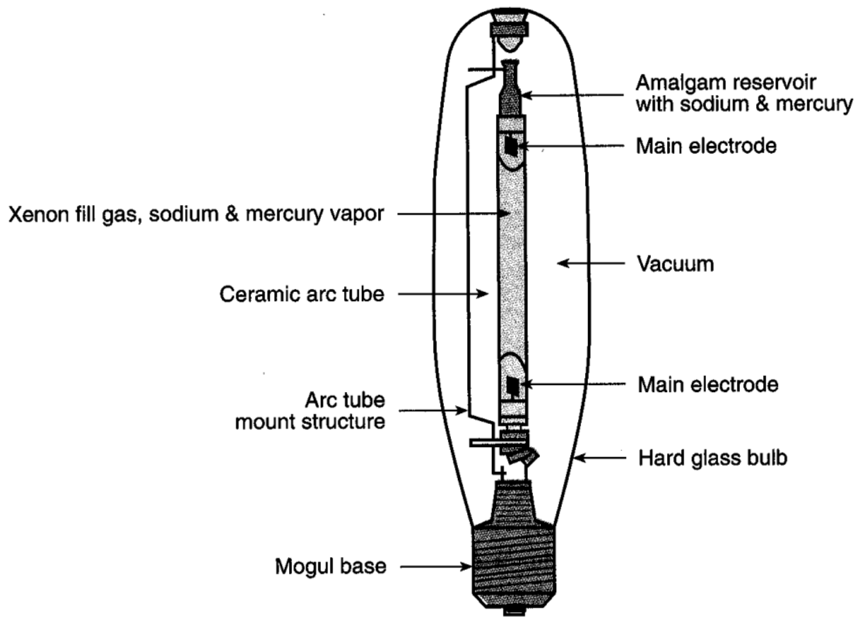


Figure 6. High-Pressure Sodium Bulb Components (Rea, 2000)

High-pressure sodium lamps radiate light across the visible spectrum. Their ability to transmit light depends on the internal pressurization of the bulb. The higher the sodium pressure, the higher the color temperature and color rendering index; however, bulb life is shortened as a result. White high-pressure sodium lamps have been developed with color temperatures between 2700K and 2800K and a CRI between 20 and 70. The efficacy of HPS ranges between 45 and 150 lumens per watt depending on the lamp wattage and desired CRI. Rated lamp life is typically defined as the time after which 50% of a large group of lamps are still in operation. The life of an HPS lamp is limited by a slow rise in operating voltage that occurs over the life of the lamp due to the buildup of impurities on the electrodes. One sign of HPS reaching the end of its life is a constant “cycling,” where the lamp turns itself on and off because it can no longer maintain the voltage needed for proper operation. The typical rated life for an HPS bulb is between 12,000 and 24,000 hours (approximately 3-6 years).

An HPS fixture is typically made up of 3 parts: the bulb, the ballast, and the fixture. Figure 7 shows the basic workings of this type of lighting system. Because of the size of HPS bulbs, no starting electrode is included in the bulb. Also, HID lamps have negative volt-ampere characteristics which create a requirement for a current-limiting device, usually in the form of a ballast or transformer, to be provided to prevent excessive lamp and line currents necessary for stable operation. For these lamps to turn on, a high-voltage, high-frequency pulse must be provided by an ignitor (typically built into the ballast) to excite the starting gas in the tube. As the gases warm up, the amalgam is slowly vaporized while the voltage continues to rise until the light has reached its operating temperature, changing color and lighting intensity as it arrives to this point. This process can take up to 10 minutes on initial startup. Restrike times are typically less than a minute with the bulb taking 3 to 4 minutes to warm up (Rea, 2000).

Advantages

When compared with other HID lighting technologies, such as metal halide (MH), HPS offers significant advantages. HPS lighting has a longer bulb life, averaging between 12,000 to 24,000 hours versus 10,000 to 15,000 hours for MH bulbs (Harder, 2007). HPS also produces approximately 42 percent more lumens per watt (W) while reducing sky glow. HPS lights are very good at providing adequate light because they are available in power ranges from 100W all the way up to 1000W for special applications.

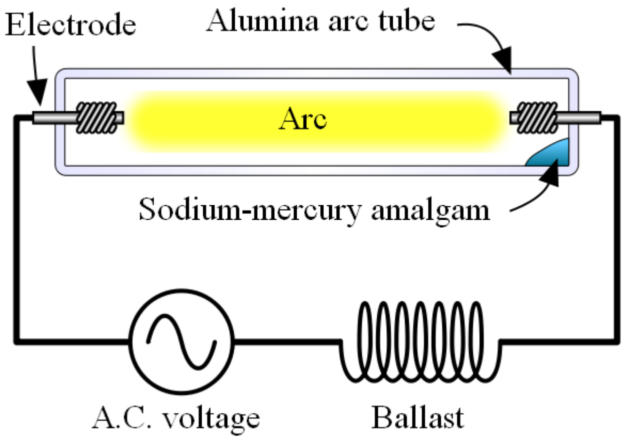


Figure 7. High Pressure Sodium Construction (Wikipedia, 2009)

Disadvantages

HPS lighting is most notable for its orange glow, which does not render colors very well, hence a lower CRI. HPS lights also require very high initial input power to start the arc in the bulb, resulting in significant energy use. At the end of their life, HPS bulbs begin to flicker and cycle, causing inconsistent light output. HPS fixtures, while designed to meet IESNA lighting standard distribution types, cause significant light pollution due to their use of a drop lens to project light from the fixture.

High Pressure Sodium Lighting Summary

HPS lighting is the lighting of choice for most cities, municipalities, and military installations (Department of the Air Force, 1996). While they may require constant maintenance and require high amounts of power to operate, they are reliable under most weather and temperature conditions. They are about 50% efficient when converting energy into light, and they are also readily available. The technology has been around for quite some time and most people have grown accustomed to the orange glow they emit.

Electrodeless Induction

Although electrodeless lamps are a relatively new lighting technology for street lighting, the principles behind the technology date to the 1890s when Nikolas Tesla demonstrated the transfer of power to electrodeless incandescent and fluorescent bulbs (Roberts, 2009). Tesla was granted patent 454,622 to cover an early form of induction lamp. Electrodeless lighting is a special form of fluorescent lighting in which an electromagnetic (EM) field, instead of an electric current through electrodes, is used to excite the gas in a bulb. There are two types of electrodeless bulbs according to how they produce EM fields. These categories are inductive discharge and microwave discharge.

Induction lamps operate using the same principles as conventional fluorescent lamps, which is through the excitement of phosphors found in those lamps. Figure 8 shows a diagram of an induction lamp. The operation of the lamp operates in the following manner (in coordination with the numbers in Figure 8) (Rea, 2000).

1. The radio frequency power supply sends an electric current to an induction coil (a wire wrapped around a plastic or metal core).

2. The current passing through the induction coil generates an EM field.

3. The EM field excites the mercury in the gas fill, causing the mercury to emit ultraviolet (UV) energy.

4. The UV energy strikes and excites the phosphor coating on the inside of the glass bulb, producing light.

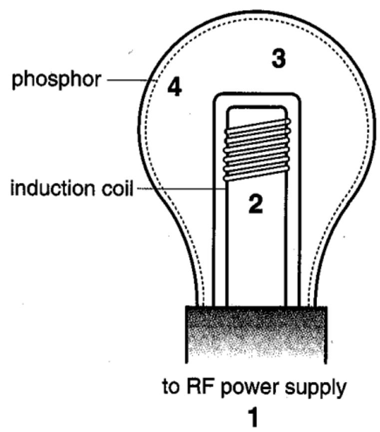


Figure 8. Induction Light (Rea, 2000)

Advantages

Because induction lamps do not require electrodes, higher efficiency gases can be used that would normally deteriorate the electrodes. These gases assist the induction bulb to last longer, anywhere from 65,000 up to 100,000 hours (Roberts, 2009; Cornerstone Energy Solutions Inc., 2009). These special gases also help increase the efficacy of the fixtures, ranging anywhere from 40 to 87 lumens per watt (Cornerstone Energy Solutions Inc., 2009). The correlated color temperatures for induction are in the range of 2700K to 4000K and their CRI is typically greater than 80 (Lai & Lai, 2004). Induction lamps are also an “instant on” technology, meaning that they light instantaneously with restrike times under 1 second. These lamps can also perform hot restrikes, meaning the bulb does not need to cool before the light can cycle back on, unlike HID technologies.

Disadvantages

One of the main disadvantages of induction lighting is the upfront cost. They are 2 to 5 times more expensive than a standard HPS fixture. Another disadvantage is the mercury present in the fixture. While induction lamps contain only 5mg of mercury, which is less than HPS, it is still a hazardous substance that requires special attention when being disposed of. Another disadvantage is the fragility of the bulb due to its glass construction. There have also been some claims that the frequency generators have had issues with 480V lines. Induction lamps also require the use of drop lenses to increase their effectiveness, which helps them contribute to various forms of light pollution (Cornerstone Energy Solutions Inc., 2009).

Electrodeless Induction Lighting Summary

While induction lamps have a higher upfront cost when compared to other lighting technologies, their equipment service life and low maintenance intervals make them very attractive for long-term projects. These bulbs operate similarly to the HPS technology, allowing adopters upgrading from HPS fixtures to be more easily familiar with their operation and components.

Light-Emitting Diode

Light-emitting diodes (LEDs) are the latest technology to appear in the street lighting industry. A light-emitting diode is an electronic component that allows current to flow in one direction and create light as the current passes, given a set threshold voltage is met. The LED is a chip made up of two semiconductor materials layered on a substrate injected with impurities to create a p-n junction. Figure 9 displays a p-n junction and how the electrons move between that junction inside the LED. Current flows easily from the p-type side, known as the anode, to the n-type side, known as the cathode; however, current cannot easily flow in the other direction. When electrons meet holes in the junction, energy is released as a photon. The color of the light emitted depends on the band gap energy of the materials that form the junction.

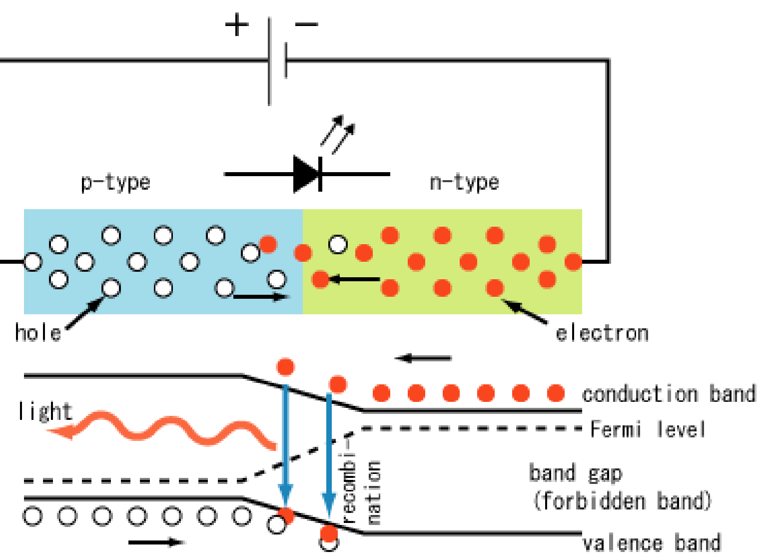
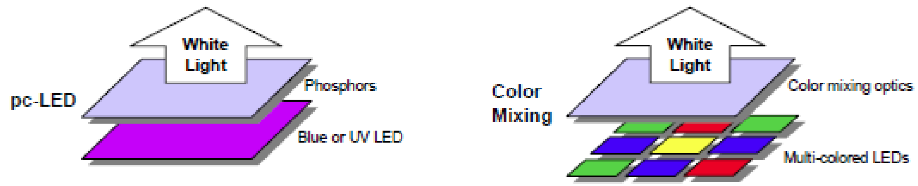


Figure 9. P-N Junction of a Light-Emitting Diode (Wikipedia, 2009)

Unlike most other lighting technologies, LEDs emit light by electronic excitation (electroluminescence) rather than heat generation (incandescence). The LED was invented in the 1920s by Russian Oleg Losev; however, it was not until 1962 when the first practical visible-spectrum LED was invented at General Electric's Advanced Semiconductor Laboratory (Navigant Consulting Inc., Radcliffe Advisors Inc., and SSLS Inc., 2009). The first LEDs were red in color, but over time green and blue LEDs were created using different material compounds. In order for LEDs to appear white, either a combination of the red, green, and blue LEDs should be made or a yellow phosphor coating can be placed on a blue LED. Figure 10 shows how these two processes work to produce white light.



(a) Phosphor-Conversion LED (pc-LED) **(b) Color-Mixing LED**

Figure 10. Methods for Making White LEDs

The LED was originally used as an indicator light for items such as radios and computers. The creation of white LEDs has paved the way for them to be used in numerous applications, such as televisions, cellular phones, and automotive lighting. LED fixtures for street and parking lot lighting package a number of LED chips onto a coated printed circuit board and enclose them in a housing suitable for the outdoor environment. The LED fixture requires no ballast or capacitors like the other lighting technologies; however, it does require a power supply to convert alternating current (AC) line voltage into low voltage direct current (DC). The power supply can either be housed in the enclosure or mounted on the printed circuit board along with the LEDs (San Diego Regional Energy Office, 2003).

Advantages

Unlike conventional HID lighting, an LED is not a one-bulb fixture. An LED fixture contains many smaller LEDs, classifying this technology as a point-source technology. Because the individual LEDs in the fixture can be directed toward a specific location, this allows flexibility in the design and greater optical control. Conventional HID fixture optical losses range from 40% to 50%, meaning that only half of the source light is directed in the desired direction. LEDs fixtures can be 80 to 90% efficient in their light transmission, allowing them to use less power to transmit the same amount of light (San Diego Regional Energy Office, 2003). LED lighting fixtures can also be designed to reduce backlight and uplight while increasing the uniformity of light distribution across the target area. Better surface illuminance uniformity and higher levels of vertical illuminance are possible with LEDs and close-coupled optics compared to HID luminaires (EERE, 2008)

LEDs are also a solid-state technology, giving them increased durability and ruggedness against the elements. Because there are no moving parts or gases in the light itself, it is capable of avoiding premature failure due to direct impact or moisture (Cornerstone Energy Solutions Inc., 2009). LEDs require low direct current voltage and low power to operate, which results in reduced energy use. Depending on the application, they can demonstrate anywhere from 50% to 90% in energy savings (San Diego Regional Energy Office, 2003). Their usable life ranges anywhere from 50,000 to 100,000 hours, depending on input current and thermal design (San Diego Regional Energy Office, 2003). The usable life of an LED fixture is determined to be when the light output of the fixture falls below 70% of its initial lumen output (Rea, 2000).

Disadvantages

Although LEDs have many advantages, there are a few significant disadvantages. Because of the construction of LEDs, they are very susceptible to high p-n junction temperatures, causing premature failure of the device if it gets too hot. Because most outdoor LED luminaires are high-power devices (>350 milliamperes), it is especially important to keep both junction temperatures and ambient fixture temperatures low to ensure that light production is not significantly affected. Most LED specifications show performance at an ambient temperature of 25°C; however, higher temperatures can significantly affect the relative flux of the colors used in LED lighting, as shown in Figure 11. To keep temperatures down, heat sinks and other cooling technologies need to be properly designed and applied in order to keep the LED luminaires from overheating.

Another issue concerning LEDs is maintaining the consistency of white light. The two methods shown in Figure 10 each have their flaws. The pc-LED has issues due to natural variations in LED wavelength or in the phosphors themselves. The light is also then susceptible to variations in LED optical power, peak emission wavelength, temperature, and optical characteristics (Navigant Consulting Inc. et al, 2009). The phosphors applied to the LED also lower its efficiency. When using color-mixing LEDs, there can be issues with the blending of the colors, especially with the green LEDs due to the absence of efficient emitters. This can significantly limit efficacy. There is also increased complexity when blending the colors, potentially requiring multi-die mounting and sophisticated optics. Color control feedback circuitry to address the different degradation and thermal characteristics may also be required (Navigant Consulting Inc. et al, 2009). Issues with power supplies, heat, and lightning protection have made consumers leery of their ability to hold up to the elements. Additionally, because LEDs are an electroluminescent light source with a significantly different luminaire construction compared to HPS and induction, current lighting regulations and testing practices are unable to properly test the LED technology.

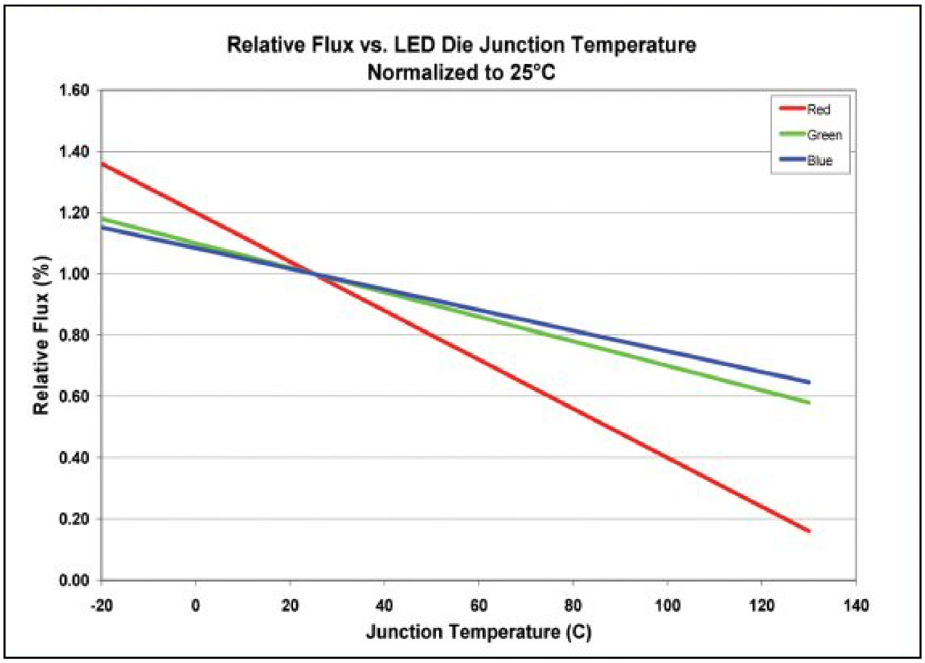


Figure 11. Relative Flux Vs LED Die Junction Temperature (Cooper, 2007)

Special Considerations

The steady improvement of LEDs makes them a very attractive technology. As Figure 12 shows, LEDs have the best growth potential out of all the lighting technologies currently on the market. Figure 13 illustrates the difference between the price and lumen output of LEDs since 1965 with projections pertaining to lumen efficiency out to year 2020; this shows the rapid pace of improvement for LED technology.

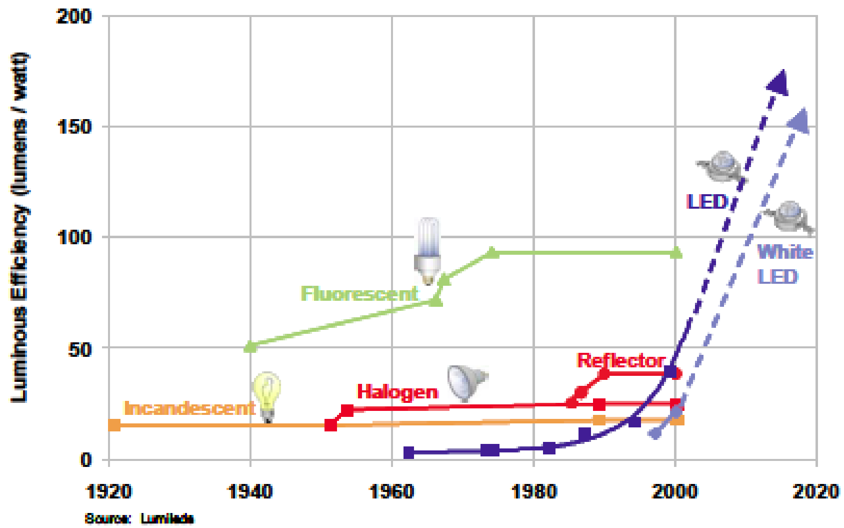


Figure 12. Increase in Lighting Efficiency from 1920 - 2020 (Navigant Consulting Inc., 2006)

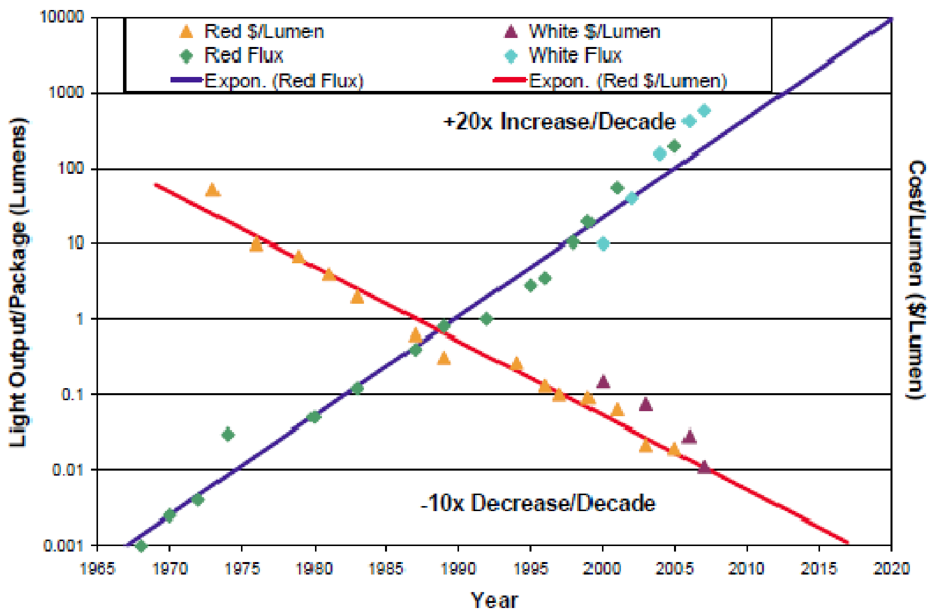


Figure 13. Light Output versus Cost (Navigant Consulting Inc., 2006)

Light-Emitting Diode Lighting Summary

Solid-state lighting (SSL) is the newest technology on the market right now. With more than $37 million being spent on the research, development, and manufacturing by the Department of Energy (DOE), SSL certainly seems to be the technology of the future (EERE News, 2010). Although SSL lighting has great potential, LEDs have been mostly used on a trial basis because the technology has yet to prove itself.

Lighting Regulations and Standards

While the illumination of streets is a standard practice across the United States and many other countries around the world, lighting standards and regulations vary. In the United States, most areas follow IESNA standards in conjunction with other organizations such as the American National Standards Institute (ANSI), Underwriters Laboratories (UL), the National Electrical Manufacturers Association (NEMA), and the National Institute of Standards and Technology (NIST). While these standards have been developed by experts, the end user determines whether a deviation from these lighting standards is required. For instance, the Air Force has developed its own set of standards.

All Air Force installations are required to abide by Unified Facilities Criteria (UFC) 3-530-01, *Design: Interior and Exterior Lighting and Controls*. This UFC is the main document applicable to both indoor and outdoor lighting. While this UFC refers extensively to the IESNA handbook, there are areas where the UFC supersedes the standards specified in the handbook. This UFC defines the critical design criteria for exterior lighting associated with parking lots and roadways as direct glare, light pollution, reflected glare, vertical illuminance, small target visibility, and target horizontal illuminance (Department of the Air Force, 2006). Some of these design criteria have already been discussed in earlier sections. The other design criteria will be explained below along with the three methods for testing the effectiveness of street lighting systems and fixtures.

Illuminance is the simplest method for determining lighting needs. This method simply measures the amount of light produced on a given surface and measures it in foot-candles or lux. Tables 2 and 3 show the recommended amounts of illuminance based on the type of pavement (Table 2) and traffic (Table 3) present for each area. The problem with this method is that it only looks at incident light and does not take into account the light reflected off of the surface. This method is not recommended according to UFC 3-530-01 because it usually produces poor small target visibility results, which can have a significant impact on peripheral vision and object recognition.

The luminance method simulates driver visibility by assessing the quantity and quality of light reflected by the pavement surface to the motorist's eye from contributing luminaires (Bureau of Design and Environment Manual, 2002). Although more complex, this method accounts for glare potential and other indirect lighting circumstances, thereby creating a better sense of how well a certain lighting system design will perform. This method is recommended as an excellent alternative to illuminance as it provides a more "real world" experience. The small target visibility (STV) method is similar to the luminance method but with an additional test for identifying targets across the ground. This collective visibility of the targets is calculated and expressed as a weighted average. This method is preferred because it has a high emphasis on security and peripheral vision (Department of the Air Force, 2006).

Table 2. IESNA RP-8-00 Recommended Illuminance for Intersections (Rea, 2000)

Pavement Classification[1]	Roadway Classification	Average Maintained Illuminance at Pavement[2] — Pedestrian/Area Classification: High (fc (lux))	Medium (fc (lux))	Low (fc (lux))	Uniformity Ratio (E_{avg}/E_{min})	Veiling Luminance Ratio (L_{vmax}/L_{avg})
R1	Major/Major	2.4 (24.0)	1.8 (18.0)	1.2 (12.0)	3.0	0.3
	Major/Collector	2.0 (20.0)	1.5 (15.0)	1.0 (10.0)	3.0	0.3
	Major/Local	1.8 (18.0)	1.4 (14.0)	0.9 (9.0)	3.0	0.3
	Collector/Collector	1.6 (16.0)	1.2 (12.0)	0.8 (8.0)	4.0	0.4
	Collector/Local	1.4 (14.0)	1.1 (11.0)	0.7 (7.0)	4.0	0.4
	Local/Local	1.2 (12.0)	1.0 (10.0)	0.6 (6.0)	6.0	0.4
R2/R3	Major/Major	3.4 (34.0)	2.6 (26.0)	1.8 (18.0)	3.0	0.3
	Major/Collector	2.9 (29.0)	2.2 (22.0)	1.5 (15.0)	3.0	0.3
	Major/Local	2.6 (26.0)	2.0 (20.0)	1.3 (13.0)	3.0	0.3
	Collector/Collector	2.4 (24.0)	1.8 (18.0)	1.2 (12.0)	4.0	0.4
	Collector/Local	2.1 (21.0)	1.6 (16.0)	1.0 (10.0)	4.0	0.4
	Local/Local	1.8 (18.0)	1.4 (14.0)	0.8 (8.0)	6.0	0.4

Notes: [1] R1 is typical for portland cement concrete surface; R2/R3 is typical for asphalt surface

[2] fc = footcandles

Table 3. IESNA RP-8-00 Guidance for Roadway and Pedestrian/Area Classification for Determining Intersection Illumination Levels (Rea, 2000)

Roadway Classification	Description	Daily Vehicular Traffic Volumes[1]
Major	That part of the roadway system that serves as the principal network for through-traffic flow. The routes connect areas of principal traffic generation and important rural roadways leaving the city. Also often known as "arterials," thoroughfares," or "preferentials."	over 3,500 ADT
Collector	Roadways servicing traffic between major and local streets. These are streets used mainly for traffic movements within residential, commercial, and industrial areas. They do not handle long, through trips.	1,500 to 3,500 ADT
Local	Local streets are used primarily for direct access to residential, commercial, industrial, or other abutting property.	100 to 1,500 ADT
Pedestrian Conflict Area Classification	**Description**	**Guidance on Pedestrian Traffic Volumes[2]**
High	Areas with significant numbers of pedestrians expected to be on the sidewalks or crossing the streets during darkness. Examples are downtown retail areas, near theaters, concert halls, stadiums, and transit terminals.	over 100 pedestrians/hour
Medium	Areas where lesser numbers of pedestrians use the streets at night. Typical are downtown office areas, blocks with libraries, apartments, neighborhood shopping, industrial, older city areas, and streets with transit lines.	11 to 100 pedestrians/hour
Low	Areas with very low volumes of night pedestrian usage. These can occur in any of the cited roadway classifications but may be typified by suburban single family streets, very low density residential developments, and rural or semi-rural areas.	10 or fewer pedestrians/hour

Notes: [1] For purposes of intersection lighting levels only

[2] Pedestrian volumes during the average annual first hour of darkness (typically 18:00-19:00), representing the total number of pedestrians walking on both sides of the street plus those crossing the street at non-intersection locations in a typical block or 656 ft (200 m) section. RP-8-00 clearly specifies that the pedestrian volume thresholds presented here are a local option and should not be construed as a fixed warrant.

Special Criteria for LED Fixtures

Because LEDs are such a radical departure from standard lighting technologies, separate standards have been and are being developed. Some of the currently available standards are ANSI C78.377-2008: *Specifications for the Chromaticity of Solid-State Lighting Products*, IES LM-79-2008: *Approved Method for the Electrical and Photometric Testing of Solid State Lighting Devices*, IES LM-80-2008: *Approved Method for Measuring Lumen Depreciation of LED Light Sources*, and IES RP-16: *Addendum a, Nomenclature and Definitions for Illuminating Engineering*. Other standards are also in development, such as NEMA SSL-1: *Driver Performance Standard,* NEMA LSD-49: *Solid-State Lighting – Best Practices for Dimming*, UL 8750, *LED Safety*, TM-21, *Method for Estimation of LED Life*, and LM-XX1, *Approved Method for the Measurement of High Power LEDs.* UFC 3-530-01 does not currently permit the installation of LED luminaires for parking lot and roadway lighting; however, LED technology is allowed for use as interior exit signage. The Air Force is creating Engineering Technical Letter (ETL) 10-02 that plans to address LED fixture design and installation criteria for exterior lighting applications.

Lighting Case Studies

With the emergence of induction and LED technologies in street lighting, there have been a multitude of pilot studies performed in different areas, using collaborations between local utilities, federal agencies, lighting manufacturers, and power companies. These studies test whether LED and/or electrodeless induction technologies truly offer an advantage over the HPS and metal halide fixtures currently in use. Energy savings and upfront costs were used in most studies to determine the economic feasibility of switching technologies. Only one of these studies looked at the environmental impact associated with differing lighting technologies.

San Diego LED Assessment

In August 2003, Tetra Tech EM, Inc., prepared a study for the San Diego Regional Energy Office (SDREO) that performed a technology assessment for LED street and parking lot lighting applications. The study was conducted under the SDREO's Public Agency Energy Partnership Program in partnership with the City of Chula Vista. The applicability, commercial availability, energy savings, and cost were assessed using data provided by product manufacturers, interviews with manufacturers and the users' community, and other reports and information from the lighting industry. Qualitative data were generated during field inspections of Chula Vista's street and parking lot lights and the limited number of LED parking lot lights.

The study compared and contrasted LED fixtures from three different companies. Fluorescent lighting technology using T-5 fluorescent lights was also mentioned in the study as another alternative, but the main focus of the study was on LED lighting. Factors such as luminaire power, lumen output, efficacy, operating temperature, warranty, and cost were included in the study, although only manufacturer's data was used in the analysis, no actual measurement. The study also performed a utility rate analysis. Because the street lights are not metered, the annual cost for each lighting fixture was estimated. An economic assessment was performed comparing a 100W HPS fixture to the different LED fixtures using estimated energy savings and maintenance cost savings based on the manufacturer data they were given. The results are outlined in Table 4.

Table 4. LED vs. HPS Power Usage and Energy Savings (San Diego Regional Energy Office, 2003)

Existing High Pressure Sodium light				**Light Emitting Diode (LED) light**				**Energy Savings**	
Product Type	**Fixture Wattage**	**Annual Operating hours**	**Annual Energy Use**	**Product Maker**	**Fixture Wattage**	**Annual Operating hours**	**Annual Energy Use**	**Annual Energy Saving**	**Annual Energy Saving**
	(W)	**(hrs/yr)**	**(kWh/yr)**		**(W)**	**(hrs/yr)**	**(kWh/yr)**	**(kWh/yr)**	**(%)**
HPS 100	130	4,165	541	Ledtronics	25	4,165	104	437	81%
HPS 100	130	4,165	541	LuxBright	42	4,165	175	367	68%
HPS 100	130	4,165	541	MoonCell	55	4,165	229	312	58%

These results show that the LED fixtures were between 58% and 81% more efficient than HPS fixtures. The simple payback period ranged from 9.2 to 20.1 years for the various LED products when replacing a 100W HPS fixture; it ranged from 6.7 to 14.3 years when 150W HPS fixtures were replaced. A comparison was also made using a 53W T-5 fluorescent lighting fixture. The estimated energy savings were approximately 59%, with an annual $41 energy cost savings when compared with a 100W HPS lamp. The simple payback was estimated at 4.9 years, suggesting that at the time of the study, fluorescent lighting would be more cost effective than using LED lighting. This conclusion was attributed to the high initial costs associated with LED technology and suggests that continued price reductions would make LED lighting more cost competitive with other technologies.

Oakland LED Assessment

A demonstration assessment of LEDs was performed in Oakland, CA, in November 2008 by the DOE and Pacific Gas & Electric (DOE and PG&E, 2008) as a follow-up to a previous street lighting assessment (Phase II report) that compared LED luminaires to a base case of HPS luminaires. The study replaced some of the LED luminaires used in the Phase II study with newer LED luminaires by the same manufacturer. The performance of all three alternatives (HPS, LED Phase II, LED Phase III) was then compared based on lighting performance, electrical power measurements, and economic analysis. The Phase III LED luminaires drew approximately 58W, 20 watts less than the Phase II LED luminaires and 63W less than the HPS luminaires.

The results of the electrical measurements can be seen in Table 5. These savings were calculated using an estimated 4,100 annual hours of operation. Despite the decrease in average power for the Phase III luminaires, they provided illumination roughly equivalent to the Phase II LED luminaires and were sufficient to meet the City of Oakland's requirements in all but the largest pole spacing scenarios. They were also similar in minimum illuminance and maximum-to-minimum uniformity ratios. The simple payback period for the Phase III luminaires ranged from 5 to 14 years, depending on the maintenance and replacement scenario, where the range was 12 to 24 years for the Phase II luminaires under the same maintenance and replacement scenarios. In essence, the study showed that LED technology continues to improve at a rapid pace, making it more economically justifiable, as was suggested by the SDREO study 5 years earlier.

Table 5. Phase II and III Power and Energy Savings (DOE and PG&E, 2008)

Luminaire Type	Average Power (W)	Power Savings (W)	Annual Energy Savings (kWh)
High-Pressure Sodium Luminaire	121.0	-	-
Phase II LED Luminaire	77.7	43.3 (36%)	178
Phase III LED Luminaire	58.3	62.7 (52%)	257

DOE CALiPER Program

The DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) program supports the testing of a wide array of Solid State Lighting (SSL) products available for general illumination. This program independently tests and provides unbiased information on the performance of commercially available SSL products. The results from CALiPER tests provide guidance for DOE planning for SSL research and development, support DOE GATEWAY demonstrations (under which the Oakland study is classified), product performance information, and guide the development of standardized test procedures and measurements (Department of Energy, 2009). All luminaires are tested by one of several prequalified lighting testing laboratories that assist the program. The tests check lighting performance, thermal performance, and electrical power measurement.

The CALiPER test involved the measurement of five LED street lights, two induction street lights, and one HPS street light as a benchmark. This test was conducted from September 2008 to January 2009. Table 6 displays the summarized testing results, showing that SSL street lights can vary significantly in power consumption, efficacy, lumen output, and color temperature. Power factor and CRI are pretty consistent throughout the range. HPS technology shows a lower CRI with significantly higher lumen output at significantly higher power consumption. The efficacy for HPS was above the SSL average for this test, while power factor was significantly lower than all the other technologies involved. The induction street lights showed a higher CRI and lumen output compared to the average SSL street light, while its power consumption and power factor were close to the averages of the SSL. It should be noted that the induction lamps were highly sensitive to thermal conditions, which resulted in the ranges shown. This test proves that not all LED street lamps are alike and that testing should be an integral step of any procurement process.

Table 6. DOE CALiPER Study Results (DOE, 2009)

--SSL testing following IESNA LM-79-08 --25ºC ambient temperature	DOE CALiPER TEST ID	Total Power (Watts)	Output (initial lumens)	Efficacy (lm/W)	CCT (K)	CRI	Power Factor
Streetlights							
SSL Streetlight	08-107	55	1028	19	14628	74	0.93
SSL Streetlight	08-108	58	3179	55	6227	75	0.99
SSL Streetlight	08-109	73	3440	47	6052	72	0.99
SSL Streetlight	08-110	37	2588	71	5210	68	0.99
SSL Streetlight	08-111	95	3105	33	3101	72	0.99
HPS Streetlight Benchmark	08-122	117	6540	56	2042	21	0.44
Fluorescent Induction Streetlight	08-152*	67-71	3695-3960	52-59	3906	75	0.96
Fluorescent Induction Streetlight	08-153*	70-71	3234-3561	46-50	4253	77	0.99

Groton Induction Study

Morante (2008) conducted a study for Groton Utilities in Groton, CT, testing the theory that tuning lower power lights to the mesopic (combination of photopic and scotopic vision in low light) needs of drivers and pedestrians would make a noticeable improvement. For the study, 100W HPS fixtures were replaced with 55W induction fixtures and ceramic metal halide fixtures. A survey was handed out to collect perceptions of the lighting change. An economic analysis was also performed to determine if either technology could cost effectively replace the existing HPS lighting. The study found that drivers and pedestrians perceived they could see better and felt safer with light sources tuned toward the needs of mesopic vision. The economic analyses showed a simple payback for the induction lamp of 7.1 years for new installations and 13.9 years when retrofitting an existing HPS installation. Energy efficiency and power data were estimated using manufacturer data for the economic analysis.

Life-cycle Comparison: Compact Fluorescent and Incandescent Bulbs

So far, all of the studies mentioned have only addressed the financial and energy savings associated with the use of different lighting technologies without mentioning any of the environmental impacts that may result from the change in technology. Soneji (2008) compared the life-cycle energy usage between compact fluorescent (CFL) and incandescent light bulbs. The study used the Process-Sum and Economic Input-Output Life-cycle Assessment (EIO-LCA) methods. The results of the study found that although manufacturing energy use for CFLs was higher, lower energy consumption in the use phase provides a significant savings over incandescent light bulbs over the life-cycle.

The study also noted that mercury use in CFLs (5mg per bulb) is offset by the reduction in power usage compared to incandescent lighting. While this study did not compare outdoor lighting technologies, it does show how EIO-LCA can be used to measure the environmental impacts associated with the use of different lighting technologies.

Summary

With an understanding of the policy, regulations, and technologies surrounding street lighting, it is clear that additional studies are necessary to determine the long-term feasibility and practicality for implementing new street lighting technologies from both an economic and environmental perspective. The case studies discussed substantiate the use of both life-cycle cost analysis and economic input-output life cycle assessment methodologies, as these tools were used successfully in their respective studies to show both the economic and environmental effects associated with different lighting technologies.

The next chapter will cover the methodologies used in this study. It builds on the studies mentioned in this chapter and addresses how both the economic and environmental aspects of the study were handled. It also shows how both methodologies were used together to create an understanding of the primary and secondary effects associated with the life-cycle process of street lighting.

III. Methodology

This chapter reviews the methods used in this study. It begins with a brief overview about life-cycle analysis and the boundaries drawn for the analysis. Then the two methods of Life-Cycle Cost Analysis and Economic Input-Output Life-Cycle Assessment are explained. Calculations, software, and information necessary for these methods will be discussed along with the preliminary setup for each analysis.

Life-Cycle Analysis

The goal of this study was to perform an economic and environmental life-cycle analysis (LCA) of the different lighting technologies currently available to the Air Force. A life-cycle analysis involves evaluating the environmental effects of a product, process, or activity holistically, by looking at the entire life-cycle of the product or process from raw materials extraction through consumer use (Conway-Schempf, 2000). Figure 14 shows the typical life-cycle process of most products from an aggregate view.

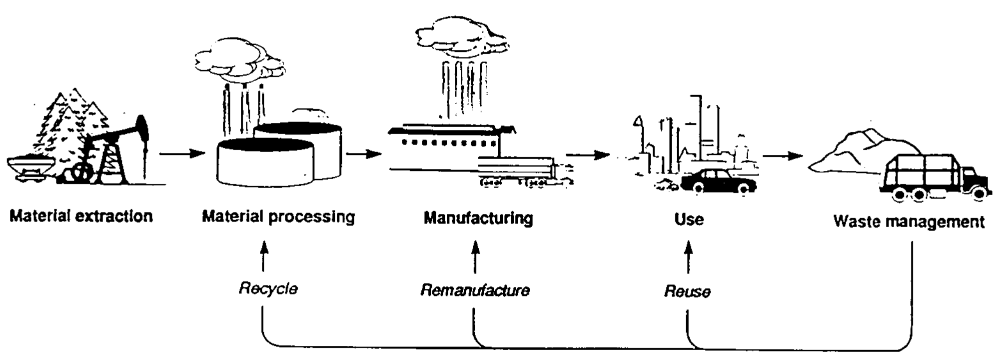


Figure 14. Stages of a product life-cycle (Office of Technology Assessment, 1992)

The product life-cycle typically has five stages. The first stage involves extracting raw materials from the natural earth, such as iron ore, oil, wood, sand, and water. The next stage is processing those raw materials into finished materials, such as oil into plastic and iron ore into steel. The third stage is to turn those materials into a final product. This stage encompasses both turning materials into parts and assembling those parts into a final product. The fourth stage is the use stage, where the product is used for its intended purpose. The final stage is the disposal or end-of-life stage, where the product is discarded to a landfill or recycled for reuse. Street lighting fixtures have a similar life-cycle process, which enables the use of LCA as a feasible process by which to analyze the data. This study used two different types of LCA to create the holistic picture necessary for a true understanding of the economic and environmental impacts associated with the different lighting technologies. For this study, the economic life-cycle analysis will focus only on the use phase, while the environmental life-cycle analysis will concentrate on the manufacturing, use, and waste management phases of the product life-cycle.

Life-Cycle Cost Analysis

The National Energy Conservation Policy Act (42 U.S.C. 8254) established the protocol for all federal agencies to use life-cycle cost methods and procedures for investment evaluations. Practical and effective present value (PV) methods should be used for estimating and comparing life-cycle costs for federal buildings, using the sum of all capital and operating expenses associated with the energy system of the building involved over the expected life of such system or during a period of 40 years, whichever is shorter, and using average fuel costs and the current discount rate (42 USC 8254, 1978). In response to this act, the Federal Energy Management Program (FEMP) under the DOE partnered with the National Institute of Standards and Technology (NIST) to create the Life-Cycle Cost Analysis (LCCA) model, which is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision (Fuller & Petersen, 1996). This model includes the calculation and comparison of facility energy projects by tracking the savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), simple payback period (SPP), and discounted payback period (DPP). The combination of these measures facilitates the direct comparison of two or more projects to determine which project is the most cost-effective solution.

While this method was originally designed for measuring the differences in energy use and long-term costs between different projects relating to a building, it can easily be applied to street lighting alternatives since the criteria used to evaluate street lights is virtually the same as those criteria needed for evaluating other facility-related energy projects. To reduce errors in calculation and streamline the use of LCCA, FEMP and NIST created the Building Life-Cycle Cost 5 (BLCC5) software. It is currently the only software recommended for use by the Air Force in calculating life-cycle costing associated with energy projects and is required under 10 CFR 436 subpart A.

Requirements for BLCC5

The BLCC5 software requires some assumptions about design life, installation and acquisition costs, energy use, and maintenance costs of each lighting technology. Therefore, the following assumptions were the basis for this analysis and were the values input into the BLCC5 software.

Design Life

To ensure this study accurately depicted a real-world scenario, a design life for the lighting technology was based on the long-term effects of using the lighting technologies during their use phase. The design life consisted of both an equipment service life and comprehensive design life. The comprehensive design life and equipment service life was used to calculate the life-cycle cost using BLCC5 software.

Equipment Design Life

An important aspect of LCA is the estimated design life of the equipment being used. The equipment design life was determined by the average service life between manufacturers of the same lighting technology. This eliminates any low or high design life estimates associated with a certain technology that could skew the analysis, as most manufacturers claim different design lives for their products based on their design goals. The estimated service lives for each technology are listed in Table 7.

Table 7. Equipment Service Life before Bulb or Fixture Replacement

Lighting Technology	Service Life
HPS	17,000
LED	50,000
Induction	88,000

The Illuminating Engineering Society of North America (IESNA) recommends standards for all types of lighting. The service life for a light is determined by the length of time the light is expected to last until it is no longer bright enough to provide sufficient illumination. In the case of HPS and electrodeless induction, the fixture has reached the end of its service life when it is estimated that half of the fixtures of that type will fail. LED standards are slightly different due to the difference in technology. LED fixtures are deemed to have reached the end of their service life when they have reached 70% of their initial lumen output. Given these service lives, the study assumed the fixtures would last to their service lives with no additional maintenance or replacement necessary.

Comprehensive Design Life

For this study, a comprehensive design life of 20 years was chosen. Although design lives of 25 years are mandated through Executive Order 13123, the continued advancements in lighting technology would render the findings of this study obsolete. A 25-year study period would also create a need to calculate salvage values for the newer technologies, as they would still have a significant service life associated with them. The 20-year study period allows for all the technologies to be used for their respective minimum service lives, providing a more realistic picture of the long-term costs and benefits associated with street lighting. Making the study any shorter would deprive future savings associated with any of these technologies. Lengthening the study period would be unrealistic as newer, more efficient technologies are likely to exist in the future, rendering current technologies obsolete.

Energy Use Calculations

The importance of energy use calculations was critical to this study, as energy use is the driver for most of the energy policy currently in existence. Street lights run only on electricity, making these calculations simple and straightforward. The power consumption for each type of fixture was calculated as a whole, meaning the individual sections of the lighting fixture (power supply, light, ballast, etc.) were not calculated individually. The energy use for all three lighting technologies was estimated by using manufacturers' specifications and confirming this data with the DOE CALiPER test results. The DOE CALiPER test showed that HPS technology ran about 17% above the nominal wattage rating, which is acceptable for ballast power consumption and losses. Both LED and induction technologies used less wattage than they were rated for; however, for this study, it was assumed that they would run at their nominal power rating to ensure a fair and unbiased study. The induction technology runs at a slightly higher wattage due to the required input power specified by the manufacturer. The nominal and estimated values used in this study can be seen in Table 8. Along with these power calculations, the number of hours the fixture is in use is also important. Based upon the average hours of darkness on earth, street lighting is necessary 50% of the time. Therefore, the calculation for hours of energy used per year is: $12\ hours\ per\ day\ \times 365.25\ days\ a\ year = 4383\ hours/year$.

Table 8. Technology Comparison Table

Lighting Technology	Power (W) Rated	Power (W) Estimated	Expected Life (years)	Fixture Cost	Bulb Cost	Annual Consumption (KWH/year)	Labor Hours per Replacement	Replacements over Study Period
High Pressure Sodium	250	293	4	-	$72	1284	1.0	4
Light Emitting Diode	131	131	11	$472	-	574	2.0	2
Induction	150	160	20	$600	-	701	2.0	1

Fixture and Fixture Installation Costs

The fixture costs for this study came from an Air Force study conducted at Peterson AFB that compared the lighting performance of four LED and one induction fixture. Fixture installation costs were estimated based on labor hours and the labor rates for each location in this study. The amount of time required for the installation of each lighting technology was assumed to be two hours per fixture based on lighting changeover activities at other Air Force bases for LED and HPS technologies. It was also assumed that it will take the same amount of time at each location as each fixture was assumed to be a direct replacement for the current HPS technology. Because HPS is the incumbent technology, there is no fixture cost associated. There is a maintenance cost associated with HPS that will be discussed in the maintenance section of this paper. The labor rates at each location were identified in an Air Force data call, and are displayed in Appendix A.

Maintenance Cost Calculations

Another key component to understanding the true cost differences between lighting technologies is the required maintenance and associated costs. This allows for a broader picture which includes both the present costs to operate and the future costs to maintain lighting technologies. Maintenance costs were calculated based on the equipment service life of the fixtures. For the HPS technology, the equipment service life dictates that the bulbs be replaced every 4 years. The cost associated with bulb replacement is $72 for the bulb plus 1 hour of labor at the location labor rate. Full fixture replacement for the LED technology was required in year 11 of this study, while no replacement is necessary for the electrodeless induction technology as its equipment service life was equal to the comprehensive design life of the study. It is possible to replace individual components in an LED fixture; however, finding replacement parts 11 years later may become difficult and it was assumed to be more cost effective to just replace the entire fixture.

Financial Calculations

The Federal Energy Management Program (FEMP), which is a part of the Energy Efficiency and Renewable Energy (EERE) branch of the Department of Energy (DOE), mandates the use of certain financial measures, which includes the savings-to-investment ratio, adjusted internal rate of return, simple payback period, and the discounted payback period.

Saving-to-Investment Ratio (SIR)

SIR is a measure of the economic performance of a project that expresses the relationship between savings and investment cost (in present value) as a ratio (Fuller & Petersen, 1996). This is similar to the cost/benefit ratio and is used to rank different alternatives amongst each other based on cost and benefits comparison over time. A SIR of 1.0 means the amount invested is equivalent to the amount saved. The higher the SIR, the more financially beneficial it is to invest in the alternative. The equation for SIR is shown below (Fuller & Petersen, 1996).

$$SIR = \frac{\Delta E + \Delta W + \Delta OM\&R}{\Delta I + \Delta Repl - \Delta Res} \tag{1}$$

Where

SIR	= Ratio of operational savings to investment-related additional costs, computed for the alternative relative to the base case
ΔE	= Savings in energy costs attributable to the alternative
ΔW	= Savings in water costs attributable to the alternative
$\Delta OM\&R$	= Difference in operation, maintenance, and repair costs
ΔI	= Additional initial investment cost required for the alternative relative to the base case
$\Delta Repl$	= Difference in capital replacement costs
ΔRes	= Difference in residual value

Adjusted Internal Rate of Return (AIRR)

AIRR is a measure of the annual percentage yield from a project investment over the study period as a relative measure of cost effectiveness (Fuller & Petersen, 1996). The AIRR is compared to a minimum acceptable rate of return (MARR) generally equal to the current discount rate being applied. In order for a project to be economically advantageous, the AIRR must be greater than the MARR. The equation for AIRR is shown below (Fuller & Petersen, 1996).

$$AIRR = (1 + r)(SIR)^{\frac{1}{N}} - 1 \tag{2}$$

Where

AIRR	= Adjusted internal rate of return
r	= Reinvestment percentage rate
SIR	= Savings to Investment Ratio
N	= Number of years in study period

Simple Payback Period (SPP) and Discounted Payback Period (DPP)

SPP and DPP measure the amount of time required to recover initial investment costs. They are expressed by the number of years elapsed between the beginning of the service period and the time at which cumulative savings (net of any incremental investment costs incurred after the service date) are just sufficient to offset the incremental initial investment cost of the project (Fuller & Petersen, 1996). The difference between SPP and DPP is that DPP requires cash flows occurring each year to be discounted to present value before accumulating them as savings and costs. SPP simply ignores any changes in price and does not discount any cash flows. The equation below is the same for both SPP and DPP, the difference being the discount rate for SPP would be zero (Fuller & Petersen, 1996).

$$\sum_{t=1}^{y} \frac{[\Delta E_t + \Delta OM\&R_t - \Delta Repl_t + \Delta Res_t]}{(1+d)^t} \geq \Delta I_0 \qquad (3)$$

Where

ΔE_t = Savings in energy costs in year *t*

$\Delta OM\&R_t$ = Difference in operation, maintenance, and repair costs in year *t*

$\Delta Repl_t$ = Difference in capital replacement cost in year *t*

ΔRes_t = Difference in residual value in year *t*

d = Discount rate

ΔI_0 = Additional initial investment cost

Economic Input-Output Life-Cycle Assessment

The Economic Input-Output Life-Cycle Assessment (EIO-LCA) model was developed at Carnegie-Mellon University in an effort to simplify the complications inherent in a process-based LCA examining the inputs and outputs in an individual product's life-cycle. Process-based LCA is very accurate for simple products like paper drinking cups; however, it becomes much more difficult when multiple items are combined to make one product, as in the case of street lamps. Finding the information necessary for this type of LCA is nearly impossible and creates boundary issues for the study. Therefore, the EIO-LCA model uses economic input-output matrices and industry sector level environmental and nonrenewable resource consumption data to assess the economy-wide environmental impacts of products and processes (Hendrickson, Horvath, Joshi, Klausner, Lave, & McMichael, 1997). The Economic Input-Output (EIO) model uses mathematical formulas to represent the monetary transactions between industry sectors associated with a product's life-cycle, from the acquisition of raw materials to create the product to the end-of-life disposal of that product. EIO models indicate what goods or services (or output of an industry) are consumed by other industries (or used as input) (Carnegie-Mellon University, 2008).

EIO models identify the direct, indirect, and total effects of changes to the economy. Direct effects are the first-tier transactions between a sector and the sectors that provide its direct output. For example, the power production sector would be directly affected by coal mining, as coal is a primary source for power production. Indirect effects are the second-tier, third-tier, etc., transactions among all sectors as a result of the first-tier transactions. Total effects are the sum of direct and indirect effects (Carnegie-Mellon University, 2008). Utilizing an input-output approach to conduct LCA, EIO-LCA utilizes sectors classified by the North American Industry Classification System (NAICS) in conjunction with economic data tables derived from the Bureau of Economic Analysis (BEA) and publicly available environmental data from the EPA and the Department of Energy (DOE) (Huang & Matthews, 2008). The environmental data linked to these tables provides data about the pollutants resulting from the economic activity associated with each sector involved in the life-cycle of a given product. The pollutants tracked are measured in metric tons and consist of the following: methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and chlorofluorocarbons (CFC). The combination of these pollutants creates an overall global warming potential (GWP) which was used to determine the overall environmental impact associated with the life-cycle of each lighting technology.

In order to streamline the use of EIO-LCA, Carnegie-Mellon University's Green Design Institute has created an online tool to determine the effect of changing the output of a single sector through multiple models based on different years. This tool facilitates the use of models for analysis and allows for customized models to be developed for custom and hybrid products. A custom model was used to analyze how the difference in materials between the lighting technologies affects environmental impact over the material processing, manufacturing, and disposal phases.

Using the EIO-LCA model

EIO-LCA was used in this study to assess the environmental impacts associated with the material processing, manufacturing, and disposal phases of the different lighting technologies. The lighting technologies were compared by analyzing the differences between them, as there are many similarities throughout the product life of the lighting technologies. These differences were input into the EIO-LCA model and the levels of change between environmental and economic impacts were compared. Because of the complexity associated with this model, every change in input can have a significant effect on the level and types of impact across all tiers and sectors. In order to minimize the number of affects possible across the 490 sectors associated with EIO-LCA, only the top 10 were analyzed for comparing direct and indirect emissions. This reduced the number of variables in the matrix calculation and allowed for a more streamlined analysis.

Inputs for the EIO-LCA Software

In order for the EIO-LCA software to calculate an accurate output, it was important to determine which NAICS sectors were going to be used as inputs for this study. Based on the findings in the literature review, the sectors shown in Table 9 were the corresponding inputs for each phase of the life-cycle associated with each lighting technology.

Table 9. EIO-LCA Input Data

Fixture Type	Manufacturing Phase	Use Phase	Disposal Phase
HPS	Electric Lamp Bulb and Part Manufacturing (100%) Cost = $54 per bulb	BLCC Emissions CO_2	Waste Management and Remediation Hazardous Disposal Cost = $1.50 per bulb EOL Fixture Disposal = $2.50 per fixture
LED	Lighting Fixture Manufacturing (20%) Semiconductor and Related Device Manufacturing (80%) Cost = $354 per fixture	BLCC Emissions CO_2	Waste Management and Remediation Fixture Disposal Cost Year 11 = $1 per fixture EOL Fixture Disposal = $1 per fixture HPS Fixture Disposal = $2.50 per fixture
Induction	Lighting Fixture Manufacturing (100%) Cost = $499 per fixture	BLCC Emissions CO_2	Waste Management and Remediation EOL Fixture Disposal Cost = $1 per fixture EOL Hazardous Disposal Cost = $1.50 per fixture HPS Fixture Disposal = $2.50 per fixture

*EOL - End of Life

Manufacturing Phase

Based on the information obtained during the literature review, the following assumptions were made about each lighting technology. For HPS, the only sector to include in the manufacturing phase was the Electric Lamp Bulb and Part Manufacturing sector because this study only looked at replacing the light bulbs at their replacement interval. The electrodeless induction fixtures are essentially the equivalent of fluorescent lamps, so the Lighting Fixture Manufacturing sector was used. Because this lighting fixture will last the duration of the study, they only needed to be manufactured once. For LED fixtures, a combination of the Semiconductor and Related Device Manufacturing sector was used at 80% and the Lighting Fixture Manufacturing sector was used at 20%. This breakdown was used because the majority of an LED fixture (LEDs, power supply, circuit board) is recognized in the semiconductor sector. However, other aspects, such as the fixture housing and wiring, are highlighted under the lighting fixture sector. These percentages are an approximation, as the content of the different LED fixtures on the market may vary. Because of the equipment service life associated with the LED technology, they were manufactured twice for this study.

The costs associated with each of these technologies were assumed to have a 25% profit already built into the cost of each bulb or fixture. This additional profit was removed for this analysis to allow a more realistic estimate of the actual cost required to produce each of these lighting technologies. The GWP emissions and fixture costs for each technology multiplied by the total number of fixtures in use by the Air Force will result in the total GWP emissions for this phase. The total number of fixtures at each location can be found in Appendix A.

Use Phase

The use phase was calculated using the BLCC5 emissions output data. The data provided by the BLCC5 software provides a more accurate estimation of CO_2 emissions output for each individual location than EIO-LCA can provide. The variance in CO_2 between states is significant enough to warrant a more detailed analysis than EIO-LCA can provide. These CO_2 emissions combined with the total number of fixtures will produce the GWP for this phase.

Disposal Phase

The Waste and Remediation Services sector was used to calculate the disposal costs for all three technologies. HPS bulbs require disposal every four years and incur an additional cost associated with the disposal of mercury inside the bulbs. The HPS fixture also incurs a fixture disposal cost at the end of the study, as it is assumed the fixture will require replacement at that time. Both LED and electrodeless induction include the cost for the disposal of the original HPS fixtures, as these disposal costs help increase the accuracy of the study. Because the equipment service life for LED does not reach the end of the study period, disposal costs were calculated for fixture disposal at the 11 year point and at the end of the study. The electrodeless induction fixtures have an equipment service life that takes them through the end of the study, so only one disposal fee related to these fixtures is necessary. An additional cost was levied on the electrodeless induction fixture for hazardous waste disposal as a result of the mercury used in the induction bulb. The average disposal fee for an HID light source due to its classification as hazardous waste is $2.50/lamp (EHSO, 2010). This disposal fee was split to segregate fixture disposal cost and hazardous material cost. This additional cost was included in the Waste and Remediation Services sector during the analysis. The GWP emissions for fixture and bulb disposal combined with the total number of fixtures will produce the GWP results for this phase of the analysis.

Summary

This chapter has detailed the methodology used in this study. Using both LCCA and EIO-LCA allowed for a more thorough analysis than using either one as the sole method for this study. The analysis provided by the BLCC5 software allowed for a clearer analysis of the advantages/disadvantages associated with each technology over the long-term for the use phase both economically and environmentally. The environmental results from the BLCC5 along with the results from the EIO-LCA model helped analyze the environmental costs and energy usage associated with each lighting technology from the manufacturing phase of product life through to the disposal phase. This helped identify any tradeoffs associated with the lighting technologies between the energy savings and environmental emissions.

IV. Results and Analysis

This chapter details the results of this study to compare high pressure sodium (HPS), electrodeless induction, and light-emitting diode (LED) street lighting technologies. The first section of the chapter analyzes the data used in the study along with relevant operation and installation costs. The second section focuses on the economic impacts associated with the technologies. Life-cycle costs for each technology will also be determined, to include the use of sensitivity analysis to examine the effects of equipment design life, fixture prices, power consumption, and carbon emission offset expenses. The third section of the chapter focuses on the environmental impacts associated with each technology. The economic input-output life-cycle assessment (EIO-LCA) tool will be used to analyze the environmental impacts associated with each technology as they relate to the overall economy. This study covers 56 independent locations covering 30 states, 4 countries, and the District of Columbia.

Economic Impact

Using the information given in earlier chapters, an economic analysis was performed to determine which lighting technology provided the best cost-benefit over the study period. The economic measures used for comparison included the savings-to-investment ratio, adjusted internal rate of return, simple payback period, and the discounted payback period. These values were calculated by comparing HPS fixtures to LED and electrodeless induction fixtures of equivalent performance. The intention of this analysis was to determine whether the newer technologies with their higher upfront costs and lower power usage were economically viable. These comparisons were made without the use of tax incentives or emissions penalties, as policies relating to these aspects can change over time. Emissions penalties are discussed later in this chapter.

Savings-to-Investment Ratio Results

The savings to investment ratio calculates how much money can be saved compared to the amount invested. An SIR of 1.0 means that the money invested is equal to the money saved. The Air Force has mandated a minimum SIR of 1.25 for energy projects. Table 10 shows the results from calculating the savings-to-investment ratio for each of the newer lighting technologies compared with its HPS equivalent fixture at each location. Table 11 displays the summary results for the entire study. The SIR comparison shows that both LED and induction technologies will have a decent return on investment when used to replace HPS lighting. There are seven locations at which LED technology and three locations at which induction technology would have an SIR under 1.0, suggesting these locations would lose money when investing in the newer technology. On the other hand, there are 10 locations at which LED technology and 12 locations at which induction technology would have an SIR greater than 2.0, suggesting that investing in the newer technologies at these locations would provide significant cost savings over HPS technology. With LED having an SIR so close to the Air Force requirement of 1.25 along with the 0.58 standard deviation, LED would be a difficult technology to suggest based on this measure. Induction is a more viable alternative for replacement, as its SIR is 0.19 higher while its standard deviation only increased by 0.06.

Table 10. Savings-to-Investment Ratio Compared with Similar HPS Fixture

Base Name	LED	IND	Base Name	LED	IND
ALTUS AFB	1.22	1.34	KIRTLAND AFB	1.41	1.52
ANDREWS AFB	1.69	1.86	KUNSAN AB	1.38	1.51
BARKSDALE AFB	1.05	1.14	LACKLAND AFB	1.24	1.42
BEALE AFB	1.09	1.27	LANGLEY AFB	1.24	1.42
BOLLING AFB	2.00	2.19	LAUGHLIN AFB	1.88	2.07
BUCKLEY AFB	1.24	1.41	LOS ANGELES AFS	1.69	1.90
CANNON AFB	1.16	1.32	LUKE AFB	1.26	1.26
CAPE CANAVERAL	1.49	1.68	MALMSTROM AFB	1.34	1.52
CHARLESTON AFB	1.13	1.28	MCCHORD AFB	0.90	1.08
CLEAR AFS	3.31	3.70	MCCONNELL AFB	1.14	1.29
DAVIS MONTHAN AFB	1.24	1.41	MCGUIRE AFB	2.04	2.26
DYESS AFB	1.39	1.55	MINOT AFB	0.94	1.13
EARECKSON	2.76	3.12	MISAWA AB	1.75	1.91
EDWARDS AFB	2.06	2.31	MOODY AFB	1.23	1.42
EGLIN AFB	1.73	1.93	MT HOME AFB	0.83	0.99
EIELSON AFB	2.21	2.48	NELLIS AFB	1.23	1.43
ELLSWORTH AFB	0.92	1.06	OFFUTT AFB	0.84	0.98
ELMENDORF AFB	1.11	1.31	ROBINS AFB	1.15	1.31
FAIRCHILD AFB	0.85	1.00	SCHRIEVER AFB	1.26	1.45
GOODFELLOW AFB	1.07	1.19	SCOTT AFB	1.08	1.23
GRAND FORKS AFB	1.04	1.23	SEYMOUR JOHNSON AFB	1.29	1.49
HANSCOM AFB	2.07	2.32	SHEPPARD AFB	1.59	1.76
HICKAM AFB	2.62	2.91	THULE AB	3.07	3.41
HILL AFB	0.74	0.89	TRAVIS AFB	1.04	1.24
HOLLOMAN AFB	1.32	1.50	USAF ACADEMY	1.01	1.16
HURLBURT FLD	1.49	1.73	VANDENBERG AFB	1.35	1.51
KEESLER AFB	1.33	1.49	WHITEMAN AFB	1.05	1.24
KING SALMON	2.97	3.35	YOKOTA AB	1.84	2.03

Table 11. Savings-to-Investment Summary

Fixture Type	Low	High	Average	Std Deviation	Met AF Requirement
LED	0.74	3.31	1.47	0.58	29
Induction	0.89	3.70	1.66	0.64	42

Adjusted Internal Rate of Return Results

The adjusted internal rate of return is the overall rate of return on the investment to include installation, operations, maintenance, and disposal costs associated with each lighting technology. This minimum allowable rate of return (MARR) must exceed 7% in order to cover the cost of capital used according to the Office of Management and Budget (OMB, 1992). Other entities and organizations may require a different discount rate depending on the funding source, but the Air Force is bound to the OMB rate. Table 12 shows the results from the AIRR analysis per location while Table 13 summarizes the results. The AIRR analysis is not supportive of these new technologies. Only 15 locations for LED and 17 locations for induction meet or exceed the MARR for this study. Both technologies have an average AIRR below the minimum required, although induction does have a slight edge over LED in this measure.

Table 12. Adjusted Internal Rate of Return

Base Name	LED	IND	Base Name	LED	IND
ALTUS AFB	5.26%	5.77%	KIRTLAND AFB	6.02%	6.44%
ANDREWS AFB	6.99%	7.51%	KUNSAN AB	5.93%	6.40%
BARKSDALE AFB	4.47%	4.90%	LACKLAND AFB	5.37%	6.08%
BEALE AFB	4.66%	5.48%	LANGLEY AFB	5.37%	6.09%
BOLLING AFB	7.91%	8.41%	LAUGHLIN AFB	7.59%	8.10%
BUCKLEY AFB	5.38%	6.06%	LOS ANGELES AFS	7.00%	7.63%
CANNON AFB	5.02%	5.68%	LUKE AFB	5.44%	5.44%
CAPE CANAVERAL	6.33%	6.99%	MALMSTROM AFB	5.78%	6.43%
CHARLESTON AFB	4.88%	5.55%	MCCHORD AFB	3.67%	4.63%
CLEAR AFS	10.66%	11.29%	MCCONNELL AFB	4.91%	5.58%
DAVIS MONTHAN AFB	5.34%	6.04%	MCGUIRE AFB	8.02%	8.58%
DYESS AFB	5.97%	6.56%	MINOT AFB	3.93%	4.87%
EARECKSON	9.67%	10.34%	MISAWA AB	7.19%	7.66%
EDWARDS AFB	8.08%	8.69%	MOODY AFB	5.31%	6.09%
EGLIN AFB	7.13%	7.73%	MT HOME AFB	3.25%	4.16%
EIELSON AFB	8.46%	9.07%	NELLIS AFB	5.30%	6.11%
ELLSWORTH AFB	3.82%	4.56%	OFFUTT AFB	3.34%	4.14%
ELMENDORF AFB	4.77%	5.67%	ROBINS AFB	4.99%	5.36%
FAIRCHILD AFB	3.37%	4.25%	SCHRIEVER AFB	5.44%	6.21%
GOODFELLOW AFB	4.59%	5.13%	SCOTT AFB	4.63%	5.32%
GRAND FORKS AFB	4.44%	5.34%	SEYMOUR JOHNSON AFB	5.58%	6.34%
HANSCOM AFB	8.09%	8.72%	SHEPPARD AFB	6.68%	7.23%
HICKAM AFB	9.38%	9.95%	THULE AB	10.24%	10.84%
HILL AFB	2.70%	3.61%	TRAVIS AFB	4.43%	5.34%
HOLLOMAN AFB	5.69%	6.36%	USAF ACADEMY	4.28%	5.00%
HURLBURT FLD	6.35%	7.13%	VANDENBERG AFB	5.80%	6.41%
KEESLER AFB	5.74%	6.35%	WHITEMAN AFB	4.49%	5.38%
KING SALMON	10.07%	10.74%	YOKOTA AB	7.46%	1.99%

Table 13. Adjusted Internal Rate of Return Results Summary

Fixture Type	Low	High	Average	Std Deviation	Met AF Requirement
LED	2.70%	10.66%	5.94%	1.85%	15
Induction	1.99%	11.29%	6.50%	1.88%	17

Simple Payback Period Results

The simple payback period is another measure of a project's financial feasibility and is commonly used in government estimates. It represents the number of years, based on operating cost savings, required to pay back the initial investment amount associated with the project. Table 14 shows the results of the simple payback analysis per location with Table 15 displaying the summarized results. The Air Force recommends a simple payback period that is under 10 years for energy projects. Using this Air Force criterion, 52 locations for LED and 29 locations for induction are able to meet the goal. Looking at the average and standard deviation values for each technology, LED has the advantage as its average is lower than the minimum SPP required and the first standard deviation is still within the allowable payback period. The average for the induction technology is 10 years, putting it right on the line of financial feasibility.

This analysis also shows that some bases can payback the financial investment in these new technologies relatively quickly. The shortest payback period for LED is 3 years, which occurs at three locations; however, 4 years is the earliest payback period for induction, which occurs at only one location. There is also one instance in which the payback period for LED technology is not realized in the lifetime of the study. Draft ETL 10-02 suggests reducing the SPP for LED lighting to 5 years in order to coincide with the typical warranty period offered by manufacturers for this technology. If the SPP is reduced to 5 years, only 12 locations would reach the required SPP for implementation.

Table 14. Simple Payback Period Results per Location (Years)

Base Name	LED	IND	Base Name	LED	IND
ALTUS AFB	8	11	KIRTLAND AFB	7	10
ANDREWS AFB	6	9	KUNSAN AB	7	10
BARKSDALE AFB	9	13	LACKLAND AFB	8	11
BEALE AFB	8	12	LANGLEY AFB	8	11
BOLLING AFB	5	7	LAUGHLIN AFB	5	8
BUCKLEY AFB	7	11	LOS ANGELES AFS	6	8
CANNON AFB	8	11	LUKE AFB	12	12
CAPE CANAVERAL	6	9	MALMSTROM AFB	7	10
CHARLESTON AFB	8	12	MCCHORD AFB	10	13
CLEAR AFS	3	4	MCCONNELL AFB	8	12
DAVIS MONTHAN AFB	7	11	MCGUIRE AFB	5	7
DYESS AFB	7	10	MINOT AFB	10	13
EARECKSON	4	5	MISAWA AB	6	8
EDWARDS AFB	5	7	MOODY AFB	8	11
EGLIN AFB	6	8	MT HOME AFB	11	15
EIELSON AFB	4	6	NELLIS AFB	7	10
ELLSWORTH AFB	10	14	OFFUTT AFB	11	15
ELMENDORF AFB	8	11	ROBINS AFB	8	11
FAIRCHILD AFB	10	14	SCHRIEVER AFB	7	10
GOODFELLOW AFB	9	13	SCOTT AFB	9	12
GRAND FORKS AFB	9	12	SEYMOUR JOHNSON AFB	7	10
HANSCOM AFB	5	7	SHEPPARD AFB	6	9
HICKAM AFB	4	6	THULE AB	3	5
HILL AFB	-	16	TRAVIS AFB	9	12
HOLLOMAN AFB	7	10	USAF ACADEMY	9	13
HURLBURT FLD	6	9	VANDENBERG AFB	7	10
KEESLER AFB	7	10	WHITEMAN AFB	9	12
KING SALMON	3	5	YOKOTA AB	5	8

Table 15. Simple Payback Results Summary

Fixture Type	Low	High	Average	Std Deviation	Met AF Requirement
LED	3	>20	7	3	52
Induction	4	16	10	3	29

Discounted Payback Period Results

This discounted payback period is similar to SPP with the exception that the time value of money is taken into account, which is important when comparing items with larger initial costs and lower operating costs over time. The results for the DPP analysis at each location are shown in Table 16 with the summarized results shown in Table 17. The results for DPP show slightly longer payback periods than those seen in SPP, which is to be expected. With the time value of money accounted for, there are seven locations for LED and three locations for induction that show no payback over the study period. The shortest payback period is 3 years for one location using the LED technology, while the shortest payback period for induction has increased to 5 years, which occurs at three locations are capable of reaching. The averages for each technology have increased by 2 and 3 years for LED and induction lighting, respectively.

Table 16. Discounted Payback Period Results per Location (Years)

Base Name	LED	IND	Base Name	LED	IND
ALTUS AFB	9	14	KIRTLAND AFB	7	12
ANDREWS AFB	6	10	KUNSAN AB	8	13
BARKSDALE AFB	10	18	LACKLAND AFB	9	13
BEALE AFB	10	15	LANGLEY AFB	9	13
BOLLING AFB	5	9	LAUGHLIN AFB	6	9
BUCKLEY AFB	8	13	LOS ANGELES AFS	6	10
CANNON AFB	9	15	LUKE AFB	15	15
CAPE CANAVERAL	7	11	MALMSTROM AFB	8	12
CHARLESTON AFB	10	15	MCCHORD AFB	-	19
CLEAR AFS	3	5	MCCONNELL AFB	10	15
DAVIS MONTHAN AFB	9	13	MCGUIRE AFB	6	8
DYESS AFB	8	12	MINOT AFB	-	18
EARECKSON	4	6	MISAWA AB	6	10
EDWARDS AFB	5	8	MOODY AFB	9	13
EGLIN AFB	6	10	MT HOME AFB	-	-
EIELSON AFB	5	7	NELLIS AFB	9	13
ELLSWORTH AFB	-	19	OFFUTT AFB	-	-
ELMENDORF AFB	10	15	ROBINS AFB	9	15
FAIRCHILD AFB	-	20	SCHRIEVER AFB	8	13
GOODFELLOW AFB	10	17	SCOTT AFB	10	16
GRAND FORKS AFB	11	16	SEYMOUR JOHNSON AFB	8	13
HANSCOM AFB	5	8	SHEPPARD AFB	7	11
HICKAM AFB	4	6	THULE AB	4	5
HILL AFB	-	-	TRAVIS AFB	10	16
HOLLOMAN AFB	8	13	USAF ACADEMY	11	17
HURLBURT FLD	7	11	VANDENBERG AFB	8	12
KEESLER AFB	8	13	WHITEMAN AFB	10	16
KING SALMON	4	5	YOKOTA AB	6	9

Table 17. Discounted Payback Period Results Summary

Fixture Type	Low	High	Average	Std Deviation
LED	3	>20	9	5
Induction	5	>20	13	4

Emissions Results

Although the BLCC5 software is mostly used for cost analysis, it is also capable of calculating the carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrous oxide (NO_X). Because it was assumed that each lighting technology would perform similarly at each base, the differences in output for these greenhouse gases was based on each state or country in which the military base is located. Each state or country has a slightly different way of producing power, resulting in differing greenhouse gas emissions. For this portion of the analysis, only CO_2 output was recorded, as this is what was used to calculate the carbon tax at each location. The results are shown graphically by state or country in Figure 15 and by base in Table 18. These results show a significant carbon footprint for the HPS technology in comparison with LED and induction technologies. LED technology produces 55% less emissions while the induction technology produces 45% less emissions compared to HPS. States such as Idaho and California produce the least amount of emissions at just fewer than 700kg of CO_2 per year for a single HPS fixture while North Dakota and the District of Columbia are the highest CO_2 emitters at around 1500kg of CO_2 per year for the same fixture.

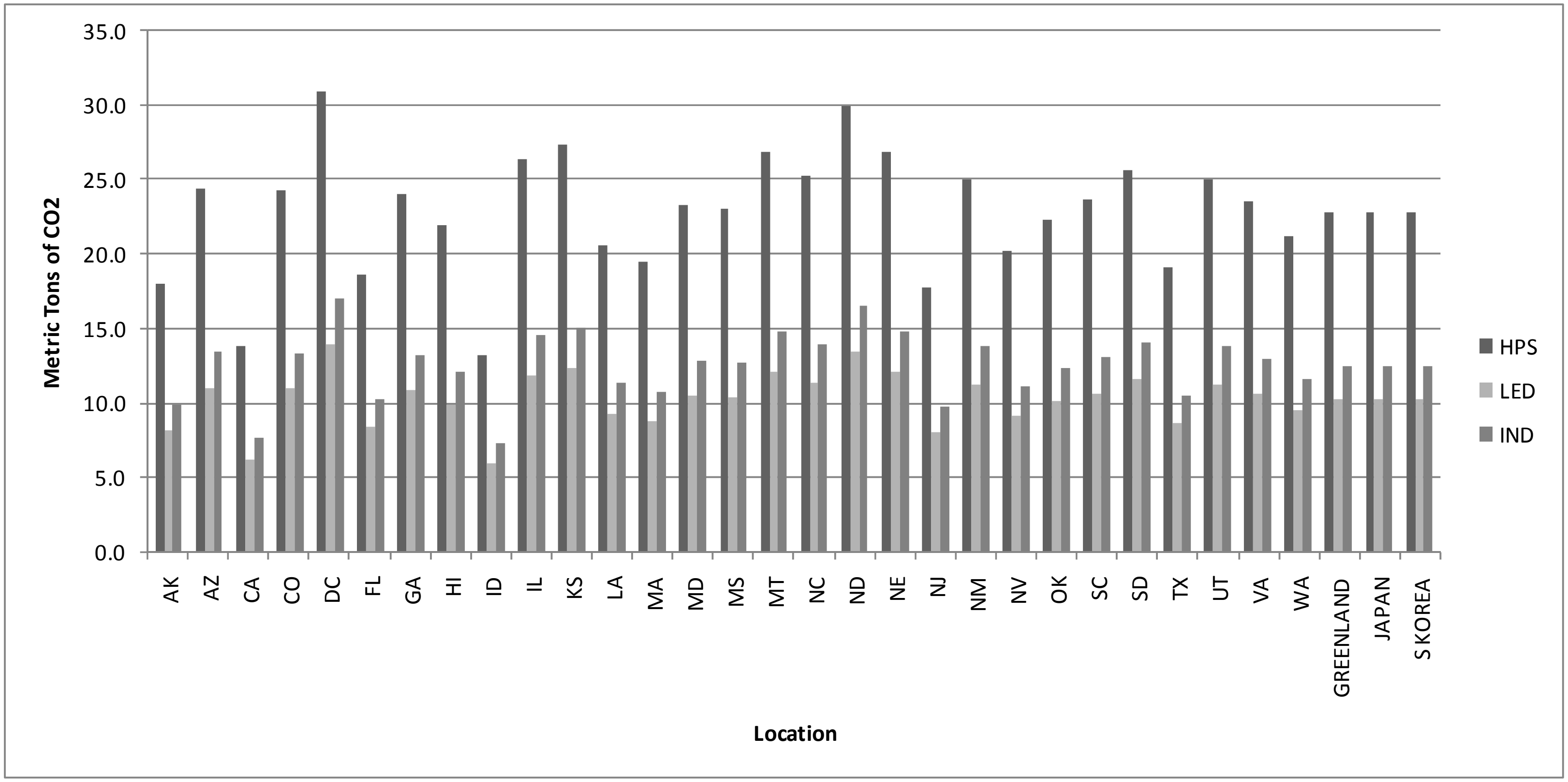


Figure 15. Life-cycle Carbon Dioxide Emissions (Metric Tons)

Table 18. CO_2 Emissions Data by Location Singe Fixture (Metric Tons)

	HPS		LED		IND	
Base Name	Annual	Life-Cycle	Annual	Life-Cycle	Annual	Life-Cycle
ALTUS AFB	1.1	22.3	0.5	10.1	0.6	12.3
ANDREWS AFB	1.2	23.3	0.5	10.5	0.6	12.8
BARKSDALE AFB	1.0	20.6	0.5	9.3	0.6	11.3
BEALE AFB	0.7	13.8	0.3	6.2	0.4	7.6
BOLLING AFB	1.5	30.9	0.7	13.9	0.9	17.0
BUCKLEY AFB	1.2	24.3	0.5	10.9	0.7	13.4
CANNON AFB	1.3	25.0	0.6	11.3	0.7	13.8
CAPE CANAVERAL	0.9	18.6	0.4	8.4	0.5	10.2
CHARLESTON AFB	1.2	23.7	0.5	10.7	0.7	13.0
CLEAR AFS	0.9	18.0	0.4	8.1	0.5	9.9
DAVIS MONTHAN AFB	1.2	24.4	0.5	11.0	0.7	13.4
DYESS AFB	1.0	19.1	0.4	8.6	0.5	10.5
EARECKSON	0.9	18.0	0.4	8.1	0.5	9.9
EDWARDS AFB	0.7	13.8	0.3	6.2	0.4	7.6
EGLIN AFB	0.9	18.6	0.4	8.4	0.5	10.3
EIELSON AFB	0.9	18.0	0.4	8.1	0.5	9.9
ELLSWORTH AFB	1.3	25.6	0.6	11.5	0.7	14.1
ELMENDORF AFB	0.9	18.0	0.4	8.1	0.5	9.9
FAIRCHILD AFB	1.1	21.2	0.5	9.5	0.6	11.6
GOODFELLOW AFB	1.0	19.1	0.4	8.6	0.5	10.5
GRAND FORKS AFB	1.5	30.0	0.7	13.5	0.8	16.5
HANSCOM AFB	1.0	19.5	0.4	8.8	0.5	10.7
HICKAM AFB	1.1	21.9	0.5	9.8	0.6	12.0
HILL AFB	1.3	25.0	0.6	11.3	0.7	13.8
HOLLOMAN AFB	1.3	25.1	0.6	11.3	0.7	13.8
HURLBURT FLD	0.9	18.6	0.4	8.4	0.5	10.3
KEESLER AFB	1.2	23.1	0.5	10.4	0.6	12.7
KING SALMON	0.9	18.0	0.4	8.1	0.5	9.9
KIRTLAND AFB	1.3	25.1	0.6	11.3	0.7	13.8
KUNSAN AB	1.1	22.7	0.5	10.2	0.6	12.5
LACKLAND AFB	1.0	19.2	0.4	8.6	0.5	10.5
LANGLEY AFB	1.2	23.6	0.5	10.6	0.6	13.0
LAUGHLIN AFB	1.0	19.2	0.4	8.6	0.5	10.5
LOS ANGELES AFS	0.7	13.8	0.3	6.2	0.4	7.6
LUKE AFB	1.2	24.4	0.5	11.0	0.7	13.4
MALMSTROM AFB	1.3	26.8	0.6	12.1	0.7	14.8
MCCHORD AFB	1.1	21.1	0.5	9.5	0.6	11.6
MCCONNELL AFB	1.4	27.3	0.6	12.3	0.8	15.0
MCGUIRE AFB	0.9	17.7	0.4	8.0	0.5	9.7
MINOT AFB	1.5	30.0	0.7	13.5	0.8	16.5
MISAWA AB	1.1	22.7	0.5	10.2	0.6	12.5
MOODY AFB	1.2	24.0	0.5	10.8	0.7	13.2
MT HOME AFB	0.7	13.2	0.3	5.9	0.4	7.2
NELLIS AFB	1.0	20.2	0.5	9.1	0.6	11.1
OFFUTT AFB	1.3	26.9	0.6	12.1	0.7	14.8
ROBINS AFB	1.2	24.0	0.5	10.8	0.7	13.2
SCHRIEVER AFB	1.2	24.3	0.5	10.9	0.7	13.4
SCOTT AFB	1.3	26.4	0.6	11.9	0.7	14.5
SEYMOUR JOHNSON AFB	1.3	25.3	0.6	11.4	0.7	13.9
SHEPPARD AFB	1.0	19.2	0.4	8.6	0.5	10.5
THULE AB	1.1	22.7	0.5	10.2	0.6	12.5
TRAVIS AFB	0.7	13.8	0.3	6.2	0.4	7.6
USAF ACADEMY	1.2	24.3	0.5	10.9	0.7	13.4
VANDENBERG AFB	0.7	13.8	0.3	6.2	0.4	7.6
WHITEMAN AFB	1.4	27.3	0.6	12.3	0.8	15.0
YOKOTA AB	1.1	22.7	0.5	10.2	0.6	12.5

Carbon Dioxide Emissions Offset Costs

There has been much debate over whether to introduce a carbon cap and trade system, where the government sets an overall emissions cap while creating allowances that enable businesses to emit a given amount. The allowances can be traded, so companies that reduce their emissions can sell surplus allowances to those who would have to pay to comply (Leybovich, 2009). Although this cap and trade system has many advantages, setting the limits of pollution for each industry can be complex and complicated. This study uses the idea of a carbon tax, which simply adds a fee for every metric ton of CO_2 emitted. Although the Carbon Tax Center suggests a $15 per metric ton tax rate with a $10 rate increase per year (Komanoff, 2009), this study uses a flat rate $25 fee, which is in line with France's proposal in 2009 (Hance, 2009). Table 19 shows the amount of carbon tax paid per metric ton at the $25 rate per lighting fixture per year. Figure 16 shows the cost difference between the use of an HPS fixture and its equivalent LED or induction fixture.

The results of this analysis show a significant cost disadvantage when using HPS fixtures, especially considering these are the results for just one fixture. The HPS fixtures have carbon taxes that range from $16 to $39 per metric ton per year while the highest carbon tax values for LED and induction are $17 and $21, respectively. These carbon dioxide emission offset costs were applied to the present value calculations in the next section to help determine how much of an impact these costs would have on the life-cycle costs associated with these lighting technologies.

Table 19. Annual Carbon Tax per Fixture

Base Name	HPS	LED	IND	Base Name	HPS	LED	IND
ALTUS AFB	$28	$13	$15	KIRTLAND AFB	$31	$14	$17
ANDREWS AFB	$29	$13	$16	KUNSAN AB	$28	$13	$16
BARKSDALE AFB	$26	$12	$14	LACKLAND AFB	$24	$11	$13
BEALE AFB	$17	$8	$9	LANGLEY AFB	$29	$13	$16
BOLLING AFB	$39	$17	$21	LAUGHLIN AFB	$24	$11	$13
BUCKLEY AFB	$30	$14	$17	LOS ANGELES AFS	$17	$8	$9
CANNON AFB	$31	$14	$17	LUKE AFB	$30	$14	$17
CAPE CANAVERAL	$23	$10	$13	MALMSTROM AFB	$34	$15	$18
CHARLESTON AFB	$30	$13	$16	MCCHORD AFB	$26	$12	$15
CLEAR AFS	$22	$10	$12	MCCONNELL AFB	$34	$15	$19
DAVIS MONTHAN AFB	$30	$14	$17	MCGUIRE AFB	$22	$10	$12
DYESS AFB	$24	$11	$13	MINOT AFB	$37	$17	$21
EARECKSON	$22	$10	$12	MISAWA AB	$28	$13	$16
EDWARDS AFB	$17	$8	$9	MOODY AFB	$30	$13	$16
EGLIN AFB	$23	$10	$13	MT HOME AFB	$16	$7	$9
EIELSON AFB	$22	$10	$12	NELLIS AFB	$25	$11	$14
ELLSWORTH AFB	$32	$14	$18	OFFUTT AFB	$34	$15	$18
ELMENDORF AFB	$22	$10	$12	ROBINS AFB	$30	$13	$16
FAIRCHILD AFB	$26	$12	$15	SCHRIEVER AFB	$30	$14	$17
GOODFELLOW AFB	$24	$11	$13	SCOTT AFB	$33	$15	$18
GRAND FORKS AFB	$37	$17	$21	SEYMOUR JOHNSON AFB	$32	$14	$17
HANSCOM AFB	$24	$11	$13	SHEPPARD AFB	$24	$11	$13
HICKAM AFB	$27	$12	$15	THULE AB	$28	$13	$16
HILL AFB	$31	$14	$17	TRAVIS AFB	$17	$8	$9
HOLLOMAN AFB	$31	$14	$17	USAF ACADEMY	$30	$14	$17
HURLBURT FLD	$23	$10	$13	VANDENBERG AFB	$17	$8	$9
KEESLER AFB	$29	$13	$16	WHITEMAN AFB	$34	$15	$19
KING SALMON	$22	$10	$12	YOKOTA AB	$28	$13	$16

Life-Cycle Cost Results

Another important aspect of this study was to examine the life-cycle cost associated with each of these lighting technologies. Present value analysis accounts for the total life-cycle costs incurred for the installation, operation, and maintenance of each lighting fixture type over the 20-year service period. Table 20 shows the present value for a single lighting fixture at each location. Table 21 summarizes the results and Figure 16 graphically expresses the cost savings, comparing HPS technology to LED and induction technology. The PV calculations show a cost savings of 21% and 23% for LED and induction technologies, respectively, when compared to HPS. LED has the best PV savings at 15 locations in this study, with 7 locations showing a negative savings; induction technology has the best PV for 38 locations, with only 3 locations showing a negative savings. HPS shows a cost advantage over the other technologies at 3 locations.

Table 20. Present Value Cost for Single Fixture

Base Name	HPS	LED	IND	Base Name	HPS	LED	IND
ALTUS AFB	$1,746	$1,549	$1,500	KIRTLAND AFB	$1,940	$1,587	$1,575
ANDREWS AFB	$2,640	$1,978	$1,992	KUNSAN AB	$2,040	$1,676	$1,647
BARKSDALE AFB	$1,463	$1,418	$1,355	LACKLAND AFB	$1,849	$1,608	$1,523
BEALE AFB	$1,710	$1,619	$1,492	LANGLEY AFB	$1,855	$1,613	$1,526
BOLLING AFB	$3,097	$2,145	$2,205	LAUGHLIN AFB	$2,895	$2,055	$2,095
BUCKLEY AFB	$1,829	$1,591	$1,513	LOS ANGELES AFS	$2,688	$1,978	$1,970
CANNON AFB	$1,653	$1,499	$1,417	LUKE AFB	$1,559	$1,457	$1,365
CAPE CANAVERAL	$2,304	$1,815	$1,771	MALMSTROM AFB	$1,998	$1,665	$1,604
CHARLESTON AFB	$1,602	$1,476	$1,389	MCCHORD AFB	$1,269	$1,377	$1,206
CLEAR AFS	$6,083	$3,553	$3,833	MCCONNELL AFB	$1,613	$1,482	$1,395
DAVIS MONTHAN AFB	$1,821	$1,589	$1,507	MCGUIRE AFB	$3,269	$2,240	$2,299
DYESS AFB	$2,047	$1,675	$1,631	MINOT AFB	$1,359	$1,420	$1,254
EARECKSON	$5,104	$3,136	$3,310	MISAWA AB	$2,604	$1,911	$1,936
EDWARDS AFB	$3,215	$2,165	$2,207	MOODY AFB	$1,864	$1,630	$1,530
EGLIN AFB	$2,709	$1,989	$1,992	MT HOME AFB	$1,106	$1,280	$1,117
EIELSON AFB	$3,718	$2,463	$2,542	NELLIS AFB	$1,884	$1,649	$1,542
ELLSWORTH AFB	$1,238	$1,311	$1,190	OFFUTT AFB	$1,101	$1,252	$1,115
ELMENDORF AFB	$1,694	$1,579	$1,436	ROBINS AFB	$1,650	$1,501	$1,415
FAIRCHILD AFB	$1,135	$1,288	$1,133	SCHRIEVER AFB	$1,919	$1,654	$1,560
GOODFELLOW AFB	$1,427	$1,364	$1,295	SCOTT AFB	$1,511	$1,436	$1,339
GRAND FORKS AFB	$1,547	$1,506	$1,357	SEYMOUR JOHNSON AFB	$1,984	$1,684	$1,596
HANSCOM AFB	$3,443	$2,341	$2,393	SHEPPARD AFB	$2,390	$1,829	$1,819
HICKAM AFB	$4,469	$2,798	$2,952	THULE AB	$5,460	$3,259	$3,493
HILL AFB	$941	$1,192	$1,028	TRAVIS AFB	$1,549	$1,508	$1,357
HOLLOMAN AFB	$1,968	$1,655	$1,588	USAF ACADEMY	$1,390	$1,382	$1,273
HURLBURT FLD	$2,438	$1,909	$1,843	VANDENBERG AFB	$1,973	$1,642	$1,591
KEESLER AFB	$1,946	$1,630	$1,576	WHITEMAN AFB	$1,560	$1,508	$1,364
KING SALMON	$5,504	$3,304	$3,516	YOKOTA AB	$2,844	$2,037	$2,067

Table 21. Present Value Cost Results Summary

Fixture Type	Low	High	Average	Std Deviation	Avg Savings
HPS	$941	$6,083	$2,279	$1,154	-
LED	$1,192	$3,553	$1,801	$529	$478
IND	$1,028	$3,833	$1,760	$628	$519

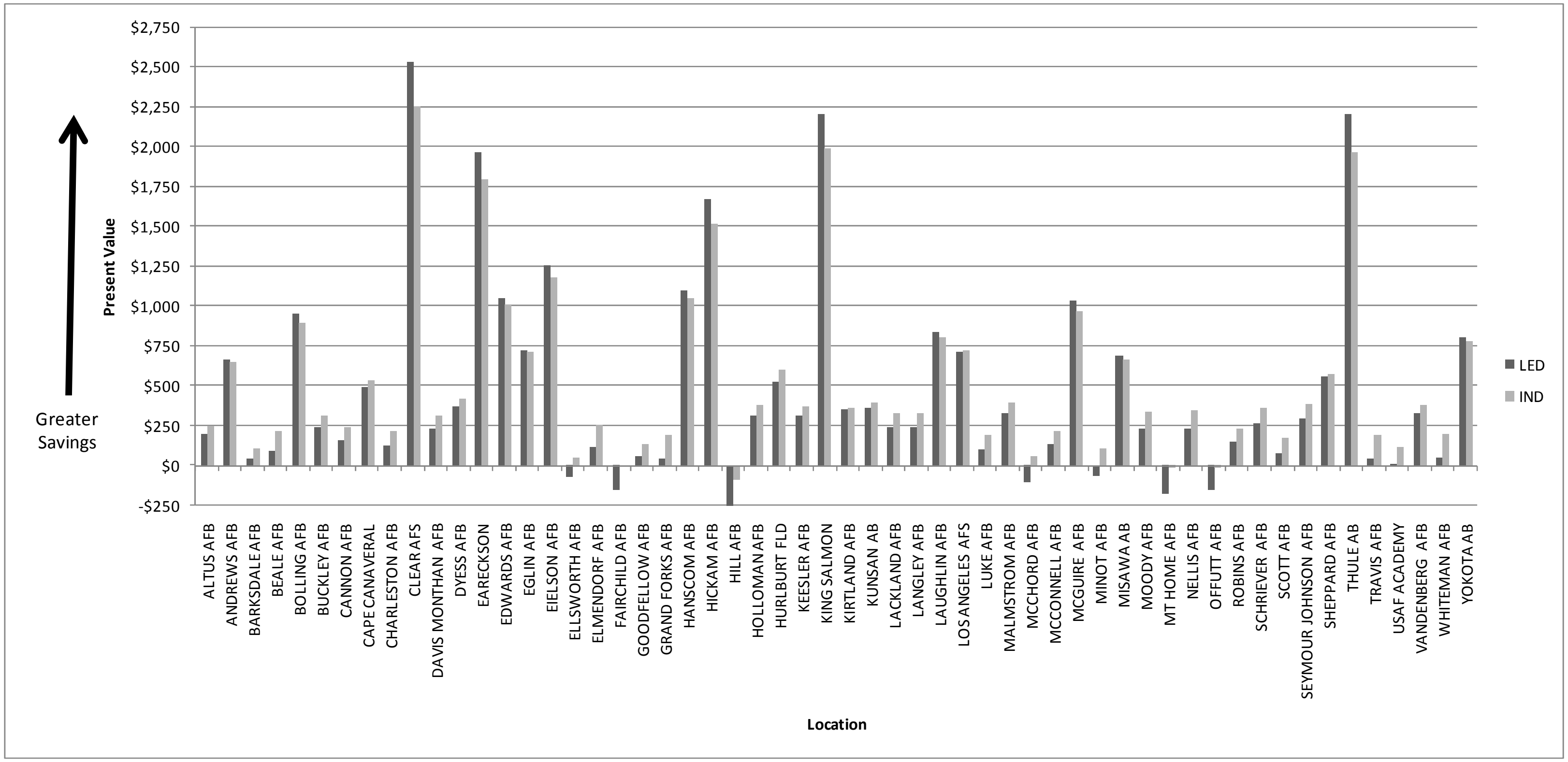


Figure 16. Present Value Savings Compared with HPS

Using this PV data, the approximate savings can be calculated by multiplying the single fixture PV by the number of fixtures located at each location. Table 22 shows the total cost savings for LED and induction technology compared to HPS. The total savings for using LED is approximately $10.9 million over the life-cycle, whereas induction would save almost $12.6 million over the life-cycle. Converting these life-cycle savings to an annual cost, the Air Force would save approximately $820 thousand and $940 thousand annually for the implementation of LED and induction technology, respectively.

Table 22. Present Value Savings for all fixtures

Base Name	LED	IND	Base Name	LED	IND
ALTUS AFB	$208,229	$260,022	KIRTLAND AFB	$143,318	$148,190
ANDREWS AFB	$1,026,762	$1,005,048	KUNSAN AB	$91,000	$98,250
BARKSDALE AFB	$6,660	$15,984	LACKLAND AFB	$383,913	$519,318
BEALE AFB	$142,961	$342,478	LANGLEY AFB	$97,526	$132,587
BOLLING AFB	$225,624	$211,404	LAUGHLIN AFB	$974,400	$928,000
BUCKLEY AFB	$102,102	$135,564	LOS ANGELES AFS	$156,910	$158,678
CANNON AFB	$113,344	$173,696	LUKE AFB	$98,328	$187,016
CAPE CANAVERAL	$97,800	$106,600	MALMSTROM AFB	$373,959	$442,462
CHARLESTON AFB	$23,436	$39,618	MCCHORD AFB	-$71,712	$41,832
CLEAR AFS	$75,900	$67,500	MCCONNELL AFB	$28,427	$47,306
DAVIS MONTHAN AFB	$91,872	$124,344	MCGUIRE AFB	$427,035	$402,550
DYESS AFB	$186,000	$208,000	MINOT AFB	-$7,625	$13,125
EARECKSON	$177,120	$161,460	MISAWA AB	$248,094	$239,144
EDWARDS AFB	$456,750	$438,480	MOODY AFB	$61,542	$87,842
EGLIN AFB	$180,000	$179,250	MT HOME AFB	-$52,200	-$3,300
EIELSON AFB	$1,316,495	$1,233,624	NELLIS AFB	$67,445	$98,154
ELLSWORTH AFB	-$17,447	$11,472	OFFUTT AFB	-$69,913	-$6,482
ELMENDORF AFB	$105,225	$236,070	ROBINS AFB	$89,400	$141,000
FAIRCHILD AFB	-$88,128	$1,152	SCHRIEVER AFB	$90,100	$122,060
GOODFELLOW AFB	$5,733	$12,012	SCOTT AFB	$38,325	$87,892
GRAND FORKS AFB	$12,956	$60,040	SEYMOUR JOHNSON AFB	$162,600	$210,296
HANSCOM AFB	$287,622	$274,050	SHEPPARD AFB	$336,600	$342,600
HICKAM AFB	$574,824	$521,848	THULE AB	$261,919	$234,073
HILL AFB	-$163,150	-$56,550	TRAVIS AFB	$21,279	$99,648
HOLLOMAN AFB	$82,006	$99,560	USAF ACADEMY	$488	$7,137
HURLBURT FLD	$509,427	$572,985	VANDENBERG AFB	$516,029	$595,538
KEESLER AFB	$317,264	$371,480	WHITEMAN AFB	$6,552	$24,696
KING SALMON	$330,000	$298,200	YOKOTA AB	$68,595	$66,045

Life-Cycle Costs including Carbon Dioxide Emissions Costs

Using the annual carbon tax values calculated in Table 19, the life-cycle costs for these technologies at each location were recalculated. The results for each location are shown in Table 23 with the summarized results in Table 24. Figure 17 displays the PV differential savings comparing HPS with LED and induction technologies. The results from this analysis shift the PV for both of the newer technologies even greater in their favor. The HPS technology saw a $400 increase for its average in the study while LED and induction technologies saw an increase of approximately $200 in the same category.

The average savings also increased from $478 to $703 for LED technology while the average savings for induction went from $519 to $703. Also, LED is now the best value at 20 locations, whereas induction is the best value at 36 locations. When the carbon tax was not present, HPS was the best value at three locations; however, the addition of the carbon tax gave induction the advantage at these locations. The carbon tax also gave LED an advantage at five locations where induction previously had the cost advantage. It is also worth noting that the standard deviation for each technology went down after the addition of the carbon tax, suggesting that charging for emissions output provides a normalizing affect on the data.

Table 23. Present Value Cost with $25 Carbon Tax

Base Name	HPS	LED	IND	Base Name	HPS	LED	IND
ALTUS AFB	$2,187	$1,753	$1,736	KIRTLAND AFB	$2,395	$1,792	$1,824
ANDREWS AFB	$3,097	$2,182	$2,244	KUNSAN AB	$2,477	$1,878	$1,897
BARKSDALE AFB	$1,872	$1,607	$1,575	LACKLAND AFB	$2,226	$1,781	$1,728
BEALE AFB	$1,959	$1,736	$1,624	LANGLEY AFB	$2,311	$1,818	$1,778
BOLLING AFB	$3,711	$2,412	$2,535	LAUGHLIN AFB	$3,273	$2,228	$2,299
BUCKLEY AFB	$2,269	$1,796	$1,762	LOS ANGELES AFS	$2,917	$2,095	$2,102
CANNON AFB	$2,108	$1,705	$1,666	LUKE AFB	$1,808	$1,575	$1,497
CAPE CANAVERAL	$2,666	$1,973	$1,975	MALMSTROM AFB	$2,496	$1,884	$1,868
CHARLESTON AFB	$2,074	$1,681	$1,641	MCCHORD AFB	$1,650	$1,552	$1,425
CLEAR AFS	$6,405	$3,699	$4,009	MCCONNELL AFB	$2,154	$1,720	$1,697
DAVIS MONTHAN AFB	$2,261	$1,794	$1,756	MCGUIRE AFB	$3,627	$2,403	$2,494
DYESS AFB	$2,424	$1,848	$1,836	MINOT AFB	$1,947	$1,690	$1,588
EARECKSON	$5,427	$3,282	$3,486	MISAWA AB	$3,041	$2,114	$2,186
EDWARDS AFB	$3,464	$2,282	$2,339	MOODY AFB	$2,336	$1,834	$1,782
EGLIN AFB	$3,071	$2,147	$2,197	MT HOME AFB	$1,340	$1,382	$1,249
EIELSON AFB	$4,055	$2,610	$2,733	NELLIS AFB	$2,251	$1,810	$1,747
ELLSWORTH AFB	$1,746	$1,533	$1,476	OFFUTT AFB	$1,641	$1,490	$1,401
ELMENDORF AFB	$2,017	$1,726	$1,612	ROBINS AFB	$2,122	$1,706	$1,667
FAIRCHILD AFB	$1,516	$1,464	$1,352	SCHRIEVER AFB	$2,359	$1,859	$1,810
GOODFELLOW AFB	$1,804	$1,538	$1,499	SCOTT AFB	$2,036	$1,674	$1,625
GRAND FORKS AFB	$2,135	$1,776	$1,690	SEYMOUR JOHNSON AFB	$2,488	$1,904	$1,864
HANSCOM AFB	$3,834	$2,520	$2,605	SHEPPARD AFB	$2,768	$2,002	$2,024
HICKAM AFB	$4,864	$2,974	$3,172	THULE AB	$5,897	$3,461	$3,743
HILL AFB	$1,396	$1,397	$1,277	TRAVIS AFB	$1,798	$1,625	$1,489
HOLLOMAN AFB	$2,422	$1,860	$1,837	USAF ACADEMY	$1,830	$1,587	$1,522
HURLBURT FLD	$2,800	$2,066	$2,047	VANDENBERG AFB	$2,222	$1,760	$1,723
KEESLER AFB	$2,402	$1,835	$1,828	WHITEMAN AFB	$2,100	$1,746	$1,666
KING SALMON	$5,826	$3,451	$3,692	YOKOTA AB	$3,281	$2,240	$2,316

Table 24. Present Value Cost with $25 Carbon Tax Results Summary

Fixture Type	Low	High	Average	Std Deviation	Avg Savings
HPS	$1,340	$6,405	$2,689	$1,134	-
LED	$1,382	$3,699	$1,987	$520	$703
IND	$1,249	$4,009	$1,986	$618	$703

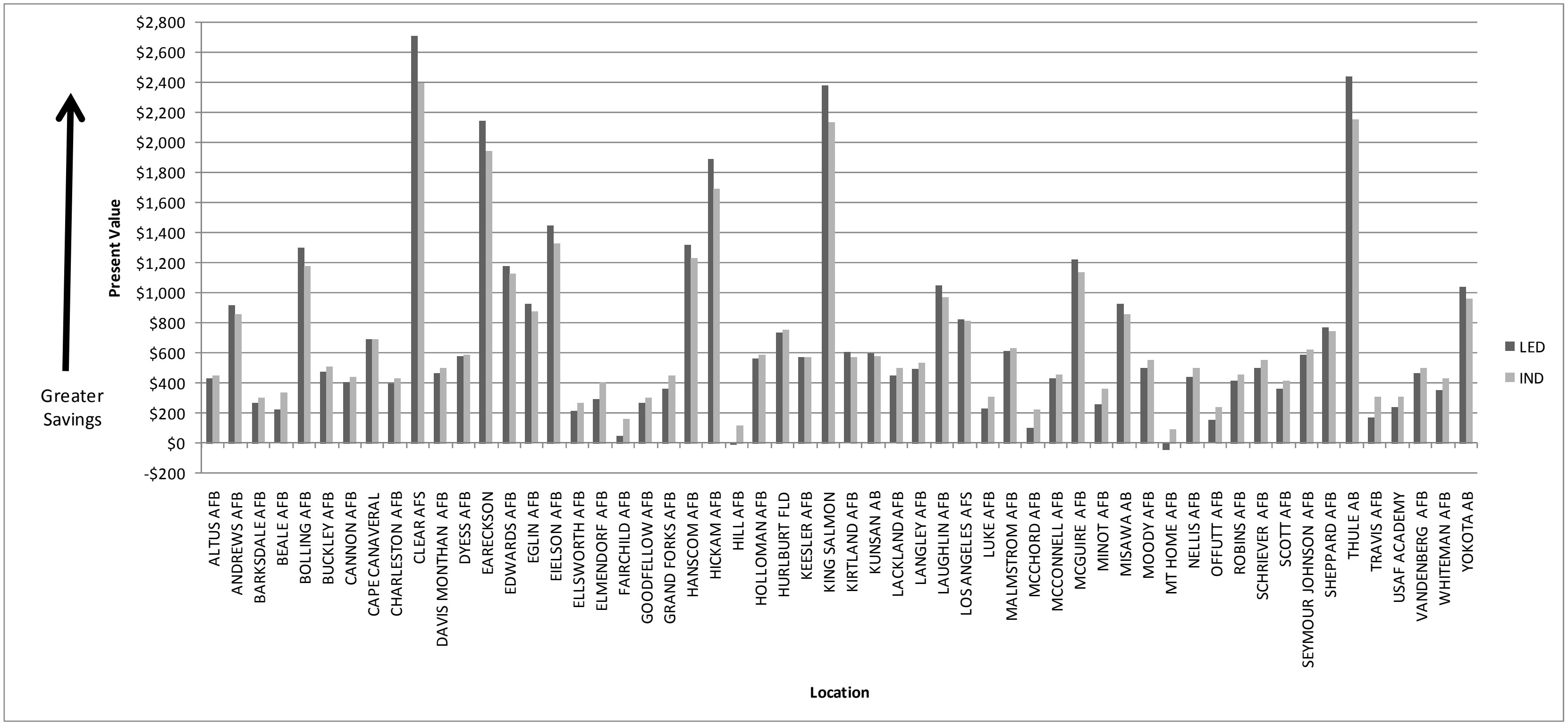


Figure 17. Present Value Savings with Carbon Tax

Life-Cycle Cost Sensitivity Analysis Results

Life-cycle cost is one of the better tools for measuring project feasibility and comparison; however, it can be impacted by several factors. It is important to investigate these factors in order to have a full understanding of how sensitive this analysis was to changes in the values of these factors. The factors that were investigated are equipment service life, fixture cost, power consumption, and carbon tax rates. Each of these factors was studied separately and the results can be found in the following sections.

All 56 locations in this study were analyzed, but five locations were chosen for additional discussion. The locations were selected based on their utility costs, labor costs, and carbon dioxide emission rates. Locations representing both the upper and lower limits of each of these factors were chosen for this analysis. Hill AFB had the lowest utility rate in this study, Kirtland AFB had the lowest labor rate, and Mt Home AFB had the lowest carbon dioxide emissions offset rate. Clear AFS had one of the higher labor rates and utility rates, while Bolling AFB had the highest carbon dioxide emissions offset rate. All bases were not used in all sensitivity analyses, as some bases had similar utility and labor rates. The sensitivity analysis was calculated using the BLCC5 software used in the previous section.

Equipment Service Life Sensitivity Results

There has been much discussion as to how long these newer lighting technologies will actually last. Possible problems with the high-frequency generators in the induction fixtures and power supply issues with the LED fixtures may cause these lighting technologies to fail prematurely. Understanding how premature failure could affect the life-cycle cost is important, as the likelihood of these lighting technologies not lasting their claimed service life is well within reason. To conduct this analysis, the PV cost was calculated for each new lighting technology with equipment service lives of 5, 10, and 20 years. No salvage values were attributed to fixtures whose equipment service life went beyond the 20-year study period. A study of less than 5 years would be unnecessary, as both induction and LED fixtures have minimum 5-year warranties. The results for three different scenarios are shown in Figures 18 through 20.

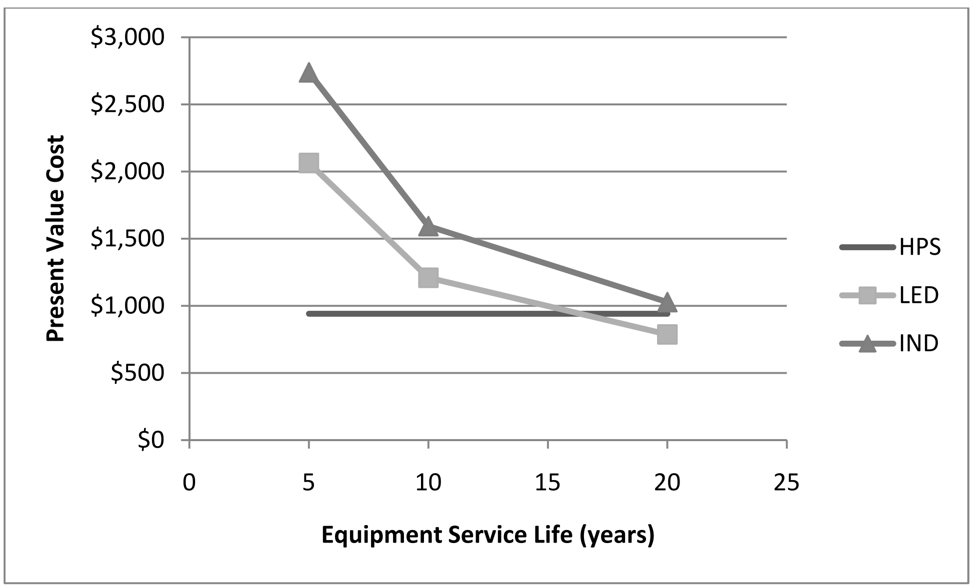


Figure 18. Equipment Service Life Sensitivity with Low Utility Rate (Hill AFB)

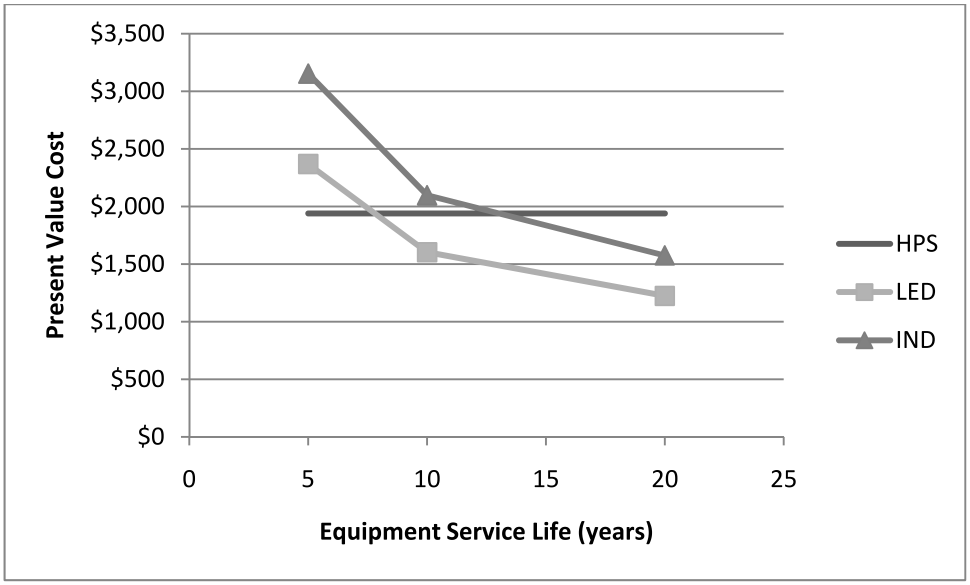


Figure 19. Equipment Service Life Sensitivity with Low Labor Rate (Kirtland AFB)

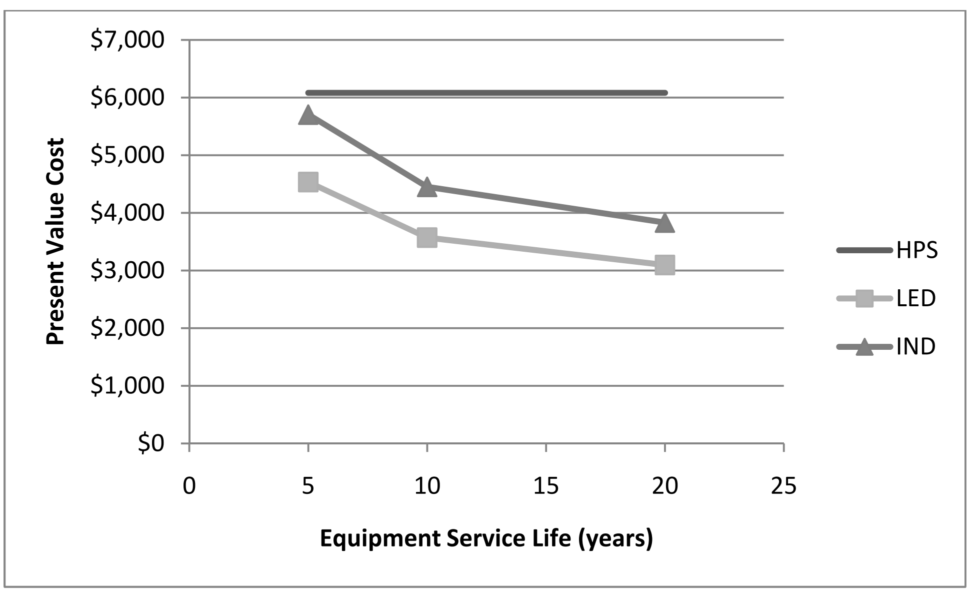


Figure 20. Equipment Service Life Sensitivity with High Utility and Labor Rate (Clear AFS)

The results show that the longer the equipment service life, the lower the PV cost for the newer technologies. LED has a better PV cost than induction at the shorter service life intervals. As the service life increases, induction begins to close the gap with LED; however, a breakeven point is not realized in this analysis. The low utility rate location shows a negative savings for both technologies until the 20-year service life is reached; at that point, only LED surpasses HPS as the most cost-effective. The low labor rate location shows both LED and induction to be less cost-effective than HPS at the 5-year service life. LED becomes more cost-effective at the 10-year service life, and induction does not surpass HPS until the 20-year service life. The high utility and labor rate location shows payback for both technologies at the 5-year service period.

Fixture Cost Sensitivity Analysis

The continuous improvements for both LED and induction technologies has increased production efficiency and reduced production costs, which are usually reflected in lower retail fixture costs. However, increases in raw material prices or supply shortages can adversely affect the cost of these lighting technologies. Understanding the sensitivity of fixture cost fluctuations can help determine the overall economic viability and flexibility these new technologies offer. To perform this analysis, the fixture costs for the induction and LED lighting technologies were changed between +10% and -50% of the current cost and the range of present value costs were calculated as shown in Table 25. Figures 21 through 23 show the outputs associated with these price variations.

Table 25. Values used for Fixture Cost Sensitivity Analysis

Fixture Type	10%	0%	-10%	-20%	-30%	-40%	-50%
LED	$519	$472	$425	$378	$330	$283	$236
IND	$732	$665	$599	$532	$466	$399	$333

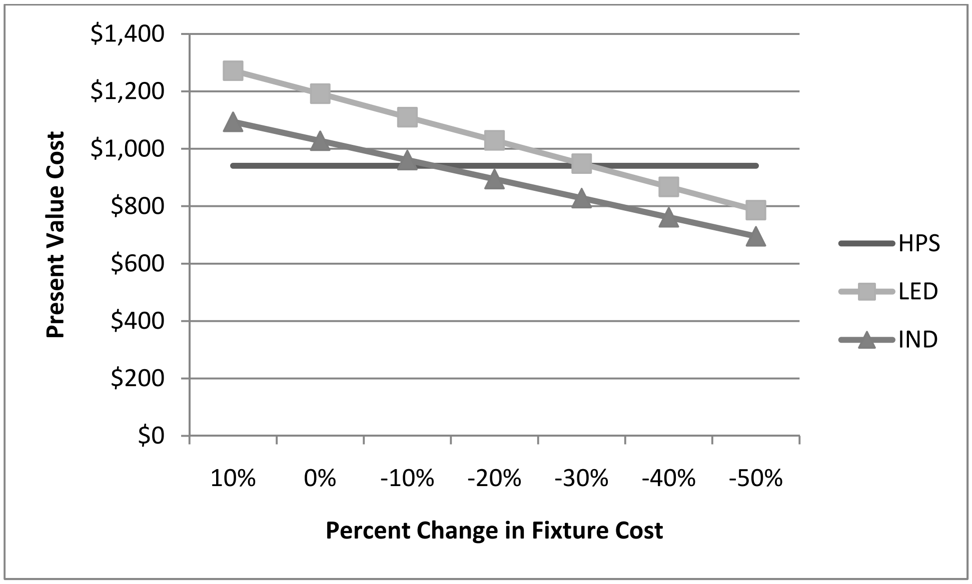


Figure 21. Fixture Cost Sensitivity with Low Utility Rate (Hill AFB)

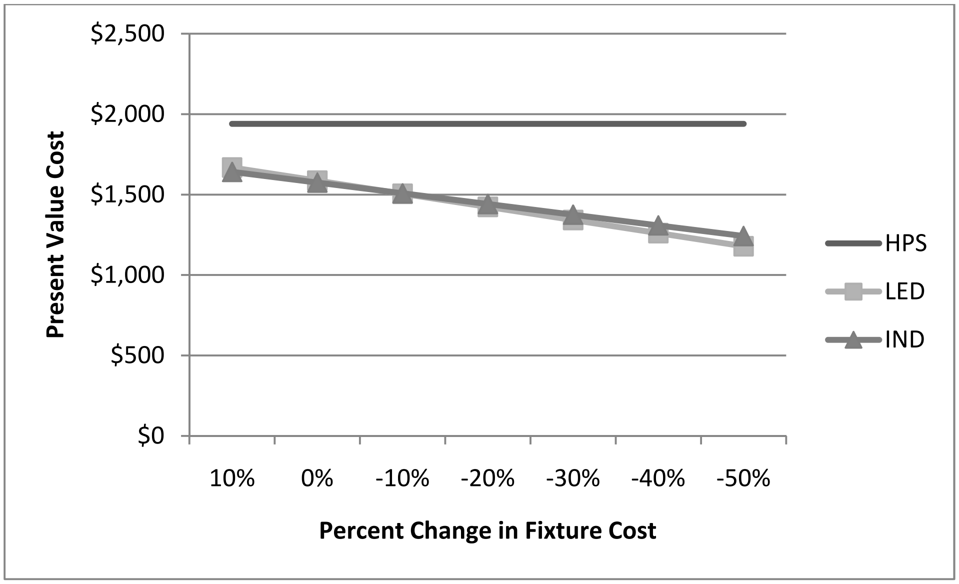


Figure 22. Fixture Cost Sensitivity with Low Labor Rate (Kirtland AFB)

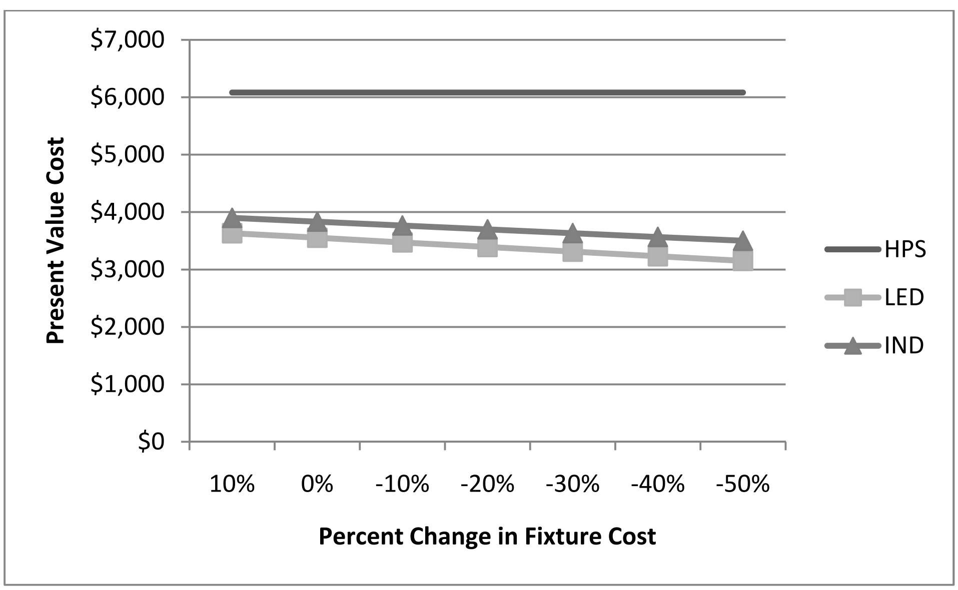


Figure 23. Fixture Cost Sensitivity with High Utility and Labor Rate (Clear AFS)

These results show that given certain price points, the economic viability of a certain lighting technology will change compared with other lighting technologies. The low utility rate location shows that induction lighting will be more cost effective than HPS if the fixture price drops by 15% or more; similarly, the LED fixture price will need to drop by 30% or more before it is more cost effective than HPS. Both the low labor rate location and high utility and labor rate location show both LED and induction technologies being more cost-effective than HPS for the complete range of price variations. These locations also show that at a certain percentage, LED will become more cost-effective than induction. The low labor rate location illustrates this behavior the best; although induction is initially the most cost effective technology, the LED technology becomes more cost-effective when the fixture cost drops by 20% or more.

Power Consumption Sensitivity Analysis

Because the power consumption was estimated, this could call into question the ability of these lighting technologies to perform similarly, as each Air Force base is slightly different. Therefore, this sensitivity analysis varies the amount of power consumed by each fixture in the study from -30% to +30% from the nominal values and calculates the associated present value costs. The nominal values used for all technologies were based on the nominal rating for the lamps themselves; no line losses or input requirements were considered. Table 26 displays the values used for this analysis with Figures 24 through 26 displaying the results of this analysis.

Table 26. Nominal Values for Power Sensitivity Analysis

Percentage	250W HPS	250W LED	250W Ind
-30%	163	92	109
-20%	192	105	122
-10%	221	118	135
0%	250	131	150
10%	279	144	165
20%	308	157	180
30%	337	170	195

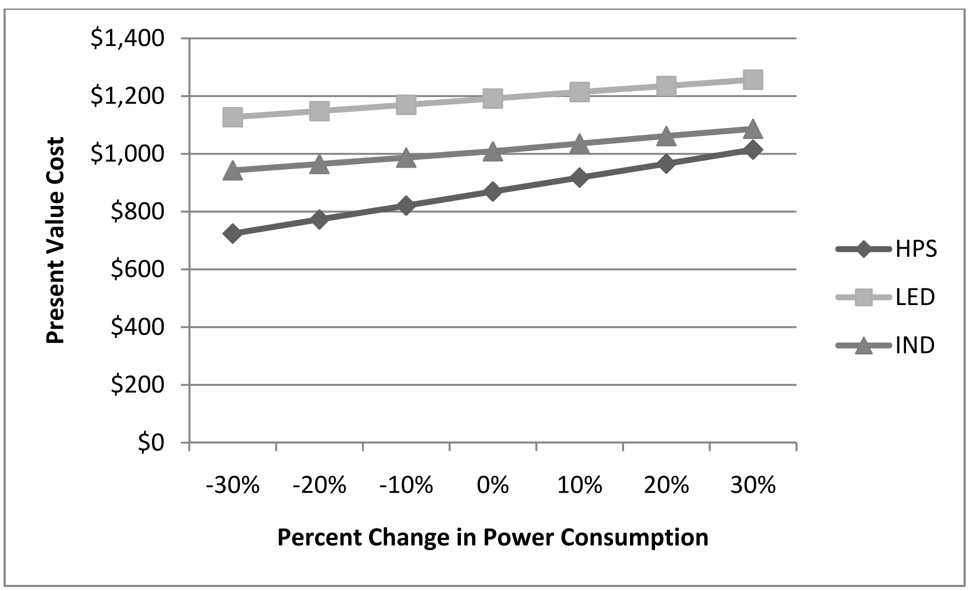


Figure 24. Power Consumption Sensitivity with Low Utility Rate (Hill AFB)

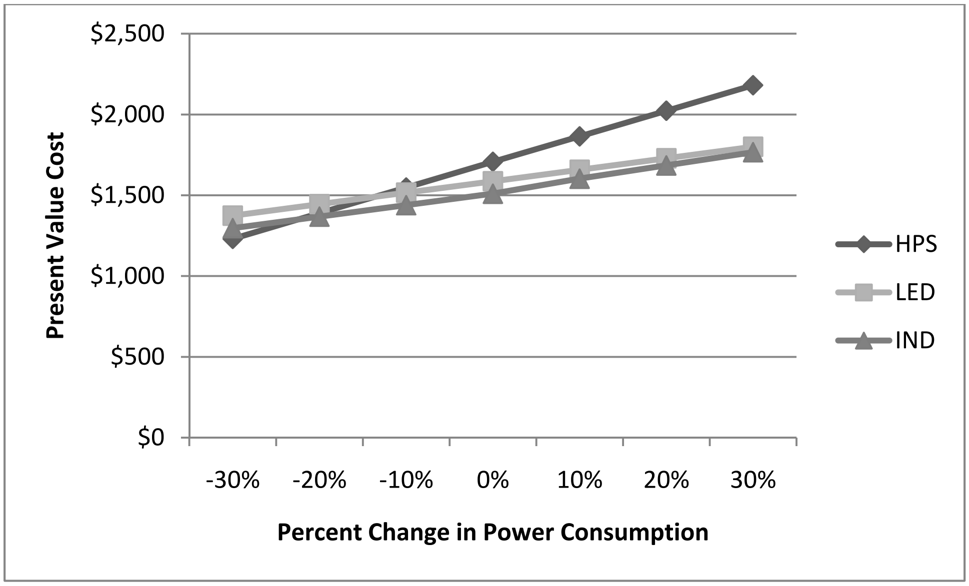


Figure 25. Power Consumption Sensitivity with Low Labor Rate (Kirtland AFB)

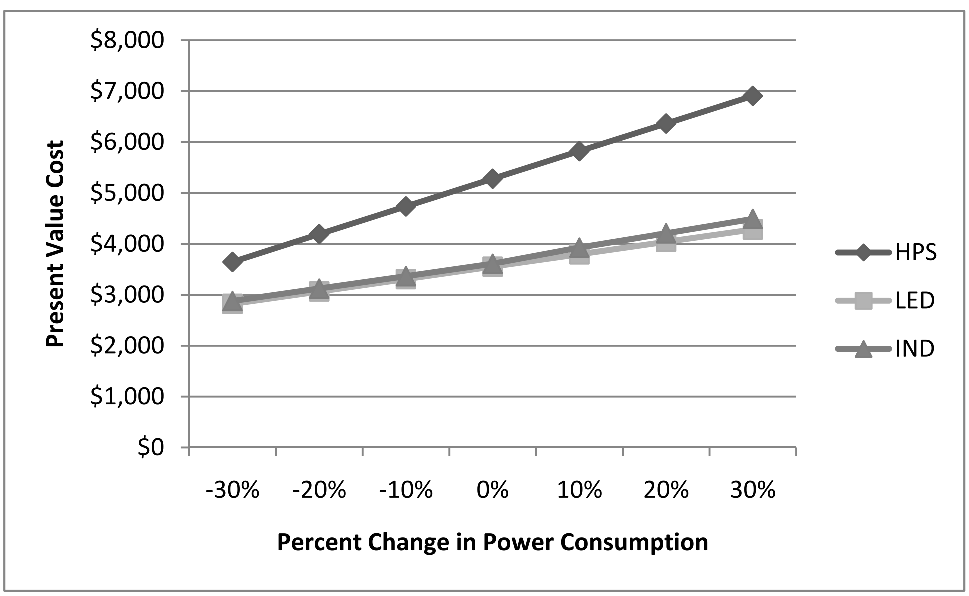


Figure 26. Power Consumption Sensitivity with High Utility and Labor Rate (Clear AFS)

This analysis shows a linear rise in present value costsfor each technology as the power consumption increases. The slope of each plot is directly related to power consumption; therefore, HPS has the steepest rise in cost while LED has the flattest cost increase. It should be noted that a power consumption lower than the nominal rate used in this analysis for the HPS technology is highly unlikely; however, it has been graphed in order to show present value trends and also to represent what type of affect a lower power HPS fixture would have on this study. The same case can be made for LED and induction technologies as well, although the DOE CALiPER test showed both technologies operating below their rated power (DOE, 2009).

The low utility rate location shows that HPS remains more cost-effective than the LED and induction technologies throughout the range of power consumption values. The low labor rate location shows a close grouping of all three technologies as power consumption values decrease; however, as power consumption increases, HPS becomes the least cost-effective of the three technologies. At 30% above nominal, LED and induction technologies have a similar PV cost. The high utility and labor rate location shows both induction and LED having an advantage over HPS throughout the range of power consumption values. HPS is only competitive if the power consumption decreased by 30% and both the induction and LED increased at least 10% ; however, such a scenario is highly unlikely.

Carbon Dioxide Emissions Cost Sensitivity Analysis

The previous section showed the PV results after incorporating a $25 carbon emission offset cost with each lighting technology. While these costs are currently not being implemented, better understanding the affect of a carbon emission offset cost can help forecast how significant the introduction of this cost will be. This sensitivity analysis varies the carbon emission offset costs from $0 to $100 per metric ton of CO_2. Figures 27 through 31 are a graphical presentation of the present values associated with the differing carbon emission offset costs.

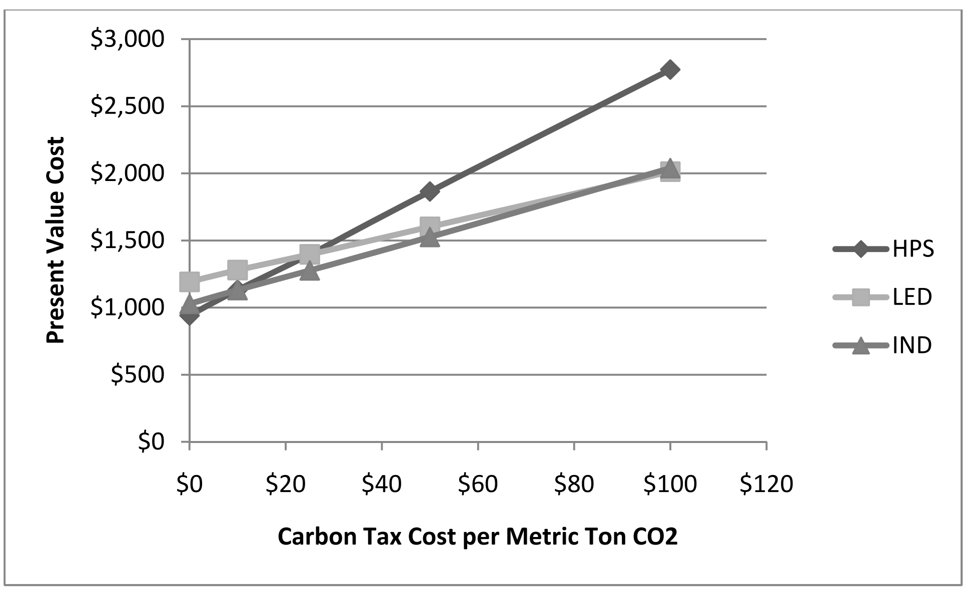


Figure 27. Carbon Emission Offset Cost Sensitivity with Low Utility Rate (Hill AFB)

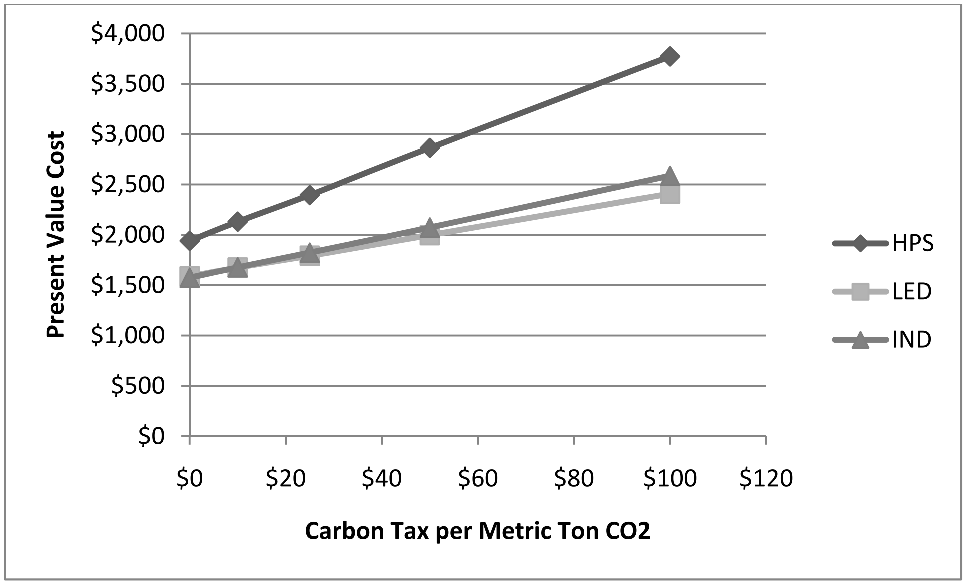


Figure 28. Carbon Emission Offset Cost Sensitivity with Low Labor Rate (Kirtland AFB)

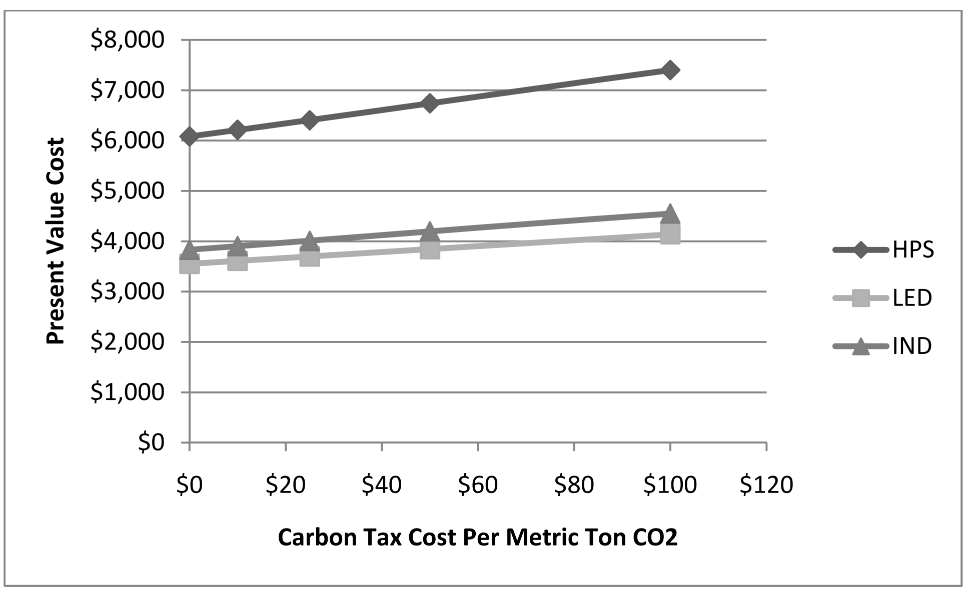


Figure 29. Carbon Emission Offset Cost Sensitivity with High Utility and Labor Rate (Clear AFS)

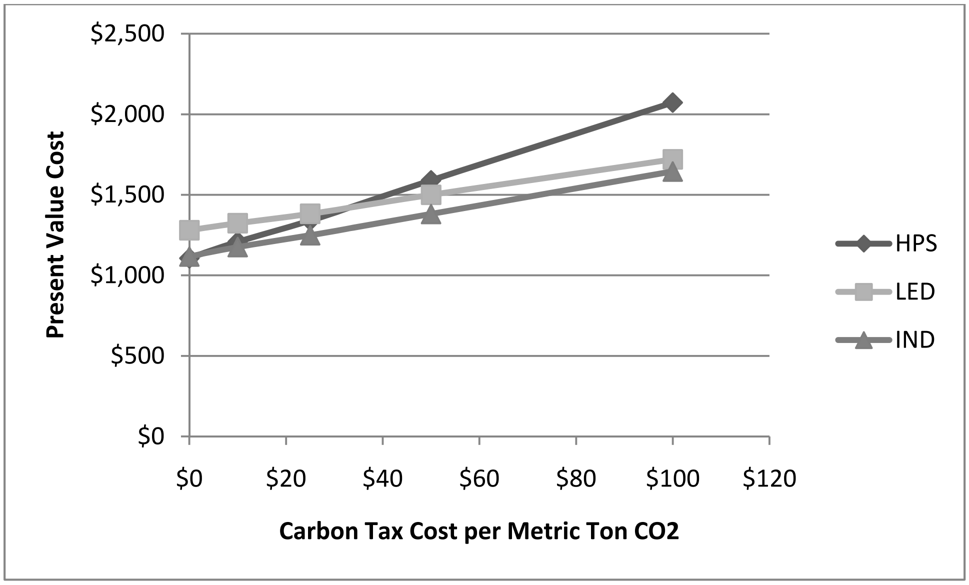


Figure 30. Carbon Emission Offset Cost Sensitivity for Low CO_2 Emission Location (Mt Home AFB)

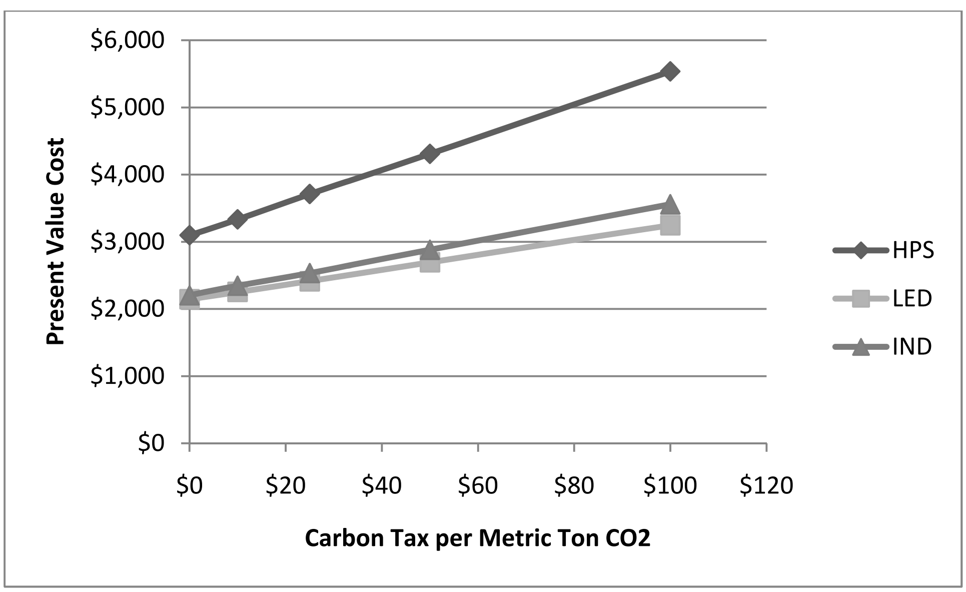


Figure 31. Carbon Emission Offset Cost Sensitivity for High CO_2 Emission Location (Bolling AFB)

The results of this analysis show the sensitivity of HPS technology to the carbon emission offset cost compared with LED and induction technology. The low utility rate location shows an almost 200% increase in PV costs when the $100 per metric ton CO_2 carbon tax is added to HPS compared to no carbon tax. The affects on LED and induction are not as dramatic as those for HPS; however, the increase for both technologies is approximately 100% when compared to the $0 carbon tax value. The graph also shows the induction and LED lines converging as the carbon tax rises, with LED becoming more cost-effective when the tax exceeds $100 per metric ton CO_2.

The low labor rate location shows both LED and induction starting at approximately the same point; as the carbon tax increases though, the LED technology becomes slightly more cost-effective. The high utility and labor rate location shows LED and induction almost parallel to each other as the carbon tax amount rises, with LED being the most cost effective. Both LED and induction technologies are clearly more cost effective than HPS throughout the range of emissions values.

For the low CO_2 emissions location, induction and HPS have similar PV costs with LED being less cost-effective. As the carbon tax increases to about $30 per metric ton CO_2, HPS becomes less cost-effective compared to the LED technology. As the carbon tax surpasses $100, the LED and induction plots begin to converge; however, induction remains the most cost-effective. The results for the high CO_2 emissions rate location are very similar to those of the low labor rate location, with a 44% increase in PV costs for HPS, 38% increase for induction, and 34% increase for LED over the range of carbon tax values.

Environmental Analysis

With the economic analysis complete, the focus of this study will now turn to the environmental effects associated with these different lighting technologies. The EIO-LCA methodology and software were used to determine which technology produces the least amount of global warming potential over their respective product life-cycles.

Manufacturing Phase Emissions Results

The global warming potential was measured for each lighting technology. The overall results for each technology can be seen in Tables 27 through 29. The tables display the top 10 contributors of GWP for each technology, along with the composition of the GWP gases and the amount of direct and indirect emissions resulting from the manufacturing of each technology.

Table 27. HPS Manufacturing Phase Emissions Data $1M

Sector	GWP	CO2	CH4	N20	CFC	Direct Econ %	Direct Emission	Indirect Emissions
Power generation and supply	216	214	0	0	3	45	97	119
Electric lamp bulb and part manufacturing	83	83	0	0	0	100	83	0
Truck transportation	27	26	0	0	0	27	7	19
Other basic inorganic chemical manufacturing	22	22	0	0	0	73	16	6
Waste management and remediation services	21	3	18	0	0	34	7	14
Glass and glass products, except glass containers	21	21	0	0	0	85	18	3
Paper and paperboard mills	19	19	0	0	0	5	1	18
Oil and gas extraction	12	2	10	0	0	1	0	12
Air transportation	9	9	0	0	0	52	5	5
State and local government electric utilities	9	9	0	0	0	46	4	5
Top 10 Sectors Total	441	410	28	0	3		240	201
All Sectors Total	576	507	45	7	18			

Table 28. Induction Manufacturing Phase Emissions Data $1M

Sector	GWP	CO2	CH4	N20	CFC	Direct Econ %	Direct Emissions	Indirect Emissions
Power generation and supply	188	186	0	0	2	23	43	145
Iron and steel mills	64	64	0	0	0	50	32	32
Lighting fixture manufacturing	47	47	0	0	0	100	47	0
Truck transportation	47	46	0	1	0	42	20	27
Primary aluminum production	32	11	0	0	21	4	1	30
Waste management and remediation services	25	4	21	0	0	27	7	18
Paper and paperboard mills	17	17	0	0	0	10	2	15
Oil and gas extraction	12	2	10	0	0	0	0	12
Coal mining	12	1	11	0	0	1	0	12
Air transportation	11	11	0	0	0	46	5	6
Top 10 Sectors Total	454	388	42	1	23		156	297
All Sectors Total	624	530	51	7	35			

Table 29. LED Manufacturing Phase Emissions Data $1M

Sector	GWP	CO2	CH4	N20	CFC	Direct Econ %	Direct Emission	Indirect Emissions
Power generation and supply	141	139	0	0	2	42	59	82
Semiconductors and related device manufacturing	80	9	0	0	71	87	70	10
Industrial gas manufacturing	53	15	0	0	38	73	39	14
Iron and steel mills	19	19	0	0	0	32	6	13
Truck transportation	18	18	0	0	0	32	6	12
Other basic inorganic chemical manufacturing	17	17	0	0	0	68	11	5
Waste management and remediation services	16	3	14	0	0	39	6	10
Primary nonferrous metal, except copper and aluminum	10	1	0	0	10	67	7	3
Lighting fixture manufacturing	9	9	0	0	0	33	3	6
Primary aluminum production	9	3	0	0	6	15	1	7
Top 10 Sectors Total	372	232	14	0	126		208	164
All Sectors Total	482	320	31	5	126			

These values were calculated using an economic input of $1 million for each lighting technology to ensure a fair comparison was performed between manufacturing processes. After analyzing the data, the lowest GWP per $1 million between the three lighting technologies is LED manufacturing. At 482 metric tons of CO_2 equivalence, LED manufacturing not only has the lowest GWP, but it is also responsible for the smallest amount of indirect emissions, suggesting most of the emissions being produced from the manufacturing of LEDs is directly attributed to the production of LEDs and not lost in residual sectors surrounding the LEDs. Induction lighting manufacturing had the worst environmental impact of the three options, producing 624 metric tons of CO_2 equivalent emissions for every $1 million of production.

Comparing these technologies on an equal scale allows for a direct comparison of manufacturing processes. While the environmental impact from manufacturing each technology is important, the three technologies do not have the same cost factors associated with them. The costs associated with each lighting technology affects how many fixtures can be produced for a given cost. Table 30 shows the total environmental impact given the costs for each technology and the Air Force requirements for those technologies. Figure 32 is the graphical representation of Table 30.

Table 30. Manufacturing Phase Emissions

Fixture Type	Fixture Cost	Replacement	# of Fixtures	Total Cost ($M)	GWP per $1M	Total GWP
HPS	$54	4	28910	$6.24	576	3600
LED	$354	2	28910	$20.47	482	9900
IND	$499	1	28910	$14.43	624	9000

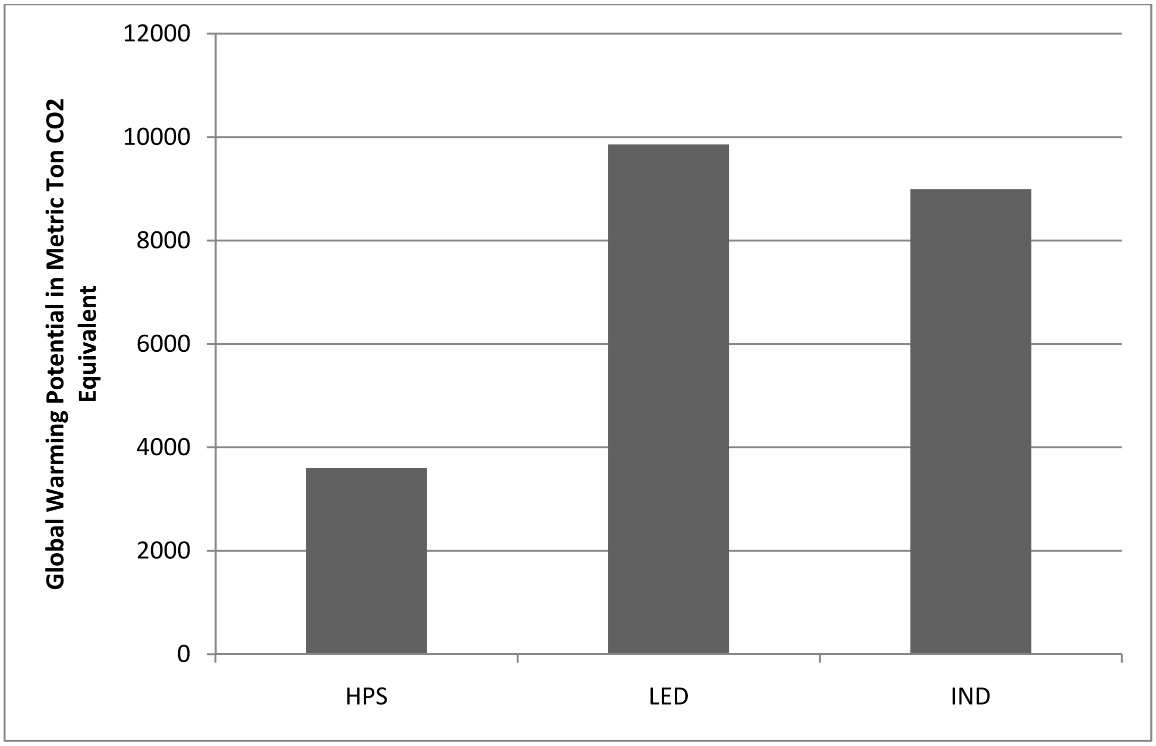


Figure 32. Manufacturing Phase Emissions

These results show that the manufacturing of HPS bulbs has a much lower environmental impact compared to either of the new technologies over the study period. This can be attributed directly to the low cost of the bulbs. Even if they need to be replaced every 4 years, the replacement cost is approximately one-seventh the cost of the other technologies, allowing more bulbs to be produced for less money and fewer emissions. The LED technology, despite having the most emissions-efficient manufacturing process, produced the highest GWP in this phase. This is the direct result of the equipment service life, which requires twice the number of fixtures to be made compared to the induction technology.

Use Phase Emissions Results

The use phase emissions were calculated using the BLCC5 software during the economic analysis. Table 31 displays the results of the emissions calculations and Figure 33 represents them graphically. The results show the LED and induction technologies have a significant advantage in life-cycle emissions over HPS, producing 55% and 45% fewer emissions than HPS, respectively.

Table 31. Total Air Force Life-Cycle Carbon Dioxide Emissions per Location (Metric Tons)

Base Name	HPS	LED	IND
ALTUS AFB	23613	10626	12987
ANDREWS AFB	36138	16262	19876
BARKSDALE AFB	3052	1373	1678
BEALE AFB	21680	9756	11924
BOLLING AFB	7333	3300	4033
BUCKLEY AFB	10425	4691	5734
CANNON AFB	18429	8293	10136
CAPE CANAVERAL	3724	1676	2048
CHARLESTON AFB	4404	1982	2422
CLEAR AFS	539	242	296
DAVIS MONTHAN AFB	9654	4345	5310
DYESS AFB	9570	4307	5264
EARECKSON	1616	727	889
EDWARDS AFB	6003	2701	3302
EGLIN AFB	4660	2097	2563
EIELSON AFB	18840	8478	10362
ELLSWORTH AFB	6128	2758	3370
ELMENDORF AFB	16433	7395	9038
FAIRCHILD AFB	12188	5485	6703
GOODFELLOW AFB	1742	784	958
GRAND FORKS AFB	9467	4260	5207
HANSCOM AFB	5095	2293	2802
HICKAM AFB	7527	3387	4140
HILL AFB	16276	7324	8952
HOLLOMAN AFB	6566	2955	3611
HURLBURT FLD	17950	8078	9873
KEESLER AFB	23152	10419	12734
KING SALMON	2694	1212	1482

Base Name	HPS	LED	IND
KIRTLAND AFB	10174	4578	5596
KUNSAN AB	5685	2558	3127
LACKLAND AFB	30522	13735	16787
LANGLEY AFB	9495	4273	5222
LAUGHLIN AFB	22226	10002	12224
LOS ANGELES AFS	3050	1372	1677
LUKE AFB	23502	10576	12926
MALMSTROM AFB	30141	13564	16578
MCCHORD AFB	14037	6317	7720
MCCONNELL AFB	5924	2666	3258
MCGUIRE AFB	7346	3305	4040
MINOT AFB	3745	1685	2060
MISAWA AB	8141	3663	4478
MOODY AFB	6307	2838	3469
MT HOME AFB	3954	1779	2175
NELLIS AFB	5792	2606	3185
OFFUTT AFB	12445	5600	6845
ROBINS AFB	14388	6475	7913
SCHRIEVER AFB	8262	3718	4544
SCOTT AFB	13480	6066	7414
SEYMOUR JOHNSON AFB	13713	6171	7542
SHEPPARD AFB	11496	5173	6323
THULE AB	2706	1218	1488
TRAVIS AFB	7162	3223	3939
USAF ACADEMY	1482	667	815
VANDENBERG AFB	21514	9681	11833
WHITEMAN AFB	3440	1548	1892
YOKOTA AB	1933	870	1063
Total	607,000	275,000	335,000

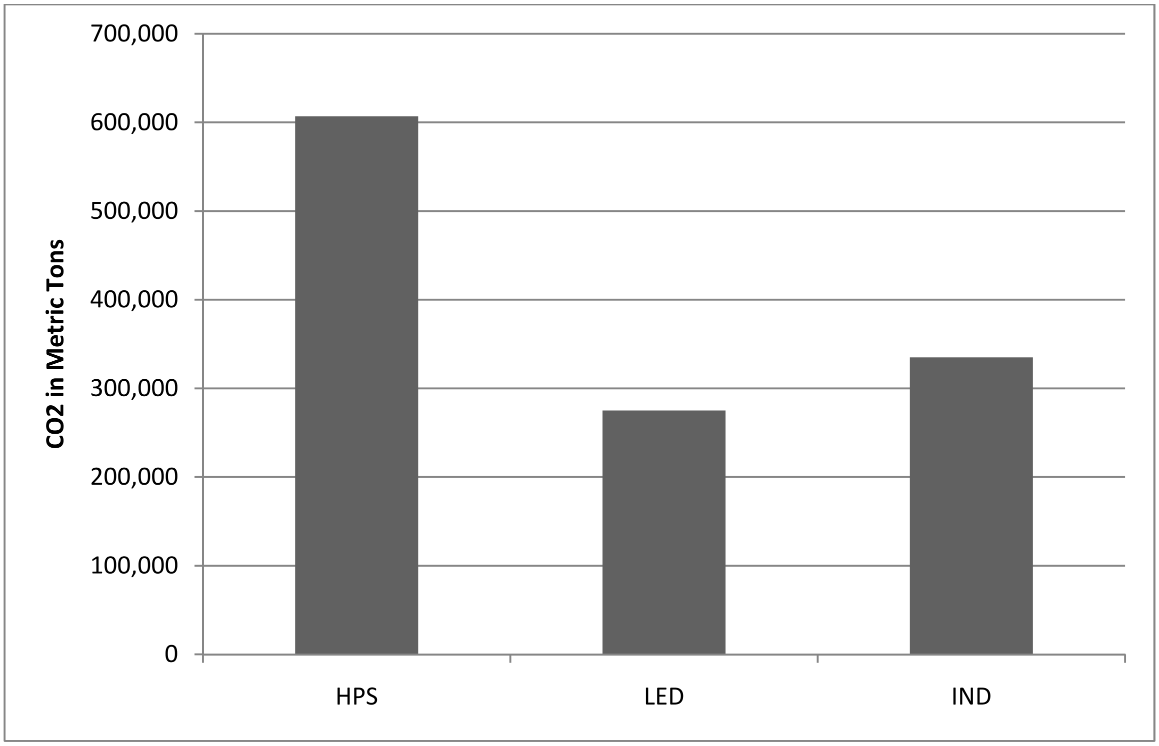


Figure 33. Use Phase Emissions

Disposal Phase Emissions Results

The disposal phase uses the Waste Management and Remediation Services sector for calculating the total GWP associated with the disposal of these lighting technologies. Table 32 shows the results for $1 million worth of waste disposal and Table 33 calculates the GWP for each lighting technology, the results of which are shown graphically in Figure 34.

Table 32. Global Warming Potential for $1M Waste Disposal

Sector	GWP	CO2	CH4	N20	CFC	Direct Econ %	Direct Emissions	Indirect Emissions
Waste management and remediation services	6800	1075	5717	8	0	98	6678	122
Power generation and supply	249	246	0	0	3	66	164	85
Oil and gas extraction	42	7	35	0	0	4	2	40
Petroleum refineries	36	36	0	0	0	70	25	11
Truck transportation	31	31	0	0	0	57	18	14
Pipeline transportation	19	9	10	0	0	9	2	17
Industrial gas manufacturing	15	4	0	0	11	70	10	4
Air transportation	11	11	0	0	0	61	7	4
State and local government electric utilities	10	10	0	0	0	64	6	4
Natural gas distribution	8	2	6	0	0	71	6	2
Top 10 Sectors Total	7220	1431	5768	9	14		6916	304
All Sectors Total	7310	1500	5780	17	15			

Table 33. Disposal Phase Emissions Calculation

Fixture Type	Bulb Disposal Cost	Fixture Disposal Cost	Bulb Disposal	Fixture Disposals	# of Fixtures	Total Cost	GWP per $1M	Bulb Disposal GWP	Fixture Disposal GWP	Initial HPS Disposal	Total GWP
HPS	$1.50	$1.00	4	1	28910	$173,460	7310	1300	500	-	1800
LED	-	$1.00	-	2	28910	$57,820	7310	-	400	500	900
IND	$1.50	$1.00	-	1	28910	$72,275	7310	-	500	500	1000

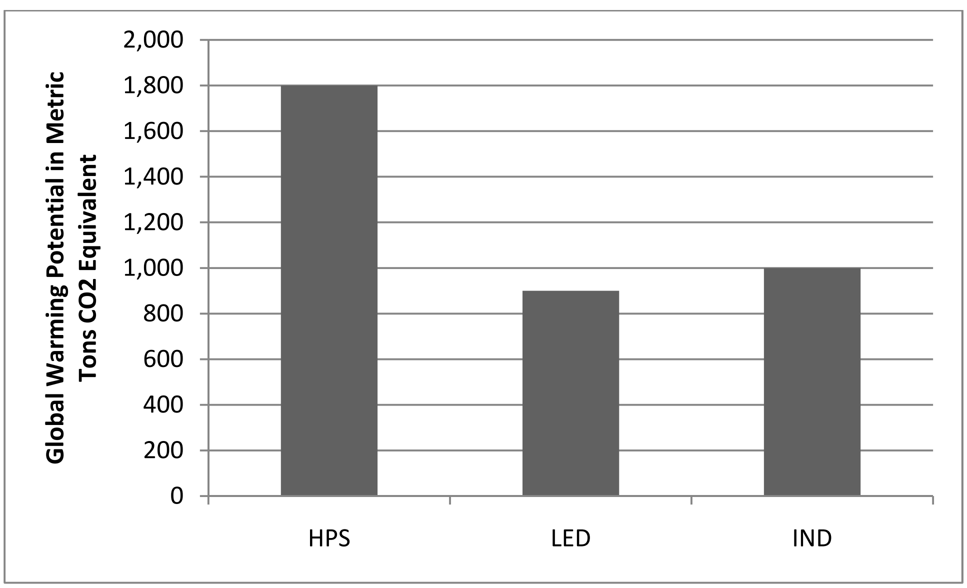


Figure 34. Disposal Phase Emissions

These results show that the HPS technology has the highest GWP in this phase, producing 50% more emissions than LED and 45% more emissions than induction; however, compared to the other two phases, the differences between the three technologies are very small. Despite having to dispose of the LED fixtures twice and the induction fixtures once, the LED technology proved to be the most environmentally friendly.

Total Combined Emissions

The total combined emission output for all three phases was calculated for each technology. The total results are displayed in Table 34 with the distribution for each phase represented graphically in Figure 35. The use phase for these lighting technologies is by far the most significant in this study, producing 96%, 97%, and 99% of all the emissions for LED, induction, and HPS technologies, respectively. Overall, the LED technology produced the least amount of emissions by roughly 60,000 metric tons of CO_2 equivalence when compared with induction technology. HPS technology was by far the highest producer of emissions, producing over 600,000 metric tons of CO_2 equivalent emissions. When comparing LED and induction technologies to HPS, they were 54% and 44% more environmentally friendly than HPS, respectively.

Table 34. Total GWP for Lighting Technologies

	Phase			
Fixture Type	Manufacturing	Use	Disposal	Total GWP
HPS	3,600	607,000	1,800	612,400
LED	9,900	275,000	900	285,800
IND	9,000	335,000	1,000	345,000

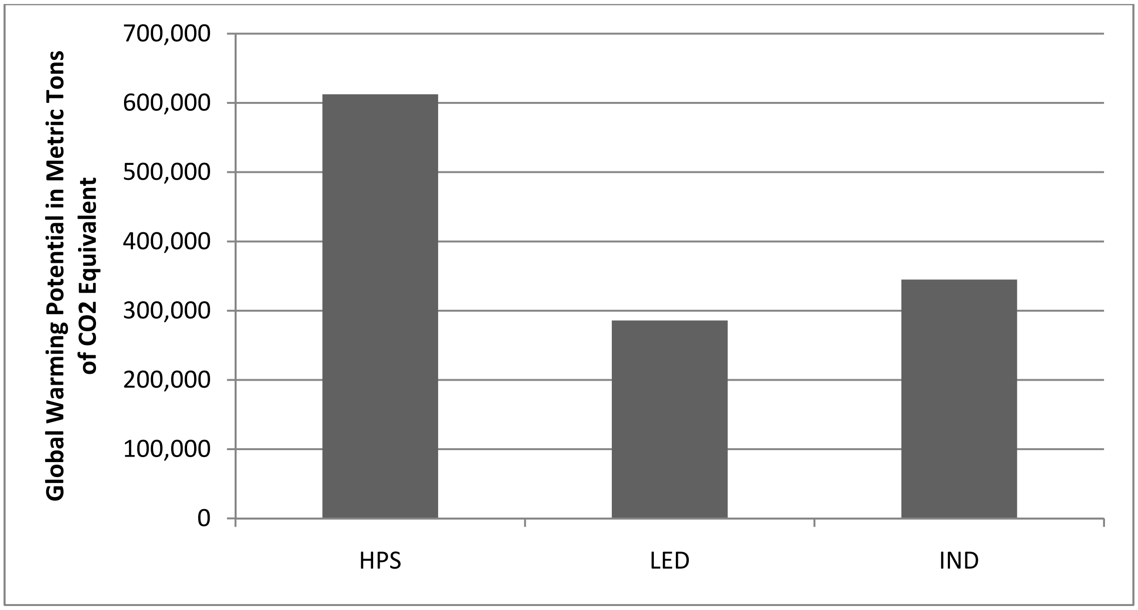


Figure 35. Life-Cycle Emissions for each Lighting Technology

V. Discussion

Summary

This research effort sought to find answers to several questions regarding the economic and environmental costs of changing roadway and parking lot street lighting technology across the Air Force. Issues such as installation costs, maintenance costs, operating costs, energy use, carbon dioxide emissions, and overall life-cycle costs were explored in this study. The literature review established a need for the research to be conducted based on government policy and a lack of available studies on both the economic and environmental aspects of street lighting. The methodology explained how the *Building Life Cycle Cost 5 (BLCC5)* and *Economic Input-Output Life Cycle Assessment (EIO-LCA)* software were applied to complete this study. The results section detailed the economic and environmental findings in this study and modeled the sensitivity of certain cost factors for each lighting technology.

Conclusions

This study provided an in-depth analysis on 56 Air Force installations around the world with regard to the economic and environmental impacts associated with three different street lighting technologies. There is significant variability between the electricity and labor costs on military installations as opposed to the local area, so these results are not necessarily applicable to the local areas surrounding these installations.

The high-pressure sodium (HPS) technology is on average more costly to operate than either induction or light-emitting diode (LED) technologies. The calculations for energy use in this study showed a significant difference between the three technologies. Comparing 250W HPS fixtures to induction and LED fixtures of equivalent performance, the induction fixture consumes 40% less energy while an LED fixture consumes 48% less energy. These energy savings became more pronounced and resulted in greater financial savings as utility rates increased.

This study utilized several financial measures to assess the value of LED and induction lighting. The savings-to-investment ratio (SIR) was used to determine the ratio between money saved versus money spent. The results showed an average SIR of 1.47 for the LED technology and 1.66 for the induction technology. These results suggest an economic advantage when investing in newer technologies, as the energy savings outweigh the upfront costs associated with these newer technologies.

The discounted payback period (DPP) determines the length of time it takes for the initial investment in either the LED or induction technology to be recouped when taking into account the time value of money. The results showed an average of 7 years for the LED technology and 10 years for the induction technology. Since both technologies have a significantly high cost of entry, the energy savings were not as large as expected, although the payback period for many locations still met the Air Force requirement of 10 years or less. The DPP was most negatively affected at locations where utility costs were low. These low utility costs give HPS a financial advantage over the newer technologies, as some locations did not reach payback within the study period with the newer technologies.

The life-cycle costs were also evaluated through the use of present value calculations. These PV calculations showed an advantage for both induction and LED technologies, averaging a 23% and 21% savings over the HPS technology, respectively. On a per fixture basis, the LED technology averaged a $478 benefit over HPS while the induction technology averaged a $519 benefit. These savings may not seem all that significant on a fixture for fixture basis over a 20-year period; however, when the amount of fixtures utilized by the Air Force is taken into account, these savings are attractive. The total 250W fixture count for all the Air Force bases in this study is 28,910 fixtures. The resulting savings for using the LED technology would be just under $11 million for LED and just over $12.5 million for the induction technology.

Studying the life-cycle environmental impact associated with these technologies through the manufacturing, use, and disposal phases was also a key component of this study. Through the use of EIO-LCA, it was determined that LEDs had the largest global warming potential in the manufacturing phase. During the use phase, the emissions were significantly higher for the HPS technology than they were for either induction or LED technology. The HPS emissions were about double those of LED and induction. The use phase was also the most significant phase of the three phases, producing between 96% and 99% of all the emissions in the product life-cycle for each technology. The disposal phase displayed a relatively small GWP for all three technologies, with HPS contributing the most GWP in this phase. Across the three phases, it is clear that HPS is the higher emitter of pollutants when compared to both LED and induction. The difference between LED and induction emissions is relatively small when looking at the big picture.

Overall, the study showed that both LED and induction technologies are worthy investments when compared with HPS. LED and induction technologies are both more economically viable and more environmentally friendly. The only situations under which economic viability comes into question are when utility rates are extremely low. The low utility rates offset the economic disadvantages associated with the high power consumption of HPS fixtures, making the introduction of newer technologies less likely with their prolonged DPP and negligible SIR in these locations. However, from an environmental standpoint, there is no doubt that HPS fixtures are creating a more significant carbon footprint than the other two technologies, indirectly contributing to environmental issues such as air pollution and mercury contamination.

Limitations and Future Research

Although this study addresses some of the shortcomings of other studies, there are still areas that can be improved or expanded upon. Four major areas could be further developed to refine the results obtained in this study.

1. The results used in this analysis were estimated values inferred from manufacturer data and DOE test data. Collecting actual usage data from more Air Force installations and other case studies using the same fixtures would allow for a more accurate depiction of how these newer technologies will perform under real-world conditions. Although the power consumption data used for this study was consistent with what was found in other studies using similar technologies, it is difficult to determine whether these particular results represent actual performance.
2. Investigating level of service issues surrounding parking lot and roadway lighting could yield some interesting results. This study assumed the entire lighting infrastructure was necessary, suggesting each fixture identified in the study would be

used and that the same amount of lighting intensity would be needed. What would the impact be if every third street lamp along a roadway were eliminated? What if 150W HPS fixtures were used in place of 250W fixtures? Would this change in wattage be a more cost-effective measure than changing to a newer technology?

3. This study assumed all the lighting technologies would be running at 100% of their lighting output. With both LED and induction technologies having dimming capabilities, future research could look into the cost-effectiveness of certain types of controls, such as proximity and ambient lighting sensors, which reduce power usage in situations where the lights are not needed.
4. Although economic and environmental factors were researched in this study, a combination of these factors could be used to address the element of social cost. Social costs are costs associated with the emissions of GWP. These costs take into account environmental remediation and health costs associated with variable levels of GWP emissions. Combining the life-cycle costs for street lighting with the cost of life-cycle emissions produced by each lighting technology could show a true overall cost to the government for implementing different lighting technologies.

Recommendations

The Air Force would benefit greatly from both LED and induction lighting technologies. This study shows that energy and maintenance dollars can be saved by moving away from HPS technology and adopting either of these newer technologies. However, before these technologies are adopted on a wide scale at each installation, there should be pilot tests performed at each base to ensure that the lights are providing the energy and maintenance savings that are expected. One factor to take into account prior to implementation is the electric utility rate. Table 35 shows the most cost-effective technology based on the utility rates found in this study. These rates suggest that HPS is only viable where utility rates are very low, whereas induction lighting is good for places with middle-of-the-road utility rates. Induction is a good choice in this range because of its long service life and lower power consumption when compared to HPS. LEDs benefit from higher utility rates because they are efficient enough to make up for the cost difference and only need to be replaced every 11 years when compared to the HPS technology. As energy markets fluctuate and utility costs begin to rise, it becomes less likely that bases with extremely low utility rates will be able to maintain them, thereby giving these newer lighting technologies a chance to make a difference both economically and environmentally.

Table 35. Lighting Technology Recommendation

Utility Rate	Most Cost-Effective
x < $0.032	HPS
$0.033< x < $0.09	Induction
x > $0.10	LED

While both the induction and LED technologies show great promise, there are still longevity and compatibility issues associated with each of these technologies. Each base should take into account its own infrastructure and lighting needs prior to making any lighting changes. With solid research, pilot, and implementation programs, the introduction of these new technologies could be a huge success for both the Air Force and the U.S. government.

Appendix A. Air Force Data Call Information

Base Name	Location	Command	Shop Rate	Utility Rate (kwh)	250W Fixtures
ALTUS AFB	OK	AETC	$31.58	0.070	1057
ANDREWS AFB	MD	OTHER	$45.93	0.112	1551
BARKSDALE AFB	LA	ACC	$69.18	0.050	148
BEALE AFB	CA	ACC	$74.45	0.066	1571
BOLLING AFB	DC	OTHER	$42.00	0.132	237
BUCKLEY AFB	CO	AFSPC	$48.79	0.073	429
CANNON AFB	NM	AFSOC	$42.00	0.065	736
CAPE CANAVERAL	FL	AFSPC	$56.57	0.090	200
CHARLESTON AFB	SC	AMC	$42.00	0.058	186
CLEAR AFS	AK	AFSPC	$83.86	0.292	30
DAVIS MONTHAN AFB	AZ	ACC	$50.87	0.072	396
DYESS AFB	TX	ACC	$42.00	0.080	500
EARECKSON	AK	PACAF	$90.00	0.24	90
EDWARDS AFB	CA	AFMC	$52.00	0.140	435
EGLIN AFB	FL	AFMC	$51.56	0.111	250
EIELSON AFB	AK	PACAF	$65.57	0.17	1049
ELLSWORTH AFB	SD	ACC	$39.76	0.040	239
ELMENDORF AFB	AK	PACAF	$77.74	0.06	915
FAIRCHILD AFB	WA	AMC	$54.13	0.035	576
GOODFELLOW AFB	TX	AETC	$22.25	0.053	91
GRAND FORKS AFB	ND	AMC	$73.00	0.049	316
HANSCOM AFB	MA	AFMC	$65.26	0.140	261
HICKAM AFB	HI	PACAF	$65.00	0.21	344
HILL AFB	UT	AFMC	$47.75	0.026	650
HOLLOMAN AFB	NM	ACC	$50.50	0.080	262
HURLBURT FLD	FL	AFSOC	$76.00	0.093	963
KEESLER AFB	MS	AETC	$42.00	0.075	1004
KING SALMON	AK	PACAF	$90.00	0.26	150
KIRTLAND AFB	NM	AFMC	$18.30	0.085	406
KUNSAN AB	S KOREA	PACAF	$44.09	0.08	250
LACKLAND AFB	TX	AETC	$53.80	0.068	1593
LANGLEY AFB	VA	ACC	$55.36	0.068	403
LAUGHLIN AFB	TX	AETC	$42.00	0.122	1160
LOS ANGELES AFS	CA	AFSPC	$56.57	0.116	221
LUKE AFB	AZ	AETC	$42.00	0.060	964
MALMSTROM AFB	MT	AFSPC	$48.58	0.082	1123
MCCHORD AFB	WA	AMC	$69.81	0.039	664
MCCONNELL AFB	KS	AMC	$42.00	0.058	217
MCGUIRE AFB	NJ	AMC	$52.37	0.134	415
MINOT AFB	ND	ACC	$72.00	0.040	125
MISAWA AB	JAPAN	PACAF	$34.42	0.11	358
MOODY AFB	GA	ACC	$63.16	0.067	263
MT HOME AFB	ID	ACC	$56.48	0.033	300
NELLIS AFB	NV	ACC	$68.26	0.072	287
OFFUTT AFB	NE	ACC	$41.42	0.033	463
ROBINS AFB	GA	AFMC	$43.90	0.060	600
SCHRIEVER AFB	CO	AFSPC	$62.52	0.075	340
SCOTT AFB	IL	AMC	$42.00	0.053	511
SEYMOUR JOHNSON AFB	NC	ACC	$62.93	0.073	542
SHEPPARD AFB	TX	AETC	$42.00	0.097	600
THULE AB	GREENLAND	AFSPC	$75.00	0.245	119
TRAVIS AFB	CA	AMC	$74.11	0.053	519
USAF ACADEMY	CO	OTHER	$42.00	0.052	61
VANDENBERG AFB	CA	AFSPC	$42.00	0.082	1559
WHITEMAN AFB	KS	ACC	$71.11	0.050	126
YOKOTA AB	JAPAN	PACAF	$44.98	0.12	85

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14. ABSTRACT

Rising global energy demand and natural disasters continuously threaten energy supplies and prices. As a result, the U.S. government has mandated all government agencies to reduce energy consumption in order to minimize dependence on foreign energy supply and reduce costs. Concern over carbon emissions and environmental impacts has also been expressed in these mandates. One solution may be to invest in newer lighting technologies, such as light-emitting diode (LED) and electrodeless induction, in order to reduce the energy consumption, environmental impact, and costs required for both exterior roadway and parking lot lighting applications. This research compared these lighting technologies with high-pressure sodium (HPS) lighting technology at 56 Air Force installations to assess the economic and environmental consequences associated with each technology over the product life-cycle. This study utilized *Building Life-Cycle Cost 5* and *Economic Input-Output Life Cycle Assessment* software packages to perform the analysis. Both the LED and electrodeless induction technologies showed moderate economic savings and less environmental impact when compared to HPS technology. The overall economic life-cycle costs for LED and induction lighting were 21% and 23% less, respectively, than HPS lighting. Environmental life-cycle assessment showed reductions of 55% and 45% for LED and induction technologies, respectively, compared to HPS lighting.

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