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Time-valued-technology: A Light-emitting Diode Case Study for Determining Replacement Strategy for High Technology Infrastructure Items

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TIME-VALUED-TECHNOLOGY: A LIGHT-EMITTING DIODE CASE STUDY FOR DETERMINING REPLACEMENT STRATEGY FOR HIGH TECHNOLOGY INFRASTRUCTURE ITEMS

THESIS

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AFIT/GEM/ENV/12-M15

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THESIS

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Kevin S. Ochs, BS

Captain, USAF

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Abstract

Infrastructure projects have typically involved long-term investments in relatively mature technologies characterized by stable performance and cost. However, with the ever-increasing rate of technological innovation, an increasing number of potential infrastructure investments involve a decision to replace a traditional technology with a rapidly evolving technology. In such circumstances, it is possible to reap significant performance or cost advantages through near-term replacement. However, this rapid adoption strategy has the potential to incur an opportunity cost due to increased performance or cost advantages the technology would provide if replacement was delayed. This research develops a cost analysis method, referred to as time-valued-technology, which may be useful in developing a strategic approach to the replacement of infrastructure with a rapidly emerging technology. The utility of this method is illustrated through an evaluation of replacement of the 250-watt streetlight fixtures on 64 United States Air Force installations with light-emitting diode based technology. Potential financial savings in implementing time valued technology over existent methods ranged from 1.10 to 14.15 percent per installation, averaging 6.77 percent.

Table of Contents

Page

List of Figures

Figure Page

List of Tables

Table Page

TIME-VALUED-TECHNOLOGY: A LIGHT-EMITTING DIODE CASE STUDY FOR DETERMINING REPLACEMENT STRATEGY FOR HIGH TECHNOLOGY INFRASTRUCTURE ITEMS

I. Introduction

In an effort to support cost effective energy consumption, agencies within the Air Force have considered installing new streetlight technologies. Light-emitting diodes (LEDs) are presently being marketed for street lighting applications with significant energy savings. As with many advancing technologies, rapid improvements in LED efficacy, cost, and capabilities leave Air Force leaders unsure of when to adopt LED technology. By using predictions in this emerging technology's efficacy, cost, lifespan, and capability, a new method of cost analysis, termed "time-valued-technology," can be used to decide when to invest. This research applies time-valued-technology to predict the optimal year to invest in LED street lighting technology for 64 Air Force installations.

Background

In 2007, the Air Force spent over 707 million dollars on facility electricity, see Figure 1, much of which is associated with lighting (Department of Defense, 2007). The Department of Energy (DOE) estimates 22% of electricity generation in the United States is used for lighting applications (U.S. Department of Energy, 2002). Even though street lighting is only one of several lighting applications, a 2010 Air Force report identified 29,000 streetlight fixtures on Air Force installations (Colon, 2010). Therefore, adoption of more efficient street lighting has the potential to result in significant energy and cost reductions.

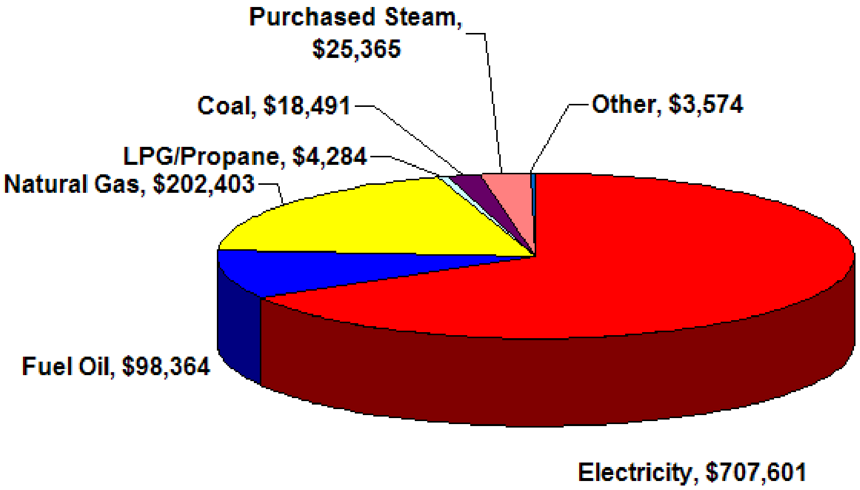

Figure 1. Air Force Facility Energy Costs FY 2007 ($000) (Department of Defense, 2007)

Several technologies are presently used for street lighting; however, light-emitting diodes (LEDs) are becoming increasingly competitive with established technologies due to their rapidly increasing efficiencies and decreasing cost. The DOE claims LEDs have the largest potential for saving energy compared to existing lighting sources (U.S. Department of Energy, 2002). Energy savings can be achieved by installing LEDs due to their ability to produce light with higher efficacy (more lumens per watt) compared to other lighting technologies and their capability to be easily controlled with faster response times and low voltage control, thus making it easier to dim these lights for further energy reduction. Although the cost of LED lamps is currently significantly higher than incumbent technologies, they have a longer lifetime which reduces the frequency of maintenance activities and associated personnel costs. Maintenance costs can be significant, consuming up to 80-90% of the lifetime cost of select building and infrastructure projects (Theriault, 2009).

Even with the advantages of LEDs, proper cost analysis should be completed for each lighting location to ensure LED lamps are an appropriate investment. Organizations in the Air Force typically use utility rates, labor rates, and initial installation costs of LEDs to compute financial metrics, such as Net Present Value (NPV), Return on Investment (ROI), Saving to Investment Ratio (SIR), and Internal Rate of Return (IRR) to determine whether to replace an existing technology with a competitive technology. However, these techniques are typically used to determine whether it is cost effective to replace the incumbent technology with a competing technology today.

Throughout the last century, several forecasts for the growth of emerging technologies have been proposed. For example, Moore's Law accurately predicted in 1965 that the number of transistors on an integrated circuit would double every two years (Moore, 1965). Similarly, in 1999, Ronald Haitz (1999) predicted that significant improvements in LED technology would occur in the next few decades. With over 40 years of supporting data, "Haitz's Law" predicts a 35% increase in luminous output and a 20% decrease in cost per lumen of a LED device each year (Haitz, Kish, Tsao, & Nelson, 1999). Similarly, the DOE has predicted LEDs will reach a 266 lumen per watt efficacy by 2020 (U.S. Department of Energy, 2011).

The primary question posed within the current work is regarding the application of these predictions in a cost analysis to determine not only whether LEDs are a beneficial investment, but the year the investment will be the most cost beneficial.

Problem Statement

In an effort to reduce expenditures, organizations within the Air Force are performing cost analyses to ensure replacing their existing infrastructures with evolving technologies is financially beneficial. Present methods of analyzing energy and cost benefits focus on existing product capabilities and prices. However, with predictions of an emerging technology, including annual reductions in price and increases in efficiency, alternate investment strategies can be explored. Therefore, an alternate cost analysis method is proposed and evaluated through a case study of 250W street lights for selected Air Force installations.

Research Objective and Investigative Questions

The primary objective of this research was to develop a method to strategically determine the optimal year to replace an existing infrastructure item with a more cost effective but rapidly evolving technology. Specifically, the researchers wished to develop a method to determine the optimal year to replace existing 250 W High-Pressure Sodium (HPS) streetlights with LED streetlights for multiple bases across the United States Air Force. The goal was to apply well-known underlying technological relationships, e.g., Haitz's Law, to facilitate the analysis of LED-based lighting systems. However, many other infrastructure items, including renewable power generation and dynamic control systems for lighting, heating, ventilation, and air conditioning systems, are also undergoing rapid technology evolution and may benefit from a similar approach. In an attempt to achieve the main objective, several questions must be answered. These questions are as follows:

1) What are the characteristics of LEDs that will influence a life-cycle cost analysis (LCCA)?
2) What is the rate of change in the characteristics of LEDs and LED light fixtures that will influence this cost analysis?
3) What standards for street lighting does the Air Force have and how are these standards likely to affect life-cycle costs for this technology?
4) Can, or when, will it be cost effective for LED streetlight fixtures to replace legacy technology on a one-for-one basis maintaining a minimum light standard?
5) What percent of the cost of an LED fixture is made up from only the LED?

Methodology

In this research, a new time-valued-technology economic analysis method is described specifically to address the 250W LED streetlight replacement decision. At its heart, this method employs one or more predictive technology relationships to calculate the NPV of several alternatives to replace the incumbent technology with the rapidly emerging technology at different time periods over a selected time horizon. Each alternative delays the replacement of the incumbent technology and accounts for predicted technological improvements. The minimum NPV of all the alternatives is then found and the replacement year corresponding to this minimum NPV is selected as the target year for technology replacement. It is also recognized, however, that a number of assumptions are necessary, which will be subject to variability, and therefore it can be useful to further employ a sensitivity analysis on key variables to understand the impact that an incorrect assumption might have upon the target year.

Assumptions/Limitations

To simplify the method and facilitate an analysis, this research makes the following assumptions.

Assumption/Limitation 1: The incumbent technology is relatively stable and will not undergo significant cost or performance changes over the time horizon of the analysis. In the current streetlight evaluation, all streetlights across the Air Force were assumed to be HPS. In fact, a majority of all streetlights used across the Air Force are HPS as this technology is presently one of the most inexpensive methods of lighting. It is therefore specifically assumed that advances in HPS bulb technology will not occur.

Assumption/Limitation 2: The replacement technology will undergo predictable changes and only the attributes of the product for which predictions exist will be included in the method. In the current evaluation, it is assumed that only the efficacy and cost of LEDs are changing. However, it is recognized that the lifetime of high power LEDs have improved in recent years. Unfortunately, current methods for quantifying the lifetime of LED lamps are still undergoing development. Specifically, the Illuminating Engineering Society of North America (IESNA) has recently adopted a method described in IESNA TM-21 for predicting the lifespan of an LED; however, validated and standardized methods for determining the lifetime of LED fixtures are still forthcoming (Illuminating Engineer Society, 2011). For the current research, it is assumed that the lifetime of an LED fixture is 24 years and that the current model of producing fixtures with integrated, non-replaceable LEDs will persist, thereby requiring replacement of the entire LED fixture at the end of its useful lifetime. Another relevant implication of this assumption is that only the cost of the LED within the LED lamp will decrease according to Haitz's law. As it has been indicated that the LED bulb currently accounts for about 45% of a typical LED fixture, only this portion of the fixture cost is expected to decrease according to Haitz's law (U.S. Department of Energy, 2010).

Assumption/Limitation 3: The current infrastructure is stable. Expectations for base closures or modifications in upcoming years are not considered.

Assumption/Limitation 4: The minimum rate of return (MARR) is assumed to be constant over the time horizon of the study. The discount rate, similar to MARR, specified by the Office of Management and Budget (OMB) Circular A-94 was assumed (Guidelines and Discount Rate, 2010). Specifically, the rate of 3% as specified in the 2010 publication for the discount rate excluding general price inflation for government energy projects was applied (Rushing, Kneifel, & Lippiatt, 2010).

Assumption/Limitation 5: The bounds of a LCCA can start from the collection of raw materials and end at the disposal of the product. However, this research bonded the LCCA to the life-cycle phase extended from the end of operation of the streetlight infrastructure.

Assumption/Limitation 6: Requirements for the treatment and cost of disposal for HPS or LED streetlights were not collected. Therefore, all disposal costs were not included in this study and should be considered a limitation.

Assumption/Limitation 7: Once a replacement technology is adopted, the replacement fixture will only be replaced at the end of its projected life. Early replacement is not considered, even if the replacement could further reduce life-cycle costs.

Implications

This research supports the use of incorporating cost and capability forecasts to all cost analyses that have reliable predictions for emerging technologies. With the inclusion of reliable technology forecasts, an investment strategy can be found which will offer a decision-maker a better asset management focused solution to infrastructure cost problems. This case study implements the method of time-valued-technology by providing data analysis to predict the specific year 64 Air Force installations should invest in LED street lighting technology to achieve the most value in cost savings.

Preview

There are four additional chapters included in this research. In Chapter II, Literature Review, a review of significant topic areas surrounding LEDs, streetlights, regulations, and cost analyses is presented. A detailed description of the method used to answer the main research objective and questions is outlined in Chapter III, titled Methodology. In Chapter IV, Results and Analysis, the outcomes of the cost analysis are provided. The results from this analysis are compared to results from traditional analyses. In Chapter V, Conclusion, recommendations for changes to infrastructure cost models involving rapidly evolving technology will be discussed, together with LED implementation on specific Air Force installations; potential audiences that can benefit from this study are also defined.

II. Literature Review

This chapter addresses reasons the Air Force is interested in investing in high efficacy lighting, metrics for qualifying the quality of illumination, a description of legacy lighting options, a description on light emitting diodes (LEDs) technology, a summary of research regarding metrics which should influence the decision to invest in LEDs, and an overview of Air Force lighting design criteria.

Air Force Infrastructure Energy Plan

The Air Force Infrastructure Energy Plan is created by combining U.S. energy policy and new Air Force asset management ideas. The Air Force uses a pillared structure analogy to describe its infrastructure energy plan, as shown in Figure 2. The roof of the figure reflects the energy goals as inspired by U.S. energy policy, while the foundation of the figure reflects the Air Force's emphasis on the importance of Asset Management (*Air Force Infrastructure*, 2010).

United States Energy Policy

In the past decade, several laws and presidential executive orders (EO) have been created which have directed a significant change in U.S. energy policy. Energy consists of much more than electricity; however, since LEDs are powered by electricity, only policies affecting electricity consumption will be discussed in this section.

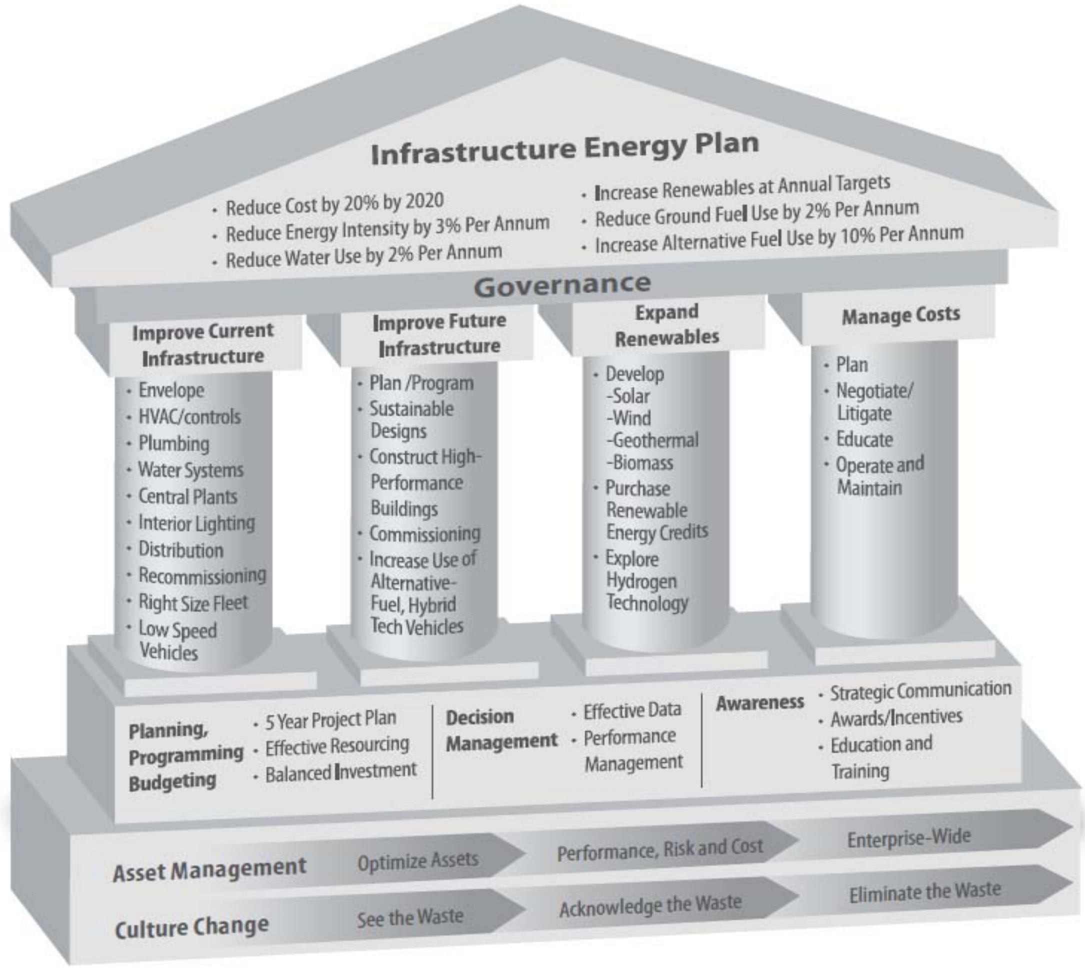

Figure 2. Air Force Energy Infrastructure Plan (*Air Force Infrastructure*, 2010)

On 29 July 2005, the Energy Policy Act (EPAct) was passed requiring federal agencies to reduce their facility energy consumption by two percent per year relative to their baseline consumption in 2003 (Congress, 2005). In 2007, EO 13423 was signed by President George E. Bush. EO 13423 increases the two percent energy goal, established by EPAct, to three percent per year, while keeping the 2003 baseline. Additionally, EO 13423 established a goal of 30% reduction in facility energy by 2015 (Bush, 2007). Later in 2007, Congress reinforced the energy reduction goals set in EO 13423 by including them in the Energy Independence and Security Act (EISA). EISA also requires improvements in light bulb efficacy. By 2014, the minimum allowable efficacy in light bulbs must increase by 25% and by 2020 minimum efficacy must increase by 200% (Congress, 2007). The increases in minimum permissible efficacy will effectively eliminate the sales of present-day incandescent bulbs, requiring the majority of American businesses and households to adopt a more efficient replacement technology. Additionally, all federal agencies will be required to use Energy Star products.

Asset Management

The Air Force Infrastructure Energy Plan defines asset management as the following:

> *The Air Force is undergoing a fundamental transformation in installation management under a concept called "Asset Management." Asset Management is the use of systematic and integrated practices through which the Air Force optimally manages its natural and built assets and the associated performances, risks, and expenditures over the life-cycle to a level of service to support missions and organizational goals. In essence, it is a structured, standardized approach that strives to make better-informed management decisions through business case analysis of risks, costs, and benefits. Energy management is leading the way in this transformation through a structured approach to understanding life-cycle cost (Air Force Infrastructure, 2010).*

The asset management approach the Air Force is developing through its energy plan not only emphasizes reducing energy demand, but attempts to achieve better decisions through life-cycle analyses (*Air Force Infrastructure,* 2010).

Lighting Characteristics

Several characteristics are commonly used when evaluating a light source. Luminous flux measures the human perceived intensity of light. Lumens are the standard International Systems Units for luminous flux. The human eye can see only certain wavelengths of electromagnetic energy and thus this metric does not consider energy outside the visible spectrum when determining perceived intensity. Additionally, the human eye's sensitivity changes over the visual spectrum of light (Rea, 2000), having a peak sensitivity around 550 nanometers. Government and organizational building codes typically determine the minimum amount of lumens required for an area based on its intended use. As a result, while energy efficiency, a ratio of watts of energy output by a lamp to watts of energy input to the lamp, can be used to evaluate a lamp, it is often of greater practical use to discuss the lamp's efficacy. The term efficacy is similar to efficiency. However, instead of power (watts) output compared to power input, efficacy is the ratio of luminous flux to power input. Efficacy is typically measured in lumens per watt.

Correlated color temperature (CCT) is a measure of the color of light based on the temperature needed to heat up a perfect blackbody to reach that color. A perfect black body is a material that absorbs all light at zero degrees Kelvin and is used as a theoretical baseline for calculating CCT. Common camp fires can be used to demonstrate changing

CCT. When fire starts, it is very red; as it begins to heat up, the flame starts to appear bluer. CCT is typically measured in Kelvin. Color rendering index (CRI) is another metric of the color of light which attempts to measure how well an array of colors is reproduced with respect to a reference light source, such as a blackbody radiator or daylight. CRI values range from 0 to 100, with 100 inferring that the lamp permits all colors to appear exactly the same when illuminated by the lamp as compared to the reference light source (Lenk & Lenk, 2011).

Legacy Lighting Technologies

There are several types of lighting technologies presently installed on Air Force installations. This section discusses the history and significant characteristics of each lighting technology. Additionally, it describes significant advantages or disadvantages of each technology.

Incandescent

Incandescent light bulbs have a filament, a thin piece of metal which is typically made of tungsten, inside a vacuum-sealed glass shell. When electricity passes through the filament, it is heated to the point that it begins to emit light. The vacuum-seal glass is used to extend the life span of the filament, which is typically about 1000 hours. The main advantage of incandescent bulbs is their inexpensive cost to produce and purchase. Additionally, an incandescent bulb’s light output has a familiar color temperature of about 2850 degrees Kelvin. It is approximately a blackbody radiator, having a continuous spectrum and approximately a perfect CRI of 100 when referenced to a blackbody radiator at the same color temperature. However, there are several disadvantages to incandescent technology. Incandescent bulbs have one of the lowest efficacies of commercially available electrical lighting sources. Their low efficacy can be directly attributed to the fact that much of the energy used inside the bulb is dispersed as heat instead of visible light. Additionally, when dimmed, incandescent light's color temperature is reduced, making the light appear more red (Lenk & Lenk, 2011; Rea, 2000).

Halogen

Halogen lamps are a specific type of incandescent lamp. Instead of a vacuum seal, halogen bulbs are filled with halogen gas, typically iodine or bromine. The halogen gas allows the filament to burn hotter, last longer, and increases its efficacy. The CCT of halogen lamps is higher than traditional incandescent lamps (Lenk & Lenk, 2011).

Fluorescent

Fluorescent lamps seal mercury and inert gasses in a tubular glass bulb. Once the mercury gas is heated by an electrode filament, a plasma arc is created causing light to be emitted at Ultra Violet (UV) wavelengths. The glass around the bulb is coated with phosphorus to transform the UV light into visible light. The typical lifespan for fluorescent lamps can reach 10,000 hours, with end of life resulting from filament degradation. Efficacy of fluorescent lamps can range from 60 to 100 lumens per watt (Lenk & Lenk, 2011; Rea, 2000). Fluorescent bulbs, while they are quite efficient, have some known disadvantages. A significant disadvantage is the fact that their light output is temperature dependent, often resulting in long effective on-times. Additionally, fluorescent bulbs contain environmentally toxic heavy metals, typically mercury. Fluorescent bulbs also include only three narrow band phosphors, which produce light with relatively low CRI values, approximately 70.

Induction

Induction lamp technology is similar to fluorescent lamps; however, the filament inside the bulb is not needed. The plasma is stimulated purely by electromagnet induction using a transformer and the air as a medium. Figure 3 illustrates the two most common forms of induction lamps. Induction lamps have a life span of up to 100,000 hours. However, induction lamps can cause electromagnetic interference at certain frequencies, depending on design. The frequency 13.56 megahertz is an approved range the meets Federal Communications Commission regulations. However, long-term health effects of human exposure to 13.56 megahertz radiation are not yet fully understood (Lenk & Lenk, 2011; Rea, 2000).

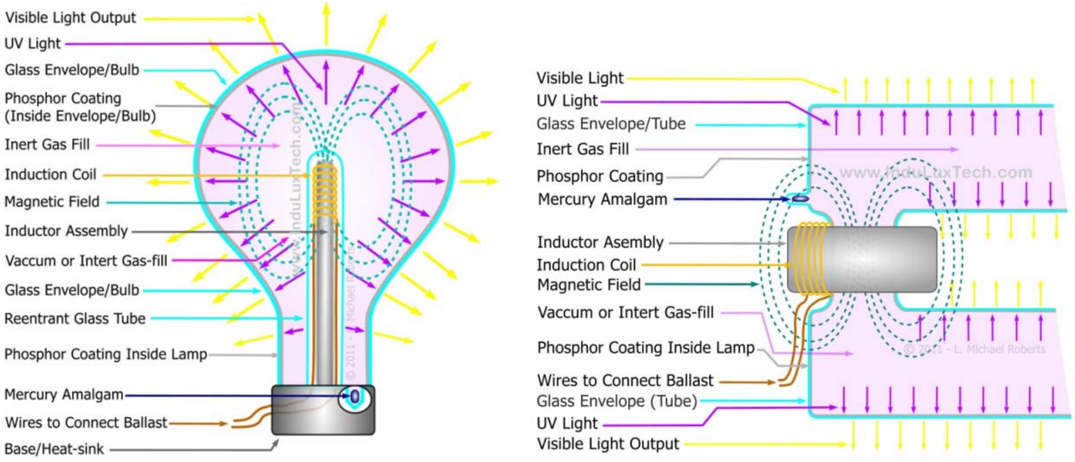

Figure 3. Induction bulbs (Roberts, 2011)

High Intensity Discharge (HID)

HID lamps are similar to fluorescent lamp technology; however, they do not require a phosphorus coating to transform the light from UV to visible wavelength spectrums. HID lamps can be made with mercury, metal halide, or high-pressure sodium (HPS). HPS lamps are widely used for street lighting applications. The efficacy of HPS lamps can reach over 100 lumens per watt. However, their CCT is low, thus giving a yellowish color. Additionally, they can take minutes to heat up to produce significant light. The lifespan of a HPS lamp ranges from 12,000 to 24,000 hours (Lenk & Lenk, 2011).

Characteristics of LEDs

LED lighting technology differs substantially from traditional forms of lighting. To be able to compare traditional forms of lighting to LED, the unique characteristics specific to LEDs must be understood. This section will describe LEDs, emphasizing their advantages and limitations.

LED Basics

A diode allows current to flow in only one direction. One-direction current flow is achieved by doping a semiconductor material with excess electrons on one side, n-type, and holes on the other, p-type. As current flows through the diode and an electron reaches a hole, the electron falls into a lower band-gap and releases photons. Figure 4 depicts a simple example of a semiconductor diode. Different semiconductor materials have different band-gaps. The size of band-gaps the electron travels through will determine the energy level of the electron and the wavelength of the photon that is emitted as the electron releases energy to fall into a lower energy orbital within the p-type material.

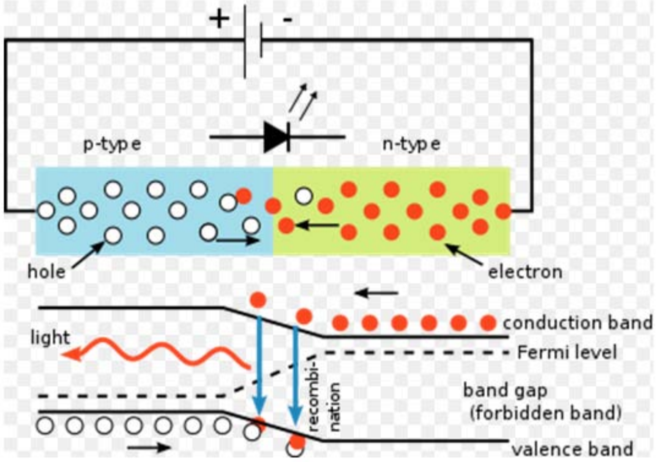

Figure 4. LED Diagram (*Schematic Diagram,* 2011)

Main Types of High Powered LEDs

There are two main types of high-powered LED designs used for lighting. The first type of LED design relies on a physical process that is similar to present fluorescent lighting. The LED emits high energy, short wavelength “blue” light which then passes through numerous phosphorous layers, which are excited by the high energy light, emitting lower energy, longer wavelength light. When light is created by each of the multiple phosphors, this light combines and appears as white light (Hecht, 2010). Figure 5a depicts the spectrum, energy as a function of wavelength across the visible spectrum, of a phosphorous-based white LED. As each LED is individually coated with the phosphors, each LED emits white light. The second common design for high-powered

LED lamps requires light to be produced by multiple separately colored LEDs, such as red, blue, and green (RGB). The light from each color of LED is combined to form white light (Hecht, 2010). Figure 5b depicts the spectrum of three typical RGB LEDs. These two types of high-powered LEDs have significant advantages and disadvantages when compared to one another.

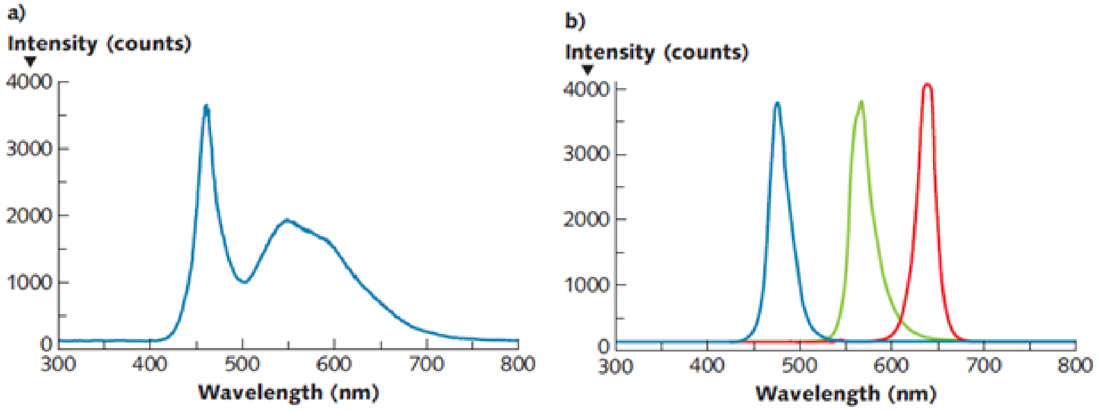

Figure 5. Wavelength Distribution of Phosphorous-Based white LEDs (a) and RGB LEDs (b) (Hecht, 2010)

A few advantages of phosphorous-based white LEDs include their tendency to be less expensive to produce and their ability to create a higher quality of light, making them more commonly produced compared to their RGB competitor. Some disadvantages of phosphorous-based white LEDs can be attributed to the lower efficiencies from passing light through the phosphorous layers (Hecht, 2010). RGB LEDs have significant representation of light in all three main colors and the color of light produced by these lamps can be precisely controlled by adjusting the current to the individually-colored LEDs. However, as shown in Figure 5b, the light spectrum created from RGB LEDs contains gaps or holes at certain wavelengths, thereby reducing the quality of light.

Further, green LEDs are harder to produce and tend to fail earlier (Hecht, 2010). Finally, combining three types of LEDs to form a single lamp that produces white light with a specified color temperature, as is necessary when applying the RGB LEDs, tends to be more expensive than lamps produced by applying single LED type, such as the phosphorous-based blue LED.

Current Droop

Current droop refers to the loss in luminance efficiency of an LED as a function of increasing current. To compete with traditional forms of lighting, manufacturers currently increase the current levels in LEDs to enable them to provide more lumens per fixture, but at the cost of efficiency. The Department of Energy (DOE) describes current droop as one of the seven essential barriers LEDs must overcome to succeed (U.S. Department of Energy, 2010). Mitigating the effects of droop is possible by lowering the drive current which will enable the LED to operate more efficiently (Egawa, Ishikawa, Jimbo, & Umeno, 1996). However, lowering the drive current will require more LEDs to illuminate the same area at the same illumination level, due to the decrease in lumen output per device. Of course, increasing the number of LEDs within a lamp also increases the manufacturing cost for the lamp.

LED Decay, Lifespan, and Lumen Maintenance

Calculating the lifespan for LEDs is much different from legacy lighting. As long as the circuit powering the LED does not fail, the LED will not burn out but only degrade in luminous flux. Rated lumen maintenance is the time it takes an LED bulb to decay to a specified percent of the bulb's initial output. Typically, once an LED has decayed to 70%, it should be considered for replacement. The IESNA has created a standard, LM-80, that describes a methodology for testing lumen maintenance. Additionally, IESNA has recently developed a technical manual, TM-21, that provides guidance on how to extrapolate LM-80 results. Using LM-80 and TM-21, manufacturers achieve rated lumen maintenances from 50,000 to 100,000 hours (Hodapp, 2011).

Controlling LEDs

Their solid-state composition, fast response times, and the ability to reduce the number of lumens output by controlling current provide LEDs the potential for an incredible advantage over traditional light sources. "Active control" and "intelligent light fixtures" are two specific strategies that use the above advantages for the potential of significant power and life-span saving rewards. Active control allows the current to the LED to be controlled to produce the precise level of lumens needed in a room; this control can be manual or automatic. As the LED light decays, the current to the LED is increased, thereby increasing the lumen output. This feature is similar to a dimmer switch used with many incandescent bulbs. Active control can achieve power savings by using power for creating only light that is needed. It produces life-span savings from reducing the average current on the light, which decreases the effects of LED decay (Lemieux, 2010). Intelligent light fixtures monitor human interaction with their environment to determine the lighting levels needed throughout an area. Intelligent light fixtures achieve energy savings by not lighting an area uniformly; areas that are not being used do not have to be lit to the same level as areas that are being used. Intelligent lighting design also increases the life-span savings of an LED because less driving current is used when dimmed.

LEDs - An Emerging Technology

In this section, the rapid and predicted pace with which LED technology is improving is described. Additionally, previous methods addressing issues of merging asset management ideas with the rapid evolution of LED lighting is discussed.

Haitz's Law

In 1999, Ronald Haitz predicted major improvements in LED technology would occur in the next few decades. His predictions included a reduction in the cost of LED production by an order of magnitude each decade and an increase in the luminous flux of LED devices by a multiple of 20 each decade. Figure 6 shows these two Haitz's law relationships, together with average LED cost and luminous flux for the past four and a half decades. As shown, since Haitz's prediction in 1999, LED manufacturers have been able to meet or surpass his predictions. Haitz also predicted efficacy would reach 100 lumens per watt (lm/W) by 2010, which was achieved, and 200 lm/W by 2020 (Haitz et al., 1999). Recently, the DOE has suggested that the future rate of increase in LED efficacy will exceed Haitz's original predictions, providing 266 lm/W by 2020 (U.S. Department of Energy, 2011). The theoretical maximum efficacy for RGB LEDs is calculated to be 350 to 400 lm/W (Ohno, 2006), providing further increases in LED efficacy beyond 2020. Figure 7 compares efficacy increases of traditional street lighting sources to LEDs. As shown in Figure 7, the rate of increase in LED efficacy is expected to far exceed the rate of increase for HPS streetlights, one of the most efficient high intensity discharge (HID) lighting technologies.

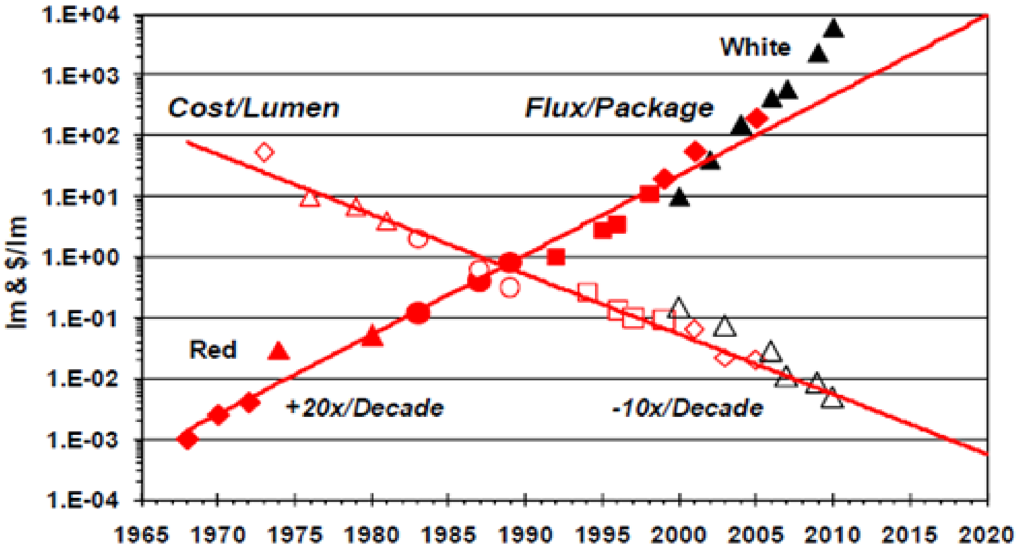

Figure 6. Haitz Law (Haitz et al., 1999; U.S. Department of Energy, 2010)

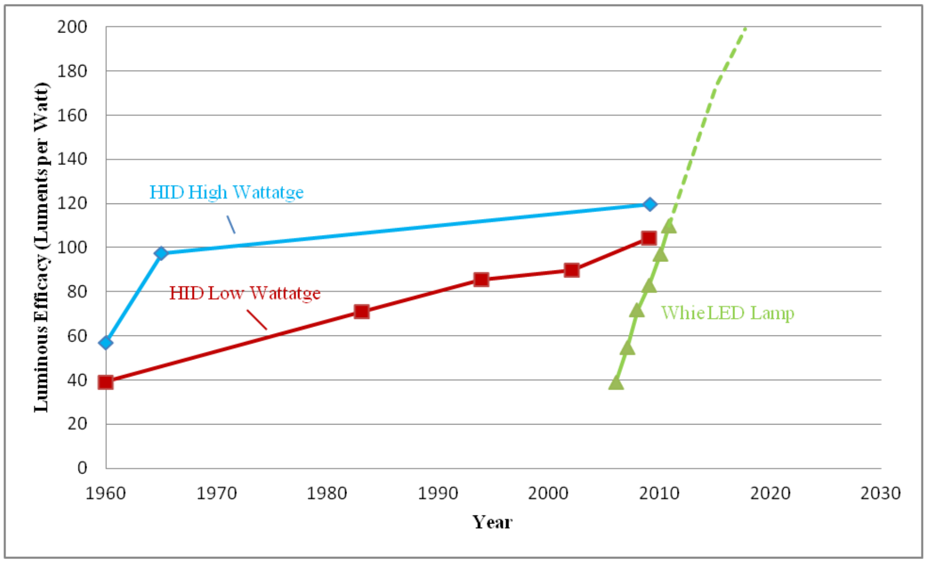

Figure 7. Historical and Predicted Efficacy of Lighting Technologies (U.S. Department of Energy, 2011)

Breakdown of LED Fixture Costs

Reviewing the DOE’s *Solid State Research and Development Manufacturing Roadmap*, indicates that in the cost breakdown for the production on an LED fixture the LED bulb is 45% of the total cost. The remaining cost breakouts for LED fixtures are provided below in Figure 8:

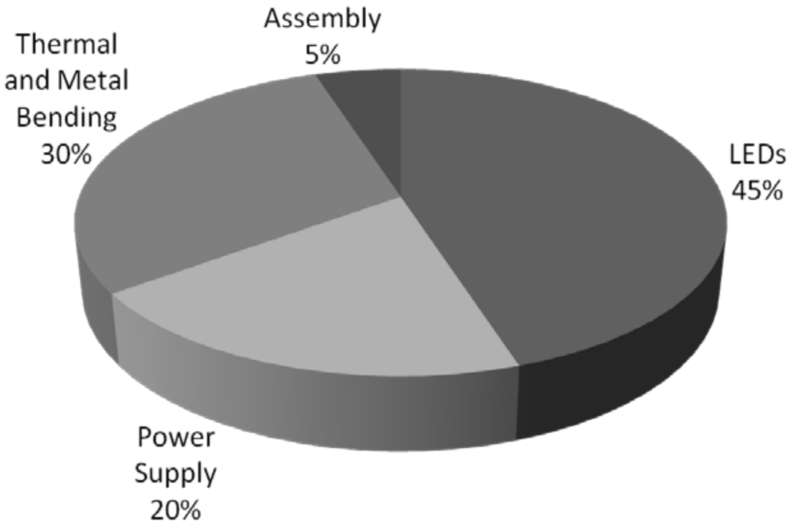

Figure 8. LED Fixture Cost Breakdown (U.S. Department of Energy, 2010)

Assessing the Economic and Environmental Impacts Associated with Currently Available Street Lighting Technologies

Colon (2010) analyzed the economic and environmental advantages of installing LED and induction lamps on over 36 Air Force bases. Using data collected by each Air Force installation, he conducted a life-cycle cost analysis (LCCA) and found 17 installations where it was economically beneficial to replace existing street lamps with

LED lamps. However, he assumed LED lamps are capable of a one-for-one replacement with existing street lamps. Research conducted in November of 2010 by the National Lighting Product Information Program (NLPIP) does not support this assumption. Additionally, Colon (2010) did not anticipate the improvements in LED technology, which limits the usefulness of his research for Air Force decision-makers in years to come.

Streetlights for Collector Roads

Radetsky (2010) evaluated the economic feasibility of installing several existing streetlight technologies and compared LEDs and induction street lighting to traditional 150 Watt high-pressure sodium (HPS) streetlights. She chose lighting fixtures produced by several different lighting companies based on the results of an online survey conducted by NLPIP in June of 2009. She tested eight LED lamps, one induction, and four HPS streetlights. Her objective metric to determine minimum standards for the experiment's lighting design was based on the street lighting criteria described in the Illuminating Society of North America (IENSA) Handbook 2005. She used the Lighting Analysts' AGi32 software to analyze the data and determine the appropriate distance of lighting poles for each light. Additionally, she used RSMeans and DOE findings to determine appropriate dollar values for labor and utility rates.

Radetsky's (2010) results support moderate energy and maintenance cost savings using LED fixtures when compared to HPS. However, she also determined that more poles are needed when using LEDs to cover the same area. Additionally, the fixture cost of LEDs is much greater than HPS fixtures. The increase in initial infrastructure, especially considering the need to change the pole spacing, financially overcomes any cost savings achieved by energy or maintenance of the LED. Radetsky (2010) also shows no benefit in using induction fixtures because of the increase in the number of poles required and no energy savings. Therefore, her research does not support the claims of the LED and induction lighting companies.

Air Force Design Criteria

The Air Force has several governing documents that set standards for designing lighting applications. This section focuses on street lighting design for all lamp types. Although not covered in this paper, Engineering Technical Letter (ETL) 12-4 contains Air Force specific requirements that must be met before the acceptance of any LED lamp.

RP-8 Criteria

The ANSI and IESNA created Recommended Practice-8 (RP-8) to identify standards for roadway lighting. RP-8 offers three different criteria for determining proper roadway lighting: illuminance, luminance, and small target visibility (STV). Illuminance design is based on the amount of light provided to a surface that is to be illuminated. However, different roads will have different reflectivity; therefore, luminance design determines how bright the road is, or how much light reflects from the road to the driver. STV design is based on the luminance of the surrounding area, to include several targets, the immediate background, and the adjacent surroundings. The luminance of the surrounded area and the glare are weighted to determine the appropriate light level (Rea, 2000).

UFC 3-530-01(to include Change 1)

The Department of Defense (DOD) produces several Unified Facilities Criteria (UFC) documents that provide criteria for planning, design, construction, sustainment, restoration, and modernization of DOD infrastructure. Unified Facilities Criteria (UFC) 3-530-01 references RP-8 for designing road lighting. STV is the UFC's preferred method, especially when safety is a significant concern. Luminance is also an acceptable method when STV is not reasonable to conduct; it is also often used as a secondary criteria. However, UFC 3-530-01 does not recommend using the illuminance criteria due to its poor STV results. Illuminance design typically allows for increased pole spacing and fewer light sources than are necessary to fulfill the luminance or the STV criteria. Illuminance design criteria can offer significant economic benefits, but is not the safest alternative (Department of Defense, 2010). It is important to note several Air Force lighting infrastructures have existed before the publications of UFC 3-530-01 and may not meet any of the RP-8 criteria.

UFC 3-530-01 also provides several "rules of thumb," or guidelines, to consider when conducting lighting designs. The UFC suggests beginning a design with a 5:1 spacing to mounting height ratio. After the 5:1 ratio starting point, the UFC recommends the engineer should adjust the spacing to meet the design criteria. The UFC also promotes the use of computer programs to assist in more accurate point-by-point calculations (Department of Defense, 2010). When replacing existing streetlights with significantly different lamps, such as LEDs, new lighting calculations should be accomplished to ensure Air Force lighting criteria are still being met as the luminance output and the distribution of illumination are likely to vary.

Summary

The Air Force can gain efficacy, quality, and maintenance cost benefits from replacing existing streetlights with LEDs lamps. However, with stringent US federal regulations and the Air Force's new focus on asset management, it is important for the Air Force to try to obtain the most energy and cost savings for their investment. As demonstrated in this research, a detailed LCCA can be achieved through the combination of Haitz's Law and previous research to implement a new economic evaluation method termed time-valued-technology.

III. Methodology

In this chapter, the cost analysis method of time-valued-technology is described specifically to address the decision of replacing 250 watt high-pressure sodium (HPS) streetlights with similar light-emitting diode (LED) lamps. This chapter is divided into sections describing each variable, LED technology forecasts, the time-valued-technology method, and the sensitivity analyses employed in this research.

Variables Impacting LCCA

There were a number of important variables used in this analysis. The following definitions explain the basic concepts and values used for each variable.

Labor Rate

Labor rate is the hourly cost of an electrician at a particular installation. Installations participating in this study were asked in November 2011 to update existing 2009 labor rates. If the labor rates were not updated, non-adjusted 2009 labor rates were used. Appendix A describes each installation's labor rate and the last time it was updated.

Electricity Rate

Electricity rate is the cost of kilowatt per hour (kWh) of electricity at each installation. Installations participating in this study were asked in November 2011 to update existing 2009 electricity rates. If the electricity rates were not updated, non-adjusted 2009 electricity rates were used. Appendix A describes each installation's electricity rate and the last time it was updated.

LED Fixture Cost

LED fixture costs include the total cost of the entire lamp, including the LED's thermal and metal bonding, power supply, assembly, shell, and bulb. LED streetlights are typically sold as a complete unit to ensure their performance. The cost of fixtures can vary for many reasons to include location, quantity, year of purchase, and type of fixture. The baseline LED fixture cost was chosen to be $1,200. The fixture cost was chosen from an unofficial estimate of the highest lumen outputting LED fixture used in this study. The accuracy of the LED fixture cost is a limitation of this study. However, as discussed later in this chapter, a sensitivity analysis was conducted to understand the impact of this limitation.

HPS Bulb Cost

The cost of an HPS bulb was assumed to be $10 for the average 250 W HPS bulb. This was chosen based on Wright Patterson Air Force Base's purchase price for a new HPS bulb in November 2011.

Hours of Usage

Hours of usage are the number of hours the streetlight is on per year. With the assumption of 11.5 hours of daily use for 365.25 days a year, this research chose hours of usage to equal to 4200 hours.

Hours to Install

Hours to install is the expected time needed to replace an LED or HPS fixture, or bulb. After interviewing the head electrician for Wright Patterson Air Force Base's exterior lighting program, 0.5 hours were used for HPS bulbs and 1.0 hour was used for

LED fixtures. It is important to note that these estimates take into account the Air Force requirement to have a spotter on the ground when using a bucket truck. The additional 0.5 hour needed to install an LED fixture includes the time to remove the entire preexisting fixture head and then wire and attach the new LED fixture.

Lifespan

Lifespan is the number of years required for the light fixture to reach its minimally-allowed light output. This variable was assumed to be about 6 years for HPS bulbs. The lifespan for LEDs can vary greatly depending on temperature, electronic drivers, and the chosen lumen maintenance factor. Most companies advertise 50,000 to 100,000 hours. This study chose 100,000 hours, around 24 years, as the baseline in the initial analysis. It should be noted, however, that the warranty period for each technology is significantly shorter than the assumed lifetimes, with HPS having a warranty period of 1 year or less and LED devices commonly having a warranty period of 5 years.

Number of Lamps

This variable is the existing number of 250W HPS lamps at each installation. The number of lamps is based on a 2009 data call from all the participating installations.

Efficacy & Power for HPS and LED

Every HPS bulb used in this study was rated at 250 watts. However, more than 250 watts are needed to power the entire HPS fixture. It is common for many HPS manufacturers to recommend around 300 watts to power a fixture containing a 250 watt bulb. This study assumed 300 watts would be used for each HPS fixture. To calculate efficacy, the average lumens output by an HPS bulb was divided by 300 watts. LED lamp efficiency and power are typically specified for the entire fixture since these lamps are sold as an integrated unit.

To determine efficacy and power, a pair of surveys were applied which identify the primary lighting companies in HPS and LED street lighting (Radetsky, 2010). Efficacy and power were then determined from a survey of the lamps provided by these companies and average values were calculated and applied in this analysis. Table 1 provides a list of the HPS bulbs that were considered with average performance values. As shown, the average efficacy of the HPS bulbs was approximately 89 lumens per Watt, with a power of 300 Watts. Appendix B provides a list of LED street lights that were considered. Table 2 shows the average efficacy of the LED lamps was about 77 lumens per Watt, with a power of 208 Watts.

Table 1. 250 Watt HPS Bulb Baseline (GE Commercial Lighting Products, 2011)

Bulb	**Initial Lumens (non directed)**	**Power (W)**	**Efficacy (lm/W)**
GE Ecolux Lucalox HPS ED28	26000	300	85
GE Lucalox Deluxe Lucalox HPS ED18	22500	300	74
GE Ecolux Lucalox HPS ED28	29000	300	95
GE Lucalox Standby Long Life Lucalox HPS ED18	27500	300	90
GE Lucalox HPS ED18	28000	300	92
GE Lucalox Standby Long Life Lucalox HPS ED18	27500	300	90
GE Lucalox HPS ED18	28000	300	92
GE Ecolux Lucalox HPS ED18	28000	300	92
Average	27063	300	89

Table 2. Average LED Streetlight Specifications for 2011 (LEDway® Streetlights, 2011; American Electric Lighting, 2011)

Lamp	Downward Lumens	Power (W)	Efficacy (lm/W)
Average SRT_LWY (BetaLED)	17654	272	65
Average ATB1_60LED (AEL)	12316	144	85
AVERAGE	**15284**	**208**	**77**

HPS Maintenance Costs

HPS maintenance costs represent the cost of actions to replace HPS bulbs. The year HPS bulbs were installed was unknown; therefore, with a lifespan of 6 years, it was assumed 1/6 of the HPS streetlights would be replaced every year. To calculate the annual HPS maintenance costs, the following formula was applied:

$$\frac{(\#\ of\ Lamps * Bulb\ Cost) + (Labor\ Rate * Time\ to\ Install * \#\ of\ Lamps)}{6} \qquad (1)$$

LED Installation and Maintenance Costs

LED streetlight technologies used in this research require the entire fixture to be replaced at the end of its life. LED installation and maintenance costs were based on the fixture costs in the year it was installed. To calculate the LED installation and maintenance costs, the following formula was applied:

$$(\#\ of\ Lamps * Fixture\ Cost) + (Labor\ Rate * Hours\ to\ Install * \#\ of\ Lamps) \qquad (2)$$

Terminal Values

In many LCCA studies, the lifespan of the equipment does not end the same year as the study. Terminal values thus provide a credit for equipment for the unused lifetime at the end of the study period. Terminal values are similar to salvage values; however, there is no expectation of actually salvaging the equipment. This study contains a 50-year study period with 22 alternatives. Each of the LED alternatives has LED streetlights installed in a different year. The HPS baseline alternative replaces 1/6 of its bulbs every year. Only two of the alternatives have streetlight life spans that end the same year of the study. To account for the unused value, researchers proportionally credited the remaining maintenance and installation costs in the final year of the study. For example, if an LED fixture was replaced in year 49 it would still have 22 years left in predicted lifespan; therefore, 92% of its maintenance and install costs would be credited back to its life-cycle cost at the end of year 50.

Light Loss Factor

Light Loss Factor (LLF) is a variable reflecting the reduction in luminous output of a light source over time. With appropriate LLFs, reductions due to pollution, dirt, bulb degradation, and optics can be accounted for to determine the appropriate luminous output throughout the lifespan of the fixture. LLFs can range drastically based on the technology, brand, design, optics, maintenance frequency, and location of a streetlight. A LLF of 0.75 was selected for both HPS and LED streetlights.

Discount Rate

Discount rate, similar to minimum rate of return (MARR), is a financial tool to help describe the monetary value of time. Typically, money now is worth more than money at a later date. For example, organizations could have a safe investment alternative that returns a particular rate; therefore, organizations can use this rate as their MARR to ensure all other investments are at least returning more than their safe investment. The federal government is required to use a discount rate to help evaluate different alternatives. Discount rates are calculated differently according to the type of investment being considered; however, the government bond rate drastically affects these calculations. Typically, the Office of Management and Budget (OMB) is responsible for publishing the federal government's discount rates. However, OMB's Circular A-94 publication details how federal energy management programs listed as exceptions to its requirements (Guidelines and Discounts, 1994). Instead, the DOE prepares annual energy price indices and discount factors for LCCA specific to government energy projects. In their 2010 publication, the real rate, excluding general price inflation, is 3% for energy projects (Rushing, Kneifel, and Lippiatt, 2010).

Constant Dollars

Financial analyses are often done using constant dollars. Constant dollars are the purchasing power at some base point in time, essentially enabling inflation to be ignored. In this research, 2011 is used as the baseline for constant dollars.

Emerging Technology Forecasts

While the time-valued-technology method discussed in this paper can be applied in multiple domains, it requires a technology-specific forecast to be implemented. In the current case study, Haitz's Law and DOE forecasts of LED improvements provided the information and functions needed to support the necessary predictions.

Haitz's Law predicts the cost per lumen of an LED will decrease by 20.57 percent each year (Haitz et al., 1999). The DOE estimates that 45 percent of the cost of each LED fixture is directly related to the LED device (U.S. Department of Energy, 2010). In this study, the initial cost per lumen of the LED was calculated by dividing 45 percent of the total fixture cost by the average LED lumen output calculated in Table 2, which was 0.036 dollars per lumen. Haitz's Law was then applied to the calculated cost per lumen to obtain the cost of the LED portion of the fixture.

In this study, the future efficacy of LED fixtures was estimated from DOE efficacy predictions which project an efficacy of 202 lumens per watt by the year 2020 (U.S. Department of Energy, 2011). A linear growth rate from the present date until 2020, with a ceiling of 202 lumens per watt, was thus assumed. After 2020, it was assumed the efficacy would stabilize and remain constant at 202 lumens per watt. It is important to note, these DOE predictions apply to the entire LED fixture, including power losses of drive electronics, rather than the LEDs alone.

The LED streetlights available today do not provide a high enough lumen output to replace an HPS streetlight on a one-for-one basis and meet basic Department of Defense (DOD) design criteria. There are many variables other than lumen output that influence the results of a lighting analysis, such as optics, light loss factors, pollution, and pole height. The argument has been made that LED-based streetlights provide a better color rendering index (CRI) and a more even lighting distribution, which provides equal visibility with lower lumen output. However, the existing lighting standards do not permit the reduction of average lumens by increasing CRI. Additionally, an initial analysis indicated that even with a perfectly uniform luminance distribution, the average LED fixture could not replace HPS on a one-for-one basis. In this analysis, it is assumed that once the average lumen capability of available LED streetlights reaches the average lumen output by a 250 watt HPS streetlight, less controversy will exist and one-for-one replacement of HPS with LED streetlamps will be possible. Therefore, it was assumed that the lumen output of LED streetlights will increase annually until their average luminous output matches the average HPS output of 27,063 lumens and replacement will not occur until this output level is achieved. The rate of average lumen output was based on the Haitz's law prediction of 35 percent flux per package increase per year, indicating that initial replacement will not occur until 2013. Further, it was assumed that the output of these lamps will not increase beyond this point.

Time-Valued-Technology Method

Within this section, several factors have been discussed which will influence the LCCA for LED street lights. However, no known method of LCCA includes variables which permit the rapidly changing improvements in LED cost and efficacy to be considered. As a result, an approach called "Time-Valued-Technology" method is proposed. This method relies on a calculation of net present value (NPV) which includes the variables discussed earlier within this section.

NPV estimates a current value of a series of future amounts to be received or paid out. Calculating the NPV of mutually exclusive alternatives can help a decision-maker choose the most economically beneficial option. Traditionally, NPV is calculated by Equation 3, where F is the future cash flow in a given year, i is the discount rate, N is the number of years of the selected time horizon for the analysis, and n is the specific year for each future cash flow (Canada, Sullivan, & Kulonda, 2005).

$$NPV = \sum_{n}^{N} \frac{F}{(1+i)^n} \tag{3}$$

Time-valued-technology has several mutually exclusive cases; however, the major difference between each case is the year the emerging technology is installed. By modifying the equation for NPV, an equation for implementing the method of time-valued-technology can be described for each alternative year for installing the emerging technology. In this method, the NPV associated with installing the replacement technology in year j is calculated according to Equation 4.

$$NPV(j) = \left[\sum_{n=0}^{j-1} \frac{I_n}{(1+i)^n}\right] + \left[\sum_{n=j}^{N} \frac{E_{n,j}}{(1+i)^n}\right] \qquad \text{Where } 0 \leq j \leq J \tag{4}$$

In this equation, the variable I is the future value of all the costs of the incumbent technology in year *n* and is calculated according to Equation 5. This equation assumes that the incumbent technology will remain in place for the *(j-1)* years and the emerging technology will replace the incumbent technology in year *j*. E is the future value of all the costs of the emerging technology in year n based on the initial year the emerging technology was installed and is calculated according to Equation 6. Equation 4 is evaluated assuming the incumbent technology is replaced with the emergent technology in each year *j*, ranging from *0* to *J*, where *J* is the last year of predicted growth of the emergent technology used in the study. The minimum NPV as *j* varies from 0 to *J* is considered the best year to install the emergent technology.

$$I_n = Iopertions_n + Imaintenance_n + Idisposal_n + Iterminal_n \tag{5}$$

$$E_{n,j} = Einstall_{n,j} + Eopertions_{n,j} + Emaintenance_{n,j} + Edisposal_{n,j} + Eterminal_{n,j} \tag{6}$$

Sensitivity Analysis

Determining the appropriate time to make a large financial investment in a new technology is a complex decision. There are multiple factors that must be considered in an economic analysis of this type. A primary component of this analysis is that the data outputs must be reliable and easily understood by the decision-makers for it to have value (Gal, 1999). Additionally, time must be spent to determine the most critical criterion for consideration, the consequences of each alternative, and the potential benefit of each alternative. Time must also be spent ensuring the correct measurements and scales are chosen for what determines success or failure (Triantaphyllou, 2000). For energy projects, it is not always as simple as selecting the option with the most dollars saved. Energy policy objectives, usage reductions, budgets, as well as the desire to portray a "green" image, can all factor into the decision-making process. Additionally, the relative importance or relative changes in any of these areas can have a significant impact on a model. This leads to the need for a sensitivity analysis to determine if any individual criterion, or combination of criteria, has a significant impact on the appropriate time to install LED streetlights. A model limits its usefulness unless it considers both the factors as well as the sensitivity of those factors (Chatterjee, 1998). In this research, several sensitivity analyses were conducted to better understand each variable's relationship to the year LED technology becomes most cost effective. The researchers chose six installations, with a range of labor and electricity rates, to evaluate the sensitivity of the preferred year for installation on many of the variables considered in this analysis.

IV. Results and Analysis

In this chapter, the results of implementing time-valued-technology in the case of replacing 250 watt HPS streetlights with equivalent LED streetlights at 64 Air Force installations are shown. However, this method requires projection of many factors far into the future, thereby reducing the likelihood of correct estimation. To compensate, this method is accompanied by a sensitivity analysis to determine the impact of critical assumptions and estimated model parameters. The researchers chose to give a more detailed description and conduct a sensitivity analysis of the results for Eglin AFB, Fairchild AFB, Clear Air Force Station (AFS), Goodfellow AFB, Los Angeles AFS, and McConnell AFB. These installations were chosen in an attempt to capture the results of locations with a diverse range of electricity and labor rates.

Results of Time-Valued-Technology LCCA

In Table 3, the results of using time-valued-technology to determine the best year to replace HPS with LED streetlights can be seen. Additionally, the first year LEDs will become financially more advantageous than HPS is shown. The "Percent Savings in waiting" column describes the percentage of dollars that can be saved by delaying replacement of HPS streetlights from the first year LEDs become financially more effective to the year chosen by implementing time-valued-technology. Potential savings in implementing time-valued-technology ranged from 1.10 to 14.15 percent, averaging 6.77 percent. Every installation where LED technology becomes financially beneficial, the implementation of time-valued-technology showed a potential for savings. There were 16 bases that did not experience a financial benefit from replacing HPS streetlights with LED street lights. These installations all had an electricity cost less than 0.053 dollars per kWh.

Table 3. Best Year to Replace 250 watt HPS with LED

Installation	When to replace HPS to LED using TVT (2011-2031)	First Year LED better than HPS	Percent Savings in waiting
ALTUS AFB	2024	2017	5.51%
ANDERSEN AFB	2017	2011	4.40%
ANDREWS AFB	2021	2014	11.29%
BARKSDALE AFB	Do Not Replace	N/A	N/A
BEALE AFB	2025	2018	3.87%
BOLLING AFB	2018	2011	8.32%
BUCKLEY AFB	2022	2015	9.25%
CANNON AFB	2026	2019	2.82%
CAPE CANAVERAL	2024	2017	5.28%
CAVALIER AFS	Do Not Replace	N/A	N/A
CHARLESTON AFB	2022	2015	8.94%
CHEYENNE MTN AFB	Do Not Replace	N/A	N/A
CLEAR AFS	2016	2011	2.45%
COLUMBUS AFB	2030	2021	1.83%
DAVIS MONTHAN AFB	2024	2017	4.92%
DYESS AFB	2022	2015	9.09%
EARECKSON	2016	2011	3.58%
EDWARDS AFB	2028	2020	2.40%
EGLIN AFB	2021	2014	10.52%
EIELSON AFB	2018	2011	6.75%
ELLSWORTH AFB	Do Not Replace	N/A	N/A
ELMENDORF AFB	2031	2023	1.10%
FAIRCHILD AFB	Do Not Replace	N/A	N/A
GOODFELLOW AFB	Do Not Replace	N/A	N/A
GRAND FORKS AFB	Do Not Replace	N/A	N/A
HANSCOM AFB	2018	2011	8.38%
HICKAM AFB	2017	2011	4.79%
HILL AFB	Do Not Replace	N/A	N/A
HOLLOMAN AFB	2022	2015	9.07%
HURLBURT FLD	2021	2014	10.20%
KADENA AB	2019	2011	11.24%
KEESLER AFB	2023	2016	6.95%
KING SALMON AB	2016	2011	3.24%
KIRTLAND AFB	2023	2016	7.24%
KUNSAN AB	2023	2016	6.57%
LACKLAND AFB	2025	2018	3.68%
LANGLEY AFB	2025	2018	3.71%
LAUGHLIN AFB	2019	2011	11.09%
LOS ANGELES AFS	2019	2011	11.09%
LUKE AFB	2030	2021	1.87%
MALMSTROM AFB	2022	2015	8.75%
MCCHORD AFB	Do Not Replace	N/A	N/A
MCCONNELL AFB	Do Not Replace	N/A	N/A
MCGUIRE AFB	2019	2011	9.81%
MINOT AFB	Do Not Replace	N/A	N/A
MISAWA AB	2020	2011	12.93%
MOODY AFB	2025	2018	3.87%
MT HOME AFB	Do Not Replace	N/A	N/A
NELLIS AFB	2023	2017	4.82%
OFFUTT AFB	Do Not Replace	N/A	N/A
RANDOLPH AFB	2030	2021	1.83%
ROBINS AFB	2026	2019	3.04%
SCHRIEVER AFB	2023	2016	6.66%
SCOTT AFB	2023	2016	6.88%
SEYMOUR JOHNSON AFB	2023	2016	7.08%
SHEPPARD AFB	2021	2012	14.15%
THULE AB	2016	2011	3.58%
TRAVIS AFB	2024	2017	5.40%
TYNDALL AFB	2020	2011	13.92%
USAF ACADEMY	Do Not Replace	N/A	N/A
VANCE AFB	Do Not Replace	N/A	N/A
VANDENBERG AFB	2022	2015	8.71%
WHITEMAN AFB	Do Not Replace	N/A	N/A
YOKOTA AB	2019	2011	11.90%

Eglin AFB

The time-valued-technology results for Eglin AFB are shown in Figure 9. Eglin AFB had labor and electricity rates that were the closest to the average of all labor and electricity rates used in this study. Eglin AFB labor and electricity rates were 51.56 dollars per hour and 0.093 dollars per kWh, respectively. The average installation labor and electricity rates were 56.47 dollars per hour and 0.09 dollars per kWh, respectively. As shown, the NPV for LEDs at Eglin AFB decreases relatively rapidly after 2013, reaching a minimum in 2021 and increasing thereafter. Note, however, that the NPV of the LED replacement strategy on this base is lower than the Net Present Value of retaining HPS, beginning in 2014. Therefore, there will be a return on investment from installing LEDs on this base during this year or any subsequent year. However, by delaying replacement until 2021 the time-valued-technology approach indicates the potential for saving an additional $79,468, or 10.52 percent of the lifecycle cost, as compared to installing LEDs in 2014. It is also interesting that while the minimum NPV is obtained in 2021, the NPV change from 2020 to 2021 is quite small and the impetus to save energy or other factors might justify implementing the LED replacement earlier than otherwise indicated by the time-valued-technology approach.

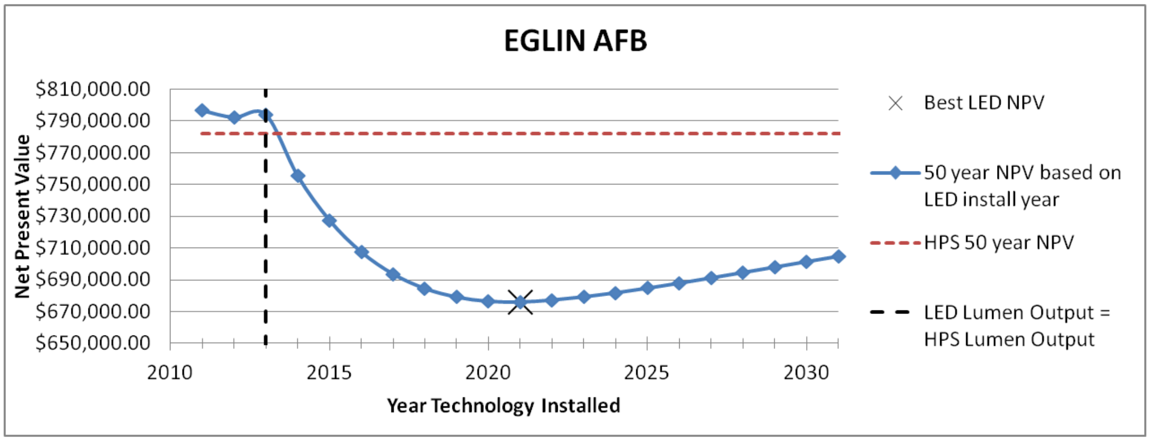

Figure 9. Best Year to Install LED 250 watt Streetlights at Eglin AFB

Figure 10 shows the effect of changes in labor rate, electricity rate, initial fixture cost, and the predicted maximum efficacy of LEDs from negative to positive 50 percent at Eglin AFB. Ranging labor rate had no affect on the best year to replace HPS streetlight. Decreases in the electricity rate and the max efficacy achievable had more impact relative to increasing. A 45 percent decrease in electricity rate does not support HPS replacement. However, a 45 percent increase in electricity rate changes the HPS replacement year only by two years, to 2019. If the max efficacy achievable lowers by 35 percent, it will not be financially beneficial to replace HPS streetlights; while a 35 percent increase moves the recommended LED install date to 2019. Changes in initial fixture cost appeared to have a more linear affect, ranging from 2017 to 2028 as fixture cost ranged from negative to positive 50 percent of its value.

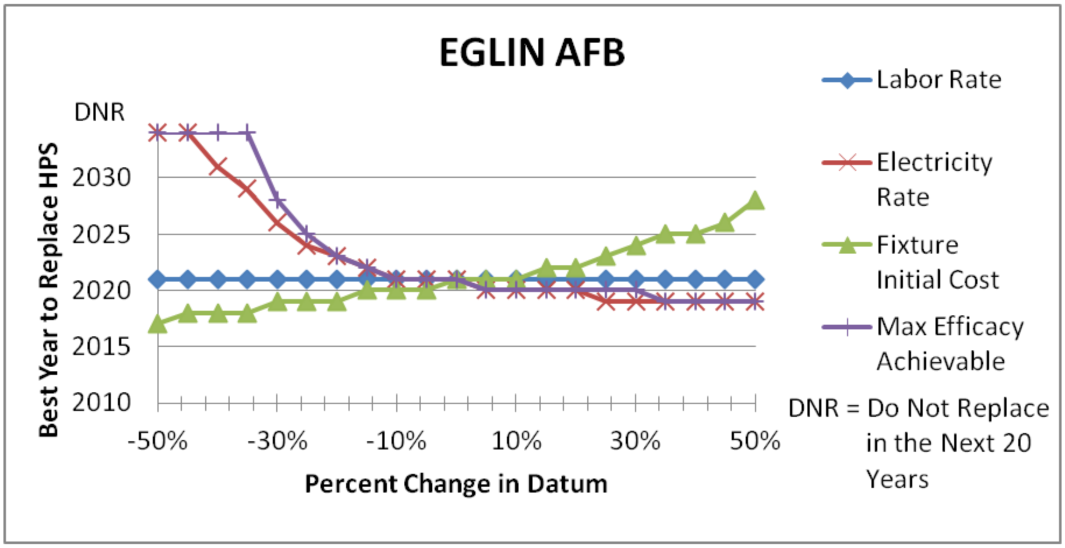

Figure 10. Eglin AFB Sensitivity on Main Variables

Figure 11 shows the effect if the projections of cost per lumen of the LED light fixture were to change for Eglin AFB. If the price per lumen of an LED device was to decrease at twice the rate of Haitz's law, the best year to replace HPS lamps becomes 2018 instead of 2021.

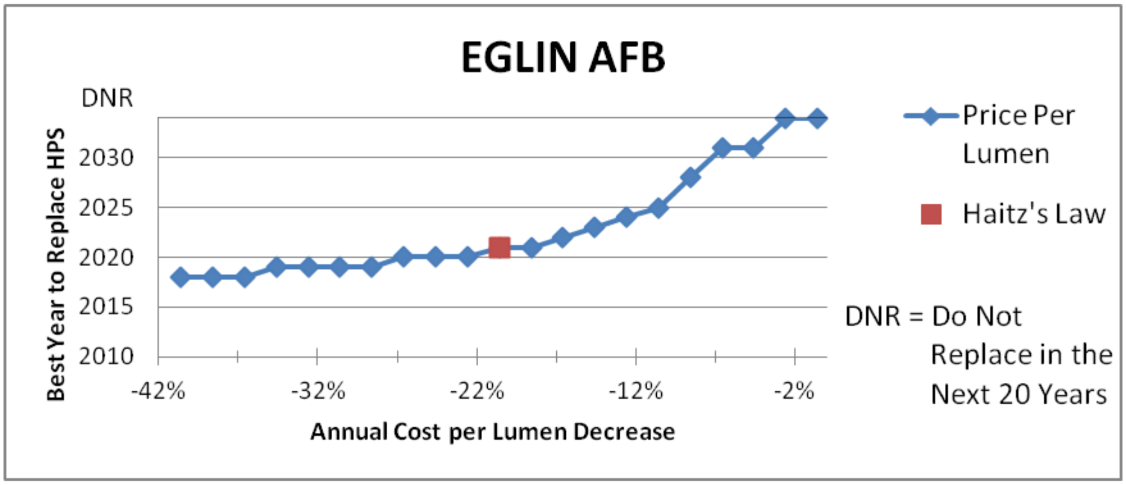

Figure 11. Eglin AFB Sensitivity on Price per Lumen

This research only considered the price of the LED devices decreasing due to Haitz's Law, while the cost of the rest of the fixture remained constant. However, it is likely that improvements in production or added requirements could also affect the cost of the LED fixture. Figure 12 depicts the effects of the change in results for Eglin AFB as non-LED parts of the LED fixture range from decreasing 20 percent to increasing by 20 percent per year for the next 21 years. Increases in the annual costs by as much as 5 percent eliminate the cost advantage of LED lamps at Eglin AFB.

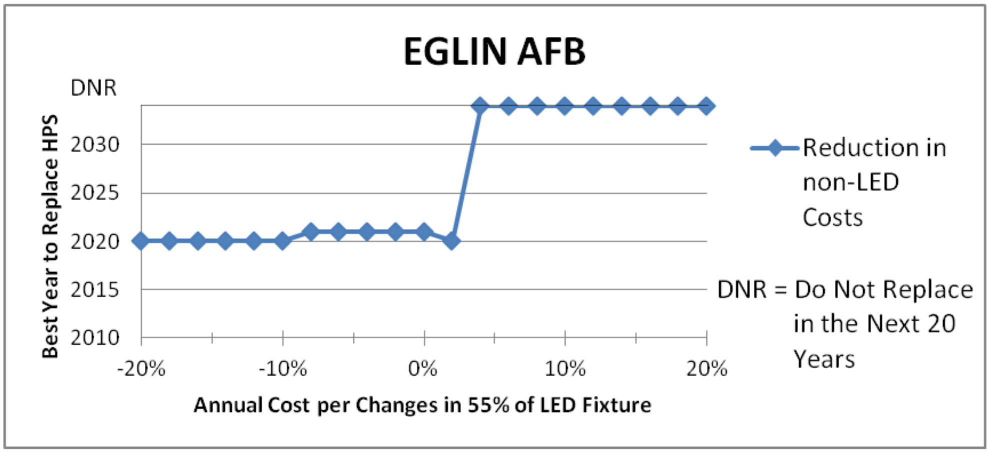

Figure 12. Eglin AFB Sensitivity on Price for Non-LED Parts

Figure 13 shows the effect of varying the LED lamp lifetime from 12 to 50 years. Lifetimes less than 20 years makes replacement of LED fixtures at Eglin less desirable. If LED fixtures have a lifespan of 12 years, instead of the 24 that was predicted, it would not be more cost effective for Eglin AFB to convert to LED streetlights. However, doubling the lifespan to 48 years only affects the decision to install LEDs by two years, replace in 2019 instead of 2021.

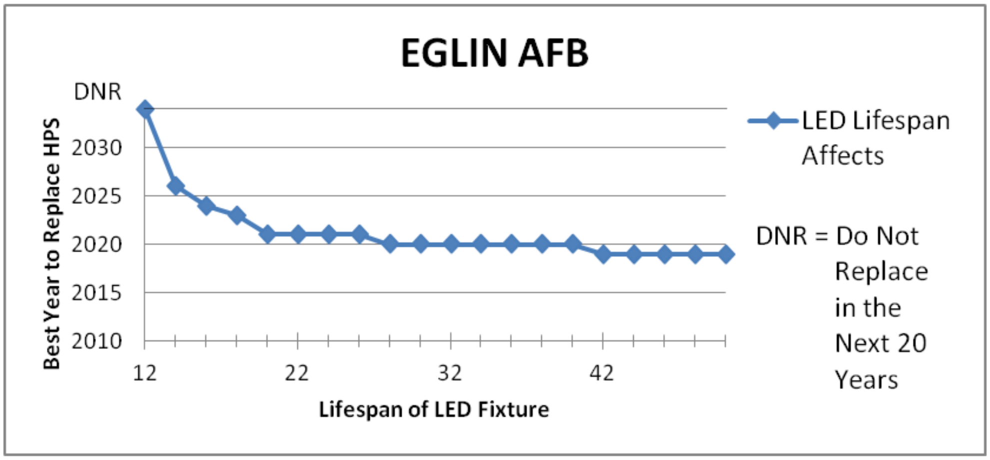

Figure 13. Eglin AFB Sensitivity on LED Lifespan

As seen if Figure 14, ranging the expected lifespan of HPS bulbs from 4 to 9 years had no effect on the year LED streetlights become more cost effective. However, the best year to install LED streetlights becomes 1 to 2 years sooner as the lifespan of HPS range from 1 to 3 years.

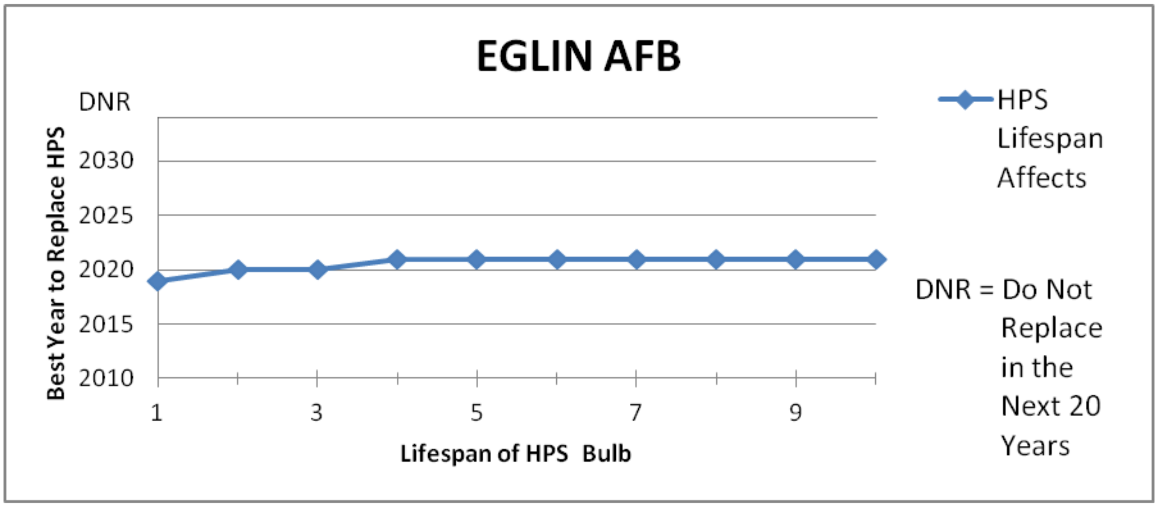

Figure 14. Eglin AFB Sensitivity on HPS Lifespan

This research assumed LED streetlights would have to output as many lumens as HPS streetlights to achieve a one-for-one replacement. However, there are several arguments, such as LEDs have a more uniform light dispersion and a better color quality, which suggests less lumens may be acceptable for LED replacements for HPS. Figure 15 shows the effects on the results if reduced luminous intensity is accepted by Eglin AFB. As shown, this factor can have a significant effect on the most desirable year for adopting LED lamps; however, regardless of the required luminous output, it is still advantageous to wait at until 2016 before replacing HPS with LED streetlights.

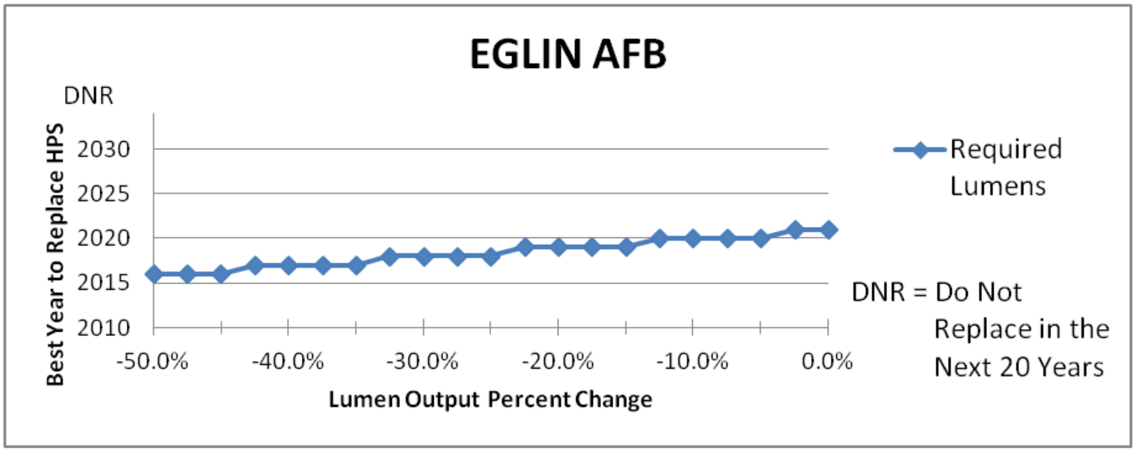

Figure 15. Eglin AFB Sensitivity on Lumen Output

Fairchild AFB

As shown in Figure 16, the results for Fairchild AFB, are quite different from Eglin AFB. The NPV for the LED lamps decreases relatively rapidly after 2013 for this base as well, but due to the relatively low cost of energy at this base, 0.030 dollars per kWh at Fairchild as opposed to 0.093 dollars per kWh at Eglin, the NPV for the LED replacement remains higher than the NPV for the HPS baseline over the entire lifespan of this analysis. As a result, LED replacement should not be considered at Fairchild AFB even after 21 years as HPS is projected to be more cost effective than LED over the entire time horizon.

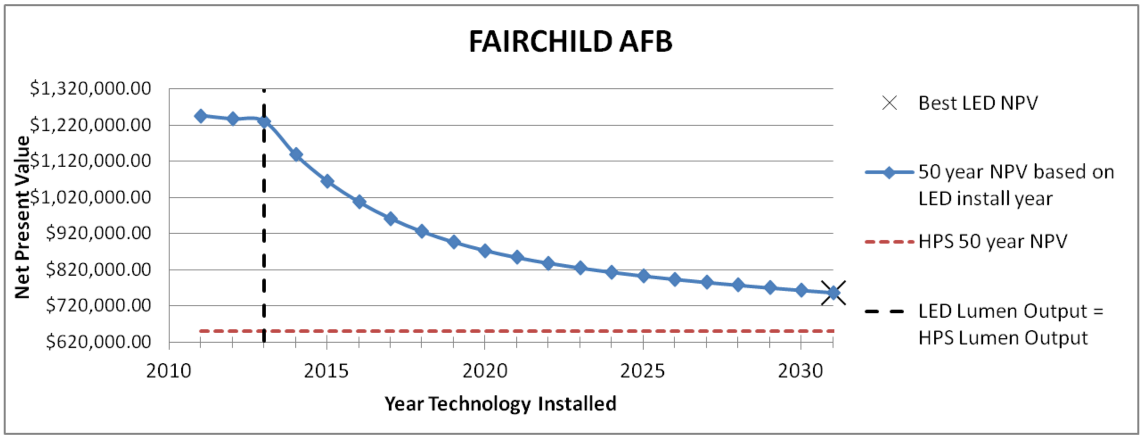

Figure 16. Best Year to Install LED 250 watt Streetlights at Fairchild AFB

Fairchild can see possible financial advantages in installing LEDs if the non-LED portion of the fixture decreases at a rate of 2 percent of more, as shown in Figure 17. However, even at a 20% annual reduction in the non-LED portion of the LED fixture, it is not until 2024 that the LED install becomes advantageous.

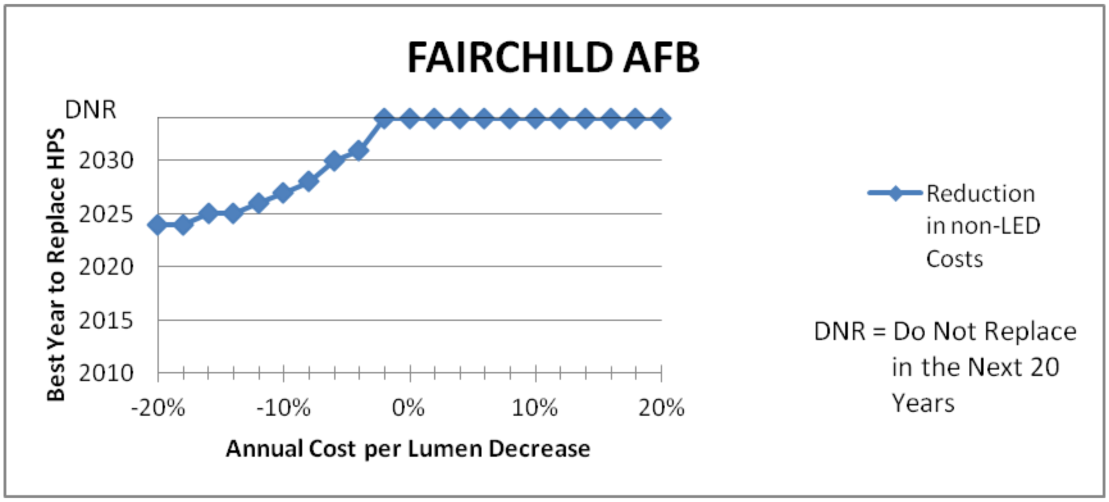

Figure 17. Fairchild AFB Sensitivity on Price for Non-LED Parts

Clear AFS

Clear Air Force Stations (AFS) had the highest electricity rate of any installation studied, 0.292 dollars per kWh. As seen in Figure 18, Clear AFS has the potential for significant cost savings if LEDs are installed immediately. Additionally, waiting to year 2016 will only save 2.45 percent compared to changing to LED streetlights in 2011.

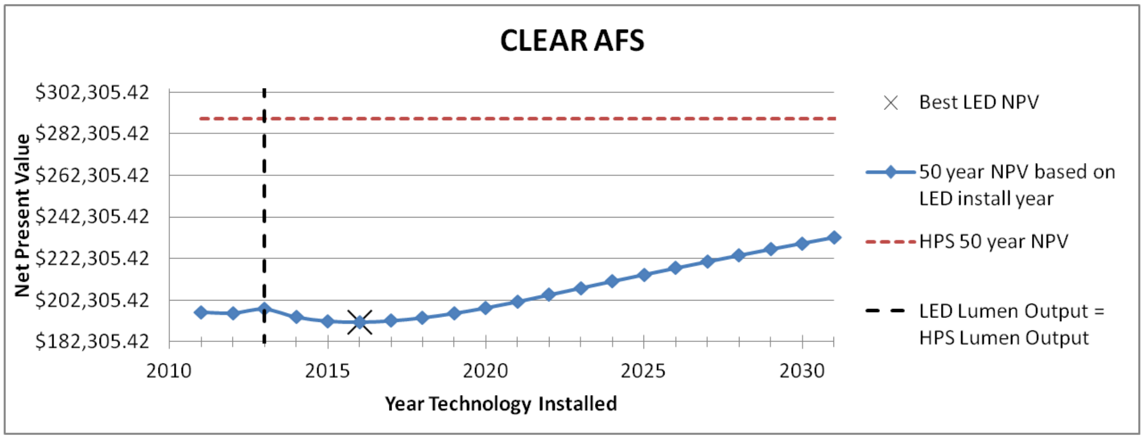

Figure 18. Best Year to Install LED 250 watt Streetlights at Clear AFS

Ranging labor rate, utility rate, and initial fixture cost by positive to negative 50 percent had relatively little change on the most cost effective year to replace HPS at Clear AFS, as seen in Figure 19. Ranging the max efficacy achievable from negative 45 to 50 percent saw a 10 year change in the best year to install LED, 2021 to 2031.

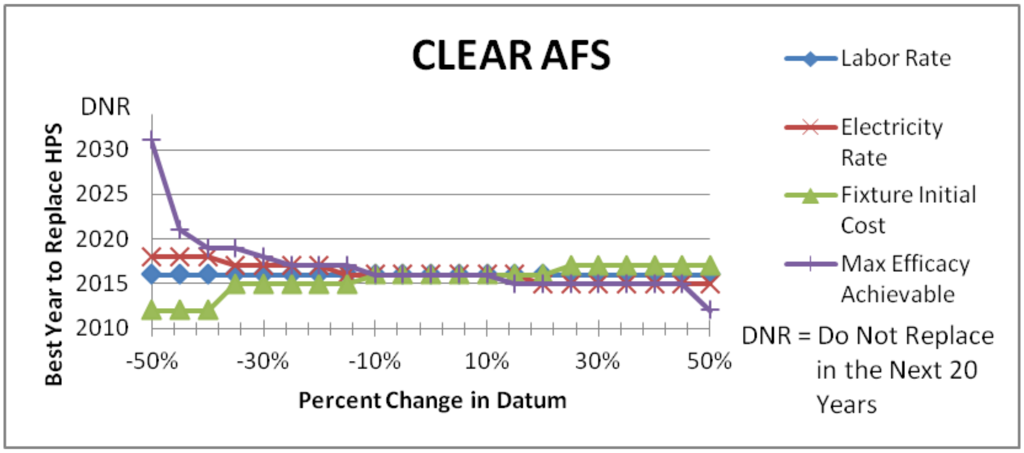

Figure 19. Clear AFS Sensitivity on Main Variables

Goodfellow AFB

Goodfellow AFB had the lowest labor rate, at 22.25 dollars per hour. It is important to note, Goodfellow AFB also had a relatively low electricity rate, at 0.053 dollars per kWh. As shown in Figure 20, LED replacement of HPS is not predicted to have cost savings at anytime during the next 21 years.

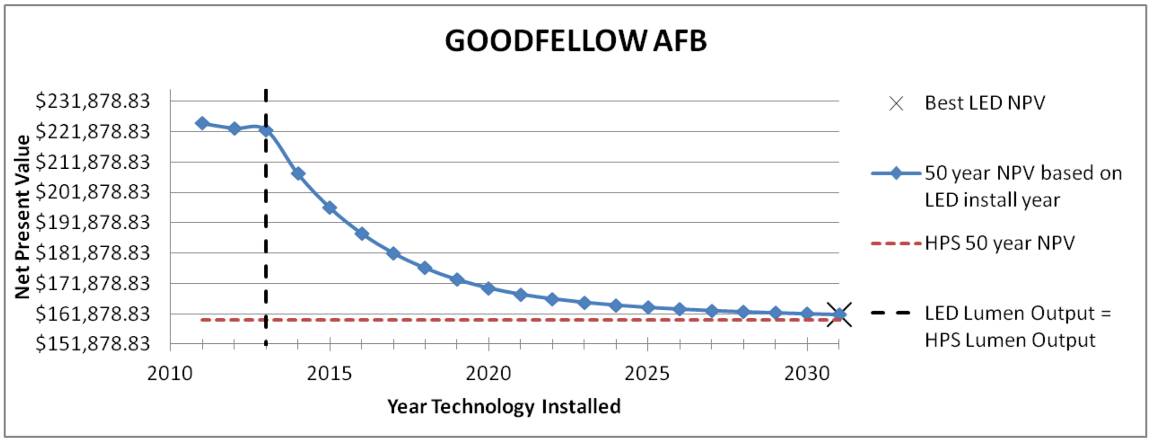

Figure 20. Best Year to Install LED 250 watt Streetlights at Goodfellow AFB

With any decrease in LED initial fixture cost, LEDs become financially beneficial at Goodfellow AFB, see Figure 21. Additionally, if the electricity rate increases as little as 5 percent or more, Goodfellow should consider HPS replacement with LEDs. Ranging labor rate had no impact on the results.

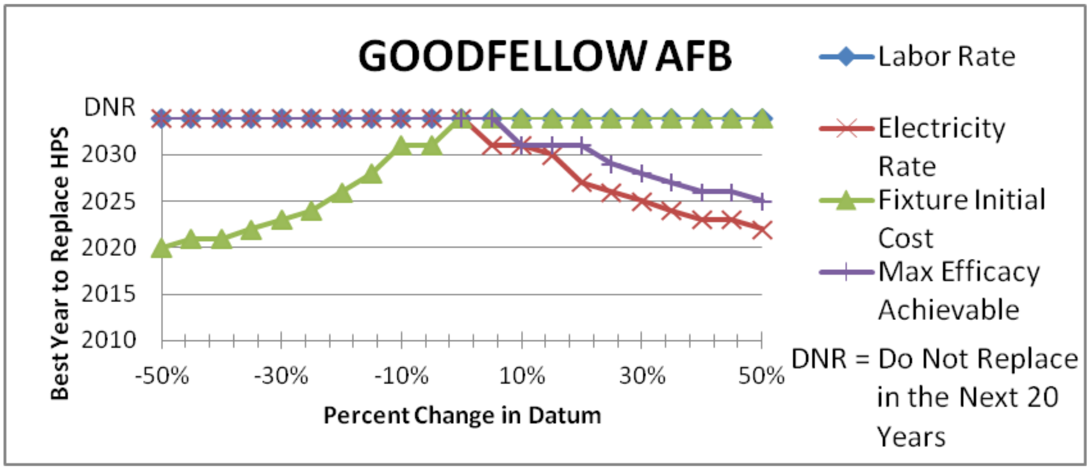

Figure 21. Goodfellow AFB Sensitivity on Main Variables

LED lifespan had a larger effect on the best year to replace HPS streetlights at Goodfellow AFB than at any other installation, shown in Figure 22. Assuming significant advances in LEDs' lifespan, Goodfellow AFB may be capable of seeing the best financial benefit of replacing its HPS streetlights occurring in 2023.

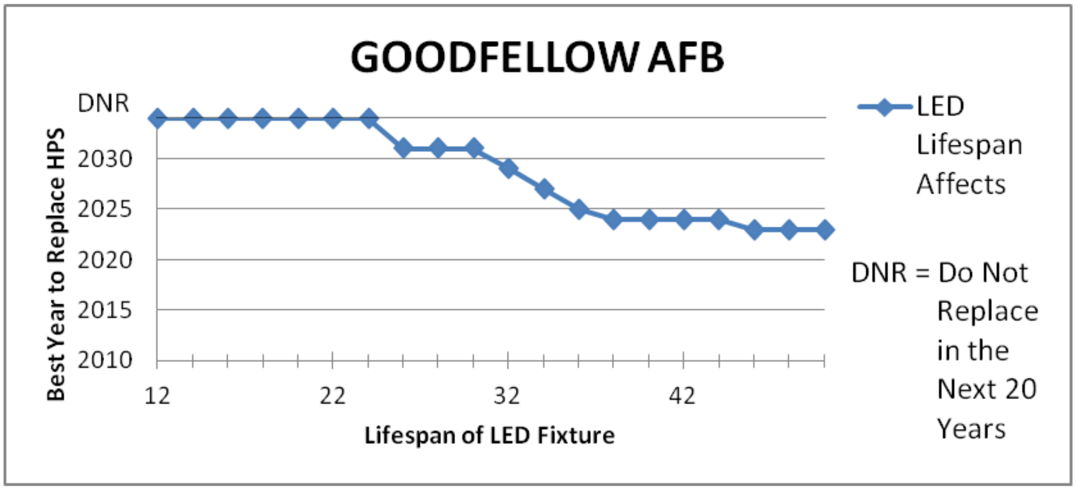

Figure 22. Goodfellow AFB Sensitivity on LED Lifespan

If the required lumen output for LED streetlights is accepted to be half the equivalent HPS streetlight, Goodfellow AFB may see the most financial benefit from replacing HPS in 2020, see Figure 23.

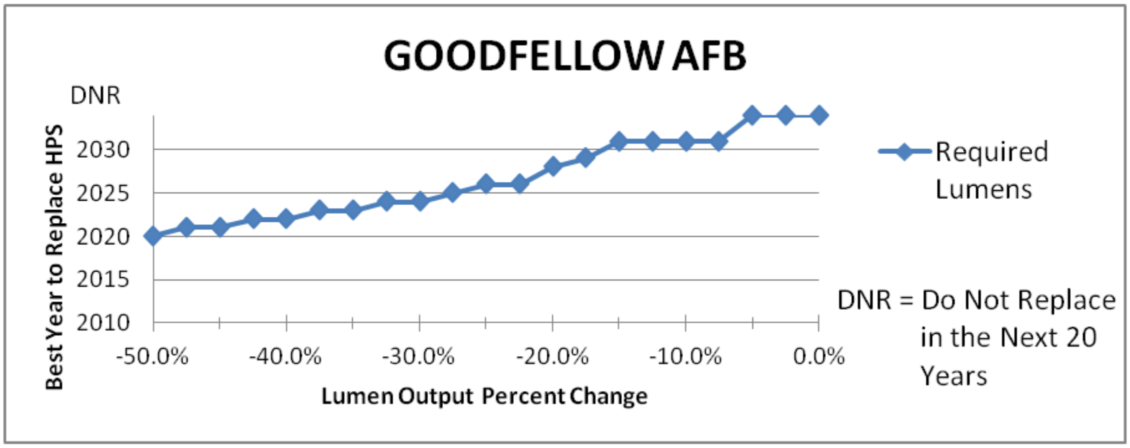

Figure 23. Goodfellow AFB Sensitivity on Lumen Output

Los Angeles AFS

Los Angeles AFS had the highest labor rate, at 112 dollars an hour. The electricity rate was slightly higher than average at .116 dollars per KHW. Shown in Figure 24, significant cost advantages can be achieved by immediately replacing HPS with LED streetlights. However, an additional 11.09 percent can be saved if replacement is delayed to 2019. Sensitivity analyses showed little change in the best year to replace HPS streetlights compared to the installations discussed earlier.

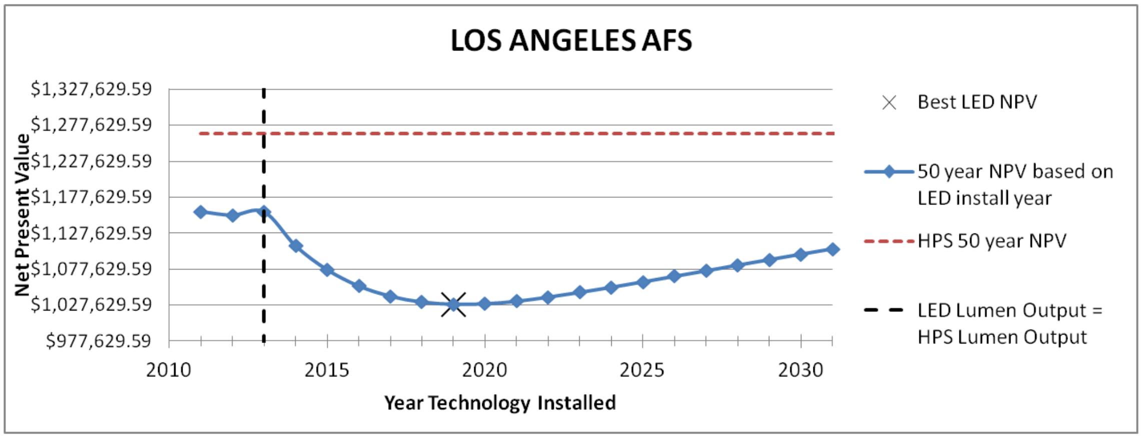

Figure 24. Best Year to Install LED 250 watt Streetlights at Los Angeles AFS

McConnell AFB

McConnell AFB had labor rate of 56.01 dollars per hour, close to the average of the 64 installations studied. Additionally, McConnell had one of the lowest utility rates, at 0.035 dollars per kWh. As seen in Figure 25, replacing HPS with LED streetlights is not predicted to have cost savings at anytime during the next 21 years

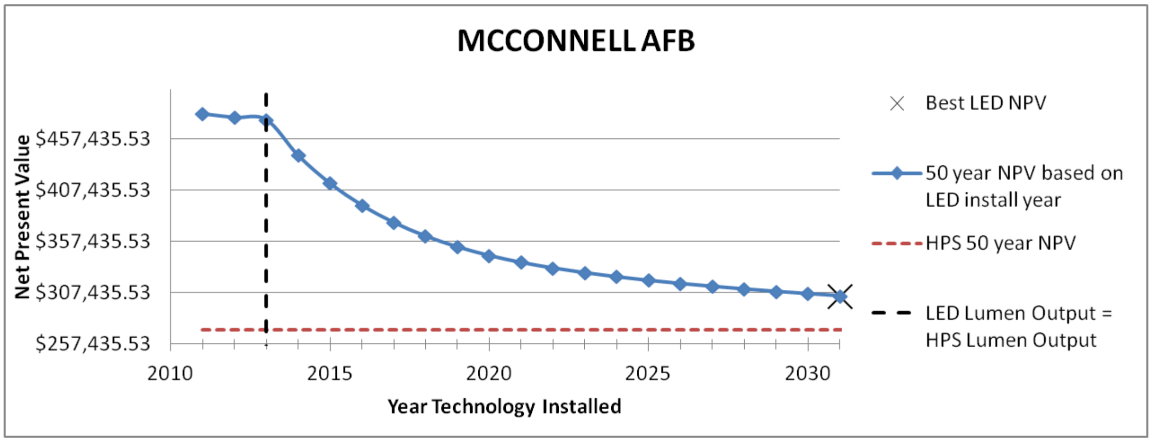

Figure 25. Best Year to Install LED 250 watt Streetlights at McConnell AFB

Potential Significant Relationships

This study did not conduct a complete statistical regression analysis of the variables used in this study. However, a strong nonlinear relationship appears to exist between electricity rate and the best year to replace HPS streetlights as shown in Figure 26 and Figure 27. This relationship only includes the 48 installations for which the results supported LED replacement of HPS in the next 21 years.

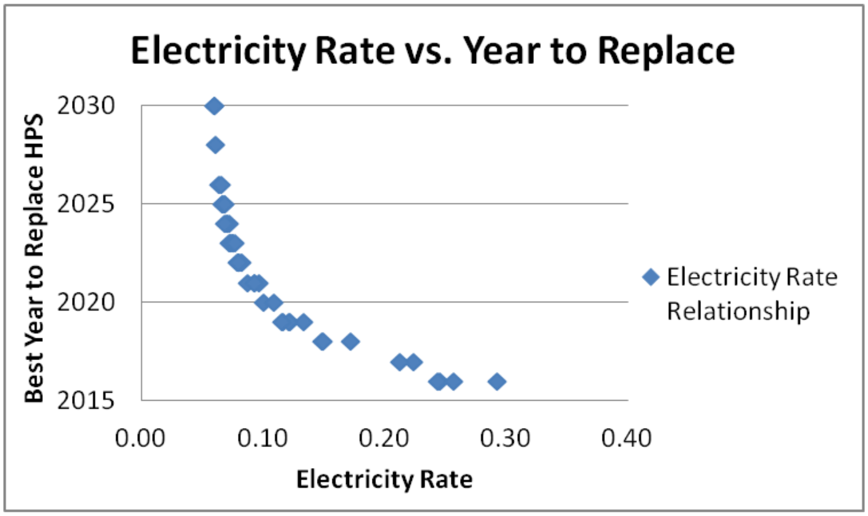

Figure 26. Electricity Rate vs. Best Year to Replace HPS

If the relationship between electricity rate and the best year to replace HPS streetlights is supported, it may be possible to provide Air Force energy managers with a tool to predict the best year to change to LED streetlight technology. Figure 27 shows the best year to replace a lamp as a function of the reciprocal of the electricity rate. As shown, the resulting function can be fit with a linear equation which predicts about 90 percent of the variability in the data. The resulting linear equation provides one possible relationship between electricity rate and the year to replace HPS, which could be used by energy managers to estimate the preferred year for installation of 250 LED street light fixtures.

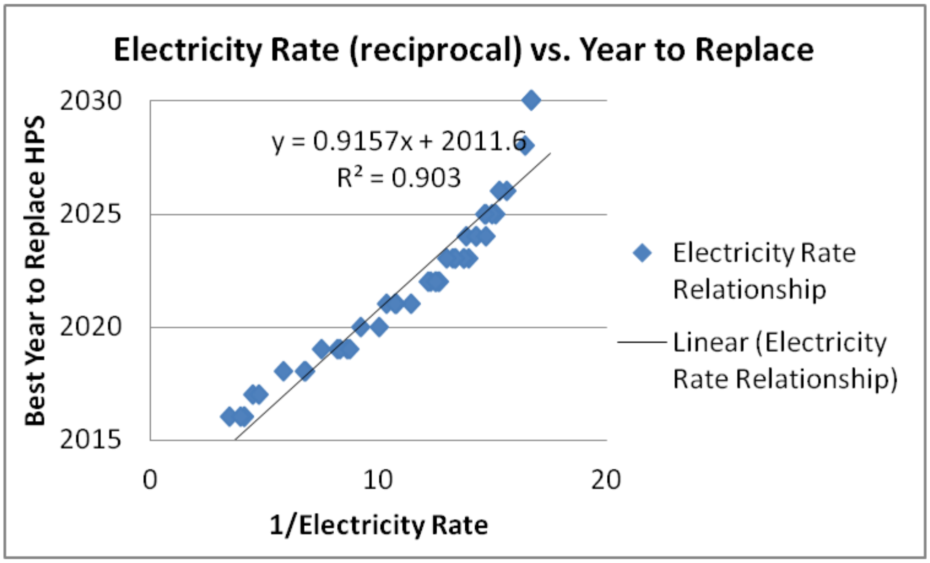

Figure 27. Reciprocal of Electricity Rate vs. Best Year to Replace HPS

V. Conclusions and Recommendations

The researchers conducting this study sought to implement a case study where a new cost analysis method, time-valued-technology, could be implemented. Time-valued-technology was created in an attempt to include predictions in emerging technology improvements into a cost analysis. This chapter concludes the findings in this case study and recommends actions and future research for the Air Force.

Conclusions

Through the application of time-valued-technology, the average Air Force installation was shown to save around 7 percent in life-cycle-cost when compared to methods that replace LEDs as soon LED lamps become cost effective. At 48 installations, the time-valued-technology methodology provides a potential benefit for evaluating the adoption of the rapidly changing LED technology over other economic evaluation methods. This method is preferred because it permits the adoption of a rapidly-changing technology to be delayed until the technology has matured to provide the largest economic benefit. Although not shown, such delays can have other benefits, due to the standardization and experience curves for such an evolving technology that are not considered within the economic evaluation method.

While this research demonstrated a possible improvement in financial decision making for 48 installations, given the current assumptions, this evaluation supported the decision not to replace existing HPS with LED lamps at 16 installations for the foreseeable future. It is believed any relevant lifecycle analysis would have supported this same decision. While care was taken to make reasonable assumptions, regarding the costs associated with this decision, it is possible that a change in assumptions would significantly affect the outcome.

The sensitivity analysis indicated that the most sensitive factors affecting the outcome of this analysis were the installation's electricity rate and LED fixture cost. Changes in other variables, specifically Haitz's Law and the required luminous output, also affected the outcome at several installations. It is important to note that 2016 was the earliest year LED installation was recommended for any US Air Force installation. However, the percent savings from waiting to install LEDs range from 1.1 to 14.15 percent. Therefore, the accuracy of the forecasts used in the cost analyses may not justify waiting to install LEDs at the installations with lower predicted savings, especially in an environment where the benefits of energy savings may not be fully reflected by financial metrics.

Significance of Research

This research demonstrated that in infrastructure cost analyses there are possible financial benefits for including the predicted improvements in a technology. As infrastructure continues to include rapidly changing and long lasting technologies the need to understand the best time to replace legacy systems will exist. The method used in this research can help decision-makers invest in replacing an emerging infrastructure technology at the optimal time, not just at the first sign of benefit.

Recommendations for Action

The researchers recommended the Air Force use this analysis, or method, in forecasting the best year to invest in LED streetlight technology. This method not only has the potential to save the Air Force money, it can help the Air Force plan for large infrastructure investments. Additionally, after finding the best year to replace LED streetlights at each installation, the Air Force will be able to predict the total number of lights that should be replaced across the Air Force each year. This could significantly benefit the Air Force's strategic sourcing initiative, reducing the overall cost by purchasing in bulk. It should additionally be recognized that the benefit of LED technology is highly dependent upon the lifetime of the fixtures and therefore, care must be taken to identify reliable suppliers that provide quality products that are capable of obtaining the desired lifetime within the environment the lamp is employed.

Recommendations for Future Research

Future research should investigate the statistical relationships of the variables used in this study. If possible, a tool could then be developed to permit installation energy managers to predict the most financially beneficial year to replace HPS streetlights with LEDs without having to conduct a full time-valued-technology cost analysis. Future research should also consider the impacts of sunk costs and how this analysis could change if conducted at different initial years.

The researchers in this study assumed financial savings was the most important factor to optimize when using time-valued-technology. However, a decision-maker may be more concerned with optimizing other resources, such as energy. Additional research should find the year to install LEDs that would save the most energy. These results can then be compared to the financial optimization conducted in this research. Adjusting the method of time-valued-technology, where a decision-maker’s most important resource is used most efficiently, can provide a more practical tool to the user.

Appendix A

Air Force Installation	MAJCOM	Labor Rate ($/hr)	Utility Rate ($/KWH)	TOTAL Fixtures
BARKSDALE AFB	ACC	69.18	0.0500	148
BEALE AFB	ACC	74.45	0.0662	1571
DAVIS MONTHAN AFB	ACC	50.87	0.0722	396
DYESS AFB	ACC	42.00	0.0800	500
ELLSWORTH AFB	ACC	39.76	0.0402	239
HOLLOMAN AFB	ACC*	50.50	0.0796	262
LANGLEY AFB	ACC*	55.36	0.0680	403
MINOT AFB	ACC*	72.00	0.0400	125
MOODY AFB	ACC*	63.16	0.0667	263
MT HOME AFB	ACC*	56.48	0.0334	300
NELLIS AFB	ACC*	68.26	0.0718	287
OFFUTT AFB	ACC*	41.42	0.0330	463
SEYMOUR JOHNSON AFB	ACC*	62.93	0.0730	542
WHITEMAN AFB	ACC*	71.11	0.0502	126
USAF ACADEMY	ACD*	42.00	0.0524	61
ALTUS AFB	AETC*	31.58	0.0700	1057
COLUMBUS AFB	AETC*	42.00	0.0600	34
GOODFELLOW AFB	AETC*	22.25	0.0527	91
KEESLER AFB	AETC*	42.00	0.0750	1004
LACKLAND AFB	AETC*	53.80	0.0682	1593
LAUGHLIN AFB	AETC*	42.00	0.1223	1160
LUKE AFB	AETC*	42.00	0.0598	964
RANDOLPH AFB	AETC*	42.00	0.0600	175
SHEPPARD AFB	AETC*	42.00	0.0967	600
TYNDALL AFB	AETC*	54.00	0.1000	9
VANCE AFB	AETC*	42.00	0.0358	4
ANDREWS AFB	AFDW	58.99	0.0875	1551
BOLLING AFB	AFDW	81.30	0.1480	237
EDWARDS AFB	AFMC	52.51	0.0610	435
EGLIN AFB	AFMC	51.56	0.0930	250
HANSCOM AFB	AFMC	62.25	0.1490	261
HILL AFB	AFMC	47.75	0.0480	650

Air Force Installation	MAJCOM	Labor Rate ($/hr)	Utility Rate ($/KWH)	TOTAL Fixtures
KIRTLAND AFB	AFMC	48.32	0.0730	406
ROBINS AFB	AFMC	43.90	0.0640	600
CANNON AFB	AFSOC*	42.00	0.0653	736
HURLBURT FLD	AFSOC*	76.00	0.0933	963
BUCKLEY AFB	AFSPC	43.81	0.0790	429
CAPE CANAVERAL	AFSPC	54.26	0.0700	200
CAVALIER AFS	AFSPC	64.90	0.0430	9
CHEYENNE MTN AFB	AFSPC	42.76	0.0470	6
CLEAR AFS	AFSPC	83.86	0.2920	30
LOS ANGELES AFS	AFSPC	112.00	0.1160	316
MALMSTROM AFB	AFSPC*	48.58	0.0815	1123
SCHRIEVER AFB	AFSPC	62.52	0.0754	340
THULE AB	AFSPC	75.00	0.2455	119
VANDENBERG AFB	AFSPC	42.00	0.0822	1559
CHARLESTON AFB	AMC	55.25	0.0800	186
FAIRCHILD AFB	AMC	66.95	0.0303	576
GRAND FORKS AFB	AMC*	73.00	0.0493	316
MCCHORD AFB	AMC*	69.81	0.0390	664
MCCONNELL AFB	AMC	56.01	0.0348	217
MCGUIRE AFB	AMC*	52.37	0.1335	415
SCOTT AFB	AMC	47.80	0.0750	511
TRAVIS AFB	AMC	77.53	0.0681	519
ANDERSEN AFB	PACAF*	52.00	0.2237	1054
EARECKSON	PACAF*	90.00	0.2437	90
EIELSON AFB	PACAF*	65.57	0.1721	1049
ELMENDORF AFB	PACAF*	77.74	0.0570	915
HICKAM AFB	PACAF*	65.00	0.2125	344
KADENA AB	PACAF*	42.00	0.1210	106
KING SALMON	PACAF*	90.00	0.2570	150
KUNSAN AB	PACAF*	44.09	0.0770	250
MISAWA AB	PACAF*	34.42	0.1084	358
YOKOTA AB	PACAF*	44.98	0.1150	85

*Data taken from 2009 survey

Appendix B

BetaLED Streetlights Specifications used in Study (LEDway® Streetlights, 2011)

Beta LED Street Light Model Number	Downward Lm	Watts	Efficacy
STR_LWY_1S_XX_12_D_XX_XX_700	23652	272	86.96
STR_LWY_1S_XX_12_D_XX_XX_700_43k	21799	272	80.14
STR_LWY_2M_XX_12_D_XX_XX_700	20013	272	73.58
STR_LWY_2M_XX_12_D_XX_XX_700_43K	18445	272	67.81
STR_LWY_2MB_XX_12_D_XX_XX_700	15075	272	55.42
STR_LWY_2MB_XX_12_D_XX_XX_700_43K	13894	272	51.08
STR_LWY_2MP_XX_12_D_XX_XX_700	17674	272	64.98
STR_LWY_2MP_XX_12_D_XX_XX_700_43K	16289	272	59.89
STR_LWY_2S_XX_12_D_XX_XX_700	21,313	272	78.36
STR_LWY_2S_XX_12_D_XX_XX_700_43K	19643	272	72.22
STR_LWY_2SB_XX_12_D_XX_XX_700	16374	272	60.20
STR_LWY_2SB_XX_12_D_XX_XX_700_43K	15091	272	55.48
STR_LWY_2SP_XX_12_D_XX_XX_700	18974	272	69.76
STR_LWY_2SP_XX_12_D_XX_XX_700_43K	17487	272	64.29
STR_LWY_3M_XX_12_D_XX_XX_700	18974	272	69.76
STR_LWY_3M_XX_12_D_XX_XX_700_43K	17487	272	64.29
STR_LWY_3MB_XX_12_D_XX_XX_700	14035	272	51.60
STR_LWY_3MB_XX_12_D_XX_XX_700_43K	12935	272	47.56
STR_LWY_3MP_XX_12_D_XX_XX_700	16634	272	61.15
STR_LWY_3MP_XX_12_D_XX_XX_700_43K	15331	272	56.36
STR_LWY_4M_XX_12_D_XX_XX_700	20013	272	73.58
STR_LWY_4M_XX_12_D_XX_XX_700_43K	18445	272	67.81
STR_LWY_4MB_XX_12_D_XX_XX_700	15075	272	55.42
STR_LWY_4MB_XX_12_D_XX_XX_700_43K	13894	272	51.08
STR_LWY_5M_XX_12_D_XX_XX_700	21053	272	77.40
STR_LWY_5M_XX_12_D_XX_XX_700_43K	19403	272	71.33
Average	17653.92	272	64.90

AEL Streetlights Specifications used in Study (American Electric, 2011)

AEL LED Street Light Model Number	Downward Lm	Watts	Efficacy
ATB1_60LED_E70_MVOLT_R3	11950.65	144.50	82.70
ATB1_60LED_E70_MVOLT_R2	11724.71	144.50	81.14
ATB1_60LED_E70_MVOLT_R3_5K	12915.00	144.00	89.69
ATB1_60LED_E70_MVOLT_R2_5K	12672.70	144.00	88.00
Average	12315.77	144.25	85.38

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14. ABSTRACT

Infrastructure projects have typically involved long-term investments in relatively mature technologies characterized by stable performance and cost. However, with the ever-increasing rate of technological innovation, an increasing number of potential infrastructure investments involve a decision to replace a traditional technology with a rapidly evolving technology. In such circumstances, it is possible to reap significant performance or cost advantages through near-term replacement. However, this rapid adoption strategy has the potential to incur an opportunity cost due to increased performance or cost advantages the technology would provide if replacement was delayed. This research develops a cost analysis method, referred to as time-valued-technology, which may be useful in developing a strategic approach to the replacement of infrastructure with a rapidly emerging technology. The utility of this method is illustrated through an evaluation of replacement of the 250-watt streetlight fixtures on 64 United States Air Force installations with light-emitting diode based technology. Potential financial savings in implementing time valued technology over existent methods ranged from 1.10 to 14.15 percent per installation, averaging 6.77 percent.

15. SUBJECT TERMS
Light-Emitting Diode, Cost Analysis, Infrastructure, Streetlight

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