



**REDUCING ENERGY CONSUMPTION IN EXISTING FACILITIES THROUGH
RETROFIT PRIORITIZATION IMPROVEMENTS**

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Jay Calvo, Captain, USAF

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Global Vigilance, Reach, and Power at home and abroad require vast amounts of energy—whether it is fuel for our aircraft, gas for our vehicles, or electricity for our space and cyberspace efforts. As the largest energy user in the federal government, the Air Force must find ways to reduce our energy consumption, especially given the current economic environment. To ensure Airmen always have reliable, secure access to energy when and where the mission requires, we will pursue an energy posture that is resilient, robust, and ready to support our global missions.

– Secretary of the Air Force Michael Donley

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Jay Calvo

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Abstract

The United States Air Force spent \$126M on facility energy in fiscal year (FY) 2014 and that cost continues to rise and be a larger part of the annual budget. Additionally, the Energy Independence and Security Act of 2007 mandated that the Air Force reduce energy intensity 30% by 2015 compared to a 2003 baseline which the Air Force has not met. This necessitates a more in-depth examination of technologies capable of reducing energy consumption in existing facilities for the broad range of climates the Air Force operates in. This research provides energy retrofit recommendations for existing facilities and examines the method the Air Force uses to prioritize energy projects.

This study simulates eight different retrofit technologies and eight different locations with the enhanced Quick Energy Simulation Tool (eQUEST) to establish retrofit recommendations tailored to Air Force facility parameters and the different climate zones. A life-cycle cost analysis is also performed to compare the Air Force's prioritization method to an industry standard method and determine which prioritization method provides the greatest return on investment (ROI). Results indicate that the best retrofit technology for existing facilities is highly dependent on climate. Additionally, it was shown that the Air Force prioritization method was inconsistent when compared to the industry standard method. Finally, the inconsistencies with the Air Force prioritization method resulted in ROIs that were significantly lower when compared to the industry standard methods. The Air Force can use these results to transition away from one-size-fits-all retrofits for existing facilities and a poor prioritization method.

Acknowledgments

I would like to thank my family, whose motivation has allowed me to succeed through all endeavors, regardless of the distance between us.

I would like to thank my friends, whose support has helped shape me and this product into something better than when it started.

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REDUCING ENERGY CONSUMPTION IN EXISTING FACILITIES THROUGH RETROFIT PRIORITIZATION IMPROVEMENTS

Chapter 1. Introduction

According to the United States Energy Information Administration, the United States (U.S.) consumed 97.3 quadrillion British Thermal Units (BTUs) of energy in 2010 and was the largest energy consumer at 19.2% of the total world consumption (EIA, 2008). To decrease the amount of energy consumed, one military branch within the U.S. government has implemented an energy management program aimed at “developing, executing, and overseeing plans, programs, and initiatives to achieve energy goals and objectives across all functional areas” (SAF/IE, 2013). Federal policies supporting the energy management program include the Energy Policy Act of 2005, the Energy Independence and Security Act (EISA) of 2007, Executive Order (EO) 13123, and EO 13693. EISA in particular was significant due to the number of issues it addressed; its purpose was 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...and to improve the energy performance of the Federal Government” (EISA, 2007). All of the policies combine to paint a clear picture that the United States government is taking energy efficiency, independence, and security seriously.

There is also a global desire to decrease energy consumption. Between 1984 and 2004, energy consumption increased 49% and major initiatives have been proposed by

countries in Asia, Europe, and South America to slow that increase (Pérez-Lombard, Ortiz, & Pout, 2008). Asian countries have proposed over \$10 billion in financial support for renewable energy as well as government subsidies as high as 70% for certain projects (Hua, Oliphant, & Jing, 2016). In 2010, the European Commission created a strategy to reduce energy consumption 20% by 2020 which includes readily available and cost effective technologies (European Commission, 2010; Wade, Pett, & Ramsay, 2003). Even South America, which has problems securing reliable energy supplies, chose to increase renewable energy supplies, including a 133% increase in renewable energy between 2008 and 2009 (Arriagada, 2010; de Oliveira, 2010).

However, energy efficiency is not a task being undertaken solely by governments. The civilian sector has also contributed greatly to reducing energy consumption by developing energy efficient technologies and strategies for different climates. Additionally, the civilian sector has developed proven methods to prioritize retrofits that reduce energy consumption in existing facilities and provide a return on investment (Ma et al., 2012). To reduce energy consumption within the military in a cost effective manner, the Department of Defense (DoD) could benefit by incorporating the contributions from the civilian sector has provided into its energy management program. One of the most promising contributions that could be incorporated is the work being done to retrofit existing facilities.

Background

Retrofitting an existing facility is more difficult than installing energy efficient technology during construction because a retrofit must work within the constraints of the

existing facility (Asadi et al., 2014; Ma et al., 2012). Despite the difficulties, strategies have been developed to reduce energy consumption in existing facilities by more than 40% (Griego, Krarti, & Hernandez-Guerrero, 2015). These strategies range from creating simulations prior to any retrofits are started to commissioning and auditing after retrofits are completed (DOE, 2010; Kadlubowski & Yates, 2009; Mills, 2009). Regardless of the strategy, all retrofits benefit from energy efficient technologies such as upgrades to lighting and Heating, Ventilation, and Air Conditioning (HVAC) systems that decrease energy consumption (Roisin et al., 2008; Wang et al., 2013). However, an effective retrofit that can simultaneously decrease energy consumption and provide a return on investment (ROI) is dependent on both the climate and the cost of energy.

Recent studies have indicated that different technologies operate better in different climates. Karabay and Arıcı (2012) found that climates identified as cold by a Turkish researcher justify retrofitting facilities with quadruple-pane windows. Other studies have found that HVAC systems, roofs, wall insulation, and even floor slabs should be based on the climate of the facility (Baecheler et al., 2010; Wang et al., 2013; Yu et al., 2015). Additionally, the cost of energy is an important consideration for retrofits because of its effect on the ROI. Although there are many different methods to determine ROI for energy retrofits (e.g., levelized cost, net present value, and benefit cost ratios), each one incorporates the cost of energy (Emhjellen & Alaouze, 2003; Eschenbach, 2010).

Due to the way energy retrofits interact with each other, even with known ROIs, selecting one energy retrofit from several or determining the sequential order of the retrofits depends on the prioritization method (Ma et al., 2012). Some prioritization

methods such as the Office Rating Methodology focus on minimizing environmental impacts (Roulet et al., 2002). Other prioritization methods focus on reducing energy consumption or reducing costs (Emhjellen & Alaouze, 2003; Juan, Gao, & Wang, 2010). Currently, the method the Air Force uses to prioritize energy projects is based on costs but may be biased towards project size; however, as the largest energy consumer within the military at 48% of the total Department of Defense (DoD) consumption, the Air Force should focus on prioritization methods that maximize ROI to fund additional projects (SAF/IE, 2013).

Maximizing ROI creates funding for additional retrofits to address the gap between mandated energy reduction goals and actual energy usage. As an example, in fiscal year (FY) 2013, the federal government consumed 321 trillion BTUs of energy at a cost of \$6.13 billion (DOE, 2014). Those numbers are an improvement compared to the 2003 baseline of 376 trillion BTUs but still not enough to meet Executive Order (EO) 13423 which mandated a 30% improvement in energy efficiency and a reduction in the carbon footprint by 2015 (Bush, 2007). While energy consumption and carbon footprint are not exactly proportional, studies have found a causal relationship between the two (Soytas, Sari, & Ewing, 2007; Wang, Chen, & Kubota, 2015).

To meet all of the energy efficiency and carbon footprint reduction requirements, the federal government allowed each federal agency to determine the best method to do so for itself. In turn, the DoD tasked each individual service component, the Army, Air Force, Navy, and Marines, to formulate plans to reduce their energy consumption. With 52% of the energy costs within the DoD, this affected the Air Force harder than the other services (SAF/IE, 2013). While a majority of the \$9 billion annual energy bill comes

from aviation fuel, 16% comes from facilities (SAF/IE, 2013). With an average facility age of 32.5 years, any decrease to that 16% would come through efficiently improving the building profiles of existing facilities and not new construction (Byers, 2010; Ma et al., 2012).

Additionally, the military, to include the Air Force, is unique in the fact that it operates across the globe. The Air Force has 189 active operating locations scattered across 16 different countries and all 50 states (Goode, 2009), over a variety of drastically different climate. With such variations in climate, an energy retrofit project designed to work efficiently at one location or facility does not have the same results or benefits at a different location in a different climate. Another attribute unique to the Air Force is that Air Force office buildings are often one-tenth the size of typical civilian office buildings and may not benefit from the same economy of scale found in previously conducted studies (Byers, 2010). This necessitates that energy retrofit projects be tailored to not just the Air Force parameters of the facility but also the climate within which that facility is operating.

Considering the age and climates of Air Force facilities, several different energy retrofits are capable of reducing energy consumption, ranging from upgrading lights with more efficient bulbs to installing new windows or HVAC systems (Chen, 2007; Soori & Vishwas, 2013; Wang et al., 2013). However, the Air Force does not have unlimited funds, so the costs of these energy retrofits are a factor. “Energy is becoming a larger share of the Air Force budget, going from three percent of the total Air Force budget in 2003 to over eight percent in 2011” (SAF/IE, 2013) and that cost continues to increase. The increase in energy costs for the Air Force necessitates a method to prioritize energy

retrofit projects in a manner that maximizes available funds with the optimal ROI. However, the current method of prioritization may be too heavily weighted towards project size and not ROI.

Problem Statement

Compared to the civilian sector, the Air Force has not thoroughly addressed energy efficiency in existing facilities. Private companies invest about 4% of their budget to renewing infrastructure, which includes energy retrofits, as opposed to the Air Force which only invests 1% (Eyring, 2013). Additionally, according to the United States Green Building Council, the organization responsible for certifying facilities as meeting Leadership in Energy and Environmental Design (LEED) levels, the Air Force has 159 LEED certified facilities but only one certification is for an existing building; this represents less than 1% of Air Force LEED certifications (USGBC, 2015). Within the private sector, LEED certifications on existing facilities account for almost 10% of all certifications (USGBC, 2015). The Air Force needs to address existing facilities by knowing what energy retrofit technologies are most capable of reducing energy consumption in different climates as well as how to prioritize those retrofits to maximize the return on investment.

Research Question

The research focused on two different areas: identifying energy efficient retrofit technologies and prioritizing retrofits in a manner that maximizes ROI. With the premise of increasing cost savings Air Force wide, the following research question was proposed: How can the Air Force save money with respect to its energy management program?

Investigative Questions

To address the overarching research question, the following investigative questions were developed:

1. Which currently available energy retrofit technologies reduce energy consumption the most in existing facilities?
2. How does location and climate affect the energy reduction of the currently available retrofit technologies?
3. Is there a significant difference between Air Force and industry standard prioritization methods for energy projects and does one of them offer a better ROI?

Methodology

Investigative questions one and two were answered by modeling a ‘prototypical Air Force building’ and simulating the different available energy retrofit technologies using the enhanced Quick Energy Simulation Tool (eQUEST). The simulation results were then compared to demonstrate which technologies perform better in reducing energy consumption in existing facilities. Additionally, by running the same simulation multiple times and changing the facility location parameter within the model, eQUEST can also demonstrate how climate affects the performance of different energy retrofit technologies. Eight locations were chosen to be representative of eight different climate zones and limit the number of simulations that were run. The final investigative question was answered by performing a cost analysis on each technology and assuming each one was a separate energy retrofit project. Those projects were then prioritized using the current Air Force method and other prioritization methods to determine which method is better suited to increasing cost savings and ROI.

Assumptions/Limitations

There are several assumptions and limitations associated with this research effort. The first assumption is that the prototypical building parameters provided by the Air Force Civil Engineer Center (AFCEC) are representative of the Air Force office building inventory. An additional assumption is that retrofits are mutually exclusive and can only be compared to the baseline model in terms of energy savings and costs. The prioritization methods depend on the energy consumption and the retrofit costs, an inaccuracy in either could result in a change to the prioritization results.

The main limitation is that only current technologies were considered for retrofit technologies. Energy retrofit technologies that are still in development could prove to be more effective than the ones being considered but certain costs are still unknown. Another limitation is the fact that only eight locations were chosen. The eight locations are representative of all Department of Energy (DOE) climates zones but some locations have unique climates and some of the technologies being considered may have an inherent advantage or disadvantage.

Implications

This research effort has two main implications. The first is an understanding of which current energy retrofit technologies are most capable of reducing energy consumption in different climates. The second is an improved way to prioritize projects within the Air Force. While the methodology is focused on Air Force facilities and prioritization, the proposed methodology can be applied to any organization looking to increase cost savings by reducing energy consumption in existing facilities.

Preview

The following sections of the thesis consist of a literature review, methodology, analysis and results, and conclusion. Chapter 2, the literature review, discusses previous research on relevant topics and the theories associated with those topics. Chapter 3, the methodology, provides a detailed account of what steps were taken to address the investigative questions. Chapter 4 presents the results and analysis of data after implementing the methodology. Chapter 5, the conclusion, expands on Chapter 4 by explaining the significance of the results and makes recommendations for future research.

Chapter 2. Literature Review

The purpose of this chapter is to discuss the initiatives the Air Force has implemented to curb energy consumption, the role climate plays in energy efficiency, the building profile properties that affect energy consumption most significantly, and eight current technologies capable of reducing energy consumption in existing facilities. Additionally, studies on cost analyses and project prioritization are discussed.

Air Force Energy Efficiency Initiatives

From a whole facility perspective, the Air Force has two primary documents that address energy efficiency: the 2011 policy memorandum mandating all new construction and major renovations be Leadership in Energy and Environmental Design (LEED) certified and the High Performance and Sustainable Building Requirements (HPSB) Unified Facilities Criteria (UFC) (Byers, 2011; UFC1-200-02, 2013). However, the 2012 National Defense Authorization Act (NDAA) prohibited funds from being used to achieve the two highest levels of LEED certification, gold and platinum, which are earned only by the most efficient buildings (NDAA, 2011). The 2013 NDAA reversed that decision by again allowing funds to be used for gold and platinum LEED certifications, but only if the designs are life-cycle cost effective (NDAA, 2013). Additionally, the HPSB UFC requires that new construction and major renovations be designed to “achieve at least 30% energy consumption reduction from ASHRAE 90.1 baseline” (2013) and be third-party certified by LEED. While there is an additional expense associated with attaining LEED certification for a facility, the federal

government wanted to be nationally recognized as a leader of energy efficiency in the construction industry after passing the Energy Independence and Security Act (EISA) of 2007 (EISA, 2007).

However, for major renovations on existing facilities, both the LEED memorandum and the HPSB suffer from lack of information. The Air Force is lagging behind in terms of metering at the facility level and creating computer models of facilities to determine the impact of energy efficient technologies (Eyring, 2013). Without meters or models, there is not enough information to know which existing facilities are meeting LEED or ASHRAE standards. The LEED policy memorandum and the HPSB UFC were implemented to help meet all the federal mandates described in Chapter 1; as can be seen in Figure 2.1 though, the lack of information has contributed to the Air Force only meeting slightly over half of the mandated energy reduction goals. In order for the Air Force to address the gap between mandated energy reduction levels and actual energy reduction levels, it must understand which properties affect energy consumption in existing facilities.

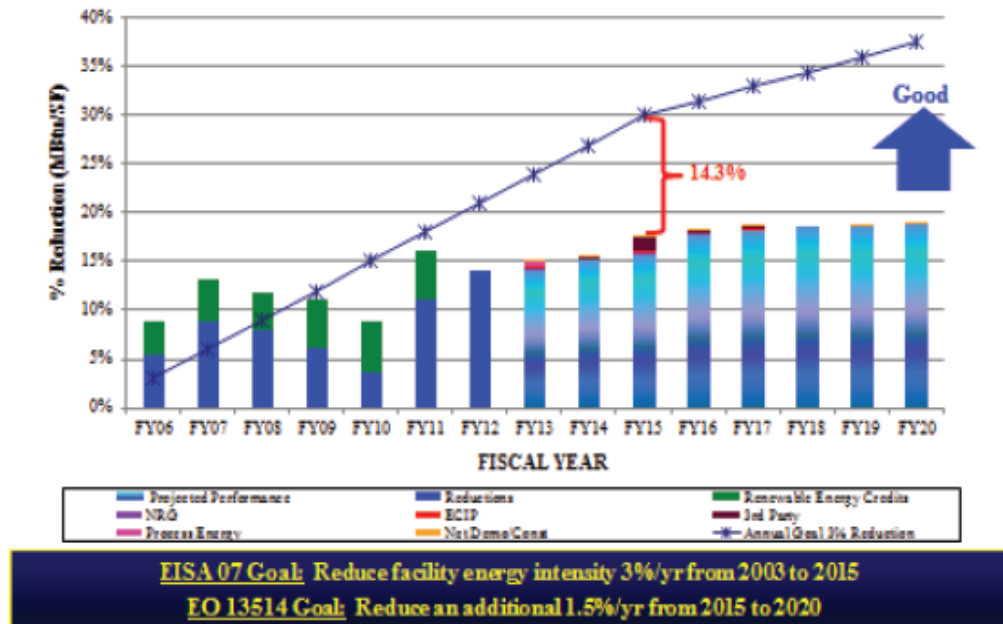


Figure 2.1. Mandated to Actual Energy Reduction Comparison (Eyring, 2013)

Climate

A building energy profile refers to the properties of the building that affect its energy consumption. Common properties include the building envelope such as the roof, walls, and windows; the location, dimensions, and orientation of the building towards the sun; and the lighting, and HVAC systems (Turner & Doty, 2013). Improvements in building profile properties can reduce energy consumption; however, improving certain properties in an existing building can be costly, such as the dimensions, or impossible to change, such as the location. One of the primary factors affecting how much energy a facility consumes that cannot be changed is the facility's location, or climate.

Studies indicate that climate has such a large impact on energy consumption that if the same facility existed in two different climates, retrofits on one facility would not necessarily be recommended on the other (DOE, 2010; Garg et al., 2015; Karabay &

Arıcı, 2012). Not recommending a retrofit for a climate can occur for two reasons. The first reason is that the technology does not save energy in that climate. For example, evaporative coolers are considered superior to traditional air conditioning in arid environments but are not recommended in humid environments (Ahmad, Rehman, & Al-Hadhrami, 2013; California Energy Commission, 2016). The second reason is that the cost of the retrofit is greater than the potential costs savings from reduced energy consumption (Rodrigues et al., 2015). For both reasons, no study has made claims to a single best retrofit technology for a given climate. Therefore, researchers are limited to recommendations based on the retrofit technologies and the specific climates for which they were investigated (DOE, 2010; Wang et al., 2013). This is significant for large countries with several different climates, such as the United States, that must ensure the retrofits are both energy efficient and economical.

To address the different climate zones within the United States, all new construction in the Air Force must meet climate based requirements established by the International Energy Conservation Code (IECC) (ICC, 2012; UFC1-200-02, 2013). These requirements include minimum standards such as insulation levels for walls and windows. For civilian facilities, the Department of Energy (DOE) has a retrofit guide that provides recommendations based on climate (DOE, 2010). However, no such guide exists within the Air Force. Prior studies within the Air Force have demonstrated how specific technologies differ across climates but did not provide recommendations based on climate zones (Lee, 2009; McCourt, 2007; Pratt, 2006). This research effort attempts to address the gap between climate-based retrofit recommendations between civilian facilities and Air Force facilities.

To adequately recommend retrofits based on climate, it is important to note how climates are categorized. There are currently three widely used systems for categorizing climate zones within the United States. The first was developed by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the second was developed by the IECC, and the third was developed by the DOE (Baecheler et al., 2010; Wang et al., 2013; Yu et al., 2015). For this research effort, the climate zones developed by the DOE were used for two reasons: ease of communication and overall acceptance of the system. The DOE climate zone system uses a naming convention that is easier to understand when compared to the IECC alphanumeric system. The DOE climate zone system is also adapted from the IECC which is internationally recognized. Both climate zone systems categorize climates based on temperature and moisture. Temperature categories are hot, mixed, and dry. Moisture categories are dry and humid. Figure 2.2 displays the climate zones within the United States using the IECC climate zone system. Figure 2.3 displays the climate zones within the United States using the DOE climate zone system. Within the United States, the DOE climate zone system has eight different climate zones varying from hot and humid to subarctic. The eight DOE climate zones are listed in Table 2.1, along with a representative city, and the Air Force location nearest to the representative city.

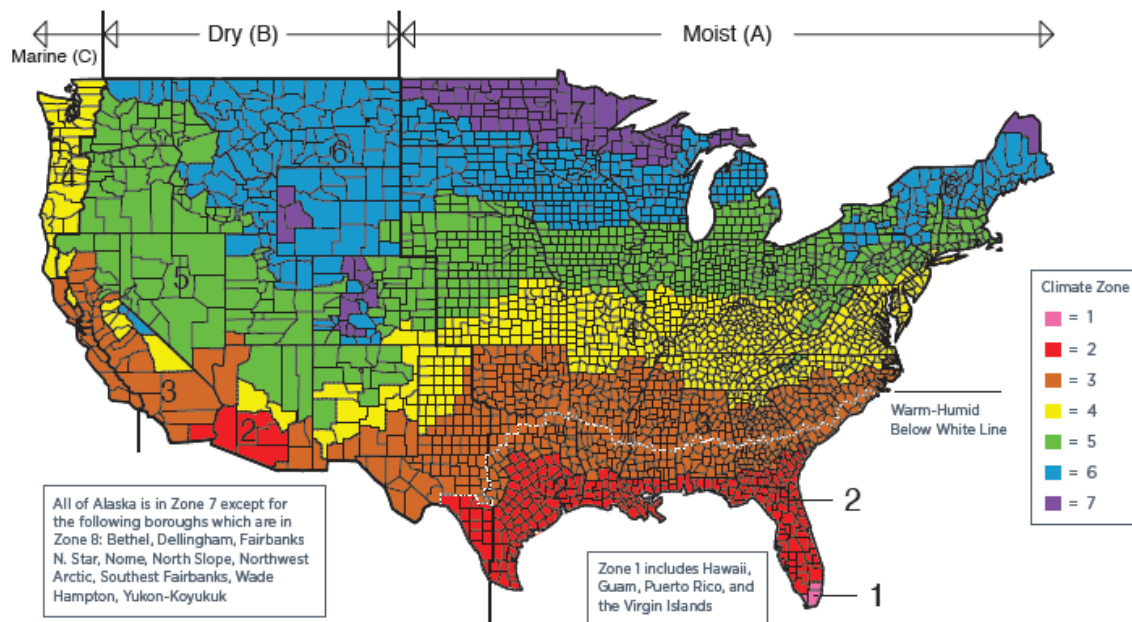


Figure 2.2. U.S. Climate Zones using the IECC System (Baecheler et al., 2010)

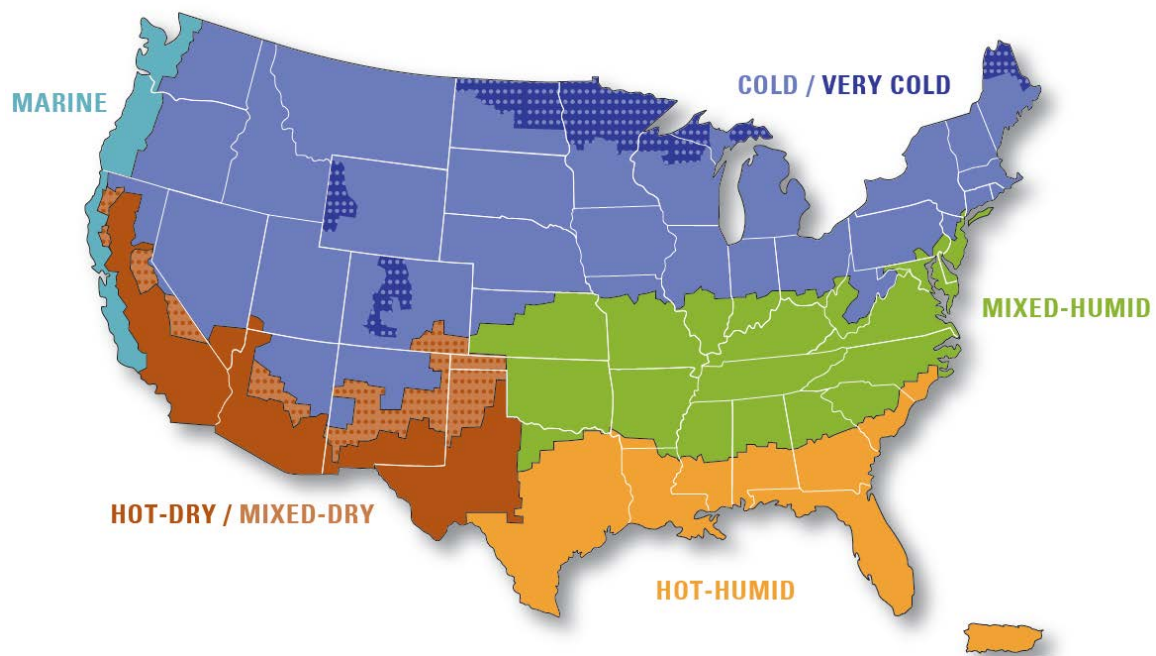


Figure 2.3. U.S. Climate Zones using the DOE System (Baecheler et al., 2010)

Table 2.1. List of Representative Air Force Installations (Baecheler et al., 2010)

DOE Climate	Chosen Representative City	Air Force Location
Hot-Humid	Houston, Texas	Ellington Field JRB
Hot-Dry	Las Vegas, Nevada	Nellis AFB
Mixed-Humid	Baltimore, Maryland	Andrews AFB
Mixed-Dry	Albuquerque, New Mexico	Kirtland AFB
Marine	Seattle, Washington	McChord AFB
Cold	Helena, Montana	Malmstrom AFB
Very Cold	Duluth, Minnesota	Duluth IAP
Subarctic	Fairbanks, Alaska	Eielson AFB

Energy Consumption

After taking the climate into account, certain properties can be more realistically altered as part of a retrofit project. Kadlubowski and Yates (2009) recommend that any retrofit projects that change more than one building profile property start with the building envelope because those retrofits reduce the load on any heating or cooling equipment. Figure 2.4 demonstrates the energy loss associated with the building envelope properties of existing facilities. As shown in the figure, windows are the most significant source of energy loss through the building envelope followed by infiltration and roofs. However, in office buildings, infiltration is less of a concern because office buildings are often slightly over-pressurized to allow the supply fan to provide the correct amount of air flow (Kissock, 2015). Therefore, retrofitting facilities with technologies that decrease energy loss through windows and roofs are better candidates for retrofit projects than technologies applied to infiltration, walls, and floors.

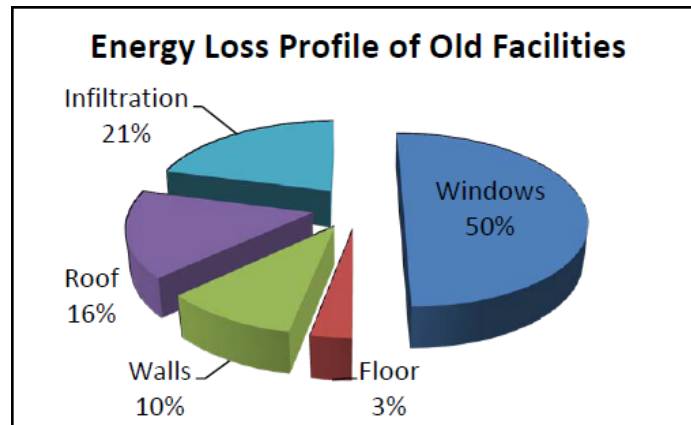


Figure 2.4. Energy Loss Profile of Old Facilities (Elder, 2000)

Beyond the building envelope, there are several properties that affect the building profile. Figure 2.5 displays the energy consumption in commercial office buildings separated by end use. As the figure shows, lighting alone consumes 39% of the energy in an office building. Space heating, cooling, ventilation, and water heating, which are all controlled by the HVAC system, represent 29% of the energy consumed in an office building.

The lighting and HVAC systems are better candidates for retrofit projects because the other properties in Figure 2.5 tend to be highly dependent on the needs of facility owners or users. Therefore, combining the highest energy loss building profile properties and the greatest energy consumption building profile properties leads to four properties that are considered the best candidates for retrofit: windows, roofs, lighting, and HVAC systems. When conducting retrofits, the DOE follows a similar methodology of preferentially applying technologies to building properties having either the highest energy losses or highest energy consumption (DOE, 2010). Table 2.2 is a summary of

the current technologies that were applied to the building profile properties and will be discussed further.

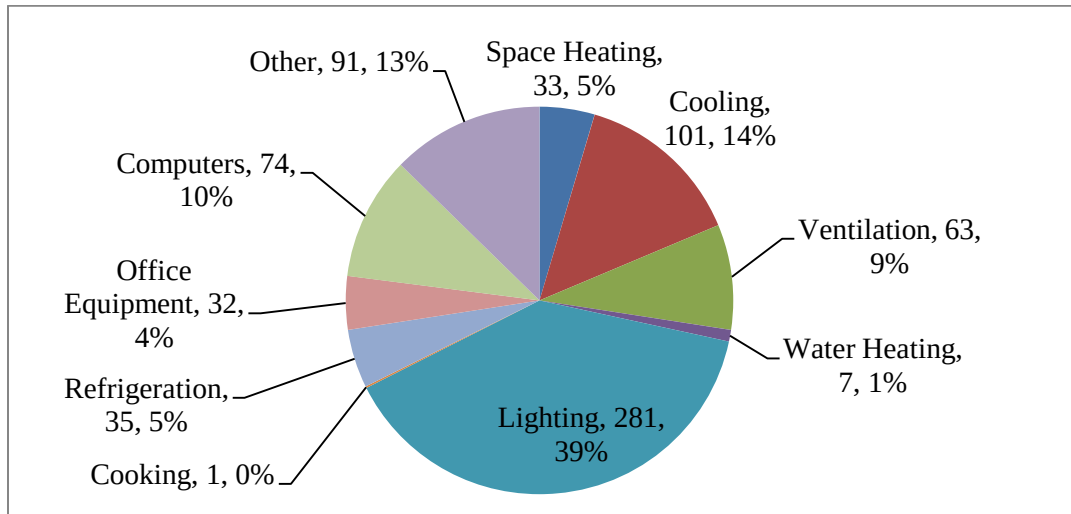


Figure 2.5. Office Energy Consumption by End Use (trillion BTU) (EIA, 2008)

Table 2.2. Summary of Current Technologies

Building Profile Properties	Current Technologies
Windows	Electrochromic Windows (EC) Multi-Paned Windows
Roofs	Built-Up Roofs (BUR) with Cool Roof Coating Standing Seam Metal Roofs (SSMR)
Lighting	Advanced Daylighting Controls (ADC) Light-Emitting Diode (LED) Upgrade
HVAC Systems	Demand Control Ventilation (DCV) Variable Speed Drives (VSD)

Windows

During daytime hours, windows allow sunlight to pass through and provide heat to facilities. Windows have two main properties that affect the amount of heat flow into a facility: conductance of the glass and the solar heat gain coefficient (SHGC).

Conductance is the amount of heat transferred through a material given an area, thickness, temperature gradient, and unit of time (Cengel & Boles, 2006). The SHGC is “the fraction of heat from incident solar radiation (sunlight) that flows through a window.... The lower a window's SHGC, the less solar heat the window transmits” (Arasteh, et al., 2007). To properly heat or cool the interior of a facility, a high SHGC is preferred in cold climates and a low SHGC is preferred in hot climates. Many studies have been conducted to show the benefits of upgrading windows but none have specifically addressed the Air Force. This may be due to the additional requirement for windows to meet Anti-Terrorism standards, thereby making energy efficiency a lower priority in windows (UFC4-010-01, 2013).

In the civilian sector, the energy efficiency of windows is a much higher priority. According to the Lawrence Berkeley National Laboratory, over 50% of windows in office buildings are single glass panes which are known to have high conductance values and therefore lower energy efficiency (Selkowitz, 2014). Multi-paned windows have been shown to decrease conductance values by 48 to 92 percent (Karabay & Arıcı, 2012). Figure 2.6 demonstrates how single and multi-pane windows are configured. A configuration with more than one pane creates a gap of air and “the stationary air layer between the two panes impedes the flow of heat” (Karabay & Arıcı, 2012). The energy savings from creating additional air gaps is significant. For example, replacing double pane windows with triple or quadruple pane windows in cold regions can reduce heat loss through windows by upwards of 50 percent (Arıcı, Karabay, & Kan, 2015).

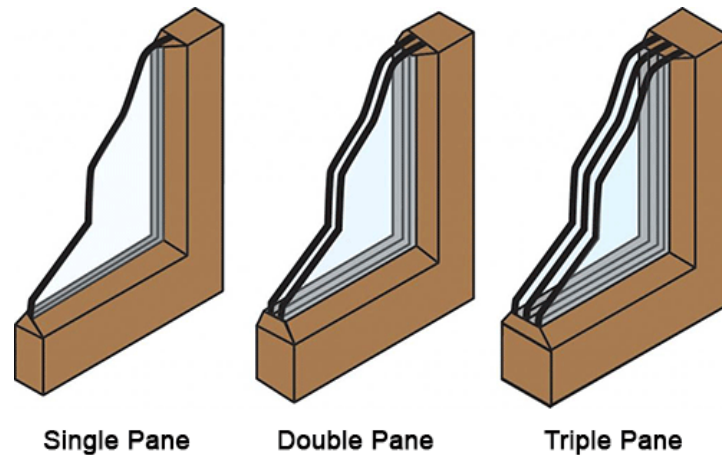


Figure 2.6. Single, Double, and Triple Paned Windows (TheWindowDog, 2015)

While triple and quadruple pane windows increase conductance, electrochromic (EC) windows can alter the SHGC. EC windows allow visible light into a facility while simultaneously blocking heat by adjusting the SHGC. EC windows are capable of adjusting the SHGC by applying a voltage that shifts electrons from one layer within the window to another (Chen, 2007). Additionally, the shifting electrons result in EC windows having two distinct states, a clear state and a colored state as shown in Figure 2.7 (Lee, 2009). According to Piccolo and Simone (2015), electrochromic windows can “switch to SHGC values as high as 0.6 ... when heating is required” or “attain SHGC values as low as 0.2... when cooling is required.” Continuing with the terminology in Figure 2.7, a SHGC of 0.6 would refer to the clear state while the SHGC of 0.2 would refer to the colored state.

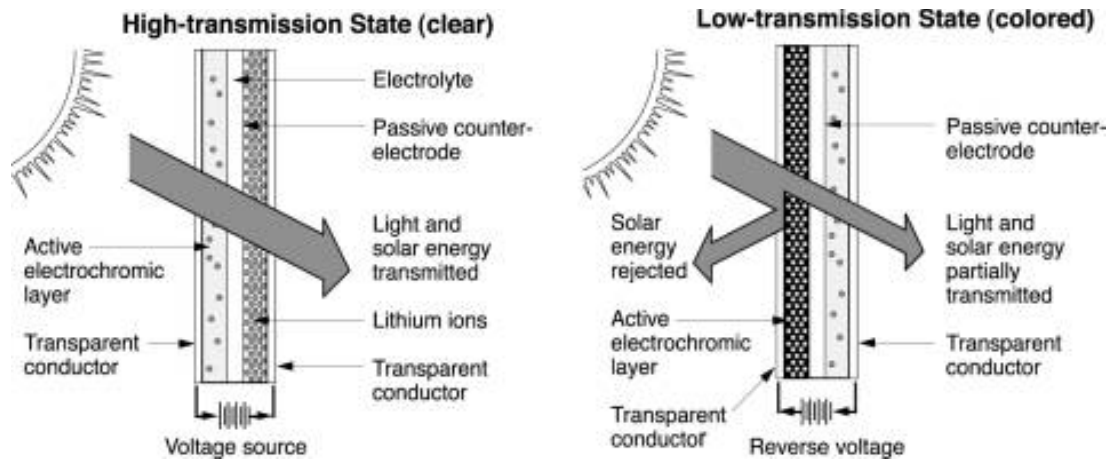


Figure 2.7. Electrochromic Window States (LBNL, 2006)

Roofs

The second building envelope property addressed is roofs, which account for approximately 16% of the energy losses in existing facilities (Elder, 2000). As demonstrated in Figure 2.8, the roof type and color affect the roof temperature by regulating the solar heat gain (EPA, 2012). The lower the roof temperature is during the summer, the less the HVAC system needs to work to remove heat. Two options for roof retrofits include built-up roofs (BUR) with cool roof coating (CRC) and standing seam metal roofs (SSMR). Both options were addressed by the Air Force in 2007; however, the prioritization method used considered non-financial aspects to prioritize the projects (McCourt, 2007).

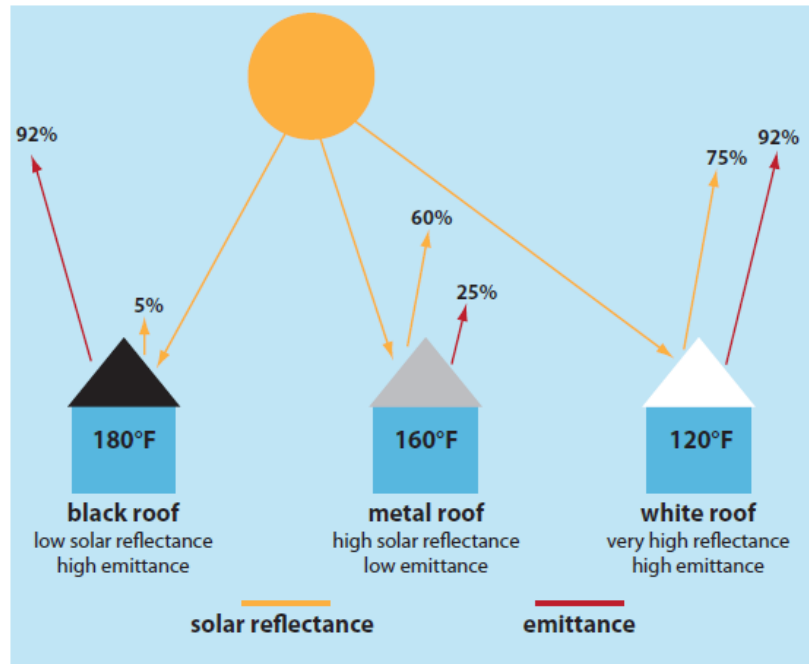


Figure 2.8. Effect of Solar Reflectance and Emittance on Roof Temperature (Akbari & Matthews, 2012)

According to a study performed in 2008 by the Pacific Northwest National Laboratory, up to 40% of commercial office buildings constructed after 1980 contain a BUR (Winiarski, Halverson, & Jiang, 2008). BURs are roofs that contain several layers, as shown in Figure 2.9, which provide insulation and waterproofing. CRCs work by increasing the reflectance and emittance of the roof, similar to Figure 2.8. Due to the decreased roof temperatures, studies have found energy savings of up to 26% associated with CRCs (Garg et al., 2015; Xu et al., 2012). This makes CRCs an excellent option for existing facilities because they can be applied on the top most layer of a BUR to reduce roof temperatures and energy consumption without modifying the underlying roof structure (Akbari & Matthews, 2012; Garg et al., 2015; Xue et al., 2015).

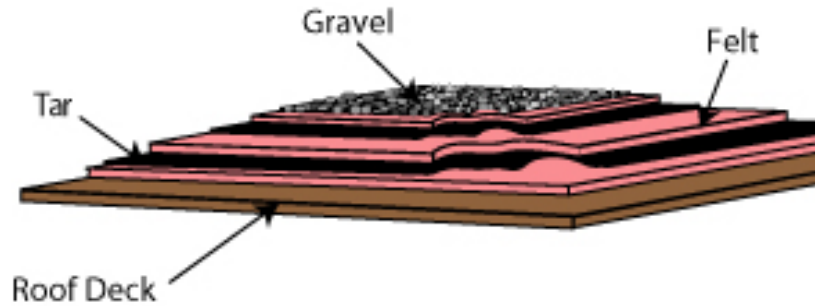


Figure 2.9. Built-Up Roof Layers (Pillar To Post Inc., 2015)

Alternatively, Standing Seam Metal Roofs (SSMRs), often require modification the roof structure to convert a low-sloped roof to a high-pitched roof similar to Figure 2.10. This is a costly retrofit because the roof structure must be able to support the weight of the steel or aluminum (UFC3-110-03, 2014). Despite the costs, SSMRs are preferred to BURs for several reasons. SSMRs have longer service lives compared to BURs, require low maintenance, and shed water due to the high pitch (McCourt, 2007). Additionally, studies have shown that SSMRs are significantly better than BURs at reflectance and emittance, thus leading to energy savings (Kültür & Türkeri, 2012).



Figure 2.10. Standing Seam Metal Roof Conversion (Greenville Metal Roof, 2015)

Lighting

After addressing the building envelope with retrofits to the windows and roofs, lighting becomes the next building profile property for improvement. According to the Pacific Northwest National Laboratory, facilities constructed prior to 1985 are often over-lit by double the modern standards (Richman, 2007). This is significant when electrical lighting can account for up to 50% of the electricity consumed (Pratt, 2006). Two methods to decrease the amount of electricity consumed for lighting are installing advanced daylighting controls (ADC) and upgrading lights to high efficiency lamps.

Advanced daylighting controls work in conjunction with an existing lighting system to regulate the amount of light in rooms by dimming the lights when there is sufficient daylight available. As can be seen in Figure 2.11, daylight does not fully penetrate the interior of an office but there is still a visible light gradient. The closer a work space is to a window, the more sunlight is available and the less artificial light is required. Additionally, the amount of light needed by work spaces for different tasks has been standardized (Richman, 2007; UFC 3-530-01, 2015). By knowing how much light is projected from the ceiling by artificial lights as represented by the red boxes in Figure 2.12, the intensity of those lights can be changed to provide the standardized amount of light in a work space. The end result is a standardized lighting level in the room that relies more on daylight and less on electricity, thereby resulting in energy savings ranging between 30% and 50% (Kamaruzzaman et al., 2015; Roisin et al., 2008).

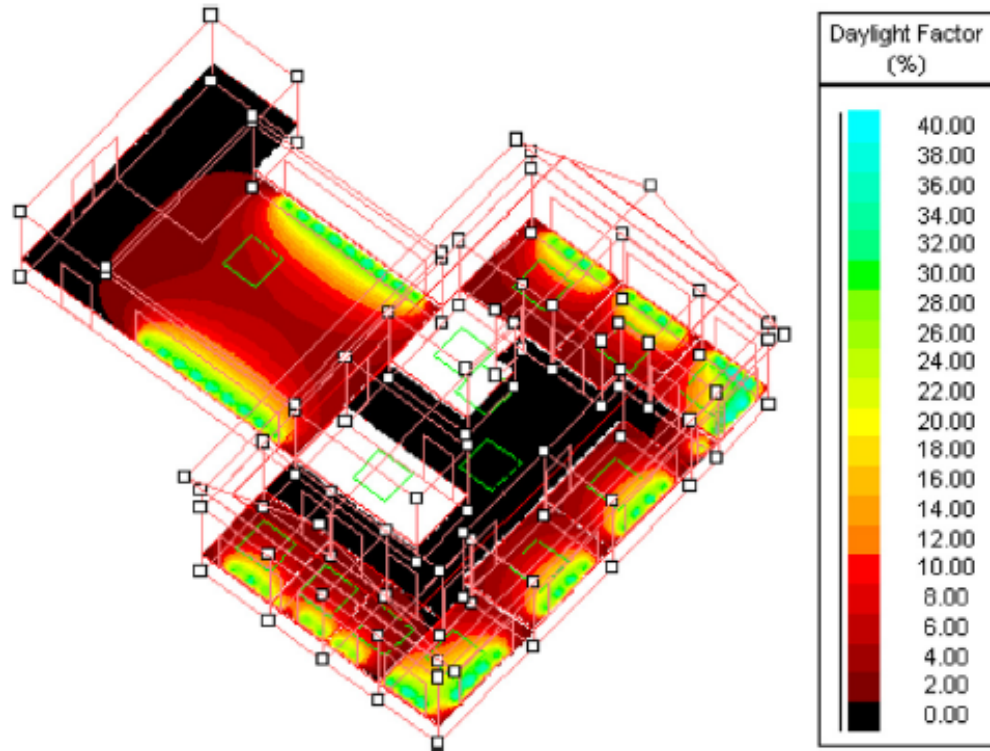


Figure 2.11. Office Floor Daylight Gradient (Kamaruzzaman et al., 2015)

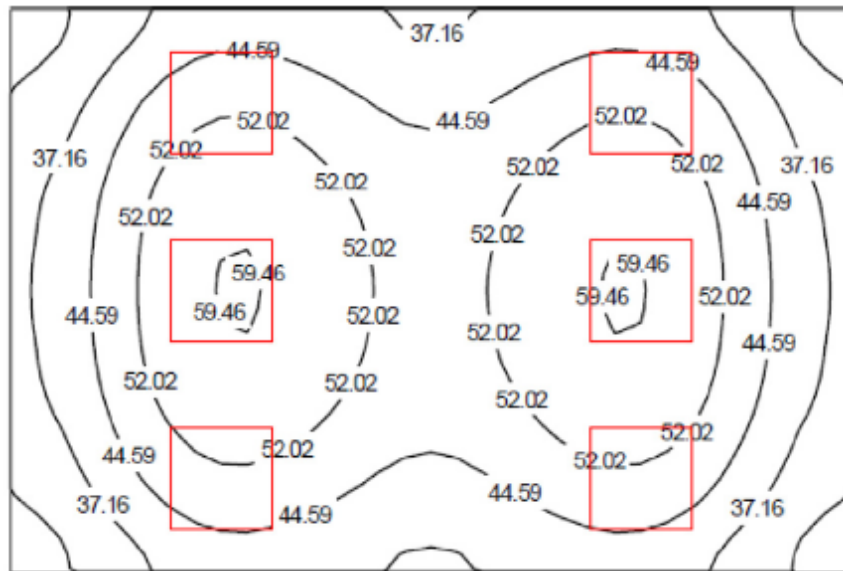


Figure 2.12. Amount of Light Projected from Ceiling (Soori & Vishwas, 2013)

Instead of regulating the amount of light using ADCs, it is also possible to use more efficient lamps that consume less energy. Aside from the lamp, the ballast and holder are the other major components in a standard office light fixture, as indicated by Figure 2.13. Upgrading lights with high efficiency lamps in existing facilities can be expensive because the ballasts which regulate the electric current into the lamps also need to be replaced (DOE, 2006). However, there are currently high efficiency lamps that can regulate the current internally, to include T5 and LED T8 lamps. Studies have shown that T5 lamps reduce energy consumption by up to 40% while LED T8 lamps reduce energy consumption by up to 70% (DOE, 2006, 2013; Gan et al. 2013; Mahlia, Razak, & Nursahida, 2011). Despite LED T8 lamps being 48.8% more effective than T5 lamps, the UFC which regulates lighting systems within the DoD has banned LED retrofits for linear fixtures similar to Figure 2.13 due to poor connections with the electrical infrastructure (Gan et al., 2013; UFC3-530-01, 2015). For the Air Force to meet mandated energy reduction levels though, it must use the best technology available. Additionally, a portion of the lighting system UFC already references a report that outlines how to mitigate potential issues between LED lamps and the electrical infrastructure (DOE, 2013). This research effort focused on LED lamps to demonstrate the potential energy savings of linear LED lamps within the Air Force.

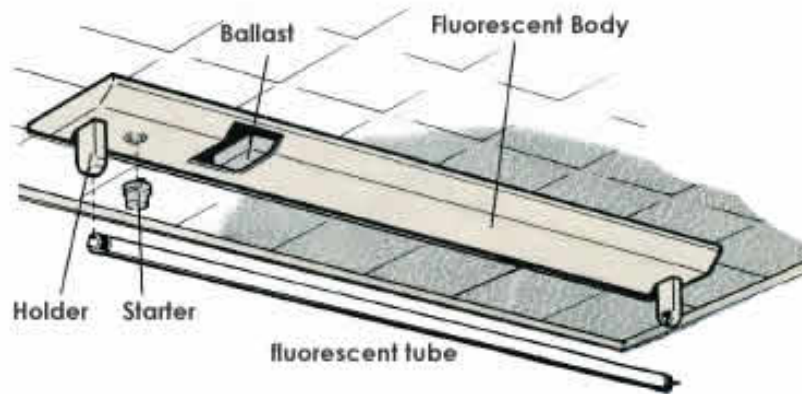


Figure 2.13. Light Fixture Components (Gadget Reset, 2015)

Heating, Ventilation, and Air Conditioning Systems

Second only to lighting, HVAC systems account for 29% of the energy used in office buildings (EIA, 2008). The reason HVAC systems consume so much energy is because HVAC “equipment is sized for a peak load that may account for only 1% of the hours of operation. The remaining hours of operation need only a fraction of the flow” (Carrier, 2005). Figure 2.14 represents a simple HVAC system; the equipment that is sized for peak load includes the compressor, condenser fan, and evaporator blower. However, most improvements to HVAC systems involve the efficiency of the components in new facilities and not existing ones (Wang et al., 2013). Two technologies capable of lowering energy consumption in HVAC systems in existing facilities are demand control ventilation (DCV) and variable speed drives (VSD). While DCV and VSDs accomplish the same goal of decreasing the load on HVAC systems, they are fundamentally different.

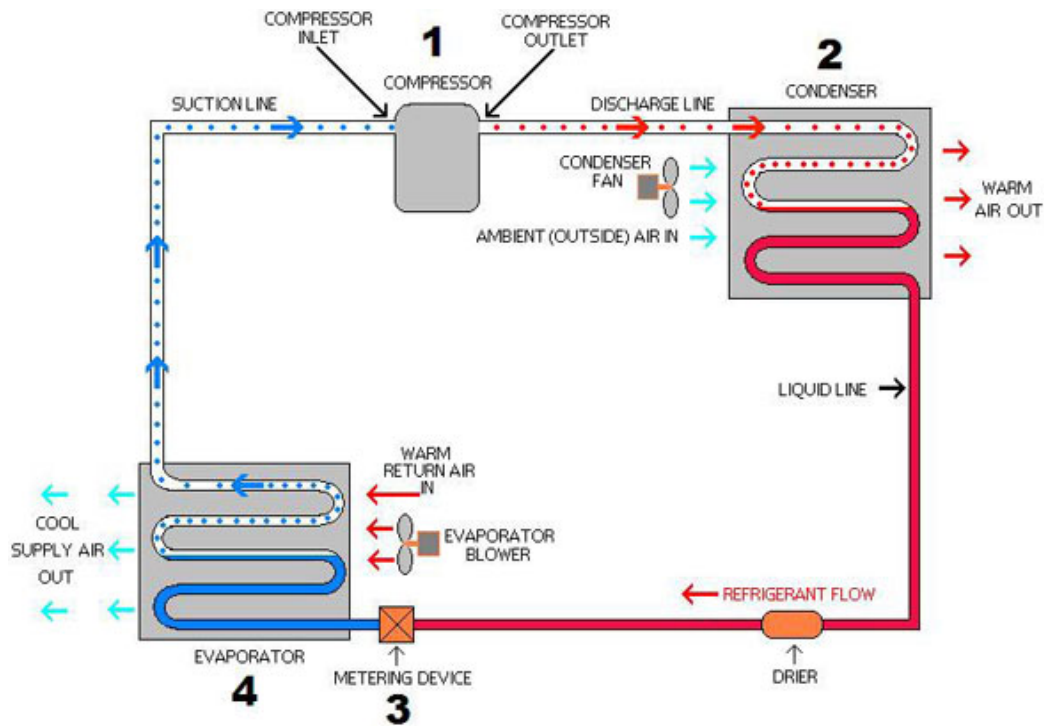


Figure 2.14. Simple HVAC System (Air Conditioning and Refrigeration Guide, 2005)

DCV is a “control strategy that varies the amount of ventilation outside air delivered to a space based on input from a single carbon dioxide (CO₂) sensor or group of sensors, which is representative of the quantity of occupants within the space” (Architectural Energy Corporation, 2007). A CO₂ sensor measures the amount of CO₂ in a zone and transmits that information to a control panel. The control panel calculates the amount of outside air needed based on the CO₂ measurement and then sends a signal to the outside air damper indicating the position the damper should be in. This control strategy is represented in Figure 2.15, where the amount of outside air is decreased from 200 cubic feet per minute (CFM) when the room is fully occupied to 120 CFM when the room is not fully occupied. DCV is an effective strategy because decreasing the amount of air based on occupancy decreases the amount of air that must be heated or cooled prior

to reaching the zone. Studies on DCVs in office buildings have found energy savings ranging from 12% to 50% compared to constant air volume (CAV) systems (Ahmed, Kurnitski, & Sormunen, 2015; Sun, Wang, & Ma, 2011).

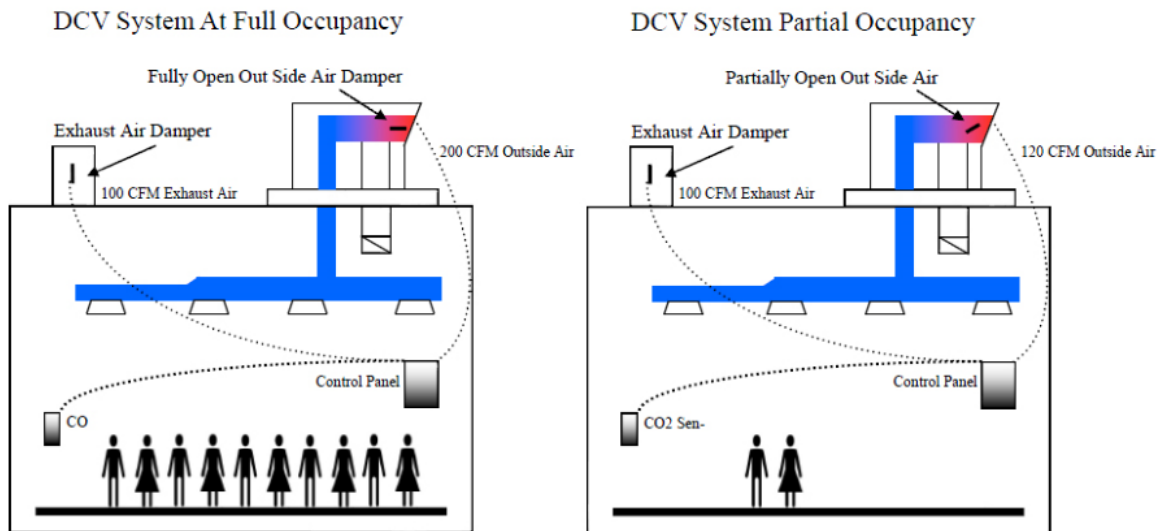


Figure 2.15. Demand Control Ventilation (Advanced Control Solutions, 2011)

As opposed to DCV systems which only affect the outside air damper, VSDs affect the speed and torque of any HVAC component with a motor to include fans, pumps, and compressors (Carrier, 2005). In a CAV system, fans, pumps, and compressors run at constant speed and if the load decreases, the system must be throttled. Figure 2.16 compares a pump in a CAV system to the same pump in a VSD system. VSDs are more efficient than CAV systems because VSDs require much less power when not operating at full load, as can be seen in Figure 2.17. Due to the significant decrease in motor power consumption with VSDs, studies have found savings of 30% to

60% in motor energy consumption when compared to CAV systems (Bose, 2009; Saidur et al., 2012).

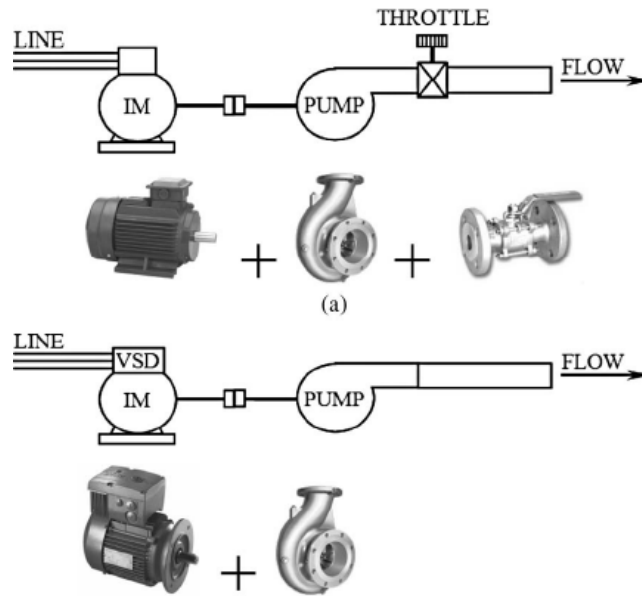


Figure 2.16. CAV Compared to VSD (Ferreira et al., 2011)

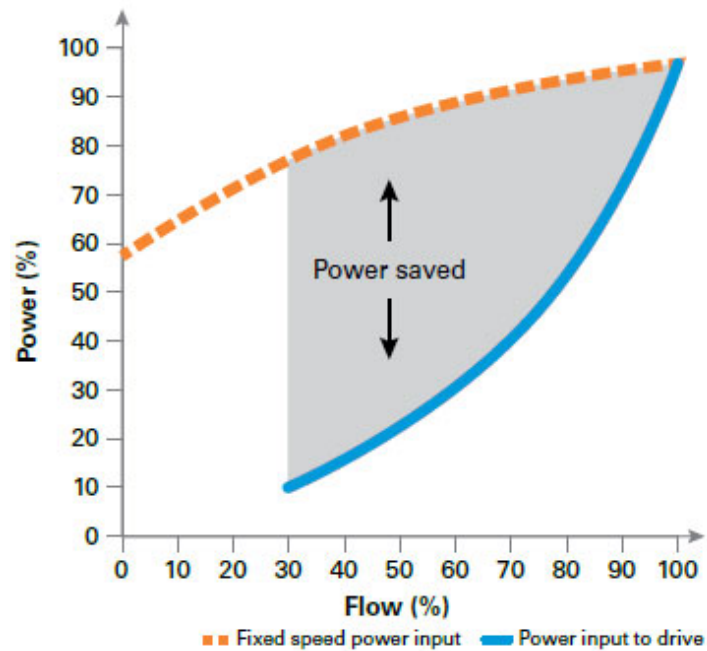


Figure 2.17. VSD Power Savings (Gozuk, 2015)

Cost Analysis and Prioritization

According to the Government Accountability Office (GAO), a cost analysis is the “summation of individual cost elements, using established methods and valid data, to estimate the future costs of a program, based on what is known today” (2009). Figure 2.18 displays the three primary cost components of capital investment, operations and maintenance (O&M), and recycling and removal, as well as the cost elements that affect each component (Sullivan, Wicks, & Koelling, 2008). For recycling and removal, due to the rate at which technology evolves, any retrofit technologies installed on a facility today face complete obsolescence by the time the Air Force chooses to demolish the facility; therefore, the final salvage value can be assumed to be zero (Žižlavský, 2014).

After performing a cost analysis, each retrofit technology must be prioritized at each location. Prioritizing projects is necessary in any environment where there are less resources available than there are requirements that must be met; however, prioritization methods vary wildly across disciplines and industries (Block, 2005; Eschenbach, 2010). For example, biologists use the project prioritization protocol to prioritize projects for threatened species based on “evolutionary distinctiveness, ecological importance, and social significance” (Joseph, Maloney, & Possingham, 2009). In engineering disciplines, industry standard prioritization methods are based more on costs. One prioritization method based on costs is net present value (NPV).

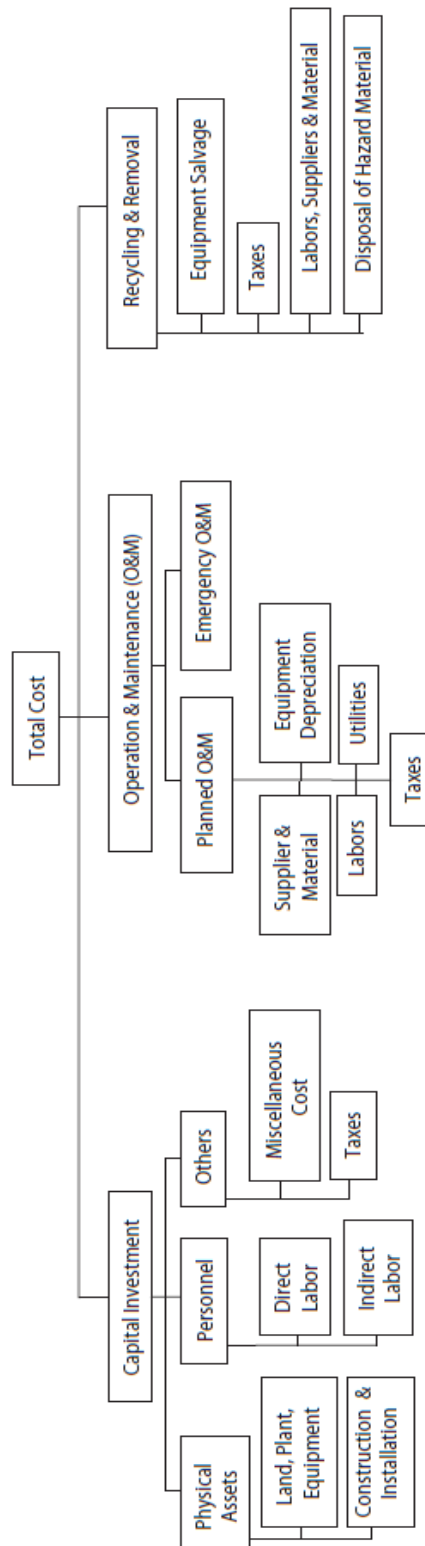


Figure 2.18. General Cost Structure

The Air Force Civil Engineer Center's (AFCEC) prioritization method, Megagallons to Investment Ratio (WIR), is also based on the time value of money but no studies have compared results between WIR and other cost based prioritization methods. Additionally, according to the AFCEC Capital Investment Plan (CIP), WIR cannot be used as a standalone prioritization metric; savings to investment ratio (SIR) and simple payback (SPB) must also have appropriate values. SIR must be greater than one and SPB must be a positive value that is less than the service life of the retrofit (AFCEC, 2013).

Once all retrofits have been prioritized, or ranked, using the different prioritization methods, WIR, and NPV, the ranking of the retrofits can be compared using simple linear regression to demonstrate if there is a significant difference between prioritization methods. Simple linear regression fits a line between a response variable and a predictor variable to determine if the regression line can be used to predict the response variable (Fabozzi, Focardi, & Rachev, 2014). Additionally, simple linear regression provides an Rsquared coefficient that encompasses the extent to which the variables fit on the regression line (Fabozzi et al., 2014; McClave & Benson, 2014). The Rsquared coefficient is the correlation between two variables with values between zero and one where zero indicates that the predictor variable can never predict the response variable and a value of one indicates that the predictor variable can always predict the response variable (Fabozzi et al., 2014; McClave & Benson, 2014). According to the Air Force's Cost Risk and Uncertainty Analysis Handbook, the strength of a relationship between variables can be described based on tiered correlation values as displayed in Table 2.3.

Table 2.3. Tiered Correlation Strengths (AFCAA, 2007)

Strength	Positive	Negative
None	0.000	0.000
Weak	0.250	-0.250
Medium	0.500	-0.500
Strong	0.900	-0.900
Perfect	1.000	-1.000

Summary

Chapter 2 discussed the initiatives the Air Force has implemented to curb energy consumption, how climate affects the performance retrofit technologies, the building profile properties that affect energy consumption most significantly, and eight current technologies capable of reducing energy consumption in existing facilities. Studies on cost analyses and project prioritization were also discussed. Chapter 3 provides the methodology used in the research and details the steps followed to generate and analyze the data.

Chapter 3. Methodology

This chapter describes the methodology in two distinct parts: data generation and data analysis. The data generation methodology includes modeling the prototypical Air Force office building in various climates, as well as simulating the energy consumption of those models with and without retrofit technologies. The data analysis methodology includes the equations and procedures necessary to analyze the data and accurately perform a cost analysis and compare prioritization methods.

Data Generation Methodology

Due to the price of testing new technologies or retrofitting a building, energy simulations have become well accepted as an accurate method to generate data regarding the energy consumed by a facility (Ke, Yeh, & Jian, 2013; Teras-Zubiaga et al., 2015). The software that was used in this research is the enhanced Quick Energy Simulation Tool (eQUEST) version 3.65 provided by the United States Department of Energy (DOE). This software is used extensively in research studies for several reasons; it is free, publicly available, sponsored by a recognized agency, and has the capability to perform parametric analyses to isolate individual building components and determine how the components affect the energy consumption for the entire facility (Arasteh et al., 2007; Lee, 2009; Pratt, 2006). However, prior to any type of analysis, a baseline model must be created.

Baseline Building Model

For this research effort, the prototypical building parameters provided by the Air Force Civil Engineer Center (AFCEC) and shown in Table 3.1 were input into the eQUEST baseline model. The building envelope parameters were kept constant across all locations as opposed to being updated to meet local building code requirements such as ASHRAE 90.1 (VanGeem, 2014). Significant parameters for energy simulations include building dimensions, roof construction, wall construction, window type, occupant schedule, Heating, Ventilation, and Air Conditioning (HVAC) system, and set point temperatures. Other researchers have used a similar methodology, in both the civilian sector and the Air Force, to represent a range of facilities with similar functions using typical facility parameters (Deru et al., 2011; Lee, 2009; Mathew et al., 2015). It is recognized that results generated using this methodology will not be particular to any facility, but it is a much faster method than creating a model for each individual facility (Deru et al., 2011).

The only detail that must be particular to each facility being modeled is the climate in which the facility operates. To generate energy consumption data based on climate, eQUEST models utilize Typical Meteorological Year 3 (TMY3) data files as an input. TMY3 data contain hourly values of temperature and solar radiation for 1,020 locations across the United States and account for “seasonal variations and represent a year of typical climatic conditions for a location” (Wilcox & Marion, 2008). TMY3 data are used extensively with simulation programs because the data are publically available and encompass a sufficiently long time-frame to account for seasonal variations (Arasteh et al., 2007; Pratt, 2006; Wilcox & Marion, 2008). Eight baseline models were created

with each one containing the TMY3 data that corresponded to a different location; the eight locations were Andrews Air Force Base (AFB), Duluth International Airport (IAP), Ellington Field Joint Recruiting Base (JRB), Eielson AFB, Kirtland AFB, Malmstrom AFB, McChord AFB, and Nellis AFB. TMY3 data for all eight locations were available from the eQUEST weather file database at <http://doe2.com/Download/Weather/TMY3/>.

Table 3.1. Prototypical Facility Parameters (Pratt, 2006)

Facility Component	Parameter
Office Building	2-Story (2 floors above grade) 25,000 sq ft Oriented North Floor to Floor height: 12 ft Floor to Ceiling height: 9 ft
Roof Construction	Metal frame, > 24 in o.c. 3-ply built up roof (BUR) Gravel finish 3 in polysocyanurate (R-21) insulation
Wall Construction	Metal frame, 2x6, 24 in o.c. Brick exterior Batt insulation (R-19) Additional 1 in polyurethane (R-6) insulation
Windows	Single pane, 1/8" Aluminum frame w/ thermal break 4 windows per side, 53.3% of total wall area
Schedule	7 am – 5 pm M-F, no weekends or holidays HVAC start/stops one hour before/after scheduled duty hours
HVAC	Packaged Single Zone Direct Expansion (DX) with furnace 11.25-20 ton Minimum 0.5 cfm/sq ft Continuous Fan
Set Points	Occupied: Cool: 76 °F Heat: 70 °F Unoccupied: Cool: 82 °F Heat: 64 °F

Retrofit Technologies

Once the baseline model was created and accounted for variations in climate, the technologies investigated were modeled through the eQUEST parametric analysis tool which modifies the baseline facility model one parameter at a time to determine the overall effect on the energy consumption of the facility (Hirsch, 2009). As an example, the prototypical Air Force building has single pane windows. The parametric analysis tool can change the window from a single pane to a triple pane while keeping all other model parameters constant; this provides the ability to determine how effective the changed parameter, the technology being investigated, is at reducing energy consumption. Table 3.1 is a summary of the facility parameters that were changed to incorporate the eight retrofit technologies. The final step of the data generation methodology is to use eQUEST to simulate energy consumption for all 72 scenarios, eight different locations with a baseline and the eight retrofit technologies.

Table 3.2. List of Changed Parameters

Retrofit Technology	Changed Baseline Facility Parameter
Electrochromic (EC) Windows	Single Pane Windows
Triple Pane Windows	Single Pane Windows
Built-Up Roof (BUR) with Cool Roof Coating (CRC)	BUR
Standing Seam Metal Roof (SSMR)	BUR
Advanced Daylighting Controls (ADC)	None
T8 Linear LED Lamps	T8 Linear Fluorescent Lamps
Demand Control Ventilation (DCV)	Constant Air Volume (CAV)
Variable Speed Drive (VSD)	CAV

Data Analysis Methodology

The energy simulations from eQUEST provided the amount of energy consumed by the baseline model for each technology retrofit during the parametric analyses. The results from the parametric analyses were compared to the baseline simulation to determine the amount of energy saved by each retrofit technology. The remaining portion of the data analysis required cost analyses to determine how the different retrofits would be prioritized using various prioritization methods and to calculate the return on investment (ROI) of each retrofit technology.

To perform the cost analyses, both the capital investment and operation and maintenance (O&M) cost components were determined. For construction projects, costs can be determined with RSMeans[®], a cost database that has become a standard in both industry and academia (Fuller, 2010; Pratt, 2006). Almost all capital investment and O&M costs were estimated with the RSMeans[®] cost books with the exceptions listed in Table 3.3. which also indicates the source of the cost data (Charest, 2015; Mossman, 2015; Plotner, 2015a, 2015b). Three important features within the capital investments and O&M cost components are the location of the retrofit, utility rates, to include electricity and natural gas, and discount rates. Table 3.4 is a summary of the area cost factors and utility rates for all eight locations where the electricity rate is dollars per kilowatt hours and gas rate is in dollars per million BTUs (MBTU). Table 3.5 lists the nominal discount rates used, nominal discount rates were used over real discount rates because the nominal discount rate accounts for inflation (Wood, 2011).

Table 3.3. List of Non-RSMeans Cost Sources

Facility Component	Cost Components	Cost Source
Triple Pane Windows	Capital Investment	(American Dream, 2014)
EC Windows	Capital Investment	(Tweney, 2013)
CRC	Capital Investment	(TAMKO®, 2012)
ADC	Capital Investment, O&M	(Anders, 2014)
T8 Linear Fluorescent Lamps	O&M	(TCP Inc., 2013)
T8 Linear LED Lamps	O&M	(OSRAM, 2015)

Table 3.4. Location Based Rates (AFCEC, 2014; EIA, 2014; Ghosh, 2015)

Air Force Location	Area Cost Factor	Region	Electricity Rate (\$/kWh)	Gas Rate (\$/MBTU)
Andrews AFB	1	Northeast	0.097	9.916
Duluth IAP	1.14	Midwest	0.0516	7.095
Eielson AFB	2.3	Alaska	0.3239	8.019
Ellington Field JRB	0.84	Texas	0.0728	7.179
Kirtland AFB	0.91	West	0.0656	6.793
Malmstrom AFB	1.1	West	0.0656	8.054
McChord AFB	1.12	West	0.0656	9.099
Nellis AFB	1.23	West	0.0656	7.215

Table 3.5. Nominal Discount Rates (OMB, 2015)

Calendar Year	3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
2015	1.7%	2.2%	2.5%	2.8%	3.1%	3.4%

Once the cost analysis was performed on each retrofit technology for a given location, the retrofits were prioritized. The net present value (NPV) was compared to the Air Force's MGals to investment ratio (WIR) to determine if there was a significant difference in rankings. Finally, for each prioritization method, the return on investment (ROI) was calculated for retrofits with positive prioritization metrics.

Air Force Civil Engineer Center Prioritization

Within the Air Force, AFCEC is the agency responsible for the “identification, development, prioritization, and execution” (AFCEC, 2013) of energy projects. According to the AFCEC Capital Investment Plan (CIP), project priority is calculated through Equation 3.1 (2013).

$$WIR = \frac{S_N E_N}{I_0 I_0} \quad (3.1)$$

where I_0 is the initial capital investment (\$), S_N is the net cost savings (\$), and E_N is the net energy savings (MBTU). Within the CIP, no criterion is provided for what is considered an appropriate WIR value for funding, therefore a positive WIR value was considered appropriate for funding. However, the CIP does indicate that prioritized projects must also have a savings to investment ratio (SIR) greater than one and a simple payback (SPB) that is lower than the life expectancy of the project. SPB is calculated with Equation 3.2 (AFCEC, 2013). The Air Force is the only agency to use WIR as a prioritization method.

$$SPB = \frac{I_0}{S_1} \quad (3.2)$$

where SPB is the simple payback (time), I_0 is the initial capital investment (\$), and S_1 is the cost savings in the first year (\$).

Net Present Value

A more popular way to prioritize alternatives is through NPV, which is calculated through Equation 3.3 (Khan, 1999).

$$NPV = \sum_{t=n}^n \frac{NCF_t}{(1+r)^t} - I_0 \quad (3.3)$$

where t is the year, NCF_t is the net cash flow generated by a project in year t (\$), r is the discount rate (%), and I_0 is the initial capital investment. Additionally, NPV can be calculated through Equation 3.4 (Eschenbach, 2010). Due to the inclusion of a discount rate, the first principle is that money today is more valuable than money tomorrow. This allows several retrofit comparisons to be compared because the NPV for each retrofit is determined using the same money baseline year. The second principle of NPV is that it accounts for all future cash flows to include O&M and not just capital investments (Žižlavský, 2014). NPV calculations can become complicated because of the need to predict all sources of cash flow, but it is a standard method to prioritize projects within the civilian sector (Emhjellen & Alaouze, 2003; Garcia, Contreras, Correia, & Muñoz, 2010). The difference in NPVs between the baseline and retrofit technology reflect the saving potential of the retrofit.

Prioritization Methods Comparisons

Both prioritization methods have different scales so to compare them; each retrofit was given a rank from one to eight at each location. WIR and NPV were then

compared using both simple linear regression analysis and ROI. The simple linear regression was performed on JMP[®], a statistical software package produced by SAS. The analysis performed was a simple linear regression between WIR and NPV. The inputs for the analysis were the rankings of each retrofit grouped by location across both prioritization methods. For example, at Andrews AFB, the eight retrofits were prioritized from one to eight using WIR and NPV. This was done for each location and the results were input into JMP[®] to perform the simple linear regression analysis using the “Fit Y by X” command.

ROI was also used to compare the prioritization methods as a metric to determine the effectiveness of the three prioritization methods and is defined as the “ratio of the net value of an investment relative to the cost of the investment” (Williams & Larocque, 2009) and can be calculated using Equation 3.6.

$$ROI = \frac{S_N}{I_0} \quad (3.4)$$

where ROI is the return on investment (%), S_N is the net cost savings, and I_0 is the initial capital investment (\$). Two different ROI calculations were performed. The first ROI calculation was for each retrofit, regardless of prioritization methods. The second ROI calculation was based only on retrofits with a positive prioritization value. For example, retrofits with negative NPVs, were not incorporated into the ROI calculations. If one of the end goals of the Air Force’s energy management program is to save money, then the Air Force should not invest in retrofits that do not have positive prioritization values.

Summary

This chapter described the methods implemented to simulate the energy consumption of the prototypical Air Force office building in different climates and determine which current retrofit technologies were most effective at reducing energy consumption. Additionally, the steps taken to perform the cost analyses and prioritization methods were also explained. Chapter 4 provides the results of implementing the methodology and analyzes the data.

Chapter 4. Results and Analysis

This chapter presents the results and analysis obtained from implementing the methodology described in Chapter 3. The results and analysis are presented using the same sections as the methodology: data generated and data analysis. Data generation results include the enhanced Quick Energy Simulation Tool (eQUEST) model and a sample energy simulation for one location. The data analysis results section answers the investigative questions and includes the energy saving calculations, the cost analyses for the retrofit technologies, and the prioritization of the retrofit technologies. Results that are not explicitly shown will be summarized or made available within appendices.

Data Generation Results

Figure 4.1 displays the three dimensional model generated by eQUEST. The model was used to generate data for the baseline energy consumption simulations as well as the parametric analyses. The model looks odd due to the overly large windows but it is consistent with the Air Force Civil Engineer Center (AFCEC) prototypical parameters of four large windows per side with a 53.3% window to wall ratio (Pratt, 2006).

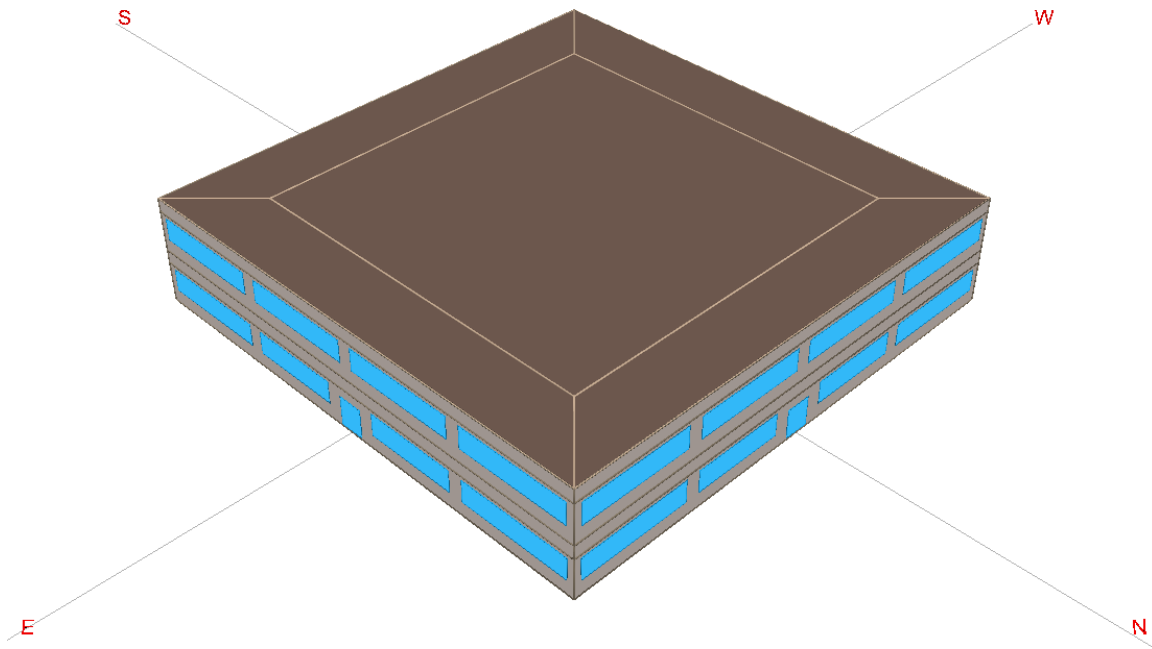


Figure 4.1. 3D Model Generated by eQUEST

Figure 4.2 and Figure 4.3 are the results of the parametric analyses in eQUEST and display the annual electricity and gas consumption, respectively at Ellington Field Joint Recruiting Base (JRB), Texas. Figure 4.4 combines the annual electricity and gas consumption into the total annual energy consumption at Ellington Field JRB. The bold horizontal lines represent the consumption from the baseline simulation to provide a visual reference of how the individual retrofit technologies compare to the baseline simulation. At Ellington Field JRB, three technologies resulted in decreased electricity consumption while simultaneously increasing gas consumption: EC windows, ADC, and LED lights. The increase in gas consumption indicates that a facility located at Ellington Field JRB uses the heat absorbed through windows or the heat produced by lights to heat the facility but when the heat is no longer available after the retrofit, the HVAC system must account for the difference to meet set point temperatures. Additionally, Figure 4.4

shows that total energy consumption for EC windows, ADC, and LED lights decreased despite the increase in gas consumption. Cases such as this are specifically why cost analyses must be performed, to determine if there is a net cost savings between both utilities. Savings from one utility may not offset the increased cost of the other utility. The electricity and gas consumption for all retrofit technologies at all locations are summarized in Table 4.1 and Table 4.2, respectively. The energy savings for each retrofit technology across all locations is listed in Table 4.4. The raw baseline data from eQUEST is available for all locations in Appendix B: Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5, Figure A.6, Figure A.7, and Figure A.8.

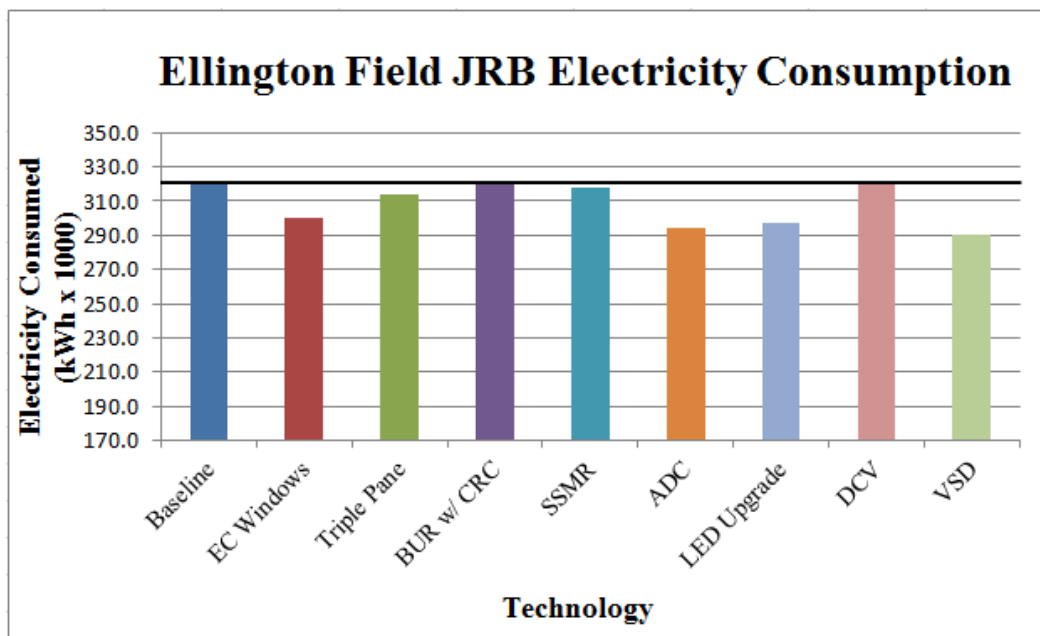


Figure 4.2. Annual Electricity Consumption at Ellington Field JRB

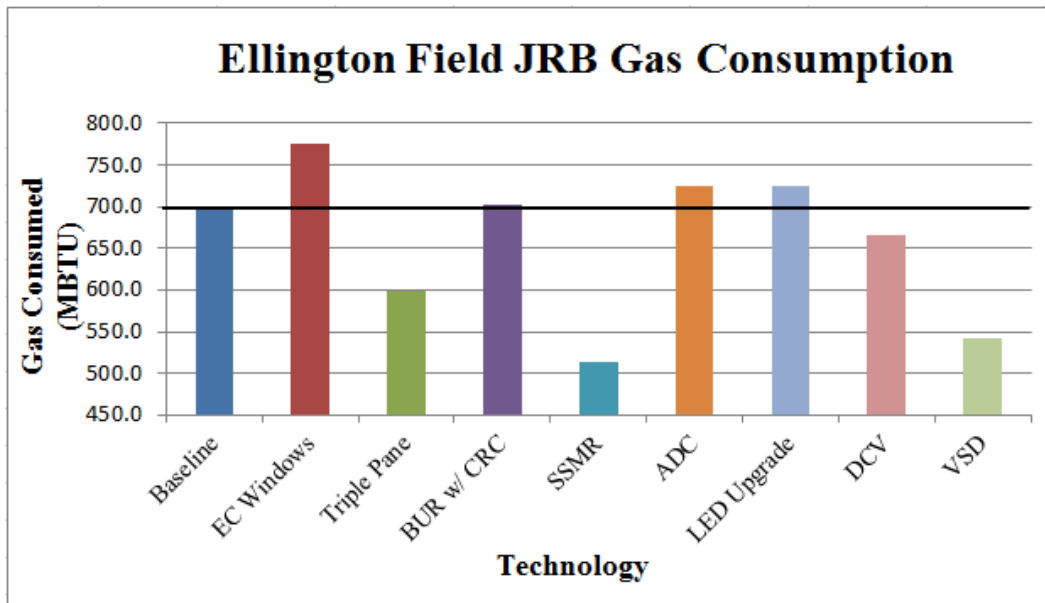


Figure 4.3. Annual Gas Consumption at Ellington Field JRB

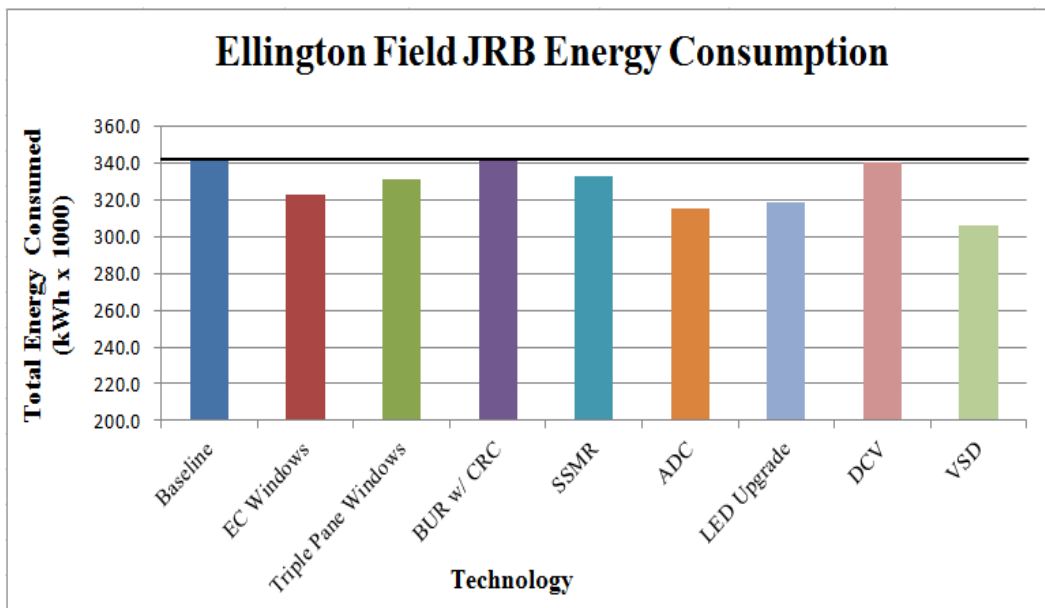


Figure 4.4. Annual Energy Consumption at Ellington Field JRB

Table 4.1. Annual Electricity Consumption by Location (in thousands of kWh)

Technology	Andrews AFB	Duluth IAP	Eielson AFB	Ellington Field JRB	Kirtland AFB	Malmstrom AFB	McChord AFB	Nellis AFB
Baseline	263.0	230.5	213.3	321.1	272.9	238.4	231.0	327.6
EC Windows	243.3	215.9	203.3	299.8	243.9	218.9	218.3	294.0
Triple Pane Windows	259.3	227.7	212.0	313.5	268.6	235.5	229.7	317.3
BUR w/ CRC	262.8	230.4	213.2	320.8	272.4	238.1	230.7	327.0
SSMR	285.6	231.5	215.8	318.0	273.5	240.0	231.6	327.9
ADC	237.2	206.7	194.2	293.8	246.4	214.2	207.2	299.6
LED Upgrade	240.8	209.5	193.1	297.4	250.4	217.1	209.5	303.9
DCV	264.2	232.3	215.0	320.7	277.0	241.3	233.1	328.6
VSD	252.6	201.9	188.4	290.0	239.8	208.1	202.5	294.4

Table 4.2. Annual Gas Consumption by Location (in MBTU)

Technology	Andrews AFB	Duluth IAP	Eielson AFB	Ellington Field JRB	Kirtland AFB	Malmstrom AFB	McChord AFB	Nellis AFB
Baseline	246.3	723.5	1082.8	701.0	130.3	491.4	255.7	64.2
EC Windows	306.9	797.3	1117.9	776.0	189.1	561.6	287.2	77.6
Triple Pane Windows	164.2	530.6	854.3	599.0	87.7	345.7	171.5	55.7
BUR w/ CRC	248.3	726.4	1085.4	702.0	132.2	494.4	257.3	64.8
SSMR	274.1	748.6	1119.4	513.0	119.9	508.7	260.6	46.0
ADC	266.6	755.8	1112.1	724.0	140.1	519.0	279.1	67.1
LED Upgrade	267.0	757.3	1126.3	725.0	141.1	521.2	282.1	67.2
DCV	213.6	645.8	973.8	667.0	102.0	405.4	221.6	60.9
VSD	298.1	730.5	1092.9	542.0	132.5	520.5	289.5	53.3

Table 4.3. Energy Saved by each Retrofit Technology (in thousands of kWh)

Technology	Andrews AFB	Duluth IAP	Eielson AFB	Ellington Field JRB	Kirtland AFB	Malmstrom AFB	McChord AFB	Nellis AFB
EC Windows	2.37	-6.97	-0.26	19.13	11.81	-1.17	3.46	29.68
Triple Pane Windows	27.78	59.39	68.30	10.55	16.91	45.56	25.96	12.80
BUR w/ CRC	-0.35	-0.70	-0.32	0.29	-0.06	-0.64	-0.23	0.53
SSMR	5.54	-8.12	-13.18	8.64	2.46	-6.74	-2.02	5.13
ADC	19.89	14.44	10.58	26.58	23.65	16.06	16.94	27.16
LED Upgrade	16.38	11.10	7.50	23.15	19.37	12.54	13.74	22.85
DCV	8.41	21.01	30.24	1.46	4.25	22.30	7.82	0.03
VSD	33.26	26.58	21.98	35.75	32.44	21.74	18.58	36.42

Data Analysis Results

Table 4.4 is the average energy saved by each technology across all locations sorted by greatest savings to least savings and does not account for cost; therefore, it makes no assumptions on the economic viability of each retrofit. The energy saved by each retrofit technology across all locations is available in Appendix Based on the retrofit technologies investigated, Table 4.4 indicates that triple pane windows and VSDs generally reduce energy consumption the most in existing facilities and that the roof retrofits, CRC, and SSMRs increase energy consumption in existing facilities. However, Table 4.4 does not account for climate; therefore, some of the retrofit technologies may not be viable in all locations.

Table 4.4. Average Energy Saved by Retrofit Technology

Retrofit Technology	Average Energy Saved (in thousands of kWh)
Triple Pane Windows	33.41
VSD	28.34
ADC	19.41
LED Upgrade	15.83
DCV	11.94
EC Windows	7.26
BUR w/ CRC	-0.19
SSMR	-1.04

Climate Based Energy Savings

As indicated in Chapter 2, climate is categorized based on temperature and moisture. Temperature categories are hot, mixed, and dry, while moisture categories are

dry and humid. Table 4.5 is the average energy saved by climate category and provides three important insights. The first insight is that although triple pane windows saved more energy on average than the other retrofit technologies, the average was skewed by the energy saved in cold climates. This is illustrated in Figure 4.5, a histogram and boxplot of the amount of energy saved across all retrofit technologies, in which the two outliers correspond to triple pane windows in cold climates. The second insight is that in certain climates, different retrofit technologies become viable. For example, in hot climates, SSMRs no longer increase energy consumption. Additionally, in cold climates, DCV has the second highest average energy saved. Outside of cold climates, VSDs, ADCs, and LED upgrades have a higher average energy saved when compared to triple pane windows. The third insight is that the highest potential for energy savings occurs in hot and dry climates, such as Nevada, where Nellis Air Force Base (AFB) is located.

Table 4.5. Average Energy Saved by Climate Category (in thousands of kWh)

Technology	Temperature			Moisture	
	Hot	Mixed	Cold	Dry	Humid
EC Windows	24.41	5.88	-2.80	20.74	8.32
Triple Pane Windows	11.68	23.55	57.75	14.86	21.43
BUR w/ CRC	0.41	-0.21	-0.56	0.23	-0.10
SSMR	6.89	1.99	-9.35	3.79	4.05
ADC	26.87	20.16	13.69	25.40	21.14
LED Upgrade	23.00	16.50	10.38	21.11	17.76
DCV	0.75	6.83	24.51	2.14	5.90
VSD	36.08	28.09	23.43	34.43	29.19
Average	16.26	12.85	14.63	15.34	13.46

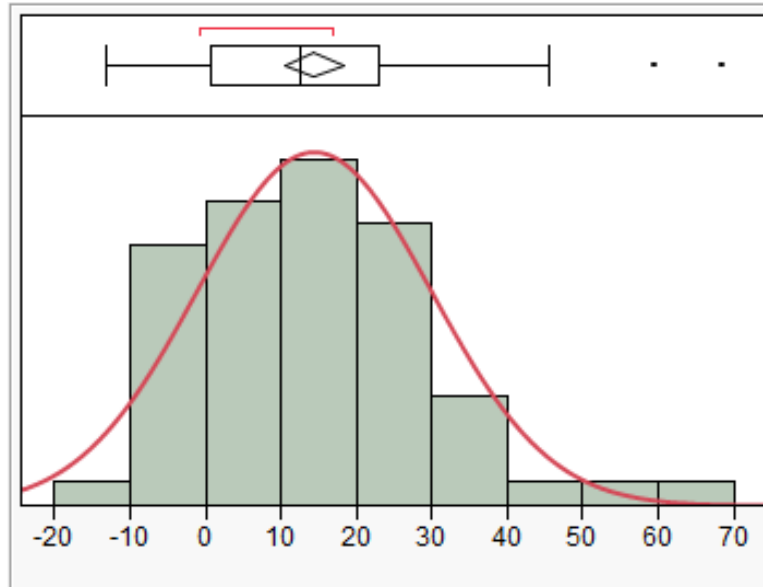


Figure 4.5. Histogram of Energy Saved across all Retrofit Technologies (in thousands of kWh)

Cost Analysis and Prioritization

Table 4.6 displays the capital investment and service lives of components within the baseline model and is based on RSMeans[®] costs and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) life expectancies (ASHRAE, 2015). Intermediary calculations for capital investments are available in Appendix Table B.1. Table 4.7 displays the capital investment and service lives associated with the retrofit technologies and is based on RSMeans[®], ASHRAE life expectancies, and other cost sources. Intermediary calculations for retrofit capital investments are available in Appendix C, specifically Table C.1 and Figure B.1. Cost savings from electricity are available in Appendix Table B.3. Once cost components are estimated, retrofits can be prioritized with both WIR and NPV. Sample calculations for the retrofit capital investment and net cost savings for LED upgrades at Andrews AFB

are shown in Table 4.8 and Table 4.9. Additionally, sample calculations for WIR and NPV are provided in Table 4.10 and Table 4.11. Due to the earned annual cost notation of negative amounts being positive, the capital investment was added instead of subtracted like the equation suggests in Table 4.11. Table 4.12 displays the prioritization values using all three prioritization methods for all retrofit technologies at Andrews AFB; prioritization values for all retrofits across all locations are available in Appendix Table B.4. Based on the prioritization values, each retrofit was given a ranking at each location from one to eight where one is the highest priority and eight is the lowest priority. Table 4.14 is the average ranking of each retrofit technology based on each prioritization method. Table 4.15 is the average ranking based on location across all prioritization methods. Individual rankings for all retrofit technologies across all locations are available in Appendix Table B.5.

Table 4.6. Baseline Capital Investment and Service Lives

Baseline Component	Capital Investment	Service Life
Single Pane Windows	\$81,066.67	30 Years
Built Up Roof (BUR)	\$49,811.57	28 Years
Linear T8 Fluorescent Lights	\$75,257.34	24,000 Hours

Table 4.7. Initial Retrofit Cost and Service Life

Technology	Cost Component	
	Capital Investment	Service Life
EC Windows	\$196,548.00	20 Years
Triple Pane Windows	\$129,863.71	20 Years
BUR w/ CRC	\$47,000.00	10 Years
SSMR	\$156,250.00	30 Years
ADC	\$37,500.00	16 Years
LED Upgrade	\$90,458.63	50,000 Hours
DCV	\$42,209.00	25 Years
VSD	\$27,000.00	15 Years

Table 4.8. Sample Calculation – Capital Investment: LED Upgrades at Andrews AFB

$I_0 = I_R \times ACF$
$I_0 = \$90,458.63 \times 1$
$I_0 = \$90,458.63$

where I_0 is the initial capital investment, I_R is the initial retrofit cost calculated using commercial catalogs and RSMeans[®], and ACF is the area cost factor for Andrews AFB.

Table 4.9. Sample Calculation – Net Cost Savings: LED Upgrade at Andrews AFB

Component	Line Item	Year 0	Year 1	Year 2	...	Year 30
T8 Linear Fluorescents	Capital Investment	\$75,257.34				
	Replace Bulbs		\$13,734.47	\$13,734.47	...	\$13,734.47
	Net Cash Flow (NCF)		\$13,734.47	\$13,734.47	...	\$13,734.47
	Net Present Value (NPV)	\$326,019.81				
	EAC (Annuity)	\$17,504.74				
LED Upgrade	Capital Investment	\$90,458.63				
	Replace Bulbs		\$7,945.87	\$7,946.87	...	\$7,947.87
	Energy Savings		-\$1,947.17	-\$1,947.17	...	-\$1,947.17
	Net Cash Flow (NCF)	\$90,458.63	\$5,998.70	\$5,999.70	...	\$6,000.70
	Net Present Value (NPV)	\$199,982.26				
	EAC (Annuity)	\$10,748.96				
	Annual Savings	-\$6,755.78				
	Net Savings (S_N)	\$125,824.01				

where net cash flow (NCF) is the sum of the cash flow for each year, net present value is the Excel function NPV, earned annual cost (EAC) is the payment function, PMT, in Excel, and S_N is the net cost savings is the difference in NPV between the baseline T8 linear fluorescent lights and the NPV of the LED upgrade retrofit.

Table 4.10. Sample Calculation – LED Upgrade WIR at Andrews AFB

$WIR = \frac{S_N E_N}{I_0 I_0}$	(4.1)
$E_N = (E_e \times CF + E_g) \times n$	
$E_N = \left(22,190kWh \times \frac{1MBTU}{293kWh} + -20.71MBTU \right) \times 30 \text{ years}$	
$E_N = 1650MBTU$	
$WIR = \frac{\$125,824.01}{\$90,458.63} \times \frac{1650MBTU}{\$90,458.63}$	
$WIR = .026$	

where S_N is the net cost savings calculated in Table 4.9, I_0 is the initial capital investment calculated in Table 4.8, E_N is the net energy savings, E_e is the electricity saved, CF is the conversion factor from kWh to MBTU, and E_g is the gas saved, and n is the service life. I_0 was calculated using RSMeans[®], the construction cost book. S_N is the net present value of the annual O&M savings over the 30 year service life of LED lamps. E_N is the annual energy savings between the LED upgrade and the baseline simulation at Andrews AFB over the 30 year service life of the LED lamps.

Table 4.11. Sample Calculation – LED Upgrade NPV at Andrews AFB

$NPV = \sum_{t=0}^n \frac{NCF_t}{(1+r)^t} - I_0$	(4.2)
$NPV = \sum_{t=n}^{30} \frac{\$5,998.78}{(1+.034)^1} + \frac{\$5,998.78}{(1+.034)^2} + \dots + \frac{\$5,998.78}{(1+.034)^{30}} + \$90,458.63$	
$NPV = \$5,801.53 + \$5,610.76 + \dots + \$2,200.12 + \$90,458.63$	
$NPV = \$199,982.26$	

where t is the year, NCF_t is the net cash flow generated by a project in year t (\$), r is the discount rate (%), and I_0 is the initial capital investment. NCF_t is the annual O&M savings and r is based on the Office of Management and Budget discount rates (OMB, 2015). Essentially, an LED upgrade retrofit at Andrews AFB would save \$125,824.01 over a 30 year time frame when compared to the NPV of T8 linear fluorescent lights.

Table 4.12. Retrofit Prioritization Values for Andrews AFB

Technology	WIR	NPV
EC Windows	0.000	-\$58,512.69
Triple Pane Windows	-0.001	-\$7,247.81
BUR w/ CRC	0.000	-\$39,012.68
SSMR	0.000	\$10,574.70
ADC	-0.005	-\$6,363.96
LED Upgrade	0.026	\$126,037.55
DCV	-0.014	-\$34,016.47
VSD	0.007	\$2,957.72

Table 4.13. Ranking based on Prioritization Method for Andrews AFB

Technology	WIR	NPV
EC Windows	5	8
Triple Pane Windows	6	5
BUR w/ CRC	4	7
SSMR	3	2
ADC	7	4
LED Upgrade	1	1
DCV	8	6
VSD	2	3

Table 4.14. Average Ranking based on Prioritization Method across all Locations

Technology	WIR	NPV
EC Windows	4.38	8.00
Triple Pane Windows	5.25	5.00
BUR w/ CRC	3.63	2.75
SSMR	2.88	3.50
ADC	7.13	5.25
LED Upgrade	1.13	1.00
DCV	7.13	6.75
VSD	4.50	3.75

Table 4.15. Average Ranking by Location across all Prioritization Methods

Technology	Andrews AFB	Duluth IAP	Eielson AFB	Ellington Field JRB	Kirtland AFB	Malmstrom AFB	McChord AFB	Nellis AFB	Average
EC Windows	6.67	6.00	6.67	6.33	6.00	6.67	6.67	5.33	6.29
Triple Pane Windows	5.33	4.67	5.33	6.00	4.67	4.33	4.67	6.00	5.13
BUR w/ CRC	4.00	4.33	5.00	5.67	5.67	4.67	4.67	5.00	4.88
SSMR	5.67	5.33	5.33	3.33	5.00	5.67	5.67	4.33	5.04
ADC	4.67	5.00	5.00	4.33	4.67	5.33	4.67	5.00	4.83
LED Upgrade	1.00	1.00	1.33	1.33	1.33	1.33	1.00	1.33	1.21
DCV	6.33	5.67	5.67	7.33	7.00	6.00	6.33	7.00	6.42
VSD	2.33	4.00	1.67	1.67	1.67	2.00	2.33	2.00	2.21

Figure 4.6 displays an analysis of variance (ANOVA) between the different prioritization methods for each technology. The Rsquare values indicate that NPV accounts for almost 83% of the variation between different retrofit technologies. The Rsquare value for WIR is 69%. Figure 4.7 displays a linear fit between the rankings of the Air Force prioritization method and NPV. WIR only produces the same results as the NPV approximately 31% of the time. Per the Air Force's Cost Risk and Uncertainty Analysis Handbook, that would be categorized as a weak correlations (AFCAA, 2007). The discrepancy between WIR and NPV as a prioritization method is significant. However, neither ANOVA nor the linear fit indicates if either prioritization methods offer a better ROI.

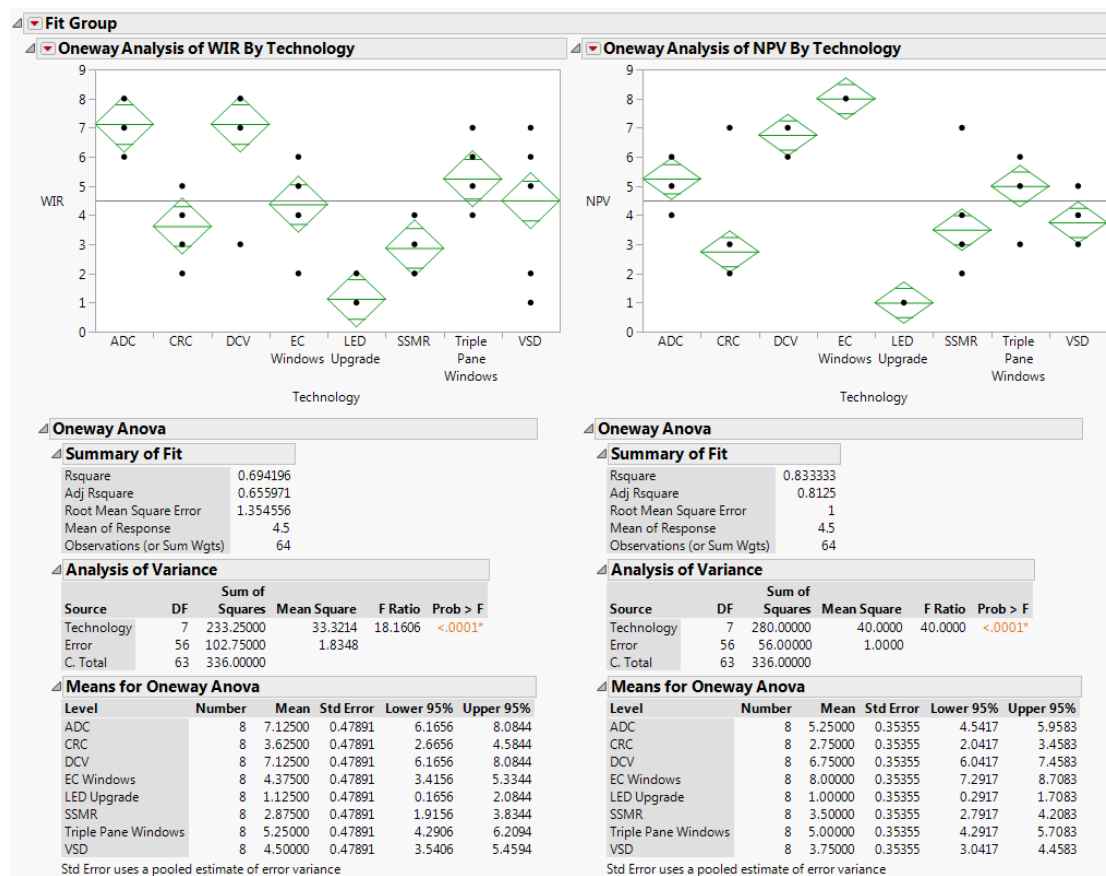


Figure 4.6. ANOVA of Prioritization Methods by Technology

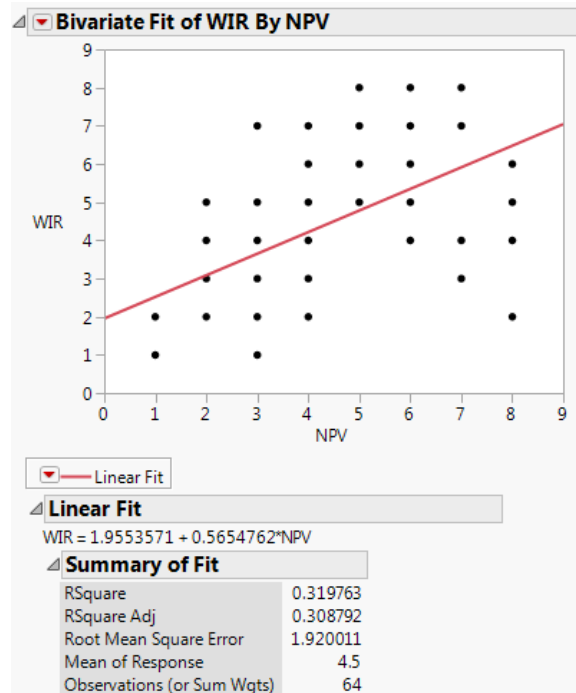


Figure 4.7. Linear Fit between WIR and NPV

The ROI can be calculated for many different categories to include location and technology. Table 4.16 is a sample ROI calculation for an LED upgrade retrofit at Andrews AFB. Table 4.17 lists the average ROI across all locations and retrofit technologies. The results indicate that three locations have a negative average ROI if all retrofits are funded. A positive ROI is indicative of sufficient cost savings through the lives of retrofits that are greater than the initial capital investment. However, Table 4.17 does not remove retrofits that have negative prioritization values. Table 4.18 is a sample calculation for ROI when funded retrofits are constrained to only retrofits with positive WIR scores. Table 4.19 is the average ROI for each location and prioritization method. Table 4.19 indicates that by only executing retrofits with positive prioritization values, locations are capable of achieving much higher positive ROIs. Table 4.19 also indicates

that on average, the Air Force’s prioritization method, WIR, has a significantly lower ROI. However, as indicated in Chapter 2, WIR cannot be looked at by itself; savings to investment ratio (SIR) must be greater than one and simple payback (SPB) must be a positive value less than the service life of the retrofit. Table 4.20 indicates that locations can achieve higher ROIs using WIR as a prioritization method if retrofits considered for funding are also limited by SIR and SPB. Once retrofits considered for funding were limited by SIR and SPB, WIR resulted in higher ROIs than NPV. Essentially, WIR as a standalone prioritization method does not provide sufficient information to accurately fund retrofit projects that produce high ROIs.

Table 4.16. Sample Calculation – LED Upgrade ROI at Andrews AFB

$ROI = \frac{S_N}{I_0}$	(4.3)
$ROI = \frac{\$126,037.55}{\$90,458.63}$	
$ROI = 139\%$	

where ROI is the return on investment (%), S_N is the net cost savings, and I_0 is the initial capital investment (\$). I_0 was calculated using RSMeans[®], the construction cost book. S_N is the net present value of the annual O&M savings over the 30 year service life of LED lamps.

Table 4.17. Average ROI across all Locations and Retrofit Technologies

		Location								
Technology	Andrews AFB	Duluth IAP	Eielson AFB	Ellington Field JRB	Kirtland AFB	Malmstrom AFB	McCord AFB	Nellis AFB	Average	
EC Windows	-29.8%	-35.8%	-33.2%	-27.9%	-26.2%	-33.1%	-34.1%	-28.0%	-31.0%	
Triple Pane Windows	-5.6%	-5.7%	-13.6%	-0.5%	-9.0%	-6.1%	-10.3%	-12.5%	-7.9%	
BUR w/ CRC	-83.0%	87.8%	46.6%	117.4%	108.8%	90.8%	89.4%	82.1%	67.5%	
SSMR	6.8%	-5.0%	-41.3%	42.7%	14.4%	-2.9%	-2.4%	-6.4%	0.7%	
ADC	-17.0%	-46.0%	-11.1%	-19.8%	-26.4%	-38.7%	-39.4%	-33.8%	-29.0%	
LED Upgrade	139.3%	100.4%	88.4%	159.4%	142.5%	110.4%	108.3%	103.2%	119.0%	
DCV	-80.6%	-73.9%	-83.1%	-76.7%	-90.6%	-72.1%	-82.6%	-88.9%	-81.0%	
VSD	11.0%	-30.5%	27.0%	42.0%	-1.6%	-21.7%	-26.9%	-15.4%	-2.0%	
Average	-7.4%	-1.1%	-2.5%	29.6%	14.0%	3.3%	0.3%	0.05%	4.5%	

Table 4.18. Sample Calculation – Average ROI based on WIR for Andrews AFB

$ROI_{Avg} = \frac{\sum \frac{S_N}{I_0}}{N}$	
$ROI = \frac{\frac{-\$39,012.68}{\$47,000} + \frac{\$10,574.70}{\$156,250.00} + \frac{\$126,037.55}{\$90,458.63} + \frac{\$2,957.72}{\$27,000}}{4}$	
$ROI = 19\%$	

where ROI is the return on investment (%), S_N is the net cost savings, I_0 is the initial capital investment (\$), and N is the number of retrofits with a positive WIR value. For Andrews AFB, the retrofits with positive WIR values were CRC, SSMR, LED Upgrade, and VSD. This process was repeated for each location and prioritization method.

Table 4.19. Average ROI at each Location across Prioritization Methods

Location	WIR	NPV	Average
Andrews AFB	19%	52%	35%
Duluth IAP	20%	94%	57%
Eielson AFB	10%	54%	32%
Ellington Field JRB	90%	90%	90%
Kirtland AFB	78%	89%	84%
Malmstrom AFB	25%	101%	63%
McChord AFB	53%	99%	76%
Nellis AFB	93%	93%	93%
Average	48%	84%	66%

Table 4.20. Comparison of WIR ROIs with and without SIR and SPB

Location	Prioritization Method			
	WIR without SIR or SPB	WIR with SIR	WIR with SPB	WIR with SIR and SPB
Andrews AFB	19%	139%	139%	139%
Duluth IAP	20%	100%	94%	100%
Eielson AFB	10%	0%	88%	0%
Ellington Field JRB	90%	138%	90%	138%
Kirtland AFB	78%	126%	66%	126%
Malmstrom AFB	25%	110%	66%	110%
McChord AFB	53%	108%	65%	108%
Nellis AFB	93%	103%	60%	103%
Average	48%	103%	84%	103%

Summary

Chapter 4 discussed the results and analysis obtained from implementing the methodology described in Chapter 3. The results and analysis were presented in two sections: data generation and data analysis. Data generation results included the eQUEST model and a sample energy simulation for one location. The data analysis results section provided the information needed to answer the investigative questions and included the energy saving calculations, the cost analyses for the retrofit technologies, the prioritization of retrofit technologies, and the ROI. Chapter 5 draws conclusions based on the data analysis and provides recommendations for the Air Force and future research.

Chapter 5. Conclusions and Recommendations

Chapter 5 answers the investigative questions based on the results and analyses of Chapter 4. Additionally, this chapter draws conclusions based on the entirety of this research effort and explains the significance of the research. Finally, this chapter provides recommendations for both the Air Force and future research while addressing limitations.

Research Questions Answered

Three investigative questions were proposed in Chapter 1 as a basis for research. Each investigative question is repeated along with a summary of the results.

- 1. Which currently available energy retrofit technologies reduce energy consumption the most in existing facilities?*

Based on implementing one retrofit technology at a time, of the eight retrofit technologies investigated, triple pane windows and variable speed drives (VSD) reduced energy consumption the most in existing facilities. Triple pane windows reduced overall energy consumption 9.4% while VSDs reduced overall energy consumption 8.7%. However, on average, both technologies had a negative return on investment (ROI), -57% and -96%, respectively; therefore, if cost is a factor, neither technology is viable as a retrofit for existing facilities yet. In order for each technology to become viable as a retrofit option for existing facilities, either the capital investment costs must decrease or the amount of energy savings must increase.

2. *How does location and climate affect the energy reduction of the currently available retrofit technologies?*

While the first question addressed overall energy savings, the second investigative question was concerned with energy savings based on climate. The analysis revealed that in hot and dry climates such as Nellis AFB, Nevada, VSDs reduce energy consumption the most, followed by advanced daylighting controls (ADC). In cold climates, triple pane windows reduce energy consumption the most, followed by demand control ventilation (DCV). In mixed or humid climates, VSDs reduce energy consumption the most, followed by triple pane windows. There was no climate category where triple pane windows reduced energy consumption the most followed by VSDs as was found in investigative question one.

3. *Is there a significant difference between Air Force and industry standard prioritization methods for energy projects and does one of them offer a better ROI?*

The research indicated a stark difference between project rankings using the Air Force's energy project prioritization method, WIR, and net present value (NPV). However, the research also indicated that by only funding retrofits with a savings to investment ratio (SIR) greater than one, a positive WIR value, and a positive simple payback (SPB) less than the service life of the retrofit resulted in higher ROIs than NPV. Therefore, WIR provides the greatest ROI with the caveat that WIR must consider two additional metrics, SIR and SPB.

Significance of Research

This research effort makes three significant contributions. First, it furthers the body of knowledge regarding retrofits on existing facilities by comparing different technologies based on their ability to reduce energy consumption. Second, it reiterates that climate plays a major role in the energy consumption of a facility and that a one-size-fits-all approach for all climates is not ideal. Finally, it demonstrates that WIR is an effective method of prioritizing energy projects after SIR and SPB constrain which retrofits can be considered in the ROI calculations. Based on the significant findings of this research, there are several recommendations.

Recommendations for Action

The first recommendation is for the civilian sector to continue improving retrofit technologies to be more efficient and cost effective so that technologies such as triple pane windows and variable speed drives (VSDs) are able to produce an acceptable ROI. The second recommendation is for the Air Force to establish a guidebook that recommends retrofits based on climate and is tailored to Air Force facility parameters, similar to the Department of Energy (DOE) retrofit guide for commercial facilities. This will enable the Air Force to temporarily address the gap identified by Eyring (2013), where energy reduction levels are only half of the federally mandated energy reduction levels, while facilities continue to have meters installed and provide installation energy managers a starting point for future retrofit projects. The final recommendation is that the Air Force should consider transitioning away from WIR as a prioritization metric. While WIR does provide a higher ROI than NPV, the industry standard method indicates

that other retrofits do provide a positive ROI; therefore, WIR is too restrictive in which projects are funded. This change would align the Air Force with industry and continue to address the gap between mandated energy reduction goals and actual energy reduction.

Recommendations for Future Research

Future research must focus on four components to help the Air Force meet mandated energy reduction levels, all of which focus on improving the information readily available on retrofits to existing facilities. The most needed research is a method to incorporate Air Force BUILDER™ data into energy simulation software.

BUILDER™ is a decision support tool that contains real property data for all facilities and component conditions (CERL, 2015). BUILDER™ would help energy simulations by providing facility parameters that are up-to-date and more representative of facilities at a given location. Additionally, BUILDER™ would provide more accurate ROI results when choosing between the sunk costs of continued operations and maintenance (O&M) of a component or a potential investment through retrofits. Second, the Air Force can expand on the recommendation for action of creating a guidebook that recommends retrofits based on climate by automating the recommendation process by creating a centrally managed database. There are several civilian retrofit databases, but none of them contain simulations using Air Force facility parameters (DOE, 2012; Lee et al., 2015; Pan, Xu, & Li, 2012; PEP LLC, 2012). Third, this research can be expanded upon by focusing on recommendations for water conservation retrofit technologies. Once water conservation is further studied in an Air Force context, those recommendations can also be incorporated into a future database. Finally, future research can investigate how

to optimize retrofit projects to maximize cost savings when multiple retrofits are selected or ordered sequentially.

Research Limitations

A major limitation of this research is the fact that retrofits simulated single technologies as opposed to different combinations of technologies. For example, a full building retrofit project could decide to install triple pane windows, ADC, and a VSD all at once. A retrofit of that size would significantly change both the amount of energy reduced as well as the cost. The enhanced Quick Energy Simulation Tool (eQUEST) has the capability to perform parametric analyses with multiple technologies but the number of simulations required would have been beyond the scope of this research. With just the eight technologies investigated, the number of simulations necessary at one location would be seven factorial, or 5,040 simulations, for a total of 40,320 simulations across the eight locations investigated with each simulation taking two to three minutes.

A secondary limitation of this research was the scope of the cost analysis performed. A more robust life-cycle cost analysis could have been performed that considered less expensive troop labor, economies of scale for retrofits that are part of a facility renovation and not stand-alone projects, and different contracting avenues such as energy conservation investment programs or utility energy service contracts (AFCEC, 2015). Those options could have potentially made some energy retrofit technologies more economically attractive and viable as Air Force projects.

Final Conclusions

The Air Force has the tools needed to address existing facilities by knowing what energy retrofit technologies are most capable of reducing energy consumption in different climates; however, it must continue to meter or model facilities to either propose future retrofits that reduce energy consumption or validate retrofits already in place to ensure mandated goals such as those in Executive Order 13693 are met in a timely manner. Finally, the Air Force should consider using an industry standard prioritization method for energy projects that requires fewer constraints and produces a ROI while still addressing the gap between mandated energy reduction goals and actual energy reduction.

Appendix A. Data Generation

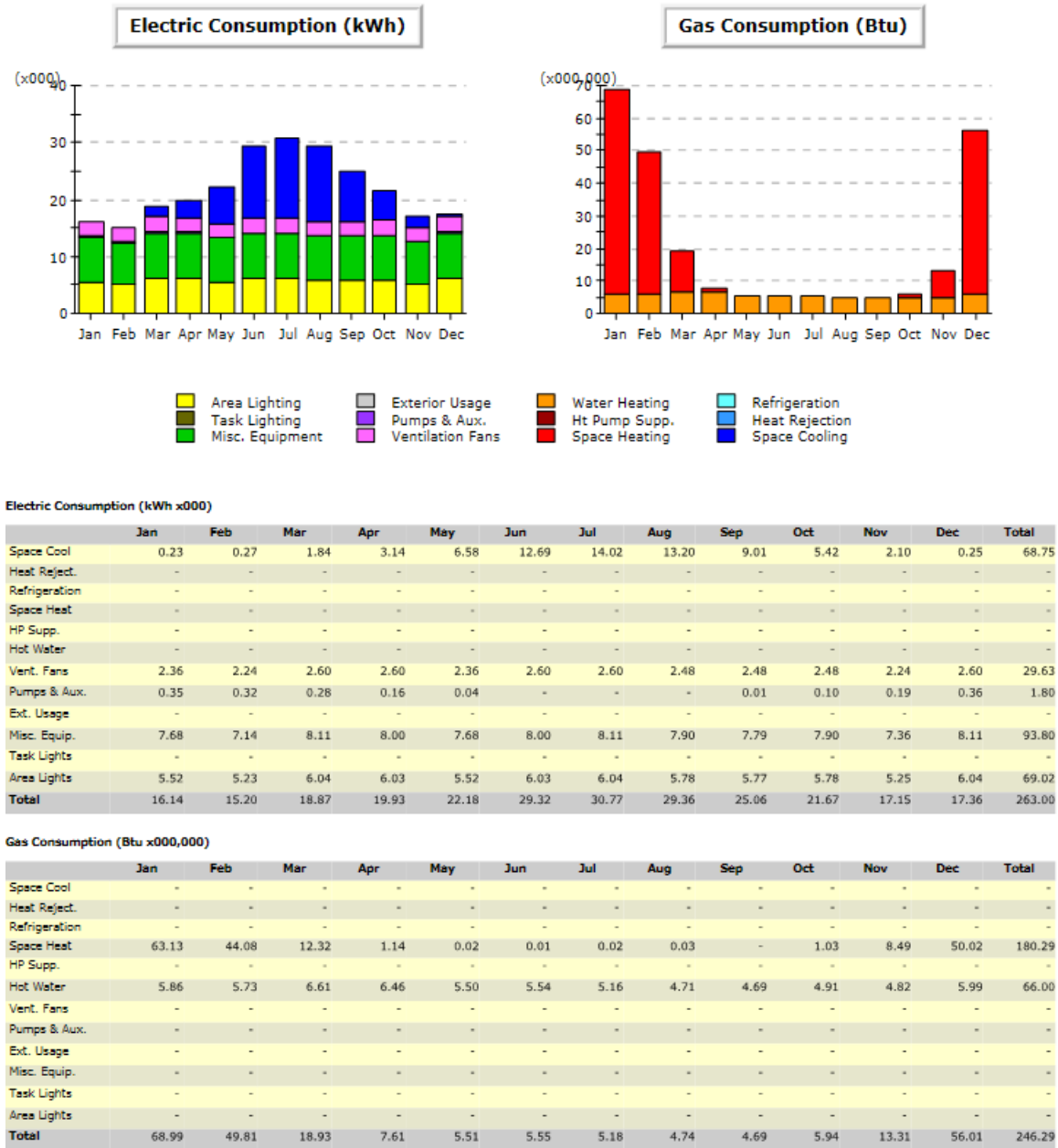
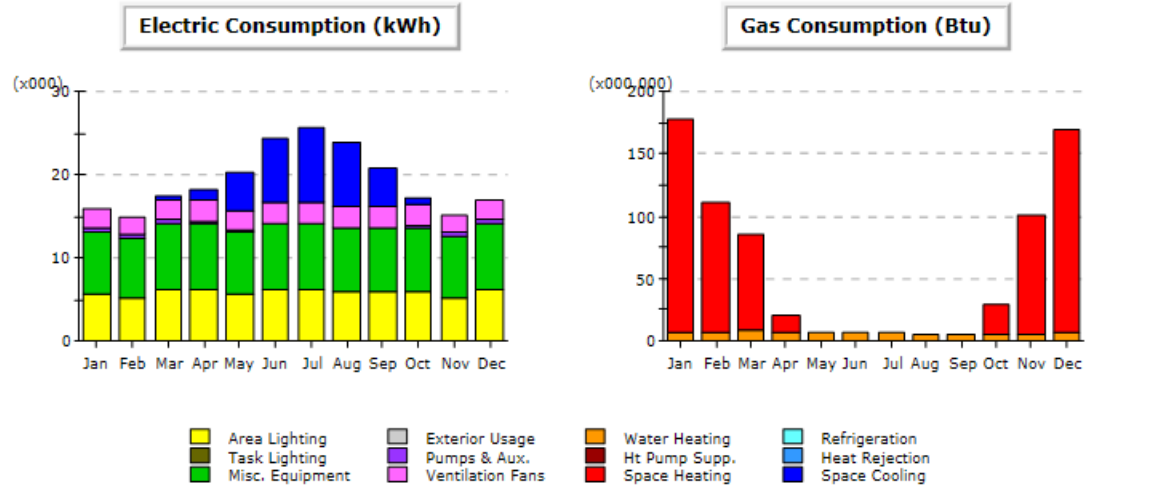


Figure A.1. Andrews AFB eQUEST Output



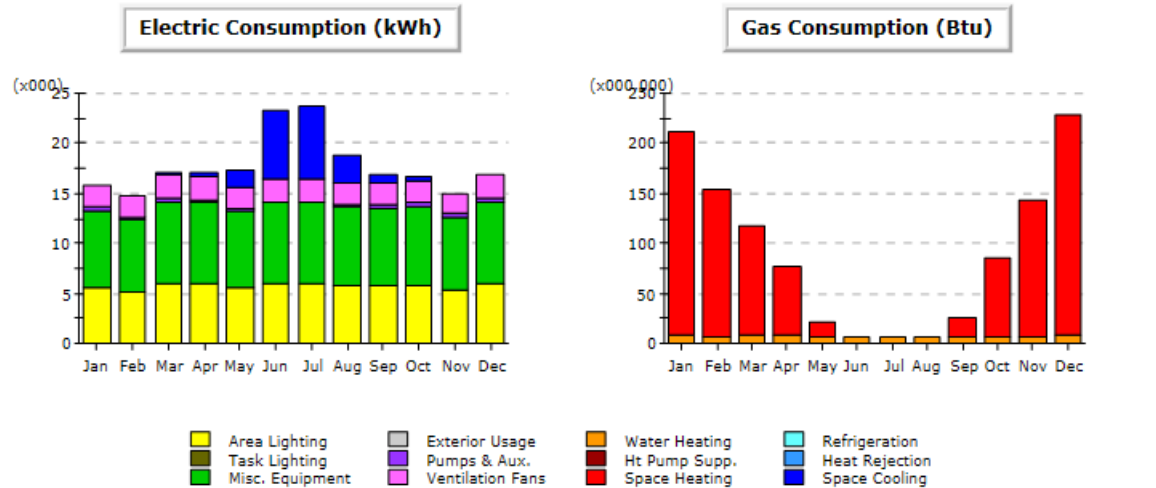
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.03	0.13	0.37	1.39	4.64	7.67	8.98	7.65	4.65	0.91	0.04	0.02	36.47
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.27	2.16	2.50	2.50	2.27	2.50	2.50	2.39	2.39	2.39	2.16	2.50	28.55
Pumps & Aux.	0.37	0.33	0.35	0.30	0.13	0.05	0.02	0.01	0.11	0.30	0.36	0.37	2.70
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	15.87	14.99	17.38	18.22	20.24	24.26	25.66	23.73	20.71	17.28	15.17	17.05	230.55

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	170.04	103.99	77.09	13.53	0.30	-	0.02	-	0.43	23.29	94.80	161.81	645.29
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	6.96	6.81	7.86	7.69	6.50	6.56	6.10	5.55	5.53	5.81	5.72	7.11	78.20
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	177.00	110.80	84.95	21.21	6.80	6.56	6.12	5.55	5.96	29.10	100.52	168.92	723.50

Figure A.2. Duluth IAP eQUEST Output



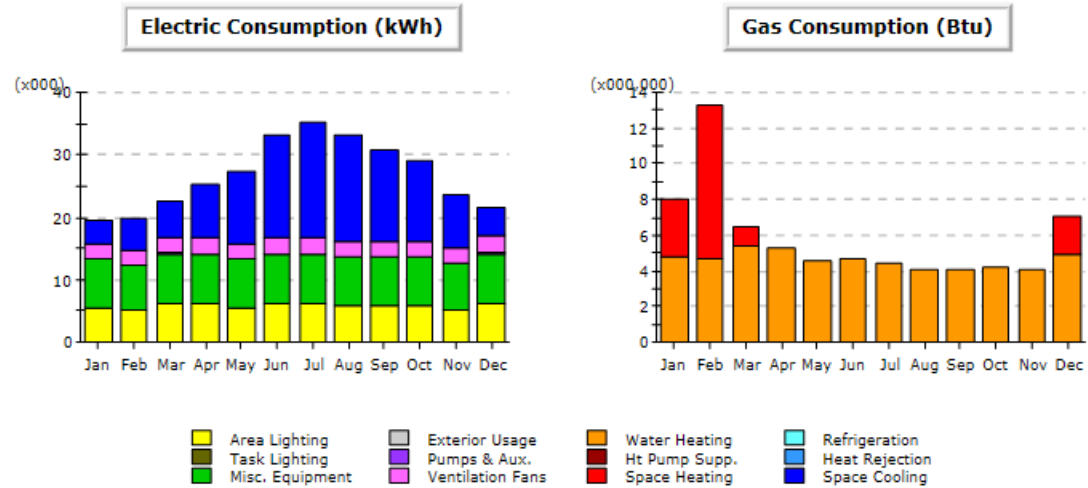
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	0.00	0.14	0.30	1.77	6.90	7.09	2.80	0.77	0.45	-	-	20.21
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.16	2.05	2.37	2.37	2.16	2.37	2.37	2.26	2.26	2.26	2.05	2.37	27.06
Pumps & Aux.	0.37	0.34	0.36	0.35	0.24	0.06	0.02	0.14	0.29	0.33	0.36	0.37	3.22
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	15.73	14.75	17.03	17.05	17.37	23.36	23.64	18.88	16.88	16.72	15.01	16.90	213.31

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	203.5	145.8	108.5	68.3	14.4	0.1	0.0	1.0	20.3	79.5	136.9	220.6	998.8
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	7.5	7.3	8.5	8.3	7.0	7.0	6.5	6.0	5.9	6.2	6.1	7.6	84.1
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	211.0	153.1	117.0	76.6	21.4	7.1	6.5	7.0	26.3	85.7	143.0	228.3	1,082.8

Figure A.3. Eielson AFB eQUEST Output



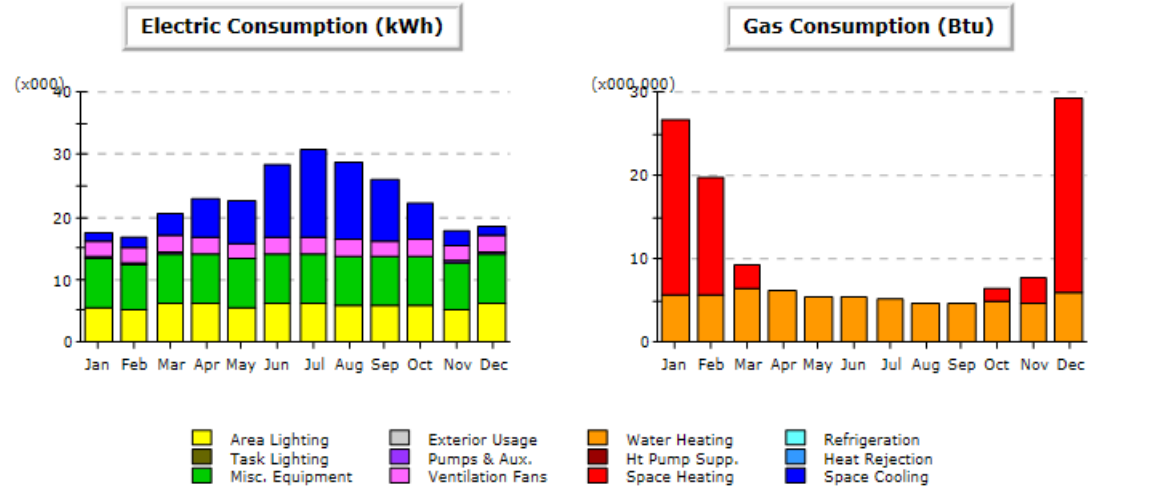
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	3.78	4.98	5.56	8.63	11.87	16.39	18.26	17.06	14.67	12.73	8.77	4.77	127.45
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.41	2.29	2.66	2.66	2.41	2.66	2.66	2.53	2.53	2.53	2.29	2.66	30.29
Pumps & Aux.	0.15	0.09	0.10	0.02	-	-	-	-	-	0.01	0.05	0.12	0.54
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	19.54	19.73	22.48	25.33	27.49	33.08	35.06	33.27	30.76	28.95	23.72	21.69	321.10

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	3.20	8.68	1.17	0.01	-	-	-	-	-	0.05	0.04	2.13	15.29
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	4.76	4.62	5.35	5.25	4.53	4.64	4.39	4.06	4.04	4.18	4.03	4.93	54.76
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	7.96	13.30	6.52	5.26	4.53	4.64	4.39	4.06	4.04	4.23	4.07	7.06	70.05

Figure A.4. Ellington Field JRB eQUEST Output



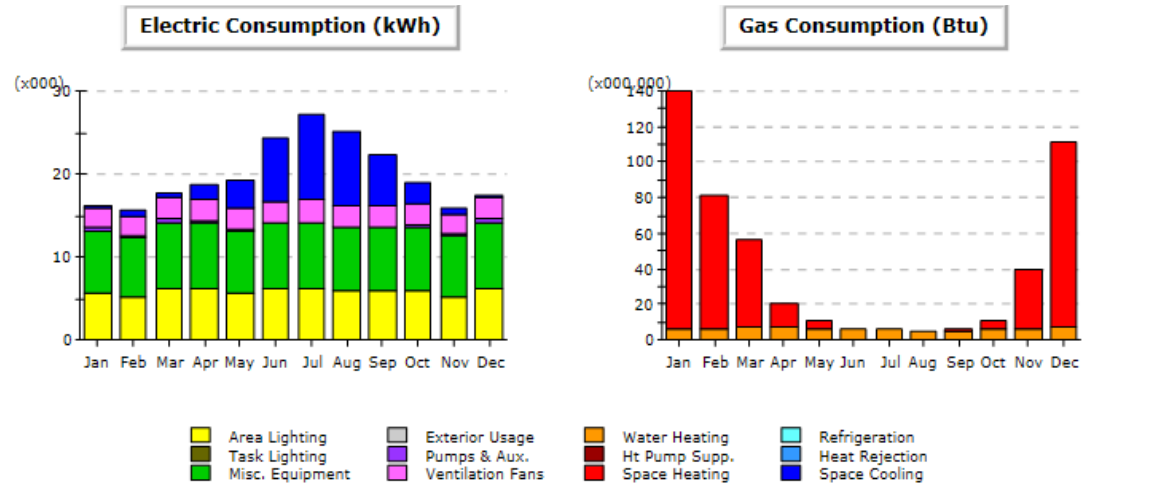
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	1.46	1.75	3.34	5.88	6.98	11.54	13.89	12.54	9.80	5.97	2.48	1.32	76.94
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.51	2.39	2.76	2.76	2.51	2.76	2.76	2.64	2.64	2.39	2.76	2.76	31.53
Pumps & Aux.	0.31	0.26	0.22	0.09	0.03	0.00	-	-	-	0.10	0.25	0.34	1.61
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	17.49	16.77	20.48	22.77	22.72	28.34	30.81	28.86	26.00	22.39	17.72	18.57	272.91

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	21.06	14.14	2.83	0.01	0.02	0.02	0.02	0.02	0.04	1.50	2.94	23.35	65.94
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5.67	5.55	6.41	6.27	5.36	5.42	5.06	4.64	4.62	4.82	4.71	5.83	64.37
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	26.73	19.69	9.23	6.28	5.37	5.44	5.08	4.66	4.65	6.33	7.66	29.19	130.31

Figure A.5. Kirtland AFB eQUEST Output



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.14	0.59	0.57	1.85	3.36	7.49	10.25	8.89	6.05	2.46	0.71	0.16	42.51
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.43	2.31	2.68	2.68	2.43	2.68	2.68	2.55	2.55	2.55	2.31	2.68	30.52
Pumps & Aux.	0.37	0.31	0.34	0.25	0.19	0.07	0.02	0.02	0.10	0.22	0.28	0.35	2.52
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	16.14	15.58	17.74	18.81	19.19	24.26	27.10	25.15	22.26	18.91	15.90	17.35	238.38

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	133.31	74.65	48.30	12.93	4.60	0.01	0.04	0.03	0.30	5.40	33.69	104.27	417.53
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	6.57	6.43	7.43	7.26	6.17	6.19	5.74	5.23	5.22	5.48	5.39	6.71	73.83
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	139.88	81.08	55.73	20.19	10.77	6.21	5.79	5.26	5.52	10.88	39.07	110.98	491.36

Figure A.6. Malmstrom AFB eQUEST Output

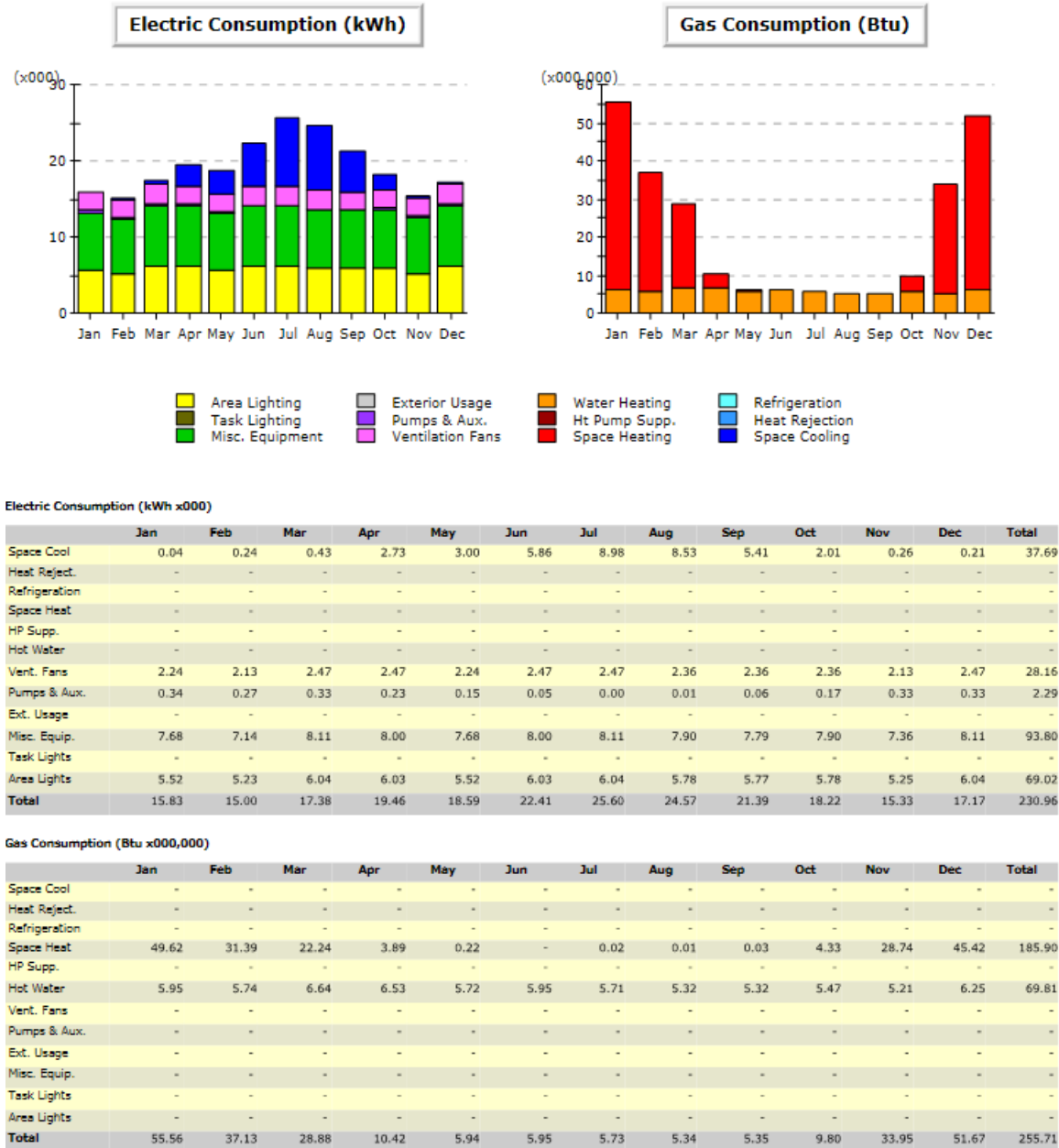
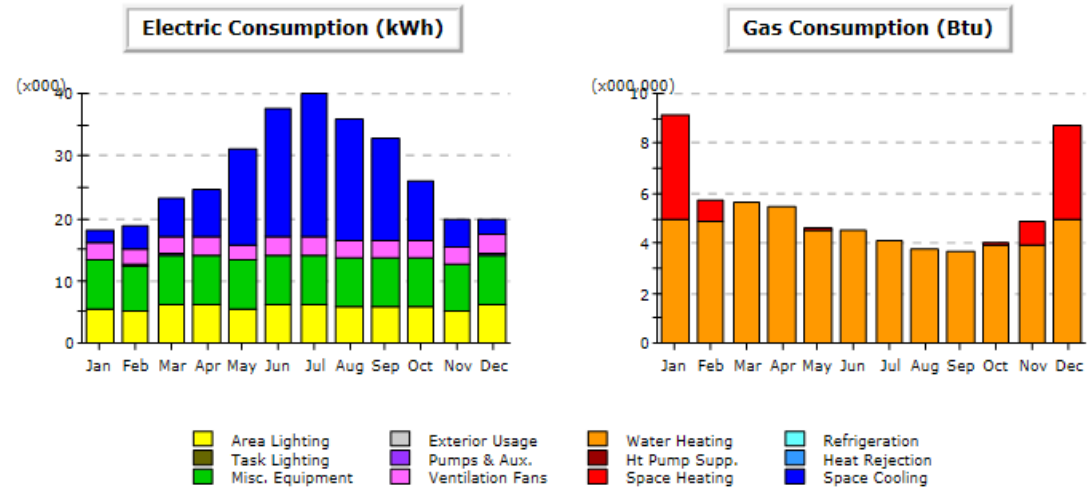


Figure A.7. McChord AFB eQUEST Output



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	2.08	3.63	6.20	7.54	15.32	20.71	22.75	19.55	16.42	9.41	4.54	2.40	130.54
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	2.66	2.53	2.93	2.93	2.66	2.93	2.93	2.80	2.80	2.80	2.53	2.93	33.44
Pumps & Aux.	0.20	0.15	0.07	0.06	-	-	-	-	-	0.01	0.15	0.20	0.85
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.68	7.14	8.11	8.00	7.68	8.00	8.11	7.90	7.79	7.90	7.36	8.11	93.80
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.52	5.23	6.04	6.03	5.52	6.03	6.04	5.78	5.77	5.78	5.25	6.04	69.02
Total	18.15	18.68	23.35	24.56	31.18	37.67	39.83	36.03	32.78	25.90	19.83	19.69	327.64

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	4.26	0.85	0.01	0.02	0.02	-	-	-	-	0.05	0.89	3.71	9.81
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	4.93	4.86	5.62	5.48	4.57	4.52	4.13	3.73	3.71	3.94	3.94	4.98	54.41
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	9.19	5.71	5.63	5.50	4.59	4.52	4.13	3.73	3.71	3.98	4.84	8.69	64.21

Figure A.8. Nellis AFB eQUEST Output

Appendix B. Data Analysis

Table B.1. Intermediary Baseline Capital Investment Calculations

Baseline Component	Line Item	Material	Labor	Overhead and Profit	Quantity	Total
Single Pane Windows	Sliding Aluminum 9' x 5'	\$530.00	\$211.00	\$950.00	85.3	\$81,066.67
SPW Total						\$81,066.67
Built Up Roof	3 ply system, installation only (per Sq.)	\$0.00	\$32.86	\$54.50	250.0	\$13,625.00
	Spunband poly. Fabric (10.8 Sq. per roll)	\$135.00	\$0.00	\$149.00	23.1	\$3,449.07
	Base and finish coat (3gal/Sq. 5gal/can)	\$7.75		\$8.55	750.0	\$6,412.50
	Coating	\$21.50	\$0.00	\$23.50	500.0	\$11,750.00
	Aluminum (2gal/sq)	\$13.50		\$14.85	500.0	\$7,425.00
	Emulsion	\$6.50	\$1.58	\$7.15	1000.0	\$7,150.00
BUR Total						\$49,811.57
Linear T8 Lights	F32T8	\$4.76	\$27.25	\$48.16	1564	\$75,322.24
Linear T8 Total						\$75,322.24

Table B.2. Intermediary Retrofit Capital Investment Calculations

Technology	Line Item	Material	Labor	Overhead and Profit	Quantity	Total
EC Windows	Demolition	\$0.00	\$0.00	\$92.50	77	\$7,104.00
	EC Window	\$0.00	\$0.00	\$50.00	3789	\$189,444.00
	EC Total					\$196,548.00
Triple Pane Windows	Demolition	\$0.00	\$0.00	\$92.50	77	\$7,104.00
	Triple Pane Window	\$486.95	\$211.00	\$725.00	85	\$61,842.50
	TPW Total					\$68,946.50
CRC	CRC	\$0.00	\$0.00	\$1.88	25000	\$47,000.00
	CRC Total					\$47,000.00
SSMR	24 ga. 1-3/4" standing seam	\$3.50	\$1.58	\$6.25	25000	\$156,250.00
	SSMR Total					\$156,250.00
ADC	Sensors and Controls			\$0.75	50000	\$37,500.00
	ADC Total					\$37,500.00
LED	LED Lamps	\$11.33	\$27.25	\$57.84	1564	\$90,458.63
	LED Total					\$90,458.63
DCV	Exhaust Fan	\$1,300.00	\$0.00	\$6,350.00	2	\$12,700.00
	Computer Programs (Enthalpy, time, duty cycle, optimum start/stop)	\$0.00	\$0.00	\$103.50	2	\$207.00
	Add'l Labor (Calibration, engineering, start-up)	\$0.00	\$0.00	\$336.00	2	\$672.00
	Sensors (space temp/humidity)	\$0.00	\$0.00	\$1,740.00	10	\$17,400.00
	Digital Output	\$0.00	\$0.00	\$340.00	2	\$680.00
	DDC Controller	\$0.00	\$0.00	\$3,275.00	2	\$6,550.00
	Dampener Control	\$0.00	\$0.00	\$2,000.00	2	\$4,000.00
	DCV Total					\$42,209.00
VSD	Remove CAV	\$0.00	\$0.00	\$6,350.00	4	\$25,400.00
	20000 CFM VAV	\$130,500.00	\$4,625.00	\$150,500.00	4	\$602,000.00
	VSD Total					\$627,400.00

Table B.3. Retrofit Energy Cost Savings for all Locations

Location	Technology	Electricity Saved (kWh*1000)	Gas Saved (MBTU)	Electricity Cost Savings (\$)	Gas Cost Savings (\$)	Total Cost Savings (\$)
Andrews AFB	EC Windows	16.69	-48.88	\$1,618.93	-\$484.69	\$1,134.24
Andrews AFB	Triple Pane Windows	3.74	82.09	\$363.07	\$814.00	\$1,177.08
Andrews AFB	BUR w/ CRC	0.23	-2.01	\$22.70	-\$19.93	\$2.77
Andrews AFB	SSMR	-2.66	27.99	-\$258.21	\$277.55	\$19.33
Andrews AFB	ADC	25.83	-20.31	\$2,505.32	-\$201.39	\$2,303.92
Andrews AFB	LED Upgrade	22.19	-20.71	\$2,152.53	-\$205.36	\$1,947.17
Andrews AFB	DCV	-1.18	32.69	-\$114.56	\$324.15	\$209.60
Andrews AFB	VSD	27.38	20.09	\$2,655.38	\$199.21	\$2,854.59
Duluth IAP	EC Windows	14.66	-73.80	\$756.61	-\$523.61	\$233.00
Duluth IAP	Triple Pane Windows	2.89	192.90	\$149.28	\$1,368.63	\$1,517.90
Duluth IAP	BUR w/ CRC	0.16	-2.90	\$8.00	-\$20.58	-\$12.58
Duluth IAP	SSMR	-0.92	-25.10	-\$47.52	-\$178.08	-\$225.61
Duluth IAP	ADC	23.90	-32.30	\$1,232.98	-\$229.17	\$1,003.81
Duluth IAP	LED Upgrade	21.03	-33.80	\$1,085.10	-\$239.81	\$845.29
Duluth IAP	DCV	-1.73	77.70	-\$89.47	\$551.28	\$461.81
Duluth IAP	VSD	28.65	-7.00	\$1,478.44	-\$49.67	\$1,428.78
Eielson AFB	EC Windows	9.99	-35.10	\$3,237.38	-\$281.47	\$2,955.91
Eielson AFB	Triple Pane Windows	1.33	228.50	\$431.43	\$1,832.34	\$2,263.78
Eielson AFB	BUR w/ CRC	0.15	-2.60	\$49.23	-\$20.85	\$28.38
Eielson AFB	SSMR	-2.47	-36.60	-\$798.74	-\$293.50	-\$1,092.23
Eielson AFB	ADC	19.13	-29.30	\$6,195.24	-\$234.96	\$5,960.28
Eielson AFB	LED Upgrade	20.24	-43.50	\$6,556.71	-\$348.83	\$6,207.88
Eielson AFB	DCV	-1.73	109.00	-\$560.99	\$874.07	\$313.08
Eielson AFB	VSD	24.93	-10.10	\$8,075.15	-\$80.99	\$7,994.16
Ellington Field JRB	EC Windows	21.35	-75.00	\$1,553.92	-\$538.43	\$1,015.49
Ellington Field JRB	Triple Pane Windows	7.55	102.00	\$549.86	\$732.26	\$1,282.12
Ellington Field JRB	BUR w/ CRC	0.31	-1.00	\$22.57	-\$7.18	\$15.39
Ellington Field JRB	SSMR	3.12	188.00	\$227.21	\$1,349.65	\$1,576.86
Ellington Field	ADC	27.27	-23.00	\$1,985.40	-\$165.12	\$1,820.28

Location	Technology	Electricity Saved (kWh*1000)	Gas Saved (MBTU)	Electricity Cost Savings (\$)	Gas Cost Savings (\$)	Total Cost Savings (\$)
JRB						
Ellington Field JRB	LED Upgrade	23.72	-24.00	\$1,726.74	-\$172.30	\$1,554.45
Ellington Field JRB	DCV	0.38	34.00	\$27.96	\$244.09	\$272.04
Ellington Field JRB	VSD	31.09	159.00	\$2,263.28	\$1,141.46	\$3,404.74
Kirtland AFB	EC Windows	29.02	-58.80	\$1,903.91	-\$399.43	\$1,504.48
Kirtland AFB	Triple Pane Windows	4.31	42.60	\$282.74	\$289.38	\$572.12
Kirtland AFB	BUR w/ CRC	0.51	-1.90	\$33.32	-\$12.91	\$20.42
Kirtland AFB	SSMR	-0.57	10.40	-\$37.72	\$70.65	\$32.93
Kirtland AFB	ADC	26.54	-9.80	\$1,740.70	-\$66.57	\$1,674.12
Kirtland AFB	LED Upgrade	22.55	-10.80	\$1,479.21	-\$73.36	\$1,405.85
Kirtland AFB	DCV	-4.06	28.30	-\$266.14	\$192.24	-\$73.90
Kirtland AFB	VSD	33.09	-2.20	\$2,170.51	-\$14.94	\$2,155.56
Malmstrom AFB	EC Windows	19.44	-70.20	\$1,275.20	-\$565.39	\$709.81
Malmstrom AFB	Triple Pane Windows	2.88	145.70	\$189.19	\$1,173.47	\$1,362.66
Malmstrom AFB	BUR w/ CRC	0.26	-3.00	\$17.19	-\$24.16	-\$6.97
Malmstrom AFB	SSMR	-1.63	-17.30	-\$107.12	-\$139.33	-\$246.46
Malmstrom AFB	ADC	24.15	-27.60	\$1,584.50	-\$222.29	\$1,362.21
Malmstrom AFB	LED Upgrade	21.30	-29.80	\$1,397.35	-\$240.01	\$1,157.34
Malmstrom AFB	DCV	-2.88	86.00	-\$189.12	\$692.64	\$503.52
Malmstrom AFB	VSD	30.30	-29.10	\$1,987.88	-\$234.37	\$1,753.51
McChord AFB	EC Windows	12.68	-31.50	\$831.68	-\$286.62	\$545.06
McChord AFB	Triple Pane Windows	1.30	84.20	\$85.54	\$766.14	\$851.68
McChord AFB	BUR w/ CRC	0.21	-1.60	\$14.04	-\$14.56	-\$0.52
McChord AFB	SSMR	-0.62	-4.90	-\$40.54	-\$44.59	-\$85.13
McChord AFB	ADC	23.77	-23.40	\$1,559.25	-\$212.92	\$1,346.33
McChord AFB	LED Upgrade	21.46	-26.40	\$1,407.58	-\$240.21	\$1,167.37

Location	Technology	Electricity Saved (kWh*1000)	Gas Saved (MBTU)	Electricity Cost Savings (\$)	Gas Cost Savings (\$)	Total Cost Savings (\$)
McChord AFB	DCV	-2.16	34.10	-\$141.96	\$310.28	\$168.32
McChord AFB	VSD	28.47	-33.80	\$1,867.30	-\$307.55	\$1,559.76
Nellis AFB	EC Windows	33.62	-13.43	\$2,205.14	-\$96.90	\$2,108.25
Nellis AFB	Triple Pane Windows	10.32	8.48	\$676.80	\$61.18	\$737.98
Nellis AFB	BUR w/ CRC	0.68	-0.60	\$44.35	-\$4.33	\$40.02
Nellis AFB	SSMR	-0.22	18.21	-\$14.17	\$131.39	\$117.22
Nellis AFB	ADC	28.01	-2.88	\$1,837.26	-\$20.78	\$1,816.48
Nellis AFB	LED Upgrade	23.73	-3.03	\$1,556.82	-\$21.86	\$1,534.96
Nellis AFB	DCV	-0.96	3.34	-\$62.71	\$24.10	-\$38.62
Nellis AFB	VSD	33.22	10.91	\$2,179.17	\$78.72	\$2,257.88

Table B.4. Retrofit Prioritization Values for all Locations

Location	Technology	WIR	NPV
Andrews AFB	EC Windows	0.00	-\$58,512.69
Andrews AFB	Triple Pane Windows	0.00	-\$7,247.81
Andrews AFB	BUR w/ CRC	0.00	-\$39,012.68
Andrews AFB	SSMR	0.00	\$10,574.70
Andrews AFB	ADC	0.00	-\$6,363.96
Andrews AFB	LED Upgrade	0.03	\$126,037.55
Andrews AFB	DCV	-0.01	-\$34,016.47
Andrews AFB	VSD	0.01	\$2,957.72
Duluth IAP	EC Windows	0.00	-\$80,240.81
Duluth IAP	Triple Pane Windows	0.00	-\$8,429.30
Duluth IAP	BUR w/ CRC	0.00	\$47,060.04
Duluth IAP	SSMR	0.00	-\$8,851.48
Duluth IAP	ADC	-0.01	-\$19,654.95
Duluth IAP	LED Upgrade	0.01	\$103,577.80
Duluth IAP	DCV	-0.03	-\$35,553.22
Duluth IAP	VSD	-0.01	-\$9,378.35
Eielson AFB	EC Windows	0.00	-\$150,053.49
Eielson AFB	Triple Pane Windows	0.00	-\$40,696.32
Eielson AFB	BUR w/ CRC	0.00	\$50,376.66
Eielson AFB	SSMR	0.00	-\$148,579.05

Location	Technology	WIR	NPV
Eielson AFB	ADC	0.00	-\$9,583.91
Eielson AFB	LED Upgrade	0.00	\$183,854.04
Eielson AFB	DCV	-0.02	-\$80,683.78
Eielson AFB	VSD	0.00	\$16,781.10
Ellington Field JRB	EC Windows	0.00	-\$46,105.43
Ellington Field JRB	Triple Pane Windows	0.00	-\$548.29
Ellington Field JRB	BUR w/ CRC	0.00	\$46,332.12
Ellington Field JRB	SSMR	0.00	\$56,102.17
Ellington Field JRB	ADC	-0.01	-\$6,224.61
Ellington Field JRB	LED Upgrade	0.05	\$121,085.99
Ellington Field JRB	DCV	0.00	-\$27,184.72
Ellington Field JRB	VSD	0.03	\$9,517.25
Kirtland AFB	EC Windows	0.00	-\$46,806.51
Kirtland AFB	Triple Pane Windows	0.00	-\$10,661.75
Kirtland AFB	BUR w/ CRC	0.00	\$46,540.87
Kirtland AFB	SSMR	0.00	\$20,436.17
Kirtland AFB	ADC	-0.01	-\$9,019.45
Kirtland AFB	LED Upgrade	0.03	\$117,308.83
Kirtland AFB	DCV	-0.01	-\$34,785.00
Kirtland AFB	VSD	0.00	-\$396.47
Malmstrom AFB	EC Windows	0.00	-\$71,660.65
Malmstrom AFB	Triple Pane Windows	0.00	-\$8,717.63
Malmstrom AFB	BUR w/ CRC	0.00	\$46,969.30
Malmstrom AFB	SSMR	0.00	-\$4,959.59
Malmstrom AFB	ADC	-0.01	-\$15,957.34
Malmstrom AFB	LED Upgrade	0.01	\$109,883.25
Malmstrom AFB	DCV	-0.03	-\$33,467.52
Malmstrom AFB	VSD	-0.01	-\$6,431.02
McChord AFB	EC Windows	0.00	-\$75,154.07
McChord AFB	Triple Pane Windows	0.00	-\$14,939.91
McChord AFB	BUR w/ CRC	0.00	\$47,045.83
McChord AFB	SSMR	0.00	-\$4,150.28
McChord AFB	ADC	-0.01	-\$16,558.11
McChord AFB	LED Upgrade	0.02	\$109,762.33
McChord AFB	DCV	-0.01	-\$39,059.91
McChord AFB	VSD	-0.01	-\$8,123.89
Nellis AFB	EC Windows	0.00	-\$67,659.30

Location	Technology	WIR	NPV
Nellis AFB	Triple Pane Windows	0.00	-\$19,994.54
Nellis AFB	BUR w/ CRC	0.00	\$47,483.74
Nellis AFB	SSMR	0.00	-\$12,205.55
Nellis AFB	ADC	-0.01	-\$15,602.02
Nellis AFB	LED Upgrade	0.02	\$114,801.65
Nellis AFB	DCV	0.00	-\$46,130.36
Nellis AFB	VSD	-0.01	-\$5,115.60

[illegible]

Figure B.1. Intermediary O&M Calculations

Table B.5. Final Rankings for all Locations and Retrofit Technologies

Location	Technology	WIR	NPV
Andrews AFB	EC Windows	5	7
Andrews AFB	Triple Pane Windows	6	6
Andrews AFB	BUR w/ CRC	7	4
Andrews AFB	SSMR	2	2
Andrews AFB	ADC	3	3
Andrews AFB	LED Upgrade	1	1
Andrews AFB	DCV	8	5
Andrews AFB	VSD	4	8
Duluth IAP	EC Windows	5	7
Duluth IAP	Triple Pane Windows	4	6
Duluth IAP	BUR w/ CRC	6	4
Duluth IAP	SSMR	2	1
Duluth IAP	ADC	7	3
Duluth IAP	LED Upgrade	1	2
Duluth IAP	DCV	8	5
Duluth IAP	VSD	3	8
Eielson AFB	EC Windows	5	7
Eielson AFB	Triple Pane Windows	6	6
Eielson AFB	BUR w/ CRC	7	4
Eielson AFB	SSMR	2	2
Eielson AFB	ADC	3	3
Eielson AFB	LED Upgrade	1	1
Eielson AFB	DCV	8	5
Eielson AFB	VSD	4	8
Ellington Field JRB	EC Windows	6	7
Ellington Field JRB	Triple Pane Windows	5	5
Ellington Field JRB	BUR w/ CRC	7	4
Ellington Field JRB	SSMR	2	1
Ellington Field JRB	ADC	3	3
Ellington Field JRB	LED Upgrade	1	2
Ellington Field JRB	DCV	8	6
Ellington Field JRB	VSD	4	8
Kirtland AFB	EC Windows	5	7
Kirtland AFB	Triple Pane Windows	6	6
Kirtland AFB	BUR w/ CRC	7	4
Kirtland AFB	SSMR	2	2
Kirtland AFB	ADC	4	3

Location	Technology	WIR	NPV
Kirtland AFB	LED Upgrade	1	1
Kirtland AFB	DCV	8	5
Kirtland AFB	VSD	3	8
Malmstrom AFB	EC Windows	4	7
Malmstrom AFB	Triple Pane Windows	5	6
Malmstrom AFB	BUR w/ CRC	7	4
Malmstrom AFB	SSMR	2	1
Malmstrom AFB	ADC	6	3
Malmstrom AFB	LED Upgrade	1	2
Malmstrom AFB	DCV	8	5
Malmstrom AFB	VSD	3	8
McChord AFB	EC Windows	4	7
McChord AFB	Triple Pane Windows	5	6
McChord AFB	BUR w/ CRC	7	4
McChord AFB	SSMR	2	1
McChord AFB	ADC	6	3
McChord AFB	LED Upgrade	1	2
McChord AFB	DCV	8	5
McChord AFB	VSD	3	8
Nellis AFB	EC Windows	4	7
Nellis AFB	Triple Pane Windows	6	6
Nellis AFB	BUR w/ CRC	7	4
Nellis AFB	SSMR	2	1
Nellis AFB	ADC	5	3
Nellis AFB	LED Upgrade	1	2
Nellis AFB	DCV	8	5
Nellis AFB	VSD	3	8

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14. ABSTRACT The United States Air Force spent \$126M on facility energy in fiscal year 2014 and that cost continues to rise. Additionally, the Energy Independence and Security Act of 2007 mandated that the Air Force reduce energy intensity 30% by 2015 compared to a 2003 baseline has not been met. This necessitates an in-depth examination of technologies capable of reducing energy consumption in existing facilities across the spectrum of Air Force operating climates. This research provides retrofit recommendations for existing facilities and examines the Air Force method to prioritize energy projects. This study simulates eight different retrofit technologies and locations to establish retrofit recommendations tailored to Air Force facilities in different climate zones. A life-cycle cost analysis was performed to compare the Air Force's prioritization method to an industry standard method and determine which method provides the greatest return on investment. Results indicate that the best retrofit technology for existing facilities depends on climate. Additionally, the Air Force prioritization method was inconsistent when compared to the industry standard method. Finally, the Air Force prioritization method resulted in lower ROIs when compared to industry standard methods. The results suggest transitioning away from one-size-fits-all retrofits for existing facilities and a poor prioritization method.					
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