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# Cost and Performance Difference of High Performance Sustainable Buildings

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# COST AND PERFORMANCE DIFFERENCE OF HIGH PERFORMANCE SUSTAINABLE BUILDINGS

THESIS

Philip A. Ramsey, Captain, USAF
AFIT-ENV-MS-18-M-230

**DEPARTMENT OF THE AIR FORCE**
**AIR UNIVERSITY**

## AIR FORCE INSTITUTE OF TECHNOLOGY

**Wright-Patterson Air Force Base, Ohio**

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AFIT-ENV-MS-18-M-230

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

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Philip A. Ramsey, BS

Captain, USAF

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# COST AND PERFORMANCE DIFFERENCE OF HIGH PERFORMANCE SUSTAINABLE BUILDINGS

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# Abstract

Varying legislation and executive orders coupled with needs for energy resiliency have led the United States Air Force to pursue sustainable construction. The limited understandings of initial costs to implement these changes have contributed to poor project cost estimating and changed implementation of legal requirements. A student t-test for populations with unequal variance was accomplished on the final normalized contract cost of 1628 Air Force Military Construction (MILCON) projects executed between 2002 and 2017. Future design considerations for net zero energy buildings were compiled from a net zero energy residential community in Fontana, California.

There was no statistically significant difference in final contract costs for fifteen of sixteen building categories between samples from before and post federal sustainability requirements. Furthermore, in a pilot study in Fontana, California, 94 percent of residential homes designed to net zero criteria failed to meet net zero in the following year due to underestimated occupant process loads. The study revealed projects influenced by numerous criteria that impact costs. Showing *green* standards are a poor indicator of additional project costs. Additionally, when designing net zero energy buildings and other highly sustainable structures, occupant behavior estimates need to be more accurately estimated.  This validates similar research and invalidates the Air Force’s two percent increase on project cost for sustainability requirements and each project should be considered on a case by case basis.

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# COST AND PERFORMANCE DIFFERENCE OF HIGH PERFORMANCE SUSTAINABLE BUILDINGS

## I. Introduction

### Background

On March 19th 2015, United States President Barack H. Obama signed Executive Order (EO) 13693. The order mandates all United States' federal government newly constructed buildings over 5,000 square feet and $3 million must be designed as net zero energy by 2020, when life-cycle cost effective. A net zero building is a structure that generates more energy than it consumes over a given time period, typically a year (Torcellini, Pless, & Deru, 2006). Life-cycle cost effective is when an upgrade in a building's components will pay back more value than what it costs to install over the building's entire usable time period (Department of Energy, 1996). Net zero buildings required by EO 13693 provide benefits for federal agencies. First, net zero energy buildings have drastically reduced energy costs. Second, net zero energy buildings are more resilient. They have the ability to operate independent of a power grid. The goal is to reduce dependency on electrical grid connections that can fail and prevent building usage due to unexpected events. Last, net zero energy buildings also have a reduced impact on climate change through reduced emissions (Lesniewski, Matthiessen, Morris, & Tepfer, 2014).

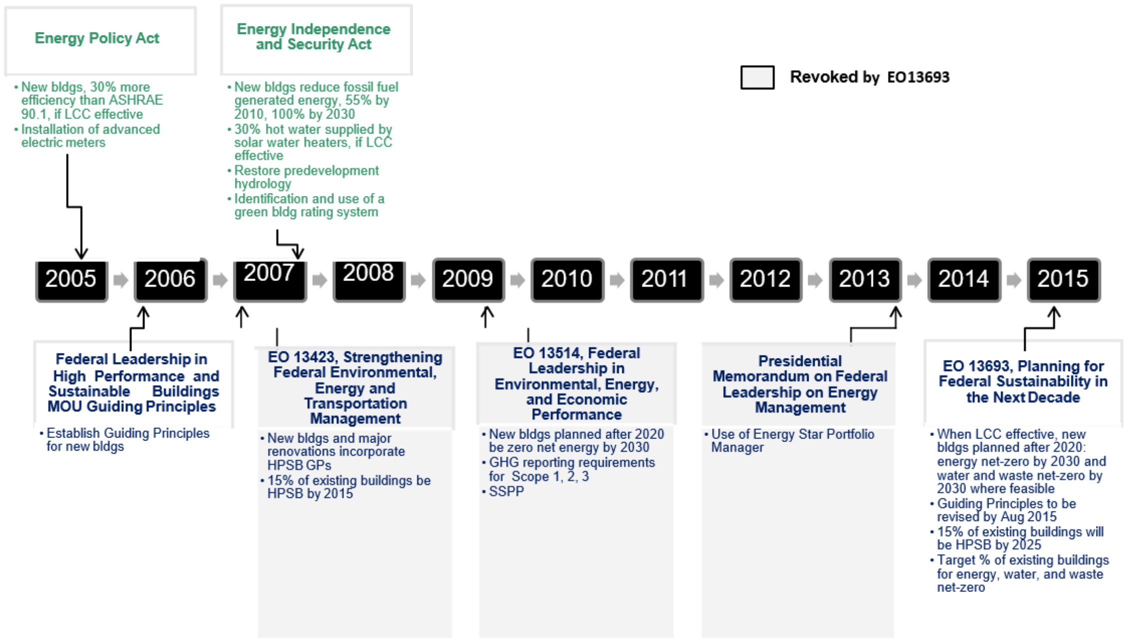

**Figure 1: Federal Sustainable Laws (Shaw, 2017)**

However, EO 13693 is just the culmination of several federal mandates for sustainability as shown in Figure 1. The Energy Policy Act of 2005 was passed by Congress and signed by President George W. Bush on August 8th, 2005. This 550 page law requires all federal agencies to achieve certain energy efficiencies, guidance on renewable energy, and provides many tax credits to various energy industries. Furthermore, it spurred federal agencies to develop a common energy design standard of sustainable buildings that resulted in the Federal Leadership in High Performance and Sustainable Building Memorandum of Understanding Guiding Principles. This succinct 19 page, initially voluntary, standard is more commonly called the Guiding Principles and was formalized in EO 13423. The Guiding Principles describes what federal buildings must incorporate to be High Performance Sustainable Buildings (HPSB). EO 13423 directed Guiding Principles’ implementation for federal agencies and set a goal of

15% of all federal buildings achieving HPSB status by 2015. President Obama added further sustainability requirements in EO 13514, specifically in the form of net zero building timelines. Additionally, his presidential memorandum required the use of Energy Star appliances and equipment to reduce plug loads. As mentioned previously, these requirements are summarized and clarified in EO 13693. All the regulatory documents shown in Figure 1 are driving the federal construction market. These efforts seek to reduce cost, increase resiliency, and limit the governments impact on climate change (President of The United States, 2015; Shaw, 2017).

Climate change is the gradual transformation of weather patterns that can be viewed on a local or global scale. This is a hotly debated topic with varying predictions of the impact and scope of climate change. A great deal of research has been performed to show how humans are impacting that change through consumption of fossil fuels and the resulting emissions (Francis, Vavrus, & Cohen, 2017; Geographic, 2017; National Research Council, 2010; Stocker & T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, 2015). Commercial and residential buildings account for 40 percent of the United States global warming emissions and 70 percent of electrical use (Berry, 2017; Energy Information Administration, 2011). Building energy use will continue to rise along with its impact on climate change unless buildings can be designed to produce energy to offset the energy used at the same building.

Net zero buildings are created through two broad strategies: reduction of energy consumption and energy generation (Crawley, Pless, & Torcellini, 2009). Reduction of energy is accomplished by limiting heat transfer via conduction, convection, and radiation to the conditioned space. This reduces the heating and cooling loads for a structure. Additionally, to reduce energy consumption requires diminishing unregulated loads such as lighting and electronics use. This objective is aided through technological advances that can increase the efficiency of current technologies. Another aspect of net zero energy buildings is renewable energy generation. Renewable energy is often described as energy collected from natural processes that are continuously replenished (Ciolkosz, 2017). These technologies include sources such as sunlight, wind, tides, rivers, and ground temperatures. Renewable energy generation produces little to no emissions that contribute to climate change. Renewable energies in the United States account for 16 percent of energy produced with the remaining 84 percent coming from fossil fuels (Energy Information Administration, 2011)

Net zero energy buildings rely on renewable energies that are often intermittent. The sun eventually sets and the wind rarely blows continuously. To account for these changes, there needs to be an energy storage mechanism most often in the form of batteries. However, batteries can have a large first cost and performance can diminish over time, thus requiring net zero energy buildings to still be connected to the electrical grid; however, over the course of time, the structure’s systems will generate more energy than it uses. To determine the amount of energy use, it is typically tracked over 12 months to account for seasonal variations. Energy can be accounted for in many forms. Torcellini et al. (2006) developed four net zero definitions. The first and most common definition is *net zero site energy* where a building produces as much energy as it uses. Second, *net zero source energy* buildings consider the efficiency of the fuel sources. Third, is *net zero energy costs*, which balances energy use based on the amount charged by the grid connection and price paid for by excess energy produced by the building.

Finally, *net zero energy emissions,* which looks at the carbon dioxide produced by each fuel type and balances this with the amount of fuel sequestered through renewable sources. The most common definition used is *net zero site energy* (Torcellini et al., 2006). Executive order 13693 requires net zero energy and the verbiage implies net zero site energy (President of The United States, 2015).

## Problem Statement

Compliance with Executive Order 13693 requires additional effort in construction beyond the industry code standard. This goal involves increasing energy efficiency and installing renewable energies through design efforts and proper material and technology selections. These objectives typically have an increased first expense. While these construction techniques may be cheaper over the lifetime of the building, it is often difficult for owners to pay for the upgrades at the start of the life-cycle. Because of this, the current push for net zero buildings is driven by regulatory forces, such as EO 13693, rather than the free market.

There has been little definitive research on the additional upfront costs associated with public net zero energy buildings. The United States Air Force budgeted to invest a total of $5 billion in infrastructure projects in 2017; of the total, $1.7 billion is planned for new construction projects (United States Air Force, 2017). With similar construction budgets each year, the Air Force needs to know how much additional funds will be needed to comply with Executive Order 13693 requirements mandated to start in 2020. A small percentage increase could reduce the number of buildings constructed or inhibit other defense related tasks.

Furthermore, the United States Air Force procures new buildings almost exclusively through contracts with private construction companies. These contracts communicate actions performed by each party. As the Air Force has yet to procure a net zero energy building, it is unknown what documentation should be included to contractually ensure a net zero building is designed and built by the contractor. The lack this knowledge has the potential to increase the risk of cost overruns, depending on contract structure. While technology and design can be specified in contracts to obtain certain levels, ultimately education of the occupants to operate the building as designed is key for net zero energy obtainment.

## Research Objectives and Questions

This research sought to understand the cost of sustainable construction and understanding energy requirements, thereby enabling enhanced budgeting and forecasting. The data around this research involves new Air Force construction projects from 2002 through 2017. All values are normalized to account for location, time of construction, size, and building type. By performing this analysis, the study focused on answering the following questions.

1. *Are Air Force construction costs statistically different from 2002-2007 compared to when sustainability requirements were imposed from 2008-2017 resulting in an estimated two percent increase in first construction costs?*

This first question seeks to understand the incremental costs of constructing a building compliant with all sustainable laws and executive orders in the public sector, which has other special requirements compared to the private sector. Can a standard percentage cost increase be applied to projects very early in the design phase for more accurate budgeting?

2. *Which performance factors should be considered when constructing a net zero building while meeting all other Air Force requirements?*

When building a net zero building, there are requirements that must be considered and designed for that are less critical in a traditional code compliant building. This question looks to understand what items the Air Force should consider in addition to what is currently being considered under UFC 1-200-02 *High Performance and Sustainable Building Requirements*.

3. *What documentation should be included in a net zero design package?*

This question takes a qualitative look at contract language and requirements that have been included in successful net zero energy buildings and determining if it is applicable to Air Force construction. This includes defining standard contract language or specific requirements to match the specific construction site.

## Methodology

During any cost analysis, the first step is to determine if there is actually a difference between two sets of data. This will entail applying a t-test on Air Force MILCON projects over the past 12 years. The costs of each project will be normalized for factors to include size, location, and relative cost of money at the time of construction, and compared against similar types of buildings. The confidence level will be selected at 95 percent. All calculations will be completed using Microsoft Excel 2013. Additional basic statistical calculations will be completed on energy data obtained from California homes designed to net zero standards. Finally, interviews with the construction agents will be conducted to determine the best documentation practices in procuring a highly sustainable building.

## Justification

All federal agencies, including the Air Force, follow a similar annual budget for procuring resources. Projects are programmed and selected based on need and budget limits (Department of the Air Force, 2016). As with any budget, accurate cost estimates enable funds to be properly allocated early in the process. The Air Force has struggled to properly create cost estimates. In 2014, 63 percent of military construction (MILCON) projects had cost growths above the industry average of five percent (Air Force Audit Agency, 2015). These growths often occurred due to poor understanding of the construction requirements (18M Graduate Engineering Management Class, 2017). The task of accurate cost estimates is further complicated by including newer construction technology and techniques associated with net zero buildings that have lesser known material and labor costs. The Air Force currently applies a two percent cost increase to meet current energy goals and standards outline in UFC 1-200-02; however, these standards are below net zero energy building requirements (Department of Defense, 2017b).

## Assumptions

The residential data obtained for this study was provided for homes built by Meritage Homes located in California. The data was provided by a private company and is assumed to be accurate. These homes were designed to be net zero through increased efficiencies and installed solar panels. These buildings were designed to be net zero energy and not require later modifications to achieve net zero if initial construction failed to meet this goal. Executive Order 13693 requires buildings are designed as net zero starting in 2020 and achieve net zero in 2030. Assuming the homes are net zero aligns with the first part of the executive order. Later research could be used to determine if the technologies used actually resulted in a net zero energy home.

While construction is often grouped into one industry, there are many parts that use varying technologies and construction strategies. One easy distinction is residential compared to commercial construction. The two sectors comply with regulations that often overlap, but they do have differences. For example, commercial projects require that electrical wires be in conduit whereas residential projects allow wires to be installed uncovered in walls. Additionally commercial projects are often larger and more expensive. In an effort to isolate the *green* construction cost, residential projects are a good case study because the designs are repeated and limit variation. For this research, the differences between commercial and residential structures are assumed to be limited and the statistics used are applicable to Air Force applications.

# II. Literature Review

This chapter provides essential knowledge of net zero energy building characteristics and how these characteristics influence each other. Additionally, the benefits of net zero energy buildings are presented along with a summary of the overall *green* building industry to include cost, energy reduction, and payback periods. Each section of the literature review demonstrates a critical understanding of building history, *green* and net zero cost premiums, sustainable characteristics, building techniques, Air Force compliance with regulations, and the lack of existing federal cost research.

## Net Zero Energy Building History

Net zero energy buildings are a subset of the larger *green* building construction industry. Before the invention of electricity, and ultimately air conditioning, most buildings had limited environmental impact; buildings were required to use passive designs for heating and cooling. Passive characteristics are those that require little to no electrical energy to use. Examples include the iconic Flatiron Building in New York, New York, that employed deep set windows and awnings to reduce heat absorbed by the building (Marble Institute, 2006). With the large-scale use of heating, ventilation, and air conditioning (HVAC) starting in the 1930s to 1960s, buildings no longer needed passive designs and their energy demand increased rapidly. Structures could be built out of any material or method and the HVAC systems could be installed to overcome the heating and cooling needs of the structure using energy created by cheap fossil fuels. A focus on energy efficiency was reborn in 1970 with the first Earth Day, and was spurred by the oil embargo in 1973 that made *green* construction more cost effective. This movement is known today as the *green* construction movement (Marble Institute, 2006; Rashkin, 2012).

One of the first official *green* certifications was developed by the United States *Green* Building Council (USGBC). The USGBC developed the Leadership in Energy and Environmental Design (LEED) which is a rating system to score construction projects based on a repeatable index of *green* construction methods to document each structure's sustainable features. LEED is one of the largest and most recognizable *green* construction certifications. American organizations such as the United States Air Force and Army, Kohl's, and PNC Bank have used LEED as their standard for new buildings. LEED includes categories such as location, energy reduction, water reduction, materials used, and indoor air quality. All of these factors look at the entire life-cycle of the building to include construction, operation, and demolition of the building (United States *Green* Building Council, 2017). However, only a few of these categories apply to net zero energy buildings. Most net zero energy buildings can and often do achieve very high LEED ratings, but a LEED building is rarely a net zero energy building. LEED points are earned based on how the building performs in various sustainable categories. Many of these categories have little to do with the building achieving net zero energy, such as reusing content, indoor air quality, access to public transportation, or even amount of parking spaces. Buildings can achieve a LEED certification and have drastically different features. LEED looks to takes a larger system view of how a building impacts the environment. This becomes problematic when using LEED as a benchmark for compliance with mandated laws.

Net zero energy buildings are a relatively new *green* construction label in the industry. The “net” means that the building is still connected to the electrical grid, but over the course of a year the building will generate more energy than it uses. A boundary is defined to account for energy usage and can be adjusted to several different definitions of net zero energy. These methods of calculating energy use include site, source, cost, and emissions method. When the building produces more energy than it needs, this energy can be supplied back to the electrical grid (Torcellini et al., 2006). The Net Zero Energy Coalition estimated there were 4,077 net zero energy residential buildings in the United States and Canada in 2016 (Edminster & Sankaran, 2017). This 33 percent increase in the inventory from 2015 demonstrates the growth in popularity. However, there were a total of 768,000 homes built in the United States in 2016 with only 0.5 percent actually built to net zero standards (United States Census Bureau, 2017). While net zero homes have increased, it still remains a niche market.

## Net Zero Energy Building Characteristics

LEED buildings and net zero energy buildings share many of the same aspects. Both philosophies emphasize early coordination with the project team and stakeholders (National Renewable Energy Laboratory, 2014). Traditional construction follows a sequential design path in which everyone involved in a major component or subsystem of the facility includes their contribution and then the building documents are passed to the next design team for their input. However, in *green* and net zero construction, many aspects are interdependent across many designers. This creates a synergistic working relationship among many architects and engineers working on the project. For example, the building orientation developed by the architect and the type of lights selected by the electrical engineer will drive the load requirements and sizing of the air conditioning specified by the mechanical engineer. Many energy-dense construction features cannot be added later in the design process; to fully implement energy saving opportunities, they must be designed at the very beginning of the facility design (National Renewable Energy Laboratory, 2014).

The design process of net zero energy buildings focuses on two aspects: reducing the building's energy demand and installing of renewable energy generation (Harkouss, Fardoun, & Biwole, 2016; International Living Future Institute, New Buildings Institute, & Skanska, 2013a; National Renewable Energy Laboratory, 2014). Reducing energy demand involves preventing heat transfer through the building and reducing process loads. Process energy includes lighting, computers, equipment, or anything that needs to be "plugged in" (Lesniewski et al., 2014). How net zero energy buildings reduce energy use varies widely, but concepts behind the strategies remain the same.

The most significant way to reduce demand is to design and construct an efficient building enclosure. The building enclosure, which consists of the walls, roof, and foundation, separates the outdoor environment from the indoors. Increased resistance to heat flow through the walls, floor, and ceiling is accomplished mainly through the addition of more insulation. Insulation of roofs and walls is measure in R-values which has units of BTU/(hr*°F*ft$^2$). An increased R-value slows energy movement across the enclosure. While energy still moves across the thermal barriers, it is at a much slower pace, which results in a lower demand for HVAC equipment to remove the thermal energy in the summer months or insert heat energy during the winter months.  Increased insulation is often the most cost effective method for reducing energy consumption (Kayfeci, Keçebaş, & Gedik, 2013).

Many buildings try to increase insulation and decrease areas in the building envelope with low R-values such as windows. Conversely, research has shown that properly designed windows can be designed to allow maximum light in and decrease energy requirements by 30-50 percent (Shen & Tzempelikos, 2012). These savings are achieved through reduced lighting loads, heat gains from the lights, and preventing heat loss through the windows. However, lighting is still required for when the sun does not shine or is hindered by clouds. Improved lighting efficiency can be obtained through light emitting diodes (LEDs) and installing occupancy sensors that turn the lights off when occupants are not in the area for a predetermined amount of time. LED lights are able to decrease electrical demand by as much as 50 percent (Brien & Borgealt, 2010).

Another energy demand reduction strategy is improving the equipment that provides heating and cooling. HVAC demand is dependent on location and season; it can account for almost 50 percent of a building's energy use (International Living Future Institute, New Buildings Institute, & Skanska, 2013b). The previous concepts discussed (envelope and lighting) directly impact the size and energy use of the mechanical systems. Additional cost savings can be realized by increasing the building enclosure efficiency and decreasing the size of the air conditioning equipment (International Living Future Institute et al., 2013b). Ground source heat pumps rely on the relatively constant temperature of the ground to provide heating and cooling rather than typical HVAC systems that rely on the highly variable outdoor air temperature (International Living Future Institute et al., 2013b).

HVAC systems are required by law to meet certain specifications. The efficiency of HVAC systems are measured in Seasonal Energy Efficiency Ratio (SEER) or Energy Efficiency Ratio (EER). The higher the number, the more efficient it is and the less energy the system will use. Similar to how regulations and laws are driving net zero buildings, new regulations and construction standards are requiring minimum SEER ratings for new installations. In 1992, a minimum SEER of 10 was required. In 2006, new construction required a SEER of 13. As of January 1st, 2015, the minimum SEER rating is 14 (American Standard, 2015; Vaughan, 2002). This just shows how federal regulations can be used to drive the market towards energy efficiency, similar to how the federal government is driving the market to net zero energy.

Reducing energy demand decreases the amount of energy production needed on-site to obtain net zero energy use. While net zero buildings are built using countless combinations of energy efficiency upgrades, there are relatively few renewable energy production methods. This is especially true for small-scale residential homes. Homes are often on smaller lot sizes and close to other homes, which makes wind, geothermal, or hydroelectric energy production impractical.  Net zero buildings' most common renewable energy source is solar production, which uses photovoltaic (PV) panels to generate electricity from the sun's radiation (Edminster & Sankaran, 2017). PV panels are easy to place on the roof or the area surrounding the building. Wind is another source of renewable energy that uses the gusts to turn turbines and generate electricity. However, wind is a rare form of renewable energy for a single building as the turbines can be unsightly and noisy (Torcellini et al., 2006). A third form of renewable energy includes using geothermal steam to power turbines. Geothermal energy is also rare for individual buildings given the large infrastructure investment and its availability only in certain seismically active regions such as Iceland (Orkustofnun, 2014). Water is another form that can be used to power turbines, but it has the same faults as geothermal production because it often requires a large water body and a dam to control the water. All four forms of renewable energy, solar, wind, geothermal, and water, can be used for large scale energy generation, but solar is typically the only practical application for individual buildings (National Renewable Energy Laboratory, 2014).

Previous research efforts and completed construction have shown there are countless ways to construct a net zero building. However, there are several principles that remain the same: reduce the overall energy demand of the structure and install renewable energy generation to offset the remaining energy demand. Given net zero energy buildings' energy variability and the relatively new appearance of net zero buildings, it has been difficult to determine a prescribed method or fully understand what the additional costs should be for future budgeting (International Living Future Institute et al., 2013a).

### ***Green* Construction Costs**

The United States construction industry employs six million individuals per year and creates almost a trillion dollars in structures every year (Simonson, 2017). These large numbers show how construction is a critical part of the economy, accounting for an average of 6.6 percent of GDP from 2015 through the second quarter of 2017 (Bureau of Economic Analysis, 2017). Construction is a relatively large expense for residential and commercial clients, with many factors influencing the cost. *Green* buildings are no different and introduce many other variables that need to be analyzed to determine costs.

Several terms are employed to describe various financial outlays during the life of a facility. These costs are referred to as the life-cycle cost or the costs of the entire time period a structure is utilized from “cradle to grave.” Part of the life-cycle is the first cost which describes the resources to obtain land and build the structure. While this is the focus of many owners and companies, it only accounts for approximately 20 percent of a building’s total lifecycle cost. The next cost is the operations and maintenance or costs to make the building work and operate to meet the intended need. These costs include daily expenses such as lighting, conditioning the air, and replacing building components when they fail. This accounts for the remaining 80 percent of life-cycle costs, because buildings are often used for 60 or more years. However, because the first costs are often the largest one-time expenditures on a building, they receive a great deal of research and focus (Goggins, Moran, Armstrong, & Hajdukiewicz, 2016).

A Delphi study was conducted by Cheng (2013) to discover how to limit first cost growth. He reported 90 construction factors broken down into four categories that lead to cost increases: project risks, scope of contract, environmental and circumstantial influence, and management and technique. This research emphasizes that for net zero energy buildings to be cost competitive, early *green* design must be implemented to limit changes, which increase project risks and scope. The changes can increase cost because many of the technologies are not industry standard and inject risk for all parties involved in the project due to the unfamiliar technologies. These increased risks can increase costs.

However, net zero energy buildings and traditional buildings serve the same function; thus, they can be compared given the numerous factors that apply.

Since LEED has been one of the leaders in *green* design, there is a great deal of research on the overall costs of a building seeking LEED certification. However, there is difficulty in determining the exact cost of a *green* building. First, LEED private contractors are not required to disclose costs of buildings. Several organizations including the New Building Institute and the Net Zero Energy Coalition have developed voluntary databases for construction teams to disclose cost and construction information. However, with this disclosed data, it is difficult to break out the incremental cost of *green* features (Kats, Alevantis, Berman, Mills, & Perlman, 2003). Incremental costs refer to the additional cost of a feature compared to a standard building without that same feature. Furthermore,  there are many variables that complicate determining the cost increase, including contractor experience, and proper design (Cheng, 2014). Looking at the final costs per square foot of *green* buildings and comparing them to the final cost per square foot of traditional buildings is one method to isolate the *green* cost premium. One of the first studies to employ this method determined that LEED certified facilities cost an additional two percent - in first costs - compared to traditional buildings (Kats et al., 2003). However, of the 33 buildings that were used in the study from across the United States and included in Kats' study, only five actually achieved certification (Nyikos, Thal, Hicks, & Leach, 2012). Kats' study laid the ground work for many others, but given the age of the study and limited sample size it seems to lack relevance today, despite the Air Force still using the findings.

To get a better statistical understanding of *green* costs, several studies sought to increase the sample size. The larger a sample size is, the less chance there is for coincidental variation.  Matthiessen and Morris (2004) conducted a point by point analysis of 45 LEED buildings and 93 non-LEED buildings and determined a cost increase of 1-10 percent. However, the cost of the buildings varied so wildly that there was no statistical significance to the study as the cost variation of LEED and non-LEED buildings were similar (Matthiessen et al., 2004). Explained another way, many non-*green* buildings cost more than *green* buildings. This runs counter to the traditional thought of *green* construction being a premium. Matthiessen and Morris (2007) repeated the study once again with a larger pool of 221 buildings (83 LEED buildings) and obtained similar results. An example of their findings can be seen in the square foot cost for 70 laboratory buildings shown in Figure 2. There is no trend on how a higher LEED rating increases the cost per square foot. In an even larger study of 160 LEED buildings, cost premiums ranged from 2.5-9.4 percent, but once again the results were not statistically significant as the variance overlaps (Nyikos et al., 2012).

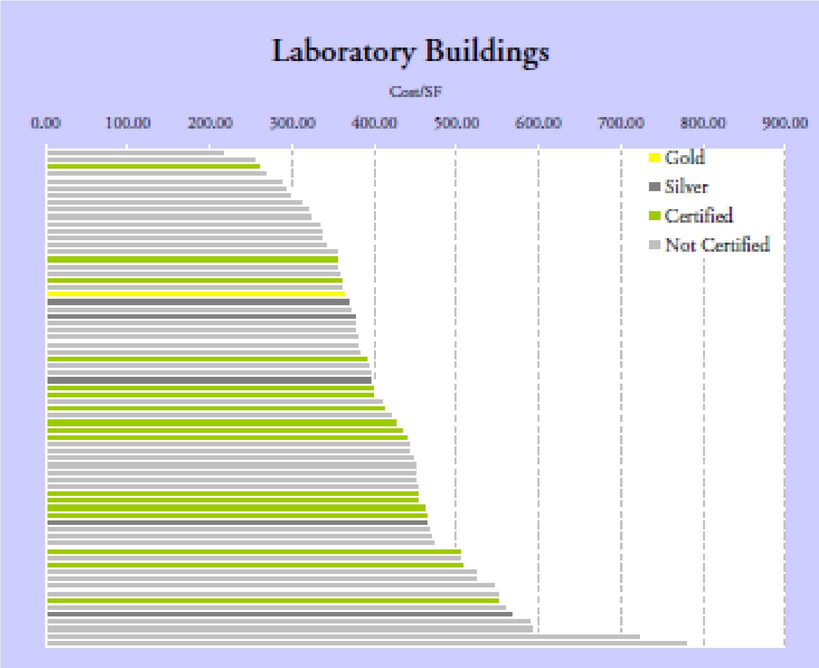

**Figure 2: Morris & Matthiessen (2004) Study Results**

Several studies have attempted to not only determine the cost premium, but also determine the value of a *green* building. In a study of 1028 LEED homes on Keesler Air Force Base in Biloxi, Mississippi, the homes used 15 percent less energy, had a 16 percent reduced environmental impact, saved two percent on life-cycle costs, and only increased the project cost by one percent (Chun, 2011). Many of the benefits of *green* construction are not directly related to costs. Much of the payback is tied to higher productivity of building occupants, lower absenteeism, or greater retail sales. These results are often ten times the savings due to energy (Miller, Spivey, & Florance, 2008). As discussed earlier in the literature review, net zero energy buildings are a higher level of *green* construction that focuses on energy rather than many of the other environmental aspects that a LEED building considers. To make a net zero energy building cost effective, a study should focus solely on the net zero energy branch of *green* construction.

## Net Zero Energy Construction Costs

Given the relatively new arrival of net zero energy buildings to the market, the sample size to analyze is small. Additionally, the costs can be wildly variable due to location, which determines heating and cooling loads as well as the amount of solar radiation for power generation. An analysis was completed on three different commercial buildings types in Washington D.C. The buildings were already designed as LEED platinum buildings (the highest LEED rating) and were analyzed to determine the incremental cost to become net zero energy buildings. The result was a 5-12 percent increase in first costs (International Living Future Institute et al., 2013b). However, the analysis was for buildings that were already more efficient than standard construction due to LEED certification. Additionally, the analysis assumed the owner could take advantage of federal tax credits. In an analysis for federal government buildings, this is not a viable option and would increase the cost premium. Furthermore, the study was a conceptual analysis based on modelling and did not use actual net zero energy construction. Modeling requires making assumptions on many aspects of a building. Also, modeling rarely predicts the actual results and is often optimistic since it is based on unregulated loads which many energy codes do not address or account for (Colker, 2017; Crawley et al., 2009; Menezes, Cripps, Bouchlaghem, & Buswell, 2012).

A retrospective look at net zero and other high *green* certifications was performed and again found no statistical difference in cost of net zero energy buildings (Lesniewski et al., 2014). Similar to the LEED study, an example of their findings can be seen in Figure 3. While some of the most expensive buildings were more sustainably built, some of the cheapest were also sustainably built. The projects that were able to reduce costs while achieving a high rating, had a constrained budget.  Additionally, scale was a large driver. The larger the project, the cheaper it is to spread out many of the infrastructure updates (Lesniewski et al., 2014).

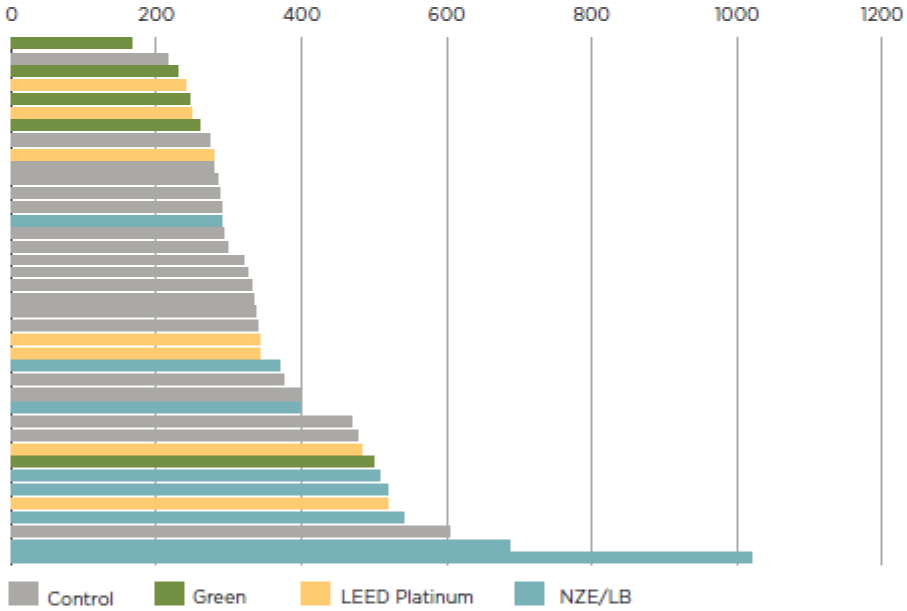

**Figure 3: Lesniewski et al. (2014) Schools SF Cost and Rating System**

When comparing constructed net zero energy building data, incremental cost results still vary. Residential homes were found to cost an additional $20-30 per square foot with most of the cost deriving from the PV installation (Davis Energy Company, 2012). Once again, the sample size of the study was rather small and used net zero energy buildings from various location and completed by various builders. A study needs to be performed to look at a high number of buildings from one location. This takes away much of the variation that can occur between buildings outside that of *green* construction features. Large residential home developments meet this requirement as homes are built in the same area, by the same contractor, and using similar floor plans with minor cosmetic changes.

**Solar Panel Costs**

As mentioned previously, solar panels are a popular option for net zero buildings. Solar panels work due to the photoelectric effect where certain materials absorb photons and as a result release electrons. This phenomenon was discovered in 1839 by French Physicist Edmund Berquerel. Albert Einstein even wrote on the effect and won the Nobel Peace Prize for this research (Knier, 2008). The first photo cell was developed in 1954. Today, solar panels consist of semiconductors such as silicon that exhibit the photoelectric effect. The semiconductors are coated so that each side of the cell is polarized with one side negative and the other positive. Electric conductors (wire) are connected to these cells to capture the energy. Cells connected together to create modules and modules are combined for form arrays that are able to produce a direct current large enough for use (Knier, 2008).

Solar panels are the most popular choice for net zero buildings because solar panels can be mounted on roofs, over parking shelters, or on ground areas close to the buildings. For single buildings, the space and infrastructure to support a wind mill or geothermal plant can be difficult. While the panels only produce when the sun is out, these times can be estimated and batteries can be used to store the energy, resulting in a more reliable option. Large concentrations of solar panel arrays are can be installed separately for generating electricity to the grid. On Air Force installations these Public-Public/Public-Private partnerships provide renewable energy and some energy resiliency, but the assets are not owned by the Air Force (Nussbaum, 2017).

The United States solar industry has experienced a recent boom. More than 260,000 American are working for over 9,000 companies in the solar industry and 39% of all new electric generating projects installed in 2016 were solar (Solar Energy Industries Association, 2017). For comparison, 93,000 Americans work in the coal industry with zero new coal plants in 2015 or 2016 (Korosec, 2015). The cost per watt of power produced by solar panels has dropped from $7.00 in the early 2000s to $1.50 in 2016. Much of this economic growth has been driven by the solar Investment Tax Credit (ITC) signed into law in 2005 and extended three times by Congress. The credit allows owners to receive a 30 percent tax credit for the cost to install the project. This tax credit is essentially a rebate subsidized by the federal government rather than a simple income deduction. This credit has enabled solar energy to become affordable while the technology develops and improves (Solar Energy Industries Association, 2017). However, entities that do not file taxes, such as the United States Air Force, are ineligible to benefit financially from the program. Federal agencies therefore have a higher initial cost to install renewable energy on efficient buildings.

## Air Force Compliance

Determining proper costs is important for all federal agencies, including the United States Air Force, to determine the cost of compliance with laws and executive orders. The Guiding Principles were established in 2006 as required by the Congressional Energy Policy Act of 2005. The Guiding Principles require several items to including designing new buildings to reduce energy by 30 percent in accordance with American Society of Heating and Refrigeration Engineers (ASHRAE) 90.1 standard, as well as verifying these actions through a third party. Starting in 2007, the Air Force used USGBC’s LEED certification as a third-party certification and allocated an additional two percent for project cost estimates to comply with *green* construction requirements, based on the Kats 2003 study. However, the requirement for LEED does not ensure that a building will comply with all laws, as there are many ways to obtain LEED certification. A project could focus on areas such as access to public transportation and site selection and not actually achieve compliance with the Guiding Principles. Because of this, in 2016 the Air Force ceased using LEED and began using a Green Building Institute or USGBC certification that only ensures compliance with the Guiding Principles mentioned above (Shaw, 2017). The process for proving compliance is very similar to USGBC’s LEED certification as a project is required to submit documentation that shows calculations and compliance with regulations.

To comply with the Guiding Principles, new building’s must cut energy use by 30 percent of the new ASHRAE 90.1 standard when life-cycle cost effective (Department of Defense, 2017b). The standard is very aggressive in reducing energy and cutting an additional 30 percent achieves the first aspect of a net zero building – decreased energy use. With current Air Force new construction needing to meet the net zero requirement, the additional cost of compliance would largely be based on the additional expense of renewable construction. Net zero energy buildings must meet Guiding Principle requirements as well as the net zero energy requirements.

To confound complying with executive orders and laws, the Air Force has a long complicated project selection model. The Military Construction (MILCON) process is directed by Air Force Instruction 32-1032 and applies to new construction on Air Force installations costing more than $1,000,000 (Department of the Air Force, 2016). To start the process, projects are proposed by the installations, based on operational need, and are coordinated by a civil engineering squadron. The projects are prioritized at many levels and communicated using a database system called Automated Civil Engineer System (ACES) and the Defense Document (DD) Form 1391 (Department of the Air Force, 2016).

Prior to project execution, it must receive funding and approval. All MILCON approvals must be authorized by Congress before design or construction efforts commence. The details are provided to Congress on the DD Form 1391. Once approved, if the cost or size of the project changes more 25 percent, it must be reapproved by Congress (Department of the Air Force, 2016). Following approval and funding, projects develop an acquisition strategy. The Air Force has limited design and construction authority and is required to utilize design and construction agents such as the Navy Facility Engineering Command (NAVFAC) and the Army Corps of Engineers (USACE) (Department of the Air Force, 2016).  The Air Force works in conjunction with these agents to solicit and procure the new structures. The new structure is required to comply with all applicable codes and regulations. This includes creating energy models to determine life-cycle costs of *green* construction methods and, starting in 2020, net zero energy options.

This process overview is to show the slow and deliberate steps taken to approve and fund Air Force projects. Much of the expertise to design the building lies outside the Air Force’s capabilities and once a project begins the process it is very difficult to shift and change the project due to the reapproval requirement.

# III. Methodology

There are three main goals to this section: outline the methods for answering each research question, explain the selection of utilized data, and provide an overview of statistical procedures used to process the obtained data.

## Research Design

To answer a research question, many researchers build an environment and control the variants between two scenarios. This approach is difficult for sustainable and net zero energy construction research due to high construction costs. To overcome this challenge, there are two predominant methods for researching incremental costs for net zero energy construction. The first is to use models. This involves determining a base case structure and adding additional *green* features until the building meets the desired goals and pricing changes (Chun, 2011; International Living Future Institute et al., 2013b). One advantage of models is the ability to create data and compare changes quickly through the use of software and databases. However, models rely on mathematical equations and assumptions to predict actual results. Models are often overly optimistic regarding occupant energy use, meaning energy consumption is often higher than expected and models often overestimate the amount of renewable energy production capacity (Colker, 2017; Menezes et al., 2012).

The second method is to use statistical analysis on the costs of sustainable buildings that have been built. Many of the most prominent studies in *green* construction cost research analyze actual costs rather than modeling (Kats et al., 2003; Lesniewski et al., 2014; Matthiessen & Morris, 2004; Morris & Matthiessen, 2007). This has the advantage of relying on actual construction data rather than relying on assumptions and models. This requires two sets of data: one set for a control or base case and another with the desired change. This approach does have drawbacks, including outside variation, which could influence the documented result. This can be minimized by selecting data that is as similar as possible, except for the required change. For net zero energy construction, this could include limiting variation by using the same builder, location, time period, structure design, and a project that has been completed several times. Given the new idea of net zero energy construction, it can be difficult to find a large sample of net zero energy buildings in one area to analyze.

## Research Questions and Hypotheses

The following documents the research questions outlined in Chapter I and how they will be analyzed.

1. *Are Air Force construction costs statistically different from 2002-2007 compared to when sustainability requirements were imposed from 2008-2017 resulting in an estimated two percent increase in first construction costs?*

With the Energy Policy Act of 2005, the Air Force was required to meet *green* requirements outlined in the Guiding Principles, including making buildings 30 percent more efficient than the ASHRAE 90.1 standard. These laws were not implemented in the Air Force until 2007. At this time, the law was perceived to negatively impact the cost of construction, which led the Air Force to apply a two percent increase to all new construction estimates to meet this requirement based on the Kats (2003) study. A statistical analysis was performed on Air Force construction data from 2002-2007 and compared to 2008-2017. The research employed basic statistical indicators such as mean, standard deviation, and variance to determine the similarities or differences in the two samples. Based on prevailing research (external to the Air Force), there is expected to be no statistical difference in cost; there are numerous factors that influence construction costs and *green* construction is often a poor indicator of overall costs (Lesniewski et al., 2014; L. Matthiessen & Morris, 2004; Morris & Matthiessen, 2007).

*2. Which performance factors should be considered when constructing a net zero building while meeting all other Air Force requirements?*

To determine the additional factors of net zero construction, a statistical comparison was made on net zero energy homes located in Fontana, California. These homes were constructed by Meritage Homes, who also collected the data on energy performance. The same statistical methods employed to answer question one will also be applied to research question two involving mean and standard deviation. The homes' additional features are expected to have additional first costs of $15,000 to $20,000 based on information provided by local construction representatives. Most of these costs result from the installation of photovoltaic panels (Herro, 2017).

*3. What documentation should be included in a net zero design package?*

The final research question is qualitative in nature and addressed by interviewing the general contractor for the homes analyzed in research question two. The documentation is expected to include modeling before construction and verification of models through analyzing energy usage following construction.

## Population and Sample

Data to answer the first research question regarding whether there has been a difference in cost of United States Air Force projects since *green* construction principles were implemented were obtained from the Air Force Civil Engineer Center (AFCEC). The report contains specific data for all Air Force MILCON projects entered in the ACES from 2002-2017. The report consisted of 1628 MILCON projects, categorized to 293 building uses, 158 locations, and over $19.7 billion in contract awards. This shows the large comprehensive sample and vast diversity of the sample. Not all 1628 projects were analyzed due to criteria cited below.

As previously discussed in the assumptions section, this data is assumed to be accurate. However, throughout the analysis, there were several missing fields that were updated through contact with subject matter experts and information made public by the Air Force in the form of budget requests. This sample of projects represents every new building constructed by the Air Force during the designated timeframe that is eligible to be analyzed as a complete population rather than a sample. This data is uniquely applicable to federal *green* construction as it limits variation by looking only at Air Force projects during the same period. The data was voluntarily provided by AFCEC.

For the second research question, energy usage data was obtained from Southern California Edison (SCE), who partnered with Meritage Homes to analyze the 20 net zero homes located in Fontana, California. SCE is a utility provider located in Southern California providing 87 billion kilowatt hours to 15 counties and 15 million individuals (Southern California Edison, 2017b). SCE received money to analyze the additional costs and feasibility of constructing net zero homes in 2015. While the study's data included 20 homes, data for 2 homes were missing from the report due to meter malfunctions. The data consisted of usage every 15 minutes for 18 designed net zero homes from 11 July 2016 to 10 July 2017. Further work showed 9 homes utilized batteries to store solar energy and 9 that did not (Southern California Edison, 2017a)

The 18 homes to be analyzed were built in the same area, by the same builder, in the same year. This data provides a unique opportunity to analyze the differences in net zero energy as there is limited variation outside of the occupants living in the spaces. The data is not a perfect comparison to Air Force buildings because the company specializes in private and residential construction. However, it should provide a useful energy projection until the Air Force has a sizable inventory of net zero energy buildings to analyze. The data was obtained voluntarily from Meritage Homes (Herro, 2017).

## Instrumentation

Microsoft Excel 2013 with the Analysis Toolpak will be used to conduct the basic statistical analysis. Excel is commonly used in academia and can quickly produce statistical figures for interpretation. The program was provided and paid for by the Air Force Institute of Technology for academic use.

## Data Analysis

The method for comparing two populations will be a t-test. Each population will make up a distribution or a range of costs. A t-test can tell if the two populations are different or whether other variation is causing the difference using calculated means, variance, and standard deviation. A t-test needs a level of confidence to determine if the samples are different. For this study, a 95 percent confidence interval will be used. This means that the conclusions will be correct 95 percent of the time. This corresponds to a five percent “type one” error. A “type one” error reports that two samples are the same when they are truly different or that the study will be incorrect 5 percent of the time if duplicated. A 95 percent confidence interval is relatively standard across many professions and research (Wheelen, 2013).

## Normality

Using a t-test requires the sample be a normal distribution. A normal distribution is the traditional “bell curve” shape where the majority of the data centers on the mean. The probability of an instance occurring is based on the data point’s distance from the central location. Any samples of the data need to be independent and generated in a way where the outcome does not depend on other values. However, in smaller samples it can be difficult to prove normality using tests such as the Shapiro-Wilkes test. When applying the Central Limit Theorem, normality can be assumed because all samples tend towards a normal distribution around the sample mean even if the samples themselves are not normal. Furthermore, the mean of the sample will approximately be the mean of the population. Therefore, t-tests were applied to all samples even if the sample did not follow a normal distribution (Wheelen, 2013).

## Data Formatting

The DoD Facilities Pricing Guide, UFC 3-701-01, addresses many factors for programming projects. In in an effort to mirror DoD estimates, Air Force MILCON cost data was adjusted to mirror the DoD pricing guide to enable appropriate comparisons and analysis. The guide covers area factors, year escalation (inflation), building type, and size adjustments. All of these factors can change the cost of a similar building.

Altering for area location involved using UFC 3-701-01 area adjustment factors in Table 4-1. These factors were last updated in 2016 and are updated annually to show an area's cost when factoring labor, materials, equipment, and construction methods (Department of Defense, 2017a). The changes from one location are based on supply and demand of the above factors, but also the difficulty to transport many of the needed resources. There are area cost factors for 423 locations, which were paired with the location of all MILCON projects. However, several new bases located overseas did not have an area cost factor. In these cases, the project record was removed from any further analysis.

Construction costs can vary year to year due to inflation effects. The principle is, "a dollar today is worth more than a dollar tomorrow." UFC 3-701-1 Table 4-2 is available but is designed for estimating building cost for MILCON projects and is only accurate to the given year, not year and month. NAVFAC Building Cost Index 2017-070-12 is consistent with UFC 3-701-01 and project inflation data for each month and year. All cost data was adjusted to October 2008.

The next adjustment to normalize the data was for building type. The Air Force assigns a category code (CATCODE) for every building that describes its use. Every CATCODE on a base is authorized a certain amount of space based on the mission at that installation. While certain CATCODEs are the same type of construction (e.g., low rise office), the requirements can be drastically different for the space and interior components. To remove variation, only buildings in the same CATCODE were compared and furthermore only CATCODEs with ten or more total projects were analyzed.

Finally, adjustments to normalize for the different size of each project were performed. These adjust for economies of scales that occur in larger projects (Thuesen & Hvam, 2012). The larger the project, the less impact fixed overhead expenses have on each square foot of the constructed facility. Typically, a larger building will have a lower per square foot cost when compared to a smaller building that is used for the same purpose.  To adjust for this occurrence, all costs were normalized by adjusting the total cost to the average square footage within the building type. An economies of scale factor was developed by dividing the total square footage by the mean square footage for the CATCODE. Smaller projects would have a factor less than one and raise the normalized costs when compared to larger projects.

## Method Implementation

When selected CATCODES are isolated and normalized for year, size, and location, the data was analyzed to determine results and findings. The data was analyzed following the steps laid out in the previous sections.

The analysis was done using Microsoft Excel 2013 and the Analysis ToolPak. This allowed for comparison using the t-test for populations with unequal variance. An analysis was performed of DD1391s starting in 2007 to determine the correct division for the populations based on *green* construction principles being implemented. While the Air Force signed documents requiring new projects to comply with Guiding Principles in December 2007, MILCON projects to be executed in 2007 were approved in 2006 and none of the DD1391s referenced sustainability for energy savings. This is the normal process as the Air Force budgets new construction several years in advance. New MILCONs require congressional approval before the construction can begin, which creates a much slower process compared to the private industry. All MILCON projects in 2008, which had time to incorporate new requirements, referenced the sustainable requirements and many included a two percent increase in the included estimate. Therefore, the populations were separated as projects awarded from 2002-2007 compared to those from 2008-2017.

During the research, an additional building designation was discovered that allows the ability to group similar buildings. Each CATCODE is assigned a Real Property Asset Type Code (RPA Type Code). This includes four:  buildings, structures, linear structures, and land purchases. Furthermore, real property assets are broken down into 41 chapters that describe the overall use of the contents of each chapter (similar to CSI format). Two chapters had building uses that could be easily compared to each other due to the lack of variation among the CATCODE types. This included Chapter 22, General Administrative buildings, which compare to office building construction and Chapter 28 Indoor Morale, Welfare and Recreation Facilities, which compare to normal commercial retail construction. This analysis will provide a larger sample by investigating several similar CATCODES at the same time (Air Force Civil Engineer Center, 2016).

The Microsoft Excel 2013 Analysis Toolpak produces a computation that compares the mean, variance, number of observations, degrees of freedom, t statistic and the probability the two samples are statistically different, based on a one-tail and a two-tail test. As outlined in the methodology, the confidence was set at the standard of 95 percent.

### Interview Implementation

Research questions two and three required conducting interviews of experts in the field of net zero energy construction, shifting from quantitative to a qualitative analysis. It was important to select experts in the field that had direct knowledge on the Fontana, California community homes used in the energy analysis. The interviews would be semi-structured to allow flexibility of responses and questions in order to cover and understand a wider breadth of net zero energy topics (Woods, 2011). Loose questions were developed ahead of time based on the literature review of sustainable construction. They sought to understand design strategies used, additional construction costs, and what items should be considered. Interviews would be constrained to employees of Meritage Homes as they were the builders of the Sierra Crest home division what was used in the energy analysis.

Each interview was set up via email correspondence. Interviews would be conducted via telephone, due to travel limitations. At the start of the interview, a brief summary of the research was given and explanation of how the respondent could add value. No benefits were provided to the respondents for their time. Following the introduction, the semi-structured questions were proposed and notes were recorded of the answers. Additional questions were asked to expound upon further topics mentioned by the interviewees.

## Case Study Implementation

To look beyond one company and the residential construction industry, a case study analysis was completed on commercial net zero energy projects. The case studies were obtained from the New Buildings Institute's (NBI) website to locate common strategies and contract methods among net zero energy buildings. NBI is a nonprofit organization that seeks to move the construction industry towards energy efficiency. They offer a third party review and database of highly efficient buildings following construction. NBI also offers several 2-4 page case study documents that look at why a building was able to achieve net zero energy, and lessons learned during design and construction. These case studies were available and can be accessed free of charge by the public (New Buildings Institute, 2017). The ten most recent projects located in the United States were analyzed for cost, design strategies, renewable energy, contract type, incentives, and other relevant information. All data was recorded in a Microsoft Excel spreadsheet for analysis of trends and commonalities.

# IV. Data Description and Analysis

This chapter is meant to describe the analysis process and the results. This involves describing the data that was collected, how it was processed, and preliminary results before conclusions and recommendations are drawn.

## CATCODE Results

The first results were to find the CATCODES that produced a sample of at least 10 projects. These show the buildings most often constructed in the Air Force and produce a sample that can be statistically analyzed. There were sixteen CATCODES identified and analyzed, which are listed in Table 1 along with their descriptions. There is no clear common attribute of the CATCODES to explain why they were the most constructed buildings from 2002-2017. Most are directly related to executing a mission, but several are related to morale, wellness, and recreation as well. These 16 categories accounted for almost 15 percent (340/1628) of the MILCON projects completed from 2002-2017. The remaining 1,288 projects were not used in this section of the analysis due to insufficient CATCODE sample size. A small sample size fails to limit the impact of outliers on the analysis.

**Table 1: CATCODES Analyzed** (Air Force Civil Engineer Center, 2016)

| CATCODE Number | CATCODE Title | Description |
|---|---|---|
| 211111 | Hangar, Maintenance | These hangers are required to support those aircraft maintenance, repair, and inspection activities which can be more effectively accomplished while the aircraft is under complete cover. |
| 141753 | Squadron Operations | Squadron operational building with space provided for planning room, briefing room, administration, and critique of combat crews. Life support storage/issue room and building support areas are also included in the function. |
| 721312 | Dormitory, Recruits | Dormitory Airman Permanent Party/PCS-STUDENT – This facility is required to house unaccompanied personnel in the enlisted ranks and comparable- grade unaccompanied civilian employees. |
| 141454 | Special Operations | Operations facility designed for use by non-flying squadrons such as intelligence, range, tactical elements, and support squadrons that have peculiar mission elements or structures required. |
| 171212 | Flight Simulator Training | This facility houses aircraft flight simulators and other special training devices. It also includes space for admin and records, classrooms, toilet facilities, trainer maintenance and storage. |
| 211152 | Shop, Aircraft, General Purpose | This facility provides space for specialized maintenance such as fabrication shops and aerospace systems repair shops; reclamation activities on wrecked or damaged aircraft, administration, tool cribs, and locker space. |
| 211159 | Aircraft Corrosion Control | This facility may be a combination of covered wash rack that accommodates one or more aircraft, a wash rack to permit spot painting, a hanger for painting an entire aircraft, contiguous or separate shop for corrosion control work on support equipment. |
| 211179 | Fuel System Maintenance Dock | This facility provides for fuel system maintenance and also includes system for mechanical ventilation, fume sensing and alarm, fire extinguishing, and wash down drainage trenches. |
| 218712 | Aircraft Support Equipment Shop/Storage Facility | This facility is used to maintain and hold in readiness powered aircraft support equipment. |
| 422264 | Storage Igloo | Facility designed for storage of all types of explosives and are preferred for mass detonating explosives where moisture and condensation is not a problem. They are earth covered and are either of a concrete or steel arch-type construction. |

| | | |
|---|---|---|
| 442758 | Warehouse Supply and Equipment Base | This LRS facility is required for bulk and bin storage of materials for which maximum protection from the weather is authorized. |
| 610243 | Headquarters, Group | This facility accommodates the staff offices of the headquarters in such groups as: operational support, air base, support commands, maintenance and supply, communications security and security police and various specialized groups. |
| 730142 | Fire Station | Facility designed to house fire protection vehicles, equipment and operating personnel of the base fire department. This facility is usually found in the community areas of the base as opposed to the Fire/Crash Rescue Station. |
| 730835 | Security Police Operations | Facility designed for use as the law enforcement center at the installation level. Functional space areas include space for control elements, law enforcement, resource protection functions, base information security. Could contain an armory and warehouse storage areas. |
| 740674 | Gymnasium | This facility may provide space for latrines, showers, dressing rooms, lockers, squash, racquetball, handball, basketball, badminton courts, weight rooms, laundries, offices, and storage it is used for the daily physical training of military personnel. |
| 740884 | Child Development Center | This facility accommodates working mothers and serves other family circumstances requiring assistance in child care. The base child care program mostly involves children under 6 years old but includes children 6 to 12. |

With the CATCODES identified, they were analyzed using a two tail t-test. A typical output using the 2013 Microsoft Analysis Toolpak is shown in Table 2. Items from the output used for further analysis include the mean and the probability of the sample being less than the t-statistic associated with a 95 percent confidence.

**Table 2: Dorms Statistical Analysis**

| | Pre-Oct 2008 | Post-Oct 2008 |
|---|---|---|
| Mean | 20,413,944 | 20,646,729 |
| Variance | 3.05579E+13 | 3.42886E+13 |
| Observations | 26 | 30 |
| Hypothesized Difference | 0 | |
| Degrees of Freedom | 54 | |
| T Statistic | 0.15 | |
| Probability Samples are not different (two tail) | 0.87 | |
| T Critical to be different (two tail) | 2.00 | |

An overview of the all adjustment factors used for analysis of all 16 CATCODES can be found in Appendix A. The most substantial result was approximately 94 percent (15/16) of CATCODES were not significantly different from 2002-2007 compared to 2008-2017 with 95 percent confidence. Out of the sixteen CATCODEs, 141753 Squadron Operations buildings was the only one significantly different. The CATCODE was cheaper after sustainable principles were implemented. No reason for the statistical difference could be determined. Statistical analysis revealed that 75 percent of the CATCODES increased in normalized cost by an average of 6.8 percent. However, the variance was large enough that the *green* construction difference could not account for all the difference in the costs. There are many different factors that result in the overall cost of a new building. The variation of cost in the projects studied resulted from other items for which data was not available to adjust. *Green* construction could not be isolated as the difference resulting in a cost premium.

## Building Type Results

**The next analysis attempted to increase the sample size and look at with similar uses and construction. Results for Chapter 22 General Administrative buildings can be seen in Table 3 and Chapter 28 Morale Welfare and Recreation buildings in**

Table 4. These were created using the same methodology for individual CATCODES, but applying them to the chapters in the CATCODE guide. This incorporated an additional 28 projects that were not included in the original CATCODE analysis. Similar results were obtained. Both chapters analyzed were found not to be statistically different. The results were very similar. While the normalized average cost rose in the different time periods, the variance overlaps enough that the null hypothesis of statistical similarity cannot be rejected. Once again, showing there is other variation causing the cost increase not solely *green* construction.

**Table 3: Chapter 22 Building Results**

| | Pre-Oct 2008 | Post-Oct 2008 |
|---|---|---|
| Mean | 13,323,913 | 15,199,310 |
| Variance | 1.33E+13 | 3.89E+13 |
| Observations | 13 | 26 |
| Hypothesized Difference | 0 | |
| Degrees of Freedom | 36 | |
| T Statistic | 1.18 | |
| Probability Samples are not different (two tail) | 0.24 | |
| T Critical to be different (two tail) | 2.02 | |

**Table 4: Chapter 28 Building Results**

| | Pre-Oct 2008 | Post-Oct 2008 |
|---|---|---|
| Mean | 12,534,514 | 15,476,682 |
| Variance | 5.66E+13 | 1.66E+13 |
| Observations | 13 | 27 |
| Hypothesized Difference | 0 | |
| Degrees of Freedom | 15 | |
| T Statistic | 1.32 | |
| Probability Samples are not different (two tail) | 0.20 | |
| T Critical to be different (two tail) | 2.13 | |

### Net Zero Energy Usage Results

While cost data for net zero energy homes was restricted due to proprietary data and California law, several other results were obtained. First, the energy data for Sierra Crest homes built by Meritage Homes were obtained from Southern California Edison (the utility supplier for the net zero development) for July 11, 2016 through July 10, 2017. Of the 20 homes, 2 had faulty meters that failed to provide reliable data. Of the remaining 18 homes, 9 were equipped with solar panels and battery storage. The other 9 homes only had solar panels. Energy readings were taken every 30 minutes for an entire year. A daily readout for each day of each home would look similar to Figure 4. Taking the area of the curve for energy usage (blue) compared to the energy under the curve for energy production. For this day the home used 4.88 more Kwh than it generated.

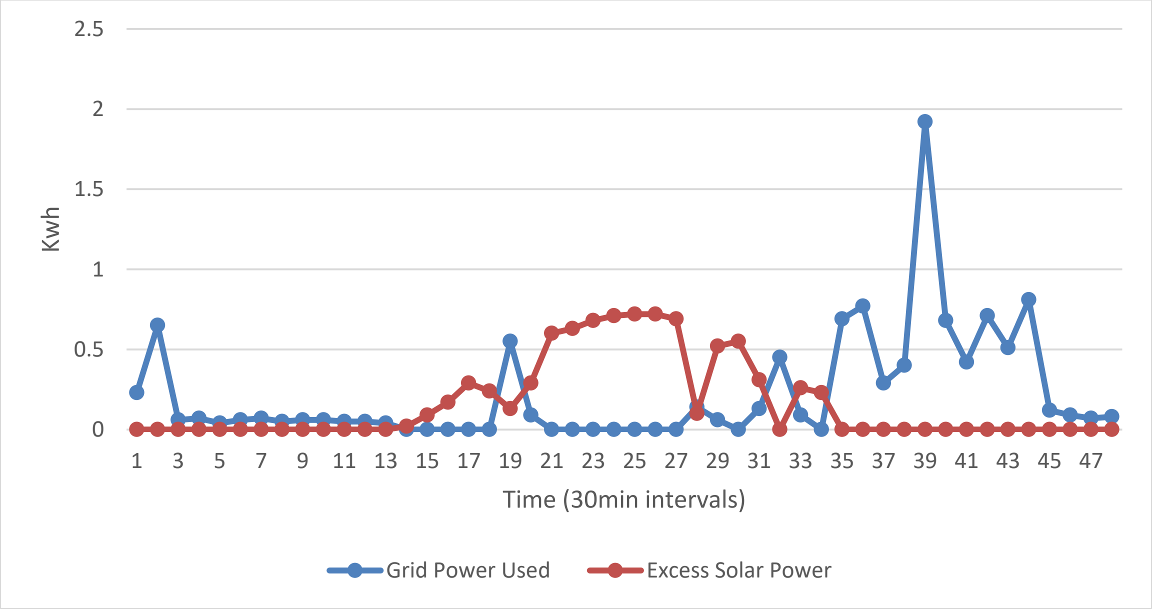

**Figure 4: Home 15 July 11 2016 Energy Usage**

While all the homes were modeled and designed to be net zero, only one home actually achieved net zero by using less energy than it generated over the course of a year. This was home number 15, which did not have a battery storage capability installed. The homes with battery storage used an average of 3,117 kWh for the year, beyond what the home was able to generate through solar panels, while homes without battery storage which used an average of 3,817 kWh. The average energy usage difference between homes with battery storage versus those without battery storage was 700 kWh or 18.3 percent. Furthermore, there was an extreme variation in energy usage despite all homes being designed and modeled to be net zero energy. The minimum usage was negative 3,128 kWh (achieved net zero) and max usage was 8,765 kWh. The standard deviation for the homes was 2589, which shows the drastic difference in the energy usage despite most construction factors variables being held constant. The homes were still very efficient when compared to the average American home which used 10,776 kWh in 2016 (Berry, 2017). Much of the variation was contributed to occupant behaviors (Herro, 2017).

Meritage Homes is one of only 2,500 Energy Star builders in the United States (Department of Energy, 2016). They have been recognized with many accolades for their commitment to energy efficiency, with Energy Star awards from 2013 to the present (Department of Energy, 2018). Meritage Homes has many established processes above and beyond the normal builders, such as using spray foam for all building envelope insulation instead of fiberglass batts. The additional cost to build net zero homes for Meritage Homes was approximately $15,000 (Herro, 2017).

## Documentation Results

Construction contracts are still a required part of *green* construction; however, there are several aspects more critical to success than conventional construction. Many *green* contracts require energy goals to be incorporated in contract documents. Traditionally, an owner pays for energy expenses, assumes the risk of a building's energy performance. A building is required to meet code and anything beyond that is up to the design team. Unless an energy goal or standard is included in the contract, there is nothing requiring a certain energy performance. Incorporating energy specifications (Btu/SF or $/year) require the design team and contractors to consider a holistic approach. Energy goals can include a year documentation period after construction to ensure the building achieves net zero or any other sustainable construction goal. 100 percent projects in the case study analysis had implemented energy goals prior to design. New Building Institute offers a certification to prove a building meets the net zero requirement or a near net zero designation (New Buildings Institute, 2017). Establishing an energy goal prior to the project allows designers to use integrated design and establish method early on to meet those goals. Even with early design goals, 30 percent of the projects had to add addition renewable energy to achieve net zero energy.

An important part of meeting high *green* construction standards is for the owner and the occupants to take responsibility for the plug loads. Equipment specification and occupant training are a critical part of ensuring energy goals are met as these loads are often hard to model and estimate due to human variability (National Renewable Energy Laboratory, 2014). 100 percent of projects aggressively tried to mitigate plug loads as they are a high percent of energy usage in high efficiency buildings. Often this included controls, education, and real time feedback for occupants on how the building is performing with respect to energy.

# V. Findings and Conclusions

This chapter discusses and elaborates on the implications of topics documented in the previous four chapters. This involves describing real-world implications and recommended changes for the United States Air Force to consider in sustainable and resilient construction, based on results and literature review of the relevant topics.

## MILCON Project Costs

There are many different factors that contribute to the cost of a construction project. This research effort was able to adjust for location, time of construction, type of building, and size of the project. However, there are more factors that the data was not available to include: experience of design and construction team, weather, type of contract, health of the construction industry, available labor, fluctuation in material prices, change in building codes, and many more that affect the overall construction costs. *Green* construction methods are just one aspect of what a construction project will cost after including all influencing factors. The research findings of no statistical difference in this study of *green* construction affirms the idea that there are so many factors of a construction project it is nearly impossible to isolate the cost of one factor (Lesniewski et al., 2014; Matthiessen et al., 2004; Morris & Matthiessen, 2007). Not only are there numerous factors, the factors could interact with each other to exacerbate or limit other factors' effect. While there was no statistical difference, the study did lack statistical significance due to the relative small sample size. This stems from the large variance of the projects that would require a much larger sample than was available.

Since 2008, the Air Force has added two percent to project estimates to account for complying with various sustainability requirements. This was based on the 2003 Kats study. If following the same logic as the Kats study, the Air Force should actually increase this sustainability factor. The average difference in the 16 CATCODEs analyzed was 6.8 percent rather than 2 percent. This ignores the fact that there was no statistical difference and the variation could be caused by something different than *green* construction. This research is not able to point to a building and determine how much additional it will cost based on using *green* construction methods. This is best displayed in Figure 5, which displays the normalized cost per square foot for all dorms, the CATCODE with the largest sample size. The most expensive cost per room and the cheapest per room were before *green* construction was required. There is no noticeable correlation in the costs based on *green* construction methods. When increasing the scope of analysis to similar building types and uses, the same trend holds. In Figure 6, while buildings constructed after 2008 were on average 12 percent more expensive, there is no noticeable trend or correlation on predicting the final cost. This once again relates to the fact that there are so many factors that determine construction cost that it is extremely difficult to isolate one feature.

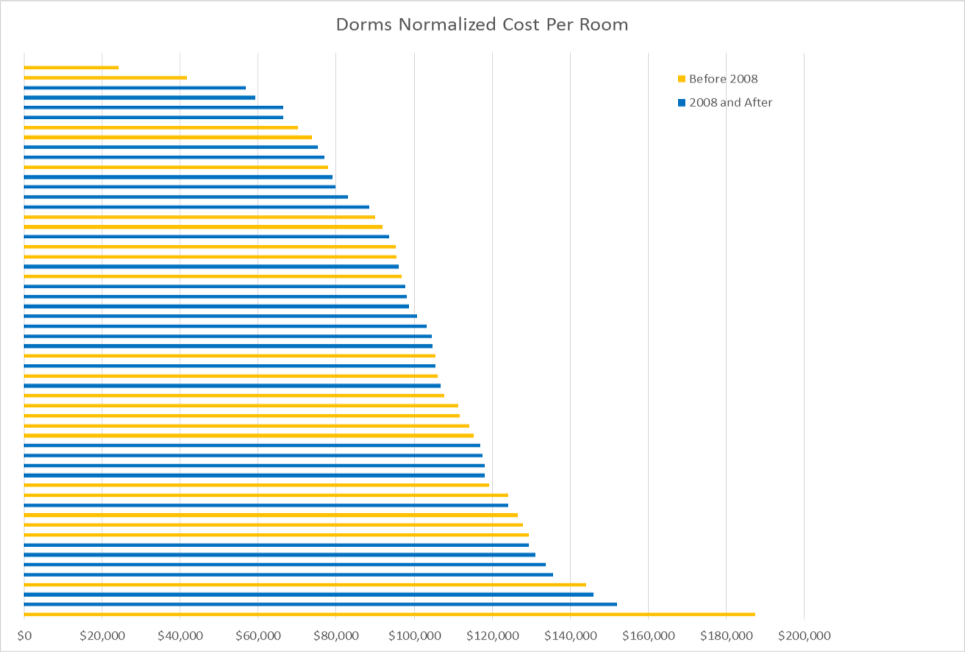

Figure 5: Constructed Dorms Cost Per Room

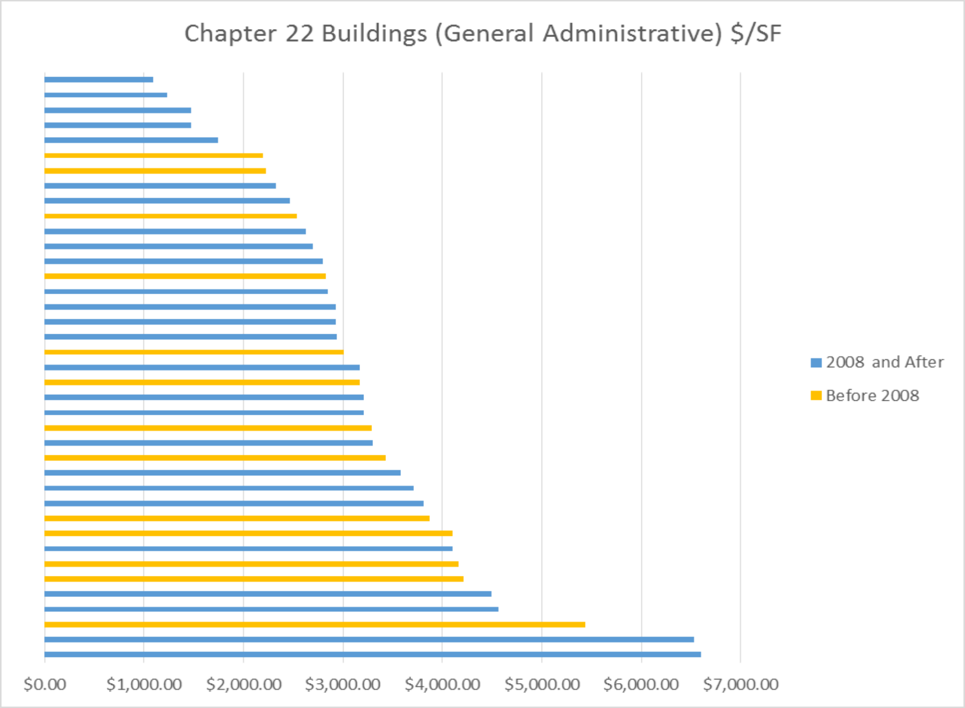

Figure 6: General Administrative Building Cost per SF

Given the results of this study, it is important to address whether a green premium per CATCODE is a viable solution. As documented, several CATCODES still have an extremely small sample size and lack enough evidence to draw accurate conclusions. Only 16 of 293 CATCODES had more than 10 samples from 2002-2017. Furthermore, there is a large standard deviation among the normalized costs, as shown in Figure 7. The CATCODES on the x-axis are ordered from average in percent difference in cost from smallest to the largest. There is no noticeable trend in standard deviation and cost. These large standard deviations and small sample sizes further indicate that each project should be estimated individually. Hence, a green premium per CATCODE should not be used.

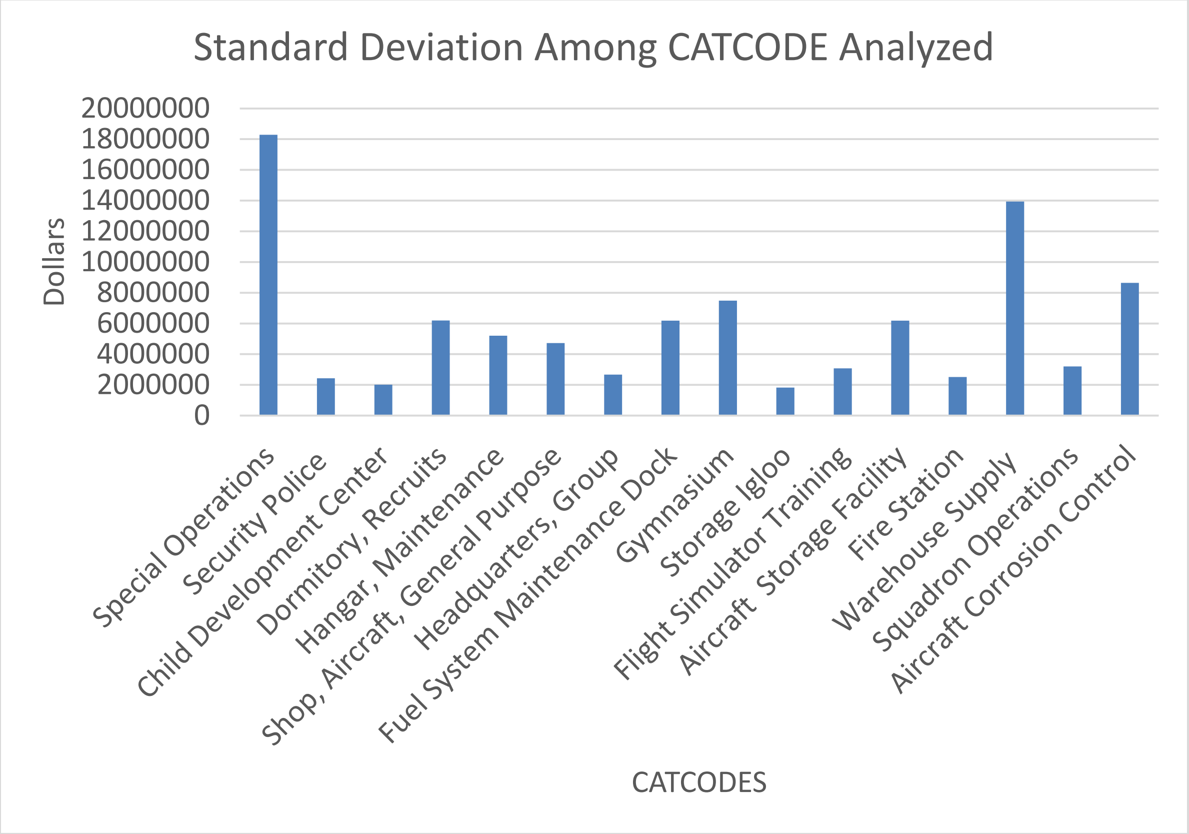

**Figure 7: Standard Deviation in CATCODES**

A two percent estimate increase is shown to be an antiquated method of project estimation. The DoD pricing guide provides unit costs for MILCON estimates and the oldest data points used are from 2012 – four years after *green* construction method were mandated (Department of Defense, 2017a). The *green* methods are already included in the estimate tool and do not need to be double counted. Even with the two percent cost increase, the Air Force has still been unable to adequately estimate and price projects with 62.3 percent of projects missing the estimate by more than 5 percent (Air Force Audit Agency, 2015). The path for better estimates is not to isolate sustainable design, but develop better estimates based on experience and training of the individuals actually making the estimates.

## Net Zero Energy Usage

Data from the net zero home energy usage in Sierra Crest, California, was very insightful for necessary design features to consider when planning for net zero energy. Meritage Homes' architects and engineers are able to design for environmental factors. This includes appropriate design of the building envelop to components such as fenestration, insulation, and roofs. The net zero homes at Sierra Crest featured spray foam, windows with low e glass, and highly insulated attics to limit heat transfer across the building envelope.

What Meritage Homes was not able to completely design for was occupant energy usage. An attempt was made to limit process energy as the homes were equipped with Energy Star appliances (required by for Energy Star certification). The research showed that while the homes were designed to be efficient, they were not operated in an efficient manner. This shows an error in modeling by overly optimistic assumptions. This is not uncommon as predicted versus actually energy usage has varied by over 80 percent in a 2012 study by Menezes et al. There are two paths to adjust for controlling energy associated with occupants – either add more controls or educate the occupants. Controls

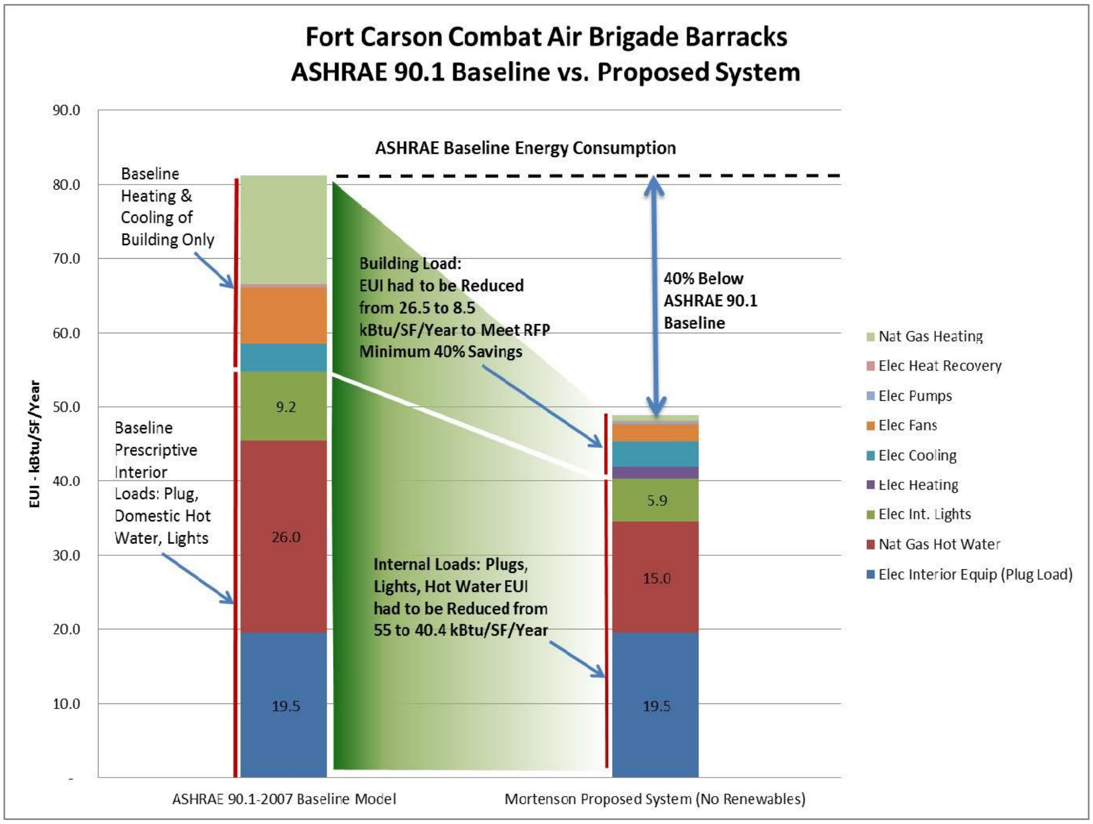

**Figure 8: Fort Carson Dorm Energy Projection (Packard et al., 2017)**

can be used in conjunction with sensors to turn off electronics when there is no one in the room. However, these can often be bypassed or lead to occupant frustration. An example case study of controls to improve occupant behavior is the 2015 Army net zero dorms built at Fort Carson, Colorado. This included installing sensors on each operable window that would shut off the conditioned air to the room if the window was opened. However, without a way to reduce electrical interior equipment (plug loads), they accounted for 47.6 percent of the overall modelled energy usage of the dorms as seen in **Error! Reference source not found.** provided by RMH group (Packard, Benson, & Tang, 2017).

The other option is to educate occupants on how their actions affect the energy consumption or better plan for occupant consumption. This applies to the Air Force as higher energy usage can lead to a less resilient building infrastructure. The building is less resilient because the more energy it consumes the less that is available for other mission critical facilities. The DoD is required to continue operations even when power from the grid is not available. When the Air Force procures a building, maintenance staff are required to be trained by the installing contractor on how to maintain and operate the building's equipment. However, there is no documentation of contractors providing the actual building occupants information on efficient operation. This aspect is even more important as occupant decisions can adversely affect the performance of the net zero buildings such as HVAC equipment required to remove higher loads created by heat generated from equipment or lights. Additionally, there can be an increased cost by requiring additional energy production, the most expensive aspect of net zero construction.

## Energy Usage Recommendation

When buildings are modeled for energy usage, criteria are outlined in ASHRAE 90.1 Appendix G (American Society of Heating Refrigeration and Air Conditioning Engineers, 2016). The model of a new building must demonstrate the ability to improve on the energy consumption based on design technologies and building materials. However, ASHRAE only provides process load estimates for 10 broad categories: assembly, health/institutional, hotel/motel, light manufacturing, office, parking garage, restaurant, retail, school, and warehouse. The Air Force has 922 different CATCODES that must be simplified into ten categories for building modeling estimates (Air Force Civil Engineer Center, 2016). Furthermore, the Air Force performs many missions that are drastically outside the scope of estimates in the ASHRAE 90.1 which are typical for commercial and retail operations of the private sector. For designing a building envelope, this is not a critical issue; however for estimating a building's process load, this can be crucial for resiliency and planning to achieve net zero.

To obtain better estimates on process load, this research suggests two options: conduct a study to analyze each CATCODE's process loads or fund a study on a building before it is replaced through construction. Having a database with the energy intensity (Btu/SF) available for each individual CATCODE (or groups of similar CATCODES) enables design teams to better understand what are the actual design needs and results in buildings that are more likely to obtain net zero, which results in more resilient buildings. This could be completed via a contract to sub meter existing buildings on circuits that are used for process loads and documenting the average across the

CATCODE in the Air Force. The accuracy could be limited by differences in location and culture across the Air Force but would provide a more realistic estimate.

The final strategy could be used for current mission MILCON funding. This opportunity presents itself when an existing building is replaced by a new project, because it is more affordable or feasible to construct a new building rather than repair an existing project. Before the building is demolished, the design team would fund a study to understand the building's process loads and how to improve or plan for the loads in the new building. This would provide an individual tailored study so the new building can be more accurately designed for resiliency and net zero energy compared to ASHRAE 90.1 estimates. From the case study analysis, a library in Berkeley, California followed this approach and performed an energy study on the library to be demolished so designers could better understand how to account for accurate plug loads.

The Guiding Principles requires all new buildings to be metered at least at the building level (U.S. Department of Energy, 2017). However, only metering at the building level does not enable the Air Force to analyze individual loads or develop process load estimates for future buildings. The newest LEED standard, version 4, recognizes the benefit of placing meters on certain loads in the building for diagnostics and awards points for sub-metering a percentage of the overall load. New buildings for the Air Force should include sub-metering of process loads to develop the database mentioned in the previous paragraph as well as provide diagnostic tools to maintenance technicians.

## Document Recommendations

The Air Force has utilized many documentation structures for energy compliance. For many years, LEED was utilized which requires a model to be completed for a baseline building and compared to the designed building. With the Air Force switching to use Guiding Principle Certification, a model and comparison will still be required. Also, all features compare life-cycle costs. If a feature will cost more over the entire usable life, including energy savings or resilient features, it is not included in the design. This has prevented many renewable energy attributes from being installed due to the high first costs (Woodhouse et al., 2016).

In all these situations, no party is responsible for verifying the actual energy usage. Thus, the owner is at risk for the costs on how the building actually performs with regards to energy usage. NREL has shown that including energy goals early in the programming, design, and construction produces a more energy efficient structure at a lower cost (National Renewable Energy Laboratory, 2014). However, there is still no responsibility to comply with the model, unless certain requirements are written into the contract. Similar to using a design-bid-build contract, the risk is on the owner that the design covers all instances that will be encountered in the construction. When the risk and responsibility is placed on the party actually performing the work, there is more reason to limit change orders and meet the specifications of the contract.

Energy efficient structures and many *green* certifications require integrated project delivery (Mccombs, 2015). This involves the owners, designers, general contractor, and subcontractors to be part of design considerations from the start. Having everyone on the same page ensure that intended results come to fruition. Integrated project delivery is required by GPC, but it is difficult to reap the rewards with design-bid-build contracts (U.S. Department of Energy, 2017). With a design-bid-build contract, it is almost impossible to truly integrate the entire team, due to the uncertainty of who will actually perform parts of the contract at different stages. It limits innovations (National Renewable Energy Laboratory, 2014). There are many benefits of a design-build contract, and energy efficient construction is better suited for design-build based on the need for continuity for innovative technologies (Rosner, 2008).

Finally, EO 13693 needs to clarify the definition of net zero so that contracts can be created to meet the requirements. As written, EO 13693 does not specify how the net zero energy should be monitored or measured such as site, carbon, cost, or source (Torcellini et al., 2006). Net zero when viewed as the owner of an individual building is great because it can reduce energy costs. However, when viewing net zero as an Air Force installation, there needs to be a increased focus on actual zero energy from the grid for resiliency (Herro, 2017). A net zero building is not capable of operating for extended periods of time during a power loss without the capability of generators. It is still largely dependent on the grid power. Including energy storage options would allow the Air Force to continue operations when commercial power from the grid is lost. If designed correctly, there would not be a utility bill for the power as it could be generated from solar panels or other renewable sources. Another benefit would be reducing the peak electrical demand by including the batteries to power operations during high demand situations.

## Conclusion

The following section to recap the findings and recommendations discovered over the research process by answering each original research question.

1. *Are Air Force construction costs statistically different from 2002-2007 compared to when sustainability requirements were imposed from 2008-2017 resulting in an estimated two percent increase in first construction costs?*

There was no statistical difference in first cost of similar buildings built before mandated sustainability requirements and those built to Guiding Principle standards even though they cost on average 6.8 percent more. This confirms previous research that sustainable construction is a poor indicator of cost. There are so many factors that influence the first cost that it cannot be easily ascertained what the difference would be, if any difference exists. The overlap in variation makes the sustainability estimate the Air Force uses on new construction estimates unreliable. It was based on an outdated study that is not supported by this study or prevailing research. This research recommends removing the sustainable increase and estimating each project on its own merit.

2. *Which performance factors should be considered when constructing a net zero building while meeting all other Air Force requirements?*

Energy performance data from 18 net zero homes in Fontana, California, demonstrated how models can be overly optimistic. Only one of the designed homes actually achieved net zero in the year following construction. Specifically, the process loads are difficult to model due to high variability and difficult to control as occupant operation of the building has a large impact. In order to comply with EO13693, the Air Force should take measures to better estimate process loads based on each CATCODE or buildings before they are replaced.

3. *What documentation should be included in a net zero design package?*

The Air Force should meet the requirement of integrated project delivery through the maximum use of design-build contracts. These enable all parties to collaborate throughout the process. Furthermore, specific energy goals should be incorporated in the contracts and verified at project completion. Finally, to truly obtain the benefits of resiliency, there needs to be a look at including energy storage options in net zero buildings to ensure mission continuity when the power is lost.

## Recommendations for Future Research

This research was able to make several advances in understanding costs associated with *green* construction and recommends best practices for the Air Force net zero construction. However, there was no readily available cost data for net zero construction projects. Future research that could obtain a large sample of net zero buildings as they become more common and compare them to the Air Force building data set used in this study would be able to potentially identify a *green* cost premium. Furthermore, this study only worked on net zero energy, but EO 13693 also requires federal agencies to achieve net zero water and net zero waste, when life-cycle cost effective. The same ideas and principles from this research could be applied to these concepts.

## Appendix A: T-Test Results

| CATCODE Number | CATCODE Title | Pre Mean | Post Mean | Percent difference | Percent Likelihood difference equals 0 |
|---|---|---|---|---|---|
| 211111 | Hangar, Maintenance | 14786120.43 | 15574622.64 | 5.06 | 68.47 |
| 141753 | Squadron Operations | 4344574.79 | 6795117.63 | 36.06 | 0.69 |
| 721312 | Dormitory, Recruits | 20413944.77 | 20646729.65 | 1.12 | 87.90 |
| 141454 | Special Operations | 33588565.59 | 13414311.58 | -150.39 | 18.26 |
| 171212 | Flight Simulator Training | 4935201.43 | 6784729.37 | 27.26 | 6.82 |
| 211152 | Shop, Aircraft, General Purpose | 13264234.71 | 14361847.51 | 7.64 | 78.18 |
| 211159 | Aircraft Corrosion Control | 14897416.85 | 23737670.14 | 37.24 | 8.85 |
| 211179 | Fuel System Maintenance Dock | 11897256.10 | 15192502.64 | 21.68 | 55.39 |
| 218712 | Aircraft Support Equipment Shop/Storage Facility | 6829755.01 | 9556734.54 | 28.53 | 34.39 |
| 422264 | Storage Igloo | 4672138.88 | 6418070.02 | 27.20 | 10.02 |
| 442758 | Warehouse Supply and Equipment Base | 19960762.10 | 29576691.38 | 32.51 | 17.57 |
| 610243 | Headquarters, Group | 9615490.69 | 11760817.51 | 18.241306 | 22.67 |
| 730142 | Fire Station | 6483387.23 | 9089292.15 | 28.67 | 8.37 |
| 730835 | Security Police Operations | 11682365.53 | 9781619.733 | -19.43 | 36.98 |
| 740674 | Gymnasium | 9994287.79 | 13347716.12 | 25.12 | 22.14 |
| 740884 | Child Development Center | 9448018.75 | 8090886.97 | -16.77 | 43.18 |

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**14. ABSTRACT**

Varying legislation and executive orders coupled with needs for energy resiliency have led the United States Air Force to pursue sustainable construction. The limited understandings of initial costs to implement these changes have contributed to poor project cost estimating and changed implementation of legal requirements. A student t-test for populations with unequal variance was accomplished on the final normalized contract cost of 1628 Air Force Military Construction (MILCON) projects executed between 2002 and 2017. Future design considerations for net zero energy buildings were compiled from a net zero energy residential community in Fontana, California.

There was no statistically significant difference in final contract costs for fifteen of sixteen building categories between samples from before and post federal sustainability requirements. Furthermore, in a pilot study in Fontana, California, 94 percent of residential homes designed to net zero criteria failed to meet net zero in the following year due to underestimated occupant process loads. The study revealed projects influenced by numerous criteria that impact costs. Showing *green* standards are a poor indicator of additional project costs. Additionally, when designing net zero energy buildings and other highly sustainable structures, occupant behavior estimates need to be more accurately estimated. This validates similar research and invalidates the Air Force's two percent increase on project cost for sustainability requirements and each project should be considered on a case by case basis.

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