



**Successfully Implementing Net-Zero Energy Policy through the Air Force Military
Construction Program**

THESIS

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**DEPARTMENT OF THE AIR FORCE
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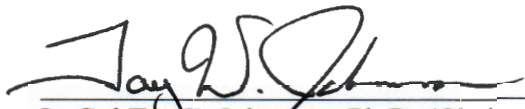
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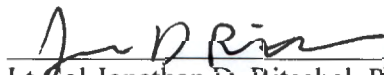
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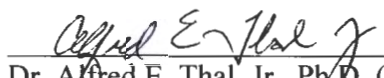
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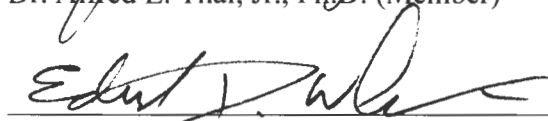
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Abstract

The U.S. government has issued numerous policies aimed at reducing federal facility energy consumption; the most recent, Executive Order 13514, requires that new construction designed after 2020 achieve net-zero energy by 2030. The policy defines a Zero-Energy Building as one that is designed, constructed, and operated to reduce energy demand to a level which can be offset from sources of renewable energy. This research develops and evaluates a feasibility assessment model based on life-cycle cost. It incorporates geospatial analysis to calculate and summarize input values for all Air Force installations in the contiguous U.S.. A comparative analysis is then conducted to rank each installation in terms of the net-savings of constructing a Zero-Energy Building. The ranking is performed for three facility types and then utilized to prove that there is a significant and direct rank correlation between them. This conclusion allows follow-on feasibility assessments to be limited to those installations and facility types maximizing the likelihood of achieving a cost-effective Zero-Energy Building. Finally, a strategy is recommended which will comply with federal net-zero energy policy, reduce facility operational costs, and ultimately allow for energy security and independence at Air Force installations.

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SUCCESSFULLY IMPLEMENTING NET-ZERO ENERGY POLICY THROUGH THE AIR FORCE MILITARY CONSTRUCTION PROGRAM

I. Introduction

1.1. Background

Buildings account for one third of the world's energy consumption; in the U.S., that number is even higher at approximately 40 percent (National Science and Technology Council, 2008). Buildings, at their current pace, are on track to become the largest consumer of energy in the world by 2025 (National Science and Technology Council, 2008). With the cost of energy increasing and the world's natural energy resources diminishing, nations across the world are placing increased emphasis on improving building energy performance. The U.S. is one of the nations directing building energy performance improvements in both the public and private sectors. The largest entity in the public sector, the U.S. federal government, operates over 500,000 facilities with a total floor area of 3.1 billion square feet (Office of the Federal Environmental Executive, 2002 ; EERE, 2011). Due to the fact that up to 80 percent of the life-cycle cost of a facility occurs after it has been constructed and that energy is a large portion of that cost, high-performance and sustainable buildings have the potential to dramatically reduce the budget required to operate federal facilities (National Science and Technology Council, 2008).

This realization resulted in numerous laws and executive orders aimed at reducing the energy consumption of federal facilities. One law and two executive orders are important to this research. First, the Energy Policy Act of 2005 requires Federal

Agencies to provide facilities which are 30 percent more efficient than the most current version of American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 90.1 (Hutchison, 2010). Next, Executive Order (EO) 13423 requires federal agencies to utilize high-performance and sustainable building design principles. The final, and most recent, is EO 13514 which strengthened the previous orders by requiring that new construction designed after 2020 is able to achieve zero-net-energy by 2030 (The White House, 2009). Zero-net-energy is defined by the policy as a “building that is designed, constructed, and operated to require a greatly reduced quantity of energy to operate, meet the balance of energy needs from sources of energy that do not produce greenhouse gases, and therefore result in no net emissions of greenhouse gases and be economically viable” (The White House, 2009, p. 10). The order urges that projects be prioritized based on life-cycle return on investment and use cost-effective and innovative strategies to achieve energy balance (The White House, 2009).

Although EO 13514 applies to both new construction and renovation projects, this research will focus on new construction through the United States Air Force (USAF) Military Construction (MILCON) program. The Air Force Center for Engineering and the Environment (AFCEE) manages the MILCON program and has been tasked to ensure compliance with EO 13514. A recent reorganization has changed the name of AFCEE and made it a field operating agency of the USAF Civil Engineer Center, but because no guidance documents or regulations have been produced under its new name, this project will use AFCEE to represent both the new and old organizations. The MILCON program is governed by Air Force Instruction (AFI) 32-1023 and is the process utilized by the USAF to provide new facilities to meet mission needs. The program applies to new

construction on USAF installations costing more than 750,000 dollars. In Fiscal Year 11, the USAF MILCON program consisted of 77 projects, totaling over 1.4 billion dollars (AFCEE, 2011).

The current MILCON procurement process can be summarized into five main stages. First, base programmers generate facilities requirements based on operational need (AFCEE, 2007). These projects are subsequently prioritized by AFCEE and Major Commands using a formalized model (Dempsey, 2006). Then, the prioritized list of projects is sent to Congress for authorization and appropriation (Department of the Air Force, 2010). Once authorized, AFCEE develops an Acquisition Strategy for each project (AFCEE, 2007). Finally, the projects are distributed to the designated design and construction agent for execution (Department of the Air Force, 2010).

The main reason the current MILCON procurement process cannot implement Net-Zero Energy (NZE) construction practices is that there is currently no way to determine, without detailed design and energy modeling, whether a project can achieve cost-effective NZE. Since Congress appropriates projects at a specific cost and scope, MILCON program managers must be able to adjust the scope and associated cost of NZE-capable projects prior to their being sent for appropriation. Therefore, the identification of NZE-capable projects must occur early during the procurement process, not only due to Congressional appropriation restrictions, but also because that is when project alternatives with the greatest potential for savings can be identified.

1.2. Research Objective and Investigative Questions

The objective of this research was to perform a Level 1 feasibility assessment of Net-Zero Energy (NZE) construction through the United States Air Force (USAF) Military Construction program. A Level 1 feasibility assessment is conducted to provide sufficient information regarding a project's technical and economic feasibility as to allow for a decision regarding follow-on analysis, while simultaneously minimizing the effort and cost necessary to obtain that information (EPA CHP Partnership, 2012). This research will allow the USAF to limit more detailed and costly feasibility assessments to those installations which are the most likely to achieve cost-effective NZE.

Upon reviewing literature and discussions with AFCEE, the following investigative questions arose and were addressed by this project:

1. What amount of uncertainty would result from using energy use and construction premium data from the commercial facility sector to predict construction premium values for similar Department of Defense facility types?
2. How well do the developed Construction Premium and Cost-Effective Net-Zero Energy models corroborate with best-available understanding of their underlying concepts?
3. What are the most critical elements of life-cycle cost in terms of obtaining quality estimates to predict the net-savings of a potential net-zero energy construction project?
4. What is the uncertainty associated with calculating a deterministic value for the net-savings of a potential net-zero energy construction project from best-available parametric estimates?
5. Which CONUS installations will maximize the cost-effectiveness of potential net-zero energy construction projects?

These investigative questions will assist the USAF in meeting the federal government's direction to obtain Net-Zero Energy facilities by 2030.

1.3. Research Approach

This research consisted of three phases. In the first phase, a review of existing pertinent literature was conducted. This phase was used to select a strategy for complying with Executive Order 13514, select a renewable energy resource and technology for incorporation into the feasibility assessment model, provide a comprehensive review of literature pertaining to Zero-Energy Buildings (ZEB), and provide justification for the selection of the elements in the feasibility assessment model.

The second phase developed a mathematical model to assess the cost-effectiveness of constructing a Net-Zero Energy (NZE) facility in the contiguous U.S. through the United States Air Force (USAF) Military Construction (MILCON) program. The model was developed in accordance with the life-cycle cost methodology developed by the Federal Energy Management Program for the economic evaluation of energy conservation, water conservation, and renewable energy projects. The model was constructed using Hierarchical Function Decomposition, Systems of Equations, and Parametric Estimation.

The developed model was then evaluated to determine how it responds to changes in input variable values, how well it corroborates with best-available understanding, and how much uncertainty it produces with best-available parametric estimates. This evaluation was utilized to communicate the risk associated with making decisions based solely on the model's output. A component of the corroboration analysis was a comparative analysis of the incremental cost of energy efficiency improvements in commercial and Department of Defense facility types.

In the final phase, the model was utilized in an installation comparative analysis which ranked each USAF installation in terms of the cost-effectiveness of constructing a ZEB. A geospatial analysis calculated and summarized all location-dependent model inputs for use during the comparative analysis. Finally, a rank correlation analysis proved that there is a very strong and direct correlation of the installation rankings between facility types.

This research effort aligned the USAF MILCON program with strategic objectives and will ensure that projects which are capable of achieving cost-effective NZE are executed appropriately. A successful NZE strategy will reduce facility operational costs and ultimately facilitate energy independence and security at USAF installations.

1.4. Assumptions and Limitations

This research contains many assumptions and limitations which were made in order to scope and define the project. Five assumptions were made to simplify the project in order to achieve a manageable scope. Each is explained below.

- It is common practice to assess the sustainability of organizations and projects using a framework with three pillars: People, Planet, and Profits; these are commonly coined the triple bottom line (Slapper & Hall, 2011). For the military, energy security and independence are also important aspects to assess. The benefits attributable to People, Planet, energy security, and energy independence are not included in the cost model for this project. Therefore, the benefit of achieving net-zero energy will only be accounted for through utility bill reduction.
- Total project cost is typically accounted for through hard and soft costs. Soft costs are those associated with planning, design, and coordination of a construction project. This project only incorporates hard costs into the Incremental Construction Cost element. For example, the contractors with the

experience and skills necessary to construct a Zero-Energy Building will likely demand a premium; this contracting premium was not been included in the cost model.

- Projects under consideration will be designed, constructed, and maintained using energy performance metrics and the contractor selected to execute the project will be incentivized to minimize the facility's energy use.
- There is not enough data available for the energy use and incremental construction cost associated with Department of Defense facilities. Because of this, this project assessed three commercial facility types as if they were constructed through the Military Construction program. As will be proven during the Installation Comparative Analysis, facility type did not have a statistically significant impact on the ranking by cost-effectiveness.
- This research did not include an increase in cost for the Photovoltaic (PV) System when all the panels cannot fit on the roof structure. The unit cost of an installed PV system will increase when structures must be constructed in order to mount additional panels. Although this will impact cost-effectiveness, it will not impact installation ranking.
- Economic assumptions were required to simplify the analysis of this project; the specific assumptions are provided in Table 11. When these assumptions are changed, the resulting economic factors will change. As these factors are only multipliers for costs and benefits, the relative difference in cost-effectiveness will not change.

This research also included six limitations which, if changed, will affect the ranking of installations in terms of a ZEB's cost-effectiveness. Each is explained below.

- A strategy of on-site distributed generation was selected for this project as it maximized the goals outlined in Executive Order 13514 and energy security and independence at installations.
- It was assumed that every installation will allow simple net-metering for potential net-zero energy facilities. In practice, the extent of simple net-metering is dependent on regional utility companies and state legislation.
- Federal, State, and local incentives regarding renewable energy installation were not incorporated into the model as a benefit. These incentives are constantly changing and are geospatial.
- Site energy was the metric utilized to validate zero energy status. If source energy were used for example, the ranking of installations could change as the site-to-source multiplier is geospatial.

- Without a detailed engineering design with energy profiles, it is not possible to quantify the true electricity bill reduction. As the cost model assessed each construction project in its infancy, each installation's average electricity rate was utilized. In reality, installations have unique rate structures that will change the actual savings obtained.
- The feasibility assessment model only provides a baseline design alternative which includes a PV system and specific energy efficiency measures (EEM). A Flat-Plate PV System, mounted with a fixed tilt equal to the site's latitude, is the most likely design option to cost-effectively offset the energy demand remaining after all technically and economically viable EEMs have been incorporated. The EEMs included in the baseline design are those prescribed in the technical support documents of the American Society of Heating, Refrigeration, and Air conditioning Engineers' 50 percent Advanced Energy Design Guides. Additional design alternatives must be considered during the design phase to select the optimal renewable generator and EEMs.

1.5. Preview of Subsequent Chapters

This project follows the traditional five-chapter thesis format. Chapter 2 provides a literature review as a foundation for the project. Chapter 3 presents the research approach used to develop, evaluate, and apply the model. Chapter 4 discusses the results from Chapter 3. The final chapter presents the key findings of the research, discuss how the developed model should be utilized, and suggest future research endeavors.

II. Literature Review

This chapter provides essential knowledge of Military Construction and Zero-Energy Buildings. It will also be utilized to select a strategy for complying with Executive Order 13514 and the renewable energy resource and technology which will be incorporated into the feasibility assessment model. Finally, the literature review will describe each element and how it will be decomposed into the final research model. The literature review will be divided into 10 main sections, each of which will provide an understanding of a particular aspect of the research.

2.1. Military Construction Overview

This section provides an overview of the Military Construction (MILCON) program. It includes a discussion of the MILCON program's purpose, provides a summary of the overarching procurement process, and presents insights into how the program could be utilized to implement net-zero energy (NZE) policy.

The MILCON program is governed by Air Force Instruction (AFI) 32-1023 and is the process utilized by the United States Air Force (USAF) to provide new facilities to meet mission needs. The program applies to new construction on USAF installations costing more than \$750,000. In Fiscal Year 11, the USAF MILCON program consisted of 77 projects totaling over \$1.4 billion (AFCEE, 2011).

The objective of the MILCON program is to provide facilities which “enable mission execution and enhance occupant safety and quality of life by providing sustainable facilities” (Department of the Air Force, 2010, p. 9). All Air Force MILCON

projects are managed from design to beneficial occupancy by the Air Force Center for Engineering and the Environment's (AFCEE) Capital Investment Management (CM) Division (AFCEE, 2011). The CM division houses the MILCON Program Management Office, which is responsible for the management of all active USAF MILCON projects, with the exception of those located in contingency areas (AFCEE, 2011).

The procurement process can be divided into five main stages. In the first stage, projects are proposed based on operational need (AFCEE, 2007). Once these projects are accepted by the Civil Engineering Work Request Review Board, they are programmed in the Automated Civil Engineer System (ACES) using a Defense Document (DD) Form 1391.

The next stage of the process requires that projects be prioritized. This is a vital stage as the USAF must ensure maximum mission impact, given the fact that not all projects will receive funding. AFCEE works with all stakeholders, especially the affected Major Commands, to prioritize the projects (Department of the Air Force, 2010). In the 1990s, USAF leadership centralized the MILCON program within the enhanced corporate structure (Dempsey, 2006). The Integrated Process Teams (IPT) established under the new structure developed a MILCON scoring model to prioritize and recommend projects for funding (Dempsey, 2006). The model is composed of four rating criteria: "[Major Command] MAJCOM priority (60 points), Investment Strategy Scoring Matrix (ISSM) (35 points), Corporate Panel Points (2 points), and MILCON IPT Factors (5 points)" (Dempsey, 2006, p. 21).

In the third stage, MILCON projects receive funding, also known as appropriation from Congress. All MILCON projects must be authorized by Congress prior to the

commencement of design and/or construction efforts (Department of the Air Force, 2010). Both the cost and scope of MILCON projects are provided to Congress via the DD Form 1391 (Department of the Air Force, 2005). Once approved, funds are appropriated for each individual project, at a specific cost and scope (Department of the Air Force, 2010). Authorization for a project expires two years after it has been approved by Congress or the start of the third fiscal year, whichever is earlier, and funds are available for five years (Department of the Air Force, 2010). If the cost or scope of an appropriated project changes by more than 25 percent, Congress must be notified and the project must be reapproved (Department of the Air Force, 2005). In 2009, the USAF implemented a policy, following changes to Title 10 U.S. Code 2853, that strictly limits the scope of a project to that indicated on the DD Form 1391 (Department of the Air Force, 2010).

In the fourth stage, the development of an Acquisition Strategy occurs after the appropriation of projects by Congress. A Project Acquisition Strategy is a strategic level roadmap which is used to guide the project toward a successful outcome (Creel & Ellison, 2008). Figure 1 shows how the Acquisition Strategy fits into the broader risk management approach and how it is utilized to address the major risks associated with a project.

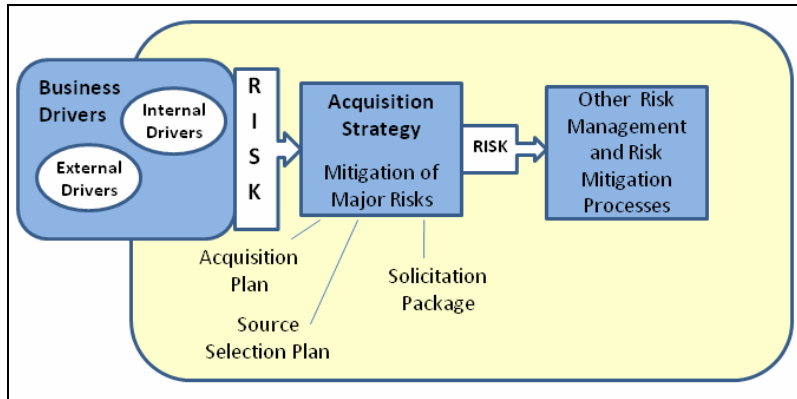


Figure 1 – Project Risk Management (Creel & Ellison, 2008)

A good Acquisition Strategy must span the project’s life-cycle and focus on managing risk (Creel & Ellison, 2008). Chapter 2 of the Defense Acquisition Guidebook, defines an Acquisition Strategy as “a comprehensive, integrated plan that identifies the acquisition approach, and describes the business, technical, and support strategies that management will follow to manage program risks and meet program objectives” (Defense Acquisition University, 2012, p. 46).

The final stage occurs after an Acquisition Strategy has been developed and is when actual design and construction begins. However, the Air Force has limited execution authority and must rely on Design and Construction Agents, such as the Navy Facility Engineering Command (NAVFAC) and Army Corps of Engineers (USACE) (Department of the Air Force, 2010). Even though AFCEE will most likely not have execution authority for a specific project, the Program Management Plans agreed to, between it and the Design and Construction Agents, explicitly state that Project Acquisition Strategy alternatives must be considered jointly for each project (Nodjomian & Hemstreet, 2008). Additionally, AFI 32-1023 states that AFCEE, as the Design and Construction Manager, will take the lead in developing these strategies.

This section has provided a brief discussion of the MILCON program and the overarching procurement process that the USAF follows to deliver new facilities in order to meet operational need and strategic objectives. The understanding gained in this section illustrates how a strategy which incorporates multiple levels of feasibility assessments could be incorporated into the current MILCON procurement process. This strategy would allow NZE-capable projects to be identified in their infancy and program managers to justify and then adjust their programmed cost and scope prior to appropriation from congress.

2.2. Strategies to Comply with Federal Energy Policy and Strategic Goals

This section provides a summary of Executive Order (EO) 13514 in an effort to uncover the intent of the policy. It then discusses Department of Defense (DoD) strategic goals relating to installation and facility energy performance. The potential strategies for complying with the EO will be presented and in conclusion, a comparison will be documented in order to select the strategy which maximizes the goals outlined in the EO and DoD policy.

EO 13514 expands on the environmental performance and building energy efficiency requirements of prior EOs. The stated objectives of the policy are to “create a clean energy economy that will increase our Nation’s prosperity, promote energy security, protect the interests of taxpayers, and safeguard the health of our environment” (The White House, 2009, p. 1). The EO creates specific goals for all federal agencies regarding building energy efficiency, greenhouse gas emissions reduction, water conservation and protection, and solid waste reduction (The White House, 2009). The

building energy efficiency goals require the implementation of high-performance and sustainable building design principles in order to design, construct, operate, maintain, and deconstruct sustainable facilities. These goals strengthen EO 13423 by requiring that new facilities entering the design process in the year 2020 or later “are designed to achieve zero-net-energy by 2030” (The White House, 2009, p. 3).

In addition to net-zero energy (NZE) policy, the DoD has developed its own goals regarding energy efficiency at military installations. All services have developed energy efficiency and renewable energy initiatives, with the Army setting an aggressive goal of obtaining five net-zero installations by 2020 (Environmental and Energy Study Institute, 2011). A net-zero installation encompasses more than energy; the Army’s definition includes no net-exports of water or solid waste (Department of the Army, 2012). The Army approach to net-zero installations is composed of the five step hierarchy illustrated in Figure 2.



Figure 2 - Army Net-Zero Installation Approach (Department of the Army, 2012)

In May of 2010, the United States Air Force (USAF) energy plan released a vision statement, stating that personnel should make “energy a consideration in all we do” (Environmental and Energy Study Institute, 2011, p. 2). The plan calls for a balanced mixture of on-base and off-base renewable energy generation (Environmental and Energy Study Institute, 2011). The ultimate goals for the DoD energy initiatives are to increase both the energy security and independence of military installations while acting as a force multiplier in contingency locations (Environmental and Energy Study Institute, 2011). Although not specifically stated, especially in the current fiscally constrained environment, another goal of NZE for both facilities and installations is to reduce the required operational energy budget.

In July of 2010, the DoD and Department of Energy (DOE) signed a memorandum of understanding (MOU) to establish a framework for cooperation in meeting federal energy policy and initiatives (Poneman & Lynn, 2010). The MOU is beneficial to both agencies as the DoD will benefit from the environmental and energy efficiency experts at the DOE, and the DOE will speed the development of energy efficiency technologies through the investment made by the DoD. One example of the DoD leveraging the expertise of the DOE is illustrated in a report on the concept of Net-Zero Energy Installations; these are defined as achieving “energy self-sufficiency based on minimized demand and use of local renewable energy resources”. The report developed a methodology for the identification, assessment, and implementation of energy efficiency initiatives and is summarized in Figure 3.

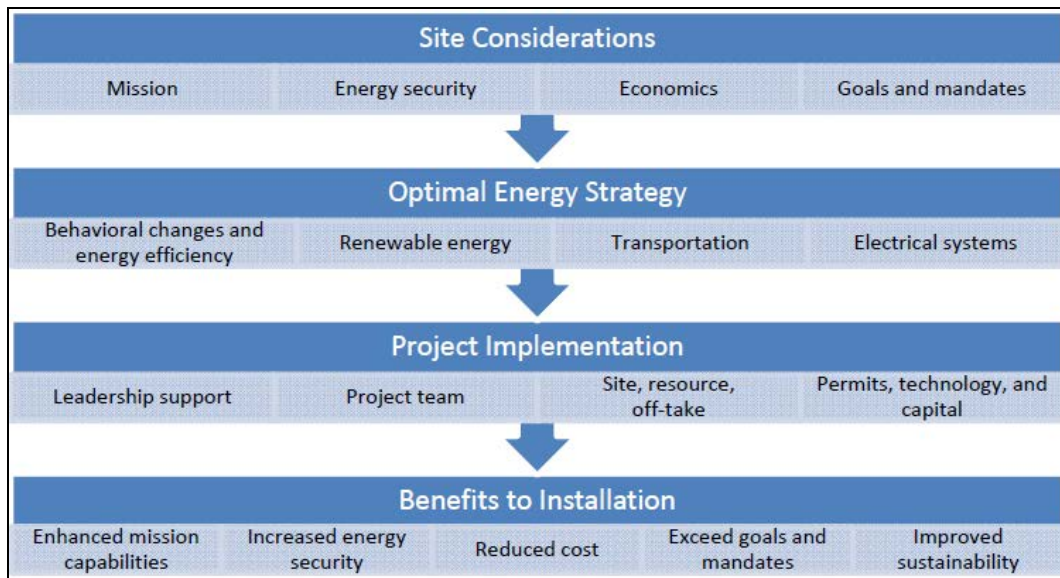


Figure 3 - Flow Diagram of Net-Zero Energy Assessment and Implementation (Booth et al., 2010)

The wording in EO 13514 of the requirement to construct facilities by 2020 to achieve zero-net energy by 2030, allows for phasing of a project to ensure it is cost-effective. For example, a facility could be designed to achieve NZE through a photovoltaic array, but the purchase of the array could be postponed until efficiency and cost improvements make the system economically viable. The policy defines an NZE building as one that is “designed, constructed, and operated to require a greatly reduced quantity of energy to operate, meet the balance of energy needs from sources of energy that do not produce greenhouse gases, and therefore result in no net emissions of greenhouse gases and be economically viable” (The White House, 2009, p. 10). This definition and the wording of the NZE goal provide the first and foremost step in any strategy for constructing a Zero-Energy Building, to reduce the energy consumption of facilities as low as economically feasible.

The second phase of a strategy to comply with EO 13514 is to obtain renewable energy to offset the demand remaining after all technically and economically practical energy efficiency improvements have been exhausted. It is possible to obtain this energy through one, or a combination of, the three methods outlined in Table 1 (Torcellini, Pless, Deru, & Crawley, 2006).

Table 1 - Comparison of Strategies to achieve NZE Objectives

Strategies	Clean Energy Economy	Energy Security / Independence	Taxpayer Interest / Budget Reduction	Safeguard Environment
Purchase Green Power	Meets	Does not meet	Does not meet	Meets
Renewable Farms	Meets	Meets	Meets	Meets
On-Site (Distributed Generation)	Meets*	Meets*	Meets	Meets
* Maximizes				

The purchasing of green power is a viable option for most of the commercial sector and is currently being utilized by the USAF (Environmental and Energy Study Institute, 2011). Although the purchase of green power would comply with policy, it does not increase energy security or independence, nor does it allow for net-zero energy installations. Developing centralized renewable energy farms is another method for obtaining power from sources which do not produce greenhouse gasses. This method takes advantage of economies of scale by utilizing larger and more efficient renewable energy generators (Department of Energy, 2011). The main disadvantage of this method is that it requires a large development site and a significant capital investment.

The final method accomplishes NZE by utilizing on-site renewable energy generation (Griffith et al., 2007). This method takes advantage of the un-utilized real estate of individual facilities. This strategy requires that individual facilities incorporate renewable energy generators. Since most renewable energy sources do not produce energy at all times, it is necessary to either store energy on-site or take advantage of distributed generation technologies (Interagency Sustainability Working Group, 2008). Due to the lack of cost-effective energy storage devices, distributed generation is by far the most popular solution (National Science and Technology Council, 2008). Distributed generation ties the facility to the existing electrical grid, allowing it to export energy to the grid when excess is being produced and then import that same quantity of energy when the facility's demand exceeds production capability. A facility utilizing distributed generation and simple net-metering would be comprised of at least the components in Figure 4.

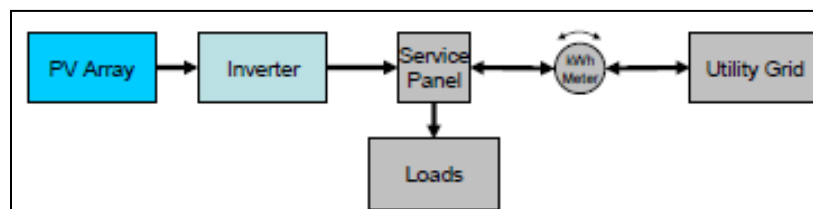


Figure 4 – One-Line of Net-Metered Facility Components (Sandia National Labs, 2007)

As required by the Institute of Electrical and Electronics Engineers (IEEE) Standard 1547, the inverter in this configuration must monitor the utility grid and disconnect when certain conditions exist (Sandia National Labs, 2007). This

configuration also does not allow communication between the meter and utility system; as Smart Grid technologies increase, Smart Meters will be incorporated which allow for more efficient management of the grid (Sandia National Labs, 2007).

As discussed in this section, the first and foremost step to achieving a ZEB is to reduce energy consumption as low as economically feasible. The strategy selected to acquire the renewable energy requirement of EO 13514, will ultimately include a combination of centralized renewable energy farms and distributed generation methods. The specific combination of methods an installation will utilize should be based on economic analysis. As this analysis is not available, and in order to scope this research, the distributed generation method has been selected for incorporation into a feasibility assessment model.

Distributed generation allows for the division of required capital investment and requires minimal additional real estate, as many sources of energy can be arranged within a facilities footprint (Booth et al, 2010). It also maximizes the energy security and independence of installations by dispersing the renewable energy generators (Scott, Holcomb, & Josefik, 2003). Additionally, meeting NZE objectives through distributed generation lies at the heart of centralized control and decentralized execution, a principle which is fundamental to the success of aerospace operations (Department of the Air Force, 2011).

2.3. Renewable Energy Resources at Air Force Installations

This section provides an overview of renewable energy resources suitable for distributed generation at United States Air Force (USAF) installations. It will then

discuss the technologies which could be utilized to harvest those resources. A comparison of those resources and technologies is provided in Table 2.

Table 2 - Summary of Potential Distributed Generation Technologies

Technology (Resource)	AF Adoption	Proven for Distributed Generation	Technology Reliability	Base-load Power *	Resource Coverage
Binary Cycle (Hydrothermal)	None	No	High	High	Low
PV (Solar)	High	Yes	High	Medium	High
CSP (Solar)	None	No	High	Medium	Low
HAWT (Wind)	Medium	No	Medium	Low	Medium
* Without energy storage					

A renewable energy resource is defined as one which is available in the natural environment and has the ability to replenish through natural processes over time (EERE, 2010). The Department of Energy's Energy Efficiency and Renewable Energy (EERE) office supports solar, wind, water, biomass, geothermal, and fuel cell renewable energy technologies (EERE, 2010). Fuel cell technologies will not be discussed as they are energy carriers rather than producers (EERE, 2010). Although these sources are renewable, they are not all clean. Due to the Executive Order 13514's restriction that sources cannot produce greenhouse gasses, biomass technologies will not be considered for this research. A further technology restriction is present due to the decision to utilize distributed generation with power produced on-site. This restriction eliminates water technologies from consideration, as the resource is not available within a facilities footprint.

A brief description of each remaining technology will be provided along with key characteristics such as reliability, power consistency, cost-effectiveness, location independence, and technology adoption.

2.3.1. Geothermal Resource.

Geothermal energy is heat energy generated by the earth (Kagel, Bates, & Gawell, 2007). This energy can be used directly in facilities, for purposes such as heating or cooling, or to produce electricity (Anderson, Antkowiak, & others, 2011). Geothermal energy is a renewable resource which produces little to no greenhouse gas emissions and provides baseload power (Anderson, Antkowiak, & others, 2011); baseload power is defined as consistent power and reduces the need to incorporate energy storage solutions (Kagel, Bates, & Gawell, 2007). There are numerous resource types which fall under geothermal energy, including coproduction, geopressured, and hydrothermal. The most widely available resource suitable for on-site distributed generation is hydrothermal.

Most power generated from hydrothermal resources is from high temperature wells; however, low temperature wells are the most common and they can be used to produce power (Anderson, Antkowiak, & others, 2011). High temperature resources are typically utilized for utility scale power generation. Low temperature resources, ones with temperatures between 80 and 150 degrees, “have the potential to be a viable solution for small to medium scale power generation needs” (Anderson et al., 2011, p. 25).

Electricity generation from hydrothermal wells employ three main technologies: dry steam, flash steam, and binary cycle. The technology utilized depends on the state and temperature of the fluid being utilized; binary cycle has shown the most promise for

producing power from low temperature wells (Kagel, Bates, & Gawell, 2007). The main difference between binary cycle and dry or flash steam systems is that the fluid never contacts the turbine (Kagel, Bates, & Gawell, 2007). The geothermal fluid is used to heat a secondary (binary) fluid, which has a much lower boiling point, through a heat exchanger (Kagel, Bates, & Gawell, 2007). The heat transfer causes the secondary fluid to vaporize, which in turn drives the turbine and generates electricity. Binary cycle power plants are closed-loop systems which produce no greenhouse gas emissions (Kagel, Bates, & Gawell, 2007).

As discussed earlier, low temperature hydrothermal resource is the most widely available geothermal energy resource suitable for distributed generation. However, the temperatures most suitable for power generation are mostly found in the western U.S, as shown in Figure 5.

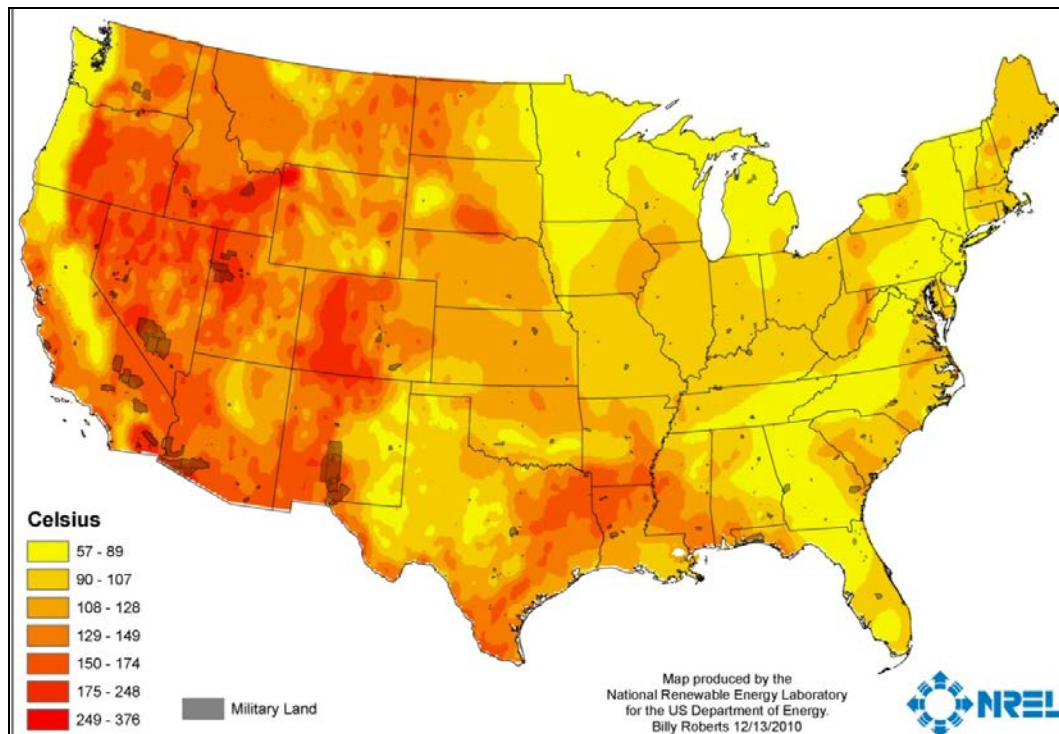


Figure 5 - Hydrothermal Resources (Anderson et al., 2011)

Hydrothermal power is often cost prohibitive to utilize for power generation. In order to prove a hydrothermal resource exists, it must be explored and then drilled. Once proven viable, infrastructure must be constructed to generate and distribute electricity. Additionally, geothermal wells are often in remote locations, significantly increasing this cost.

2.3.2. Solar Resource.

There are two main energy producing technologies which directly utilize solar resource. Each will be discussed below.

2.3.2.1. Photovoltaic Technology.

Photovoltaic (PV) technologies convert solar irradiance into direct current (DC) electricity using solid-state semiconductor devices (Anderson et al., 2011). A variety of semiconductor materials are used in various types of PV cells; crystalline silicon is the most common. Crystalline cells are commonly used as a benchmark of cost and conversion efficiency metrics during cell type comparisons (Anderson et al., 2011).

All PV systems produce DC electricity. Therefore, in applications where alternating current (AC) electricity is used, an inverter is needed to convert the power generated by the system. Inverters are solid state electronic devices with DC to AC conversion efficiencies near 95 percent (Anderson et al., 2011). Most inverters include a maximum power point tracking (MPPT) function which operates the inverter to obtain peak power output throughout the day and year. Due to these high efficiencies, converting DC power to AC power for use by the facility is most often more advantageous than locating and powering individual DC loads (Anderson et al., 2011).

Solar radiation is a term used to describe the electromagnetic radiation emitted from the sun (DOE, 2011). The technical and economical feasibility of utilizing the radiation depends on the total available resource. The solar resource is the amount of solar radiation reaching the earth's surface and is a factor of geographic location, time of the day, season of the year, geographic landscape, and weather (DOE, 2011). Sunlight is reflected, refracted, and absorbed by a variety of particles in the earth's atmosphere (DOE, 2011). The radiation that has been scattered is termed diffuse; that which has not been diffused is known as direct beam. The total solar radiation reaching the earth's

surface is the sum of the diffuse and direct beam radiations. PV technologies can utilize both of these forms of radiation. Figure 6 shows the solar resource available to a flat-plate latitude-tilt available across the US.

The most common PV array for use as on-site renewable energy generation is the flat-plate panel affixed to the building's roof structure (DOE, 2011). These arrays achieve maximum efficiency when tilted to the site's latitude (Marion & Wilcox, nd). Tracking arrays are more efficient, but must be analyzed on a case-by-case basis as they also weigh more and are more costly over their life-cycle. Manufacturing and efficiency improvements have resulted in a reduction in system cost of one-third in the last year; installation costs have also decreased due to scale, learning curves, and increased competition (NREL, 2012). The wide adoption has also improved the reliability of PV systems; analysts state the useful life of PV panels to be 20 to 40 years (NREL, 2012).

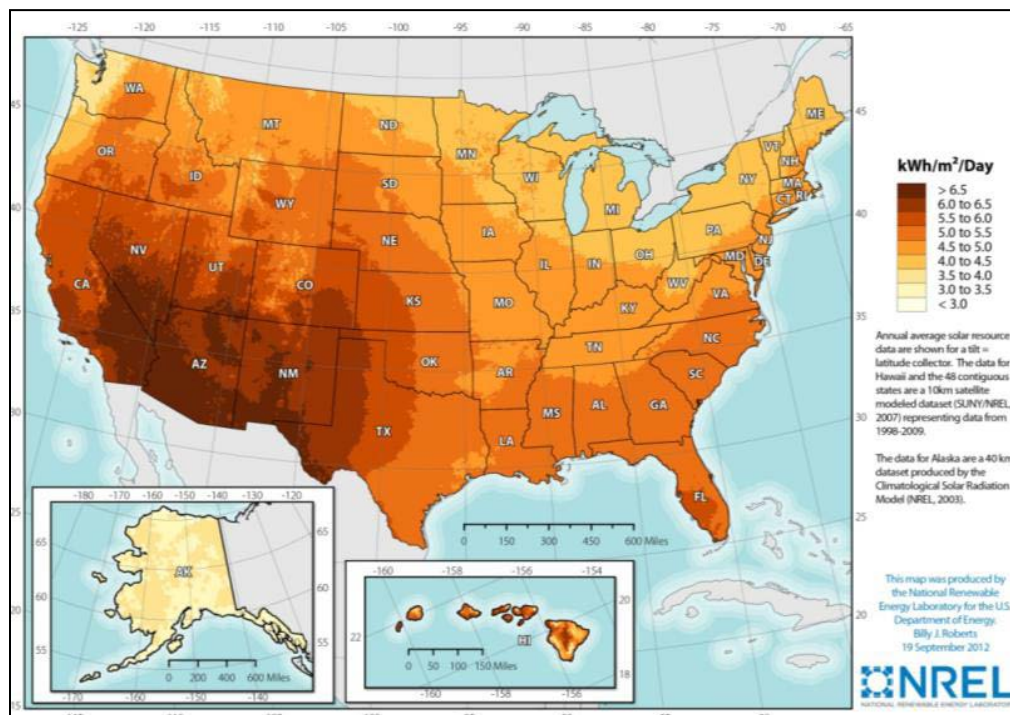


Figure 6 - Solar Resource in the U.S. (EERE, 2012)

2.3.2.2. Concentrating Solar Power.

Concentrating solar power (CSP) technologies use mirrors to reflect and concentrate sunlight onto receivers that collect solar energy and convert it to heat (Anderson et al., 2011). These systems concentrate solar energy 50 to 10,000 times to produce high-temperature thermal energy. This thermal energy can then be used to produce electricity via a steam turbine or heat engine that drives a generator (Anderson et al., 2011).

CSP technologies have mostly been utilized for utility scale applications, but smaller CSP systems can be used in a distributed generation scheme (Anderson et al., 2011).. For example, a parabolic dish concentrator and engine system can produce 3 to 25 kilowatts of power. The modular nature of the systems make them well suited for distributed applications.

Unlike PV, CSP technologies can only use direct beam insolation (Anderson et al., 2011). Direct beam insolation occurs when the sun's electromagnetic energy arrives unobstructed to the earth's surface; during cloudy weather for example, this technology is not viable for producing electricity without the use of stored thermal energy. CSP is a viable energy generator only when the direct beam insolation is greater than 6.75 kilo Watts per square meter per day (Anderson et al., 2011). In the U.S., this restricts its use to the Southwest; Figure 7 shows direct beam solar resource throughout the southwestern US.

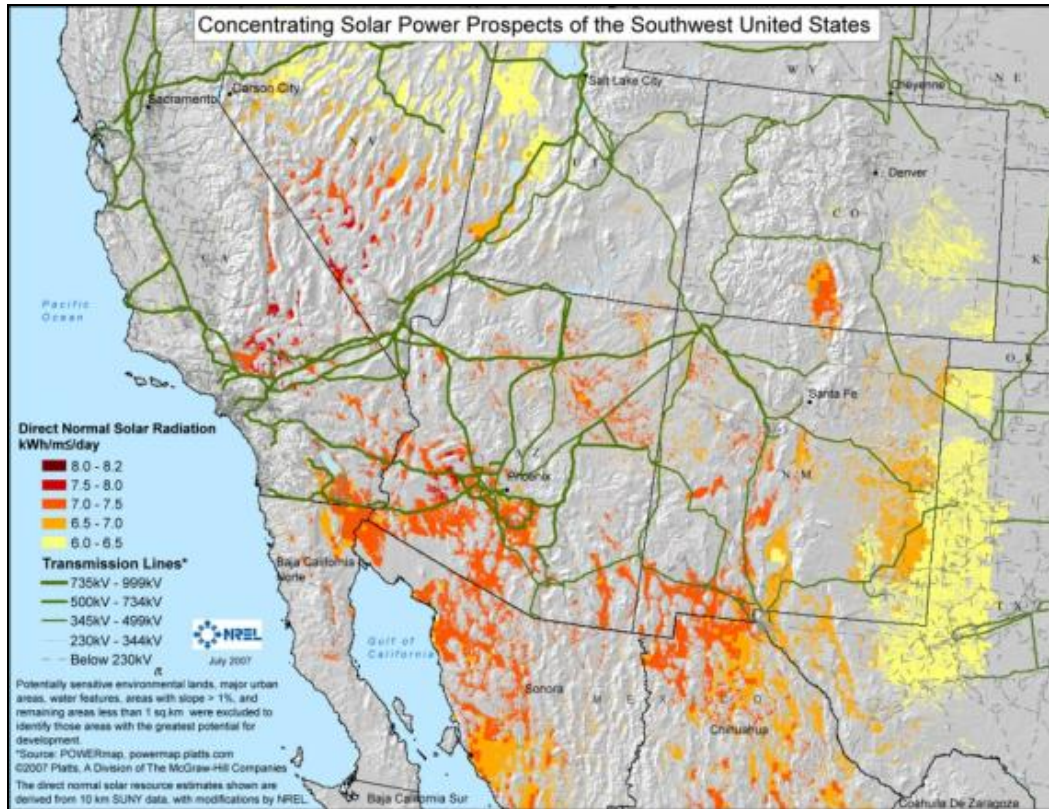


Figure 7 - Direct Beam Solar Resource in the Southwestern US (EERE, 2012)

2.3.3. Wind Resource.

Modern wind turbines are complex systems used to convert wind energy into mechanical energy, which is then converted into electrical energy by a generator (Wind Powering America, 2011). Wind is a form of solar energy and is created by the uneven heating of the earth's atmosphere. Wind turbine generators convert wind energy into electricity via a direct drive generator or a planetary gearbox connected to and synchronized with the grid (Anderson et al., 2011). For smaller turbines, DC to AC inverters are required to obtain grid-quality power (Anderson et al., 2011).

There are two types of wind turbine technologies used to generate electricity. They are horizontal axis (HAWT) and vertical axis (VAWT). Generally speaking,

HAWT are the most reliable and cost-effective of the technologies (Anderson et al., 2011). Only smaller HAWT turbines, below 100 kilo Watts, are suitable in a distributed generation scheme (Anderson et al., 2011). Small turbines can vary widely in size and shape, with towers ranging from 1 to 40 meters and rotor diameters from 2 to 21 meters. There have been very few turbines designed and tested for use on commercial rooftops, and most companies who have tried have abandoned the technology in favor of more viable alternatives (Anderson et al., 2011).

During the national wind resource assessment of the U.S., conducted in 1986 by the DOE, the U.S. was divided into grid cells (Pacific Northwest National Lab, 1986). Every grid cell was assigned a wind power class ranging from 1 to 6, with 6 being those with the most energy potential. Each wind power class has a range of possible power densities which are likely to occur (Pacific Northwest National Lab, 1986). Figure 8 shows the wind power classifications across the U.S..

The power class values in Figure 8 are calculated assuming exposed sites and must be derated if the wind flow will be impeded (Pacific Northwest National Lab, 1986). For on-site installations, where the wind flow will be reduced, it is important to account for a loss in power. As the wind velocity decreases, the power generated will decrease as the cube of the wind velocity (Anderson et al., 2011). For example, if the wind velocity is reduced by one-half, then the power generated will be reduced by one-eighth. This effect has a profound impact on both the energy production and cost-effectiveness of the wind turbine. Department of Defense studies have shown that the cost of energy for distributed generation using wind turbines is more than 2.6 times the national average electricity rate (Anderson et al., 2011).

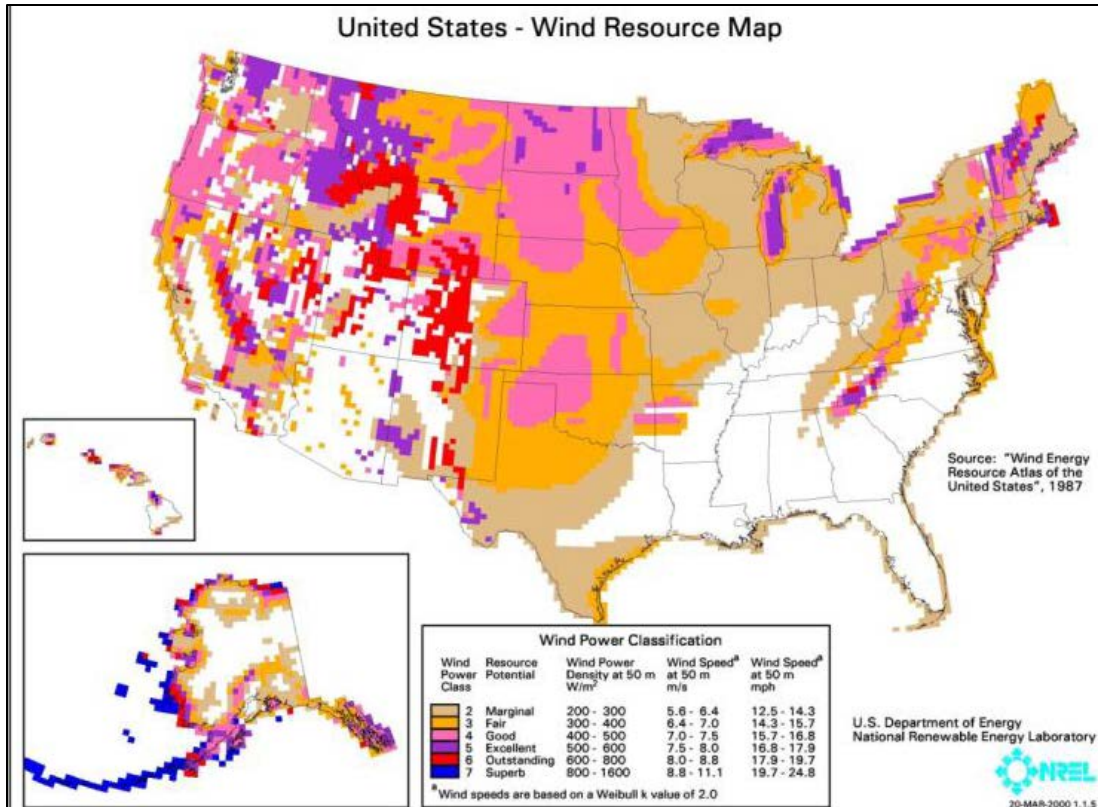


Figure 8 - US Wind Resource (EERE, 2012)

Newer wind turbines are better designed and have lower installed and lifetime operations and maintenance (O&M) costs than machines deployed in the last decade. This is likely the reason that the cost of fixed O&M has declined by 40 percent in the last year; O&M is now in the 30 to 40 dollars per kilo Watt range (NREL, 2012). An indication of the reliability of these turbines is included in assessments of their useful economic life. Most turbines have a useful economic life of 20 years (NREL, 2012).

This section has reviewed available renewable energy resources and discussed power generation technologies suitable for on-site distributed generation at USAF installations. As shown in Table 2, wind and PV are the only renewable resources that are available at most USAF installations. Additional justification for PV is provided by

observing each technology's Cost of Energy (COE). Table 3, modified to include only the technologies and sizes of interest, shows the installed and O&M costs to be lower for PV than wind (NREL, 2012). An observation of current Zero-Energy Buildings (ZEB) provides final justification for the selection of PV as the renewable generator for the feasibility assessment model. Each of the 21 current ZEBs has utilized PV technologies to generate the energy needed to offset their demand.

Table 3 - Costs for Electric Generating Technologies (New Buildings Institute, 2012)

Technology	Mean installed cost (\$/kW)	Fixed O&M (\$/kW-yr)	Expected Useful Life
Solar PV 10 – 100 kW	\$4,425	\$26	25 - 40
Solar PV 100 – 1,000 kW	\$3,671	\$24	
Wind 10 – 100 kW	\$6,066	\$44	20
Wind 100- 1000 kW	\$3,567	\$38	

2.4. Net-Zero Energy Overview

This section provides a background of Zero-Energy Buildings (ZEB) and justification for the selection of a definition of net-zero energy (NZE) for this research project. It will then summarize the current and expected market for ZEBs in the construction industry. Finally, it will address some pertinent lessons learned from NZE case studies.

The concept of a NZE building involves significantly reducing energy requirements through the use of energy efficiency technologies and designs such that the remaining energy needs can be offset by renewable technologies (Torcellini, Pless, Deru, & Crawley, 2006). ZEBs are not a new concept; civilizations throughout history have constructed facilities which do not need outside energy sources to function. The

challenge arises when trying to meet our society's indoor environmental comfort expectations, while simultaneously reducing energy consumption. These challenges are being addressed by government policies around the globe, which are promoting high performance and sustainable facilities. One noteworthy leader in government support for NZE construction is the European Union. Its Energy Performance of Buildings Directive will require nearly zero energy buildings in the public sector by 2019 and in all construction by 2021 (Pike Research, 2012).

Although NZE construction has seen conservative growth, recent studies have shown that it will grow rapidly and aggressively in the coming decades, mainly due to technological innovations and the increasing cost of energy (Pike Research, 2012). The revenue from zero-energy buildings is expected to grow worldwide over the next 20 years and is expected to reach \$690 billion by 2020 and nearly \$1.3 trillion by 2035 (Pike Research, 2012).

To achieve success in the construction of a ZEB, it is necessary to clearly state which definition of zero-energy will be used for the project. The definition chosen will have a dramatic impact on the design strategy used to achieve success (Torcellini, Pless, Deru, & Crawley, 2006). There are four well documented definitions of NZE. They are source, cost, site, and emissions; each will be discussed below.

The first definition is Net-Zero Source. A Net-Zero Source building is one that uses as much energy over a year as it produces, when accounted for at the source (Torcellini, Pless, Deru, & Crawley, 2006). When accounting for energy at the source, it is necessary to use site-to-source multipliers to account for the prime energy required to transport, produce, and deliver the power (Griffith, Long, Torcellini, & Judkoff, 2007).

Site-to-source multipliers are commodity and location dependent, but the national average for electricity is 3.37 to 1 (Torcellini, Pless, Deru, & Crawley, 2006). This means that it takes 3.37 units of prime energy, such as coal, to produce one unit of electricity at the building's site. Using this definition of NZE requires the conversion of energy consumed; each energy commodity must be converted, and in some situations multiple site-to-source multipliers may be required for each commodity. This definition is sensitive to the fluctuation of site-to-source multipliers (Torcellini, Pless, Deru, & Crawley, 2006).

The second definition is Net-Zero Cost. A Net-Zero Cost facility is one where the payment for exported energy is equal to the energy purchased, when accounted for over a year (Griffith, Long, Torcellini, & Judkoff, 2007). Zero cost is very difficult to obtain since utility companies typically pay much less for power imported to the grid than they charge for power consumed from it (Torcellini, Pless, Deru, & Crawley, 2006). Defining NZE in terms of cost also creates uncertainty in the verification of zero energy, as energy prices are continuously changing (Griffith, Long, Torcellini, & Judkoff, 2007). Additionally, the prices of energy commodities have typically escalated faster than general inflation, meaning that it will be increasingly more difficult to maintain ZEB status in the years following construction (Rushing, Kneifel, & Lippiatt, 2011).

The third definition is Net-Zero Site. A Net-Zero Site facility is one where the sum of energy imported to the facility is equal to the energy exported from it when accounted for at the site. This definition is easier to manage as no calculations are necessary to convert to source energy (Griffith, Long, Torcellini, & Judkoff, 2007). Accounting for energy at the building site means that all energy types are accounted for

at a one to one ratio. Site ZEBs have the fewest fluctuations in achieving zero energy, as this definition provides the most repeatable and consistent metric. For this reason, most research in NZE has used this definition for analysis (Griffith, Long, Torcellini, & Judkoff, 2007 ; New Buildings Institute, 2012).

The final definition is Net-Zero Emissions and is defined as a building using as much energy from emissions-producing sources as it does from emissions-free sources (Torcellini, Pless, Deru, & Crawley, 2006). This definition allows for the purchase of green power and the achievement of an off-site ZEB (Torcellini, Pless, Deru, & Crawley, 2006). The main advantage of a Net-Zero Emissions building is that it strives to minimize its environmental impact. The concern with utilizing this definition is that it creates a metric which will fluctuate and that it also requires computations similar to Net-Zero Source (Torcellini, Pless, Deru, & Crawley, 2006).

As alluded to in the Net-Zero Emissions definition, it is possible to achieve either an on-site or off-site NZE building. The best strategy is dependent on economic analysis and strategic objectives, but most commercial NZE buildings use on-site renewable energy generators in a distributed generation scheme (New Buildings Institute, 2012). Creating a stand-alone NZE building, one that is not connected to the utility grid, requires either over-sizing the renewable energy generator or storing power on-site. Except in isolated facilities, both of these will negatively impact the life-cycle economics of the project.

By utilizing commercially available and off-the-shelf technologies, it is possible to reduce the energy consumption of a facility by 30 to 50 percent (National Science and Technology Council, 2008). Those same technologies, if designed using a holistic and

collaborative effort, can reduce energy consumption by up to 70 percent (National Science and Technology Council, 2008). As shown in Figure 9, once energy demand has been reduced, it becomes possible to offset that demand with renewable energy sources. Figure 10 shows the average percent energy savings required to achieve NZE for certain commercial facility types.

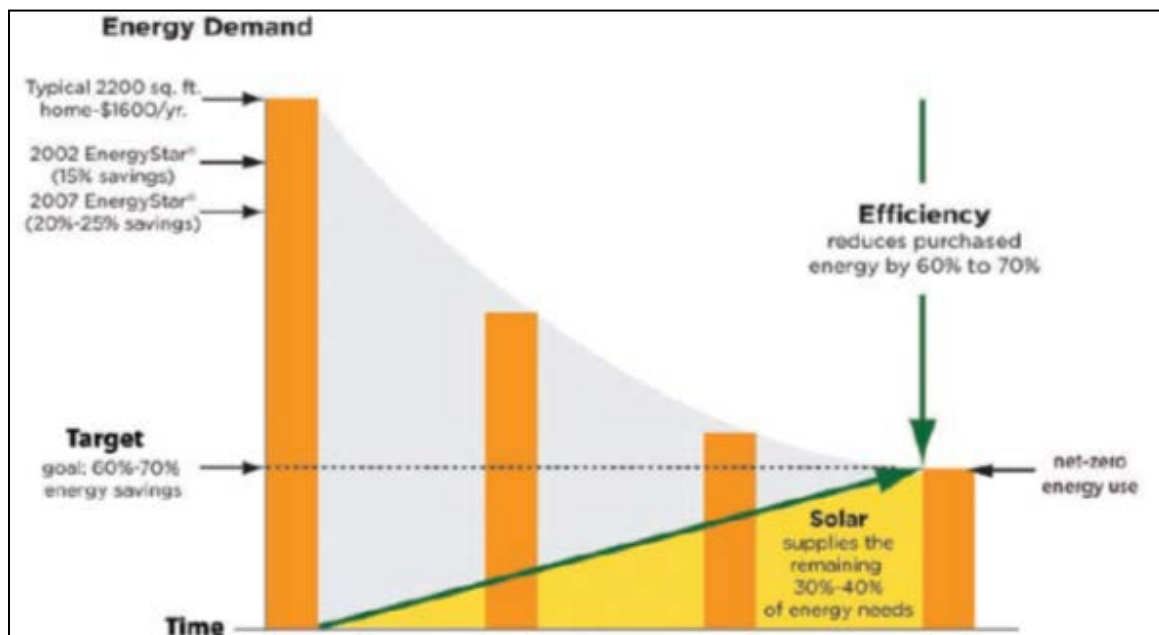


Figure 9 – Approach for Achieving NZE Buildings (National Science and Technology Council, 2008)

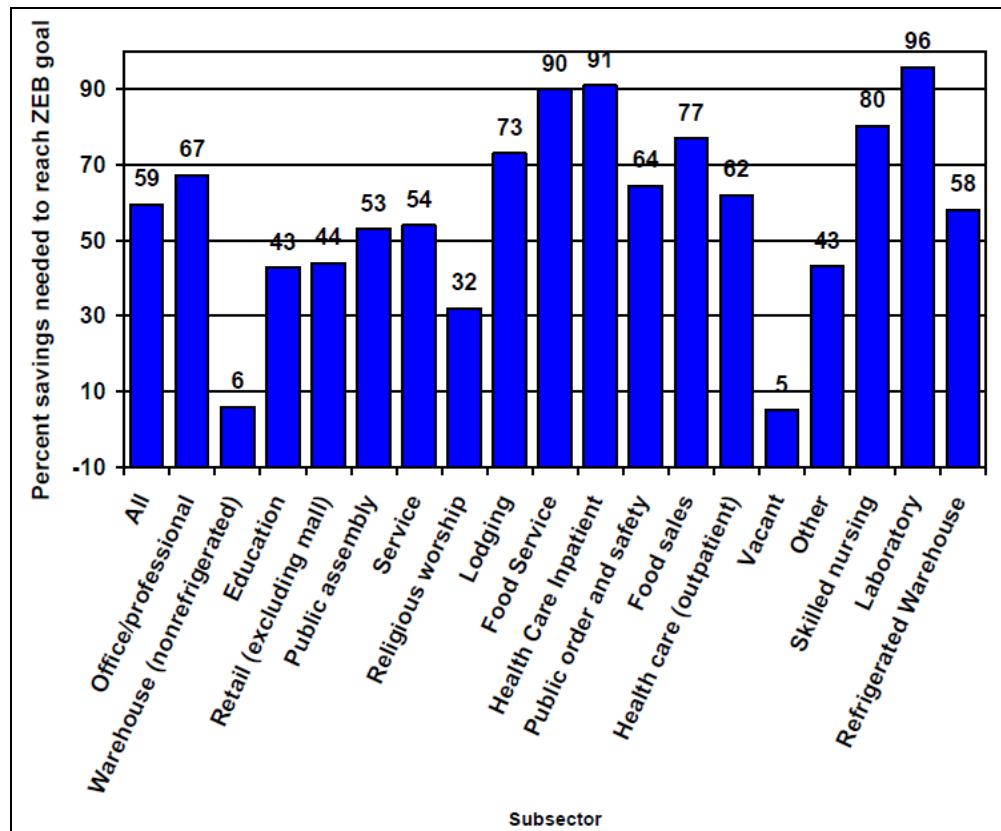


Figure 10 – Percent Energy Savings to Reach ZEB Goal (Griffith, Long, Torcellini, & Judkoff, 2007)

A report produced in 2007 by the National Renewable Energy Lab (NREL) concluded that 62 percent of the commercial building sector is capable of reaching NZE status (Griffith, Long, Torcellini, & Judkoff, 2007). This study is supported in practice by 21 existing ZEBs in the U.S. (New Buildings Institute, 2012). A 2012 study conducted by the New Buildings Institute (NBI) discovered 60 facilities in the U.S. that are either NZE or have low enough energy use to be capable of achieving NZE. A key conclusion of the study found that NZE buildings are uncommon, but growing in both number and complexity. The study also concluded that reducing energy levels to those required for NZE are obtainable at a reasonable incremental cost.

There are a limited number of case studies available for NZE buildings, but they

provide valuable insight into best practices. One common conclusion from these studies is that there is a necessity for the incorporation of computer simulations into the design process. Each of the facilities that successfully reached NZE used whole-building computer simulations to optimize the building's energy performance and account for interactions among building systems (Torcellini, Deru, Griffith, Long, Pless, & Judkoff, 2004 ; New Buildings Institute, 2012). However, just incorporating energy modeling does not ensure success.

It has been shown that many energy models fail to accurately predict energy use because engineers were too optimistic in developing assumptions (Torcellini, Deru, Griffith, Long, Pless, & Judkoff, 2004). To maximize the benefit of the whole-building simulations and achieve the deep energy reductions necessary for NZE, an integrated design approach, one that includes all stakeholders, must be utilized (New Buildings Institute, 2012). Another observation similar to the integrated approach is that design teams which set energy performance metrics as a high priority early in the design process, will produce buildings with lower energy consumption than teams which do not (Torcellini et al, 2004).

Another common conclusion of the reports relates to the operation of the facility. Occupant behavior is a significant barrier to a high-performance building performing as designed and achieving consistent ZEB status (Torcellini et al, 2004). As NZE buildings become larger and more complex, occupant behavior and subsequent plug-loads must be regulated (New Buildings Institute, 2012). During the operations phase of a high-performance building's life-cycle, maintaining maximum energy performance is a constant effort (Torcellini et al, 2004). Many of the studied facilities did not incorporate

this constant monitoring and subsequently suffered reduced energy savings (Torcellini et al, 2004). Smart Building technologies can assist with regulating power requirements, but a life-cycle cost analysis should be conducted before incorporating them into the design.

Additional conclusions regarding NZE buildings can be drawn from looking at the National Renewable Energy Laboratory's (NREL) recently completed Research Support Facility (RSF). The RSF project was extremely complicated as the DOE was pursuing a goal of demonstrating that high-performance and NZE construction is currently a commercially viable option, not just a dream for the future (Department of Energy, 2011). The NREL's RSF facility is currently the largest net-zero energy building in North America; at 360,000 square feet, it provides a comfortable workspace for over 800 employees (Department of Energy, 2011). The project is viewed as an overwhelming success by the industry; it has received extensive press coverage and awards from organizations such as the American Institute of Architects and the American Institute of Steel Construction (Department of Energy, 2012). The project met all the goals set for it, including a Leadership in Energy and Environmental Design (LEED) Platinum rating with maximum points attained for energy use (Department of Energy, 2011). The project was also completed on schedule and below its \$64 million budget (Department of Energy, 2011). Even with all the innovative solutions required to achieve an Energy Use Intensity of 10,250 kilowatt hours per square foot per year, the facility cost of \$254 per square foot is well below the average LEED certified building cost of \$335 per square foot (Department of Energy, 2011).

This section has provided an understanding of net-zero energy and an indication

of the current status of ZEBs in the construction industry. It has also provided the definitions often used in analyzing NZE, providing the justification for the selection of Net-Zero Site for this research project.

2.5. Life-Cycle Cost Analysis for Facility Energy Projects

This section will define what costs are typically associated with the term, Life-Cycle Cost (LCC). It will then provide an overview of common facility LCC models. Finally, it will describe how LCC can be used in a decision framework, such as Economic Analysis, to identify the most cost-effective alternative for a project.

LCC is defined in the Life-Cycle Costing Manual (LCCM) as the total cost of owning, operating, maintaining, and disposing of a facility (Fuller & Peterson, 1995). The general formula for the present value of all costs and benefits occurring during a facilities life-cycle is shown in Equation 1 (Fuller & Peterson, 1995).

$$LCC = \sum_{t=0}^N \frac{C_t}{(1+d)^t} \quad (1)$$

where C_t is the sum of all relevant costs occurring in year t , N is the total number of years in the study, and d is the discount rate.

A simplified equation for determining the LCC of building-related projects is given by Equation 2 (Fuller & Peterson, 1995).

$$LCC = I + Repl - Res + E + W + OM\&R \quad (2)$$

where I is the present value of investment costs, $Repl$ is the present value of capital replacement costs, Res is the present value of residual values minus disposal costs, E is

the present value of energy costs, W is the present value of water costs, and $OM\&R$ is the present value of nonfuel operations, maintenance, and repair costs. The definition represented by Equation 2 utilizes present worth factors, provided in the annual supplement to the Federal Energy Management Program (FEMP), which significantly reduces the computational effort required during analysis (Fuller & Peterson, 1995). Using economic factors enables all reoccurring costs or benefits to be expressed as a single variable.

LCC has little value until it is used in a decision-making framework; this is commonly referred to as Life-Cycle Cost Analysis (LCCA) (Fuller & Peterson, 1995). LCCA is a tool under the more broad approach of Economic Analysis (EA). Both LCCA and EA are used to evaluate project alternatives to select the one which provides the greatest benefit (NAVFAC, 1993).

The Naval Facilities Command Economic Analysis Handbook provides a six-step approach which identifies the essential elements of any economic analysis; a similar approach is outlined in the LCCM. A summary of the six steps are provided below, nomenclature has been modified to more directly align with this project (NAVFAC, 1993):

1. Define the requirements
2. Formulate viable alternatives
3. List economic assumptions
4. Select and modify an appropriate life-cycle cost model
5. Incorporate cost-effectiveness supplementary measure
6. Perform sensitivity analysis

Step four of the EA framework incorporates a supplementary metric which enables the identification and selection of the most cost-effective alternative design. As this project is concerned with whether it is cost-effective to design and construct a Zero-Energy Building versus a minimally-energy-policy-compliant facility, only two designs need to be evaluated. An accept or reject decision relates to the economic evaluation of a project having a single alternative system option which is under consideration (Fuller & Peterson, 1995). The mutually exclusive alternative must be evaluated against a base case, generally a continuation of an existing solution, also referred to as the status quo case (Fuller & Peterson, 1995). This type of analysis is referred to as relative, as the resulting values only have meaning when they are compared to the base case values (Fuller & Peterson, 1995).

When evaluating an accept or reject decision, the following criteria are generally used (Fuller & Peterson, 1995):

1. LCC less than base case
2. Net savings (NS) greater than 0
3. Savings to investment ratio greater than 1
4. Adjusted internal rate of return greater than Discount Rate

NS is typically utilized when benefits occur primarily in the form of future operational cost reductions. The NS of an alternative relative to the base case is given by Equation 3 (Fuller & Peterson, 1995).

$$NS = LCC_{Base} - LCC_{Alternative} \quad (3)$$

If the NS is greater than 0, the alternative is considered cost-effective and should be selected (Fuller & Peterson, 1995). Both NS and LCC methods provide identical solutions and can be used interchangeably. The most significant advantage of utilizing the NS metric is that the costs and/or benefits which are identical between the base and alternative systems will cancel and can therefore be omitted from the LCC calculation (Fuller & Peterson, 1995). Since similar costs cancel using the NS metric, only the costs and/or benefits which are different must be included in the fundamental equation.

This section has provided an understanding of the typical cost elements discussed in an LCCA. It has also outlined some of the key steps which are fundamental to any solid Economic Analysis. The LCCA utilizing the supplementary NS metric is one of the methodologies which will be utilized by this research.

2.6. Cost Estimation Techniques

This section will justify the need for accurate cost estimates as a part of any Life Cycle Cost Analysis (LCCA) and outline the most common approaches to obtain those estimates. A discussion of the benefits and limitations of each approach will lead to the selection of the estimation technique which will be used by this research.

Obtaining and utilizing accurate estimates for all costs and benefits included in an LCCA is vital to the accuracy of results (New South Wales Treasury, 2004). There are three main methods for estimating cost elements: Engineering, Analogous, and Parametric (NAVFAC, 1993 ; New South Wales Treasury, 2004).

An engineering estimate is a consolidation of multiple detailed cost estimates into a total system cost (NAVFAC, 1993). It is often called a “bottom-up” estimate as it

separates the total estimate into components. This estimating method is the most accurate, but relies on having a detailed design upon which to base the individual estimates.

The analogous method is similar to the engineering method except it utilizes historical data to obtain estimates of components within the larger system or product (New South Wales Treasury, 2004). This method again relies on the availability of detailed designs.

Early in a project's life-cycle, the detailed designs required for the above estimation techniques will not be available; therefore, estimates must be obtained using a parametric cost estimating method (NAVFAC, 1993). The parametric cost method utilizes historical data and characterizes it in terms of known parameters (New South Wales Treasury, 2004). The available cost data "from existing cost analyses are used to develop a mathematical regression or progression formula that can be solved for the cost estimate required" (New South Wales Treasury, 2004, p. 8). Regression analysis provides an indication of the uncertainty contained in the estimate. This uncertainty in input data is important in any economic analysis and is a basis for conducting sensitivity and uncertainty analysis of the cost model's outputs.

This section has discussed three methods of cost estimation in an LCCA. It also highlighted the need, due to the infancy of projects being evaluated, for utilizing parametric estimation techniques for this research project.

2.7. Decomposition as a Model Building Tool

As discussed in Chapter 1, this research will develop a feasibility assessment model based on life-cycle cost. Decomposition is a technique which can be utilized to divide a complex entity into simpler and more manageable parts. This section will define common approaches to decomposition and discuss how they could be utilized as part of a model development methodology. The section will conclude with the selection of a decomposition approach for this research.

Functional decomposition is a process of resolving a functional relationship into subsequent parts in such a way that the integrity of the original function is maintained. In general, the process of decomposition is undertaken for the purpose of gaining insight into the identity and relationship of the function's fundamental components (Functional Decomposition, 2012). The process is inherently hierarchical, as subsequent equations are typically decomposed further until the desired relationships are uncovered. The goal of the decomposition, in the context of model building, is to obtain independent and predictable variables. Hierarchical function decomposition is similar to a work breakdown structure (WBS) and Cost Breakdown Structure (CBS).

A WBS is widely used in project management and systems engineering disciplines and is the division of a project into smaller components. It is undertaken to identify discrete work packages which can be used for scheduling and scoping purposes (Department of Defense, 2011). In project management, the WBS is developed by dividing the objective of the project into manageable components in terms of size, duration, and responsibility; these components include all necessary activities to achieve

the project's objective (Department of Defense, 2011).

A CBS is widely used in economic evaluations and is undertaken to identify, define, and organize all cost elements to be considered in an LCCA (New South Wales Treasury, 2004). A CBS identifies all relevant cost categories, at the appropriate timing, in the project's life cycle (New South Wales Treasury, 2004). Cost categories are subsequently divided until each cost elements can be accurately estimated (New South Wales Treasury, 2004).

Work and cost breakdowns develop elements, that when summed, equal the total cost of the original project or system. The main advantage of function decomposition over a WBS or CBS is that it allows for multiple mathematical operators to be included in the model. This fact is important in this research because addition, subtraction, multiplication, and division relationships must be maintained in the final equation.

This section has discussed the process of decomposition and outlined common approaches utilized to conduct it. The justification has been provided for the selection of Hierarchical Function Decomposition as a part of the research approach for this project.

2.8. Model Evaluation Techniques

This section will justify the need for model evaluation as part of the development process. It will highlight three common techniques used to evaluate and communicate the risk associated with making decisions based solely on the deterministic output of a model.

As stated by the *NRC Committee on Models in the Regulatory Decision Process*, “models will always be constrained by computational limitations, assumptions, and

knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions...model evaluation (must) be viewed as an integral and ongoing part of the life cycle of a model” (Council for Regulatory Environmental Modeling, 2009, p. 19). Model evaluation is defined by this committee as, “the process used to generate information to determine whether a model and its analytical results are of a quality sufficient to serve as the basis for a decision” (Council for Regulatory Environmental Modeling, 2009, p. 19).

To determine if a model produces results of sufficient quality for the given decision environment, an understanding must be gained with regard to the uncertainties of the model (Council for Regulatory Environmental Modeling, 2009). Four approaches are commonly used to gain this understanding: expert opinion, sensitivity analysis, corroboration, and uncertainty analysis (Council for Regulatory Environmental Modeling, 2009). Expert opinion has not been included in this research, the remainder are described below.

Sensitivity analysis, is conducted to understand how a change in a dependent variable will affect the model’s output (Fuller & Peterson, 1995). “Sensitivity analysis is recommended as the principal evaluation tool for characterizing” how critical variables are to the uncertainty of the model’s output (Council for Regulatory Environmental Modeling, 2009, p. 31 ; Fuller & Peterson, 1995). Relative sensitivity analysis is a deterministic approach to rank variables in terms of the need for quality data (Fuller & Peterson, 1995). One common approach to examine relative sensitivity is to conduct a one-at-a-time (OAT) analysis (Council for Regulatory Environmental Modeling, 2009). An OAT analysis is performed in four simple steps (Fuller & Peterson, 1995):

1. Select a base case for dependent variables.
2. Vary each variable by a given percentage, for example 10%, while holding all other variables constant.
3. Recalculate the model output for each change
4. Analyze the resulting changes

Corroboration is an evaluation of how closely a model aligns with reality (Council for Regulatory Environmental Modeling, 2009). Corroboration can be performed using both qualitative and quantitative methods. Qualitative methods are used in situations in which quality data does not exist. This method, for example, would use expert opinion to obtain validation that the model agrees with the best-available understanding, and eventually move the model toward consensus (Council for Regulatory Environmental Modeling, 2009). Quantitative methods, on the other hand, use statistics to calculate how closely the model correlates to measured or observed data points (Council for Regulatory Environmental Modeling, 2009).

The final approach to model evaluation is uncertainty analysis. As previously discussed, it is essential to provide an estimate of the uncertainty of the model's output. When a model is used in the appropriate niche, there are two fundamental sources of model uncertainty: framework uncertainty and data quality (Council for Regulatory Environmental Modeling, 2009). Framework uncertainty is related to the understanding of the model's underlying relationships. In this project, framework uncertainty is minimal, as the fundamental topics are well understood. Data quality is affected by both uncertainty and variability. Data quality is related to the imprecision of variable estimates, typically attributable to measurement error and limited sample sizes, while

data variability results from the natural randomness of model elements due to heterogeneity (Council for Regulatory Environmental Modeling, 2009). Both of these sources of data quality reduction exist in this research, although variability is more prevalent due to the parametric estimation technique utilized.

In order to perform a quantitative uncertainty analysis, the probability distributions of each uncertain input variable must be specified (Hammonds, Hoffman, & Bartel, 1994). The distributions may be driven by available data, but most often subjective judgment must be “used to reflect the degree of belief that the unknown value for a parameter lies within a specified range” (Hammonds, Hoffman, & Bartel, 1994, p. 10). The two distributions utilized during this research are the normal and triangular.

When the uncertainty in a variable is present due to the summation of uncertain parameters, the distribution of that variable will tend to conform to a normal distribution, regardless of the probability distributions of the underlying parameters (Hammonds, Hoffman, & Bartel, 1994). This property is known as the central limit theorem. The normal distribution is provided in Figure 11 and random variates from this distribution are easily created using the Random Number Generator in Microsoft Excel.

When there is little data available for a variable, but the range of values and their central tendency is known, the triangular distribution can be used to model the distribution (Hammonds, Hoffman, & Bartel, 1994). Figure 12 graphically depicts a triangular probability distribution. When a random number between zero and one, denoted as U , is known, Equation 4 can be utilized to generate random variates from the triangular distribution (Triangular Distribution, 2013).

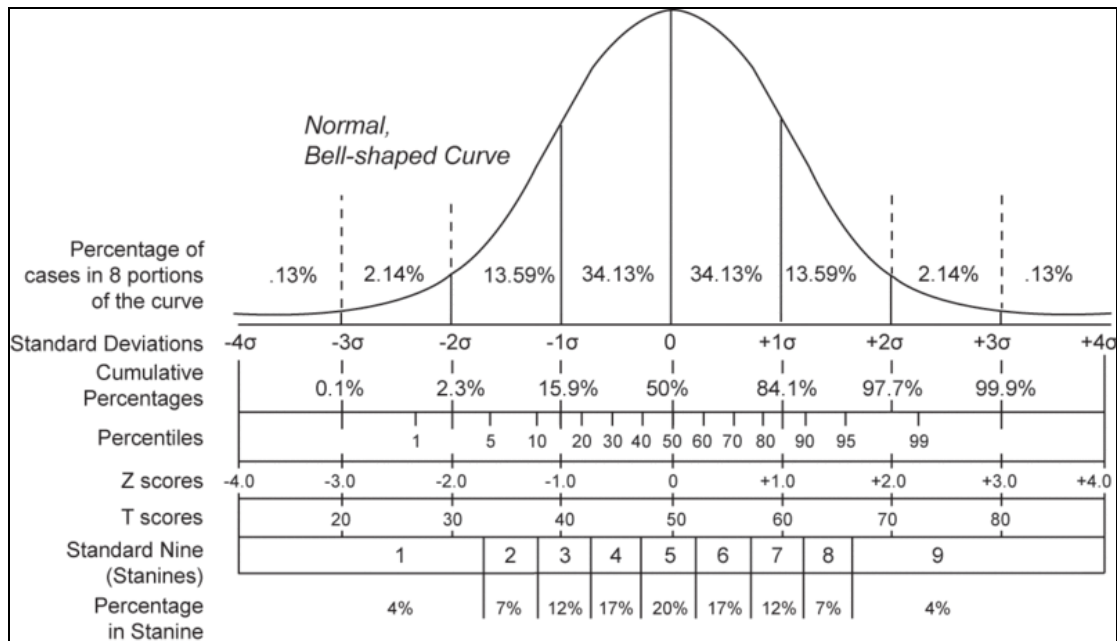


Figure 11 – Normal Distribution

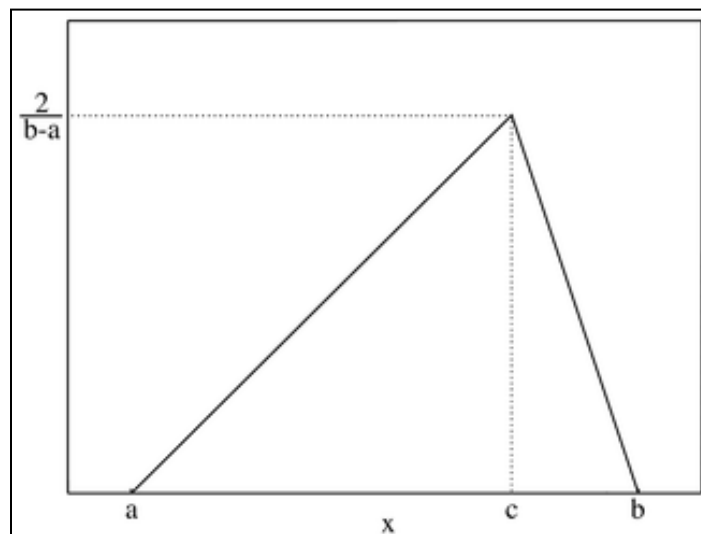


Figure 12 – Triangular Probability Density Function (Triangular Distribution, 2013)

$$\begin{cases} X = a + \sqrt{U(b-a)(c-a)} & \text{for } 0 < U < F(c) \\ X = b - \sqrt{(1-U)(b-a)(b-c)} & \text{for } F(c) \leq U < 1 \end{cases} \quad (4)$$

where $F(c) = (c-a)/(b-a)$.

In general, as long as the mean and variance of a distribution are held constant, the exact shape of that distribution will have a minimal effect on the confidence interval of the model's output (Hammonds, Hoffman, & Bartel, 1994). This particularly holds true when no single input dominates the overall uncertainty of the model.

Uncertainties are inherent to model building, identifying and communicating those that significantly impact the model's output, is key to making good decisions (Council for Regulatory Environmental Modeling, 2009). The most popular and powerful method for determining the impact of data uncertainties is Monte Carlo simulation. In this approach, the model is repeatedly run using randomly sampled input values from the probability distribution of the variable's estimate (Hammonds, Hoffman, & Bartel, 1994). Monte Carlo simulation uses multiple input scenarios to generate multiple output values; the set of output values can then be characterized quantitatively using descriptive statistics (Risk Assessment Forum, 1997). The analysis is performed in a few steps (Clemen & Reilly, 2001).

- Code the model into a computer-based simulation tool.
- A random input value for each of the variables being studied is selected from their respective probability distributions.
- The model's output to each case is then be calculated and stored.
- The prior two steps are repeated until the desired number of simulations have been completed, typically 10,000.
- Finally, descriptive statistics are utilized to portray output uncertainty.

2.9. Incorporating Geospatial Analysis

This section will discuss the basics of Geospatial Analysis. It will define what a Geospatial Information System (GIS) is and highlight which tools and techniques will be utilized by this research.

A GIS is designed to capture, manipulate, and display spatially related information on a map for visualization and analysis (ESRI, 2010). It has three integrated components: graphics program, database, and tools (ESRI, 2010). The graphics program draws shapes on a map for visualization. The database stores and links information, while the tools allow that information to be manipulated, analyzed, and stored.

Information is stored in the form of features and attributes (ESRI, 2010). Features represent natural or manmade objects on the earth's surface, while attributes describe those features. Features can be represented by points, lines, or polygons (ESRI, 2010). All features must have a location specified to display properly or to be analyzed using the tools of a GIS. Features can also be represented as a vector or raster file (ESRI, 2010). A vector uses shapes to define a feature and then uses coordinates to specify its location. This type of representation is useful for displaying features with distinct boundaries. The raster method of data storage is used to represent continuous information, that which does not have distinct boundaries or a well-defined shape (ESRI, 2010). A raster file is divided into cells, each of which contains a value that is of importance to the analysis being conducted (ESRI, 2010). Every raster file has an origin which defines its location on earth and each cell contains a unique position relative to that origin (ESRI, 2010).

Analyzing features is a primary function of a GIS (ESRI, 2010). Geospatial analysis utilizes the tools available in GIS to manipulate, store, and manage information. One of the benefits of geospatial analysis is that new datasets are created from existing ones, meaning that the new information can be used to solve problems (ESRI, 2010). The tools which will be used for this project and a brief description of each are discussed in the remainder of this section.

The Clip tool is used to define an area of interest or to remove data points which are not of interest to the current analysis (ESRI, 2010). It functions by using features in another feature class as a template from which to extract data points (ESRI, 2010). The tool is commonly used to create a new feature class which “contains a geographic subset of the features in another, larger feature class” (ESRI, 2010, p. na).

The Merge tool combines two or more line or polygon features of the same layer into one feature. During the operation, the analyst selects which attributes will be preserved. If the features being merged are not adjacent, a multipart feature is generated.

The Join Field tool combines the contents of one table to another table, using a common attribute field (ESRI, 2010). After the operation, the input table will contain the selected fields from the join table. The analyst defines which fields will be included. The tool functions by matching the records in the Input Table to those in the Join Table.

The Intersect tool calculates the geometric intersection of two or more feature classes (ESRI, 2010). The features that are common to all layers will be written to a new feature class (ESRI, 2010).

The Feature to Point tool creates a feature class containing points generated from the representative locations of input features (ESRI, 2010). If the inside option is not selected, the point resulting from a polygon will be located at the polygon's center of gravity.

The Inverse Distance Weighting (IDW) tool is a method used to interpolate sampled data points into a raster file. An estimate for the value of each cell in the raster file is obtained by averaging the data points in the neighborhood of the cell (ESRI, 2010). IDW assumes that the influence of data points degrades as the distance from the cell increases (ESRI, 2010). Interpolation using the IDW method is exact, meaning that the surface must go through the data points. This also means that the maximum and minimum values will occur at sampled data points, as shown in Figure 13.

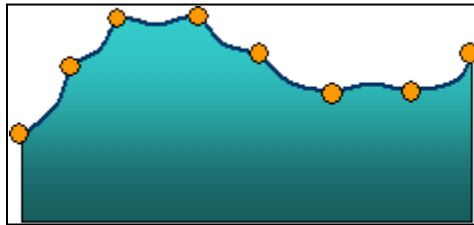


Figure 13 – IDW Interpolation Profile (ESRI, 2010)

This section has discussed geospatial analysis and described each of the tools which will be utilized by this research to calculate and summarize variable inputs for the Installation Comparative Analysis.

2.10. Model Variable Descriptions

This section will describe aspects of photovoltaic systems, facility energy use, electricity rates, facility cost, and engineering economic factors which will guide the

decomposition process utilized to develop the feasibility assessment model. Each of the following subsections will discuss these aspects by topic and will also highlight sources of data which will provide estimates for model variables.

2.10.1. Photovoltaic Systems.

This section will provide a background of Photovoltaic (PV) technology, discuss how PV systems can be sized to offset the electrical energy demand of a facility, highlight the costs associated with a PV system over its life-cycle, and determine how constructing a facility to be PV ready will reduce future investment required to achieve net-zero energy.

2.10.1.1. PV Technology.

PV materials convert solar electromagnetic radiation into electricity. French physicist Edmond Becquerel discovered in 1839 that some materials could be used to convert sunlight into an electrical current. It took nearly a century following that discovery for scientists to truly understand the phenomenon (DOE, 2011). They eventually learned that the photovoltaic or photoelectric effect causes materials to generate electricity when exposed to a solar resource. PV technologies have been effectively and cost-efficiently utilized in numerous implementations such as watches, road signs, satellites, and buildings (DOE, 2011).

The most common PV array uses flat-plate modules (DOE, 2011). These can be fixed at a tilt and direction or allowed to track the sun using controls for maximum

efficiency. The simplest and most common PV array, for use as on-site renewable energy generation, is a flat-plate panel fixed to the building's roof structure (DOE, 2011). These arrays achieve maximum efficiency when tilted to the site's latitude (Marion & Wilcox, nd). Tracking arrays are more efficient, but must be analyzed on a case-by-case basis as they also weigh and cost more.

While PV modules have no moving parts, the modules can be tilted or rotated to maximize exposure to the sun (Anderson et al., 2011). Electricity generation is maximized when PV modules are perpendicular, or normal, to the incoming sunlight. Mechanical tracking is used to enable PV panels to have greater access to sunlight, when compared to fixed panels, throughout the day and the year (Anderson et al., 2011). Single-axis tracking systems are oriented on a north-south axis and move the panels from east to west throughout the day. These systems allow the panels to track the sun daily, but do not provide the capability to track north and south as the sun's angle changes throughout the year. Two-axis tracking changes the PV module orientation in both directions, such that it always faces the sun (Anderson et al., 2011). Figure 14 shows the increase in efficiency between fixed, single, and two-axis configurations. As shown in the figure, significant efficiency is gained by along east-west tracking, but minimal from the additional north-south tracking. The life-cycle cost associated with a tracking system must be analyzed on a case-by-case basis.

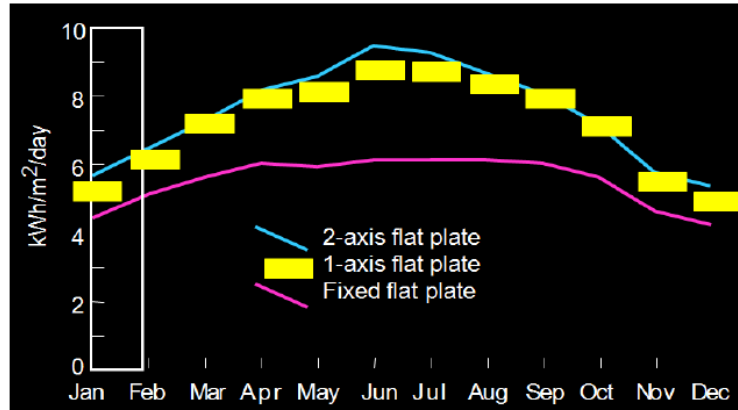


Figure 14 – Efficiency Improvements with Tracking Configuration (Anderson et al., 2011)

2.10.1.2. PV System Sizing.

Solar radiation is a term used to describe the electromagnetic radiation emitted from the sun (DOE, 2011). The measure of solar radiation falling on a fixed plate or tracking surface over a period of time is known as solar resource (DOE, 2011). Solar resource data is utilized to determine how much power can be produced by a PV panel and is expressed in kilowatt hours per square meter per day (DOE, 2011). The technical and economical feasibility of utilizing the radiation depends on the total available resource. Countries such as the U.S., located in the middle latitudes, receive the most solar energy in the summer months (DOE, 2011). The difference between seasons is due to the solar radiation contacting the earth's surface at different angles. The difference between the available solar resource during summer and winter months can vary as much as 300 percent in many locations (DOE, 2011).

A PV system is comprised of a collection of arrays, which are further comprised of numerous modules, which are each comprised of numerous individual cells (DOE, 2011). In order to characterize the efficiency of a system, the individual cell efficiencies

must be analyzed. A PV cell typically produces only a small amount of power, one to two Watts; therefore, a system is composed of hundreds to thousands of cells. Module performance is typically measured in both peak wattage and normal operating conditions, the latter of which describes a more realistic on-suite performance rating (DOE, 2011). Another description of array performance is the solar conversion efficiency. This value is a percentage of the energy output from the array to the solar resource provided to that array (DOE, 2011).

Current polycrystalline thin-film PV systems have an efficiency of around 16 percent (Murphy, 2011). Due to the fact that PV panels are rated at Standard Test Conditions (STC) and the efficiency decreases as cell temperature increases, simply multiplying that efficiency by the solar resource will not provide an accurate representation of a system's power output (Menicucci, 1986). The main cause of this efficiency change is temperature; under STC, a module's efficiency is measured at 25 degrees Celsius (NREL, 2012). The efficiency at which a PV module will perform when installed is given by Equation 5 (Menicucci, 1986).

$$n_a = n_o * (1 - \beta * (t_c - t_r)) \quad (5)$$

where n_o equals the efficiency at reference cell temperature, β equals the rate of efficiency change, t_r equals the reference cell temperature, and t_c equals the actual cell temperature.

PV Watts, a computer simulation program utilized by nearly every stakeholder in the PV industry, uses an efficiency change factor, β , of 0.5 percent per degree Celsius for crystalline silicon PV panels (NREL, 2012). Given the actual efficiency of the PV panel,

it is possible to calculate the Direct Current (DC) power using Equation 6 (Menicucci, 1986).

$$P_{DC} = n_a * POA \quad (6)$$

where n_a equals the true efficiency of the panel and POA is the total insolation incident the PV panel.

Due to the cyclical nature of temperatures throughout a day and year, using average temperature in Equation 5 does not provide an accurate representation of a PV panel's power output. Therefore, simulation is required utilizing historical meteorological data to develop a time-series, typically per hour, representation of power produced (NREL, 2012). These data can then be summed to calculate the total annual power produced by the PV system. The PV system size can be related to the area and efficiency of the panels by Equation 7.

$$SystemSize_{STC} = Area * n_o \quad (7)$$

The formula utilized by PV Watts to calculate the annual Alternating Current energy produced by the PV system is given by Equation 8.

$$AC_{annual} = \sum_{n=1}^{8760} SolarRes * Area * n_a * CF \quad (8)$$

where *SolarRes* is the hourly solar incidence per square meter, *Area* is the number of square meters occupied by the PV system, and *CF* is the ratio of a systems actual output to its rated output. More simply stated, the Capacity Factor (CF) is the percentage of a PV system's power that is available to the facility. The CF is also known as the AC to DC derate factor and is composed of the characteristics in Table 4.

Table 4 - Derate Factors for PV Watts (NREL, 2012)

Component Derate Factors	PV Watts Default	Range
PV module nameplate DC rating	0.95	0.80–1.05
Inverter and transformer	0.92	0.88–0.98
Mismatch	0.98	0.97–0.995
Diodes and connections	0.995	0.99–0.997
DC wiring	0.98	0.97–0.99
AC wiring	0.99	0.98–0.993
Soiling	0.95	0.30–0.995
System availability	0.98	0.00–0.995
Shading	1.00	0.00–1.00
Sun-tracking	1.00	0.95–1.00
Age	1.00	0.70–1.00
Overall DC-to-AC derate factor	0.77	0.09999–0.96001

PV Watts calculates the time-series power produced by a crystalline silicon PV panel and is widely used to size PV systems. The latest version of PV Watts can accurately predict the AC power output from a PV system to within 10 percent (Marion, Anderberg, George, Gray-Hann, & Heimiller, 2001). As indicated in Equation 4, the efficiency of a panel depends on the rate of efficiency change (β) and difference from the STC temperature (Δt). Once the PV Watts simulation program has modeled a specific PV panel's characteristics, at a specific location, both of these values will become constants for analyzing a different size panel's power output. This means that "energy production numbers are linearly scalable for larger PV systems" (Stafford, Robichaud, & Mosey, 2011, p. 3). Therefore, calculating the ratio of system size to power output, given the location and system configuration is constant, provides a continuous parametric estimate which can be used to size the system.

Another factor which must be accounted for when sizing and performing a life-cycle cost analysis of a PV system is that the power output from the system reduces with

time; this characteristic is known as degradation (Stafford, Robichaud, & Mosey, 2011). The actual annual loss varies by panel, but a median value of 0.5 percent per year is common, as shown in Figure 15.

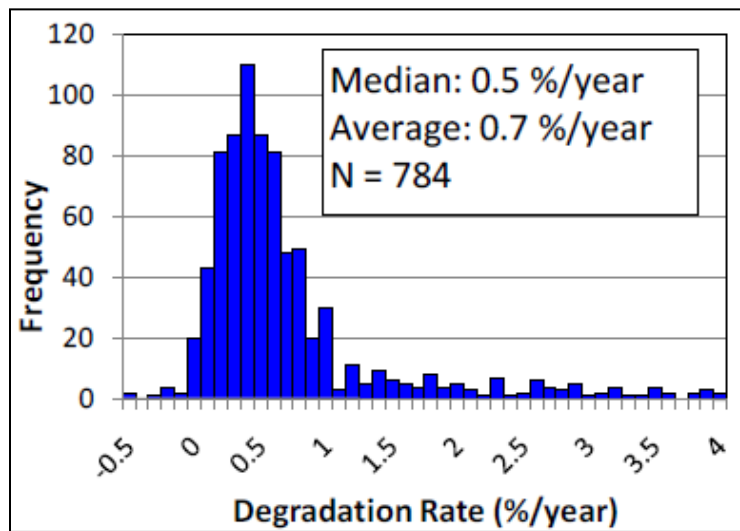


Figure 15 - Histogram of Annual PV Degradation (Jordan, Smith, Osterwald, Gelak, & Kurtz, 2011)

2.10.1.3. PV System Costs.

When discussing the cost of a PV system, it is common to divide it into three subsystems: PV modules, power electronics, and Balance of System (BOS). PV modules are composed of numerous cells which convert light into electricity. PV cells are made from a semiconductor material, for example crystalline silicon, that absorbs the energy from photons and then releases an electron from the molecule in response (Solar Energy Technologies Office, 2012). The electron and hole, absence of electron, pair then travels to opposite poles, creating direct current (DC) electricity (Solar Energy Technologies Office, 2012). This property is defined as the photoelectric effect.

PV panels, composed of numerous modules, have declined in price by about 20 percent for every doubling of cumulative global production (Solar Energy Technologies Office, 2012). The 2010 price of PV panels was about \$2/watt. PV panels have no moving parts; as such, they are typically the most reliable component in a PV system (Stafford, Robichaud, & Mosey, 2011). Panels have a 25 to 30-year useful life and most manufactures warrant them against defects and excessive degradation for 25 years (Stafford, Robichaud, & Mosey, 2011 ; Anderson et al., 2011).

In the vast majority of situations, it is more efficient to convert all DC electricity into alternating current (AC) electricity, as opposed to feeding a limited number of DC circuits directly. Power electronics, the second subsystem, are used to convert and condition the electricity from the PV system into quality AC power which the facility can utilize or distribute to the utility grid if not needed (Solar Energy Technologies Office, 2012). The two primary devices in the power electronics components group are the inverter and transformer. The inverter converts the DC electricity to AC, while the transformer increases the voltage to the appropriate level (Solar Energy Technologies Office, 2012).

There are numerous sources of data for the cost per Watt of an inverter. Goodrich et al., found an average inverter price of 37 cents per Watt in 2010 dollars; in the 2012 Solar Technologies Market Report, that price dropped to 23 cents per Watt (GTM Research, 2012). When replacing an inverter at the end of its useful life, there is very little labor required. Typically, labor costs total less than \$3,000 (Goodrich, James, & Woodhouse, 2012). Most inverters are purchased with a 10-year warranty; the length of the warranty is consistently getting longer, and the useful life of inverters are typically

assumed to be 15 years (Anderson et al., 2011 ; Solar Energy Technologies Office, 2012). Transformers are rugged devices with a useful life of 25 to 30 years (Garcia, nd).

All other components of a PV system, excluding the panels themselves or power electronics are lumped into Balance of System (BOS). BOS components consist of all items such as wiring, mounting hardware, meter, installation, design fees, etc., required to create an operational system (Solar Energy Technologies Office, 2012). Non-hardware BOS components are considered sunk costs when calculating salvage value. Wiring accounts for two cents per Watt, while mounting hardware accounts for six cents per Watt (Goodrich, James, & Woodhouse, 2012). The remaining BOS components, such as disconnects and utility meter, all have useful lives greater than 25 years (Collins, 1999).

Although individual component pricing is important, the most simplistic and useful metric of PV system capital price is installed cost per rated Watt (Morgan et al., 2012). Commercial PV systems take advantage of some economies of scale, making them less expensive per installed Watt than residential systems (Goodrich, James, & Woodhouse, 2012). There are numerous sources of data for the installed cost metric of commercial systems. The most recent estimate of \$4.38 per Watt is from the second quarter of 2012 Solar Technologies Market Report. The report also noted that commercial systems over 100 kilowatts have seen a dramatic drop in cost to between \$2.50 and \$2.75 per Watt. The Department of Energy's Sunshot initiative sets a benchmark price of \$4.59 per Watt in 2010 dollars. Another study by the DOE found a grid-tied system to cost \$3.67 for systems between 100 and 1,000 kilowatts (NREL, 2012).

2.10.1.4. PV Ready Construction Cost.

Even with the cost of PV systems dramatically declining over the last few years, they remain a significant capital investment which may not be economically feasible at the time of construction (Lisell, Tetreault, & Watson, 2009). Constructing new facilities with the characteristics to easily accommodate and maximize a PV system's power output, whether the system is installed during construction or at a later date, will improve the cost-effectiveness of the investment (Lisell, Tetreault, & Watson, 2009). A facility which is constructed so that it can easily accommodate a future PV system is known as PV-Ready. By one estimate, the capital investment required to retrofit a facility with PV would be reduced by up to ten percent if the facility were constructed to be PV-Ready (California Statewide Utility Codes and Standards Team, 2011).

Table 5, modified from the General Solar Guidelines checklist, outlines the characteristics which should be accounted for when constructing a Solar Ready facility. Table 6, modified from the Additional Guidelines for Photovoltaic (PV) Systems checklist, outlines the additional characteristics which should be addressed when constructing a PV Ready facility.

Table 5 - General Solar Guidelines (Lisell, Tetreault, & Watson, 2009, p. 6)

Avoid shading from trees, buildings, etc. (especially during peak sunlight hours).
Check the zoning laws for the proposed site to ensure that future, neighboring construction will not cast shade on the array.
Determine where a future solar array might be placed.
If the roof is sloped, the south-facing section will optimize the system performance; keep the south-facing section obstruction-free if possible.
Minimize rooftop equipment to maximize available open area for solar collector placement.
The type of roof installed can greatly affect the cost of installing solar later.
The roof must be capable of carrying the load of the solar equipment. (PV – between 3 and 6 lb/ft ²) (ST – between 2 and 5.5 lb/ft ²)
The wind loads on rooftop solar equipment must be analyzed in order to ensure that the roof structure is sufficient. See the American Society of Civil Engineers (ASCE) international building code 7-05 for the method of how to calculate these loads.
Record Roof Specifications on Drawings.
Add additional safety equipment for solar equipment access and installation.

Table 6 - Additional Guidelines for PV Systems (Lisell, Tetreault, & Watson, 2009, p. 9)

Identify electrical panel location for convenient PV system inter-connections, and keep space available in the electrical panel for a PV circuit breaker.
Specify panel capacity sufficient to accommodate the total power coming into the building (proposed PV system size power generation plus size of breaker protecting main panel). NEC allows for the sum of these two sources of power to be 20% greater than the panel rating. Consult the local authority having jurisdiction.
Lay out the locations for the inverter and the balance of system (BOS) components.
Identify the inter-connection restrictions for the location of the building site that apply to grid-tied PV systems.
Run electrical conduit from the solar collector location to the electrical panel and other electrical components.
Consider any special load needs (i.e., uninterrupted power supply) and consider whether storage is needed.
PV panels are much more sensitive to shading than Solar Thermal panels. Avoid shading as much as possible. Due to the individual modules of a PV panel being connected in series, even a narrow strip of shading (lightning rods, antennas, etc.) can limit the current of the entire array.
Find out what the energy production of the proposed system will be using the PVWatts calculation tool, and adjust the system size as needed.

Constructing a Solar-Ready facility requires only a capital investment, as there are no operations or maintenance costs associated with the required characteristics (California Statewide Utility Codes and Standards Team, 2011). A couple of studies have shown that the incremental cost to construct a PV-Ready facility is minimal, ranging from zero to one percent (California Statewide Utility Codes and Standards Team, 2011) (Hendrick Automotive Group, 2009).

2.10.2. Facility Energy.

This section will provide a background of facility energy use, energy benchmarking, and electricity rates. The overview of these topics will guide the decomposition process and allow for the identification and categorization of model variables. Each of the topics will be discussed in the following subsections.

2.10.2.1. Facility Energy Use.

In any energy reduction initiative, it is necessary to measure and compare the energy performance of facilities. This can be done utilizing simple monthly and annual utility bill averages or through detailed time-series measurements which categorize energy by end-use. A building's energy use is the total energy consumed for heating, ventilating, air conditioning, lighting, hot water, plug loads, and other energy necessities (PNNL, 2010). A building's energy use intensity (EUI) is a normalized value of the building's energy use, calculated by dividing the total energy use by the square area of the facility over a given time period (PNNL, 2010). This value allows for the comparison

of the building to that of a benchmark building of the same characteristics. This provides an indication of how well the facility is performing regarding energy and can be used by facility managers to take corrective action or by code agencies, such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), to verify compliance.

There are two primary energy codes which can be adopted by local, state, and federal jurisdictions (PNNL, 2010). The first is the International Energy Conservation Code (IECC), which is produced by the International Codes Council. The second is standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings, which is produced by ASHRAE. The IECC address both residential and commercial buildings, while ASHRAE 90.1 only covers commercial buildings. Commercial facilities are defined by ASHRAE 90.1 as buildings other than single-family or multifamily of three floors or less (PNNL, 2010). The IECC has adopted ASHRAE 90.1 by reference, meaning that if a building meets 90.1, then it also meets the IECC standard (PNNL, 2010). All new federal facilities must meet Title 10 Code of Federal Regulations 434, which is based on ASHRAE 90.1 (VanGeem, 2010). Standard 90.1 is developed using the American National Standards Institute's consensus process to ensure that the interests of all stakeholders are balanced and considered (PNNL, 2010). Standard 90.1 separates facilities by use and climate zone.

Climate is one of the most significant factors impacting the energy use of a facility. To generalize and allow discussion regarding the impact of climate, it is necessary to classify it. Climate classification techniques were first introduced by ancient astronomers, who analyzed the earth as a sphere and deduced five climate zones (Briggs,

Lucas, & Taylor, 2002). The first quantitative technique was introduced by Aristotle in the 4th century BC when he classified a region termed the tropics (Briggs, Lucas, & Taylor, 2002). These early classification techniques were termed “genetic” as they attempted to explain observed geospatial variations in climate characteristics (Briggs, Lucas, & Taylor, 2002).

Earlier works were limited by the availability of data; by the 1980s, there was a significant amount of climactic data available for the U.S. (Briggs, Lucas, & Taylor, 2002). This data drove the adoption of new techniques for climate classification. One very powerful technique, called hierarchical cluster analysis, emerged which could be utilized to group together similar observations (Briggs, Lucas, & Taylor, 2002). Hierarchical cluster analysis uses a metric representing the similarity between observations to group like observations together (Briggs, Lucas, & Taylor, 2002). The distance metric can be any descriptive characteristic which the observations have in common. In the case of climatology, common metrics include heating and cooling days, precipitation, solar irradiation, wind, weather patterns, etc.

Many of the initial cluster analysis models failed to classify all points in the U.S. In order for the classification to be utilized for code requirements, all locations must be clearly defined by the system. To correct this, ASHRAE performed an analysis for the creation of standard 90.1-1989 which resulted in 38 categories covering all U.S. locations (Briggs, Lucas, & Taylor, 2002). The goal of the climate classification discussed by Briggs et al. (2002) was to produce a simple and accurate way to classify the U.S. climate in order to better prescribe energy efficiency measures for buildings. This work has been adopted by numerous organizations and programs including, but not limited to ASHRAE

90.1, ASHRAE 90.2, ASHRAE Advanced Energy Design Guides, Building America, and ENERGY STAR (Energycodes.gov, 2009).

The final zones were not based solely on geostatistical analysis; the results from the model drove the classification of existing county boundaries as an approximation (Briggs, Lucas, & Taylor, 2002). This allows for the climate zones to be more easily implemented in building energy codes. The study resulted in the 17 climate designations as shown in Table 7.

Table 7 - Building America Climate Zones (Briggs, Lucas, & Taylor, 2002)

B. Thermal Zone Definitions					
Zone No.	Climate Zone Name and Type	Thermal Criteria^(1,8)	Representative U.S. City*	Köppen Class.	Köppen Classification Description
1A	Very Hot – Humid	5000 < CDD10°C	Miami, FL	Aw	Tropical Wet-and-Dry
1B ⁽⁷⁾	Very Hot – Dry	5000 < CDD10°C	---	BWh	Tropical Desert
2A	Hot – Humid	3500 < CDD10°C ≤ 5000	Houston, TX	Caf	Humid Subtropical (Warm Summer)
2B	Hot – Dry	3500 < CDD10°C ≤ 5000	Phoenix, AZ	BWh	Arid Subtropical
3A	Warm – Humid	2500 < CDD10°C ≤ 3500	Memphis, TN	Caf	Humid Subtropical (Warm Summer)
3B	Warm – Dry	2500 < CDD10°C ≤ 3500	El Paso, TX	BSk/BWh/H	Semiarid Middle Latitude/Arid Subtropical/Highlands
3C	Warm – Marine	HDD18°C ≤ 2000	San Francisco, CA	Cs	Dry Summer Subtropical (Mediterranean)
4A	Mixed – Humid	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	Baltimore, MD	Caf/Daf	Humid Subtropical/Humid Continental (Warm Summer)
4B	Mixed – Dry	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	Albuquerque, NM	BSk/BWh/H	Semiarid Middle Latitude/Arid Subtropical/Highlands
4C	Mixed – Marine	2000 < HDD18°C ≤ 3000	Salem, OR	Cb	Marine (Cool Summer)
5A	Cool – Humid	3000 < HDD18°C ≤ 4000	Chicago, IL	Daf	Humid Continental (Warm Summer)
5B	Cool – Dry	3000 < HDD18°C ≤ 4000	Boise, ID	BSk/H	Semiarid Middle Latitude/Highlands
5C ⁽⁷⁾	Cool – Marine	3000 < HDD18°C ≤ 4000	---	Cfb	Marine (Cool Summer)
6A	Cold – Humid	4000 < HDD18°C ≤ 5000	Burlington, VT	Daf/Dbf	Humid Continental (Warm Summer/Cool Summer)
6B	Cold – Dry	4000 < HDD18°C ≤ 5000	Helena, MT	BSk/H	Semiarid Middle Latitude/Highlands
7	Very Cold	5000 < HDD18°C ≤ 7000	Duluth, MN	Dbf	Humid Continental (Cool Summer)
8	Subarctic	7000 < HDD18°C	Fairbanks, AK	Dcf	Subarctic

2.10.2.2. Benchmark Energy Use.

The National Renewable Energy Lab has developed building model simulations based on a representative sample of the commercial building sector, categorized by facility type and climate zone. The purpose of these models was to create standardized

benchmarks with which to analyze the improvements generated through energy code changes and energy efficiency initiatives (Griffith B. , Long, Torcellini, Judkoff, Crawley, & Ryan, 2008). The models were generated using probabilistic modeling from literature reviews and data from the 2003 Commercial Building Energy Consumption Survey (CBECS).

CBECSs are conducted every 4 years by the Energy Information Administration, but due to funding and methodology challenges, the 2003 CBECS is the most recent study. The 2003 CBECS included results from 4,820 non-mall facilities, making it the most statistically accurate description of the U.S. commercial building sector available (Griffith et al., 2008). Table 8 summarizes some of the key modeling aspects used to generate the benchmark facilities. The three dimensional renderings of the Small Office, Medium Office, and Small Hotel benchmark facilities are shown in Figure 16 through 18.

Table 8 – DOE Benchmark Facility Aspects (Thornton, et al., 2011)

Building Prototype	Floor area (ft ²)	Number of Floors	Aspect Ratio	Window-to- Wall Ratio (WWR)	Floor-to- Floor Height (ft)	Floor-to- Ceiling Height (ft)
Small Office	5,500	1	1.5	15%	10	10
Medium Office	53,630	3	1.5	33%	13	9
Large Office	498,640	12 ^(a)	1.5	40%	13	9
Standalone Retail	24,690	1	1.28	7%	20	20
Strip Mall	22,500	1	4	11%	17	17
Primary School	73,970	1	NA	35%	13	13
Secondary School	210,910	2	NA	33%	13	13
Outpatient Healthcare	40,950	3	NA	20%	10	10
Hospital	241,410	5 ^(a)	1.33	16%	14	14
Small Hotel	43,210	4	3	11%	9 11 ^(d)	9 11 ^(d)

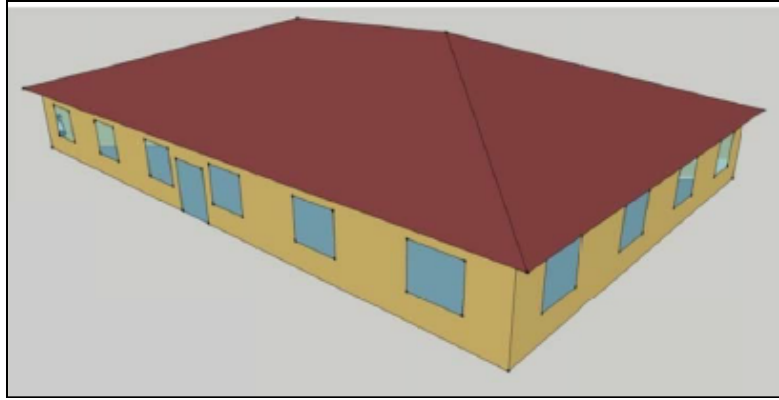


Figure 16 – 3D Rendering of Small Office Benchmark Facility (Thornton, et al., 2011)

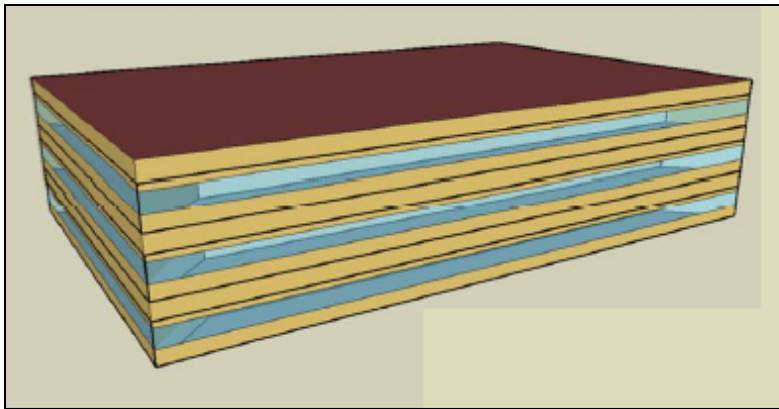


Figure 17 – 3D Rendering of Medium Office Benchmark Facility (Thornton, et al., 2011)

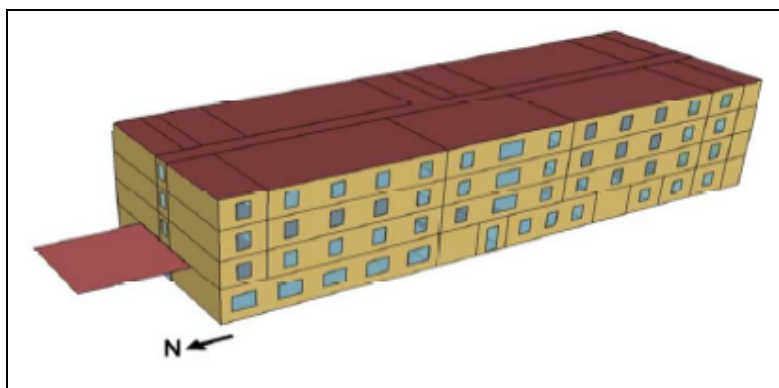


Figure 18 – 3D Rendering of Small Hotel Benchmark Facility (Thornton, et al., 2011)

The models were validated by comparing the energy profile predictions from EnergyPlus, an energy simulation program created by the DOE, to the data sets from the CBECS. Overall, the models agreed to within 12 percent, with the exceptions of education, food service, inpatient health, and public order and safety, for the 16 facility types modeled (Griffith et al., 2008). The model predictions also obtained satisfactory results for all climate zones except East North Central and Mountain (Griffith et al., 2008).

To determine the improvements in energy use due to energy code revisions, code compliant energy models needed to be created. To create these models, the Pacific Northwest National Laboratory modified the DOE models to comply with ASHRAE Standards 90.1-2004, 90.1-2007, and 90.1-2010 (Thornton et al., 2011). These code-compliant models were used to analyze the building energy consumption savings from Standard 90.1-2010, which was under development. This study produced the three code-compliant versions for all 16 benchmark facility types and analyzed them in 17 climate zones. This resulted in 816 models, which were run simultaneously, to produce energy profiles applicable across building types and locations (Thornton et al., 2011). It is important to note that energy modeling does contain uncertainty. The sources of uncertainty are due to assumptions made about input values, such as occupant behavior and component energy performance (Clevenger & Haymaker, 2006). A well calibrated model should produce results to within 10 percent (Clevenger & Haymaker, 2006). The resulting Benchmark Energy Use Intensity values for ASHRAE 90.1 – 2004 compliant facilities are summarized in Table 9.

Table 9 – Benchmark EUI Summary (Thornton et al., 2011)

Zone	Small Office EUI (kWhr/ft²)	Medium Office EUI (kWhr/ft²)	Small Hotel EUI (kWhr/ft²)
1_moist	12.074484	14.975932	20.954505
1_dry	12.689931	15.65	20.544207
2_moist	11.840028	15.15	21.335496
2_dry	12.279633	15.03	20.632128
3_moist	11.576265	14.71	21.745794
3_dry	11.546958	13.98	20.280444
3_marine	10.316064	12.51	19.401234
4_moist	11.986563	15.36	23.181837
4_dry	11.781414	13.69	21.188961
4_marine	11.107353	13.86	21.569952
5_moist	13.012308	16.35	25.057485
5_dry	12.01587	14.68	22.800846
5_marine	10.990125	13.95	21.950943
6_moist	13.77429	17.32	26.640063
6_dry	13.363992	15.97	24.705801
7	13.012308	18.99	29.336307
8	19.606383	23.45	34.699488
* Averages taken for climate zones not covered			

2.10.3. Electricity Cost

Electricity rates are composed of numerous components, such as usage, peak demand, customer charges, etc. (Fuller & Petersen, 1995). In a Level 1 feasibility study, it is acceptable to use the average electricity rate at the building's site (EPA CHP Partnership, 2012). The average rate is composed of both usage and demand charges and is expressed as dollars per kilowatt per hour. Utilizing the average electricity rate for a feasibility study provides a conservative cost savings estimate, as reductions in overall

energy use could cause a transition to a lower rate structure (Fuller & Petersen, 1995). This transition could dramatically lower the electricity cost for the facility.

Historically, Department of Defense (DoD) average electricity rates have tracked between commercial and industrial rates, as reported to the Energy Information Administration (Andrews, 2009). As seen in Figure 19, electric rates have recently trended toward the more expensive commercial rate; therefore, estimating the DoD rate as the average will provide a conservative estimate.

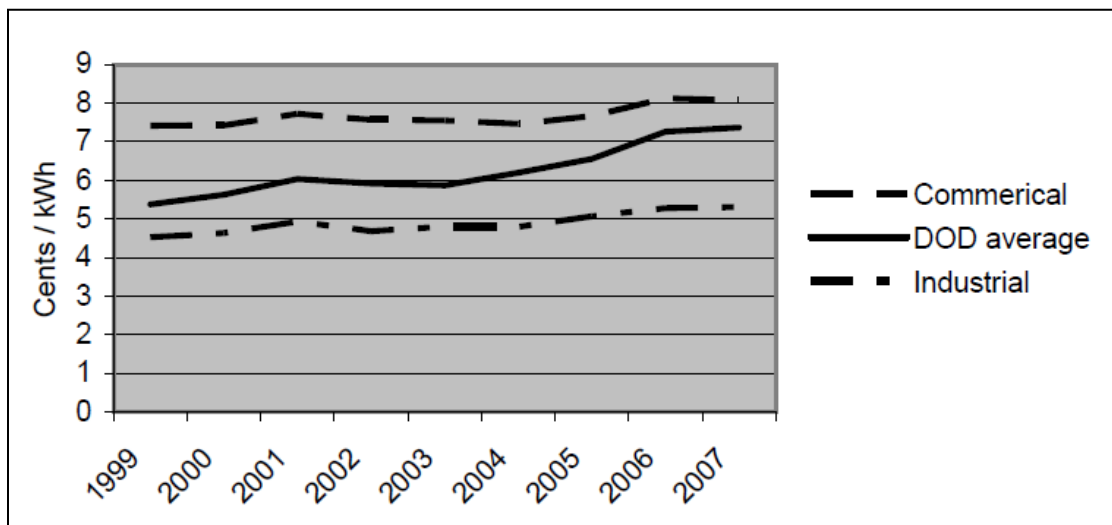


Figure 19 – DoD versus EIA Reported Average Electric Rates (Andrews, 2009)

2.10.4. Facility Costs.

There are numerous components of facility cost which are incorporated into the feasibility assessment model. Each will be discussed in the following subsections.

2.10.4.1. Facility Construction Cost.

There are three main methods for estimating the costs of constructing a facility: engineering, analogous, and parametric (NAVFAC, 1993). Early in a project's life-cycle, detailed designs are not available to base engineering or analogous estimates from; therefore, estimates at the programming stage must be obtained using parametric estimation techniques (US Department of Defense, 2011). This method is utilized to characterize historical data in terms of known parameters; for facilities, these are commonly expressed in cost per square foot and categorized by facility type (New South Wales Treasury, 2004).

The DoD, and each service, provide guidance to project programmers regarding the use of unit costs to provide programming-level estimates of a facility's cost. These unit costs are categorically separated by facility type to more accurately reflect the cost of potential facilities (US Department of Defense, 2011). There are numerous distinctions between DoD and commercial facility cost; for example, DoD facilities are required to meet minimum antiterrorism specifications and sustainable design features which are required for federal facilities. To make these parametric estimates more accurate, unit cost guides include three main adjustment factors. First, costs are adjusted for the size of the project (AFCESA, 2007). This is conducted by multiplying the unit costs by a factor which corresponds with the ratio of the proposed building size to the typical building size (AFCESA, 2007). This factor accounts for economies of scale and is shown in Figure 20.

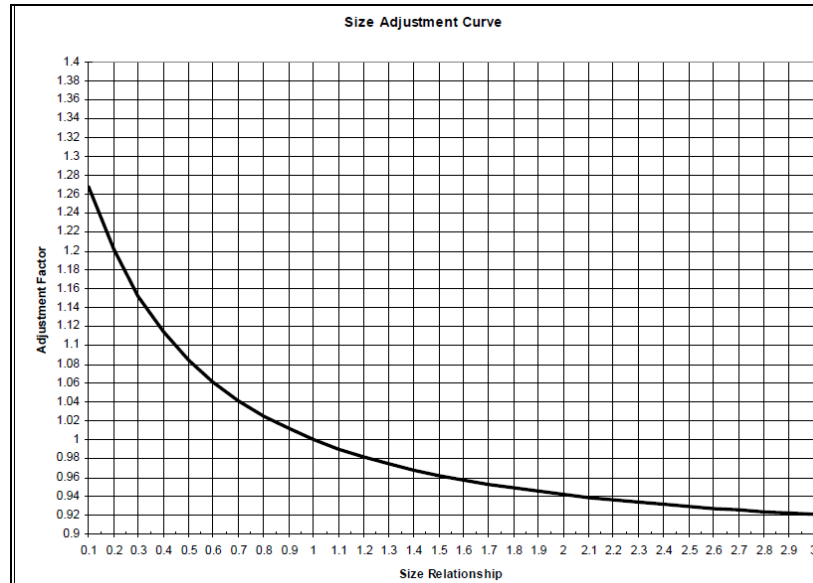


Figure 20 - Size Adjustment Curve (AFCEA, 2007)

The second main adjustment factor is for escalation. This factor uses inflation estimates from the Office of Management and Budget for Military Construction (MILCON) (AFCEA, 2007). It is calculated by dividing the escalation index of the midpoint of construction by the escalation index of the unit cost data (AFCEA, 2007). The final main adjustment factor is for the location at which the facility will be constructed. The unit cost provided in DoD pricing guides is normalized to a national average cost factor (US Department of Defense, 2011). As the cost of construction varies by location, every installation has a specific area cost factor which is multiplied by the unit cost to determine the cost of the facility at that installation (AFCEA, 2007).

In addition to adjustment factors, Air Force construction must also be adjusted for supervision, inspection, and overhead (SIOH) and a buffer included for contingencies (AFCEA, 2007). As described in Section 2.1, the design and construction agent for USAF MILCON is usually not internal; therefore, SIOH must be included to account for

additional management personnel. In the contiguous U.S., SIOH for both the Navy Facilities Engineering Command and the Army Corps of Engineers is 5.7 percent (AFCESA, 2007). The USAF also requires unit cost estimates to include a five percent contingency; providing a buffer to absorb unforeseen circumstances (AFCESA, 2007).

2.10.4.2. Incremental Construction Cost.

A facility which utilizes less energy than its benchmark, will, assuming all other factors remain constant, cost more money to construct (Jiang, Gowri, Lane, Thornton, Rosenberg, & Lui, 2011). This fact is known as incremental construction cost. The New Buildings Institute study provides some generalized indication of incremental costs and percent reductions associated with Zero-Energy Buildings (ZEB). The study used facilities with an energy-use-intensity (EUI) of less than or equal to 10,250 kilowatt hours per square foot per year. This is 62 percent lower than the average building of the same type and climate zone from the 2003 Commercial Building Energy Consumption Survey (CBECS) (New Buildings Institute, 2012). The research found that the incremental cost required to decrease EUI to ZEB levels was in the 3 to 18 percent range, with the vast majority of office buildings falling below 10 percent, depending on facility type and climate zone (New Buildings Institute, 2012). With these cost increases, many of the facilities were able to achieve a payback period of 10 to 15 years (New Buildings Institute, 2012).

Due to the natural variability in construction and the limited data available regarding the construction premium required to achieve a low-energy building, historical data cannot be used to provide an accurate parametric estimate. Since adequate historical

data does not exist, computer simulations must be used. Computer simulation can be used to obtain an estimate of construction premium by modeling and comparing the energy use and incremental construction cost of the two design alternatives (Jiang, Gowri, Lane, Thornton, Rosenberg, & Lui, 2011). If the simulations are conducted for each facility type and in each climate zone, they will produce data points which can be used in a life-cycle cost analysis (Jiang, Gowri, Lane, Thornton, Rosenberg, & Lui, 2011).

The DOE utilized the above approach to determine the incremental construction cost of meeting their advanced energy design guides (AEDG). AEDGs are developed to explain to engineers and designers how to apply new techniques and incorporate new technologies such that results are maximized, consistent, and predictable (Higa, McLean, Mack, & McHugh, 2012). The US DOE and ASHRAE have produced Advanced Energy Design Guides (AEDG) for common commercial facility types. The two most aggressive AEDGs apply to Small and Medium Office and Highway Lodging (Small Hotel) facility types and provide design guidance to achieve a building which uses 50 percent less energy than one constructed to ASHRAE 90.1–2004 (ASHRAE, 2011). Meeting the goal of constructing and operating a facility to use 50 percent less energy requires changes to many common practices. The AEDG outlines a few which are essential to success (ASHRAE, 2011, p. 5):

- Obtain building owner buy-in.
- Assemble an experienced, innovative design team.
- Adopt an integrated design process.
- Consider a daylighting consultant.

- Consider energy modeling.
- Use building commissioning.
- Train building users and operations staff.
- Monitor the building.

The AEDG includes topics such as Integrated Project Delivery, Integrated Design Strategies, Design Strategies and Recommendations by Climate Zone, and Good Practices for Implementation. They present prescriptive recommendations by climate zone including “enhanced envelope technologies, interior and exterior lighting technologies, heating, ventilating, and air conditioning (HVAC) and service water heating (SWH) technologies, and miscellaneous appliance technologies” (Jiang, Gowri, Lane, Thornton, Rosenberg, & Lui, 2011, p. 5). The technical support documents associated with the ASHRAE’s 50 percent AEDGs provide a reliable source of energy reduction and construction premium data through the use of energy modeling and simulation. The data obtained from these documents is summarized in Table 10.

Incremental construction cost data for USAF facilities is limited to a few Air Force Center for Engineering and the Environment (AFCEE) sponsored feasibility studies. Expanding from USAF to DoD facility types provides more data; the most significant study was conducted by the Army Corps of Engineers to determine strategies for compliance with the Energy Independence and Security Act (EISA) of 2009 (Carpio & Soulek, 2011). Although this research provides more data points, there are not enough to predict construction premiums for all climate zones reflective of installations in the contiguous U.S.

Table 10 – AEDG Data Points Summary

Zone	Small Office		Medium Office		Small Hotel	
	Construct Premium	Percent Reduction	Construct Premium	Percent Reduction	Construct Premium	Percent Reduction
1_moist	3.50%	50.00%	5.40%	54.00%	8.40%	51.00%
1_dry	3.80%	50.00%	5.40%	54.00%	8.40%	51.00%
2_moist	3.70%	56.00%	5.90%	56.00%	8.50%	54.00%
2_dry	3.75%	57.00%	5.90%	57.00%	8.50%	51.00%
3_moist	3.80%	54.00%	6.30%	54.00%	8.40%	54.00%
3_dry	3.25%	53.00%	6.60%	54.50%	8.40%	51.00%
3_marine	3.40%	55.00%	6.50%	58.00%	8.70%	54.00%
4_moist	3.40%	57.00%	6.00%	57.00%	8.60%	56.00%
4_dry	3.10%	56.00%	5.70%	55.00%	8.60%	53.00%
4_marine	3.40%	57.00%	6.40%	58.00%	8.60%	55.00%
5_moist	4.00%	59.00%	6.10%	56.00%	8.60%	58.00%
5_dry	3.60%	58.00%	5.80%	55.00%	8.60%	56.00%
5_marine	3.80%	58.50%	5.95%	55.50%	8.60%	57.00%
6_moist	3.70%	59.00%	5.80%	56.00%	8.70%	59.00%
6_dry	3.60%	58.00%	5.80%	56.00%	8.70%	58.00%
7	3.80%	56.00%	5.50%	59.00%	8.70%	60.00%
8	3.70%	51.00%	5.80%	59.00%	8.60%	60.00%

2.10.5. Economic Factors

To compare costs and benefits in an economic analysis, those costs and benefits must be expressed at the same point in time (Fuller, 2005). These adjustments are necessary due to the time-value-of-money, which is caused for two reasons. First, alternative investment opportunities require money to be expressed in terms of real earning potential. For example, money can be placed into an account with a guaranteed rate of return or that same money could be placed into an investment which yields

benefits in the future. The value of the real earning potential is typically representative of the riskiness of the investment. Second, in our inflationary economy, the value of money erodes over time. Therefore, an investor would require more than a dollar at some future time to equate to one dollar today.

The process of converting costs and benefits received at different points in time to their equivalent present value is called discounting. The mathematics of compound interest is typically accounted for through the use of economic factors. In the commercial sector, these factors are based on a discount rate equal to the investor's minimum attractive rate of return. For the federal government, the Department of Energy (DOE) or Office of Management and Budget (OMB) provides these discount rates (Fuller & Peterson, 1995). The DOE discount rates are required for energy conservation and renewable energy projects, while the OMB rates are for projects that are not primarily concerned with energy or water conservation. The underlying methodologies are identical for both organizations; the solutions differ due to the discount rates utilized.

A tri-services Memorandum of Agreement (MOA) entitled "Criteria/Standards for Economic Analysis/Life-Cycle Costing for MILCON Design" provides guidance on life-cycle cost analysis (LCCA) for the MILCON program. This MOA is consistent with the rules outlined in both the DOE and OMB methodologies. The MOA recommends, but does not require, the use of middle-of-year discounting for all recurring cash flows (Fuller, 2005). Middle-of-year discounting conflicts with standard practice for manual life-cycle cost (LCC) calculations, which uses end-of-year convention (Fuller, 2005).

A brief description and the formula for each of the economic factors which were utilized during this project will be discussed below. The Single Present Value (SPV)

factor is used to discount a single future cost or benefit to its equivalent present value and is given by Equation 9 (Fuller & Peterson, 1995).

$$SPV_{t,d} = \frac{1}{(1 + d)^t} \quad (9)$$

where d is the discount rate and t is the number of periods from the base date.

The Uniform Present Value (UPV) factor is used to sum and discount a recurring uniform cost or benefit and is given by Equation 10 (Fuller & Peterson, 1995).

$$UPV_{d,N} = \frac{(1 + d)^N - 1}{d * (1 + d)^N} \quad (10)$$

where d is the discount rate and N is the number of periods over which the money reoccurs.

The Modified Uniform Present Value (UPV*) factor is used to sum and discount a recurring cost or benefit that is expected to change from year to year at a constant rate and is given by Equation 11 (Fuller & Peterson, 1995).

$$UPV^*_{d,e,N} = \frac{(1 + e)}{(d - e)} * \left[1 - \frac{(1 + e)^N}{(1 + d)^N} \right] \quad (11)$$

where d is the discount rate, e is the escalation rate, and N is the number of periods over which the cash flow reoccurs.

Due to fluctuations in an energy commodity's escalation rate, the Federal Energy Management Program (FEMP) recommends using cost indices to calculate the UPV* factor instead of Equation 11 (Rushing, Kneifel, & Lippiatt, 2011). A cost index represents the future cost of energy in relation to a base-date price. This approach allows for the incorporation of energy price projections based on estimates by the Department of Energy. Indices are provided for four separate census regions. The formula for

calculating the UPV* factor, given the applicable cost indices, is provided by Equation 12 (Rushing, Kneifel, & Lippiatt, 2011).

$$UPV^*_N = \sum_{t=1}^N \frac{I_{2011+t}}{(1+d)^t} \quad (12)$$

where the cost index is I , the year of the study is t , and the discount rate is d .

To account for a change in the volume of the energy savings benefit, attributable to the photovoltaic panel degradation over time, an arithmetic gradient must be subtracted from Equation (12). The FEMP does not include an arithmetic gradient factor, but the factor is widely used in engineering economic analysis. The factor is determined by Equation 13 (Eschenbach, 1995).

$$APV_{i,N} = \frac{(1+i)^N - i * N - 1}{i^2 * (1+i)^N} \quad (13)$$

where i is the discount rate and N is the number of periods over which the gradient occurs.

If future values are expressed in constant dollars, i.e., money in terms of base-date dollars, then a real interest rate may be used to discount them (Fuller, 2005). This real rate is equal to the earning potential of money over time. In contrast, if values are expressed in current dollars, where inflation is included in the future values, then a market, also known as nominal, discount rate must be used (Fuller, 2005). This rate takes into account both inflation and the earning potential of money over time. If performed correctly, both approaches produce identical results. The advantage of using constant dollars is that it simplifies the analysis. The factor tables produced in the annual supplement are based on a constant dollar assumption (Fuller, 2005).

Most construction projects consist of a planning and construction (P/C) period which must be accounted for in an economic analysis. Initial investments can be phased in during this period or assigned to a single point in time (Fuller & Peterson, 1995). The Federal Energy Management Program stipulates a maximum study period of 25 years, plus the length of the P/C period. All costs must be discounted to their present value as of the base date. The service period begins when the building is occupied and represents the period of time that operational costs and benefits are incurred. The study period is the sum of the P/C and service periods.

This relationship is illustrated in Figure 21. The delayed service date, for recurring costs or benefits, is easily accounted for by determining the present value using the total study period and then subtracting the present value using the P/C period. For example, given a uniform series, the present value can be determined by $UPV_{StudyPeriod} - UPV_{P/C}$.

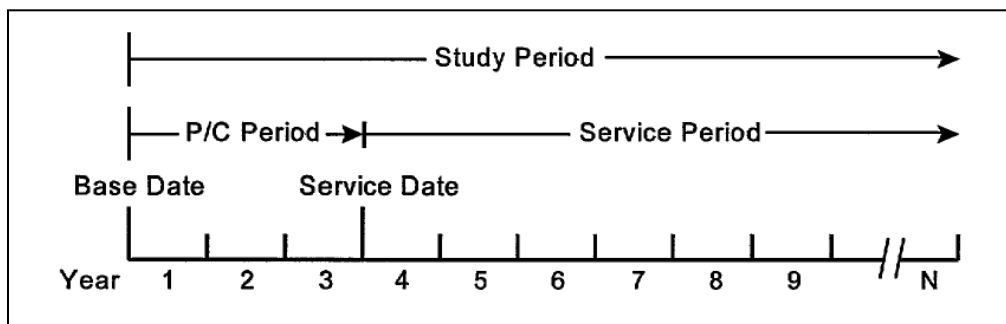


Figure 21 - Study Period with Delayed Service Date (Fuller & Peterson, 1995)

Another aspect of life-cycle cost which must be accounted for are replacement costs. The FEMP requires the incorporation of capital replacement costs for major building systems, the timing of which is based on the estimated life of the system. These

costs are incurred at points in time and must be discounted to their present value (Fuller & Peterson, 1995).

If the life of major building systems does not match the service period, the salvage values of those systems should be included in the economic analysis (Fuller & Peterson, 1995). The residual value of a system is the initial value minus the value at the conclusion of the study. Residual values, even if present, can be negligible due to an offset by removal and disposition costs (Fuller & Peterson, 1995). The FEMP states that if a building or major building system will remain in service after the conclusion of the study, the in-situ residual value should be used (Fuller & Peterson, 1995). The in situ residual value means that removal and disposition costs should not be included. In general, linear prorating is acceptable to estimate the salvage values for building systems (Fuller & Peterson, 1995). Linear prorating provides a residual value, at a specified point in time, by using a straight line interpolation between the initial cost of the system and its value at the conclusion of its useful economic life.

III. Research Approach

This chapter describes the approach utilized by this research to answer the investigative questions outlined in Chapter 1. The overall approach is a combination of methodologies from the disciplines of Model Building, Economic Analysis, and Geospatial Analysis. The research approach is divided into three phases: Model Development, Model Evaluation, and Model Application. Figure 44 in Appendix A outlines the approach which developed the Cost-Effective (CE) Net-Zero Energy (NZE) model. Figure 45 in Appendix A outlines the approach which determined the sensitivity of the CE NZE model to input value variations and will rank the variables in terms of the need for quality data. Figure 46 in Appendix A outlines the approach which ranked installations in terms of the net-savings (NS) of constructing a Zero-Energy Building (ZEB). It also proved that this ranking, which will also be termed the most likely installations to achieve CE NZE, is statistically similar between facility types. In each of the three graphics described above:

- Inputs to each process are contained in the circle above the process.
- Processes are in the middle of each graphic and the corresponding actions are contained in each.
- Outputs to each process are contained in the circle below the process.
- Outputs within the box defining the phase are intermediate, while those outside the box are products of the research which will be used to answer investigative questions.

Each phase will be discussed in more detail in the following sections.

3.1. Model Development

This section outlines the methodologies and actions necessary to generate a net-zero energy (NZE) feasibility assessment model which uses a Net-Savings (NS) metric to determine if the potential project will be cost-effective (CE). This phase is divided into four distinct processes; each will be discussed in the following subsections.

3.1.1. Fundamental Model Development.

This section outlines the process which will generate the two fundamental equations defining the CE NZE feasibility model. The first equation represents the requirement for the facility to be NZE and the second represents the requirement that the NZE design be cost-effective. The following sections describe the methodology utilized to generate the fundamental mathematical equations.

3.1.1.1. Generate Net-Zero Energy Fundamental Equation.

This section develops the mathematical equation which represents the definition of NZE chosen for this research. The input required to generate the equation is the definition selected for NZE. As described in Section 2.4, this research will utilize the net-zero site definition; according to this definition, the facility reaches NZE status when the energy produced in a given year offsets the energy demand in that same year. The equation resulting from this section is an input to the functional decomposition process.

3.1.1.2. Generate Cost-Effectiveness Fundamental Equation.

This section develops the mathematical equation which represents the requirement for the NZE design alternative to be CE. The process of this section aligns with the Life-Cycle Cost (LCC) methodology established by the Federal Energy Management Program (FEMP) for the economic evaluation of energy conservation, water conservation, and renewable energy projects (Fuller & Peterson, 1995). The FEMP rules are published in Title 10, Code of Federal Regulations 436, subpart A, and apply to all federal agencies (Fuller & Peterson, 1995). Although this methodology was developed for federal agencies, it is consistent with the American Society of Testing and Materials economic analysis standards (Fuller & Peterson, 1995).

The input to this process is the model chosen to account for all costs arising during the facility's life-cycle. The LCC model in Equation 2 was chosen for this research. Once the model is chosen, it must be modified to account for the costs specific to each of the project alternatives (New South Wales Treasury, 2004). Deductive reasoning was used to ensure that the modified LCC models are equivalent to those provided by Equation 2 (Fieser & Dowden, 2003). Once the LCC models were modified, the NS metric was incorporated to analyze the cost-effectiveness of the NZE design alternative. Upon incorporating the NS metric, all costs which are equivalent between the two alternatives will be canceled. The process outlined above generates the second fundamental equation, which is an input to the Functional Decomposition process.

3.1.2. Function Decomposition.

This section decomposes the two fundamental equations into independent and predictable elements. The process which generates the decomposed functions is Hierarchical Function Decomposition; more detail regarding this methodology is available in Section 2.7. Function decomposition is used for each element in the fundamental equations and was repeated until all major costs can be estimated (New South Wales Treasury, 2004). Function decomposition utilizes deductive reasoning to ensure that the relationships present in the fundamental equations and all costs contributing to the elements in the LCC model are maintained. This fact is critical to obtaining a cost estimate with acceptable accuracy, but results in costs being included which do not significantly contribute to the decision being made.

Numerous federal cost estimating guides allow costs, which do not contribute to an objective of the analysis, to be excluded (Department of the Air Force, 2008). The goal of any LCCA should be to include all relevant costs; when costs are excluded, established best practice is to explicitly state which costs will be excluded and provide justification for why each is insignificant (GAO, 2009). Although there are no specific thresholds for determining if a cost is significant, the FEMP defines significant costs as those which are “large enough to make a credible difference in the LCC of a project alternative” (Fuller & Peterson, 1995, p. 55).

The inputs required for the decomposition process are the two fundamental equations developed in Section 3.1.1, the threshold to determine if a cost is substantial, and the relationships identified in literature review which guided the decomposition.

This project utilizes a threshold of one percent to determine if a cost or benefit is significant. The relevant literature review is described in Section 2.10. The decomposed NS equation will be an input to the Engineering Economics process and the decomposed NZE equation will be an input to the function combination process.

3.1.3. Engineering Economics.

This section will add engineering economic factors to the Net-Savings (NS) equation in order to account for the time-value of money. The incorporation of economic factors is consistent with the methodology outlined in the Federal Energy Management Program (Fuller & Peterson, 1995). To simplify the environment of this research, assumptions are made; these assumptions are those related to the economic methodology and did not limit the accuracy of the model (NAVFAC, 1993).

The inputs required for this process outlined above are the decomposed NS equation, economic assumptions, and the factors to convert all cash-flows to present worth. More detail regarding the economic factors utilized can be found in Section 2.10.5. The assumptions utilized are outlined in Table 11. The output to this process is an input into the Function Combination process.

Table 11 – Model Economic Assumptions

Variable	Assumption
Discount Rate	3%
Study Period	27
Planning and Construction Period	2
Service Period	25
Base-date	2011
Discounting Approach	End of Year
Inflation Adjustment Method	Constant Dollars
Inverter Replacement	15

3.1.4. Function Combination.

This section combines the net-zero energy (NZE) and net-savings (NS) equations into the single cost-effective (CE) NZE model. The combination process begins with the incorporation of variables, representing the estimation technique, for each element into the decomposed equations. Each equation is a function of the percent energy reduction from the baseline and the size of the PV system necessary to offset the remainder of energy demand. The model is a system of equations as they involve the same set of independent variables (System of Linear Equations, 2012). As this is a system of equations with two equations and two unknowns, a unique solution to the system exists (System of Linear Equations, 2012).

There are numerous methods for solving a system of equations, the simplest of which is to repeatedly eliminate variables (System of Linear Equations, 2012). In this method, the first equation is solved for one of the variables in the remaining equations and the resulting relationship is then substituted into the remaining equations (System of

Linear Equations, 2012). The NZE equation is solved in terms of *system size*. This relationship was then substituted into the NS equation. Once the final equation is obtained, a dictionary is produced to define each variable.

The inputs to the function combination process are the decomposed NZE equation, decomposed NS equation in factor notation, and estimation variables used to represent the estimation technique for each model element. The estimation technique and resulting variables for model elements, which are not constants, are outlined in Table 12. The equation resulting from the combination process is the model utilized by the Model Evaluation and Model Application phases.

Table 12 – Estimation Variables

Element	New Variables	Source
Energy Produced	Output to Size Ratio[installation] * System Size	(Stafford, Robichaud, & Mosey, 2011)
Benchmark Energy Use	Benchmark EUI [type,zone] * Area	(PNNL, 2010)
Inverter Cost	Unit Inverter Cost * System Size	(NREL, 2012)
Benchmark Energy Cost	Benchmark EUI [type,zone] * Area * Average Electric Rate [state]	(Andrews, 2009)
Construction Premium	Construction Premium[type,zone,perc red] * (1+SIOH) * (1+Contingency)	(Jiang et al, 2011)
Benchmark Cost	Benchmark Unit Cost[type] * Size Factor * Location Factor * Escalation Factor * Area * (1+SIOH) * (1+Contingency)	(AFCESA, 2007)
PV System Installed Cost	Unit Installed PV Cost[sys size] * System Size * (1+SIOH) * (1+Contingency)	(Goodrich, James, & Woodhouse, 2012)
Inverter Installed Cost	Unit Installed Inverter Cost * System Size	(NREL, 2012)
PV System O&M Cost	Unit PV O&M Cost[sys size] * System Size	(NREL, 2012)

3.2. Model Evaluation

This section outlines the methodologies and actions necessary to evaluate the cost-effective (CE) net-zero energy (NZE) model. This phase is divided into four distinct processes; each will be discussed in the following subsections.

3.2.1. Sensitivity Analysis.

This section performs a sensitivity analysis of the CE NZE model to determine which input variables contribute most to the uncertainty of the model's output. The process utilized to conduct the sensitivity analysis is one-at-a-time (OAT) analysis. A prerequisite to performing an OAT analysis is that all input variables are independent. As this project utilizes deductive reasoning through decomposition, all resulting variables are independent. Prior to performing the analysis, the CE NZE model must be coded into Microsoft Excel. Model coding transforms the mathematical equation into a computer-based analysis tool (Council for Regulatory Environmental Modeling, 2009). A separate Excel worksheet was developed for each variable being considered; this allows that variable to be changed by plus and minus 10 percent, in one percent increments, while holding all other variables constant. The calculated NS value is computed for each percent change in each variable's input. The range of values for each variable is plotted together using a scatter plot. A line was fitted to each variable's NS distribution using the Trend Line function in Excel. The slope of these lines was annotated and subsequently used to rank the variables.

The inputs to the OAT process are the CE NZE model, list of uncertain variables, economic factor values, and values for the selected base-case. The list of uncertain variables is provided in Table 13.

Table 13 – Uncertain Variables for Sensitivity Analysis

Variable
Unit Inverter Installed Cost
Benchmark EUI
Construction Premium
Output to Size Ratio
Average Electric Rate
Annual Arithmetic Degradation
Benchmark Unit Cost
Unit PV Installed Cost
Unit PV O&M Cost

The base-case will be a 53,628 square foot medium office building constructed at Beale AFB, California. The values for model inputs are provided in Table 14. The output of this process will be used to answer Investigative Question 3.

Table 14 – Base-Case Variable Values for Sensitivity Analysis

Variable	Value
Inverter Useful Life	15
Unit Inverter Installed Cost	0.37
Benchmark EUI	13.98
Percent Reduction	0.545
Output to Size Ratio	1374
Average Electric Rate	14.305
Annual Arithmetic Degradation	0.005
Construction Premium	0.066
Benchmark Unit Cost	120
Size Adjustment	0.93
Location Adjustment	1.28
Escalation Adjustment	1*
SIOH	0.057
Contingency	0.05
Unit PV Installed Cost	3557.17
Unit PV O&M Cost	23.26
* This will be assumed for all remaining base-cases	

3.2.2. Construction Premium Comparative Analysis.

This section performs a comparative analysis of construction premium to determine if commercial facility incremental construction cost data can be used to predict the incremental construction cost for Department of Defense (DoD) facility types. The analysis is divided into two processes: curve interpolation and correlation analysis. Each will be discussed in the following subsections.

3.2.2.1. Curve Interpolation.

This section fits a curve to construction premium data obtained for commercial facilities. Curve fitting can use interpolation or smoothing. Interpolation requires the curve to go through data points, while smoothing determines a best-fit (Curve fitting, 2012). As the curves being fit only include a single data point, interpolation is used. To interpolate a curve for each facility type in each climate zone, a generalized form of the equation being fitted was coded into Microsoft Excel. The solver tool in Excel was then used to determine the remaining unknown variable in the general equation; this insures the resulting curve goes through the provided data point. Finally, the curve developed for each facility type in each climate zone was annotated.

The inputs required for the curve interpolation process are the data points for the commercial facility types being studied, generalized form of the equation being fit, and additional constraints available from literature review. The data points for Small Office, Medium Office, and Small Hotel facility types are provided in Table 10. Due to the Law of Diminishing Return, there is a theoretical reason to select a function with an exponential form (Igor Pro, na). This relationship is modeled in the exponential approach function provided in Equation 14 (Elert, 2012).

$$y = a * (1 - n^{-bx}) + c \quad (14)$$

With the form of the equation specified, the coefficients must be determined using additional constraints (Igor Pro, na). In general, a curve of degree n, requires n+1 constraints to fit a curve. These constraints are provided by the following two facts:

- At zero percent energy reduction, there should be a zero percent construction premium. This dictates that the function must go through the origin.

- A facility, while maintaining the baseline's level of indoor environmental comfort, can never reach zero energy demand. This constraint sets the natural asymptote of the function equal to one

These constraints set the values of a equal to one and c equal to zero in Equation 14. As shown in Figure 22, the selection of the base of the exponential function is irrelevant, as the value of b will adjust the fitted curve to match the provided data point. As such, base e was chosen for this research.

<i>Curve Fit with Base e</i>			<i>Curve Fit with Base 10</i>		
b	Construction Premium	Percent Reduction	b	Construction Premium	Percent Reduction
15.40	0.045	0.5	6.69	0.045	0.5
	0.01	0.142756265		0.01	0.142756087
	0.02	0.265133179		0.02	0.265132874
	0.03	0.370040022		0.03	0.370039629
	0.04	0.459970756		0.04	0.459970307
	0.05	0.537063314		0.05	0.537062833
	0.06	0.603150427		0.06	0.603149931
	0.07	0.65980319		0.07	0.659802694
	0.08	0.708368416		0.08	0.70836793

Figure 22 - Comparison of Chosen Exponential Bases

Equation 14 contains *Construction Premium* as the independent variable. In order to obtain an estimate for *Construction Premium* directly, the equation must be solved in terms of *Percent Reduction*. The new equation is provided in Equation 15 and is the one coded into Excel in the process outlined above.

$$\text{Construction Premium} = -\frac{\ln(1 - \text{Percent Reduction})}{b} \quad (15)$$

The outputs of this process are curves which can be used to determine the *Construction Premium* at any *Percent Reduction* from baseline. An upper limit of 70 percent has been assigned to the interpolation, as that is the maximum energy reduction achievable utilizing currently available technology and construction techniques (National Science and Technology Council, 2008). The developed curves are utilized as an input into the correlation analysis process.

3.2.2.2. *Correlation Analysis.*

This section performs a correlation analysis to determine if the data from commercial facilities can be used to predict the construction premium associated with an energy reduction from baseline for Department of Defense (DoD) facilities. The process which will be used to determine whether commercial facility data can be used to predict the construction premium of DoD facilities is cross-validation. A cross-validation is an evaluation method to determine how well a model predicts data it was not fitted to (Schneider, 1997). This research performs a cross-validation utilizing a Pearson correlation analysis (McClave, Benson, & Sincich, 2011). A scatter plot was constructed by graphing, in Microsoft Excel, the values predicted by the construction premium curves on the x-axis and the values from the EISA study on the y-axis (Council for Regulatory Environmental Modeling, 2009).

The Coefficient of Determination, R^2 , is obtained by fitting a straight line through the data points (Patten, 2009). R^2 is interpreted as a certain percentage better than no relationship (Patten, 2009). An observed significance level will not be reported for this correlation as there are only eight data points and no knowledge regarding the

distribution of the correlations. The inputs required for the Pearson correlation analysis are the construction premium curves from Section 3.2.2 and the data points extracted from the EISA study. The data points from the study are provided in Table 15.

Table 15 – EISA Construction Premium Data Points

Facility Type	Climate Zone	Benchmark EUI	Percent Reduction	Observed Construction Premium
UEPH	1_moist	14.97	0.3517	0.0468
UEPH	2_moist	15.15	0.3517	0.0587
UEPH	3_dry	13.97	0.509	0.0441
UEPH	4_moist	15.35	0.3768	0.052
UEPH	4_marine	13.86	0.4152	0.0451
BG HQ	4_moist	15.35	0.314	0.0468
BG HQ	4_marine	13.86	0.3175	0.0587
BG HQ	6_moist	17.32	0.2931	0.0441

The strength of the correlation coefficient will statistically determine if the commercial facility construction premium curves can be used to predict the values for DoD facility types. The output of this process will be used to answer Investigative Question 1.

3.2.3. Corroboration Analysis.

This section performs a corroboration analysis of both the construction premium curves and cost-effective (CE) net-zero energy (NZE) model. Corroboration data for this research is limited; therefore, a combination of qualitative and quantitative methods is used. In general, quantitative techniques are used to generate graphs of model outputs,

which are then qualitatively compared to best-available understanding. More detail concerning corroboration analysis can be found in Section 2.8. Each analysis is discussed in the following subsections.

3.2.3.1. Construction Premium Corroboration.

This section determines how well the construction premium curves generated in Section 3.2.2 align with best-available understanding. The process utilized to generate the graph for comparison is similar to one-at-a-time analysis. First, the construction premium curves are coded into Microsoft Excel. Next, the curves are used to generate values for a 0 to 70 percent energy reduction from baseline; the values will be calculated in increments of five. These values will then be plotted using a line graph in Excel.

The inputs required to generate the three graphs are the construction premium curves from Section 3.2.2 for Small Office, Medium Office, and Small Hotel facility types at Beale Air Force Base, California; Beale AFB is in Climate Zone three-dry. The graphs will be compared to best-available understanding and used to answer Investigative Question 2.

3.2.3.2. CE NZE Model Corroboration.

This section determines how well the cost-effective (CE) net-zero energy (NZE) model aligns with best-available understanding. The process utilized to generate the graph for model corroboration is performed in two phases. The first phase assesses the net-savings (NS) in response to a change in percent energy reduction and will be

performed three times: one for the overall NS, one for the NS related to energy reduction, and one for the NS related to energy production. The second phase assesses the NS in response to a change in facility size.

In the first phase, the NS values are calculated for a 0 to 70 percent energy reduction from baseline, in increments of five percent. In the second phase, the NS values are calculated for a facility size range of 30,000 to 60,000 square feet, in increments of 5,000 square feet. The NS values from both phases will be graphed. The inputs required to generate the graphs are the energy reduction and energy production portions of the CE NZE model, economic factor values from Section 3.3.1, and base-case values. The base-case will be a 53,628 square foot medium office building constructed at Beale Air Force Base, California; the values are provided on the next page in Table 16. The graphs are compared to best-available understanding and used to answer Investigative Question 2.

Table 16 – Base-Case Estimates for CE NZE Model Corroboration

Variable	Value
Inverter Useful Life	15
Unit Inverter Installed Cost	0.37
Benchmark EUI	13.98
Percent Reduction	0.545
Output to Size Ratio	1374
Average Electric Rate	14.305
Annual Arithmetic Degradation	0.005
Construction Premium	$-\text{LN}(1-\text{PercRed})/11.93$
Benchmark Unit Cost	120
Size Adjustment	0.93
Location Adjustment	1.28
SIOH	0.057
Contingency	0.05
Unit PV Installed Cost	3557.17
Unit PV O&M Cost	23.26

3.2.4. Uncertainty Analysis.

This section provides a quantification of the uncertainty associated with making decisions based on the output from the cost-effective (CE) net-zero energy (NZE) model. Monte Carol simulation is the process utilized to perform the uncertainty analysis. More information regarding uncertainty analysis and Monte Carlo simulation is provided in Section 2.8. The simulation begins with the model being coded into Microsoft Excel, with a specific column for each variable included in the analysis. Next, the Random Number Generator (RAND) in Excel is used to calculate 10,000 values of each variable with a normal distribution. Then the RAND function is used to generate 10,000 normally

distributed numbers between zero and one. Equation 4 is then utilized to generate the triangularly distributed variates. The net-savings (NS), cumulative NS, and Incremental Capital Investment (ICI) values are then calculated for each of the 10,000 scenarios. A plot of cumulative NS is produced to illustrate convergence and a histogram is produced for both the NS and ICI distributions. A Kolmogorov-Smirnov-Lilliefors (KSL) test is subsequently performed for both distributions to prove normality. Next, a cumulative distribution function is produced for both distributions and utilized to discuss their respective variance. Finally, descriptive statistics of mean, median, minimum, maximum, and standard deviation of the NS and ICI distributions is calculated using the Descriptive Statistics tool in Excel.

The results from the Sensitivity Analysis process of Section 3.2.1 is used to reduce the number of variables included in this analysis. Construction Premium is not included in the uncertainty analysis as there are no sources of data regarding its error or probability distribution. The variables which are included are Benchmark Energy Use Intensity, Output to Size Ratio, Average Electric Rate, PV Installed Unit Cost, and Benchmark Unit Cost. The inputs required to assess the model's uncertainty are the CE NZE model, base-case values, and variable probability distributions.

The base-case is a 53,628 square foot medium office building constructed at Beale Air Force Base, California; the base-case values and variable probability distributions are provided in Table 17. The standard deviations and distributions associated with the base-case are utilized to answer Investigative Question 4.

Table 17 – Base-Case Estimates for Uncertainty Analysis

Variable	Value	Distribution	Uncertainty
Inverter Useful Life	15	None	
Unit Inverter Installed Cost	0.37	None	
Benchmark EUI	13.98	Triangular	ME = 10%
Percent Reduction	0.545	None	
Output to Size Ratio	1374	Triangular	ME = 10%
Average Electric Rate	14.305	Triangular	High = 16.24 Low = 12.37
Annual Arithmetic Degradation	0.005	None	
Construction Premium	0.066	None	
Benchmark Unit Cost	120	Normal	Std Dev = 42.71
Size Adjustment	0.93	None	
Loc Adjustment	1.28	None	
SIOH	0.057	None	
Contingency	0.05	None	
Unit PV Installed Cost	3557.17	Normal	Std Dev = 673
Unit PV O&M Cost	23.26	None	

3.3. Model Application.

This section outlines the methodologies and actions necessary to apply the cost-effective (CE) net-zero energy (NZE) model in order to determine which installations are the most likely to achieve cost-effective NZE. This phase is divided into three distinct processes; each will be discussed in the following subsections.

3.3.1. Geospatial Analysis.

This section utilizes geospatial analysis to calculate and summarize all geospatially related variables needed for inputs to the cost-effective (CE) net-zero energy (NZE) model. ArcGIS is used to perform the geospatial analysis for this project. It has an extensive selection of data management and geospatial analysis tools; each of which are outlined in Section 2.9.

The process begins with all shapefiles being added to a geodatabase. Then, the county shapefile and climate zone table are combined and reconciled in Microsoft Excel. The combination begins with the attribute table from the county shapefile and the climate zone table being added to separate worksheets. A formula then compares the two tables and adds the climate zone to the county shapefile's attribute table for each county. When the formula encounters an error, the tables will be reconciled. Once all counties have a climate zone attached, a field is added to the states shapefile to represent the Census Regions described in the Federal Energy Management Program (FEMP) Annual Supplement; the select by attribute tool is used to populate this field. Once complete, the states shapefile is modified to remove polygons outside of the contiguous U.S. (CONUS). Next, model builder is used to perform all actions required to calculate and summarize the variables. Once all calculations have been performed, a report is generated to extract the calculated values into tabular format. Finally, the Location Adjustment Factor for each installation is added to this table.

The inputs required for the above geospatial analysis are four shapefiles, three non-spatial tables, and the model representing all necessary tools and actions to calculate

and summarize variable values for each CONUS installation. The shapefiles are provided in Table 18.

Table 18 – Shapefile Data Requirements

Shapefile	Source
US States	US Census Bureau
US Counties	US Census Bureau
Zip_Codes	US Census Bureau
DoD Installations	US Census Bureau

The non-spatial table which dictates the climate zone for each county in the US is obtained from the Building America Program. The non-spatial table which dictates the Census Region of each state in the U.S. is obtained from the FEMP Annual Supplement. The non-spatial table which provides the Location Adjustment Factor for each installation was obtained from Table 4.1 of Unified Facility Criteria 3-701-01.

The model is described graphically in Figure 23. The table resulting from this analysis is used as input to the PV Watts calculation and installation comparative analysis processes.

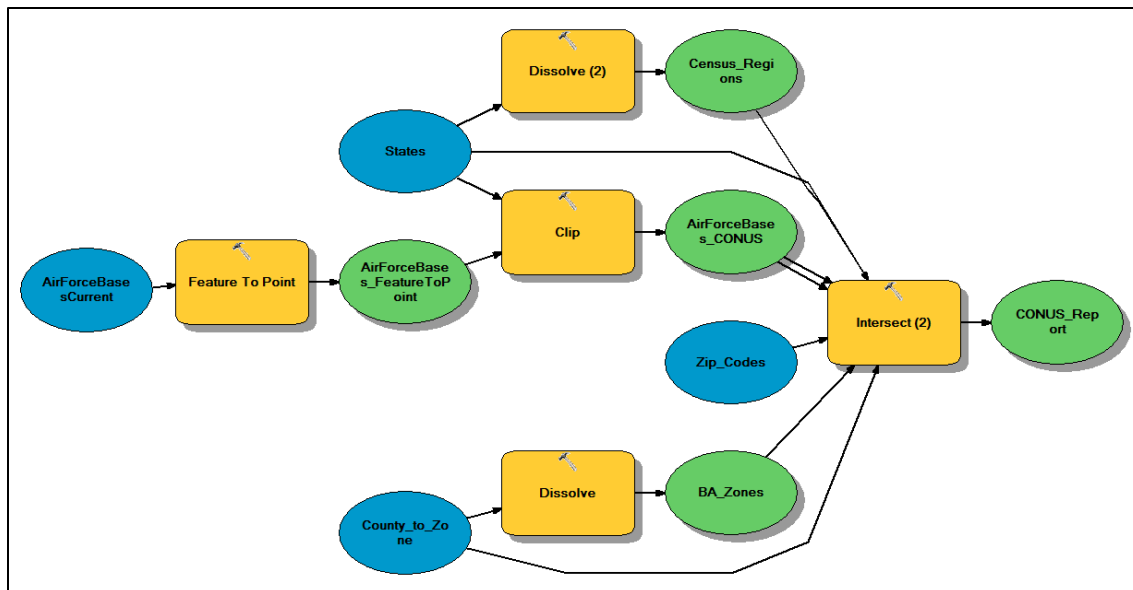


Figure 23 – Model of Tools and Actions for Geospatial Analysis

3.3.2. PV Watts Calculation.

This section calculates the output to size ratio for the specified photovoltaic (PV) system at each Contiguous U.S. (CONUS) installation. PV Watts is used to calculate the time-series power produced by a crystalline-silicon PV panel at each CONUS United States Air Force (USAF) installation. The location of each installation is determined in the PV Watts Version 2 map tool by zip code. Solar resource and climactic data for each location is then imported into PV Watts. Next, the characteristics of the panel are set; these will remain constant for all installations. Finally, a simulation will be run to estimate the annual alternating current power output from a 1 kilowatt rated PV system at each installation.

The inputs necessary for the PV Watts calculations are the zip code for each installation, system configuration, and overall derate factor. The system configuration and derate factor are provided in Figure 24. The output from the process outlined above is utilized as an input to the installation comparative analysis process.

PV System Specifications:

DC Rating (kW):

DC to AC Derate Factor:

Array Type:

Fixed Tilt

Fixed Tilt or 1-Axis Tracking System:

Array Tilt (degrees):
(Default = Latitude)

Array Azimuth (degrees):
(Default = True South)
[What's this?](#)

Figure 24 – PV System Configuration and Derate Factor

3.3.3. Installation Comparative Analysis.

This section ranks contiguous U.S. (CONUS) installations in terms of the likelihood of achieving a cost-effective (CE) net-zero energy (NZE) facility. The effect of location on net-savings (NS) is evaluated by conducting a comparative analysis. Comparative analysis looks at two or more similar alternatives to determine their similarities and differences (Reutlinger, Schurz, & Hüttemann, 2011). In economics, this type of research is often performed by using a Ceteris Paribus (CP) clause (Bierens & Swanson, 1998). In Latin, CP literally means “with all things being equal.” To perform this analysis, the CE NZE model is coded into Microsoft Excel with one worksheet for each facility type; each installation is a row in the three worksheets. Next, the base-case

values which are not geospatially related are copied for each installation. The VLOOKUP function in Excel is utilized to populate all geospatial variable values for each installation. Once all values are populated, the NS is calculated for each installation. The NS values are then imported into Arc GIS and an inverse distance weighting interpolation is performed on the NS values for each facility type. In parallel with the interpolation, the NS values are imported into another Excel spreadsheet and the rank function used to list the installations from highest to lowest in terms of NS.

In order to determine if the rankings between facility types are statistically consistent, three correlation analyses are conducted, one for each facility type combination. The correlation analysis is performed utilizing the Spearman's Rank Correlation Coefficient, r_s . The first step in calculating r_s is to average any tied rankings. The square of the differences between the rankings of the facility types being analyzed are then calculated; these are summed and utilized in Equation 16 (McClave, Benson, & Sincich, 2011).

$$r_s = 1 - \frac{6 * \sum d^2}{n * (n^2 - 1)} \quad 16$$

where $\sum d^2$ is the sum of squared differences and n is the number of observations. The significance of the correlation is then assessed by constructing a hypothesis test. The null hypothesis is that the population rank correlation coefficient, ρ_s , is equal to zero and the alternative hypothesis is that ρ_s is greater than zero; this is termed a one-tailed test (McClave, Benson, & Sincich, 2011). The test statistic in Equation 17 is then calculated (McClave, Benson, & Sincich, 2011).

$$t = \frac{r * \sqrt{n - 2}}{\sqrt{1 - r^2}} \quad 17$$

where r is the sample correlation coefficient, n is the number of data points, and the Student's t-distribution depends on $n - 2$ degrees of freedom. Once the test statistic is calculated, the p-value is reported utilizing the `tdist` function in Excel. The p-value is the extent to which the calculated test statistic disagrees with the null hypothesis and is often called the *observed significance level* (McClave, Benson, & Sincich, 2011). The p-value is interpreted as the probability of observing a correlation in the population that is equal to or larger than the one calculated from the sample data (McClave, Benson, & Sincich, 2011).

The inputs required for the comparative analysis are the CE NZE model, installation report, output to size ratios, model representing all necessary tools and actions required for the IDW interpolations, economic factor values, and variable estimates. The model is described graphically in Figure 25.

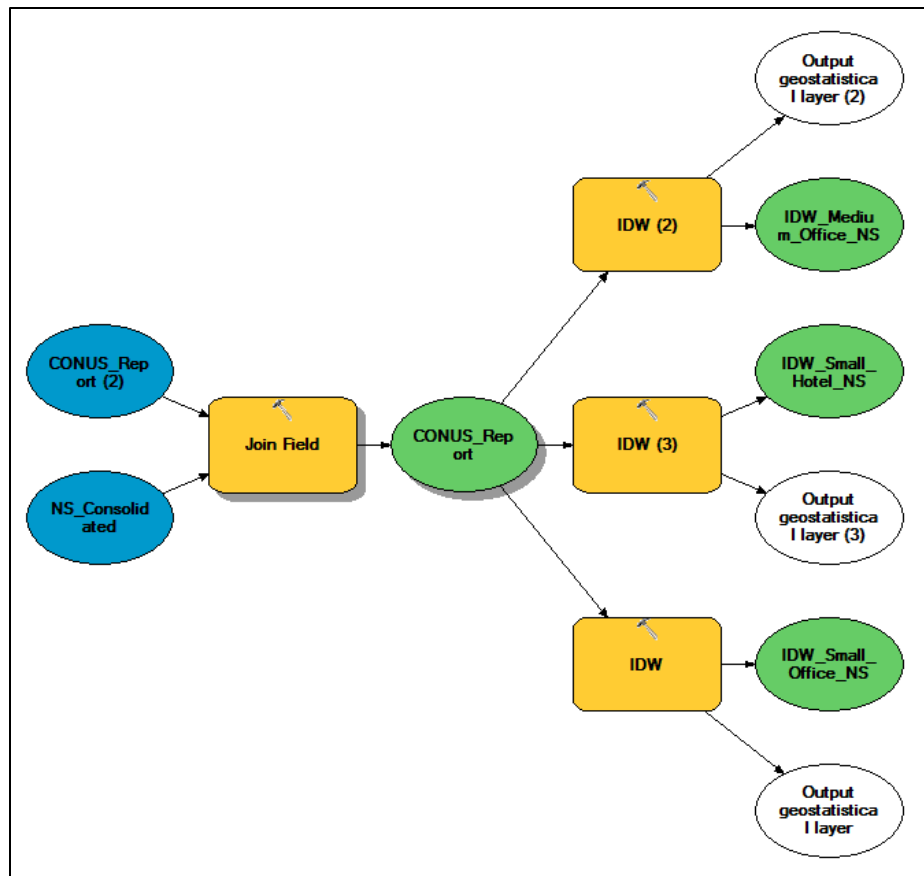


Figure 25 – Model for IDW Interpolation

The variable estimates are provided on the next page in Table 19. When the variable changes by facility type, it will be listed in the order: Small Office, Medium Office, and Small Hotel. The variables which are geospatially related will be stated as such. The installation report and output to size ratios are available in Appendices B and C respectively. The economic factor values were calculated in Section 3.1.3. The IDW raster files, installation rankings, and rank correlations are utilized to answer Investigative Question 5.

Table 19 – Base-Case Variable Estimates for Installation Comparative Analysis

Variable	Value
Unit Inverter Installed Cost	370/kW
Benchmark EUI	Geospatial - Lookup
Percent Reduction	Geospatial - Lookup
Zone	Geospatial - Lookup
Area	5502, 53628, 43202
OSR	Geospatial – Lookup
Installation	Variable
Average Electric Rate	Geospatial - Lookup
Annual Arithmetic Degradation	0.5%
Construction Premium	Geospatial - Lookup
Benchmark Unit Cost	120, 120, 102
Size Adjustment Factor	1.17, 0.93, 0.99
Location Adjustment Factor	Geospatial - Lookup
SIOH	5.7%
Contingency	5%
Unit PV Installed Cost	Size < 100 kW – \$4,287.79/kW Size >= 100kW - \$3,557.17/kW
Unit PV O&M Cost	Size < 100 kW – \$25.19/kW Size >= 100kW - \$23.26/kW

IV. Analysis and Results

This chapter presents the results of the phases described in Chapter 3. The outputs from individual processes are utilized as inputs to other processes and to answer the investigative questions outlined in Chapter 1.

4.1. Fundamental Equation Development

This section presents the results from the model development phase. The output of this phase was utilized by processes in the Model Evaluation and Model Application phases. Figure 26 modifies the life-cycle cost (LCC) model from Equation 2 to apply to the benchmark facility.

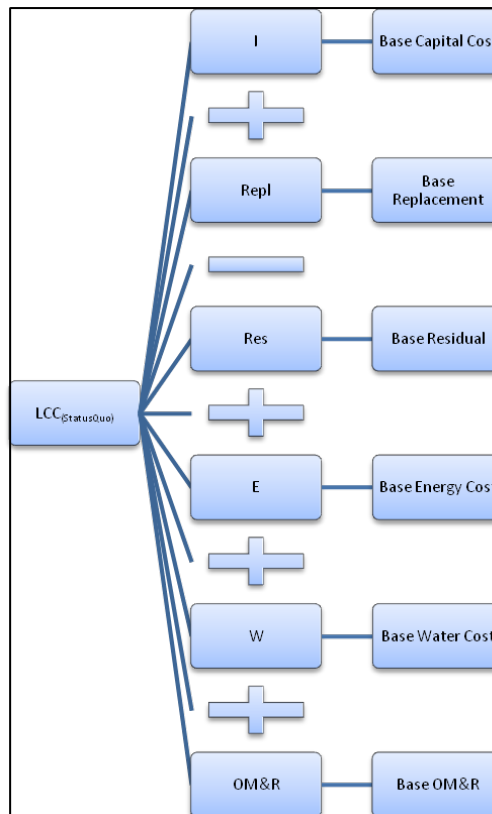


Figure 26 – Benchmark LCC Model

Figure 27 modifies the LCC model from Equation 2 to apply to the net-zero energy (NZE) facility.

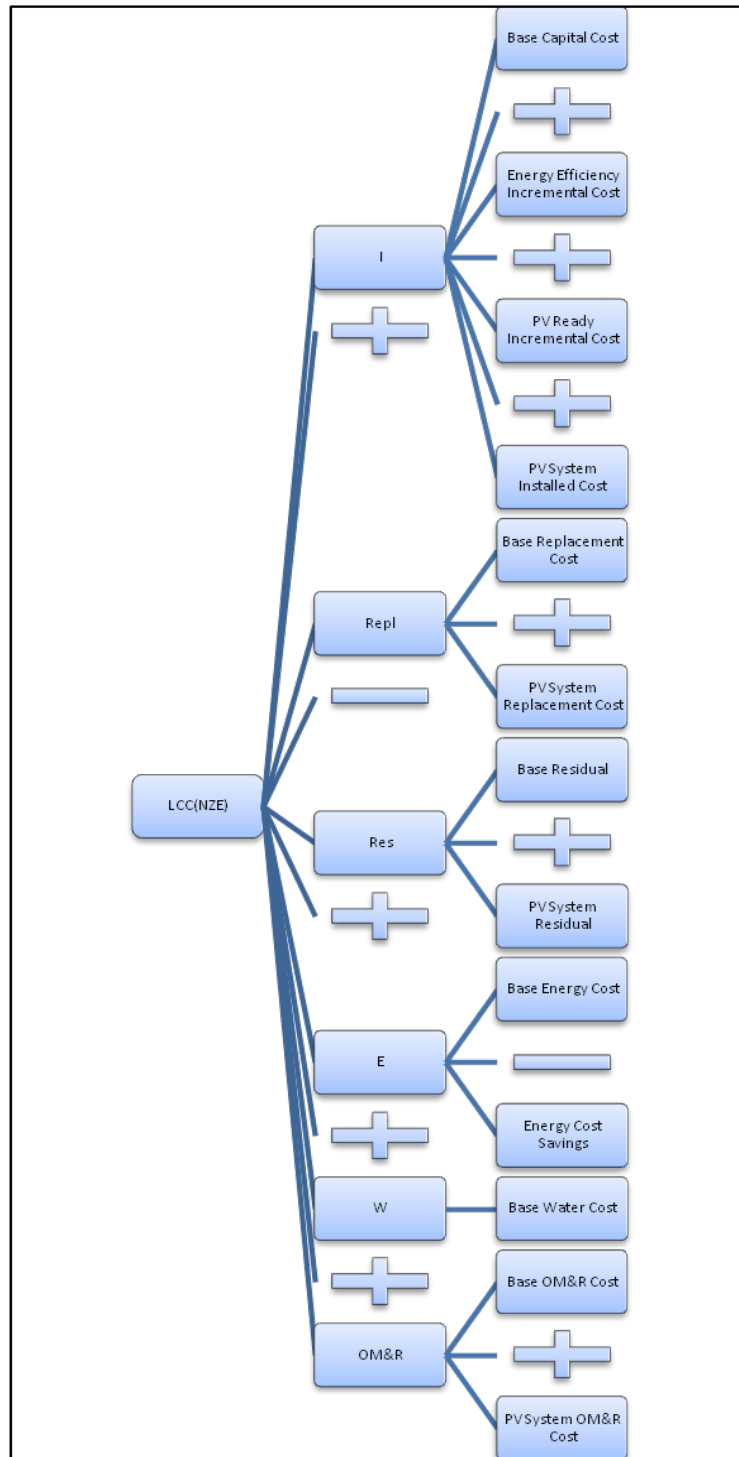


Figure 27 – NZE LCC Model

After incorporating the NS metric and canceling like costs the resulting fundamental equation is presented in Equation 18. The mathematical model for the NZE fundamental equation is provided in Equation 19.

$$PW((PV \text{ System Residual Value}) + (\text{Energy Cost Savings}) - (\text{Energy Efficiency Incremental Cost}) - (PV \text{ Ready Incremental Cost}) - (PV \text{ System Installed Cost}) - (PV \text{ System Replacement Cost}) - (PV \text{ System OM\&R Cost})) \geq 0 \quad (18)$$

$$NZE \rightarrow \text{EnergyUse} - \text{EnergyProduced} = 0 \quad (19)$$

4.2. Function Decomposition

This section presents the results from the Function Decomposition process. It graphically shows the decomposition of the fundamental equations into independent and predictable elements. It also lists and provides justification for the model elements which were not included in the final model. Finally, it presents the resulting net-zero energy (NZE) and net-savings (NS) equations.

Figure 28 depicts the decomposition of the NZE fundamental equation.

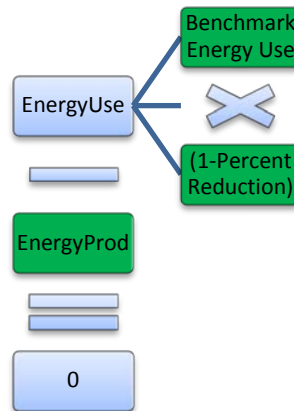


Figure 28 – NZE Decomposition

Figure 29 depicts the decomposition of the Capital Investment life-cycle cost (LCC) element.

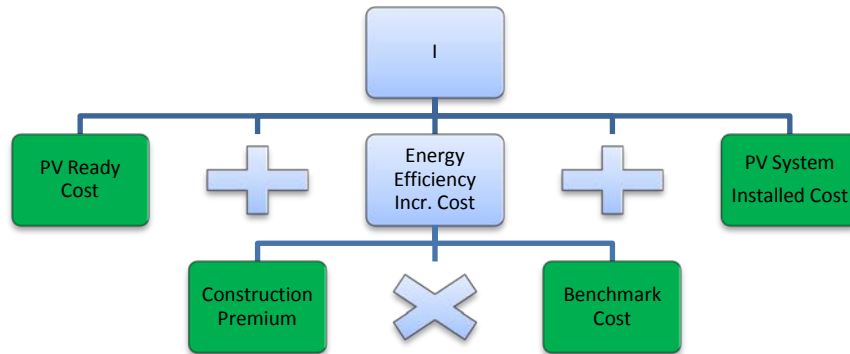


Figure 29 – Capital Investment Decomposition

Figure 30 depicts the decomposition of the PV System Replacement LCC element.

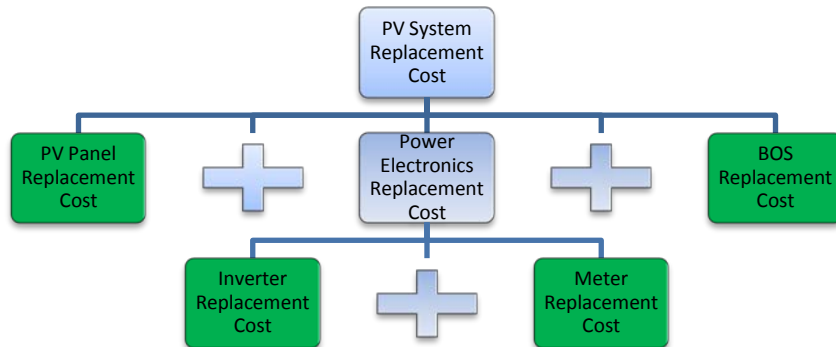


Figure 30 –Replacement Cost Decomposition

Figure 31 depicts the decomposition of the PV System Replacement LCC element.

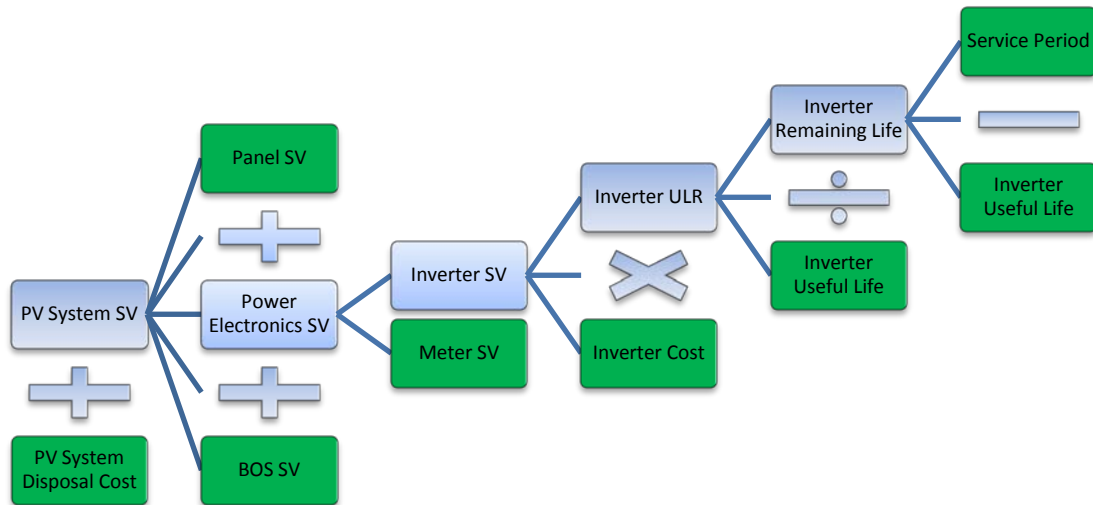


Figure 31 – Residual Cost Decomposition

Figure 32 depicts the decomposition of the Energy Cost Savings LCC element.

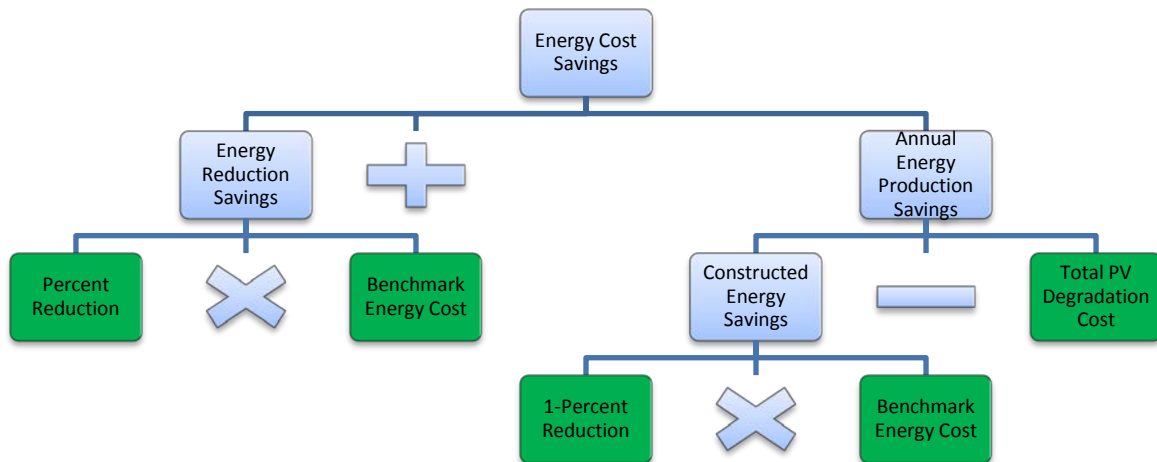


Figure 32 – Energy Savings Decomposition

Figure 33 depicts the decomposition of the PV System Replacement LCC element.

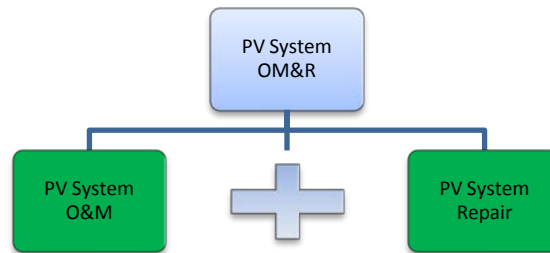


Figure 33 – OM&R Cost Decomposition

Table 20 summarizes the costs removed from the final model because they did not significantly contribute to NS.

Table 20 – Insubstantial Cost Elements

Element	Reason
PV Ready Cost	Some structural support cost, but most is design awareness
Panel Replacement Cost	25 year warranty matches service period of LCCA
Meter Replacement Cost	25-30 year life matches service period of LCCA
BOS Replacement Cost	Many are sunk costs, remainder are high life components
Panel SV	25-30 year life matches service period of LCCA
Meter SV	25-30 year life matches service period of LCCA
BOS SV	Sunk costs
PV System Disposal Cost	PV system will remain in place after study
PV System Repair Cost	Major components remain under warranty during study

Equation 20 is the resulting decomposed NZE equation.

$$\text{Energy Produced} = \text{Benchmark Energy Use} * (1 - \text{Percent Reduction}) \quad (20)$$

Equation 21 is the resulting decomposed and simplified version of the NS equation.

$$\begin{aligned}
 PW \left(-(\text{Construction Premium} * \text{Benchmark Cost} + \text{PV System Cost}) - \right. \\
 (\text{Inverter Replacement Cost}) + \left(\frac{\text{Study Period} - \text{Inv Useful Life}}{\text{Inv Useful Life}} * \right. \\
 \left. \text{Inverter Cost} \right) + (\text{Benchmark Energy Cost} - \\
 \left. \text{Total PV Degradation Cost}) - (\text{PV System O\&M Cost}) \right) \geq 0
 \end{aligned} \tag{21}$$

4.3. Engineering Economics

This section presents the results from the incorporation of engineering economic factors into the decomposed and simplified version of the net-savings (NS) equation. It also presents the calculated values for all economic factors utilized in the new equation. Equation 22 is the resulting NS equation with economic factor notation included.

$$\begin{aligned}
 & SPV_{d,stp} * \left(\frac{\text{Study Period} - \text{Inv Useful Life}}{\text{Inv Useful Life}} * \text{Inverter Installed Cost} \right) + \\
 & (UPV^e_{d,stp} - UPV^e_{d,pcp}) * (\text{Benchmark Energy Cost}) - APV_{d,sp} * SPV_{d,pcp} * \\
 & \quad ((1 - \text{Percent Reduction}) * \text{Benchmark Energy Cost} * \\
 & \quad \text{Arithmetic Degradation}) - (SPV_{d,pcp}) * (\text{Construction Premium} * \\
 & \quad \text{Benchmark Cost} + \text{PV System Cost}) - SPV_{d,InvLife} * SPV_{d,pcp} * \\
 & \quad (\text{Inverter Installed Cost}) - (UPV_{d,stp} - UPV_{d,pcp}) * \\
 & \quad (\text{PV System O\&M Cost}) \geq 0
 \end{aligned} \tag{22}$$

Table 21 presents the values for each non-energy economic factor. The APV factor was calculated using its formula, while all others were determined using tables.

Table 21 – Non-Energy Economic Factor Values

Factors	Value
$SPV_{d,stp}$	0.450
$APV_{d,sp}$	182.434
$SPV_{d,pcp}$	0.943
$SPV_{d,InvUL}$	0.642
$UPV_{d,stp}$	18.33
$UPV_{d,pcp}$	1.91

Table 22 presents the values for each energy economic factor. All factors were determined using tables.

Table 22 – Energy Economic Factor Values

Region	$UPV^e_{region,d,stp}$	$UPV^e_{region,d,pcp}$
1	17.05	1.80
2	17.31	1.88
3	18.40	1.88
4	17.24	1.91

4.4. Function Combination

This section presents the results from the function combination process. It also presents the net-savings (NS) equation after parametric estimation variables were incorporated and the two functions were combined using substitution. The resulting equation is the final model for the research. Finally, a variable dictionary is presented to define all variables in the final model.

Equation 23 represents the final cost-effective (CE) net-zero energy (NZE) model which will be utilized during the evaluation and analysis phases of this research.

$$\begin{aligned}
& SPV_{d,stp} * \left(\frac{sp-Inv\ UL}{Inv\ UL} * Unit\ Inv\ IC * \frac{Bench\ EUI[type,zone]*(1-Perc\ Red)*Area}{OSR[zip]} \right) + \\
& (UPV^e_{d,stp,region} - UPV^e_{d,pcp,region}) * (Bench\ EUI[type,zone] * Area * \\
& \quad Avg\ E\ Rate[state]) - APV_{d,sp} * SPV_{d,pcp} * \\
& ((1 - Perc\ Red) * Bench\ EUI[type,zone] * Area * Avg\ E\ Rate[state] * \\
& \quad PV\ Deg) - SPV_{d,pcp} * (Con\ Prem[type,zone] * Bench\ UC[type] * \\
& \quad Size\ Adj\ Factor * Loc\ Adj\ Factor[installation] * Esc\ Factor * Area * \\
& \quad ((1 + SIOH) * (1 + Contingency))^2 + Unit\ PV\ IC[size] * \\
& \quad \frac{Bench\ EUI[type,zone]*(1-Perc\ Red)*Area}{OSR[zip]} * (1 + SIOH) * (1 + Contingency)) - \\
& SPV_{d,Inv\ UL} * SPV_{d,pcp} * \left(Unit\ Inv\ IC * \frac{Bench\ EUI[type,zone]*(1-Perc\ Red)*Area}{OSR[zip]} \right) - \\
& \quad (UPV_{d,stp} - UPV_{d,pcp}) * \\
& \quad \left(Unit\ PV\ O\&M[size] * \frac{Bench\ EUI[type,zone]*(1-Perc\ Red)*Area}{OSR[zip]} \right) \geq 0
\end{aligned} \tag{23}$$

Table 23 on the next page is the variable dictionary for the CE NZE model.

Table 23 – CE NZE Model Dictionary

Variable	Description
d	Discount rate.
stp	Study period.
region	Census region for energy escalation rates.
pcp	Planning and construction period.
sp	Service period.
Inv UL	Useful economic life of inverter.
Unit Inv IC	Inverter installed cost per kilo-watt.
Bench EUI	Benchmark facility energy use per square foot.
Type	Facility type.
Zone	Building America climate zone of installation.
Perc Red	Percent energy reduction from benchmark facility.
Area	Total building floor area in square feet.
OSR	PV system AC power output per PV system rated size.
Zip	Zip code of installation.
Installation	Installation where building is located.
Avg E Rate	Average Electric Rate in dollars per kilo-watt-hr. Obtained as average of EIAs Commercial and Industrial rates.
State	State in which installation is located.
PV Deg	Annual percent loss of PV system power output.
Con Prem	Construction premium of energy efficiency improvements.
Bench UC	Cost of benchmark facility per square foot.
Size Adj Factor	Size adjustment for normalized facility cost.
Loc Adj Factor	Location adjustment of normalized facility cost.
Esc Factor	Adjustment factor to convert normalized facility cost to base-date price.
SIOH	Supervision, inspection, and overhead cost for design and construction agent.
Contingency	Safety factor for construction cost.
Unit PV IC	Unit installed PV system cost.
Unit PV O&M	Unit cost to operate and maintain PV system.
Size	Size category of PV system.
Econ Factors	Present worth factors.

4.5. Sensitivity Analysis

This section presents the results from the Sensitivity Analysis process. It also presents a relative sensitivity plot of all uncertain variables in the cost-effective (CE) net-zero energy (NZE) model. Finally, the ranking of independent variables in terms of the need for quality data is presented.

Figure 34 shows the relative sensitivity of the cost-effective (CE) net-zero energy (NZE) variables which are subject to uncertainty. As illustrated, the Cost-Effective (CE) Net-Zero Energy (NZE) model is extremely sensitive to variability in model input values. For example, an increase of one percent in the average electric rate results in an increase of over 16,000 dollars in net-savings (NS).

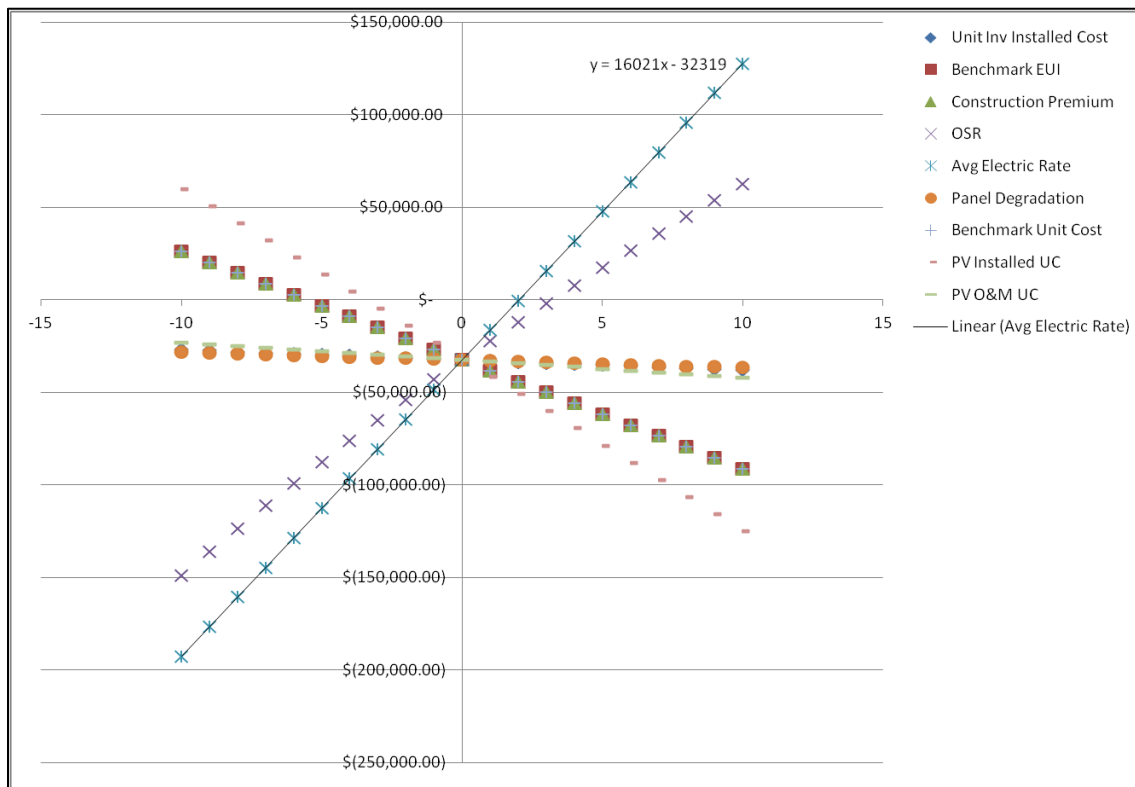


Figure 34 – Relative Sensitivity Plot

The model is most sensitive to the variability of inputs which impact the recurring benefit obtained by achieving NZE; this is because that variability is compounded over the 25 year study period. The most critical variable in terms of the need for quality data is the average electric rate; this intuitively makes sense as the savings obtained from the energy efficiency improvements and the installation of a PV system are subject to the electric rate. This is opposed to the impact of other variables which only reduce the savings from one of the above components.

One of the benefits of sensitivity analysis is that it provides justification for the expenditure of resources which are required to obtain higher quality data. Table 24 highlights two areas of concern for United States Air Force (USAF) Civil Engineer (CE) leadership in trying to predict the NS of a potential ZEB. They are the variables of Construction Premium and Benchmark Energy Use Intensity; both of which reduce NS by \$5,300 for every one percent increase in value.

Table 24 – Variable Sensitivity Rank

Variable	Slope	Direction	Rank
Average Electric Rate	\$ 16,020.69	Positive	1
OSR	\$ 9,619.60	Positive	2
PV Installed UC	\$ 8,327.68	Negative	3
Benchmark UC	\$ 5,291.58	Negative	4
Construction Premium	\$ 5,291.58	Negative	4
Benchmark EUI	\$ 5,291.58	Negative	4
PV O&M UC	\$ 948.01	Negative	7
Inverter Installed UC	\$ 556.10	Negative	8
Panel Degradation	\$ 419.73	Negative	9

The USAF CE community has not produced benchmark facilities in order to develop quality energy use baselines. The USAF also does not have an adequate

knowledge of the construction premiums required to reduce energy consumption in its facilities. The above concerns are not limited to NZE construction, as they are fundamental to managing a construction project in order to minimize energy use.

4.6. Construction Premium Comparative Analysis

This section presents the results from the construction premium comparative analysis. The construction premium curve interpolations are summarized and the resulting predictions for the data points obtained from the Energy Independence and Security Act (EISA) of 2009 study are presented. Finally, the scatter plot which is utilized to calculate the Pearson Correlation Coefficient is presented.

Table 25 summarizes the values of b for use in Equation 15 to predict construction premium given percent energy reduction from baseline.

Table 25 – Curve Interpolation Summary

Small Office		Medium Office		Small Hotel	
Zone	b	Zone	b	Zone	b
1_moist	19.80	1_moist	14.38	1_moist	8.49
1_dry	18.24	1_dry	14.38	1_dry	8.49
2_moist	22.19	2_moist	13.91	2_moist	9.14
2_dry	22.51	2_dry	14.30	2_dry	8.39
3_moist	20.44	3_moist	12.33	3_moist	9.24
3_dry	23.23	3_dry	11.93	3_dry	8.49
3_marine	23.49	3_marine	13.35	3_marine	8.93
4_moist	24.82	4_moist	14.07	4_moist	9.55
4_dry	26.48	4_dry	14.01	4_dry	8.78
4_marine	24.82	4_marine	13.55	4_marine	9.28
5_moist	22.29	5_moist	13.46	5_moist	10.09
5_dry	24.10	5_dry	13.77	5_dry	9.55
5_marine	23.14	5_marine	13.61	5_marine	9.81
6_moist	24.10	6_moist	14.15	6_moist	10.25
6_dry	24.10	6_dry	14.15	6_dry	9.97
7	21.60	7	16.21	7	10.53
8	19.28	8	15.37	8	10.65

Table 26 shows the predicted construction premium value for the Energy Independence and Security Act study data points.

Table 26 – Predicted Construction Premiums for EISA Data Points

Energy Facility Type	Zone	Predicted Construction Premium
Small Hotel	1_moist	0.051
Small Hotel	2_moist	0.047
Small Hotel	3_dry	0.083
Small Hotel	4_moist	0.049
Small Hotel	4_marine	0.057
Small Office	4_moist	0.015
Small Office	4_marine	0.015
Small Office	6_moist	0.014

Figure 35 shows the construction premiums from the EISA study on the y-axis and the predicted values on the x-axis.

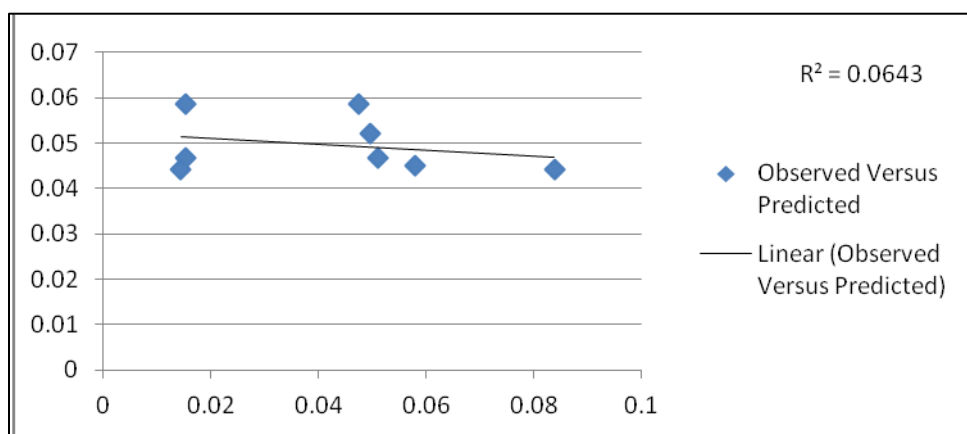


Figure 35 – Scatter Plot of Construction Premium

As shown in the figure, the coefficient of determination for the correlation analysis is 0.0643. This is interpreted as only 6.4 percent better than no relationship or alternatively that 6.4 percent of the variance in the construction premium for DoD facilities is explained by commercial facilities. The lack of correlation means, for the

facility types studied, that the commercial facility data from the Advanced Energy Design Guides cannot be used to estimate the construction premiums for DoD facilities; the lack of correlation matches the Army's EISA study conclusion that plug loads limit the energy reduction and increase the incremental construction cost for DoD facilities in relation to similar commercial facilities (Carpio & Soulek, 2011). As the construction premium for DoD facilities cannot be estimated, an assumption must be made, for subsequent analysis conducted by this research, that commercial facilities are constructed on United States Air Force (USAF) installations through the Military Construction Program. This assumption limits the applicability of specific model output values, but, as proven in Section 4.11, will not statistically impact the installation rankings.

4.7. Corroboration Analysis

This section presents the results from the corroboration of the construction premium and cost-effective (CE) net-zero energy (NZE) models. The scatter plot for the construction premium curves and the two scatter plots for the CE NZE model are presented. The corroboration of these models utilizes sources of information which were not used to construct them, thereby increasing their validity.

The corroboration of the Construction Premium Curves utilizes findings from a study of current Net-Zero Energy and NZE Capable facilities in the U.S., which was conducted by the New Buildings Institute (NBI). In this study, it was found that the typical Incremental Construction Cost due to energy efficiency improvements ranged from three to 10 percent (New Buildings Institute, 2012). For this incremental cost, these buildings were able to achieve an energy reduction of approximately 60 percent.

Although the baseline used in the NBI study was the Commercial Building Energy Consumption Survey database, the Energy Use Intensity values associated with this baseline are similar to those produced by complying with the ASHRAE 90.1 – 2004 baseline.

As shown in Figure 36, the construction premium curves match the above findings. The graph shows the incremental construction costs for small and medium office buildings to range from four to eight percent at 60 percent energy reduction. The incremental construction cost for small hotels is a bit higher at 11 percent; the increase for hotels is explained by occupant behavior and the difficulty of reducing point loads in this facility type (Carpio & Soulek, 2011).

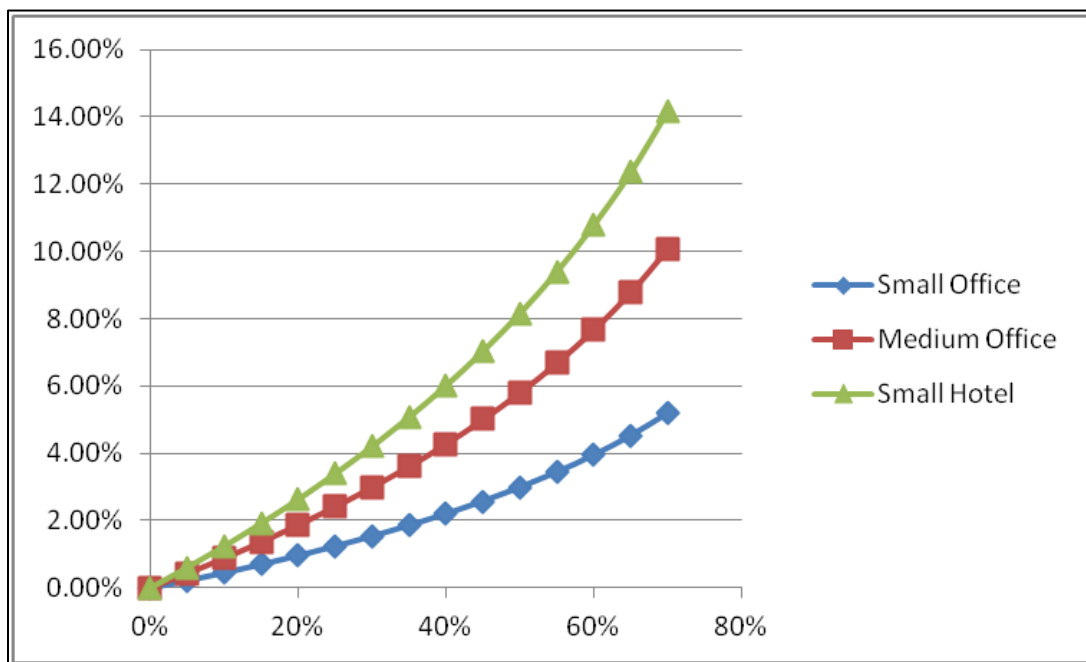


Figure 36 – Construction Premium Corroboration Plot

The corroboration of the CE NZE model will utilize the law of diminishing returns, the fact that the fundamental step necessary to create a Zero-Energy Building (ZEB) is to drastically reduce energy consumption, and a finding from the NBI study that the vast majority of NZE-facilities were small buildings. The law of diminishing returns dictates that cost savings will reduce with each incremental energy efficiency improvement (McIlvaine, et al., 1994).

First, as shown in Figure 37, the Net-Savings (NS) associated with energy reduction is an increasing function until an approximate 60 percent reduction, where it reaches a maximum and then decreases rapidly. This matches the understanding that each increment of energy efficiency improvement results in less savings. Second, the figure shows that the components of the NS model corroborate well with the fundamental approach to creating a ZEB.

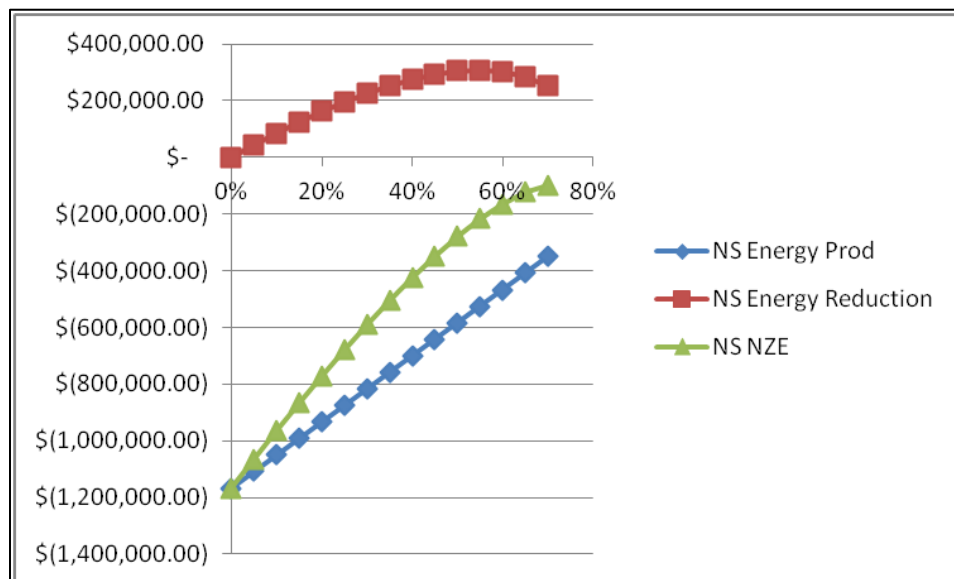


Figure 37 – NZE Model Corroboration Plot

As shown in the graph, the NS of energy efficiency improvements are always higher than the NS of on-site energy production through a Photovoltaic (PV) System. This relationship results in the maximum overall NS occurring beyond that of the NS of energy efficiency improvements alone; this is because, until deep energy reductions, the incremental cost to reduce energy remains lower than that to produce that same amount of energy. Also shown in the graph, the NS of the energy production component increases as the energy efficiency is improved. This occurs because the reduction of energy use allows for a smaller PV system to be installed.

The final corroboration is related to facility size. As shown in Figure 38, as the size of a facility is reduced, the associated NS increases. This is because, as the facility size is reduced, the associated energy demand decreases. A decrease in demand results in a smaller PV system being required. This corroborates well with the NBI study finding that most ZEBs are small administrative facilities. The results of corroboration analysis show that both the construction premium and CE NZE model behave as would be expected from best-available understanding of their respective underlying concepts.

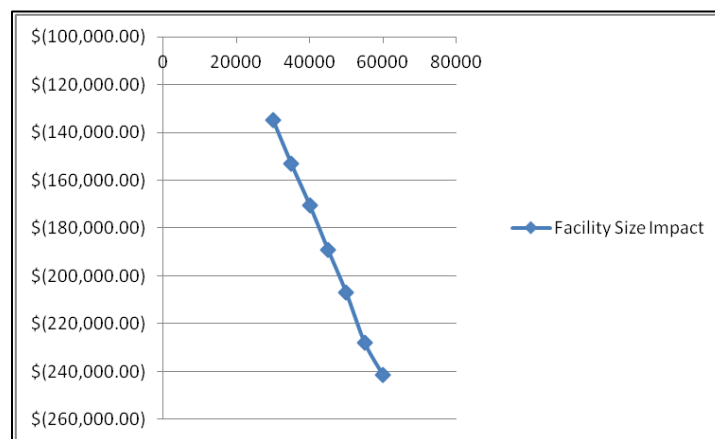


Figure 38 – Facility Size Corroboration Plot

4.8. Uncertainty Analysis

This section presents the results from the uncertainty analysis process. First, the plot of cumulative net-savings (NS) is presented to illustrate convergence around the mean NS value. Next, the histogram and cumulative distribution functions (CDF) of NS and Incremental Capital Investment (ICI) values are presented. The histograms are utilized to prove the distributions are Gaussian, while the CDFs are utilized to discuss variance. Finally, descriptive statistics for the NS and ICI distributions are presented.

Figure 39 presents the cumulative NS value after each of the 10,000 iterations included in the Monte Carlo simulation. This graph shows that NS converges around the mean value and is an indication that the Monte Carlo simulation was conducted properly.

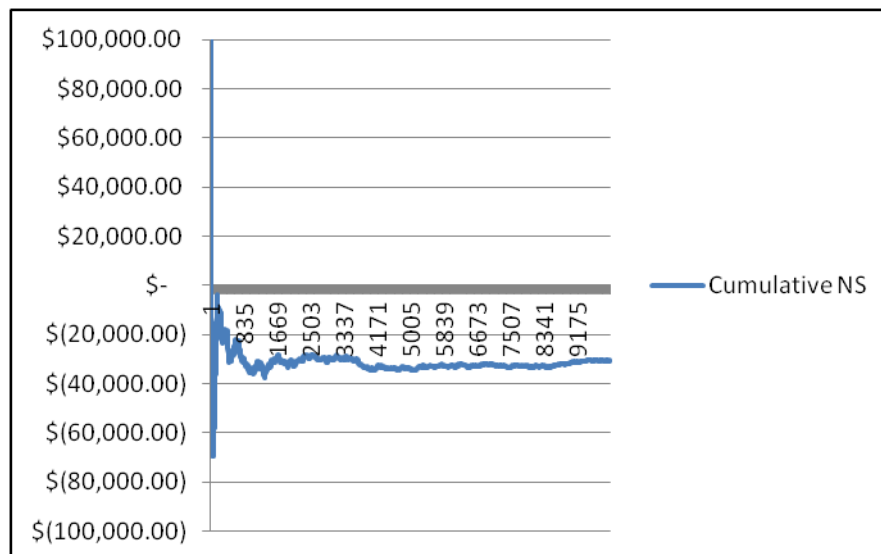


Figure 39 – Cumulative NS Plot

Figure 40 and 41 show the distributions of the NS and ICI values.

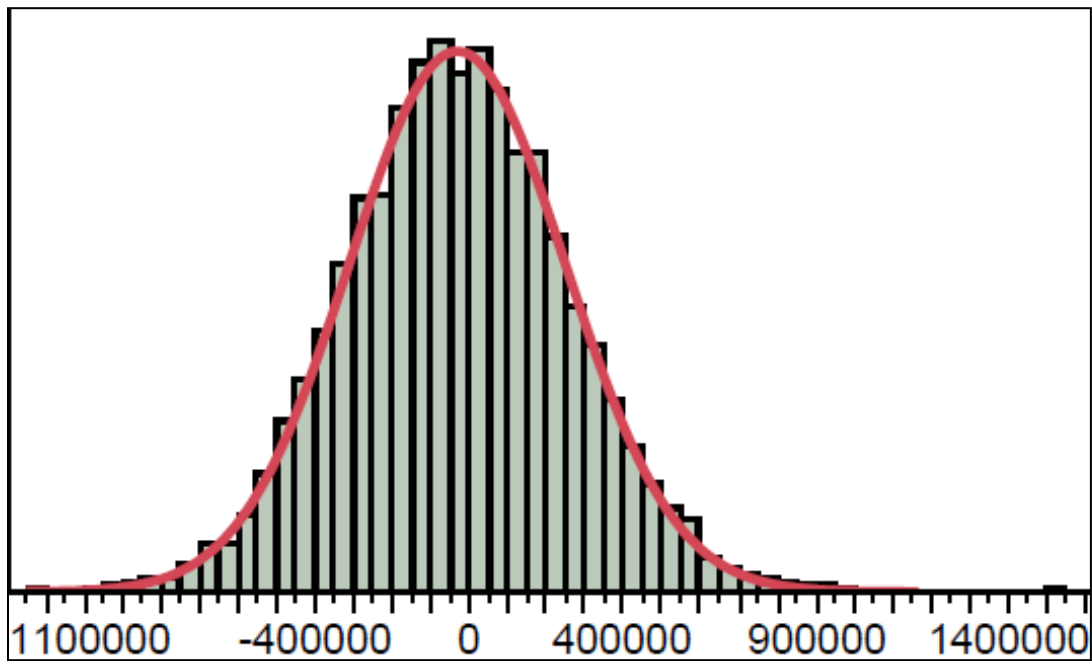


Figure 40 – NS Histogram Plot

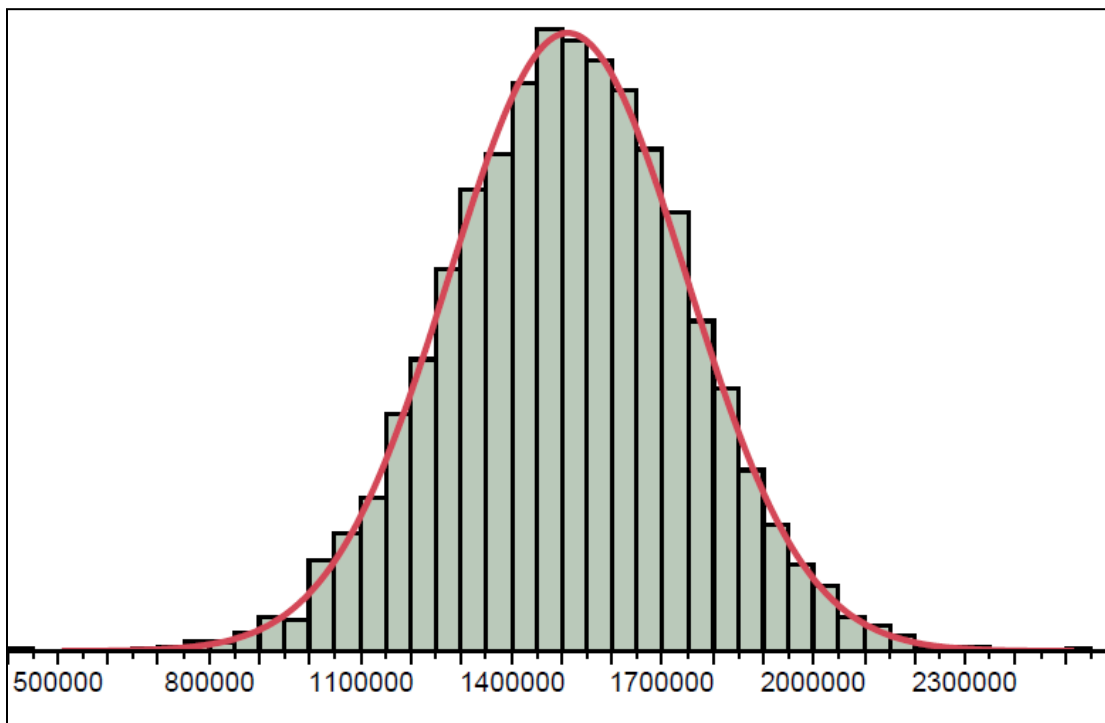


Figure 41 - ICI Histogram Plot

Figure 42 and 43 show the CDFs of the NS and ICI values.

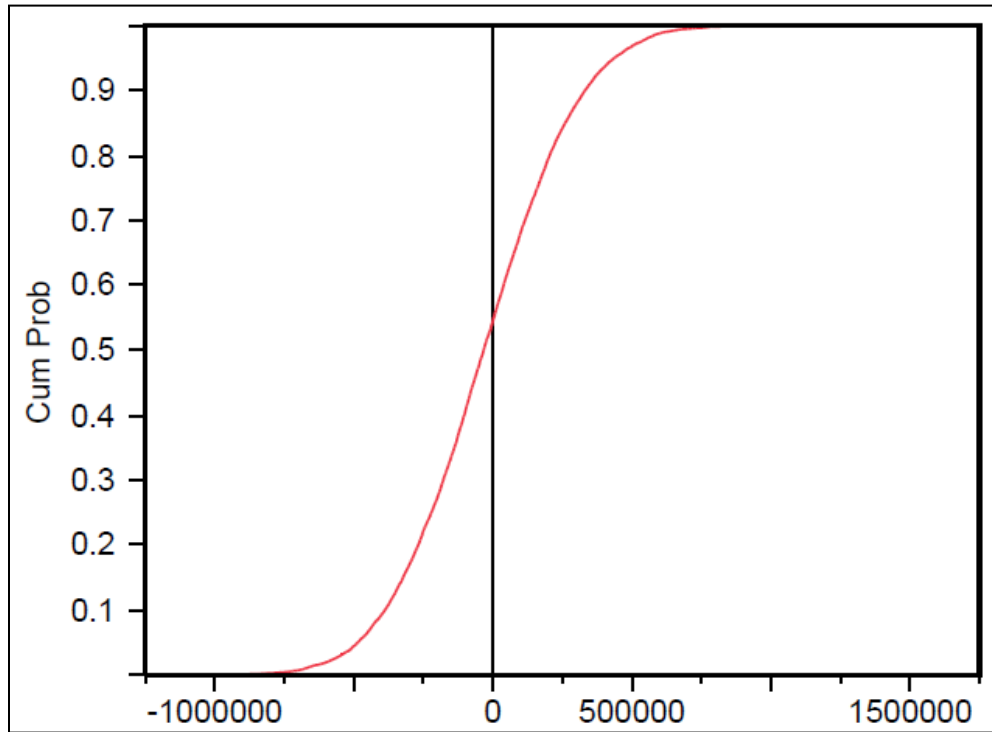


Figure 42 – NS CDF

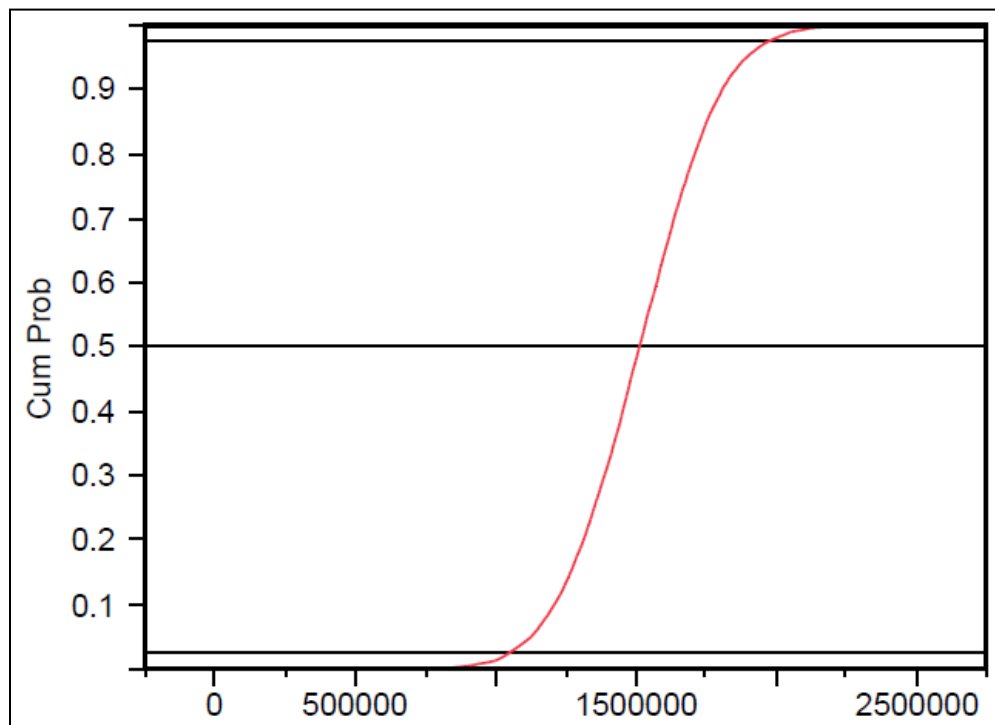


Figure 43 – ICI CDF

Table 27 presents the normality test and statistics describing the NS distribution.

Table 27 – NS Distribution Statistics

Attribute	Value
Normality p-value	0.15
Mean	\$ (35,279.40)
Median	\$ (37,053.24)
Standard Deviation	\$ 255,463.49
Minimum	\$ (1,026,372.34)
Maximum	\$ 1,515,180.41

Table 28 presents the normality test and statistics describing the ICI distribution.

Table 28 – ICI Distribution Statistics

Attribute	Value
Normality p-value	0.15
Mean	\$ 1,511,803.37
Median	\$ 1,512,581.89
Standard Deviation	\$ 235,468.29
Minimum	\$ (110,545.85)
Maximum	\$ 2,544,777.57
0.975 Quantile	\$ 1,972,520
0.025 Quantile	\$ 1,049,466

The histograms in Figure 40 and Figure 41 and the normality p-values described in Table 27 and Table 28 prove that both distributions are Gaussian. As illustrated by the CDF in Figure 42, only 46 percent of the distribution is cost-effective. This means that the CE NZE model does not have the accuracy required to predict if the specific project outlined in Table 17 will be cost-effective. Although the NS value is uncertain, the model does provide a more accurate ICI prediction.

As shown in Table 28, the model provides a Rough Order of Magnitude estimate for ICI. By subtracting the 0.975 and 0.025 quantiles from the CDF in Figure 43, an interval is determined which encompasses 95 percent of the values in the distribution. This interval, [\$1,972,520 \$1,049,466], equates to a 31 percent Margin of Error. This result is significant as it provides some justification for increasing the programmed cost and scope for projects which will attempt to achieve NZE.

The model's uncertainty regarding NS does not dictate that it cannot be utilized to produce significant results. When models contain considerable uncertainty, a comparison of output values holds more significance than the actual values themselves (Clevenger & Haymaker, 2006 ; Thornton et al., 2011).

4.9. Geospatial Analysis

As the geospatial analysis process merely produces results which were utilized by the PV Watts calculation and installation comparative analysis processes, results will not be discussed. A summary of all geospatial variables for each installation is presented in Appendix B.

4.10. PV Watts Calculation

As the PV Watts calculation process merely produces results which were utilized by the installation comparative analysis process, results will not be discussed. A summary of the ratio of alternating current power output to photovoltaic system size for each installation is presented in Appendix C.

4.11. Installation Comparative Analysis

This section presents the results from the Installation Comparative Analysis process. The analysis utilizes a *ceteris paribus* clause to study the effect of location on Net-Savings (NS). More simply stated, the analysis holds all values which are not geospatial constant, and then calculates the NS value for each installation. In effect, this section performs an analysis of alternatives to determine which installation will maximize the NS of a potential NZE facility. The raster files which illustrate the distribution of net-savings (NS) across the contiguous U.S. for each facility type are presented in Appendix C.

The ranking of the top 20 installations in terms NS is provided in Table 29. The complete list of NS by installation is provided in Appendix D.

Table 29 – Installation Cost-Effectiveness Ranking

Installation	Small Office		Medium Office		Small Hotel	
	NS	Rank	NS	Rank	NS	Rank
Edwards AFB	12,512	1	191,579	1	288,279	1
LA AFB	2,096	2	113,363	2	169,455	2
March ARB	-926	3	86,114	3	133,642	5
Los Alamitos RC	-1,699	4	66,180	6	119,180	8
Hamilton AFB	-2,533	5	83,184	4	153,194	3
Mill Valley AFS	-2,533	5	83,184	4	153,194	3
Travis AFB	-3,425	7	42,450	9	95,386	10
Almaden AFB	-4,402	8	65,833	7	129,461	6
Vandenberg AFB	-4,533	9	56,183	8	125,123	7
McClellan AFB	-6,660	10	18,511	11	59,184	13
Point Arena AFS	-7,132	11	40,493	10	94,798	11
Beale AFB	-10,649	12	-32,318	12	5,838	14
Hanscom AFB	-19,644	13	-72,624	13	95,964	9
Westover AFB	-22,366	14	-102,185	14	59,855	12
Stewart AGS	-25,052	15	-147,307	16	-11,401	16
New Boston AS	-25,709	16	-149,289	17	-7,356	15
McGuire AFB	-25,983	17	-129,321	15	-107,094	17
Davis-Monthan AFB	-31,810	18	-222,341	19	-362,378	26
Avon Park AA	-32,413	19	-191,907	18	-247,288	19
Macdill AFB	-35,247	20	-227,198	20	-284,128	21

This section performs a Level 1 feasibility assessment, which includes both technical and economic components. Because of this, the construction premium and associated percent reduction data were obtained from the technical support documents for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers' Advanced Energy Design Guides. Utilizing these data points ensures that the technical feasibility component is met, while allowing the assessment of economic feasibility.

As summarized in Table 19, there are seven variables in the Cost-Effective (CE) Net-Zero Energy (NZE) model which are dependent on location. The output of the model is dependent upon the specific combination of the seven geospatial variable values for each installation. The raster files provided in Appendix C graphically illustrate the influence of location on the value of NS. As can be seen, the most cost-effective locations for NZE facilities are in the South West, South East, and North East U.S. This result matches what was learned from the sensitivity analysis provided in Section 4.5, as these locations generally have good solar resource and a relatively high cost of electricity.

Another important conclusion can be made by conducting a comparative analysis between facility types. As seen in the rasters mentioned above, the gradients between the three facility types remain relatively constant. A more analytical approach to portraying this relationship is to convert the interval level data from the CE NZE model into ordinal level data, and then to compare that order between facility types. Table 30 presents the results of the Spearman's rank correlation analysis. As there are 140 installations for each correlation analysis, the Central Limit Theorem states that the test statistic for each correlation is normally distributed. As such, the Student's t-distribution can be utilized to determine the observed significance level of the correlations. As shown in the table, all p-values for the rank correlations are essentially equal to zero. These values are well below our burden of proof, which for this research is 0.05; therefore, we can state that there is an extremely strong, direct, and significant rank correlation of installations between facility types. This is an important finding as it allows the results from this installation comparative analysis to be applicable to other facility types, including those of DoD and USAF facilities.

Table 30 – Rank Correlation

Attribute	SO-MO Rank	SO-SH Rank	MO-SH Rank
Difference Squared	11346	12788	12584
r_s	0.975189696	0.972036474	0.972482561
Test Statistic	51.74974343	48.62601373	49.03551868
P-value	1.471E-92	5.085E-89	1.702E-89

V. Conclusions and Recommendations

This chapter presents the conclusions from this research. The significance of the research is discussed along with specific actions regarding how to implement the research's findings. Finally, future research is identified to strengthen the model's results and to address the lack of data for United States Air Force (USAF) facilities.

5.1. Significance of Research

This research has justified the incorporation of varying levels of feasibility assessments into the early stages of the current United States Air Force (USAF) Military Construction Procurement Process. This allows for an adjustment to the cost and scope of a potential Net-Zero Energy project, prior to the stage where funds are appropriated from Congress. The Level 1 feasibility assessment performed during this research narrows the required follow-on feasibility assessments to the installations which will maximize the chance of obtaining a cost-effective (CE) Zero Energy Building (ZEB). Although the research did not utilize USAF facility types to calculate net-saving (NS), it has proven that there is an extremely large and direct rank correlation between facility types. This correlation allows for the installation ranking by NS to be applied to other facility types, including those of USAF facilities. The findings of this research will save the USAF time and money by limiting the quantity of follow-on feasibility assessments. This research also provides a framework for future Level 1 feasibility assessments through the use of model building, geospatial analysis, and comparative analysis. Finally, it provides a strategy to comply with federal facility energy policy.

5.2. Recommendations for Action

This project clearly highlights a need for the United States Air Force (USAF) to better understand both the *benchmark energy use* and *cost premium to reduce the energy use* of its facilities. In regard to benchmark energy use, it is recommended that the USAF establish representative code compliant benchmarks for key facility types. These benchmarks should follow the methodologies of previously completed work by the Department of Energy (DOE) and the U.S. Army Corps of Engineers (USACE). The benchmark energy use should be categorized by Building America climate zones in order to capture the effects of climate on energy use. These benchmarks should be utilized to set the energy efficiency targets for future construction projects.

In regard to construction premiums associated with energy efficiency improvements, it is recommended that the USAF establish advanced energy design guides for key facility types. Again, the design guides should follow the methodologies of previously completed work by the DOE and USACE. These guides should be prescriptive and set standards for conducting and reporting energy simulations, including realistic internal load assumptions. Supporting documentation should be created which documents the construction premium associated with meeting the energy reductions prescribed by the design guides.

This research indicates that the USAF does not always strictly follow the guiding principles for high performance and sustainable facilities, which are required by the Energy Policy ACT of 2005. These guiding principles are foundational to the construction of low-energy facilities, the most important of which are the use of an

integrated systems engineering approach and the incorporation of facility commissioning into contract requirements. Another principle the USAF should investigate is the use of performance-based contracting. This type of contracting method encourages innovative solutions and incentivizes contractors to exceed project goals related to cost, schedule, and energy performance. As illustrated by the case-study of the Department of Energy's Research Support Facility, a great project team combined with performance-based contracting can produce a facility with drastic energy use reduction and a minimal incremental cost (Department of Energy, 2011).

This research project advocates for an adjustment to current USAF strategy related to meeting federal energy policy through the Military Construction Program. It is recommended that all future facilities be designed and constructed to drastically reduce energy use, with a goal of at least 50 percent reduction. As was shown by this research, specifically in Figure 37, these reductions are always cost-effective when assessed utilizing this project's economic assumptions. If the facility being constructed cannot achieve cost-effective NZE, as demonstrated by feasibility assessments, it should be constructed Photovoltaic (PV) Ready. This will minimize the capital investment necessary to install the PV system when it is determined cost-effective to do so. This approach is further validated in the wording of Executive Order 13514, which states that new construction must be designed after 2020 to achieve NZE by 2030.

5.3. Recommendations for Future Research

There are several assumptions and limitations of this research which could be addressed by follow-on efforts. First, expert opinion could be utilized to develop

quantifiable soft-benefits for obtaining a Zero-Energy Building (ZEB) and net-zero installations. Soft-benefits are those not directly associated with utility bill reductions, such as energy security and independence. Second, investigate the other strategies to meet EO 13514, namely off-base green power purchase agreements and on-base renewable energy farms. Any assessment of the cost-effectiveness of these strategies should address the soft-benefit reduction from a reduction in energy security and independence. Third, energy efficiency and renewable energy technology rebates and incentives should be incorporated into the cost-effective (CE) net-zero energy (NZE) model. These will result in an increase in net-savings (NS) and may produce a change in installation ranking.

This research has limited the number of necessary follow-on feasibility assessments to the most likely installations to achieve a CE ZEB. More detailed assessments are required at these installations to more accurately estimate the life-cycle savings of the potential ZEB. These assessments should be closely monitored and controlled to ensure they follow proven methodologies and utilize facility benchmarks. As indicated by the NZE feasibility assessment of a Dormitory at Keesler AFB, wildly conflicting results are produced when these assessments are not managed to accurate benchmarks (TranSystems Corporation, 2011).

The final recommendations for follow-on research address two of the recommendations for action described in Section 5.7. There is a critical need to develop benchmark buildings for key United States Air Force (USAF) facility types in order to determine a legitimate baseline energy use. This baseline should be the foundation for measuring improvements in building energy efficiency and also serve as the foundation

for the creation of Advanced Energy Design Guides. These guides should provide a prescriptive path to obtaining deep energy savings from the established baseline for key facility types. Both of the above efforts should follow established methodologies developed by the Department of Energy and Army Corps of Engineers.

Appendix A

This appendix presents graphical representations of the three phases of this research's approach.

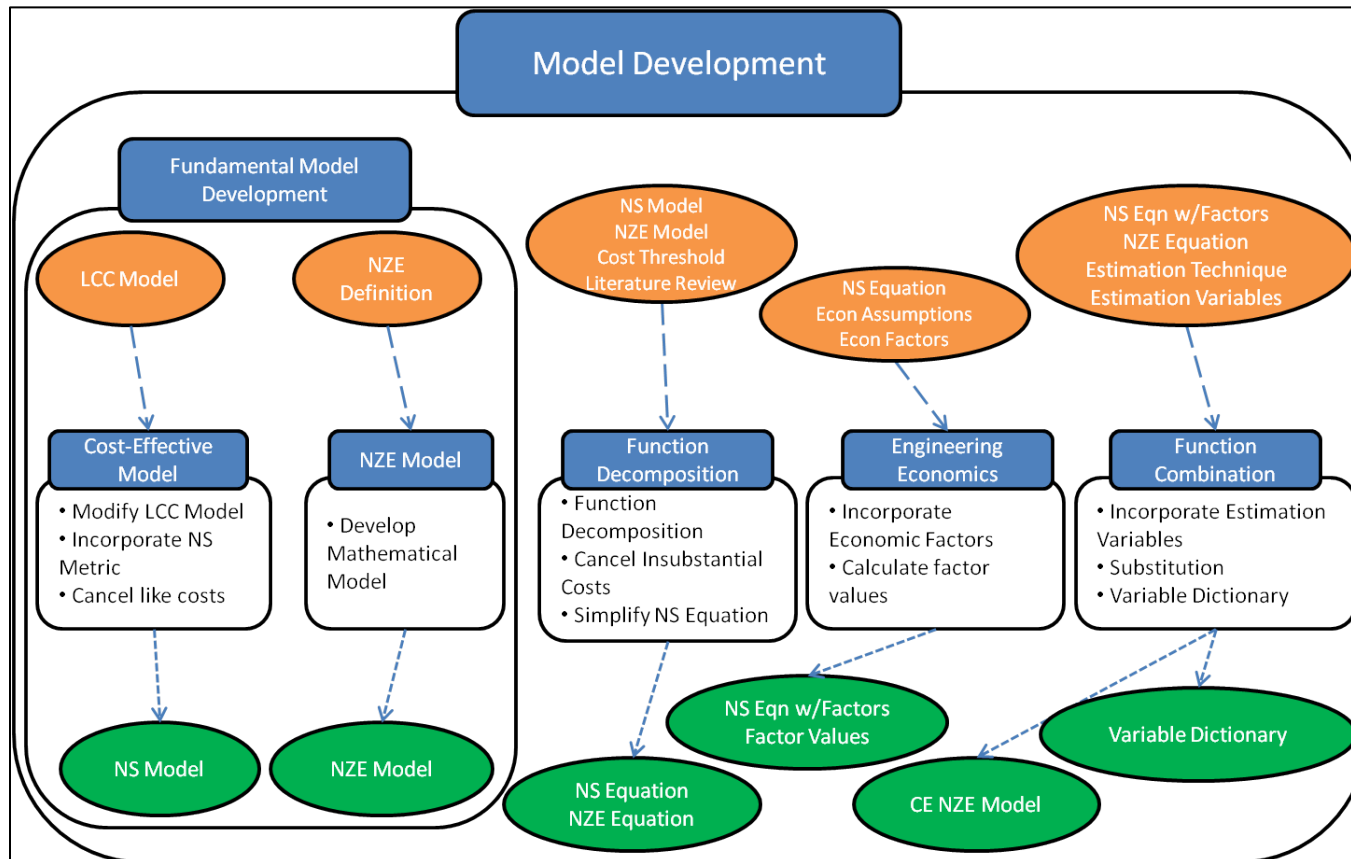


Figure 44 – Model Development Phase

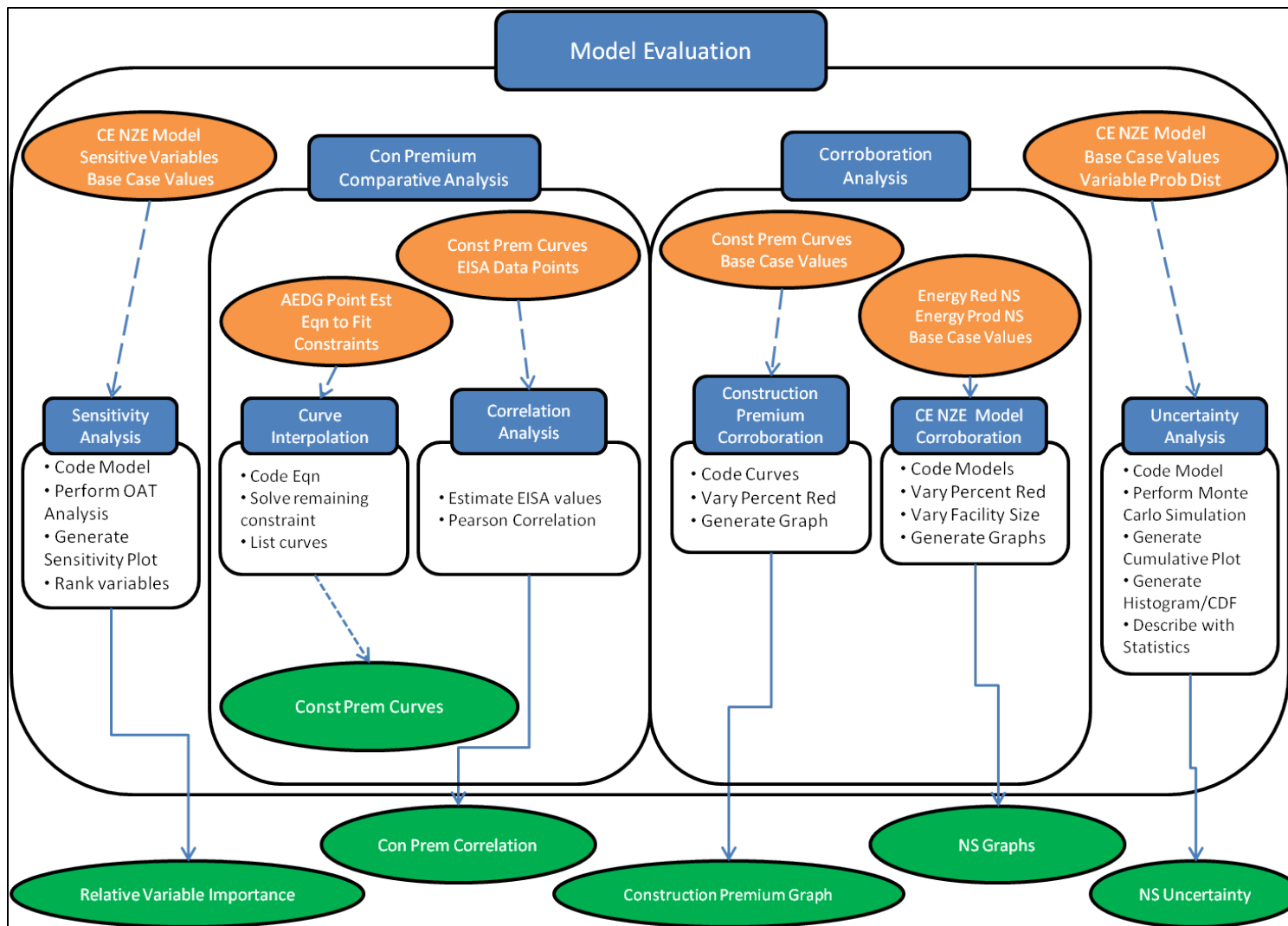


Figure 45 – Model Evaluation Phase

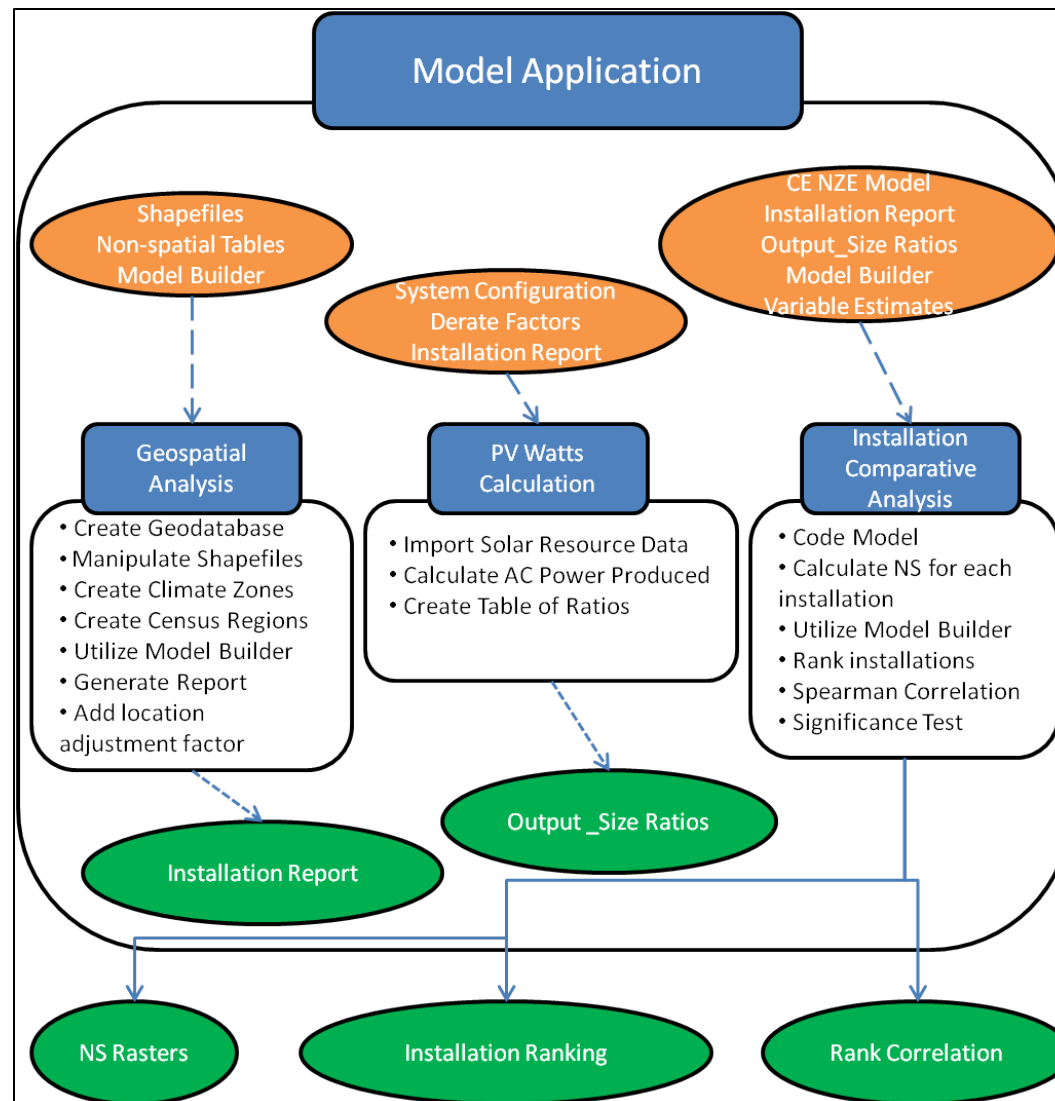


Figure 46 – Model Application Phase

Appendix B

This appendix presents the values obtained for each installation during the geospatial analysis process.

Table 31 – Geospatial Values by Installation

Installation	County	State	Zone	Region	Zip Code	Area Cost Factor	Unique ID
Air Force Dare County Bombing Range	Dare	North Carolina	3_moist	3	27953	0.84	72
Almaden AFB	Santa Clara	California	3_marine	4	95120	1.21	40
Altus AFB	Jackson	Oklahoma	3_moist	3	73521	0.96	34
Andrews AFB	Prince George's	Maryland	4_moist	3	20762	1.03	118
Arnold AFB	Coffee	Tennessee	4_moist	3	37355	0.92	61
Avon Park Auxiliary Airfield	Polk	Florida	2_moist	3	33898	0.84	48
Barksdale AFB	Bossier	Louisiana	3_moist	3	71110	0.81	56
Beale AFB	Yuba	California	3_dry	4	95903	1.28	85
Benton Air Force Sta	Sullivan	Pennsylvania	5_moist	1	17814	1.07	126
Boise Air Terminal Air Guard Sta	Ada	Idaho	5_dry	4	83705	0.93	93
Brooks AFB	Bexar	Texas	2_moist	3	78235	0.81	4
Buckley AFB	Arapahoe	Colorado	5_dry	4	80011	1.02	87
Cannon AFB	Curry	New Mexico	4_dry	4	88103	1.03	32

Cavalier Air Force Sta	Pembina	North Dakota	7	2	58220	1.06	104
Chanute AFB	Champaign	Illinois	5_moist	2	61866	1.21	112
Charleston AFB	Charleston	South Carolina	3_moist	3	29404	0.9	65
Chocolate Mountains Gunnery Range	Imperial	California	2_dry	4	92257	1.21	21
Claiborne Range	Rapides	Louisiana	2_moist	3	71424	0.86	52
Columbus AFB	Lowndes	Mississippi	3_moist	3	39705	0.87	58
Cp Dawson Air Force Reserve Center	Preston	West Virginia	5_moist	3	26764	0.99	120
Cp Perry Air National Guard Sta	Ottawa	Ohio	5_moist	2	43452	0.89	128
Creech AFB	Clark	Nevada	3_dry	4	89018	1.26	39
Davis- Monthan AFB	Pima	Arizona	2_dry	4	85730	1.02	11
Dixie Target Range	McMullen	Texas	2_moist	3	78072	0.81	2
Dobbins Air Reserve Base	Cobb	Georgia	3_moist	3	30060	0.84	59
Dover AFB	Kent	Delaware	4_moist	3	19901	1.09	119
Dyess AFB	Taylor	Texas	3_dry	3	79607	0.91	12
Dyess Air Force Base (Hermleigh Emitter Site)	Fisher	Texas	3_dry	3	79526	0.91	13
Dyess Air Force Base (Lake Thomas Emitter Site)	Borden	Texas	3_dry	3	79527	0.91	14
Dyess Air Force Base (Nine Point Mesa Emitter Site)	Brewster	Texas	3_dry	3	79830	0.91	8

Dyess Air Force Base (Snyder Winston Field Electronic Scoring Site)	Scurry	Texas	3_dry	3	79549	0.91	15
Dyess Air Force Base (Union Emitter Site)	Scurry	Texas	3_dry	3	79549	0.91	16
Edwards AFB	Kern	California	3_dry	4	93523	1.29	36
Ellington Fld	Harris	Texas	2_moist	3	77034	0.81	41
Ellsworth AFB	Meade	South Dakota	6_moist	2	57706	1	94
Ellsworth Air Force Base (Antelope Butte Mini Mute Radar Bomb Scoring Site)	Butte	South Dakota	6_moist	2	57717	1	97
Ellsworth Air Force Base (Belle Fourche Radar Bomb Scoring Site)	Butte	South Dakota	6_moist	2	57717	1	96
Ellsworth Air Force Base (Conner Radar Bomb Scoring Site)	Butte	South Dakota	6_moist	2	57717	1	98
Ellsworth Air Force Base (Horman Radar Bomb Scoring Site)	Butte	South Dakota	6_moist	2	57717	1	95
Escondido McMullen Range	McMullen	Texas	2_moist	3	78072	0.81	1
F E Warren AFB	Laramie	Wyoming	6_dry	4	82001	1.09	90
Fairchild AFB	Spokane	Washington	5_dry	4	99011	1.01	102

Finland Air Force Sta	Lake	Minnesota	7	2	55603	1.1	138
General Mitchell Air Reserve Sta	Milwaukee	Wisconsin	6_moist	2	53207	1.05	117
Goodfellow AFB	Tom Green	Texas	3_dry	3	76908	0.84	9
Grand Forks AFB	Grand Forks	North Dakota	7	2	58204	0.96	139
Grissom AFB	Miami	Indiana	5_moist	2	46970	1	113
Gulfport-Biloxi Regional Airport Air National Guard	Harrison	Mississippi	2_moist	3	39507	0.89	45
Hamilton AFB	Marin	California	3_marine	4	94949	1.21	77
Hanscom AFB	Middlesex	Massachusetts	5_moist	1	01731	1.18	131
Havre Air Force Sta	Hill	Montana	6_dry	4	59501	1.11	106
Hill AFB	Davis	Utah	5_dry	4	84056	1.06	89
Hill Air Force Base (Little Mountain Test Facility)	Weber	Utah	5_dry	4	84404	1.06	91
Homestead Air Reserve Base	Miami-Dade	Florida	1_moist	3	33033	0.88	47
Hurlburt Fld	Okaloosa	Florida	2_moist	3	32544	0.84	46
Inkey Barley Range	Imperial	California	2_dry	4	92250	1.21	18
Jackson Barracks Air National Guard Sta	Orleans	Louisiana	2_moist	3	70117	0.86	42
Keesler AFB	Harrison	Mississippi	2_moist	3	39534	0.89	44
Kitty Baggage Range	Imperial	California	2_dry	4	92250	1.21	20
Lackland AFB	Bexar	Texas	2_moist	3	78227	0.85	6
Langley AFB	Hampton	Virginia	4_moist	3	23665	0.94	74

Langley Air Force Base (Bethel Manor Housing Area)	York	Virginia	4_moist	3	23665	0.94	75
Laughlin AFB	Val Verde	Texas	2_dry	3	78843	0.89	5
Little Rock AFB	Pulaski	Arkansas	3_moist	3	72076	0.86	60
Loom Lobby Range	Imperial	California	2_dry	4	92004	1.21	17
Los Alamitos Reserve Center and Air Sta	Orange	California	3_dry	4	90720	1.21	25
Los Angeles Air Force Base (Area A)	Los Angeles	California	3_dry	4	90250	1.15	28
Los Angeles Air Force Base (Area B)	Los Angeles	California	3_dry	4	90245	1.15	29
Los Angeles Air Force Base (Area C)	Los Angeles	California	3_dry	4	90260	1.15	27
Los Angeles Air Force Base (Fort Macarthur Housing Area)	Los Angeles	California	3_dry	4	90731	1.15	23
Los Angeles Air Force Base (Pacific Crest Housing Area)	Los Angeles	California	3_dry	4	90732	1.15	24
Los Angeles Air Force Base (Sun Valley)	Los Angeles	California	3_dry	4	91352	1.15	30
Luke AFB	Maricopa	Arizona	2_dry	4	85309	1.02	22
Macdill AFB	Hillsborough	Florida	2_moist	3	33621	0.93	49
Malmstrom AFB	Cascade	Montana	6_dry	4	59405	1.13	101
March Air Reserve Base	Riverside	California	3_dry	4	92518	1.14	26

Marietta Air Force Sta	Lancaster	Pennsylvania	5_moist	1	17547	1.07	123
Maxwell AFB	Montgomery	Alabama	3_moist	3	36113	0.82	54
Maxwell Air Force Base (Family Housing Annex)	Montgomery	Alabama	3_moist	3	36108	0.82	53
Maxwell Air Force Base (Gunter Annex)	Montgomery	Alabama	3_moist	3	36115	0.82	55
McChord AFB	Pierce	Washington	4_marine	4	98438	1.13	100
McClellan AFB	Sacramento	California	3_dry	4	95652	1.21	79
McConnell AFB	Sedgwick	Kansas	4_moist	2	67210	0.96	107
McEntire Air Guard Sta	Richland	South Carolina	3_moist	3	29044	0.86	67
McGuire AFB	Burlington	New Jersey	4_moist	1	08641	1.22	122
Melrose Range	Roosevelt	New Mexico	4_dry	4	88118	0.95	31
Mill Valley Air Force Sta	Marin	California	3_marine	4	94930	1.21	76
Minneapolis-St Paul International Airport Air Reserve Sta	Hennepin	Minnesota	6_moist	2	55450	1.12	137
Minot AFB	Ward	North Dakota	7	2	58704	1.16	103
Moody AFB	Lanier	Georgia	2_moist	3	31641	0.81	51
Mountain Home AFB	Elmore	Idaho	5_dry	4	83648	1	92
Navy Dare County Range	Dare	North Carolina	3_moist	3	27953	0.84	73
Nellis AFB	Clark	Nevada	3_dry	4	89115	1.22	37
New Boston Air Sta	Hillsborough	New Hampshire	5_moist	1	03070	1.09	133
Niagara Falls International	Niagara	New York	5_moist	1	14304	1.1	134

Airport Air Reserve Sta							
Offutt AFB	Sarpy	Nebraska	5_moist	2	68113	0.98	114
Offutt Air Force Base (Capehart Housing Area)	Sarpy	Nebraska	5_moist	2	68123	0.98	116
Offutt Air Force Base (Housing Area and Golf Course)	Sarpy	Nebraska	5_moist	2	68123	0.98	115
Opheim Air Force Sta	Valley	Montana	6_dry	4	59250	1.11	105
Patrick AFB	Brevard	Florida	2_moist	3	32925	0.84	50
Peterson AFB	El Paso	Colorado	5_dry	4	80914	1.07	82
Pittsburgh Airport Air Reserve Sta	Allegheny	Pennsylvania	5_moist	1	15108	1	124
Point Arena Air Force Sta	Mendocino	California	3_marine	4	95468	1.21	83
Point of Marsh Target Airfield	Carteret	North Carolina	3_moist	3	28516	0.84	69
Pope AFB	Cumberland	North Carolina	3_moist	3	28308	0.9	70
Portland Air Guard Sta	Multnomah	Oregon	4_marine	4	97218	1.04	99
Quonset Air Guard Base	Washington	Rhode Island	5_moist	1	02852	1.08	129
Randolph AFB	Bexar	Texas	2_moist	3	78148	0.85	7
Reno Tahoe International Airport	Washoe	Nevada	5_dry	4	89502	1.21	86
Rickenbacker International Airport	Franklin	Ohio	5_moist	2	43217	0.89	121
Robins AFB	Houston	Georgia	3_moist	3	31098	0.87	64
Schriever AFB	El Paso	Colorado	5_dry	4	80930	1.07	81

Scott AFB	St. Clair	Illinois	4_moist	2	62225	1.11	108
Searay Target Range Complex	Noxubee	Mississippi	3_moist	3	39341	0.88	57
Selfridge Air National Guard Base	Macomb	Michigan	5_moist	2	48045	1.12	132
Seymour Johnson AFB	Wayne	North Carolina	3_moist	3	27531	0.8	71
Shade Tree Range	Imperial	California	2_dry	4	92251	1.21	19
Shaw AFB	Sumter	South Carolina	3_moist	3	29152	0.87	68
Shaw AFB (Poinsett Range)	Sumter	South Carolina	3_moist	3	29125	0.87	66
Smoky Hill Range	Saline	Kansas	4_moist	2	67425	0.93	80
Springfield-Beckley Air Guard Sta	Clark	Ohio	5_moist	2	45502	0.89	111
Stewart Air Guard Sta	Orange	New York	5_moist	1	12550	1.05	127
Tinker AFB	Oklahoma	Oklahoma	3_moist	3	73145	0.91	62
Townsend Air-To-Ground Range	McIntosh	Georgia	2_moist	3	31331	0.84	63
Training Site Ethan Allen Range	Chittenden	Vermont	6_moist	1	05465	0.91	140
Travis AFB	Solano	California	3_dry	4	94585	1.25	78
Tucson International Airport Air Guard Sta	Pima	Arizona	2_dry	4	85706	0.98	10
Tyndall AFB	Bay	Florida	2_moist	3	32403	0.81	43
U.S. Air Force Academy	El Paso	Colorado	5_dry	4	80840	1.07	84
U.S. Air Force Plant 42	Los Angeles	California	3_dry	4	93550	1.21	33

Utah Air National Guard	Salt Lake	Utah	5_dry	4	84116	1	88
Vance AFB	Garfield	Oklahoma	3_moist	3	73703	0.94	38
Vandenberg AFB	Santa Barbara	California	3_marine	4	93437	1.26	35
Volk Field Air National Guard Base	Juneau	Wisconsin	6_moist	2	54618	1.05	135
Volk Field Air National Guard Base (Hardwood Range)	Juneau	Wisconsin	6_moist	2	54646	1.05	136
Westover AFB	Hampden	Massachusetts	5_moist	1	01022	1.16	130
Whiteman AFB	Johnson	Missouri	4_moist	2	65305	1.1	109
Wright-Patterson AFB	Greene	Ohio	5_moist	2	45433	0.87	110
Yankee Target Range	McMullen	Texas	2_moist	3	78072	0.81	3
Youngstown-Warren Air Reserve Sta	Trumbull	Ohio	5_moist	2	44473	0.9	125

Appendix C

This appendix presents the output to photovoltaic system size ratios calculated for each installation.

Table 32 – Output to Size Ratios by Installation

Installation	Zip Code	Default OSR (kW_r/kW)
Air Force Dare County Bombing Range	27953	1335
Almaden AFB	95120	1442
Altus AFB	73521	1457
Andrews AFB	20762	1206
Arnold AFB	37355	1273
Avon Park Auxiliary Airfield	33898	1362
Barksdale AFB	71110	1283
Beale AFB	95903	1374
Benton Air Force Sta	17814	1186
Boise Air Terminal Air Guard Sta	83705	1365
Brooks AFB	78235	1380
Buckley AFB	80011	1459
Cannon AFB	88103	1580
Cavalier Air Force Sta	58220	1215
Chanute AFB	61866	1245
Charleston AFB	29404	1336
Chocolate Mountains Gunnery Range	92257	1565
Claiborne Range	71424	1294
Columbus AFB	39705	1265
Cp Dawson Air Force Reserve Center	26764	1099
Cp Perry Air National Guard Sta	43452	1152
Creech AFB	89018	1602

Davis- Monthan AFB	85730	1663
Dixie Target Range	78072	1253
Dobbins Air Reserve Base	30060	1345
Dover AFB	19901	1226
Dyess AFB	79607	1493
Dyess Air Force Base (Hermleigh Emitter Site)	79526	1563
Dyess Air Force Base (Lake Thomas Emitter Site)	79527	1564
Dyess Air Force Base (Nine Point Mesa Emitter Site)	79830	1634
Dyess Air Force Base (Snyder Winston Field Electronic Scoring Site)	79549	1563
Dyess Air Force Base (Union Emitter Site)	79549	1563
Edwards AFB	93523	1732
Ellington Fld	77034	1220
Ellsworth AFB	57706	1408
Ellsworth Air Force Base (Antelope Butte Mini Mute Radar Bomb Scoring Site)	57717	1408
Ellsworth Air Force Base (Belle Fourche Radar Bomb Scoring Site)	57717	1408
Ellsworth Air Force Base (Conner Radar Bomb Scoring Site)	57717	1408
Ellsworth Air Force Base (Horman Radar Bomb Scoring Site)	57717	1408
Escondido McMullen Range	78072	1396
F E Warren AFB	82001	1459
Fairchild AFB	99011	1181
Finland Air Force Sta	55603	1222
General Mitchell Air Reserve Sta	53207	1227
Goodfellow AFB	76908	1463
Grand Forks AFB	58204	1245
Grissom AFB	46970	1166
Gulfport-Biloxi Regional Airport Air National Guard	39507	1214
Hamilton AFB	94949	1473
Hanscom AFB	01731	1148

Havre Air Force Sta	59501	1275
Hill AFB	84056	1399
Hill Air Force Base (Little Mountain Test Facility)	84404	1399
Homestead Air Reserve Base	33033	1339
Hurlburt Fld	32544	1265
Inkey Barley Range	92250	1549
Jackson Barracks Air National Guard Sta	70117	1277
Keesler AFB	39534	1240
Kitty Baggage Range	92250	1549
Lackland AFB	78227	1378
Langley AFB	23665	1244
Langley Air Force Base (Bethel Manor Housing Area)	23665	1244
Laughlin AFB	78843	1482
Little Rock AFB	72076	1297
Loom Lobby Range	92004	1498
Los Alamitos Reserve Center and Air Sta	90720	1467
Los Angeles Air Force Base (Area A)	90250	1467
Los Angeles Air Force Base (Area B)	90245	1467
Los Angeles Air Force Base (Area C)	90260	1467
Los Angeles Air Force Base (Fort Macarthur Housing Area)	90731	1467
Los Angeles Air Force Base (Pacific Crest Housing Area)	90732	1467
Los Angeles Air Force Base (Sun Valley)	91352	1497
Luke AFB	85309	1546
Macdill AFB	33621	1364
Malmstrom AFB	59405	1309
March Air Reserve Base	92518	1449
Marietta Air Force Sta	17547	1168
Maxwell AFB	36113	1301
Maxwell Air Force Base (Family Housing Annex)	36108	1301
Maxwell Air Force Base (Gunter Annex)	36115	1301
McChord AFB	98438	943
McClellan AFB	95652	1399

McConnell AFB	67210	1385
McEntire Air Guard Sta	29044	1310
McGuire AFB	08641	1179
Melrose Range	88118	1526
Mill Valley Air Force Sta	94930	1473
Minneapolis-St Paul International Airport Air Reserve Sta	55450	1224
Minot AFB	58704	1321
Moody AFB	31641	1285
Mountain Home AFB	83648	1365
Navy Dare County Range	27953	1324
Nellis AFB	89115	1664
New Boston Air Sta	03070	1157
Niagara Falls International Airport Air Reserve Sta	14304	1075
Offutt AFB	68113	1315
Offutt Air Force Base (Capehart Housing Area)	68123	1315
Offutt Air Force Base (Housing Area and Golf Course)	68123	1315
Opheim Air Force Sta	59250	1297
Patrick AFB	32925	1303
Peterson AFB	80914	1458
Pittsburgh Airport Air Reserve Sta	15108	1118
Point Arena Air Force Sta	95468	1399
Point of Marsh Target Airfield	28516	1272
Pope AFB	28308	1312
Portland Air Guard Sta	97218	1028
Quonset Air Guard Base	02852	1159
Randolph AFB	78148	1337
Reno Tahoe International Airport	89502	1534
Rickenbacker International Airport	43217	1124
Robins AFB	31098	1297
Schriever AFB	80930	1458
Scott AFB	62225	1248
Searay Target Range Complex	39341	1273
Selfridge Air National Guard Base	48045	1159

Seymour Johnson AFB	27531	1304
Shade Tree Range	92251	1534
Shaw AFB	29152	1278
Shaw AFB (Poinsett Range)	29125	1278
Smoky Hill Range	67425	1439
Springfield-Beckley Air Guard Sta	45502	1154
Stewart Air Guard Sta	12550	1201
Tinker AFB	73145	1392
Townsend Air-To-Ground Range	31331	1297
Training Site Ethan Allen Range	05465	1167
Travis AFB	94585	1459
Tucson International Airport Air Guard Sta	85706	1562
Tyndall AFB	32403	1274
U.S. Air Force Academy	80840	1494
U.S. Air Force Plant 42	93550	1777
Utah Air National Guard	84116	1382
Vance AFB	73703	1386
Vandenberg AFB	93437	1465
Volk Field Air National Guard Base	54618	1180
Volk Field Air National Guard Base (Hardwood Range)	54646	1180
Westover AFB	01022	1118
Whiteman AFB	65305	1315
Wright-Patterson AFB	45433	1137
Yankee Target Range	78072	1396
Youngstown-Warren Air Reserve Sta	44473	1041

Appendix D

This appendix presents the raster files which depict net-savings across the contiguous U.S. for each facility type.

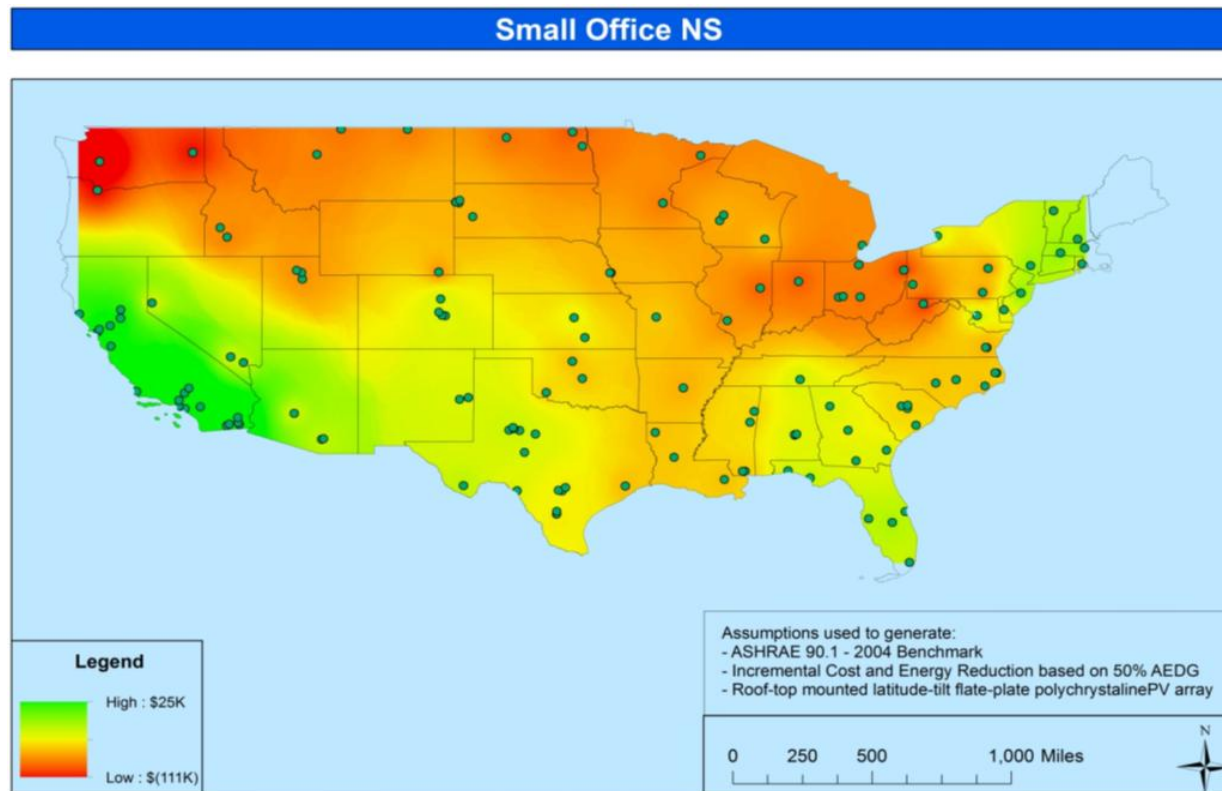


Figure 47 – Small Office NS Raster

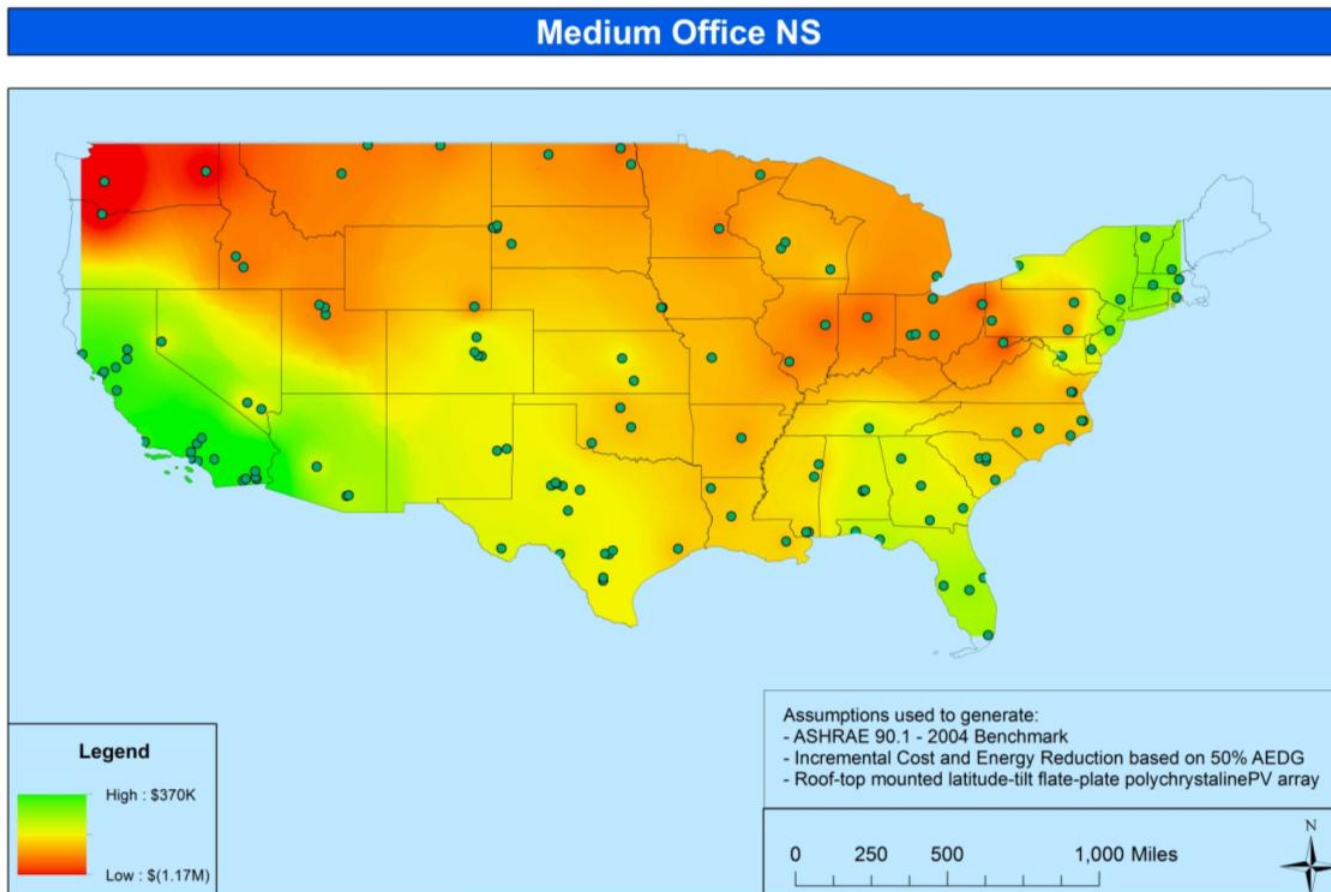


Figure 48 – Medium Office NS Raster

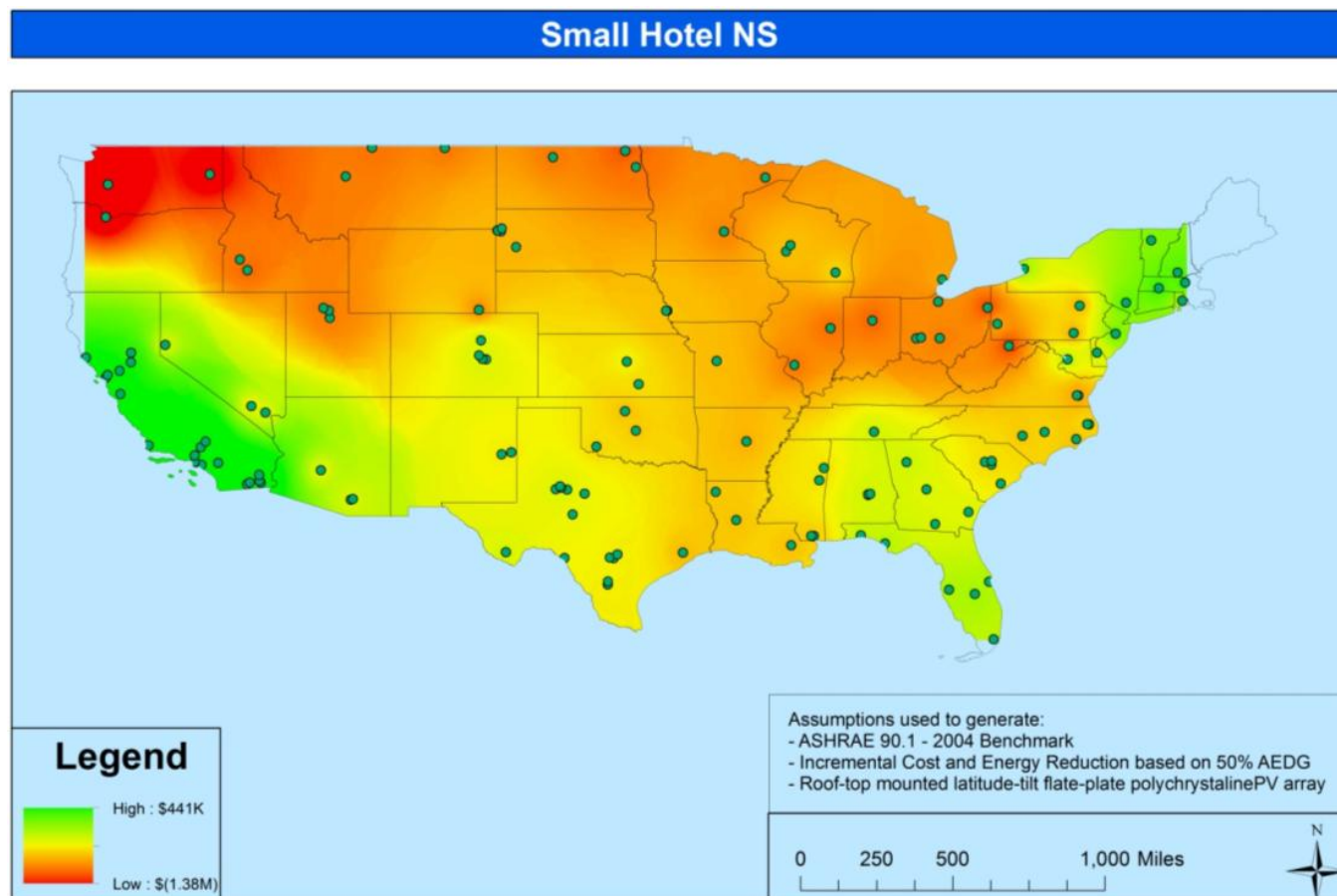


Figure 49 – Small Hotel NS Raster

Appendix E

This appendix presents the net-savings for each installation and for each facility type.

Table 33 – Installation Relative NS

Installation	County	State	Small Office	Medium Office	Small Hotel
Air Force Dare County Bombing Range	Dare	North Carolina	-61,302	-555,934	-581,463
Almaden AFB	Santa Clara	California	-4,402	65,833	129,461
Altus AFB	Jackson	Oklahoma	-60,030	-560,184	-575,023
Andrews AFB	Prince George's	Maryland	-39,412	-295,502	-321,684
Arnold AFB	Coffee	Tennessee	-41,779	-333,403	-373,691
Avon Park Auxiliary Airfield	Polk	Florida	-32,413	-191,907	-247,288
Barksdale AFB	Bossier	Louisiana	-65,560	-599,446	-636,148
Beale AFB	Yuba	California	-10,649	-32,318	5,838
Benton Air Force Sta	Sullivan	Pennsylvania	-64,916	-632,668	-608,455
Boise Air Terminal Air Guard Sta	Ada	Idaho	-69,992	-732,107	-821,080
Brooks AFB	Bexar	Texas	-49,442	-407,151	-491,451
Buckley AFB	Arapahoe	Colorado	-40,004	-384,874	-382,255
Cannon AFB	Curry	New Mexico	-41,727	-413,511	-505,695
Cavalier Air Force Sta	Pembina	North Dakota	-87,212	-730,031	-826,634

Chanute AFB	Champaign	Illinois	-78,856	-807,922	-816,435
Charleston AFB	Charleston	South Carolina	-58,438	-521,561	-534,784
Chocolate Mountains Gunnery Range	Imperial	California	10,791	294,807	202,680
Claiborne Range	Rapides	Louisiana	-61,230	-540,285	-644,443
Columbus AFB	Lowndes	Mississippi	-61,430	-546,015	-566,777
Cp Dawson Air Force Reserve Center	Preston	West Virginia	-85,773	-877,264	-911,649
Cp Perry Air National Guard Sta	Ottawa	Ohio	-72,759	-726,937	-738,526
Creech AFB	Clark	Nevada	-43,249	-449,203	-468,830
Davis- Monthan AFB	Pima	Arizona	-31,810	-222,341	-362,378
Dixie Target Range	McMullen	Texas	-59,998	-517,905	-622,798
Dobbins Air Reserve Base	Cobb	Georgia	-47,582	-388,741	-383,235
Dover AFB	Kent	Delaware	-44,482	-365,049	-402,176
Dyess AFB	Taylor	Texas	-47,469	-444,001	-507,070
Dyess Air Force Base (Hermleigh Emitter Site)	Fisher	Texas	-42,262	-390,619	-438,991
Dyess Air Force Base (Lake Thomas Emitter Site)	Borden	Texas	-42,716	-397,968	-449,133
Dyess Air Force Base (Nine Point Mesa Emitter Site)	Brewster	Texas	-38,716	-359,711	-400,984
Dyess Air Force Base (Snyder Winston Field Electronic Scoring Site)	Scurry	Texas	-42,878	-399,708	-451,323
Dyess Air Force Base (Union Emitter Site)	Scurry	Texas	-42,878	-399,708	-451,323
Edwards AFB	Kern	California	12,512	191,579	288,279
Ellington Fld	Harris	Texas	-63,925	-561,940	-674,312

Ellsworth AFB	Meade	South Dakota	-60,727	-610,386	-591,978
Ellsworth Air Force Base (Antelope Butte Mini Mute Radar Bomb Scoring Site)	Butte	South Dakota	-60,727	-610,386	-591,978
Ellsworth Air Force Base (Belle Fourche Radar Bomb Scoring Site)	Butte	South Dakota	-60,727	-610,386	-591,978
Ellsworth Air Force Base (Conner Radar Bomb Scoring Site)	Butte	South Dakota	-60,727	-610,386	-591,978
Ellsworth Air Force Base (Horman Radar Bomb Scoring Site)	Butte	South Dakota	-60,727	-610,386	-591,978
Escondido McMullen Range	McMullen	Texas	-48,248	-394,626	-476,599
F E Warren AFB	Laramie	Wyoming	-68,537	-681,841	-719,593
Fairchild AFB	Spokane	Washington	-93,713	-997,306	-1,142,653
Finland Air Force Sta	Lake	Minnesota	-80,612	-634,140	-706,085
General Mitchell Air Reserve Sta	Milwaukee	Wisconsin	-57,515	-551,802	-500,645
Goodfellow AFB	Tom Green	Texas	-47,385	-430,508	-500,715
Grand Forks AFB	Grand Forks	North Dakota	-80,670	-656,868	-740,142
Grissom AFB	Miami	Indiana	-80,138	-817,341	-841,513
Gulfport-Biloxi Regional Airport Air National Guard	Harrison	Mississippi	-61,554	-529,702	-635,482
Hamilton AFB	Marin	California	-2,533	83,184	153,194
Hanscom AFB	Middlesex	Massachusetts	-19,644	-72,624	95,964
Havre Air Force Sta	Hill	Montana	-76,520	-754,289	-799,598

Hill AFB	Davis	Utah	-68,397	-718,498	-795,846
Hill Air Force Base (Little Mountain Test Facility)	Weber	Utah	-68,397	-718,498	-795,846
Homestead Air Reserve Base	Miami-Dade	Florida	-49,356	-250,218	-372,044
Hurlburt Fld	Okaloosa	Florida	-40,505	-276,804	-347,970
Inkey Barley Range	Imperial	California	9,830	285,155	190,521
Jackson Barracks Air National Guard Sta	Orleans	Louisiana	-62,709	-555,799	-662,841
Keesler AFB	Harrison	Mississippi	-59,072	-503,657	-604,595
Kitty Baggage Range	Imperial	California	9,924	286,278	191,936
Lackland AFB	Bexar	Texas	-50,656	-421,801	-504,165
Langley AFB	Hampton	Virginia	-63,524	-600,532	-700,141
Langley Air Force Base (Bethel Manor Housing Area)	York	Virginia	-63,260	-597,203	-693,686
Laughlin AFB	Val Verde	Texas	-43,663	-342,396	-514,262
Little Rock AFB	Pulaski	Arkansas	-69,162	-647,267	-688,298
Loom Lobby Range	Imperial	California	6,628	253,016	150,033
Los Alamitos Reserve Center and Air Sta	Orange	California	-1,699	66,180	119,180
Los Angeles Air Force Base (Area A)	Los Angeles	California	50	93,709	144,719
Los Angeles Air Force Base (Area B)	Los Angeles	California	50	93,709	144,719
Los Angeles Air Force Base (Area C)	Los Angeles	California	50	93,709	144,719
Los Angeles Air Force Base (Fort Macarthur Housing Area)	Los Angeles	California	50	93,709	144,719
Los Angeles Air Force Base (Pacific Crest	Los Angeles	California	50	93,709	144,719

Housing Area)					
Los Angeles Air Force Base (Sun Valley)	Los Angeles	California	2,096	113,363	169,455
Luke AFB	Maricopa	Arizona	-38,439	-288,886	-446,210
Macdill AFB	Hillsborough	Florida	-35,247	-227,198	-284,128
Malmstrom AFB	Cascade	Montana	-74,011	-729,969	-769,897
March Air Reserve Base	Riverside	California	-926	86,114	133,642
Marietta Air Force Sta	Lancaster	Pennsylvania	-66,828	-653,817	-633,373
Maxwell AFB	Montgomery	Alabama	-49,682	-406,033	-404,888
Maxwell Air Force Base (Family Housing Annex)	Montgomery	Alabama	-49,682	-406,033	-404,888
Maxwell Air Force Base (Gunter Annex)	Montgomery	Alabama	-49,682	-406,033	-404,888
McChord AFB	Pierce	Washington	-121,726	-1,260,527	-1,568,738
McClellan AFB	Sacramento	California	-6,660	18,511	59,184
McConnell AFB	Sedgwick	Kansas	-50,761	-464,921	-527,997
McEntire Air Guard Sta	Richland	South Carolina	-59,257	-526,783	-544,835
McGuire AFB	Burlington	New Jersey	-25,983	-129,321	-107,094
Melrose Range	Roosevelt	New Mexico	-42,705	-413,011	-511,474
Mill Valley Air Force Sta	Marin	California	-2,533	83,184	153,194
Minneapolis-St Paul International Airport Air Reserve Sta	Hennepin	Minnesota	-73,119	-742,151	-732,432
Minot AFB	Ward	North Dakota	-80,190	-651,952	-729,506
Moody AFB	Lanier	Georgia	-45,943	-348,251	-428,972
Mountain Home AFB	Elmore	Idaho	-72,253	-760,332	-851,585

Navy Dare County Range	Dare	North Carolina	-62,216	-565,461	-592,806
Nellis AFB	Clark	Nevada	-38,601	-397,388	-409,689
New Boston Air Sta	Hillsborough	New Hampshire	-25,709	-149,289	-7,356
Niagara Falls International Airport Air Reserve Sta	Niagara	New York	-41,211	-327,346	-220,341
Offutt AFB	Sarpy	Nebraska	-61,016	-600,540	-584,458
Offutt Air Force Base (Capehart Housing Area)	Sarpy	Nebraska	-61,016	-600,540	-584,458
Offutt Air Force Base (Housing Area and Golf Course)	Sarpy	Nebraska	-61,016	-600,540	-584,458
Opheim Air Force Sta	Valley	Montana	-74,460	-733,141	-774,444
Patrick AFB	Brevard	Florida	-37,192	-242,040	-306,742
Peterson AFB	El Paso	Colorado	-41,685	-405,736	-404,904
Pittsburgh Airport Air Reserve Sta	Allegheny	Pennsylvania	-69,952	-686,451	-676,295
Point Arena Air Force Sta	Mendocino	California	-7,132	40,493	94,798
Point of Marsh Target Airfield	Carteret	North Carolina	-66,752	-612,725	-649,085
Pope AFB	Cumberland	North Carolina	-65,277	-602,313	-630,937
Portland Air Guard Sta	Multnomah	Oregon	-96,776	-975,375	-1,212,211
Quonset Air Guard Base	Washington	Rhode Island	-41,982	-348,689	-254,795
Randolph AFB	Bexar	Texas	-54,119	-458,700	-550,358
Reno Tahoe International Airport	Washoe	Nevada	-39,101	-383,162	-368,450
Rickenbacker International Airport	Franklin	Ohio	-75,942	-762,131	-779,994
Robins AFB	Houston	Georgia	-52,300	-438,556	-438,823

Schriever AFB	El Paso	Colorado	-41,685	-405,736	-404,904
Scott AFB	St. Clair	Illinois	-71,623	-708,509	-816,803
Searay Target Range Complex	Noxubee	Mississippi	-61,042	-542,790	-561,978
Selfridge Air National Guard Base	Macomb	Michigan	-69,070	-679,316	-659,870
Seymour Johnson AFB	Wayne	North Carolina	-62,554	-565,675	-596,895
Shade Tree Range	Imperial	California	8,910	275,924	178,892
Shaw AFB	Sumter	South Carolina	-62,406	-560,422	-583,931
Shaw AFB (Poinsett Range)	Sumter	South Carolina	-62,406	-560,422	-583,931
Smoky Hill Range	Saline	Kansas	-45,993	-411,939	-464,565
Springfield-Beckley Air Guard Sta	Clark	Ohio	-72,537	-724,489	-735,641
Stewart Air Guard Sta	Orange	New York	-25,052	-147,307	-11,401
Tinker AFB	Oklahoma	Oklahoma	-63,034	-587,346	-612,157
Townsend Air-To-Ground Range	McIntosh	Georgia	-45,904	-349,698	-429,017
Training Site Ethan Allen Range	Chittenden	Vermont	-30,214	-210,572	-79,165
Travis AFB	Solano	California	-3,425	42,450	95,386
Tucson International Airport Air Guard Sta	Pima	Arizona	-36,128	-262,791	-416,775
Tyndall AFB	Bay	Florida	-38,706	-256,079	-325,062
U.S. Air Force Academy	El Paso	Colorado	-39,384	-381,037	-374,692
U.S. Air Force Plant 42	Los Angeles	California	16,105	237,268	334,509
Utah Air National Guard	Salt Lake	Utah	-67,683	-707,447	-785,773
Vance AFB	Garfield	Oklahoma	-64,513	-605,245	-630,595
Vandenberg AFB	Santa Barbara	California	-4,533	56,183	125,123

Volk Field Air National Guard Base	Juneau	Wisconsin	-62,572	-607,759	-565,251
Volk Field Air National Guard Base (Hardwood Range)	Juneau	Wisconsin	-62,572	-607,759	-565,251
Westover AFB	Hampden	Massachusetts	-22,366	-102,185	59,855
Whiteman AFB	Johnson	Missouri	-58,808	-559,639	-634,816
Wright-Patterson AFB	Greene	Ohio	-73,727	-737,095	-751,771
Yankee Target Range	McMullen	Texas	-48,248	-394,626	-476,599
Youngstown-Warren Air Reserve Sta	Trumbull	Ohio	-86,741	-881,822	-920,381

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14. ABSTRACT The U.S. Government has issued numerous policies aimed at reducing federal facility energy consumption; the most recent, Executive Order 13514, requires that new construction designed after 2020 can achieve net-zero energy by 2030. The policy defines a Zero-Energy Building as one that is designed, constructed, and operated to reduce energy demand to a level which can be offset from sources of renewable energy. This research develops and evaluates a feasibility assessment model based on life-cycle cost. It incorporates geospatial analysis to calculate and summarize input values for all Air Force installations in the Contiguous U.S.. A comparative analysis is then conducted to rank each installation in terms of the net-savings of constructing a Zero-Energy Building. The ranking is performed for three facility types and then utilized to prove that there is a significant and direct rank correlation between them. This conclusion allows follow-on feasibility assessments to be limited to those installations and facility types which will maximize the likelihood of achieving a cost-effective Zero-Energy Building. Finally, a strategy is recommended which will comply with federal net-zero energy policy, reduce facility operational costs, and ultimately allow for energy security and independence at Air Force installations.				
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