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Dissertation

Improving Energy Security for Air Force Installations

David Schill

RAND CORPORATION

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Improving Energy Security for Air Force Installations

David Schill

This document was submitted as a dissertation in September 2015 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Paul Dreyer (Chair), Don Snyder, and Beth Lachman.

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Abstract

Like civilian infrastructure, Air Force installations are dependent on electrical energy for daily operations. Energy shortages translate to decreased productivity, higher costs, and increased health risks. But for the United States military, energy shortages have the potential to become national security risks. Over ninety-five percent of the electrical energy used by the Air Force is supplied by the domestic grid, which is susceptible to shortages and disruptions. Many Air Force operations require a continuous source of energy, and while the Air Force has historically established redundant supplies of electrical energy, these back-ups are designed for short-term outages and may not provide sufficient supply for a longer, sustained power outage. Furthermore, it is the goal of the Department of Defense to produce or procure 25 percent of its facility energy from renewable sources by fiscal year 2025. In a government budget environment where decision makers are required to provide more capability with less money, it is becoming increasingly important for informed decisions regarding which energy supply options bear the most benefit for an installation.

The analysis begins by exploring the field of energy supply options available to an Air Force installation. The supply options are assessed according to their ability to provide continuous and reliable energy, their applicability to unique requirements of Air Force installations, and their costs. Various methods of calculating energy usage by an installation are also addressed. The next step of this research develops a methodology and tool which assesses how an installation responds to various power outage scenarios. Lastly, various energy supply options are applied to the tool, and the results are reported in terms of cost and loss of installation capability. This approach will allow installation commanders and energy managers the ability to evaluate the cost and effectiveness of various energy investment options.

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Chapter 1: Introduction

Specific Aims and Research Questions

Military installations supporting critical military and Homeland Defense missions are almost entirely dependent on the commercial power grid and this dependence can put these missions at a high risk of disruption. This study will help the Air Force economically address and respond to its reliance on the domestic grid while maintaining its ability to support the national security strategy and its federally mandated renewable energy requirements. Additionally, this study will help Air Force leaders at the installation and enterprise levels make informed energy investment decisions by providing a framework that assesses how various energy supply options fit within an installation's energy plan, and how those options can reduce the impact of power outages.

The Air Force defines energy security as the "assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet operational needs" (*U.S. Air Force Energy Strategic Plan,* page 21). In addition to facility energy, this definition also encompasses securing the supply, distribution, and storage of fuels for transportation. The focus of this study is on facility energy and the need for electrical power, and thus energy security is here defined as having sufficient energy to allow the execution of critical missions through reliable electrical power to the network grid, to critical facilities, and to support infrastructure. An Air Force installation must have the technological, systems, and manpower capability to power mission-critical assets. By evaluating a range of energy sources and how an installation responds to various power outage scenarios, this analysis will show how an installation can better structure its energy resources to reduce the impact a power failure has on mission success. The specific aim of the research seeks to answer the following research questions:

1) What energy sources can be developed and operated efficiently and reliably on an Air Force installation?
2) How can the Air Force assess potential energy generation options and their impacts on installation vulnerability to power failure?
3) In what ways can Air Force installation leaders and base energy managers reduce their risk to mission failure due to electrical energy disruption, and at what cost?

The answers to the preceding questions will help inform Air Force leaders as to the choices they can make to minimize risk to a disrupted power supply. At the installation level, Air Force leaders can directly contract and purchase energy systems which best minimize their mission risks and potentially reduce overall installation energy cost. Installation commanders can also institute energy reduction policies and ensure compliance through routine monitoring oversight activities. Furthermore, Air Force and other Department of Defense leaders will have a methodology and tool for catering this analysis to their specific needs. At the enterprise level, leaders can choose new disruptive technologies for which they should partner in investing research and development dollars. Lastly, the results of the study will aid the energy community in discussing the future of reliable energy supply in the United States.

Motivation

On 15 August 2008, a power problem at one of Peterson Air Force Base's critical facilities caused the shut-down of operations within the facility as well as an evacuation of the personnel. With the operations center for the North American Aerospace Defense Command (NORAD) recently moved into its basement, the facility is a critical piece of national security; NORAD is charged with the missions of aerospace warning and aerospace control for North America. After the power failure, authority for NORAD's mission was temporarily transferred to a nearby building, but not without delay and disruption to the operation. According to an after-action review, the facility's "poorly defined power" and "unstructured evolution" of networks contributed to the failure. The facility was originally constructed without the power distribution system required by current electronic and computing systems, and thus the additional demand exceeded the facility's power delivery capabilities. As a result, the event called "into question the concept of redundant power" required for facilities of such criticality (Yoanna and Gertz, 2008).

In its Fiscal Year 2013 Annual Energy Management Report to Congress, the Department of Defense reported 180 utility disruptions lasting eight hours or longer, with an average financial impact of about $220,000 per day (DoD FY13 Annual Energy Management Report, pgs 41). The NORAD case provides an example of how national security is at risk when power failure occurs, and the scale of disruption reported in the DoD Annual Energy Management Report brings to light the need for reliable redundant power systems across its installations.

NORAD's mission of identifying and tracking missile threats is a mission which requires continual surveillance and monitoring. Given the short amount of time it takes an Intercontinental Ballistic Missile (ICBM) to launch, travel, and strike a target, a power outage for just ten minutes at NORAD means reporting of a missile launch could have been missed. Other examples, such as the disruption of live-video feed of deployed Remotely Piloted Aircraft (RPAs) with pilots up to thousands of miles away, show how current operations could potentially be disrupted in the event of power failure to infrastructure on an installation.

The issue of power failure on military installations was raised in a report to the Secretary of Defense (Defense Science Board, 2008), which concluded that the Department of Defense faces two primary energy challenges. First, the Department of Defense has developed an unnecessarily high battlespace fuel demand, which continues to grow. Second, military installations supporting critical military and homeland defense missions are almost completely dependent on the commercial power grid and this dependence puts military and homeland defense missions at an unacceptably high risk of disruption. This study focuses on the Defense Science Board's second conclusion, and will provide an analytic approach for the Department of Defense to address this vulnerability.

The Air Force has taken steps away from complete reliance on the domestic grid and toward alternative methods of energy generation, distribution, and storage. In 2008, Air Force installations reached 11% of electrical use from "alternative," or renewable energy sources, though these were still largely procured from the commercial sector and delivered over the power grid or purchased in the form of renewable energy credits, thus not freeing installations from the reliance on the domestic grid. Furthermore, it is a Department of Defense goal (10 USC Section 2911) that military services produce or procure 25% of electrical energy from renewable sources by year 2025. As an example toward meeting that goal, Nellis Air Force Base (AFB) in Nevada arranged the private construction and operation of a large solar photovoltaic generating facility on 140 acres of installation property. Consisting of 72,000 photovoltaic panels, this solar plant has a maximum generating capacity of 14.2 megawatts, and has achieved an annual energy output of over 30 million kilowatt hours. Nellis AFB energy personnel reported that its contract to buy power at a guaranteed rate through 2027 will yield an estimated annual savings of over $1 million.

Many alternative energy options being pursued are achieving the goal of increasing the government's use of alternative sources of energy and reducing the amount of energy drawn from the domestic grid at-large, but often these solutions do not address energy reliability or response to disruption of the electric grid. There still exists little analysis on how to minimize the risk of power failure, either deliberate or natural. This report aims to look at the energy supply solutions as well as the security aspect of supplying power, and to assess how these solutions impact an installation's costs and overall security environment.

Preliminary Studies

A number of experts assert that the United States domestic grid is vulnerable to power failure. For example, one text argues that the United States has been running on an energy supply and grid that is considered brittle, and that the system can be easily shattered by accident or malice. More importantly, this poses a grave and growing threat to the nation's security, and remains a potential and continual catalyst for international conflict. Additionally, as the energy infrastructure continues to move toward a smart grid concept, the systems become more susceptible to cyber threats (Lovins and Lovins, "Brittle Power"). In 2014, the president of the North American Electric Reliability Corporation told the Senate Energy and Natural Resources Committee that he is "…most concerned about the coordinated physical and cyber attacks intended to disable elements of the power grid or deny electricity to specific targets, such as government or business centers, military installations, or other infrastructures." At the same hearing, the acting chairman of the Federal Energy Regulatory Commission noted the Metcalf attack, where a team of gunman fired on a California substation severely damaging critical infrastructure, and said threats to electrical infrastructure are "fast-changing" and called for better information sharing about threats between government and industry (Gertz, "Inside the Ring").

The 2008 Defense Science Board Task Force Report, "More Fight – Less Fuel" also points to the fragile and vulnerable commercial grid. The Task Force reported its concern not only with the condition of the grid, but also on the ability to effect timely repairs (DSB, "More Fight – Less Fuel, pg 19). When assessing the Department of Defense energy policy, the Defense Science Board also found that there is no unifying vision, strategy, or governance structure for the DoD energy portfolio. Within the Department of Defense, the individual services have developed an energy plan and/or strategy, and these tend to reference common documents which are discussed here. First is the Energy Policy Act (EPAct) of 2005, which provides national goals with respect to energy. From the executive branch comes Executive Order (EO) 13423, issued 24 January 2007. The order sets goals for federal agencies in the areas of energy efficiency, acquisition, renewable energy, sustainable buildings, and others. The Department of Defense also released Department of Defense Instruction 4170.11 shortly after the EPAct of 2005 and updated it in 2009; this document outlines responsibilities at the Deputy Under Secretary level and for the military services, provides guidance, and prescribes procedures for Department of Defense installation management.

In response to the previously mentioned policies, each component within the Department of Defense manages their own energy programs in order to meet military and national requirements. Secretary of the Air Force Michael Donley released the *Air Force Energy Program Policy Memorandum* (AFPM 10-1) on 19 December 2008. The document provides an overview of Air Force energy policy, and serves to implement Air Force energy policy until the release of Air Force Policy Documents and Instructions. With respect to energy, the Air Force is governed by Air Force Policy Directive (AFPD) 90-17, *Energy Management*, and the Senior Energy Official responsible for managing Air Force energy is the Under Secretary of the Air Force. The Assistant Secretary of the Air Force for Installations, Environment, and Energy (SAF/IE) serves as the Office of Primary Responsibility (OPR) and oversees energy program development and implementation. SAF/IE is also responsible for developing energy policy and strategy for the Air Force. The Air Force Energy Strategic Plan is structured to achieve all goals listed by the President, the Office of the Secretary of Defense, EPAct of 2005 and EO 13423. The Air Force Energy Strategy, as outlined in AFPM 10-1, consists of three components: reduce demand, increase supply, and change the culture to be more aware of energy usage. AFPM 10-1 details goals, objectives, and metrics related to each component, and lists Air Force organizations charged with responsibilities.

The latest version of the *U.S. Air Force Energy Strategic Plan*, published in March 2013, lists four priorities for the Air Force: improve resiliency, reduce demand, assure supply, and foster an energy aware culture. Within each of these priorities, the report lists specific goals and objectives for helping the Air Force identify the resources and for supporting planning activities related to that priority. For example, one of the Air Force's goals in improving resiliency is to

“Mitigate the likelihood for disrupted energy and water supplies to impede operations.” The first objective within that goal is to “Identify where and how alternative fuels and energy can be integrated into the Air Force energy portfolio” (*U.S. Air Force Energy Strategic Plan,* page 11). This dissertation addresses this objective and others within the *Strategy Plan,* and thus will assist the Air Force in incorporating new information into their adaptive framework for accomplishing its energy goals and improving its energy security.

Department of Defense Directive 3020.40 establishes policy and assigns responsibilities for compliance with Homeland Security Presidential Directive 7, “Critical Infrastructure Identification, Prioritization, and Protection,” and ensures consistency with the Homeland Defense’s “National Infrastructure Protection Plan (NIPP)” (DoD Directive 3020.40). Air Force Policy Directive 10-24 implements DoD Directive 3020.40, establishes the Air Force Critical Asset Risk Management (CARM), formally known as the Air Force Critical Infrastructure Program, and assigns responsibilities for execution of the program. The purposes for both documents are to coordinate, develop, and implement strategy and policy associated with the identification, prioritization, assessment, and protection of critical assets (AFPD 10-24). However, it’s not always the case that the identification of critical assets at lowest levels makes it to the Homeland Defense’s NIPP. In 2008, the U.S. Government Accountability Office (GAO) found that the Department of Defense had fallen short in ensuring highly sensitive critical assets are accounted through the critical infrastructure process (GAO-08-373R, “Defense Critical Infrastructure”). The link between energy security and the critical assets is not overly clear in any of the critical infrastructure documents. Furthermore, there is little to no policy guidance related to alternative or renewable energy sources for use as a backup supply for critical asset protection.

In 2009, the Air Force Scientific Advisory Board conducted a study examining alternative sources of energy for U.S. Air Force bases. The study provides four main recommendations. First, implementing alternative energy sources requires a more concerted systems approach, and this requires developing better in-house competencies and providing for more resources. Second, current policies and guidance on energy security should be implemented including acceleration of base vulnerability assessments and risk mitigation strategies. Third, the Air Force should integrate energy storage with backup power sources, as well as exploiting the availability of abundant aviation fuel stored on base. This includes partnering with academia, industry, and other research organizations in developing technologies to generate aviation fuels. In the near-term, this incorporates integrating micro-grid control systems and load leveling supplies. Lastly, the fourth recommendation is for the Air Force to analyze the potential for making nuclear energy a part of its energy solution (*Alternative Sources of Energy for US Air Force Bases: Opportunities and Challenges*, pgs 11-12).

The Air Force faces considerable challenges in securing its energy supply while meeting federal mandates. Organizationally, the Air Force must continually assess its performance and execute its strategic plan. At the installation level, base leaders and energy managers are charged with ensuring their mission is executed without interruption from energy failure, and they must do so in a fiscally constrained environment. This work aims to support those local decision-makers as they assess their installation's energy needs and potential solutions. Ultimately, this study aims to help address the overarching policy question: how can the Air Force build resilience into its installation energy architecture?

Research Design and Methods

Overall Design

This dissertation involves three phases. The first phase establishes the baseline for understanding energy supply options at Air Force installations. This phase involved a literature search of the field of energy security and resiliency on government installations, and it also included collecting energy consumption and supply data for Nellis Air Force Base. The second phase uses the information from the first phase to develop a spreadsheet-based model which details the electrical network at an Air Force installation. Additionally, a simple statistical method is described in this phase that allows for relatively quick estimation of individual-building level energy usage given readily available facility information. The third and final phase of the project uses data collected from Nellis Air Force Base and applies it to the model developed in the second phase. The results are analyzed and presented in a way that is useful to an installation decision maker, so that the decision maker can best assess his or her allocation of resources toward improving the installation's energy security.

It is best to describe the population of interest in a multi-tiered fashion. The first tier resides at the individual base level, which falls under the command of the Civil Engineering Squadron or equivalent function. Particularly, this study will use data from Nellis AFB, with base energy oversight operated under the command of the 99th Civil Engineering Squadron. The developed models and data analyses are specifically tailored to their site-specific attributes. Related to this tier are the base leadership and mission support staff at the installation level. For Nellis AFB, the 99th Mission Support Group under the 99th Air Base Wing provides installation support to Nellis AFB, Creech AFB, and the Nevada Test and Training Range. Also at Nellis AFB and included in this first tier are the 57th Wing which houses, among other groups, the Thunderbirds. The second tier is represented by higher authority organization level decision makers who approve funding and project execution. These include both the operational chain of command within the Department of Defense as well as organizations with the role of providing policy and oversight for installations like the Air Force Energy Office, or those who help evaluate and implement energy strategies across the Air Force such as the Air Force Installation and Mission Support Center (AFIMSC) and its Energy Directorate in the Air Force Civil Engineer Center (AFCEC). The third tier represents the field of industry partners, academia, and research and development centers. Though this study is focused on providing decision makers in the first tier the methods and tools required to aid in their decision process, the other two tiers should continue to implement and advance the Air Force Energy Strategy as the Air Force continues to improve its energy security posture.

Phase One – Data Collection and Literature Review

There are two areas of effort within the first phase of this study. The first area explored the various forms of energy supplied to an Air Force installation and characterized them with respect to how vulnerable they are to power failure as well as how feasible they are for use on an Air Force installation. This task was performed through extensive literature search and by visiting sites where alternative energy is currently used, both on Air Force installations and commercial sites.

The second area involved the collection of data from Nellis AFB. This included power distribution schematics and installation level grid structure. Data collection also included facility level power usage for all available metered buildings, and information on all facilities such as type, size, and location. Metered buildings account for 43% of the on-base electrical use, and non-metered buildings, distribution line losses, and exterior lighting account for the rest. At the time of data collection in spring 2009, buildings on this installation considered "mission critical" were assessed for their power usage and this data was added to the set. Lastly, total electrical energy use and cost for Nellis AFB was collected.

Phase Two – Model Development

The second phase of this research developed a discrete-time network model for characterizing the functional electrical network of an installation. Specifically, the electrical grid was modeled as a network of nodes and links. Buildings, electric switches, generators, back-up power supplies, and substations were modeled as nodes, and the power distribution lines connecting the nodes were modeled as links. The model allows for inputting and analyzing a range of energy sources, and it outputs both cost and how the installation's facilities respond to power outage scenarios over a period of time. The data from Nellis AFB collected in the first phase was then applied to the model. The Nellis AFB model included over 800 nodes and links, and since Nellis AFB is an average size base, from a modeling perspective it is feasible to apply this type of model to many Air Force installations. However, it may not be appropriate for all installations, as will be discussed more later.

Electrical usage data was also summarized in the second phase. When possible, exact data from building meters was used. When data for buildings was not available, the usage data was estimated using a simple regression analysis. Four energy outage scenarios were developed with the coordination of Nellis AFB personnel and described in detail, including the duration of the power outage, location or origin of the failure, and expected response. Certain functions, or buildings, on an installation are more critical than others, and local base leaders and energy managers aided in the identification of critical facilities for Nellis AFB. Per requirements listed in Department of Defense Directive 3020.40, military services report on their critical assets, or those assets of such extraordinary importance to operations in peace, crisis, and war that incapacitation would have serious effect on the ability of the Department of Defense to fulfill its mission (DoD Directive 3020.40, pg 16). It is important that installation personnel understand the level of power use for those critical facilities, the length of time the facility can go without external energy and still maintain operational and mission capability, and the degree to which power failure equates to mission failure.

Phase Three

The final phase populates the model with the collected data and desired scenarios. The initial run of the model establishes the no-failure baseline, and represents typical operations without power failure. Then power failure scenarios are applied, and the baseline for each scenario is established. This second baseline shows the current impact of each power failure scenario to the installation in terms of facilities lost, or mission failure. Numerous methods of aggregating and reporting these energy outages and their impacts are explored. At this point, modifications to the model, such as additional generators, can be applied, and the incremental gains from these modifications are compared to the baseline case. At this incremental level, single modifications or combinations of energy sources can be examined with respect to how they change the cost to the installation as well as how they influence the number and duration of buildings without power across the power outage scenarios.

The data from Nellis AFB is presented in this phase. This phase was performed in concert with the installation personnel, such that the on-ground experts provided advice and knowledge regarding the inputs and modifications to the model. This ensured that the model is assessing changes perceived to be actually implementable. Installation personnel can use the model to explore the field of energy options available, and thus can be a useful tool in early concept development. The decision maker is faced with the task of minimizing both cost and the impact of power failure at his or her installation. This method and tool will help ensure that leaders are aware how to reduce their risk to mission failure.

Strengths and Weaknesses of the Methodology

A weakness of the model is that the power outages, though realistic because they have already occurred or are rationally developed, are difficult to predict. Actual power failures are quite complex and adequately modeling human and system responses correctly is difficult. Furthermore, using only Nellis AFB as a case study has the weakness that the model may not be accounting for the entire range of energy security possibilities available at other bases. In the same line of reasoning, the geography of the desert surrounding Nellis AFB enhances the utility of some alternatives, such as solar power, and this option may not be applicable at bases with less intense solar availability. As long as these aspects are specified in the model and decision-makers are aware that the model is applied to an installation in the desert, any bias or inadequacies will be minimal.

Estimating energy consumption data using a regression approach, though good for generalization, lacks the specificity provided by an engineering approach to estimating usage. Furthermore, this model uses energy consumption and supply on an hour time scale. This method is appropriate for base managers and installation leaders, but is not appropriate for accurately reflecting energy use fluctuations that occur much more quickly. Advanced computer modeling incorporating real-time or near real-time data would enhance the accuracy of the analysis.

The first strength of the model is in the flexibility it allows to provide leadership recommendations for how to reduce mission failure due to energy shortages. This flexibility is at the organizational level, so the model can be easily be modified to fit other bases' environment and characteristics. The model is equally adaptable at the individual base level, where base energy managers can modify the power failure scenarios or the nodes and links, and combinations of both. Additionally, because an installation can never be completely secure from an energy outage, the internal process of deciding which functions, assets, and buildings are most critical to mission success is an analytical strength of the methodology.

Significance of Policy

In a time when energy remains at the forefront of politics, this report will add to the discussion of how various sources of energy can be used by military installations to decrease dependence on the domestic grid. From a policy standpoint, this study will help inform Air Force decision-makers on their policy options for alternative energy use within the realm of infrastructure electricity use. It will also allow them to address how they can incorporate resiliency specific to energy into their force protection plans. Analytically, it will provide a framework for other institutions which are contemplating a plan for implementing alternative energy use and are concerned about the vulnerability to their energy supplies. The results from this analysis can directly lead to similar analyses for the other military departments for their installations. Further research should be done to assess whether this methodology and tool can be applied to the energy and security infrastructure for overseas bases, or for deployed locations and remote forward operating bases. In these cases, though the installation's size, security posture, access to energy supplies, and operational tempo may be different, it is reasonable to expect the methodology to be applicable.

Furthermore, from a methodology standpoint, this study will verify the applied use of empirical modeling to quickly estimate energy usage at the installation and individual building level. The methodology developed for this analysis can either be directly applied to a similar base, or can be modified to be applicable more broadly. The model framework and specifications are such that the researcher can quickly modify the energy supply inputs, energy consumption characteristics, and the power failure scenarios in order to assess potential solutions for improving the current infrastructure, thus reducing risks to future power failures and their associated costs.

As outlined in its *U.S. Air Force Energy Strategic Plan*, the Air Force is actively improving resiliency, reducing energy demand, assuring supply, and fostering an energy aware culture. Some Air Force installations are already strategically addressing energy security and doing many of the analyses and assessments considered in this study. The methodology developed here is not a replacement for already excellent work in progress, but can be used to help Air Force installations in their activities. In addition, this study mentions a few Air Force and other military components' installations as examples, but there are many more energy security activities that could be acknowledged as well.

Chapter 2: Air Force Energy Sources

Overview

In FY13, the Department of Defense's total energy bill was $18.9 billion. Seventy percent of the energy consumption was operational energy, defined as the energy required for training, moving, and sustaining military forces and weapons platforms for military operations (10 U.S.C. Sec. 2924, 2011). Thirty percent of the energy consumption, with a total cost of $4.1 billion, was facility energy, defined as energy for fixed installations and non-tactical vehicles. At 217,000 billion British thermal units (BBtu) of facility energy, this represents nearly 1 percent of the total U.S. commercial sector's energy consumption, and makes the Department of Defense the largest consuming entity in the United States (EIA, "Annual Energy Outlook 2014 Early Release"). Within the Department, the Army is the largest consumer of facility energy, followed by the Air Force, as seen in Figure 1 below.

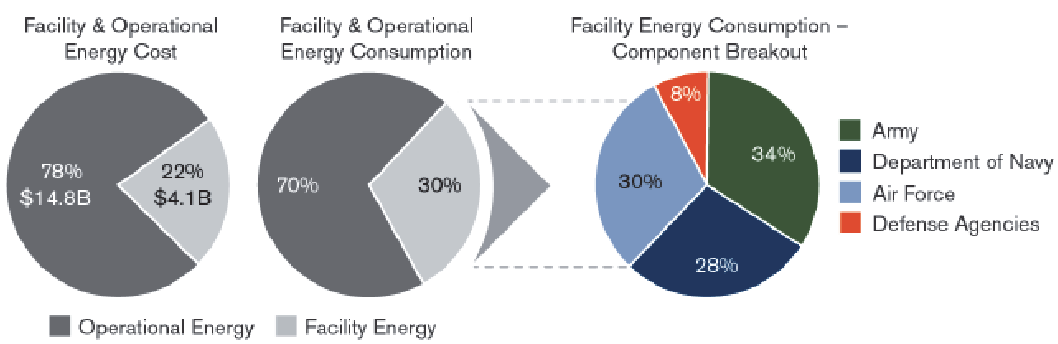


Figure 1: DoD FY 2013 Facility Energy Consumption
Source: DoD FY13 Annual Energy Management Report

Of the $4.1 billion, the Department of Defense spent $3.8 billion to power, heat, and cool buildings and $0.3 billion to supply fuel to the non-tactical vehicles. Of the Department's facility energy consumption, electricity and natural gas accounted for approximately 49 percent and 32 percent, respectively, and the remaining portion included fuel oil, coal, and liquefied petroleum gas (DoD FY13 Annual Energy Management Report, pgs 16-17).

Where does the electricity that powers the installation grid come from? Under normal operating conditions, Department of Defense installations typically receive electric power from the domestic grid. Large commercial plants generate electrical energy which is transmitted at high voltage through a network of substations and transformers. The power is distributed to the on-base loads via a government owned distribution system, typically on multiple circuits. Generally, the Air Force owns all on-base utility distribution systems, though it is possible for the Air Force to utilize public or private ownership of on-base utility distribution systems if it is in the best interests of the Air Force.

Title 10 U.S.C. §2911 (e) established a goal for the Department of Defense to produce or procure not less than 25 percent of its facility energy by FY 2025 from renewable energy sources. Annually, the Department of Defense publishes an Energy Management Report, and the FY13 Report stated the Department's progress toward that goal as 5.6 percent. Taking into account credits for renewable energy such as procured Renewable Energy Credits, the Department's progress in FY13 toward the 25 percent renewable energy goal was 11.8 percent (2013 Annual Energy Management Report, pg 33).

This 5.6 percent comes from a variety of sources. For FY13, the Department of Defense's nearly 900 renewable energy projects generated approximately 9,000 BBtu. Geothermal electric power represents the largest renewable energy source in the Department, accounting for over half the power from renewable sources. Generating electricity and steam from Municipal Solid Waste (MSW) accounts for 19 percent of the production. Approximately 10 percent of the total renewable energy produced on military installations comes from 511 solar photovoltaic systems (2013 Annual Energy Management Report, pg 37). Figure 2 below depicts the renewable supply mix by technology type.

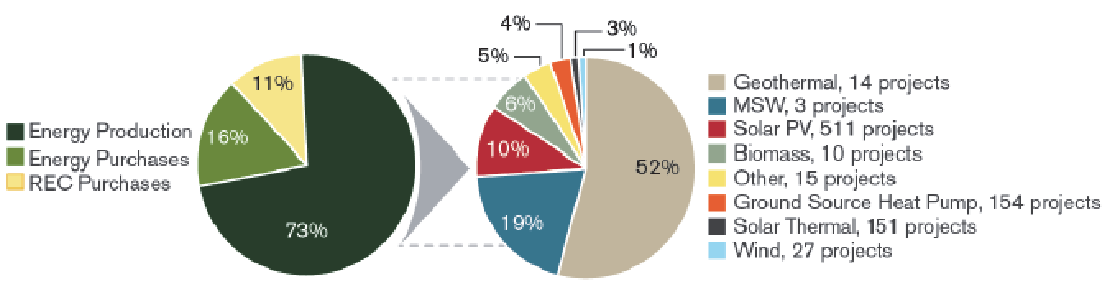


Figure 2: DoD FY 2013 Renewable Energy Production
Source: DoD FY13 Annual Energy Management Report

The Department of Defense differs from total renewable energy capacity and generation at the national level in that it generates over 50 percent of its renewable energy from geothermal sources. In comparison, geothermal energy at the national level accounts for 7 percent of renewable energy consumption. Likewise, 662 solar projects at 10 percent of its capacity in the

Department of Defense play more significantly than the national level, where solar photovoltaic and solar thermal account for 2 percent. Lastly, wind, at only 1 percent of total renewable energy production, is much smaller in the Department of Defense than the national level. Figure 3 and Table 1 below show the distribution of renewable energy generation for the United States.

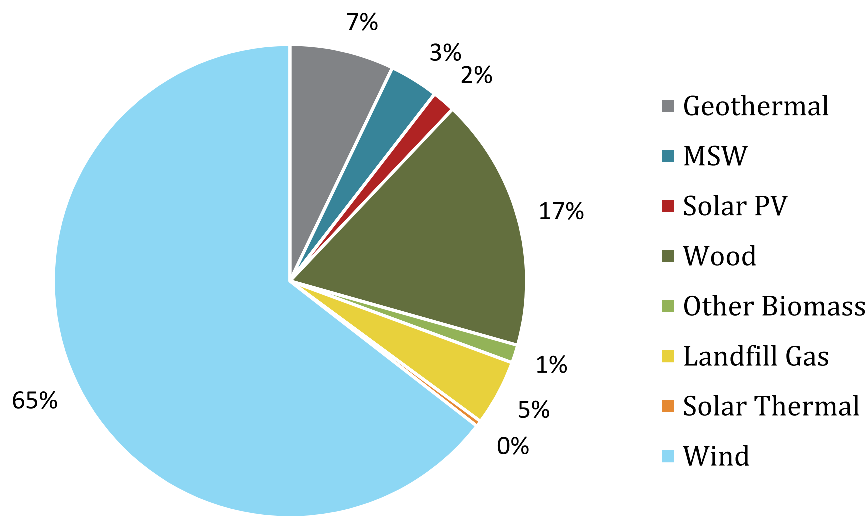


Figure 3: Net Generation from Renewable Sources, All Sectors, United States
Source: EIA, "Electric Power Annual," Table 3.1.B. Found at < http://www.eia.gov/electricity/annual/ >.

Table 1: Existing Capacity in Megawatts by Energy Source, 2007 and 2012

Energy Source	2007 Number of Generators	2007 Generator Nameplate Capacity (MWh)	2012 Number of Generators	2012 Generator Nameplate Capacity (MWh)
Coal [1]	1,470	336,040	1,309	336,341
Petroleum [2]	3,743	62,394	3,702	53,789
Natural Gas [3]	5,439	499,389	5,726	485,957
Other Gases [4]	105	2,663	94	2,253
Nuclear	104	105,764	104	107,938
Hydroelectric Conventional [5]	3,992	77,644	4,023	78,241
Wind	389	16,596	947	59,629
Solar Thermal and Photovoltaic	38	503	553	3,215
Wood and Wood Derived Fuels [6]	346	7,510	351	8,520
Geothermal	224	3,233	197	3,724
Other Biomass [7]	1,299	4,834	1,766	5,527
Pumped Storage	151	20,355	156	20,858
Other [8]	42	866	95	2,005

Source: EIA, "Electric Power Annual," Table 4.3. Found at < http://www.eia.gov/electricity/annual/ >.

[1] Anthracite, bituminous coal, subbituminous coal, lignite, waste coal, and synthetic coal.

[2] Distillate fuel oil (all diesel and No. 1, No. 2, and No. 4 fuel oils), residual fuel oil (No. 5 and No. 6 fuel oils and bunker C fuel oil), jet fuel, kerosene, petroleum coke, and waste oil.

[3] Includes a small number of generators for which waste heat is the primary energy source.

[4] Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[5] The net summer capacity and/or the net winter capacity may exceed nameplate capacity due to upgrades to and overload capability of hydroelectric generators.

[6] Wood/wood waste solids (including paper pellets, railroad ties, utility poles, wood chips, bark, and wood waste solids), wood waste liquids (red liquor, sludge wood, spent sulfite liquor, and other wood-based liquids), and black liquor.

[7] Biogenic municipal solid waste, landfill gas, sludge waste, agricultural byproducts, other biomass solids, other biomass liquids, and other biomass gases (including digester gases, methane, and other biomass gases).

[8] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, tire-derived fuels and miscellaneous technologies.

As seen in the previous table, the nation heavily relies on power generated from coal, natural gas, nuclear, and hydroelectric sources. During the time period between 2007 and 2012, the nation saw a large increase in solar and wind generation. As stated earlier, Air Force installations receive nearly 95% of their electricity from the national grid. Like the nation, the Department of Defense is aggressively adding renewable energy to their electrical energy generation mix.

Energy Sources for Air Force Installations

The first task for this project is to explore the various forms of energy sources that can be used to supply electricity to Air Force installations. The purpose of this task is to understand how feasible each energy technology is for use on an average Air Force installation. The technologies will be characterized with respect to their reliability, their ability to be integrated into the installation and its grid, and their costs. Though the comments are general, it is important to note which technologies are most suitable for an individual installation will vary based on local conditions. This task was performed through extensive literature search and by visiting sites where alternative energy is currently used, both on Air Force installations and commercially.

This chapter will discuss electrical energy derived from coal, petroleum, natural gas, nuclear, hydro, wind, solar, bio-material, synthetic, geothermal, and fuel cell sources. Figure 4 below summarizes the four criteria used to assess each of the energy technologies. The criteria were chosen because they represent the areas that influence installation leadership as they make energy investment decisions. After going through numerous technologies and detailing how they perform against the criteria, the chapter concludes with an overall summary of the technologies.

Power Supply Reliability

- Immediate access to fuel supply with highly reliable generation technology
- Limits to fuel supply access and/or constraints to highly reliable generation
- Variable or uncertain fuel supply or unreliable for backup power generation

Installation Considerations

- Easily integrated on Air Force installations
- Minor issues with operations or minor environmental/siting concerns
- Major issues with operations or major environmental/siting concerns

Grid Integration Considerations [1]

- Operates at high capacity factor; can be base load
- Generally matches load, but with grid stability concerns
- Does not load match

Cost

- Capital and operating costs are competitive with domestic grid; (< $0.10 per kwh)
- Financing through public/private partnerships makes capital and/or operating costs competitive with domestic grid; ($0.10 - $0.20 per kwh)
- Median costs exceed domestic grid by 100% (> $0.20 per kwh)

1]. Borrowed from Scientific Advisory Board, "*Alternative Sources of Energy for US Air Force Bases: Opportunities and Challenges,*" *pg 34.*

Figure 4: Criteria for Assessing Energy Technology Applicability to AF Installations

The *Power Supply Reliability* criterion takes into account two factors. The first is a qualitative assessment on the accessibility of the energy source for the particular energy generation technology. Supply chains can be adequately established for certain fuels, such as diesel or natural gas. Other power supply sources are completely dependent on weather patterns, and are thus less reliable. The second is a qualitative assessment on the reliability of the electrical generation source itself. Some technologies have many moving parts, and are prone to failure more frequently than systems with less moving parts. Additionally, some technologies are more mature and have a history of implementation and technology improvement. These technologies are inherently more reliable.

The *Installation Considerations* criterion takes into account the complexity of integrating the particular electrical generation source onto the base. For example, certain generation technologies have specific geographical requirements. Some generation technologies require sources of cooling or large swaths of open land. Further factors include the complexity of environmental, safety, and security compliance since Air Force installations need to comply with other governmental agency regulations related to the technologies. In addition, local and state governments, as well as private utility stakeholders, influence the degree of difficulty or ease in integrating a generation source onto an installation. Lastly, there will be significant variability based on location and specific implementation. The energy sources are therefore assessed for *Installation Considerations* in the aggregate.

The *Grid Integration* criterion assesses the physical integration of the generation source into the installation grid. Factors such as how well the generation technology matches load or is capable of handling the base load are taken into consideration. Additionally, the scalability of the technology is assessed. Technologies could be clean, efficient, and cheap, but if they are only practical in the gigawatt range then they may not be suitable for integrating into the installation's grid.

The *Cost* criterion assesses the wide variety of cost estimates that exist for the electrical energy generation sources. Over time, the estimates have varied and will continue to vary as technologies become more mature and as suppliers move in and out of the market. Cost estimates are also dependent on the market price of the particular fuel, as evidenced by the volatility in the price of crude oil from the 1960s through the 2010s. Estimates will also vary with respect to geography and location of the particular source. Numerous other variables exist which can impact the costs of a particular energy source; for example the cost associated with environmental regulatory compliance. This study does not attempt to provide a comprehensive summary of all the estimates in the literature. It does, however, provide a range of the most commonly found estimates.

In particular, three sources were primarily used for reporting cost. The first is from the United States Energy Information Administration (EIA). The EIA publishes an Annual Energy Outlook for the United States, and an interactive, searchable database including information such as total energy generation by source, estimated costs by source and by region, total capacity, and total consumption. This data is available online (found at http://www.eia.gov/forecasts/aeo/). The second source is the 2012 Global Energy Assessment, a report undertaken by a council of 36 leading energy experts from across the globe and spawned from the Intergovernmental Panel on Climate Change (found at http://www.globalenergyassessment.org/). The last source is jointly sponsored by the Department of Energy and the National Renewable Energy Lab and is an interactive open source database containing a variety of energy data (found at http://en.openei.org/apps/TCDB/).

The cost estimates cited in this chapter have a wide range. There are many reasons for the variability. The data from all three sources is reported as the Levelized Cost of Electricity (LCOE). The LCOE is an estimate that takes into account upfront capital investment and installation costs, fixed operations and maintenance costs, fuel costs, and a discount rate over a period of time. The EIA also reported historical retail prices. Each input into the LCOE can vary, resulting in a wide range for the technologies considered. Discount rates ranged from one to ten percent across the sources, and estimated capital costs varied dramatically. Estimated operations and maintenance costs are driven by capacity factor, location, economies of scale, and other inputs, and can vary. Fuel cost estimates use historical data, which vary as well. Additionally, it is not always clear if cost estimates include government subsidies or not. For Chapter Two, the estimates are the LCOE estimates cited from the sources above and are not calculated. This study uses LCOE estimates because they are the most consistently reported and represent as close to the total expected cost for a government customer without the presence of public-private partnerships, long term contracts, renewable energy credits or other cost reducing mechanisms. For costs used in Chapters Four and Five, the estimates are defined and explained. This study reports cost estimates in dollars per kilowatt-hour.

Coal

Taking millions of years to form, coal is a combustible substance made of gradually decomposed plant and animal matter stored in the earth's crust. Because it takes millions of years under high pressure to form, coal cannot be replenished once extracted and burned. Once extracted from the earth, coal is typically milled into a fine powder to increase its surface area. For these pulverized coal combustion systems, the powder is burned at a high temperature. The hot gases convert water into steam, and at high pressure the steam rotates a turbine producing electricity.

Power Supply Reliability

Coal is capable of providing enough electrical power to a system given that sufficient fuel and infrastructure exists. The Defense Logistics Agency supplies coal to 11 Department of

Defense installations ranging from Alaska to Texas (DLA Energy FY14 Factbook, page 50). When the system is properly operated and maintained, coal plants tend to be highly reliable. For example, the harsh weather conditions of Alaska make supporting the military mission at Eielson AFB, Alaska unique, requiring on-site generation which is met by a coal plant fed by a local ample supply of coal. Sites like the Central Heat and Power Plant at Eielson AFB require continuous deliveries of coal. This technology is extremely mature.

Installation Considerations

Coal power plants are one of the most pollutant-heavy sources of electrical energy, and are recently showing decline in total number of generators. Across the entire electrical utility industry, coal power plants account for a significant portion of the sulfur dioxide and nitrogen oxide emissions. By burning coal, carbon stored in the coal is released back into the atmosphere as carbon dioxide. The mining, processing, and transportation of coal can have harmful effects on the environment, especially when coal is removed through strip mining.

The low price for energy derived from coal power plants can be partially attributed to economies of scale. Typical coal power plants are sized around 500 MW, and require large shipments of coal to be transported in by rail. Once unloaded from the railcar, coal will sit in a large mound until it is moved into the boiler. Such large plants require a substantial amount of land, and annually need billions of gallons of water for cooling waste heat from the combustion process.

Thus four major hurdles exist for putting coal plants on Air Force installations. The Air Force is generally not postured to navigate the regulatory burden of ensuring safe, clean coal production on their installation. Even if a utility is willing to shoulder the majority of the regulatory work, the physical infrastructure of transporting coal to Air Force installations would be financially burdensome, and often impractical, especially in the case of new locations. In the case of new development, it's possible that the installation may be in a nonattainment area for a particular pollutant under the Clean Air Act. Nonattainment areas are locations that do not meet, or contribute to a nearby area that does not meet, the National Ambient Air Quality Standards as defined in the Clean Air Act. Lists of nonattainment areas for pollutant standards can be found on the EPA website (EPA, "The Green Book Nonattainment Areas for Criteria Pollutants"). If the installation is within one of these areas, they may not even be able to apply for and build a coal plant. Lastly, recent history of base realignment and closure tends toward downsizing military installations. The installations remaining typically don't have natural access to significant amounts of water for cooling waste heat.

Grid Integration Considerations

A coal-fired power plant can be attractive for a military installation. During planning, the power plant can be correctly sized for the forecasted energy demand of the installation, and can provide prime power for the base load. Though the smaller size would drive up the marginal cost of energy, in event of a power failure to the domestic grid, the base could island itself off and continue operations. However, the base remains vulnerable to routine failure on site, which results in loss of power from the power plant. The military could also decide to size the plant larger than the base demand, and sell excess power to the local utility. Utilities are often open to such partnerships, though regulations limiting the amount of energy generating capacity on residential and commercial sites are gaining traction and are state dependent. Regulators are balancing the objectives of allowing individuals to install solar and other generating capacity and ensuring local utilities are not unduly burdened with managing a changing network too quickly or costly.

Cost

Coal is a low-cost energy source with generally stable prices. The stable prices are reflective of large capital costs associated with establishing extraction centers at mines, and these mines tend to operate for a long period of time. Similarly, expensive rail transportation systems have been built to support the coal industry, and these upfront costs keep coal prices stable. The supply of coal worldwide is plentiful, especially in the United States. Historically, coal has been lower per kilowatt-hour than oil and natural gas prices for electrical production. Coal is often reported in the range of $0.06 to $0.15 per kilowatt-hour, with a median at $0.09 per kilowatt-hour (found at http://en.openei.org/apps/TCDB/). These cost estimates are a reasonable reflection of the price charged to the consumer for electricity use, as coal has historically led the United States in total generation capacity.

For on-site generation of coal, the Clean Air Act will likely introduce costs to the installation either directly or indirectly. Direct costs include the application for and renewal of permits for sources that release pollutants into the air. Other direct costs include measuring particulate in the air and implementation of steps and plans to reduce air pollution. Indirect costs include costs such as the manpower expended understanding and complying with local, state, and federal regulations.

Though coal has been the largest player in electrical generation for the United States, its share in the total generation capacity is decreasing. Planned capacity additions in the United States report less than one-third of new generation to be coal fired facilities. In the developed world, it is becoming less attractive to build coal plants due to environmental requirements. Likewise, the risk of facing future air pollutant (carbon-tax) penalties is high enough to dissuade further growth, and as the price of carbon emissions rises, so too does the price of coal powered electricity.

Petroleum

Petroleum is a naturally occurring liquid trapped in rock formations in the earth. A mixture of hydrocarbons and other organic compounds, petroleum has a high energy density and can easily be transported. In the 20th century, oil was the world's most important source of energy, driving the transportation sector and used for electrical power generation. Petroleum based power plants work similarly to a coal plant, except the fuel is liquid instead of solid. The Department of Defense has established a standard family of diesel generators that range in size from large prime power generators to small tactical quiet generators. The Air Force manages its power plants and supply of generators in accordance with AFI 32-1062 requirements, which is discussed further in Chapter Four. Per a Fiscal Year 2004 annual generator report, Nellis Air Force Base used 41real property installed equipment (RPIE) generators and 23 Equipment Authorized Inventory Data (EAID) generators. 59 of the 64 generators used diesel as the fuel source, while the remainder used regular unleaded gasoline.

Power Supply Reliability

Like coal, oil is capable of providing enough electrical power to a system given that a sufficient fuel supply exists and the infrastructure exists to support generation. When properly operated and maintained, oil-based electrical generators tend to be highly reliable. Due to the relative ease in acquiring and storing oil based fuels like diesel fuel or gasoline, these generators hold the largest share in backup power generation. Of the FY2004 Nellis AFB numbers above, 46 were fixed site backup generators, meaning they served as a backup generator to a specific facility. The other generators were used as mobile generators, serving locations like wells, barrier pits, and security entry control points, or as standby for the fixed site generators. Prime power for deployed operating locations is typically supplied by diesel fuel-based generators.

Installation Considerations

There are numerous reasons most back-up power capability for military installations uses a generator which runs off of fuel derived from petroleum. First, the fuel can be easily stored near the generating source, reducing logistic demands on transportation, storage, and force protection. Second, Air Force installations often have large amounts of fuel stored onsite, like jet fuel JP-8. These fuels can supplement stored supplies for backup electricity generation. Additionally, because of the high reliability of properly maintained generators, these generators often last for long periods of time and have low operating costs.

Some fuels, however have a short shelf life and must be monitored for storage container degradation and leaks. Further, installations must adhere to the Environmental Protection Agency technical standards and regulations for underground storage containers containing petroleum based products, as codified in Parts 280 and 281 of Title 40 of the Code of Federal Regulations. These same fuels can be very flammable, increasing risk to nearby infrastructure and personnel. If spilled, they can cause significant environmental problems. In use, emissions from these generators give off carbon monoxide and other harmful air pollutants. The Clean Air Act allows generators classified as emergency to avoid emission limits, but installations must be cognizant of the potential for additional environmental compliance requirements if the generators are used as part of a demand response program.

Grid Integration Considerations

Petroleum based generation is highly scalable to fit installation energy requirements. Generators can be large and fixed to a specific site, providing dedicated base or back-up power. Likewise, generators can be much smaller and mobile, and can provide power on-demand and responsive to turbulent needs. These generators naturally work well as back-up power when connected along with an automated transfer switch to a facility.

Cost

Oil is typically a low-cost energy source; though the price of crude oil peaked in the late summer of 2008 at $150 a barrel before dropping in 2009 to less than $40 a barrel (EIA, "Petroleum Weekly Spot Price"). The capital costs are fairly small and the commercial market for diesel and gasoline generators is competitive. Operating costs are low, and maintenance costs are minimal. As with coal, electrical energy production from petroleum is decreasing. Also, as the carbon dioxide emissions costs begin to increase, the cost of petroleum and its products are likely to rise as well. Larger, fixed site and new construction will face environmental and Clean Air Act regulatory costs. Cost estimates from $0.035 to $0.18 per kilowatt-hour, and the range is largely a reflection of the oil market and to a lesser extent, the size of the generator (found at www.eia.gov). Though there may be additional indirect costs due to regulatory compliance, asset management, and personnel support, these are minimal especially considering the history of generator use across the Department of Defense.

Natural Gas

Often found in the same locations as coal and petroleum, natural gas is a fossil fuel formed from organic material subjected to intense heat and pressure over thousands of years. Not only is natural gas used for cooking and heating, it is also a major source of power generation through gas turbines and cogeneration. Cogeneration is the simultaneous production of two forms of energy from the same source, and results in higher efficiency systems. Cogeneration, or combined heat and power, systems commonly use natural gas as the fuel; the hot gases drive a steam generator and the byproduct heat is captured for use. Cogeneration has been successfully used at Twentynine Palms Marine Corps Air Grounds Combat Center in California, reducing dependency on the unstable California grid (Kaufman K., "Twentynine Palms Cogeneration Plant Aims for Efficiency).

Collecting gas emissions from landfills are a unique way of generating electricity in a way that is considered renewable. Landfill gas differs from natural gas in that it is derived from bacterial decomposition of organic material in landfill waste, and this process occurs over much shorter periods of time than natural gas. Landfill gas can be collected through a series of pipes, and the useable gasses like methane can be cleaned and transported to an energy generation site. Most of the landfill gas projects use internal combustion engines, or can be used like natural gas in cogeneration projects. Marine Corps Air Station Miramar built a 3.2 megawatt landfill gas plant on the San Diego Miramar landfill. The city of San Diego landfill sits on land leased from the U.S. Navy and is adjacent to Miramar. In total, the plant provides over 50 percent of the Air Station's energy requirement (Max, "Landfill Providing Power for Miramar").

Power Supply Reliability

Like coal and petroleum, natural gas generators provide enough electrical power to a system given that a sufficient fuel supply exists and the infrastructure exists to support generation. Combined heat and power systems have the added benefits of increased efficiency and reduced electrical demand by providing a source for water or space heating. Although dependent on location, natural gas supplies are generally easy to acquire and distribution pipelines and storage solutions at typical Air Force locations are available. Likewise, landfill gas projects, if properly managed, can provide a reliable supply of gas for energy generation. Analysis should be performed to ensure that the landfill gas production rate is high enough for demand.

Installation Considerations

Though Air Force installations do not have large amounts of natural gas stored onsite like they do for JP-8, the domestic commercial market for purchase and transportation of natural gas is mature. However, due to its low density, it is not easy to store, which is a consideration during long periods of use. Leaks in gas lines can have negative effects, being a waste of expensive fuel and having the potential to result in explosions and fire. From an environmental standpoint, natural gas burns more cleanly than other hydrocarbon fuels. Gas from landfill plants will have more contaminants than pure natural gas, though total emissions remain low. Additionally, gas generators perform comparatively well in cold climate locations.

Grid Integration Considerations

Not only can natural gas generators supplement grid power, but they can be sized to take over prime power. Because most grid peaking power plants use natural gas, it is well suited to provide supplemental power on grid dominated Air Force installations. Similarly, it also compliments renewable sources which have difficulty matching loads. Cogeneration provides another layer of flexibility because it can either be sized for heat driven operations and used for excess electricity, or conversely can be sized as a power plant and drawn on for its waste heat generation. Though flexible for sizing and matching loads, gas generators are not as mobile as typical liquid fuel based generators.

Cost

Natural gas prices remain competitive as a source of electricity. Because natural gas generators burn cleaner, the engine life expectancy is relatively higher when compared to diesel generators. Cogeneration systems have higher capital costs, and once the system is in place these systems require frequent maintenance and upkeep in order to optimize performance. Cost estimates lie in the range of $0.02 to $0.12 per kilowatt-hour (found at http://en.openei.org/apps/TCDB/). Additionally, landfill gas estimates range from $0.06-$0.14 and are dependent on how much the landfill charges for the gas and the costs associated with transporting the fuel from the landfill to the generation plant (found at www.eia.gov).

Solar

Solar energy is the process of converting sunlight into a useful form of energy. Though there are numerous methods of extracting electrical energy from sunlight, two of the most common are photovoltaic cells and concentrating solar power. Photovoltaic cells, commonly called solar cells, directly convert sunlight into electricity. One of the most well-known applications of a photovoltaic cell is in some handheld calculators, in which the calculator is powered by the photovoltaic cell and functions even with limited exposure to sunlight. Other small-scale uses of photovoltaics include watches and GPS handheld devices. Additionally, larger solar modules, or groups of solar cells on a single frame, can be regularly found on road signs and street lights. Larger solar cell arrays, in which many modules are joined together, are used to power electrical systems on satellites and are often found on or around residential housing. The largest use of photovoltaic cells is for large-scale energy generation and distribution, with photovoltaic farms producing tens of megawatts of electrical power. Considerable growth has occurred in the construction of solar energy projects over the last decade, and over 10 photovoltaic power plants now exist that exceed 200 MW.

Photovoltaic cells are made of semiconductors. When light strikes the cell, the semiconductor material absorbs the energy associated with the light. This energy frees electrons from the semiconductor and in the presence of an electric field, the electrons flow together, creating a current. With contacts at each end of the photovoltaic cell, the current is drawn off and used as electricity. Because most semiconductor material can be quite reflective, an antireflective coating is often applied to reduce reflection losses. A transparent cover plate is also added in order to protect the cell from the environmental effects, such as heavy rain and hail (Beckman and Duffie, pg 768). Solar cell efficiencies have gradually been growing as advanced material development has progressed. Solar cell efficiency losses are due primarily to the incapability of the cell to capture the energy from photons at lower or higher wavelengths than the band given by the specific semiconductor. Other losses are caused by metal contacts on the upper and lower sides of the solar cell, and further losses stem from internal resistance of the semiconductor material itself.

Photovoltaic systems can be stationary or can be set up to track the sun during daylight hours. In the northern hemisphere, stationary or non-tracking photovoltaic cells are oriented south and inclined at an angle equal to the area's latitude. Individual users may change the orientation or inclination in order to maximize energy production relative to demand. Adding single-axis solar tracking systems increases the amount of direct sunlight exposure to the cells, and can be a relatively inexpensive addition.

Whereas photovoltaic cells directly convert sunlight into electricity, concentrating solar power (CSP) systems use mirrors, lenses, and tracking systems to concentrate a large area of sunlight into a more condensed beam. This concentrated light has an elevated temperature, and this heat is used as a heat source for a conventional power plant. Though CSP systems differ with respect to how the sun is tracked and how light is concentrated, all CSP systems heat a working fluid by concentrated sunlight, and the working fluid is used for electrical power generation. CSP systems trace their lineage to Auguste Mouchout, who in 1866 used a parabolic trough to produce steam for the first solar steam engine. Since then, concentrated solar has been developed for use in irrigation, refrigeration, locomotion, and large-scale energy generation. The most common CSP technologies include the solar trough, the parabolic dish, and the solar power tower.

As seen in Figure 5 below, the solar trough consists of linear parabolic reflectors which serve to concentrate light onto a receiver. Most solar trough systems follow the sun during the day by tracking along a single axis. One of the larger solar trough systems in the United States is Nevada Solar One, a 400-acre scale solar trough in Nevada, and it operates with a nominal capacity of 64 MW costing $266 million (Acciona Solar Power).

Figure 5: Solar Trough Array
Source: NREL webpage (www.nrel.gov)

The parabolic dish system is typically the smallest CSP system. These stand-alone systems use a dish-shaped reflector to concentrate solar energy on a superheated fluid at the focal point of the reflector. The high temperature fluid is then used to generate power in a small engine located at the focal point. Parabolic dish systems, particularly those with high levels of concentrated solar energy, give the greatest efficiency among the three CSP technologies discussed here ("An Assessment of Solar Energy Conversion Technologies and Research Opportunities"). Figure 6 below shows an example of a parabolic dish system.

Figure 6: Parabolic Dish Stirling System, Spain

The third CSP discussed here is the solar power tower, which is made up of a system of movable mirrors and a tower. The mirrors are oriented according to the position of the sun, and the light is reflected to a receptor located on the top of the tower. The heat from the concentrated solar radiation is transferred to a fluid with the purpose of generating steam that turns a turbine coupled with a generator for producing electricity. Figure 7 below shows an example of a solar tower system.

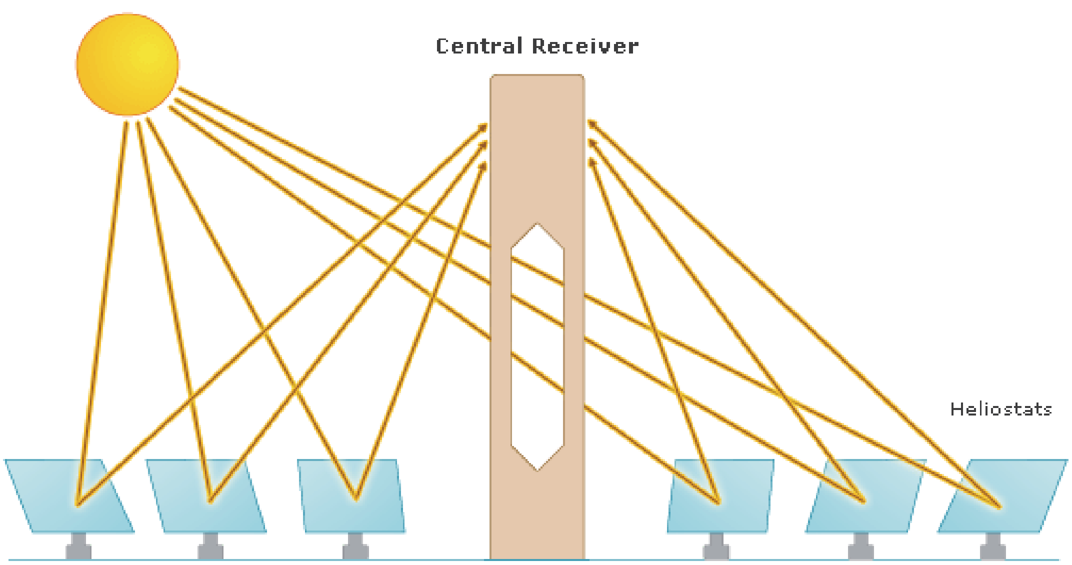


Figure 7: Solar Tower System
Source: Abengoa Solar webpage (www.abengoasolar.com)

The performance of both photovoltaic cells and concentrated solar cells is measured in how efficient the system is at turning sunlight into electricity. For example, a solar cell with an efficiency of 15% indicates that about one-sixth of the sunlight striking the cell generates electricity. Improving the efficiency of solar cells has been and remains an important goal of the solar technology community. Solar cell efficiencies have continuously improved since early commercial development. Figure 8 below shows solar cell efficiencies for photovoltaics. The multi-junction cells near the top of the chart use multiple thin films bonded together in order to absorb more of the electromagnetic spectrum. Significant progress has been made since the 1970s, though cells remain below their thermodynamic efficiency limits of 31% for single junction and 50% for 3 cell multi-junction stacks (Green, “Third Generation Photovoltaics”). According to Green, parabolic troughs and solar power towers reach peak efficiencies around 20%. Parabolic dish systems, as mentioned earlier, are the most efficient and have reached upwards of 30% solar-to-electric efficiency.

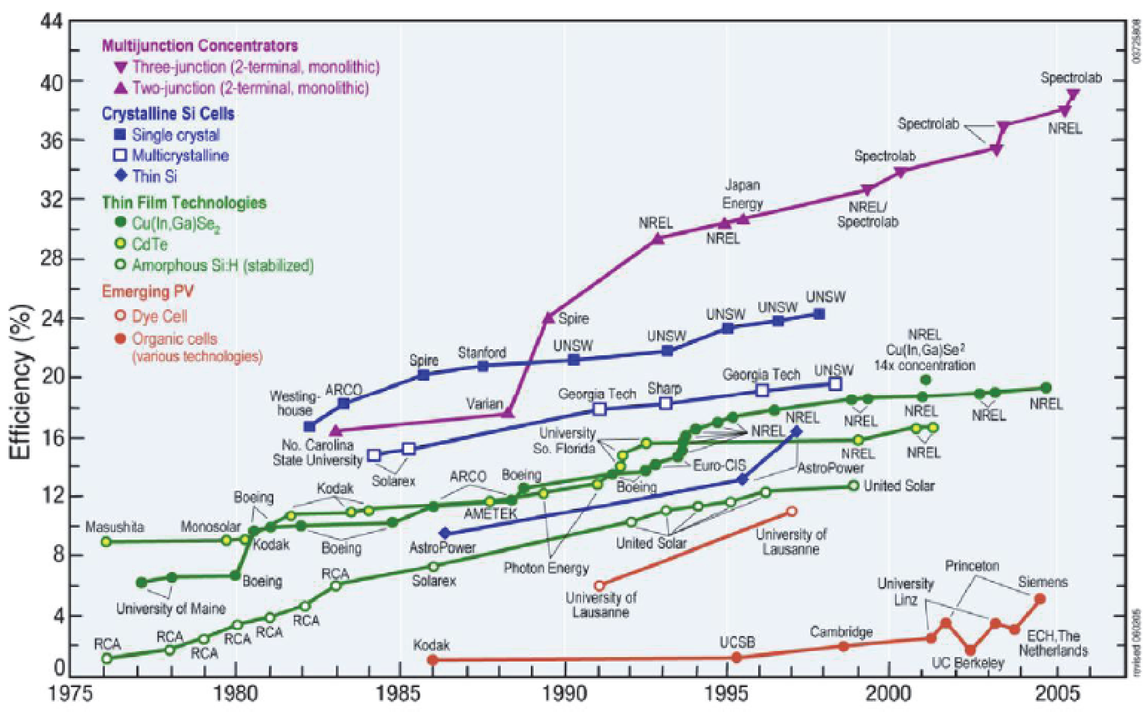


Figure 8: Efficiency Ratings of Solar from 1975 to 2006

Source: Green, et al, pg 425-430.

Solar energy received additional attention in this study due to the fact that of the nearly 900 renewable energy projects in the Department of Defense in 2013, 662 were solar photovoltaic and thermal systems (2013 Annual Energy Management Report, pg 37). For example, Nellis AFB in Nevada and the Air Force Academy in Colorado operate a 14 megawatt and a 6 megawatt photovoltaic power station, respectively. The Nellis AFB site uses a sun tracking system designed and built by SunPower. Nellis AFB leases the land for free, and entered into a Power Purchase Agreement where they agreed to buy power for 20 years at $0.022 per kilowatt hour, approximately $0.07 per kilowatt hour less than the price paid for electricity to the local utility Nevada Power. Additionally, Nellis AFB is planning to expand its use of solar by building a second site delivering up to 19 megawatts of photovoltaic power ("McCabe, Nellis AFB to Add Second Large Solar Plant").

Power Supply Reliability

Given accurate weather forecasting, solar power can be predictable. However, solar power is not available at night, and even clouds can decrease power production. Further, without a system of regulating and storing energy output, solar systems are impractical as an installation energy solution for improving reliability. The ability to generate electricity and store the excess energy during high solar periods would allow solar power to become more responsive to the demand and thus be a more reliable supply. The National Renewable Energy Laboratory, in partnership with the Raytheon Company, Primus Power, and Advanced Energy successfully demonstrated an energy storage system microgrid with conventional photovoltaic cells. This test demonstrated the capability of a solar system, coupled only with battery backup power, to completely satisfy critical facility loads. The system is in the process of being fielded at Marine Corps Air Station Miramar (Raytheon Company, "Raytheon Demonstrates Advanced Microgrid System and Control Capabilities").

Installation Considerations

Evidenced by the 662 solar photovoltaic projects across the Department of Defense, the military is familiar with installing and using solar on installations. Many of these systems can be found on rooftops or covering parking lots; these systems tend to be small and can be easily integrated on existing infrastructure. Larger systems like the 14MW site on Nellis Air Force Base require significant tracts of open land. This can produce an obstacle for numerous installations, though the military tends to have large tracts of land available for housing a solar generation plant.

It is also important to note that solar arrays can reflect unwanted sunlight into flight paths; thus consideration must be made locally to ensure glare risks are mitigated. Training bases are highly sensitive to risks to their training programs, and those installations will have to mitigate potential risks associated with solar equipment, such as visual impacts or encroachment. Though unwarned reflections and glare are hazardous to the training mission, if adequate safeguards and procedures are in place, the environment itself can be useful for training pilots to operate in solar reflected environments.

Solar energy becomes significantly less cost effective and produces far less energy in areas of the county that have regular cloud cover. What is a great option for bases located in a desert might not work well for bases in more moderate climates. There is also a class of stand-alone solar systems, in particular flexible, thin-film solar technologies that can be easily installed and transported. These offer the possibility to reduce the fossil-fuel burden on expeditionary bases or sites far from supply lines.

Lastly, solar power is pollution free during use. There are minimal production wastes and emissions, and disposal costs are manageable with existing technologies and pollution controls. Solar energy generation also creates Renewable Energy Credits (RECs), which the base can use in meeting its federally mandated renewable goals or can sell back to industry.

Grid Integration Considerations

Energy output varies with solar intensity. A single cloud causes a corresponding drop in electrical output, thus increasing grid stability concerns. However, load-leveling and storage technologies exist, though these increase the cost of the system. Additionally, since the hottest part of the day corresponds to the highest solar intensity of the day, solar energy generation displaces the highest cost electricity during these peak times of demand. Since the system is placed on-site, grid connected solar energy is used locally and reduces transmission losses.

Cost

The concept of generating a significant amount of the world's electrical energy from solar radiation is generally viewed as an attractive energy solution: solar energy is one of the cleaner forms of renewable energy and capturing/using the energy has limited negative effects on the environment. The underlying advantages of solar energy are that the fuel is free, abundant, and environmentally friendly. Long range modeling of the role of solar by the National Renewable Energy Laboratory shows higher solar inclusion in the domestic grid if electrical demand increases over time, and significant cost and performance improvements in photovoltaic and concentrating solar power technologies (NREL, "Renewable Electricity Futures Study," pg 10-38).

The current cost of producing solar energy remains higher than both conventional, nonrenewable sources and other renewable sources. Total cost estimates are found to be between $0.16 and $0.37 per kilowatt-hour, with the lower estimates representing concentrating solar power and the higher costs representing photovoltaic solar power (found at http://en.openei.org/apps/TCDB/). While current tax and renewable credits bring the estimate down further, these credits may not be available as government officials move in and out of office, and will vary based on the details of each state's program. The tax credits are not applicable to a government customer, but are applicable for utilities or private companies who perform the construction and operation of the site. Though operating and maintaining the sites requires minimal levels of effort, installation costs are very large. Depending on state and federal incentives, and local rates, typical payback periods for solar systems can be 14-20 years (*Alternative Sources of Energy for US Air Force Bases,* pg 68). Funding projects within the government that have payback periods of 14-20 years can be difficult to secure. However, there are a number of financing opportunities available for the government that make the purchase of photovoltaic systems cost efficient, such as Energy Savings Performance Contracts (ESPC), Utility Energy Service Contracts (UESC), or Enhanced Use Leases (Lachman, et al, *Making the Connection: Beneficial Collaboration Between Army Installations and Energy Utility Companies*).

These financing opportunities, coupled with the national and state renewable energy goals backed with incentives and credits, make solar energy generation an increasingly competitive option. For example, the State of Colorado House Bill 10-1001 created a renewable energy portfolio standard under which utilities are required to achieve 30% renewable generation by 2020. Colorado military bases are impacted by this legislation from the perspective that they partner with utilities seeking to meet the 30% standard. The Air Force Academy's $18.3-

million, 6 megawatt project, funded by the American Recovery and Reinvestment Act of 2009 is an example of such partnership. Colorado Springs Utilities, as the service utility and energy purchaser, benefits for its renewable energy portfolio while the Air Force saved $802,000 in avoided power purchases over the first year of operation (Baillie, "AFA Solar Array Saves Taxpayers $802,000 in First Year").

State incentives also exist that make solar cost effective in moderate climates. For example, in the state of New York, utilities provide net metering for residential sites up to 25 kilowatts and commercial and industrial applications up to 2 megawatts. The New York Sun Solar PV program offers incentives to reduce installation costs, such as an income tax credit of 25 percent of the installation cost, exemption from state sales tax for passive solar installed in residential and multi-family residential buildings, and a 15-year property tax exemption for the cost of solar and other renewable to ensure property taxes do not rise (NY State, "Solar Energy in New York").

Wind

Wind energy is a renewable energy source that captures the energy in wind and converts it into electrical energy. Long rotors, or blades, which rotate on a shaft, capture wind energy. This shaft is connected to a gearbox which increases the rate of rotation. Windmills for grinding grain or for drawing water from wells mechanically convert the energy from this rotating shaft. For electrical generation, this rotating shaft is connected to a generator which ultimately produces the electricity. Wind power is a mature technology, with wind turbines first being used for electricity in the late 19th century. The Air Force operates two wind turbines at Cape Cod Air Force Station in Massachusetts. The energy from the two 1.68 megawatt turbines is sold directly to the local utility company, and the military unit receives energy credits back on its bill.

Two concepts are important when considering the turbine size for a wind generator. The first is capacity factor, which is a ratio of the actual productivity to the generator's full-load sustained capacity, or nameplate capacity. Sites with consistent wind have higher ratios, while more intermittent areas have a lower capacity factor. Many factors go into predicting the capacity factor at a particular site; choosing a location with consistently high or constant wind quality is a key factor. The second is penetration, which is the ratio of energy produced by wind compared to total energy produced for a particular grid.

Power Supply Reliability

Wind power generation is highly variable across numerous timescales; wind speeds vary by the minute, by the hour, by the day, and even by the season. Power generation and consumption must remain balanced for a grid, so wind turbines are rarely used as a sole energy source since power is only generated when the wind is actively driving the generator. Like solar power, without a system of regulating and storing energy output, wind turbines are impractical as a backup power supply. The ability to store the excess wind energy allows wind power to become more responsive to the demand. Likewise, the ability to operate wind power along with other diverse generation sources allows the grid to become a more reliable system. Because the technology is fairly mature, when properly operated and maintained, wind generation turbines require little maintenance and upkeep.

Installation Considerations

In practice, the penetration level for wind power is typically low and wind turbines are sized to contribute on average no greater than 20% of total capacity. This would be typically true if a wind turbine is considered for an Air Force installation that is looking for solutions when disconnected from the local grid. However, low penetration ratios should not preclude a wind turbine for consideration as long as the installation officials understand the variable nature of wind energy.

Geographic considerations are of primary concern for installing wind power across Air Force installations. Some bases have poor wind quality, while other bases that have good wind quality may not have the physical accommodations for a turbine. Bases are often located in heavily populated areas, and there may be local or regional regulations that prohibit wind turbines in certain zones. Base planners must consider radar transmission and receive stations, and environmental concerns such as habitat protection when determining where on the installation that wind turbines could be located.

In 2006, the Department of Defense issued a report to Congress on the effects of windmill farms on military readiness, including an assessment of the effects on military radar installations. In particular, wind turbines in radar line of sight can impact the return signal, adversely degrading the mission. Physical mitigations such as terrain masking exist, but must be assessed on a case-by-case basis to measure their impact on mission degradation. Data processing mitigations, such as wind turbine clutter algorithms, can mitigate weak environmental returns that are created by the rotating blades. These mitigations must also be assessed on a case-by-case basis, as the algorithms may not be available or implementable on older, legacy radar systems, and the results are dependent on the distance from the wind turbine to the radar source (DoD, "The Effect of Windmill Farms on Military Readiness").

For instance, in 2006 air traffic controllers at Travis Air Force Base noticed unusual activity after they turned on their Air Surveillance Radar after a digital upgrade to the system. The controllers observed persistent but non-existent weather cells, and tracks of aircraft they were following would disappear and reappear. Experts assessing the situation found that the problem with the Primary Surveillance Radar returns only occurred in areas that had both wind turbines in the Montezuma Hills Wind Resource Area and heavy traffic along a nearby highway. Furthermore, the perceived weather cell changed based on the quantity and type of wind turbine rotating. Because the area is traversed by both commercial and military aircraft, Travis AFB officials promptly responded by issuing a notice advising pilots flying in the area without transponders that Travis AFB's ability to provide air traffic control over the area could be limited. Additionally, Travis AFB notified the local Solano County Department of Resource Management, and in turn the developers in the area agreed to halt future development operations until the radar issue was resolved (Losco and Collick, "When Wind, Wind Turbines, and Radar Mix," pg 236-240).

The FAA noted the problem created by the wind turbines in the Wind Resource Area, but decided the problem was not serious enough to issue a hazard determination, and development restarted. Travis AFB and AMC leadership continued to voice concerns about both the safety impact of additional turbines, as well as a lack of a validated predictive tool to assess the impact. Ultimately, through a Cooperative Research and Development Agreement, a joint Air Force, county, and turbine developer working group determined through analysis that the development would not degrade the Air Surveillance Radar performance nor impact air safety or flight operations at Travis AFB. More broadly, this case and others established the need for a Department of Defense clearinghouse to address wind development impacts on Air Force and other radar operations, and it identified the need for Air Force involvement earlier in the development process (Losco and Collick, "When Wind, Wind Turbines, and Radar Mix," pg 242-267).

Other installation considerations include the effects on birds, bats, and their habitats. Research in the area cites increased mortality rates for migratory birds, as well as local impacts such as habitat disruption and reduced nesting/breeding density. The cumulative impact, on the other hand, remains several orders of magnitude lower than the estimated impacts from leading causes of bird mortality such as vehicles, buildings and windows, toxic chemicals, agriculture equipment, and habitat destruction from general construction (DoE, "Wind Turbine Interactions with Birds, Bats, and Their Habitats," pgs 2-4). Another consideration for training installations is the impact on their training missions due to the proposed location of windmills. Having tall structures like windfarms in environments that may not have exquisite terrain features could allow soldiers to orient themselves, thus degrading navigation instruction.

Base planners must also consider safety of flight for its aircraft. For example, the Federal Aviation Administration (FAA) regulates and oversees civil airspace, and in Part 77 of the Federal Aviation Regulations, it establishes standards and requirements for objects affecting airspace. In particular, the FAA assesses hazards for any construction or alteration exceeding 200 ft above ground level or for new construction within height limitations up to 20,000 feet away from civilian or military runways (Federal Aviation Regulation, 14 C.F.R. § 77.13). Care should be taken in identifying hazards and implementing mitigation measures for enhancing safe air navigation. Thus, megawatt class systems appear to be impractical for most Air Force installations that do not have open tracts of land available away from airfield operations. Smaller systems are more practical, but would still face considerable challenges in terms of location relative to airfield operations, radar receivers, and training locations.

Grid Integration Considerations

Wind power typically does not operate at a high capacity factor, and cannot handle the base load on its own. Because of fluctuations in wind speed, grids with wind generation require reserve capacity that can compensate for both wind power unavailability and prime generation failure. Excess generation capacity or storage systems fulfill that reserve capacity requirement. Conventional hydroelectricity complements wind power well across the domestic grid. Automated systems detect when wind power generation is high, and can reduce the load on hydroelectric stations. During low wind power generation, hydroelectric stations can react quickly and increase generation capacity. Furthermore, pumped storage hydroelectricity can take advantage of high wind generation to pump water to a reservoir and store the energy for use during lower generation periods.

Air Force installations are not typically located with hydroelectricity resources on site, but can partner with local utilities that have those resources. Where they aren't available, compressed air and thermal energy systems could store energy, as well. These storage solutions reduce the variability present in wind generation and can reduce grid stability concerns. Introducing wind power to an installation raises the requirements for system management as load shedding during high wind periods must be controlled and storage systems must be incorporated and maintained.

Cost

Wind power installation costs are competitive for three reasons. First, the technology is mature and when sited properly, can displace a significant portion of energy demanded. Numerous manufacturers have developed generators for varying sizes, so profit margins are lower compared to newer or more specialized technologies. Second, renewable energy credits can be sold or used to meet otherwise costly metrics. Third, operation and maintenance costs are very low for wind turbines. Other than the blades or tower, replacement parts are neither difficult nor costly to acquire and store. Turbines often operate for longer than 20 years, and with low maintenance costs this leads to significantly reduced costs for energy production. Cost estimates for wind are commonly reported in the range of $0.03 to $0.11 per kilowatt-hour (found at http://en.openei.org/apps/TCDB/). Offshore wind estimates are higher at $0.07 to $0.25 per kilowatt-hour (*Global Energy Assessment,* pg 54)

However, intermittency of wind energy production raises costs due to the requirement for operating reserves, energy storage solutions, and system monitoring. Regulatory costs, either in terms of dollars or manpower, can also be burdensome when initiating a wind generation project. Some of these costs are coming down as storage technologies become more mature, and smartly applied storage solutions can decrease an installation's cost if the stored wind energy is used to displace demand during peak demand periods.

Geothermal

Geothermal energy is collected by exploiting the temperature differential below the surface of the earth. The Earth's internal heat is used to warm water to steam to drive turbines that generate electricity. Ground source heat pumps are an additional way to generate energy from the temperature differential below the surface of the earth. These systems differ from typical geothermal systems in that they take advantage of the moderate temperature of the ground very near to the surface of the earth, which is typically found to be between 50-60 degrees Fahrenheit. In the winter, the earth is used as a heat source and a heat pump transfers heat from the ground to a facility. In the summer, the cycle is reversed and the heat pump transfers heat from the facility into the ground.

The temperature differential in geothermal systems is enough to generate steam and therefore meaningful levels of electricity. Ground source heat pumps are located in locations where the temperature differential is not high enough to generate steam, and are not commonly used for electricity. Instead their primary purpose is for heating and cooling buildings or water tanks. The sections below discuss geothermal energy used for generating electricity, though Air Force installations should consider the use of ground source heat pumps as a way to reduce heating and cooling loads.

Naval Air Weapons Station China Lake is home to one of the largest renewable energy projects in the Department of Defense. The site is home to a 270-megawatt geothermal power plant directly connected to the California grid. The site has operated since 1987, and it was fully financed by private investment. Additionally, the site has been a test bed for the Department of Energy, which has used the location and access to geothermal energy for research and development activities, such as the advancement of hydraulic fracturing technology.

Power Supply Reliability

As an electrical energy source, geothermal energy has the ability to provide continual power on demand. In regions where ground temperatures are accessible for geothermal piping, the interior of the Earth serves as a highly reliable supply of geothermal energy. Furthermore, geothermal energy is a closed loop system; water is pumped to the heat source in the ground and it is returned as steam. Once the steam is used for generating electricity, it is cooled and returned back to the earth. The system includes few moving parts, and therefore requires only infrequent replacement of piping and rotating equipment due to the gradual development of corrosion over time.

<u>Installation Considerations</u>

Geographic considerations are the primary issue for installing geothermal systems. Although the continental United States offers numerous desirable locations for tapping into earth's geothermal energy, not all Air Force bases are located at these regions. Figure 9 below shows an overlay of Air Force installation locations on a map of temperatures of the earth 10 kilometers from the surface.

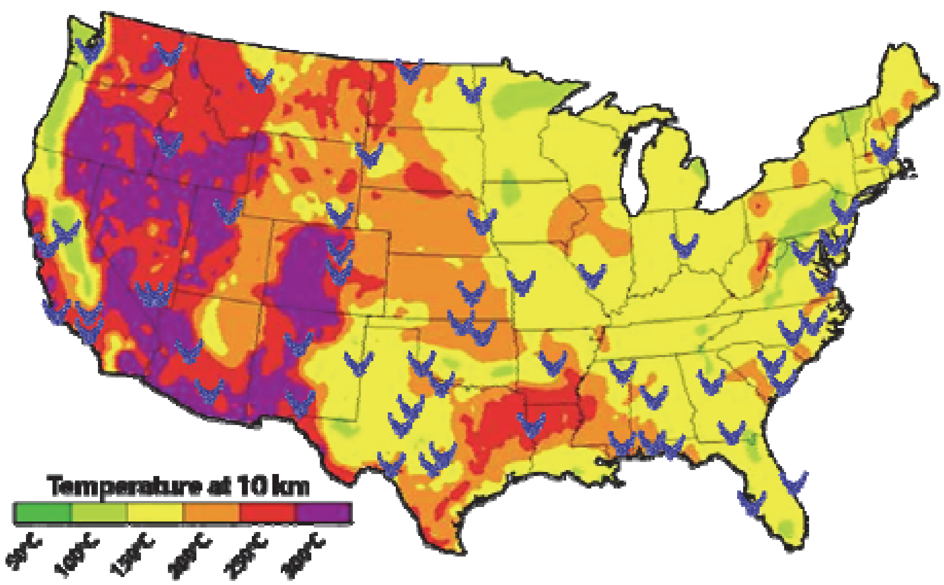


Figure 9: Air Force Installations and Geothermal Temperatures at 10 km
Source: MIT Study "The Future of Geothermal Energy," pg I-14 and SAB Report "Alternative Sources of Energy for U.S. Air Force Bases, pg 60.

As shown, the best regions are located in the western United States. Another issue to consider for operating a geothermal energy system is that cooling water is required and this resource may not be economically available. Environmental concerns are low, as some plants may have carbon dioxide or hydrogen sulfide emissions. But these emissions are low in comparison to coal or liquid-fuel based energy generation sources.

Grid Integration Considerations

Geothermal plants operate best as at a high capacity factor and should be considered a base load resource. The energy source is abundant and energy can be generated all day and night, independent of weather. Geothermal systems are scalable, and can be sized as distributed applications ranging from 1-50 MWs, or can be sized greater than 200 MWs of base load capacity. The installation should match the size of the geothermal power plant to an adequate estimate of the near and long term demand of the installation for optimal long-term operation. The sizing of the power plant must also consider an assessment of the longevity of the geothermal heating capacity of the source below the surface of the earth.

Cost

Like many alternative energy sources, most of the cost for geothermal energy is in the upfront costs. Drilling technology is competitive and reasonably cheap, though if physical access to the site for the large drilling equipment is not available then costs could rise dramatically. Construction of the power conversion facilities is likewise competitive and reasonably cheap, as is any cost calculations for discounted future re-drilling. Geothermal plants have been constructed for decades, and the Navy has operated its China Lake geothermal plant since 1987.

Cost quotes range from $0.03 to $0.09 per kilowatt-hour (*Global Energy Assessment*, pg 54). Estimates for ground source heat pumps are lower than geothermal because the ground source heat pumps do not transfer the heat into electricity. Instead, they directly transfer heat to and from a facility, thereby decreasing a facility's demand for natural gas or electrical heating and cooling. Thus, total costs are competitive with the domestic grid.

Biomass

A large and diverse category of energy supply is biomass energy, which is the energy derived from organic matter like plants. Typical sources of biomass are wood, plants, residue from agriculture, residue from paper generation, and organic components of municipal and industrial wastes. Crops grown specifically for use in energy production are known as biomass feedstocks. It is useful to categorize biomass energy into three categories: biofuels, bioproducts, and biomass power. Biofuels are liquid energy sources used in transportation, and are created when biomass is converted to a liquid form. Ethanol and biodiesel are prime examples of biofuels, and are widely used in South America and Europe. Bioproducts are the result of converting biomass into chemicals that can then be used for a wide variety of products, just as petroleum is used to create plastics, acids, and other compounds. Biomass power is the conversion of biomass into electricity, and is the category considered for this analysis.

There are five major types of biomass power systems. The first two, direct-fired and cofired systems are thermal conversion processes that use heat to generate steam and electricity. Direct-fired systems are the most common throughout the world, and are often found as combined heat and power systems where the heat from the steam is also used for manufacturing processes or heat for buildings. Cofiring systems involve the use of biomass as a supplemental energy source, for example, when biomass is cofired in existing coal plants. The last three types are gasification, anaerobic digestion, and pyrolysis, which are chemical and biochemical conversion processes. Gasification systems use high temperatures and control the amount of oxygen in order to convert biomass into a gas, which is a mixture of carbon monoxide, hydrogen, methane and carbon dioxide. These gases can be separated and used to fuel a gas turbine, which in turn generate electricity. Pyrolysis is similar to gasification, but oxygen is absent at the high temperatures and products, such as pyrolysis oil, can be burned like petroleum to generate electricity. Anaerobic digestion, which naturally occurs in soils, lakes, and sediment, is the decomposition of biomass using bacteria in the absence of oxygen. The resultant methane can be used as an energy source in numerous ways, including as a fuel source in fuel cells.

There is a similar renewable energy technology to direct-fired biomass systems: waste-to-energy processes that use municipal garbage as the fuel source. These systems produce electricity through the incineration of the waste, and the heat is used to drive a steam turbine. The supply of solid waste is already established through garbage collection companies, and cost estimates should be similar to other biomass technologies. The Air Force has begun implementation of a waste-to-energy system at Dyess Air Force Base, which uses city and base waste.

Power Supply Reliability

Across the United States, electricity generated from biomass has provided high quality electrical energy for decades. The reliability of the supply of biomass is generally very high, but it is dependent on the particular source. Biomass power systems that are located near industrial centers, wood and paper processing plants, or near large farming centers have access to an abundant and a continual supply of biomass for generation. On the other hand, if significant transportation is required or if the biomass is weather dependent as in the case of biomass feedstock crops, then the source is not as reliable. The steam-electric generators used in biomass power generations are similar to those used in coal, petroleum, and geothermal plants, so they are highly reliable.

Another component of reliability for biomass relates to the quality of the fuel source. Waste-to-energy (WTE) electrical generation requires a large amount of waste, and this is shipped in by truckloads from municipal waste collection and from installation waste collection. If municipal waste is part of the fuel source, there can be security concerns. However, these can be addressed by locating the WTE plant at the perimeter of the installation, as was implemented at the Harford WTE Facility at Aberdeen Proving Ground in Maryland (Harford County, "Waste-to-Energy").

Whereas most biomass stocks are relatively pure in terms of foreign materials in the supply, waste collection can include a variety of hazardous material. For example, a major problem for the military in deployed environments where they have to dispose of their own trash through incineration is the presence of unused ammunition. The likelihood that ammunition, or other dangerous waste, finds its way into the waste supply is high, and this degrades the quality of the fuel source. Through the incineration process, this could damage hardware, decreasing the reliability of the system.

Installation Considerations

As noted above, locating the biomass power plant near to the supply source of biomass makes the system more reliable in terms of transportation. Air Force installations are dispersed throughout the country, and have reasonable access to biomass supply sources. Like coal and natural gas sites, direct-fired and cofired biomass systems typically need access to water for cooling, but smaller systems that would be applicable to Air Force installations wouldn't require copious amounts of water. Biomass plants can be compact and fit on small tracts of land, so the impact on operations would be minimal.

Burning biomass releases large amounts of pollutants into the air, including nitrogen oxides, sulfur dioxide, lead, mercury, carbon monoxide, and others. Environmental regulations will need to be addressed per the Clean Air Act Amendments and National Environmental Protection Act. In particular, the National Environmental Protection Act requires environmental assessments or environmental impact statements for projects utilizing federal funding, and the reports need to address air quality, hazardous materials and hazardous waste, soils and storm water, biological resources, socioeconomics, transportation, and utilities. As an example, access to the Dyess Air Force Base Environmental Assessment can be found in the references (Dyess AFB, "Waste-to-Energy Plant Environmental Assessment"). Lastly, if the plant is located on the base, military installations will have to consider a security concept of operations for screening the vehicle and personnel movement onto the base, as well as physical security and monitoring of the site and the waste.

Grid Integration Considerations

Biomass power systems are scalable in size, and can be designed to meet a variety of loads. The system can be developed to be small and generate less than 5 MW of power. They can also be larger, though systems above 200 MW are rare. The installation should match the size of the biomass power plant to an adequate estimate of the near and long term demand of the installation for optimal long-term operation, as well as taking into account the long term availability of the biomass supply. Like coal and petroleum based generators, biomass power systems operate at a high capacity factor and can be the base load. Utilities should find integrating biomass power systems on Air Force installations as a good partnership, as the systems are easily integrated into the grid, improve grid reliability, and serve as a distributed energy resource.

Cost

Biomass cost estimates range from $0.02 to $0.22 per kilowatt-hour (Global Energy Assessment*,* pg 54). The wide range is due to the fact that the biomass power field is so diverse. Processes that are not as developed and that require monitoring and constant input, like anaerobic digestion and pyrolysis tend to have higher costs, while direct-fired costs are much lower. Larger plants tend to cost less per kilowatt-hour delivered than do smaller plants.

Furthermore, biomass supplies are often secondary products. The range of prices the suppliers will charge for their byproducts can vary dramatically, as some view the byproducts as a source of income and others view it as waste.

From a capital investment cost perspective, biomass power systems are similar to coal plants in that the initial plant will have a moderate initial investment. Operations and maintenance costs are also more similar to coal plants than renewable sources in that a supply chain of biomass material must be established, acquired, and managed. At a global level, as long as worldwide prices of coal and natural gas remain relatively low, biomass feedstocks will not be competitive and emerge as a large contributor to power. However, secondary products such as wood chips and waste agriculture will continue to exist and produce cost efficient opportunities for biomass power systems. Developed as a combined heat and power system, biomass power could be competitive with energy supplied to Air Force installations from the domestic grid.

Nuclear

Nuclear energy uses the energy released from the nucleus of an atom to generate electricity. The energy, in the form of heat, is transferred to a cooling system that generates steam. Just like coal, geothermal, and other energy sources, the steam drives a turbine which is connected to a generator producing electricity. As an energy source, nuclear power produces very little carbon emissions but requires a significant amount of cooling capacity.

Nuclear power comes in a variety of sizes. Current nuclear power plants in the United States range from 500 to 4,000 megawatts. Nuclear power is also used for naval propulsion, where the primary output is torque for rotating the main propellers of the vessel. These plants range from 45 to 175 megawatts. Small nuclear reactors specifically for generating electricity are also gaining momentum. Though not commercially available, the technology behind small nuclear reactors does not require significant investment. Through policy initiatives, requests for proposals, and research and development efforts, the Department of Energy, the Department of Defense, and the Nuclear Regulatory Commission have all expressed growing interest in renewing nuclear energy efforts. On the other hand, the general public is wary of nuclear power and implementation of a nuclear fuel source on a military installation will require a significant and careful public relations effort.

Power Supply Reliability

Nuclear power plants are fueled by nuclear material like uranium. Sources of uranium are not as abundant as coal or petroleum, but the need to replenish the fuel supply at the nuclear plant is infrequent and in units of years. The process of mining, converting, and enriching uranium into a usable form for electricity generation takes time, but occurs infrequently during the initial stages of building a plant and whenever the fuel is needed to be replaced. Nuclear plants for submarines and for small reactors could operate upwards of 20-30 years without replacing the fuel supply (Ingersoll 2009).

Nuclear power plants are also quite mature, and they have been operated safely for decades. Accidents have occurred, and officials considering implementation of a nuclear site need to consider the highly negative consequences of failure. Furthermore, an advantage of smaller reactors is that they could employ passive safety features that make them safer than their larger counterparts, such as being located underground.

Installation Considerations

Some Air Force installations have large tracts of unused land which could be home to a large nuclear power facility, but often bases are located close to populated areas and communities are likely to resist a nuclear plant being place near them. Furthermore, nuclear plants require large amounts of water for cooling, which may not be present near Air Force installations. Smaller nuclear systems with their nuclear reactors underground could be located much closer to populated areas than larger systems, and be applied to a wider range of Air Force installations. Keeping in mind that an Air Force installation's typical load is no more than 50 megawatts, even the smallest nuclear power plants would generate enough electricity to push power back into the domestic grid.

Though nuclear power reactors are environmentally clean with respect to greenhouse and carbon emissions, the consequences of failure demand significant attention. Safety analyses and licensing for a plant would be extensive and timely, and during the 1990s and 2000s, the nuclear production community lost more sites than gained. Recently, however, the Nuclear Regulatory Commission has seen a dramatic increase is new nuclear plant requests. According to its website, the Nuclear Regulatory Commission has approved 5 licenses and is processing over 25 applications for new nuclear power units in the United States.

Security and safety are also two major concerns when considering nuclear power on Air Force installations. The Air Force is well equipped to secure and protect critical infrastructure, though the Air Force would have to navigate and comply with the Department of Energy's security regulations. Safety analyses would need to be completed, and serious consideration would be required regarding overflight restrictions and various other risks to the plant that are specific to the military. In addition, the installation would need to assess the likely level of public resistance, as well as how a nuclear plan could impact the base-community relationship.

Grid Integration Considerations

Nuclear power plants operate at capacity factors over 90% and are a stable source of base load power. Although not yet commercially available in smaller sizes, nuclear plants are scalable. Larger systems would have a significant impact on the local grid, as power delivered by the nuclear plant would supply considerably more than the demand for the installation. It is likely that additional transmission capacity would need to be installed for large systems developed on Air Force installations. Smaller designed systems, if sized appropriately, would allow an installation to become a micro-grid where it can disconnect itself from the traditional grid and operate autonomously. Because nuclear fuel lasts so long, this characteristic would be even more advantageous in prolonged outage scenarios.

Costs

Cost estimates for large nuclear sites range from $0.06 to $0.13 per kilowatt-hour (found at http://en.openei.org/apps/TCDB/). Larger plants tend to have lower costs per unit of energy. However, large plants are unlikely to be pursued by the Air Force. Cost data for small fission systems such as those less than 100 MW are not readily available, though one can reasonably conclude that the estimates will be higher. Even though the estimates listed above include operations, maintenance, and other life-cycle costs, there are likely additional regulatory and compliance related costs that are not included. These costs would be in the form of additional manpower and staffing related to increased safety, security, and administrative compliance requirements.

Hydroelectric Power

Hydroelectricity is the generation of electric power from flowing water. The common form of hydroelectric power uses a dam to store a large body of water, creating a reservoir. When the dam is opened, gravity pulls water from the top of the dam into and through piping. The flowing water spins turbines, and is released out the bottom of the dam. The spinning turbine powers a generator which converts the hydropower into electricity. A second type of hydroelectric power does not require the use of a dam. Instead, a small canal is used to channel flowing water through a turbine, generating electricity.

Power Supply Reliability

Hydroelectric power in the United States is a very mature and very reliable technology. The supply of water for reservoirs and dams is consistent and predictable. The main threat to water supply is droughts, but energy operators can decrease water throughput to compensate as reservoir levels drop. Dams in the United States require very little maintenance, and some dams have been in operation over 50 years.

Installation Considerations

Because hydroelectricity has been used for power in the United States for over 100 years, the market is nearly saturated for new development. Furthermore, few Air Force installations have the location necessary to host a hydroelectric power plant. Environmental concerns are an issue as well, as dams can have negative effects on communities and ecosystems upstream and downstream. Sediments can fill a reservoir and render a hydroelectric plant useless. Regular attention needs to be applied to the structural integrity of the dam, as dam failure or flooding can have catastrophic consequences.

Although military installations do not own and operate their own hydroelectric systems, there are many examples of partnerships. Joint Base Lewis-McChord buys its power from Tacoma Power, and Tacoma Power generates over 90% of its electricity from seven dams in western Washington (Tacoma Public Utilities, "Dams and Our Power Sources"). Similarly, Nellis Air Force Base purchases some of its power from the Bureau of Reclamation and their Hoover Dam Power Plant.

Grid Integration Considerations

Hydroelectric power is an extremely flexible source of power supply. Changes in the flow volume of water correlate directly to the energy produced by a hydroelectric plant. This change can be ramped up and down very quickly to adapt to demand fluctuations. Typically, hydroelectric turbines require less than 90 seconds to bring a unit up to full speed. Hydroelectric power can be used as a base load, but are more often used for matching peak power loads. If surplus power generation exists, hydroelectric plants can decrease quickly and remain idle until required again.

Costs

Cost estimates for hydroelectric plants are often the cheapest found, with estimates ranging from $0.02 to $0.12 per kilowatt-hour, with a median at about $0.06 per kilowatt-hour (found at http://en.openei.org/apps/TCDB/). There is virtually no fuel required for the operation of hydroelectricity, as the water supply is renewable and replenishes itself naturally. Additionally, history has proven that hydroelectric plants can operate for long periods of time, further reducing the life-cycle costs. Few personnel are on site during operations, thus keeping operating and maintenance costs low.

Synthetic and Other Fuels

The diverse technologies of synthetic and other fuels have the potential to supply electrical power to Air Force installations. Synthetic fuels can take the form of liquid fuels which can be burned like petroleum-based products to create electricity. These are derived from a variety of sources like coal or agricultural waste. Similarly, biofuels like recycled cooking oil and ethanol-based fuels exist in commercially available quantities. Some of these fuels can be directly burned in diesel engines, or they can be chemically processed to be usable in a variety of generators. Biofuels have similar characteristics as petroleum energy sources, but would have lower life-cycle greenhouse gas emissions and likely cost more. Numerous processes exist that can convert waste to various forms of energy. The output from waste-to-energy processes can include a variety of gasses and liquids, such as syngas, methane, ethanol, and methanol.

Research and implementation of various technologies that convert products into synthetic or biofuel are more focused on replacing petroleum as a fuel source rather than for use as electrical generation. For example, even though the Fischer-Tropsch process was developed in the early 1900s, in the last decade it gained favor as fuel prices reached high levels. In particular, the Air Force took action and by the early 2010s had certified its aircraft fleet on a Fischer-Tropsch/JP-8 synthetic blend, though the program remains challenged by high carbon dioxide emissions and large scale production limitations. If synthetic and biofuels play a large role in the future of the Air Force for aviation fuel, the fact that an Air Force installation would be holding significant storage of surplus fuel should be a critical component of an installation's back-up power generation plan.

Power Supply Reliability

Synthetic fuels and biofuels are derived from a wide supply of sources. As long as the supply chain is established and adequate storage is available for the source of fuel, then the system can provide power reliably. Generators used with synthetic fuels or biofuels are mature, and as long as they are properly maintained then the systems will be highly reliable. If the fuels are created on Air Force installations, then the overall system reliability is increased as supply chains and transportation are decreased.

Installation Considerations

If the synthetic fuels are produced on-site, then little to no storage capacity is required for the electric generation. However, storage would be necessary for the products that are used to create the synthetic or biofuels. In the case of methane and syngasses derived from waste-to-energy plants, an installation will have to be ready to accept deliveries of waste and waste storage areas. The fuels can be flammable and hazardous, so installations will need to address safety and environmental risks, though these are likely no greater than similarly sized natural gas or petroleum power plants. Biofuel projects will also need to complete environmental assessments and address state and local compliance with the Clean Air Act.

Grid Integration Considerations

Synthetic and biofuels can couple directly into the installation and domestic grids. Electric generation plants for synthetic and biofuels can be either small or large. The smaller plants can be used similarly to petroleum-based backup generation. The larger plants, like those that create syngas which is directly used for gas turbine power generation, could handle base loads at a high capacity factor.

Cost

Cost estimates are difficult to find for synthetic fuels and biofuels for use in electric generation, especially considering that synthetic fuels and biofuels are primarily used for offsetting other transportation fuels. Those cost estimates available fall in the $0.08 to $0.22 per kilowatt-hour range (found at www.eia.gov). The lower end reflects traditional and more readily available biofuel and synthetic fuel technologies that are in regular use in the transportation industry. The higher end reflects technologies with more complex or heat intensive processes, or for which significant infrastructure costs would be required.

Fuel Cell

Fuel cell energy sources generate electricity through a chemical reaction between a fuel supply source, such as hydrogen and an oxidizing agent like oxygen. The hydrogen can be directly supplied or it can be derived from natural gas or alcohols. Stacking fuel cells in series or in parallel increases the voltage and current, respectively, supplied to the system. Fuel cells have been used for primary and backup power in a wide variety of applications ranging from communication centers to automobiles and spacecraft. The Department of Defense has experience in the automobile application of fuel cells; the Defense Logistics Agency (DLA) Distribution Susquehanna, PA used 40 forklifts powered by fuel cells as part of a pilot study initiated in 2008. Sprint and AT&T have extensively used fuel cells as backup power for their distributed telecommunications equipment. These 1-10 kilowatt systems are generally applicable to the Department of Defense for a variety of uses, including backup generation, runway lighting, and entry control point power requirements (Gross, Poche, and Ennis, "Beyond Demonstration: The Role of Fuel Cells in DoD's Energy Strategy," pg 19-26).

In 2010, the Departments of Defense and Energy initiated a collaboration effort between the two federal entities for the installation of 18 fuels cells across 8 installations. The purpose of the initiative was to test how fuel cells perform in real world operations, to identify technical improvements, and to highlight the benefits of fuel cells for emergency backup power applications. The $6.6M project included a variety of fuel cells ranging from 1.2 kilowatts to 20 kilowatts. Though the project was not completed due to vendor financing issues, the Departments of Defense and Energy remain interested in understanding and measuring fuel consumption, component failures, and operating costs for establishing procedures for use on installations (DLA, "Departments of Energy, Defense Partner to Install Fuel Cell").

Power Supply Reliability

Implementing a fuel cell energy system requires a consistent supply of fuel. Since the most common fuel supply, hydrogen gas, is only rarely found naturally, it must be produced. Fortunately, there are a couple mature methods of obtaining hydrogen. The first is electrolysis, which is the separation of the hydrogen and oxygen atoms from water. Electrical input for this method can be from any source, including renewable sources such as wind and solar. The second method, and that which delivers the most hydrogen currently, is steam-methane reforming. This method extracts hydrogen from methane, a commonly found and processed gas in commercial industry.

Fuel cells used for primary and backup power generation are moderately reliable for a couple reasons. First, the number of moving parts is small and this decreases the need for regular maintenance. Fuel cells involve two chemical reactions across three segments: the anode, cathode, and an electrolyte. There is no combustion, increasing the reliability of the system. However, similar to combustion, the chemical reaction occurs at a high temperature, and sufficient cooling must be provided.

Installation Considerations

If the hydrogen fuel source is produced on-site, then little to no storage capacity is required. However, storage would be necessary for a system that requires the shipment of hydrogen onto the installation. For larger systems, this could be prohibitive at typical Air Force installations, but for smaller systems compressed hydrogen storage solutions are simple and inexpensive. Another consideration for on-site generation is that in order to generate a fuel source like hydrogen through electrolysis, electrical input is needed and during power failure scenarios it may be available.   Plants for generating hydrogen using the steam-methane reforming method will produce greenhouse gas emissions driving Clean Air Act compliance requirements. Hydrogen derived from water using electrolysis, powered by a renewable, clean energy source would have little environmental concerns. The overall system would require a cooling mechanism.

Grid Integration Considerations

Fuel cells are scalable at power levels ranging from 1 kilowatt to 3 megawatts, so they can meet small load requirements at a high capacity factor or they can be used as a back-up power supply (Fuel Cell Energy Inc, "Types of Fuel Cells"). Because the amount of fuel provided can be quickly modified, fuel cells are excellent for matching fluctuating load characteristics. Though fuel cells are similar to batteries, if used as a backup power supply they should be compared to diesel or natural gas generators. This is because they require a supply of fuel and would take a small period of time to start.

Costs

Fuel cell cost estimates are commonly reported in the $0.10 to $0.22 per kilowatt-hour range (found at http://en.openei.org/apps/TCDB/). If hydrogen is purchased from sites that generate it as a byproduct or waste product in mass, then the price to the installation would be reasonably low. On-site generation or smaller systems would generate higher costs to the installation. As fuel cell technology matures, both for electricity generation and for vehicle use, the cost for fueling the systems will likely decrease.

Energy Storage Technologies

Energy storage technologies play an important role in energy generation, distribution, and use across the electric infrastructure. There is an expanding field of storage options available, and these options vary with respect to cost, storage capacity, and ability to provide quality power for differing outages. When properly paired with electrical generating sources, they have the ability to eliminate or reduce the impact of power failure.

There are some general rules of thumb regarding energy storage technologies, and these are briefly discussed here. Uninterruptible power supply (UPS) batteries are designed to provide a limited amount of energy in order to bridge the time between grid failure and standby (or backup) startup. UPS batteries are common and reasonably priced for use with office electronic equipment, though they have shortcomings. Though individual units are reasonably priced, having an UPS on every computer, server rack, and other electronic medium can add up. Additionally, typical UPS batteries need regular replacement as their power supply decays after time and they become exhausted after repeated use. These systems are optimized for voltage distortions, spikes, sags, or minor fluctuations, and are not intended for long term use.

This example illustrates the difference between power needs versus energy needs. Power is measured as energy per unit of time. Certain storage devices are optimized to provide power, such as lead-acid batteries, nickel-cadmium batteries, flywheels, and capacitors. These devices, which address power needs, handle transient outages lasting seconds or less, but typically cannot provide sufficient power for long periods of time. Storage devices that address energy needs, on the other hand, meet the requirement to provide sufficient power for longer periods of time. Devices such as pumped storage hydroelectricity, compressed air energy, and flow batteries are better suited to deliver energy to users for durations in units of minutes or longer.

One can see a natural pairing of energy storage systems to generation systems. Renewable generators such as solar or wind do not have a reliable supply of the source fuel, but become better equipped to provide continual supply when paired with storage systems suited for long term energy needs. Conversely, power storage systems that can handle large outages over a short period of time nicely bridge the gap until natural gas or diesel generators start and take over the base load.

Not surprisingly, energy storage systems cost significantly more than similarly sized diesel generators. Large scale systems are often cost prohibitive and are not common for military installations. Smaller systems, though costly as well, are used in a couple ways for critical facilities. The first protects the individual equipment, by connecting UPS batteries directly to the critical device. The UPS devices are on a separate electrical line within a facility, and a generator is connected to that line but not the whole facility. When a power failure is identified, the automatic transfer switch system detects a change to the supplied grid power, disconnects from the grid, and turns on the generator. While the generator is starting up, the UPS provides power. The second way uses a similar dual-line facility power concept, but the power supply is located at the building level and not the individual electronic device level. The same detecting and switching of power occurs.

Utility companies have long used pumped storage as a way of smoothing energy consumption and providing peak power during high demand periods. Having the correct geography in terms of large, elevated basins for stored water or naturally impermeable caverns for stored air is critical to using these as solutions. Although many installations don't have these available, the military is home to large installations that could support pumped storage. A mutually beneficial arrangement could be made with the local public utility, where the installation provides cheap, secure land and the utility promises the military first rights to the stored energy during outages. During times of normal grid operations, the pumped storage could be used for peak power.

Summary

No one energy source is perfect for the Air Force, but some are more suitable based on the previous described criteria. Conversely, no one technology is so difficult to implement or so costly that it should be prohibited, but some are less suitable. When installation decision makers are considering adding new generation capacity, they should start by assessing the four criteria relative to their installation's specific characteristics. Figure 10 below generally summarizes how the energy sources explored over the last few pages perform against the criteria described in the introduction of the chapter, and summarized in Figure 4. Technologies that score well across the four criteria are generally more suitable for an average Air Force installation than technologies that have criteria with noted reliability concerns, grid or installation integration issues, or high estimated costs.

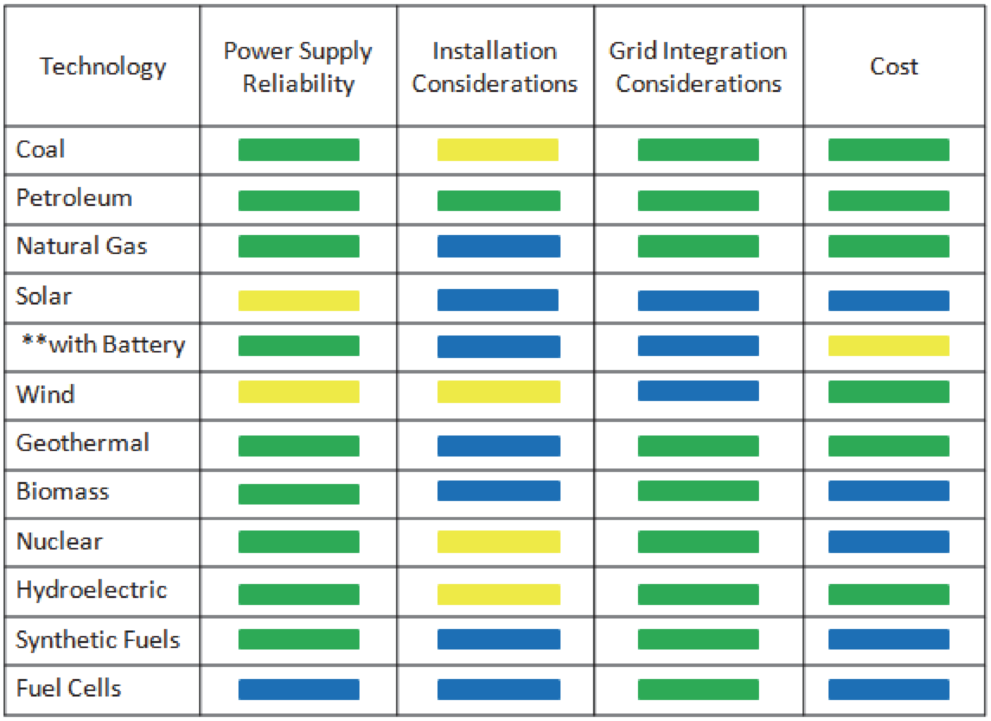


Figure 10: Assessment of Energy Sources

First, it is important to state what the figure is not concluding. It is not saying that certain energy sources should be discarded because they have one or more criteria against them. It is, however, stating that certain energy generation technologies are generally less suitable for use on an average Air Force installation. However, the reasons for suitability will vary by energy source and by installation. Local circumstances will often determine which set of technologies are most appropriate. Coal, for example, often suffers from demanding regulatory compliance requirements and major environmental pressures. However, coal works very well in areas where it is cheap, plentiful, and environmental requirements are not as strict, or where reliability is so highly valued that the effort, cost, and complexity are worth it. The chart is also not recommending certain energy sources over others. It is stating that installations will generally benefit more from certain energy sources in the context of their particular climate and environment, their local, state, utility, and private partnerships, and their mission.

Additionally, the figure tells the reader nothing about how the energy sources can be used together to achieve better results. Ultimately, military installations will likely employ a portfolio approach when addressing their installation energy needs. This would allow base leaders to combine energy sources to take advantage of cheaper technologies while still investing in the more reliable and more secure sources. Similarly, the base leader can choose a portfolio of small and large options, further diversifying the sources of energy used which minimizes risk to the installation. Such a portfolio approach increases energy security.

Some military installations are already taking a portfolio approach to energy security, such as Fort Knox, Kentucky. Because of a 2009 ice storm which knocked electrical power out to the installation for several days, Fort Knox has invested in additional energy security with a combination of different energy sources, efficiency technologies, real time energy management systems, and demand side management. Over the course of the last 20 years, Fort Knox has developed 1.57 megawatts of rooftop solar photovoltaic cells, a 2 megawatt solar photovoltaic farm, and a ground heat pump system spanning 600 miles of underground piping that provides heating and cooling to over 250 facilities. The installation implemented efficient infrared heating at 110 buildings, upgraded insulation across the installation, and upgraded windows and lighting to energy efficient products. In response to the 2009 snowstorm, which caused an extensive power failure to the base stopping operations for a week, Fort Knox took several actions specific to increasing energy security. First, Fort Knox installed prime generators fueled by diesel for use when the domestic grid is down, which can also be used to offset buying power from the public utility at peak demand when the cost is the most expensive. Additionally, Fort Knox tapped into a local natural gas reservoir, which provides on-post, direct natural gas for heating and powers five natural gas-powered electric generators. Lastly, the energy team operates a central, automated control system. The control center manages the installation's energy program by tracking energy consumption, diagnosing technical issues, and compiling data analysis. It also directly monitors control sensors in more than 300 buildings. In total, the Fort Knox community has embraced energy awareness, and through online reporting of real time output and energy use, facility residents can monitor and change energy consumption. Though not formally "pulling the plug" from the domestic grid, Fort Knox has shown how a portfolio approach can increase energy security, reduce costs, and be energy independent (Smoke, Jo, "Twenty Years of Energy Investment Pay Off for Fort Knox").

There are other technologies that can provide power to installations that are not listed here, for example, space-based solar power, osmotic power, algae biofuels, or sunshine-to-petrol technologies. Though promising, numerous technological, architectural, or infrastructural challenges remain that make them unviable as a commercial, cost-efficient source in the next 15-

20 years. Energy generation technologies that harvest an aspect of the ocean, whether thermal imbalances, tidal patterns, or wave energy are the most mature, but few Air Force installations are located along the coast. For those located along the coasts, it would be much more likely that another organization or department of the government would champion, implement, and administer the project.

In the near term, the Air Force has focused its installation energy efforts on implementing new renewable energy projects. As seen, the Air Force and Department of Defense have implemented a large number of projects across a diverse set of energy sources. Furthermore, as the Air Force continues toward its program goals of achieving 25 percent renewable energy by the year 2025 and as the technologies looked at in this chapter become more prevalent, the Air Force needs to address how the technologies being implemented affect how their installations are impacted by power failure. Integrating how renewable technologies improve resiliency and assure supply into investment decisions will improve upon the Air Force energy strategy.

In the next 10-15 years, the Air Force also needs to posture itself to be flexible regarding diversification of its energy sources. Significant research has been performed, and will continue to be performed on renewable energy technologies. The Air Force should continue to leverage those investments and seek out cost effective solutions for future on base energy generation. The Air Force uses a lot of energy, and will continue to play a role in energy research and development by selectively choosing investment opportunities and partnerships that are unique to the Air Force. The Air Force could partner with the Department of Energy, utilities, and academic institutions, trading Air Force land, security, and a stable energy demand for technology development, maturation, and validation resources. For example, the Air Force could seek further research on the benefits of an in-house production facility for producing liquid fuels and on understanding how these fuels and their byproducts could be used to increase installation reliability in addition to their primary goal as a replacement to traditional jet fuel. Ultimately, as seen in Figure 10 above, the research and development activities should focus on driving down costs for technologies to make them competitive with the domestic grid, and on driving down risk in terms of integrating technologies on installations.

Additionally, the Air Force should continue its progress toward resilience through "net zero" initiatives and implementation of microgrids. The Marine Corp is undergoing a demonstration at Marine Corps Air Station Miramar that the rest of the Department of Defense should be closely watching. The site has a landfill gas project, solar energy, and a zinc bromide flow battery based energy storage system. Raytheon, though its Intelligent Energy Command and Control technology, is connecting all of Miramar infrastructure with intelligent power management to show deep discharge levels, high reliability, scalability, grid integration, and operational safety needed for use on Department of Defense installations (DoD, "Zinc Bromide Flow Battery Installation for Islanding and Backup Power").

The microgrid lessons from Mirimar, as well as lessons from across the spectrum of energy projects in the Department of Defense, could also be implemented for forward deployed locations. The extreme costs of transporting and protecting fuel in a war environment are well documented, in both dollars as well as soldiers' lives. Renewable technologies can reduce that dependency, but only if they are cost effective and can easily be integrated to meet critical demand. Fortunately, in terms of meeting the energy demand for the military mission, the differences between a war environment and domestic environment are few. The unique aspects of a wartime environment are the demand that the systems be more robust in terms of maintainability, have a higher degree of portability, and respond faster to dynamic loads. Thus, the same criteria used in this chapter can be applied to assess deployed energy sources; power supply reliability, specific installation or forward operating base considerations, grid integration, and costs all play a role.

Per the most recent Air Force Energy Strategic Plan, the Air Force is committed to diversifying energy sources and securing quantities to perform its missions. The Air Force is accomplishing a lot of work in this area, and has made significant progress through the implementation of over 300 renewable energy projects. As seen throughout this section, there are a number of energy options available to the Air Force at competitive costs. From an installation energy perspective, diversification of energy sources is the first step and one the Air Force is obtaining positive results. Continuity of operations, on the other hand, is dependent on the reliability of the energy source and on how it is implemented at the installation. The Air Force must continue to emphasize selection of sources that have these attributes so that installations can be insulated from grid failure or other supply disruptions.

Chapter 3: Estimating Energy Consumption

This section discusses the methods for estimating energy use on an installation. Furthermore, the section addresses how the Air Force has historically gathered its own energy data and how to move forward with energy data collection efforts. As will be shown, it is possible to accurately estimate facility energy use without the ability to continuously collect and monitor energy data using meters. Ultimately, energy consumption estimation methods and advanced metering capabilities can benefit the Air Force and how its installations manage electrical energy use.

Energy Consumption Data Collection

Utilities bill residential, commercial, and industrial customers for electrical energy based on how much energy is used during a specific time period. Customers typically have an electric meter attached to the building which is located near the main service disconnect, and which regulates power to the building from the distribution grid. To bill the customer, the utility company can dispatch a service member who reads the electric meter and determines how much energy has been used since the last reading. As electrical systems become more advanced, these readings can be automated and sent to a data collection center. Furthermore, many utilities have begun to implement peak-pricing, in which the customer is billed a higher rate for energy demand during peak energy demand periods. The ability to properly bill customers based on peak-pricing requires near real-time or continuous monitoring of electrical energy demand.

Utilities bill an Air Force installation in a similar way. Many installations are connected to the domestic electric grid via one electric substation, and the utility can monitor the total amount of energy delivered through the substation to the base. The installation is then billed for the total amount of energy used during a specified time period. The local Air Force utility manager for the installation is charged with planning, supervising, and coordinating delivery of electrical power to on-base customers. In addition to paying the bill to the local utility company, the base utility manager also establishes a billing plan for on-base customers. The utility manager thus acts as an internal utility company, checking the meters on the customer's buildings and billing them for their energy use.

Thus, there is a mechanism for which energy consumption data is collected on an Air Force installation. Some buildings have automated metering that is connected through a network to a central database where the utility manager can pull total electrical use. For buildings with meters that are not connected to the network, the utility manager manually reads the meters and determines the level of energy used for a specified time period. By shortening the period of time the meter is read, the utility manager can gather more precise data on installation energy use. However, not all buildings on an Air Force installation are metered. When the utility manager needs to know the electrical energy use for one of the non-metered buildings, his or her options for finding the exact value are limited, expensive, and often time-consuming. A manager could read the voltage and currents manually, though this requires experienced technicians and a large amount of time. Therefore, the utility manager often resorts to an energy use estimation technique, which is described in the following section.

EPAct 2005 mandated that all federal buildings install energy metering by the year 2012, reasoning that better control and visibility of infrastructure energy usage would lead to reduced energy use. The language of the Act directed the metering of all facilities for electrical use where "economically feasible." The Air Force interpreted this language broadly and through the Air Force Civil Engineer, Headquarters U.S. Air Force, created a policy directing its installations to provide electrical meters to facilities over 35,000 square feet or for those with renovations valued over $200,000 (AF/A7C Memo, "DoD Facility Metering Installation Initiative").

It is the responsibility of the individual installations to ensure the metering plan is followed and that energy consumption, consumption per square foot, and costs are accurately reported. The Department of Defense established the Defense Utility Energy Reporting System (DUERS) to analyze energy use trends, measure progress, and report against various energy use metrics established by the federal government and the Department of Defense. Sometimes the data reported by the installation to DUERS is manually entered into the system, creating the possibility of errors and missing data. Additionally, base energy officials noted that facilities over 35,000 square feet represent less than one-quarter of the facilities on a typical installation. Therefore, even though all buildings over 35,000 square feet must be metered, that still left nearly three-quarters of Air Force buildings sized less than 35,000 square feet with no electrical energy use metering requirement.

In 2013, the Office of Secretary of Defense issued a memorandum directing Components to develop a Meter Data Management Plan for Component-specific metering goals. The updated goal is for Components to "install sufficient advanced meters on individual facilities to accurately capture a minimum of 60 percent of electricity use with a goal of 85 percent … by the end of Year 2020" (OSD ATL, "Utility Meter Policy"). In response, the Air Force Civil Engineer Center (AFCEC) implemented the Advanced Meter Reading System, and plans to provide meters to over 30 bases in the next five years, per the Director of the AFCEC Energy Directorate (Serbu, Jared, "AF Modernizes Its Bases through Utility Privatization"). Though advanced metering is forthcoming, it has been difficult for base energy managers to completely and precisely collect energy demand data. As the Air Force continues to maintain its metering policy, it behooves the Air Force to develop an accurate, consistent, and timely way to estimate energy use for non-metered buildings. Such estimation could supplement metering activities, provide accurate billing statements for host/tenant arrangements, and increase accuracy and transparency for Air Force energy reporting requirements.

Energy Consumption Estimation

At the installation level, reporting for aggregate energy use is quite precise. An installation takes the total energy used during a specific time period which it receives from the local utility provider, and divides this number by the total square feet of its buildings. The result, electrical energy use per square foot, is a measure of energy intensity and is a key metric in the Air Force's Energy Strategic Plan. However, this measure of energy intensity allows for building square footage variations to inaccurately influence energy consumption. For example, adding a large, storage warehouse to an installation will increase installation energy consumption and square feet. How it impacts the overall energy intensity depends on the ratio of energy use to square feet. Thus, an installation could show progress on the energy intensity metric by adding large, empty warehouses to its building density list. Instead of actually decreasing energy intensity for current infrastructure as is the objective of the Air Force Energy Strategic Plan, an installation could obtain similar results by adding empty buildings that consume no electrical energy.

Breaking down the aggregate energy demand into its various components is also difficult. If the Air Force wants accurate energy demand or energy intensity data for non-metered buildings, the Air Force must either directly measure the building energy use, estimate it, or require metering for those facilities. Since directly measuring electrical energy can be time consuming and costly, finding an accurate and quick method to estimate building specific energy consumption is important if adding metering capability is unavailable.

The two main tradeoffs for estimating building-specific energy consumption are accuracy and complexity. More complex, and therefore more time consuming and costly, estimation techniques are generally more accurate estimators while simple techniques often provide a lower degree of accuracy. One technique used by some in the Air Force is a low complexity / low accuracy estimation which obtains a calculation of energy intensity for the base and scales the intensity down by square feet. For example, a base divides its monthly electrical usage adjusted for a 30-day month by the total square feet of its building property, resulting in a per square foot intensity ratio, as seen in Eq. (3.1) below.

Eq. (3.1): $$\text{Base Energy Intensity}\left(\frac{\text{Kwh / Month}}{\text{SqFt}}\right)=\frac{\text{Total Base Energy Use (Kwh / Month)}}{\text{Total Base Square Feet (SqFt)}}$$

This ratio is then multiplied by the square feet of the building under consideration, giving the base an estimate for the amount of energy used in kilowatt-hours during the month, as seen in Eq. (3.2) below. Daily estimations would simply divide the monthly estimate by the number of days per month.

Eq. (3.2): $$\text{BuildingEnergy Use}\left(\frac{\text{Kwh}}{\text{Month}}\right)=\text{BaseEnergyIntensity}\left(\frac{\text{Kwh /Month}}{\text{SqFt}}\right)\times\text{BuildingSq Ft}(\text{SqFt})$$

This technique has been used by some installations, and tenants are billed for their monthly energy use on the installation by estimations using this technique.

The other extreme of the tradeoff is to use a much more complex and accurate way to estimate energy use. These methods tend to be classic aggregation models in which the energy consumption is estimated from summing the individual estimates of energy drawn from equipment within a building such as heating and cooling systems, water heating, refrigeration, lighting, and computing resources. Total man-hours required for these engineering or aggregation methods are high, and resources are often not available at the installation.

A moderate approach, then, decreases some of the accuracy while allowing for the method to be much simpler. The Department of Defense, led by the Navy, has developed a tool for estimating current and future energy consumption for buildings, ships, and other energy users. The technique is explained in a 104 page military handbook "Estimating Energy and Water Consumption for Shore Facilities and Cold Iron Support for Ships," or MIL-HDBK-1133 (Department of Defense Handbook 1133), and it is intended as a tool for estimating current and future energy and water consumption attributable to buildings and other uses at Navy installations. It presents a suggested methodology based on detailed knowledge of the base, the buildings, and metered electrical use. Once estimates are made for the entire base, the estimates are reconciled with actual or metered energy consumption data for the installation through the use of an adjustment factor.

This dissertation follows this last estimation technique, although there are three primary differences. The first difference is that the methodology for the handbook relies on initial individual estimates, and these values are expressed in terms of monthly or annual estimates. As will be described in the following sections, this dissertation's estimate is based on similar facilities which perform similar functions. Thus, this gives a higher fidelity estimate and allows for the case where initial building-level energy estimations are not available for an installation. The second difference is that the model illustrated in this dissertation allows calculations for any given time period, while the estimates derived from the military handbook are presented only in energy use per month. The third difference is that the facility estimates are calculated using a multiple linear regression, which MIL-HDBK-1133 does not use.

Building-Level Energy Consumption Estimation for Nellis AFB

As noted, this dissertation follows much of the reasoning and logic behind MIL-HDBK-1133, with some modifications. The modifications provide the Air Force with a straightforward, easy-to-apply method that is generally applicable across the spectrum of global installations. Any base energy manager or utilities manager has access to all the required information, and can apply the technique with moderate knowledge of a computer spreadsheet and regression capability (Microsoft Excel, STATA, SAS, R, etc). The process is described below, using Nellis AFB as an example.

Data Collection

The first step in estimating building-level energy consumption is to collect data on the buildings themselves. Air Force Real Property Offices establish and manage records on each of the buildings located on their installation. Appropriate information includes the building number, the category code of the building, the type or description of the building, and the total area (in square feet). Each building on a base is assigned a building number, and this building number serves as its unique identifier. Installations collect and report this data to comply with 1) 10 United States Code (USC) Section 2721 which directs OSD to maintain records of fixed property and installations on both a quantitative and a monetary basis, and 2) Department of Defense Instruction 4165.14, "Inventory of Military Real Property" which specifies Department procedures for implementation of real property asset management.

Each military service is responsible for establishing and managing its own set of numerical codes, or Category Codes. For example, the Army uses a five-digit identifier and the Air Force uses a six-digit hierarchy. The Category Code identifiers are published annually in the Real Property Categorization System. The Category Code is a numerical value given to each building and helps to identify the function of the building. Each building is also given a description, though this can be modified based on the category code and base-specific knowledge of the building function. Table 2 below shows the top-level, one-digit identifier for Department of Defense Real Property (AF Manual 32-1084, "Facility Requirements").

Table 2: One-Digit Category Codes for Buildings on Air Force Installations

Category Code	Title
1	Operation and Training
2	Maintenance and Production
3	Research, Development, Test, and Evaluation
4	Supply
5	Hospital and Medical
6	Administrative
7	Housing and Community
8	Utility and Ground Improvements
9	Land

In coordination with local leadership, this analysis rolled up many of these categories to come up with four functional categories for describing buildings on Nellis AFB. The first category, operational / critical, combines installation facilities which typically operate 24 hours a day, every day of the week with similar consumption rates. Additionally, from a decision maker standpoint, if power is lost to these facilities, they have the highest levels of impact on the mission. The second category focused on facilities associated with office or administrative work, such as hangers, labs, maintenance bays, and research facilities. Typical energy profiles for these facilities will be similar in terms of high energy demand during the day and decreased demand in the evenings and nights. The third category included the remainder of the facilities, such as dorms, housing, gyms, retail facilities, etc which have more variable energy demand than office or administrative facilities. The final category includes the rest of the infrastructure on base which is metered and not included in the previous three. It is intended that this category contains the facilities with the most variable energy demand. The categories are further described in Table 3 below.

Table 3: Description of Functional Categories for Buildings on Air Force Installations

Functional Category	**Description**	**Category Code**
Operational / Critical	Includes buildings which physically execute military operations from them, including control towers, radar stations, network and communications centers, air operations centers, command and control functions, emergency care, and security operations	1, 5
Administration / Office	Includes buildings which support operations, including most administrative buildings, hangers, labs, electronic shops, heating and cooling facilities, and non-essential security operations	2, 3, 6
Base Support, Services, and Housing	Includes support capabilities, such as morale, welfare, and recreation, dining facilities, schools, grocery and retail facilities, chapel, and storage. Housing includes on-base housing, enlisted dormitories, temporary living facilities, and guest lodging	4, 7
Other	Includes other buildings not suitable for combining into the categories above, for example campgrounds, stables, and kennels	8, 9

Often, buildings are home to multiple tenants, and therefore may include more than one functional category, which raises a problem since the data are defined and analyzed at the building-level. For this analysis, the solution is to give the building the highest functional category. For example, if an operations center is collocated in the same building as numerous administrative offices, it is assumed that the building itself is categorized as *operational* and not *administration*. Although during the analysis this will attribute more energy use to the higher mission critical functional categories, the problem is at least bounded by representing the worst possible scenario of power failure at the building (assuming loss of power to higher functional categories is quantitatively and qualitatively worse than loss of power to lower categories). Another possible solution would be to assign percentages to a building based on occupancy square footage. Assigning percentages would allow more accurate estimation of facility energy consumption, but to be an accurate representation for power failure scenarios it would require detailed knowledge on the internal building distribution network.

The next set of data to collect is all the metered energy data for the buildings on the installation for the time interval required by the analysis. This analysis uses hourly readings of kilowatt-hours, which directly equates the average demand measured in kilowatts to the kilowatt-hour reading for that hour. Although the kilowatt demand will vary above and below the hourly kilowatt-hour consumption reading, the data suggests that it does not vary enough to require finer measurements.

Additionally, installation level data needs to be collected. Total energy used per month can be obtained from the installation utility manager, and some bases have the capability to provide installation level data for smaller periods of time. This value will be useful for reconciling the estimated energy consumption with actual energy usage. Outdoor lighting and any information on losses from distribution of electrical power or from transformers is important and will help determine total power use for the installation.

Lastly, building energy assessments should include a factor which takes into account the temperature of the local area. Because MIL-HDBK-1133 assesses energy demand from a monthly perspective, it requires the cooling degree-days greater than 65 degrees F, heating degree-days below 65 degrees F, and wet-bulb hours greater than 73 degrees F. The values for these can be obtained from the installation weather office or from local weather reports. If the analyst is looking for historical temperature data, the National Climatic Data Center is a good place to start. As discussed later, for this analysis at Nellis AFB where heating is not used during the summer months, it is sufficient to gather raw temperature data. The hourly temperature data was collected from the National Climatic Data Center for the time period in which the energy consumption data was obtained from the installation.

Data Analysis

The goal of the analysis is to estimate energy consumption data for those buildings that do not have metered data available. By collecting data from metered buildings with similar characteristics such as square feet and functional category, and by controlling for common effects such as time of day and temperature, it is possible to estimate energy consumption data for the non-metered buildings from the buildings with metered data. The technique used in this study is a multiple linear regression, in which kilowatt-hours for a building at a particular hour is a function of some combination of the variables given. The literature suggests that using a multiple linear regression for estimating energy consumption is reasonable. Braun, Altan, and Beck use multiple linear regression to estimate supermarket energy consumption (Braun, et al, "Using Regression Analysis to Predict Future Energy Consumption of a Supermarket in the UK"), Lam, Wan, Lui, and Tsang use multiple regression models for office buildings in five major climates in China (Lam, et al, "Multiple Regression Models for Energy Use in Air-Conditioned office Buildings in Different Climates"), and O'Neill, Crawley, and Schliesing use statistical regression equations and predictions of heating and cooling loads to determine relative importance of envelope parameters (O'Neill, et al "Using Regression Equations to Determine the Relative Importance of Inputs to Energy Simulation Tools").

Based on a scan of the literature, and more importantly based on what is typically available to Air Force energy managers, the variables used for this regression are described in Table 4 below. There may be additional variables which cause the energy consumption of a facility to be comparative across groups, such as similar insulating material, construction type, number of windows, etc. These additional variables could be tested for significance in the regression, but one must consider how readily available that information is, and how much time it would take to gather the additional data.

Table 4: Description of Variables Used to Estimate Energy Consumption

Variable (*var*)	**Description**
Kilowatt-hour (*Kwh*)	The variable being estimated, a measure of energy representing the total kilowatts used over the period of an hour
Square Feet (*Sqft*)	The square footage of the building
Functional Category (*Func*)	The category of the building which generally identifies what mission takes place in a building, as described in Table 3.
Day (*Day*)	A variable which allows for differences in energy use across days
Hour (*Hour*)	A variable which allows for differences in energy use across hours
Temperature (*Temp*)	A variable measuring air temperature in the local area, units are Degrees Fahrenheit

As discussed previously, not all military facilities are metered. When the data was gathered for this project at Nellis AFB in 2009, facility metered data was consistently available for 29 facilities, not including residential housing. Most of this data was reported every 30 minutes, but a few facilities only reported data every four hours or daily. The mix of facilities by type is broad. The median building size in the dataset is 7,820 square feet with the largest being of 350,000 square feet. After adding the functional categories to the dataset, the total number of observations selected for analysis was 3,852. An observation represents an energy data point for which corresponding time, facility, and temperature data exist.

The relationship between the *kilowatt-hour (kwh)* response variable, y, and *Square Feet (SqFt)*, x, is defined by Eq (3.3) below, where the intercept $\beta_0$and the slope β_1 are constants estimated by the regression equation using the data collected.

Eq. (3.3): $y = \beta_0 + \beta_1 x$

It is expected the data would suggest that, in general, buildings with more square feet have higher energy consumption. The results for Nellis AFB indicate that an increase in one square foot for a building corresponds to an increase in 0.00278 kilowatt-hours, as seen in Table 5 below.

Table 5: Summary Statistics for Estimating Kilowatt-hours Using Square Feet, Eq. (3.3)

Parameter	Estimate	Standard Error	*t*-Statistic
$\boldsymbol{\beta_0}$	0.55941	2.785	0.20
$\boldsymbol{\beta_1}$	0.00278	3.07E-05	90.71

Number of Obs=3852 R-Squared = 0.6813 Mean Squared Error = 146.54

The *t*-Statistic of 90.71 for *SqFt* is strong, meaning we can reject the hypothesis that $\beta_1 = 0$. The coefficient of determination, or R-squared, is a measure of the variability in *y* explained by the regression model. For the Nellis AFB data in Table 5, a value of 0.6813 indicates that 68.13 percent of the variability in the data is accounted for by the regression model. The Mean Squared Error for the regression is 146.54.

The first regression is a simple linear regression, and does not account for any other variables which likely influence how much energy a building consumes. This model would conclude that the same amount of energy is used in a facility whether it is noon or midnight, or whether it is a warehouse or a school, as long as they have the same square feet. However, there is reason to believe a number of other variables influence the *kilowatt-hour* estimate in addition to the *SqFt* variable. It is expected that as *Temp* changes, the demand for heating and cooling changes. An interaction variable between *Temp* and *Sqft* can help the model account for expected efficiencies in larger heating and cooling equipment for larger facilities. Because the energy use peaks in the afternoon and reaches a low during the night hours during the summer, an hour-squared term (*HourSq*) was added to account for a daily energy peak. *HourSq* has a strong influence on the estimation, and when included with the *Hour* variable in the regression it allows for a bell-shaped or parabola functional form.

Given that there is reason to believe the terms in the previous paragraph influence the energy use for a facility, the relationship between the variable, *y*, measured in *kilowatt-hours (kwh),* and the additional regressors was explored. The relationship is defined by Eq. (3.4) below, where the coefficients β_0 and β_i are constants estimated by the regression equation using the data collected. The subscript *i* indicates that multiple coefficients are considered.

Eq. (3.4): $y = \beta_0 + \beta_i x_i,$

The results from the multiple linear regression exploration are seen in Table 6 below. The number of observations is the same at 3852, and the values for R-squared and Mean Square Error are reported to the right of the coefficients.

Table 6: Coefficient Estimates for a Range of Kilowatt-hours Predictors

SqFt β_1	***Temp*** β_2	***Temp-SqFt*** β_3	***Func1*** β_4	***Func2*** β_5	***Func3*** β_6	***Hour*** β_7	***HourSq*** β_8	**R-Square**	**Mean Squared Error**
0.00278								0.6813	146.54
0.00278	3.2094							0.6913	144.23
		0.000033						0.7087	140.09
-0.00325	-0.1861	0.000071						0.7193	137.54
		0.000036	-116.99	59.65	-61.74			0.7352	133.63
-0.00296		0.000070	-108.17	61.56	-62.30			0.7445	131.28
0.00299	3.2402		-108.83	61.39	-61.52			0.7164	138.30
-0.00304	-0.1579	0.000071	-108.13	61.57	-62.30			0.7445	131.29
-0.00305	-3.2090	0.000071	-107.45	61.69	-61.86	-17.18	0.76	0.7514	129.55

The Mean Squared Error generally decreases as more regressors are added to the model, indicating the added variables are not decreasing the usefulness of the model. As expected, the R-squared increases as the number of regressor variables is added to the equation, though not significantly.

During the analysis, it became apparent that the largest of the buildings on the base were dramatically skewing the regression. These buildings include the commissary, the Base Exchange, the hospital, and a storage warehouse, and they measure over 100,000 square feet each. These represent four of the five largest buildings on the base, with the fifth building being base billeting. Intuitively, it makes sense these particular large facilities would consume power differently than the rest of the facilities on the installation. The commissary and Base Exchange contain industrial sized refrigeration systems for food processing and storage, and the hospital and storage warehouse house large electronic equipment. It is possible to add a large building indicator variable, so that all buildings greater than some square foot threshold could be separately estimated in the regression. However, in this study, because these buildings were metered, the actual metered data will be used for the model and an estimate is not required. Thus, these four observations were dropped for use in the regression analysis. There was no reason to think that the fifth building, base billeting, would alter the regression coefficients, so it was left in the model.

Another building which had metered data, a Visiting Airman's Quarters (VAQ) with 28,710 square feet, had an odd characteristic to its energy use, such that it was only using four kilowatt-hours of energy per hour across the data set. Because the data set had energy data for other VAQ facilities that were variable and reflected realistic power consumption, it was safe to assume the data was not reflective of actual energy consumed at the facility, but was instead instrumentation or data recording error. The observation was significantly skewing the regression, and was subsequently dropped.

Table 7 below shows the regression of the variables on *kilowatt-hours*, taking into consideration the dropped observations. The relationship is defined by Eq. (3.5) below.

Eq. (3.5): $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 x_3 + \beta_5 x_4 + \beta_6 x_5 + \beta_7 x_6 + \beta_8 {x_6}^2$, *w*here

- x_1= Square Feet
- x_2= Temperature
- x_3= Indicator variable for Operational / Critical Buildings
- x_4= Indicator variable for Administrative / Office Buildings
- x_5= Indicator variable for Base Support / Services / Housing Buildings
- x_6= Time of day

Table 7: Summary Statistics for Estimating Kilowatt-hours Using Variables in Eq. (3.5)

Parameter	Estimate	Standard Error	*t*-Statistic
$\boldsymbol{\beta_0}$ – *Intercept*	-10.32	8.76	-1.17
$\boldsymbol{\beta_1}$ – *SqFt*	1.16E-3	2.06E-4	7.84
$\boldsymbol{\beta_2}$ – *Temp*	0.634	0.099	6.35
$\boldsymbol{\beta_3}$ – *TempSqFt*	-1.25E-5	2.63E-6	-4.69
$\boldsymbol{\beta_4}$ – *Func1*	50.38	1.83	27.59
$\boldsymbol{\beta_5}$ – *Func2*	-18.73	1.44	-13.01
$\boldsymbol{\beta_6}$ – *Func3*	-16.88	1.44	-11.76
$\boldsymbol{\beta_7}$ – *Hour*	2.54	0.37	-6.77
$\boldsymbol{\beta_8}$ – *HourSquared*	-0.104	0.015	-6.85

Number of Obs=3109 R-Squared = 0.5198 Mean Squared Error = 23.74

As can be seen, the coefficients make intuitive sense. All else held constant, as outside temperature increases so too does the energy use in the building. With temperatures ranging from just below 70 degrees Fahrenheit to nearly 105 degrees Fahrenheit, any increase in temperature will correspond to more use of the air-conditioning units. For practical purposes, the regression used raw temperature data and not heating or cooling degree-hours. Locations that require heating and cooling across the dataset should use heating and cooling degree-hours and not raw temperature data. An increase in square feet of the building corresponds to an increase in building energy use. The coefficient for the interaction variable between *Temp* and *SqFt* is negative, indicating there is some form of efficiency savings as those two variables increase together. An operational building (*Func1*) tends to use more kilowatt-hours than the baseline other category, which uses more than administration/office (*Func2*) and base support/service/housing (*Func3*). The *Hour* and *HourSquared* coefficients make sense as well; all else constant, the effect of these two variables on *kilowatt-hours* peaks between *Hours* 12 and 13 every day, and is at a low at *Hour* 24.

Given the regression in Table 7 above, the energy consumption data for all of the unmetered facilities can be estimated using the Eq. (3.6) below. *EnergyUsed*, $\hat{y}$, is measured in kilowatt-hours.

Eq. (3.6): $$\hat{y} = 0.00161x_1 + 0.634x_2 - 0.0000125x_1x_2 + 50.38x_3 - 18.73x_4 - 16.88x_5 - 2.54x_6 + 0.104x_6^{\ 2} - 10.32$$

In addition to the R-squared and Mean Squared Error, the residuals play a key role in determining model adequacy. The residuals can be plotted and compared to the regressor variables for identifying underlying patterns not captured by the regression equation. For Eq. (3.6) the residuals were plotted against each of the regressors; the plots did not exhibit any patterns and the correlations were all less than 0.01. Additionally, the residuals can be correlated versus the corresponding fitted values and used to detect model inadequacies. For Eq. (3.6), the calculated correlation was again less than 0.01, but the graph implied the variance increases as *kwh* increases due to the slight presence of an outward-opening funnel pattern. This does not come as a complete surprise since the dataset includes more data reflecting moderate energy consumption and less at the higher ranges. Figure 11 shows a plot of the residuals versus the fitted values $\hat{y}_i$ for the *kwh* data.

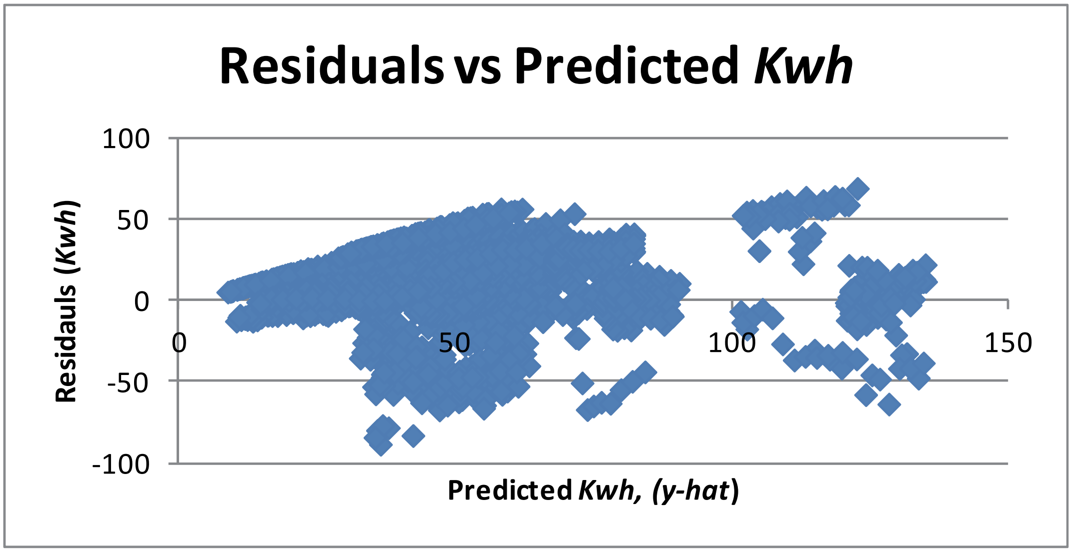


Figure 11: Plot of Residuals versus Fitted Values from Eq. (3.6)

Additionally, since the data in the regression is time dependent, it is important to assess the assumption of uncorrelated residuals knowing that residuals in time series data are often autocorrelated. This dissertation used the widely used Durbin-Watson statistic for testing autocorrelation (Durbin and Watson, "Testing for Serial Correlation in Least Squares Regression"). The Durbin-Watson statistic for the data presented is 0.09, which is less than the lower limit of a conservation value of 2, so it is possible to conclude from the data that the errors are positively autocorrelated.

One option to solve autocorrelation is to use a missing regressor and incorporate it in the data. However, given the data available, finding and using a missing regressor is not an option. Therefore, the autocorrelation is noted and an appropriate parameter estimate is calculated to remove the autocorrelation. This dissertation follows the Cochrane and Orcutt method described in "Introduction to Linear Regression" by Montgomery and Peck, 1982. The parameter estimate, $\hat{p}$, is estimated from the residuals and is used to obtain new transformed regressor and response variables. In this case, $\hat{p}$ is 0.954. The regressor and response variables are transformed using this autocorrelation parameter, and a least squares fit to the transformed variables yields a set of transformed coefficients. The Durbin-Watson statistic for the transformed data is 2.01. Comparing this with the conservative critical value of 2, it is possible to conclude that the errors in the transformed model are uncorrelated. Table 8 below shows the transformed coefficients and variables for Eq. (3.7), also below.

Eq. (3.7): $\acute{y} = \acute{\beta_0} + \acute{\beta_1}\acute{x_1} + \acute{\beta_2}\acute{x_2} + \acute{\beta_3}\acute{x_1}\acute{x_2} + \acute{\beta_4}\acute{x_3} + \acute{\beta_5}\acute{x_4} + \acute{\beta_6}\acute{x_5} + \acute{\beta_7}\acute{x_6} + \acute{\beta_8}\acute{x_6}^2$, where

- $\acute{x_1}$= Square Feet
- $\acute{x_2}$= Temperature
- $\acute{x_3}$= Indicator variable for Operational / Critical Buildings
- $\acute{x_4}$= Indicator variable for Administrative / Office Buildings
- $\acute{x_5}$= Indicator variable for Base Support / Services / Housing Buildings
- $\acute{x_6}$= Time of day

Table 8: Summary Statistics for Estimating Kilowatt-hours Using Variables in Eq. (3.7)

Parameter	Estimate	Standard Error	*t*-Statistic
$\boldsymbol{\beta_0}$ – *Intercept*	0.217	0.350	-0.62
$\boldsymbol{\beta_1}$ – *SqFt*	1.24E-3	2.16E-4	5.74
$\boldsymbol{\beta_2}$ – *Temp*	0.400	0.079	5.05
$\boldsymbol{\beta_3}$ – *TempSqFt*	-7.97E-5	2.48E-6	-3.21
$\boldsymbol{\beta_4}$ – *Func1*	108.02	4.52	23.90
$\boldsymbol{\beta_5}$ – *Func2*	-23.95	3.55	-6.73
$\boldsymbol{\beta_6}$ – *Func3*	-26.26	4.70	-5.59
$\boldsymbol{\beta_7}$ – *Hour*	2.22	0.30	-7.38
$\boldsymbol{\beta_8}$ – *HourSquared*	-0.091	0.012	-7.56

Number of Obs=3108 R-Squared = 0.2858 Mean Squared Error = 7.47

In comparing Tables 7 and 8, the Cochrane-Orcutt procedure produced estimated coefficients that only slightly differed from that found by ordinary least squares. In some cases, the standard error increased and in other cases it decreased. The values for the *t*-Statistic declined in all regressors except for the *Hour* and *HourSquared* terms.

As a way of validating the model for accuracy, the data can be used to estimate the regression coefficients with half of the given data and test the accuracy of the results against the other half. This is done by randomly assigning an indicator variable to half of the data points and using these data points for the regression analysis. With the coefficients determined, the equation can be used to predict *Kwh* for each building at every hour. Then, the actual energy use is compared to the predicted energy use for data points that were not assigned the indicator variable.

This technique was applied to various combinations of predictor variables, and the results are summarized in Table 9 below. A simple way to calculate the differences in actual and predicted energy consumption is to take the sum of the squared errors for observations, and the model with the lowest sum is considered the most accurate given the data fit for the functional form. Similar to the method used above, the same outlier observations are dropped from the regression.

Table 9: Estimation Coefficients Using Randomly Assigned Indicator Variable

SqFt	***Temp***	***Temp-SqFt***	***Func1***	***Func2***	***Func3***	***Hour***	***HourSq***	**R-Square**	**Sum of Squared Errors**
0.0028								0.6715	4,047,170*
9.6E-4								0.3002	1,322,252
9.6E-4	0.7625							0.3344	1,254,590
0.0023	1.0903	-1.55E-5						0.3398	1,252,662
0.0023	0.8301	-1.57E-5				1.53	-0.0452	0.3459	1,251,345
0.0019	0.8257	-1.49E-5	56.24	-16.68	-17.41	1.62	-0.0497	0.5295	945,036

*This data point is shown to illustrate the effect of the outliers. As seen, the Sum of the Squared Errors is much higher when they are included. For the remainder of the table, the outliers are discarded.

As seen and expected, the model which provides the smallest difference between observed and predicted values is one in which *Kwh* is predicted by all of the assigned variables. Furthermore, the regression coefficients do not change much even though half of the data set is not used for the regression. Dropping from the regression additional buildings with the largest difference in observed and predicted *Kwh* (in this case a particular building with *SqFt* equaling 10,700) allows for a lower total sum of the squared errors. However, with only 29 buildings worth of data, dropping buildings from the regression decreases the variance for which the estimation uses to establish the coefficient values, and thus no further buildings are dropped in the analysis.

For the last regression in the table above, the median squared error has a value of 291, implying that the median error is just over 17 kilowatt-hours. The maximum error for the 3,000 observations is just above 76 kilowatt-hours, and this error occurs on a medium sized building which uses an extraordinary amount of power on the final day of the data. In fact, the top four error values are from this particular building on the last day.

As an additional check on the model, the data was tested to see if a normal distribution would be a better functional form than a parabola. A normal distribution takes the form:

Eq. (3.8): $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$

Where

σ = standard deviation of the normal density
μ = mean of the normal density

By definition, the density is symmetric about the maximum at the mean, such that the following Eq. (3.9) holds:

Eq. (3.9): $f(x-\mu) = f(-(x-\mu)$

Normal densities are often referred to as bell shaped curves, and the standard deviation controls the rate at which the slopes fall off. Because of this aspect, fitting a normal distribution to the data can lead to a better estimation.

With this equation, it is necessary to find the mean and standard deviation which best minimize the difference between the actual *kwh* and the predicted *kwh*. The optimal solution is a mean of 13.78 and a standard deviation of 7.58, implying that the peak energy demand for the data set occurred most frequently at 1:46 PM. Using these values, the functional form of the normal distribution was included in the regression. In Table 10 below, the first column represents the method used above, and the normal distribution is applied to the same set of data. As can be seen in the table, adding the functional form of a normal distribution slightly to the pre-transformed model improves the regression, though either method is sufficient for an accurate estimation.

Table 10: Regression Coefficients with Parabola vs. Normal Distribution Functional Forms

Form	**Parabola**	**Normal Distribution**
Sum Squared Errors	660,646	656,294
R-Square	0.6075	0.6076
SqFt	0.0020	0.0020
Temp	0.8832	0.8054
Temp-SqFt	-1.54E-5	-1.53E-5
Func1	57.34	57.45
Func2	-13.56	-13.61
Func3	-12.94	-12.98
Hour	1.42	
HourSq	-0.0458	
NormHour		259.4

Reconciliation

The analysis above provides hourly estimates of energy consumption for every building on Nellis AFB. In particular, this data set is for a time period of seven days in June 2009. Reconciliation of the estimated energy consumption data with the actual consumption is the next step in ensuring the estimated data is as accurate as possible. The reconciliation accounts for inaccuracies in building-level estimation by forcing the sum of all the estimated and metered values to equal the total consumption. Total consumption is an easy number to obtain as the Base Utilities Manager regularly receives a monthly bill delineating both cost and electrical energy use from the utility.

The base energy consumption at Nellis AFB for the seven day time period of the data is just over 2,720,000 kilowatt-hours. Due to time constraints, Eq. (3.5) and not the transformed regression was used to calculate the total estimated energy use for the buildings in the dataset, resulting in 2,514,237 kilowatt-hours. There are other areas of an installation which use electricity and are not accounted for in the total building estimate. These include exterior lighting, sewage and water control, and distribution and transformer losses. A similar process to that used in MIL-HDBK-1133 is applied for these estimates.

Energy consumption for street and exterior lighting, defined as lighting other than that typically found around a building and including parking areas, floodlighting, and security lighting, is found by determining the total number of lights in use and multiplying each type by their energy usage. The number of lights can be found from procurement records or from inventory files similar to those obtained from the Real Property Office. If possible, the outdoor lighting load should be defined by type, number of lights, rating, and total operating hours. For simplicity, total operating hours will equal the average hours between sunset and sunrise for the month in which the data is collected, in this case 9.6 hours for Nellis AFB in June.

For Nellis AFB, there are 1,385 lights used for airfield apron lighting, 1,658 lights used for street lighting, and 65 lights used as flood lights. Airfield lighting is assumed to be sized around 200 watts, street lighting is the standard commercial 80 watts, and flood lights are averaged to 450 watts. Outdoor lighting for each lighting type is found by Eq. (3.10) below.

Eq. (3.10): $E = Rating * N * H * Time$

Where

> *E* = Energy consumption in kilowatt-hours
> *Rating* = Lamp rating in watts
> *N* = Number of lamps
> *H* = Illuminating hours per day
> *Time* = Time period of interest

Table 11 below shows the assumed energy consumption of each category of lighting, the number of lamps for the rating, the illuminating hours, and the amount of energy devoted to lighting by individual category and as a sum total for the base.

Table 11: Exterior Lighting Energy Use

Type of Lighting	**Rating in watts**	*** Number of Type**	*** Illuminating Hours / Day**	*** Total Days**	**= Energy Consumption in kilowatt-hours**
Street and Exterior	80	1,658	9.6	7	8,913.41
Apron	200	1,385	9.6	7	18,614.40
Flood	450	65	9.6	7	1,965.60
Total Lighting					29,493.41

Electric distribution and transformer losses are also accounted for in this analysis. In some cases across the Department of Defense, analyses of the distribution grid exist and should be used to provide the best estimate of distribution and transformer losses. Without previous studies, MIL-HDBK-1133 describes an approach for calculating these losses which depends on transformer device configuration and design, materials used, and power voltage and frequency. As this process can be complex, MIL-HDBK-1133 also cites estimated losses at various military installations between 3 and 10 percent of total electricity consumption, including Vandenberg (Halverson, et al, 1993) and Robins Air Force Base. Without more knowledge, using an estimate between the values derived from previous studies is sufficient for distribution and transformer losses. This analysis uses 5 percent as its estimate, as Nellis AFB has newer infrastructure and shorter lengths of distribution lines than other Air Force installations cited, as seen in Eq. (3.11) below

Eq. (3.11): *Transformer & Distribution Losses = Total Consumption * 0.05*
= 2,721,654 *kwh * 0.05*
= 136,083 *kwh*

Where

T&D Losses = Electric Transformer and Distribution Losses, measured in kilowatt-hours
Total Consumption = Measured total consumption in kilowatt-hours for the time period

Water supply and sewer systems require electrical energy associated with potable water and sewage waste pumping, processing, and distribution. This analysis accounts for these functions at the building-level, so estimations will not be needed during reconciliation. Likewise, steam and hot water distribution is accounted for at the building where the power is used.

Table 12 below shows estimates for electrical energy use at Nellis Air Force Base. Actual base energy use for the seven day period totals 2,721,654 kilowatt-hours, and the total from buildings (metered and non-metered estimates), exterior lighting, and 5% transformer and distribution losses is approximately 1.5% less at 2,679,813 kilowatt-hours.

Table 12: Estimates of Electrical Energy Load

Category of Electrical Energy Load	Estimate
Sum of Metered Data and Building Estimates	2,514,237 kwh
Exterior Lighting	29,493 kwh
Transformer and Distribution Losses	136,083 kwh
Estimated Base Energy Use	2,679,813 kwh
Actual Base Energy Use	2,721,654 kwh

The last step of the reconciliation accounts for inaccuracies in the estimates by forcing the sum of the estimated values to equal the actual base energy consumption through the use of an adjustment factor. These inaccuracies can be a result of losses not accounted for or errors in distribution and exterior lighting energy estimates. The strength in this process is that the estimated base energy consumption for a specified period of time will exactly equal to actual consumption even though individual components may be inaccurate to some degree. According to MIL-HDBK-1133, reconciliation is appropriate for anything within a 20% difference between the estimation and actual consumption.

1) The first step is to calculate the difference between estimated and actual energy consumption at the base level. In this example, the difference is shown in Eq. (3.12) below.

Eq. (3.12): *Base Level Difference = Actual Energy Use – Estimated Energy Use*
= 2,721,654 kwh - 2,679,813 kwh
= 41,841 kwh

2) The next step is to determine which components of base energy are to be reconciled. At this point, there is some flexibility in the reconciliation process. The analyst can choose to apply the adjustment factor to any combination of the base components - the estimated buildings, metered buildings, exterior lighting, and distribution and transformers. In this case, the energy components chosen for adjustment are those which at one point were estimated; thus, building estimates, exterior lighting estimates, and distribution and transformer estimates are adjusted while all metered data are not adjusted, as reported in Table 13. Metered data could be adjusted as well, but only if the validity of the metered loads is believed to be inaccurate.

Table 13: Components of Installation Energy Consumption to Adjust

Category of Electrical Energy Load	**Apply Adjustment?**
Building Estimates	Yes
Metered Building Data	No
Exterior Lighting Estimate	Yes
Distribution and Transformer Estimates	Yes

3) After the components have been chosen for reconciliation, the adjustment factor is calculated. The adjustment factor is determined by dividing the difference in actual and estimated energy consumption by the energy consumption sum of the selected components from step two.

Eq. (3.13): *Adjustment Factor = Base Level Difference / Sum of Selected Components*
= 41,841 kwh / (1,451,707 kwh + 29,493 kwh + 136,083 kwh)
= 0.02587

4) Lastly, the adjustment factor is multiplied by each of the energy components selected for reconciliation. At this point, the new sum of estimated energy consumption should

closely match the actual base energy consumption. This calculation is shown in Table 14 below.

Table 14: Adjusted Estimates of Electrical Energy Load

Category of Electrical Energy Load	**First Estimate**	*** Adjustment Factor**	**Final Estimate**
Non-Metered Building Estimates	1,451,707 kwh	1.02587	1,489,263 kwh
Metered Building Data	1,062,530 kwh	1.00000	1,062,530 kwh
Exterior Lighting	29,493 kwh	1.02587	30,257 kwh
Distribution and Transformer Losses	136,083 kwh	1.02587	139,603 kwh
Estimated Base Energy Use	2,679,813 kwh		2,721,653 kwh
Actual Base Energy Use	2,721,654 kwh		2,721,654 kwh

It is important to remember that these loads are an estimate for a specific seven day period during the summer months in a desert environment. The loads will be different during other parts of the year. Particularly, the energy load may be slightly higher during other periods of the summer due to a higher difference between ambient outdoor temperatures and indoor temperature. During the spring and fall, the aggregate loads will be less than those seen here as cooling requirements diminish. During the winter months, the load drastically decreases; it is not uncommon to see winter loads that are significantly less than those seen in the summer.

Critical Infrastructure Consumption

The energy loads estimated above are for normal operations at Nellis Air Force Base during the summer period. The loads are estimated hourly for each building, and the aggregate totals are shown in the final table. It is expected that during holidays, military exercises, and power failure scenarios that these loads will differ from normal operations. Most important for ensuring mission success is to estimate the maximum load required for a building to support its mission critical equipment. After establishing the maximum load for mission critical equipment and determining that the building is mission critical, it is common practice to place a generator at the building with a 50% greater capacity than the maximum load.

Often, there are pieces of equipment or specific rooms in a building which are mission critical and other areas which are not. In this case, the generator is sized only to the extent to which it is required to provide power to the mission critical aspects of the building. This implies that there are different building load characteristics dependent on whether the building is under a power failure environment or operating under normal circumstances. Thus, buildings which contain mission critical functions could have two energy load estimates. The first estimate is based on the previous analysis, and will be applied during normal operations. The second estimate will be based on generator reports kept by the Power Production team in the Civil Engineering Squadron. These reports detail many characteristics of each of the generators on the installation. Specifically, it lists which building the generator services and the maximum energy demand requirement for that building. This maximum energy demand requirement will be used as the estimate for mission critical buildings when external power failure to the building is present.

Conclusion

Ideally, every facility on an Air Force installation would be metered. Energy managers would then be able to use historical data to predict future consumption. After many years of collecting data, further data refinement could occur and the predictions would grow increasingly more accurate. However, for facilities that don't have metering available, there are multiple ways to calculate the energy use for any given period of time. This analysis showed a multiple linear regression approach that uses energy data from metered buildings and applies those coefficients to non-metered buildings of similar type.

Though the data applied to this model is from Nellis AFB, the methodology itself is installation agnostic and can be used by the Air Force across its installations. As with any model, it has limitations and there are a number of considerations to take into account when implementing the model. First, the results from the analysis are only as good as the data that it is derived from. As seen in the case with the VAQ, some of the metered data can be inaccurate, and must be discarded. Indicator variables can be used to group buildings into similar categories of energy use. In this analysis, four categories were used, but one could use all nine AF category codes or develop a separate structure that is more accurate to the installation being considered. In addition to the category code or function, facility energy use at a specific base is also dependent on the age of the building and how well kept it is. Energy efficient upgrades like new windows, low-watt lighting, and more efficient heating and cooling systems could also change the energy demand. For Air Force bases in the northern hemisphere, the presence of south facing windows could also have a significant impact on the heating demand placed on a facility in the winter.

Similarly, indicator variables could be used for exceptionally large buildings or for buildings with unusually high energy use, such as facilities with servers, supercomputing systems, or with unusually low energy use, such as empty facilities or infrequently used storage warehouses. The temperature variable could be modified to take into consideration cooling and heating degree-days or degree-hours, measurements designed to reflect energy demand for cooling and heating, instead of using raw temperature data. Raw temperature data works for locations that typically cool or heat, but may not be as accurate as temperature data that is more closely tied to heating and cooling demands. Additionally, a variable for day of the week could be added, given that some office buildings will exhibit smaller usage due to inactivity on weekends.

In predicting energy consumption for non-metered facilities, it is important to consider the risks associated with extrapolating data beyond the region containing the original observations. In this analysis, the four of the five largest buildings on the installation were dropped from the regression, and the fifth was included. If a larger facility existed and did not have metered data, the model might not accurately predict consumption data for that facility. As an additional precaution, the regression in Eq. (3.4) is for a specific seven day period in the summer at Nellis AFB. Using these coefficients with the equation for a different period of time or for a different base would not yield accurate results. Using the process for different installations at different periods of time should yield new coefficients that accurately estimate consumption for the facilities without meters.

A strength of this process is that it can be iterated or modified to take into account installation specific characteristics or activities in order to achieve a more accurate result. Likewise, as more facilities come online with metering capability, the same method and tools can be used to refine estimations. Likewise, though the analysis above used hours as the time period, any time period for which data exists and for which the user wants to estimate energy use can be applied. As seen, though, the model is influenced by outliers, and care must be taken to appropriately remove data which may produce unusual or questionable results. Lastly, the process of randomly assigning half the data to predict coefficients and using the other half to calculate how the prediction performed is a useful tool for understanding the validity of the model. Ultimately, the process in this section outlined a recommended method for calculating accurate energy use data at the facility level for those buildings without metered energy data. This data will be applied to the model described in the next chapter.

Chapter 4: Power Failure Response Model

Air Force installations receive electrical energy from many sources. As seen from chapter two, there are many potential sources of electrical energy. Each source is unique with respect to how it integrates into the grid of the installation, and how it supports the user demand on base. This section addresses how energy supply is characterized and modeled for this analysis. As an example, specific sources of supplying power to Nellis AFB will be discussed, and future options for Nellis AFB electrical energy generation will be defined. A range of power failure scenarios are then developed and applied to the model.

Electrical Energy from the Domestic Grid

Under normal operating conditions, Air Force installations typically receive electric power from the domestic grid. Air Force Instruction 32-1061 (AFI 32-1061) provides guidance and direction to base officials who manage utility services on Air Force installations. Previous versions of this instruction guided base managers to obtain electric service from a supplier (public or private utility company) transmission voltage source to a supplier-owned substation. From the substation the power is transmitted to the loads via a government owned distribution system, typically on multiple circuits. The current AFI 32-1061 takes into account that the Air Force may or may not own the energy supply, the substation, or the on-base utility distribution systems. Per AFI 32-1061, in descending order of preference, the combinations are listed in Table 15. The third is the most common in the Air Force.

Table 15: Acquiring Electric Service for Air Force Installations (AFI 32-1061)

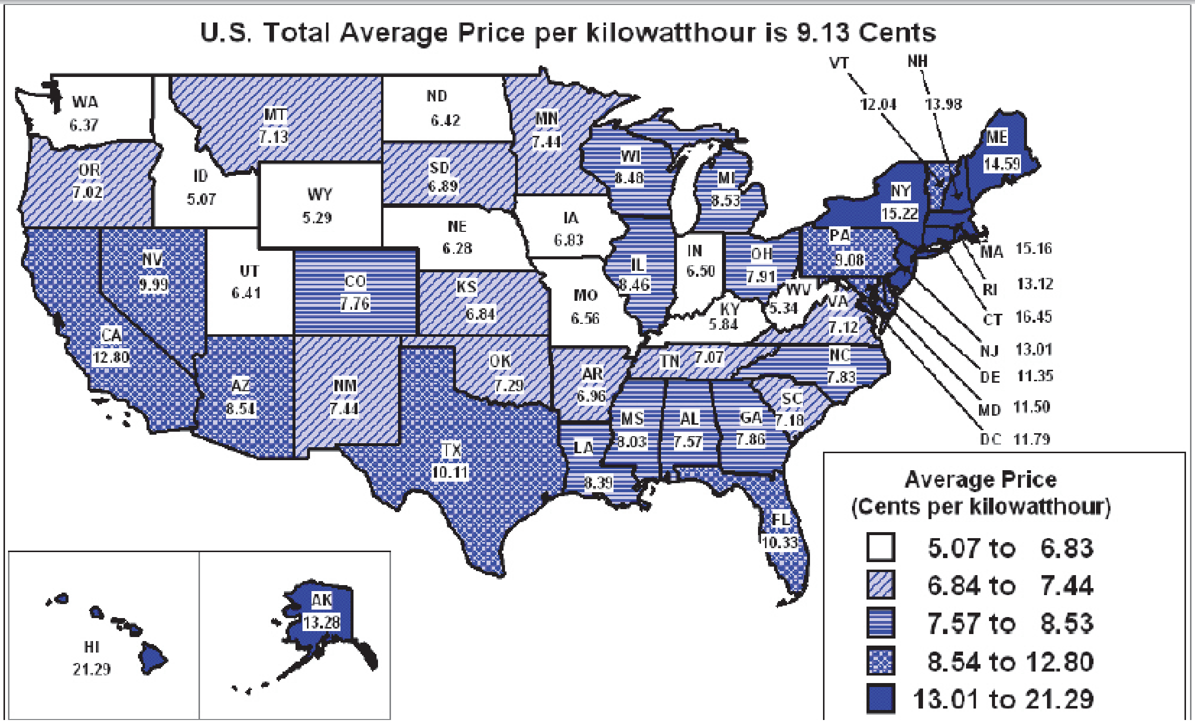
Energy Source	Substation Owner	On-Base Distribution System
Suppliers transmission voltage	Supplier	Supplier/Privately Owned
Suppliers transmission voltage	Government	Government
Suppliers transmission voltage	Supplier	Government
Suppliers transmission voltage	No substation*	Government
Government owned central plant	Government	Government

*Input voltage matches government system voltage

As the Air Force moves toward its 25 percent renewable energy goal and increased energy generation on site, the mix of ownership in acquiring electric services will need to be revisited. In particular, costs for supplier provided substations and distribution systems in concert with government owned plants will need to be considered. Furthermore, evolution of the language in the AFI and the precedence in the table indicate that the Air Force desires moving toward a supplier managed grid. The costs or savings, benefits, and risks associated with this shift should be addressed, especially those concerning energy security.

Most installations will continue to own and service the on-base distribution system, even though the electric service, power source, and substation are not typically government owned. Due to constant manpower and resource limitations, the government loses efficiencies that a local utility or public/private partnership has, as evidenced by the lack of energy meters on real property infrastructure and facilities. Divesting will allow the Air Force to utilize installation manpower more efficiently and take advantage of local utility or private provider expertise and scale. Furthermore, if properly structured, the incentives can encourage the local utility or the private provider to upgrade the distribution system to decrease line losses and more effectively network the local grid. The costs, benefits, and risks associated with these incentives should be addressed through further research.

The cost of electric power from the grid varies considerably and is dependent on location and time of use. Night hours typically have the lowest rates and afternoon hours have the highest rates. Figure 12 below shows the average price per kilowatt-hour of electricity in the U.S. by state in 2007. Prices range from 5.07 cents per kilowatt hour in Idaho to 21.29 cent per kilowatt hour in Hawaii; Nevada sits at 9.99 cents per kilowatt hour (EIA, “Electric Power Annual 2007”).



Note: Data are displayed as 5 groups of 10 States and the District of Columbia.
Source: Energy Information Administration, Form EIA-861. "Annual Electric Power Indsutry Report."

Figure 12: Average Price of Electricity per Kilowatt-hour in the United States

Electrical power for Nellis AFB is provided by the Nevada Power Company. The power is delivered to the base through a utility owned substation. Then, the power is transferred to the installation facilities via nine government-owned circuits with over 1.8 million linear feet of cable, of which over 1.1 million feet are underground cable (Headquarters ACC, *Nellis and Creech AFB Capital Improvements Program*). Nellis AFB also tracks the prices it is charged by the local utility provider, though due to restrictions on price data those values are not published here. During the summer months, an estimate of 10 cents per kilowatt-hour is accurate and will be used for electrical power delivered to Nellis AFB from the domestic grid.

Model Overview

The Power Failure Response Model will show how an installation responds to power failure scenarios. Before describing the model, it is worth mentioning the human element as part of how well an installation responds to power failure scenarios. During Air Force installation outages, the base commander, the base civil engineer team, the PowerPro staff, and the local utility personnel play critical roles in maintaining core missions and operations. The levels of their training, experience, and relationships will likely factor into the response and duration of the power failure. This study does not attempt to characterize the human element in the model, but acknowledges this element of installation response to power failure as critical and important. The impact of power failure will be measured by the extent to which the network is capable of supporting its infrastructure in terms of facilities without power. The analysis will be implemented in Visual Basic, with Microsoft Excel serving as the front end for collection and organization of data.

Sets of Objects:

Source The set of electrical energy sources currently available at Nellis AFB as well as those energy options considered for implementation, defined by:

- ➔ Total power capacity (by the unit of *time*)
- ➔ Nodes that the source can supply power to (0, 1)

Time The unit of time (*Time*(1), *Time*(2), … *Time*(N))

Building The set of buildings requiring energy, defined by class (critical/operational, support/service, administrative/office, other)

Scen The list of possible power failure scenarios

Tran The set of distribution lines, switches

Description of Nellis Air Force Base:

The initial plan in setting up the model was to configure all of the individual buildings as nodes and the distribution lines connecting the buildings as edges. Due to the nature of the electrical grid on Air Force installations, it became apparent that electrical switches and poles would also need to be modeled as nodes in order to more accurately reflect actual electric circuits. For example, in the schematic in Figure 13 below there are four nodes and three edges. It would be inaccurate to model building one as attached to both buildings two and three. Instead, building one is connected to electrical pole one which is then connected to buildings two and three. Electrical poles two and three are not modeled as individual nodes in this analysis; instead they would be included as part of the edge which connects electrical pole one to building two.

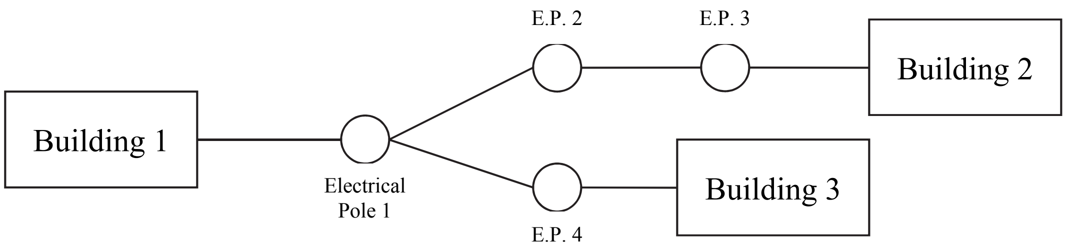


Figure 13: Example of Modeling Nodes

The physical layout of the buildings and electrical distribution system on installations is typically available from the Civil Engineering Squadron. At Nellis AFB, the layout was provided by the Nellis AFB Geo Integration Office via an AutoCad drawing. This drawing was then entered into an adjacency matrix in Microsoft Excel. For this analysis, 338 buildings, wells, storage units, and housing groups are modeled as individual nodes. Though there is additional detail for on-base housing communities, all of the housing buildings are labeled as one node. In addition, 79 electrical switches and poles are modeled as nodes. There are 426 edges representing a total of nine circuits at Nellis AFB.

<u>Constants:</u>

Network(Building, Source)

Network is an adjacency matrix, which lists the *buildings*, *sources*, and distribution switches and poles as nodes. Adjacent nodes are labeled with a one, and nonadjacent nodes are labeled zero.

EnergyDemand(Building, Time)

The amount of energy a *building* uses for a given time period, *time.* These values are estimated using supplied data and/or regression analysis, as seen in Chapter Three, and are measured in kilowatt-hours.

CriticalEnergyDemand(Building, Time)

Also, for those buildings in which generator data is available, the energy demand will decrease if it relies strictly on backup/generator power. This is due to the fact that generators are usually sized for critical loads inside the building, and not sized for non-critical aspects. Figure 14 below shows a typical relationship between normal and critical demand.

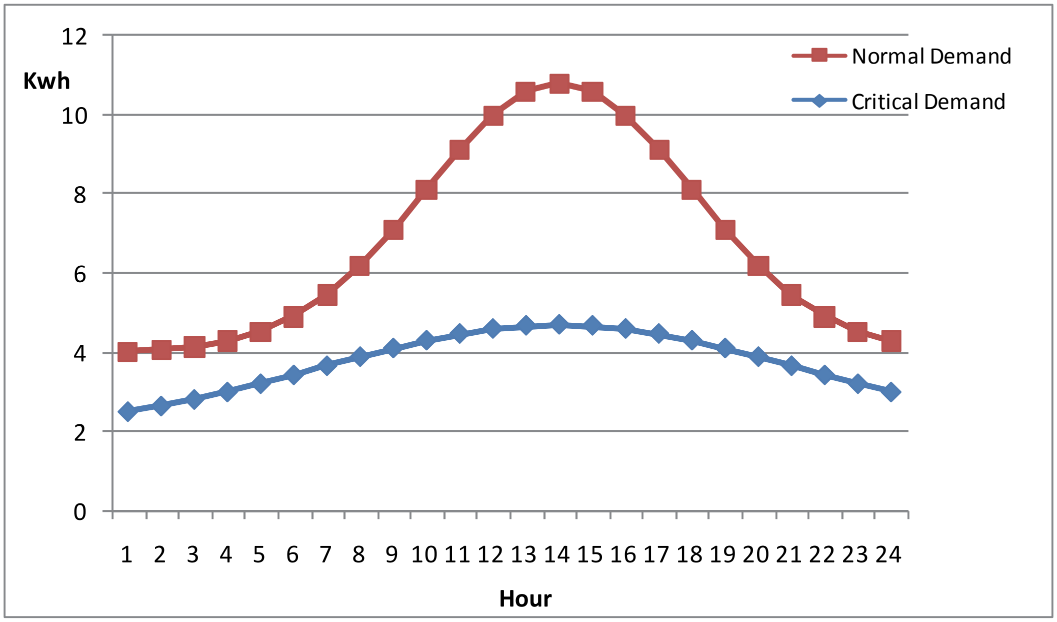


Figure 14: Energy Demand Function with Normal and Critical Demands

MaxSupply(Source, Time)

The amount of energy a *source* can supply for a specified *time* period, measured in kilowatt-hours. For diesel or natural gas generators, these values will be constant. For solar, wind, or variable electric generators, they will be a function of what time of the day it is.

SourceOpsCost(Source, Time, Scen)

This value represents the estimate for how much a *source* costs for operation. The costs will be estimated as total kilowatts supply (and used) per *time* period. These costs include actual energy costs, the maintenance costs, and any other costs associated with use.

Switch(Building, Source, Scen, Network)

This allows for the incorporation of electrical switchgear, which includes the electrical disconnect, switches, and fuses used to control and isolate electrical equipment. The *switch* value allows for segments of the base *network* to function with local generation in the event of a power failure elsewhere in the *network*. A segment is an enclosed group of *buildings* within a pair, set, or any combination of electrical switches (or circuit breakers). When power failure occurs in a *scenario*, the *sources* begin to fulfill local energy demand to the *buildings* available to it within its segment.

For example, an automated transfer switch is connected to two buildings for its output power and to the base distribution system and a generator for input power. In the event of a failure at the substation level or anywhere on the distribution system leading up to the switch, the model checks the *switch* value to see if a building is connected to an energy supply other than the grid. In this case, the answer is yes, so the system automatically transfers to that generator, and the buildings connected to the switch receive power from the generator and continue to function.

<u>Variables:</u>

EnergyUsed(Building, Time, Scen, Network)
The amount of energy a *building* is supplied for a given *time* period, or the amount of energy a *building* uses from the list of available sources for a given *time,* measured in kilowatt-hours

EnergySupplied(Source, Time, Scen, Network)
The amount of energy supplied by a *source* for a given *time* period, measured in kilowatt-hours. This differs from *MaxSupply* in that there will be times when a *source* doesn't operate at full capacity.

Source_Func(Source, Scen)
This is a variable, which equals one when the *source* is functioning. This is dependent on the scenario, *Scen.* Toggling the value to zero would be representative of time periods where the sun doesn't shine (solar) or windless days (wind).

<u>Constraints (subject to:)</u>

$\forall$ *Building, Scen, Time:*
EnergyUsed(Building, Time, Scen, Network) $\leq$ *EnergyDemand(Building, Time)*
This constraint guarantees that a *building* is not using more energy than it is demanding.

$\forall$ *Source, Scen, Time:*

EnergySupplied(Source, Time, Scen, Network) $\leq$ *MaxSupply(Source, Time)*

This constraint guarantees that a *source* is not supplying more energy than its capacity.

$\forall$ *Scen, Time:*

$\sum$ *EnergyUsed(Building, Time, Scen, Network)* = $\sum$ *EnergySupplied(Source, Time, Scen, Network)*

This constraint ensures that total energy generation equals energy actually used in the system.

Assumptions:

A few assumptions allow the model to function properly. First, generators work when used as backup power; they do not have a random failure element. This assumption allows simplification of *Source_Func*. Second, energy usage remains relatively constant over the course of the *time* period selected, and this holds for the following variables: *EnergyDemand, EnergyUsed, CriticalEnergyDemand, MaxSupply,* and *EnergySupplied.* Additionally, in the event of a failure, switches open and close automatically. For the implementation of this model, the unit of time will be hours. This was primarily chosen since most of the consumption data was given in hourly increments. Lastly, this particular example will model a seven-day period.

Model Outputs:

The outputs from running the model are the following sets of data.

Total_EnergyUsed(Source, EnergyUsed, Scen)

The total amount of *energy used* from the active *sources* during a particular s*cenario.*

Total_OpsCost(Source, EnergySupplied, SourceOpsCost, Scen)

The total energy costs for the installation during a particular *scenario,* taking into account the *energy supplied* from specific *sources* and their operating costs.

Without_Power(*Building, SourceFunc, Scen)*
For a given *scenario*¸ this array lists the number of *buildings* in a particular category that were without power during the scenario, and for how long they were without power.

Installation Solar Power

In December 2007, Nellis AFB completed construction of a 14.2 megawatt photovoltaic solar array. As the power purchaser and site host, Nellis AFB signed a 20 year land lease allowing the solar panels to be constructed on base land. Covering 140 acres of Nellis AFB property including 33 acres of a capped landfill, the solar array provides 20-30% of the installation's power needs. Sun Power Corporation designed and developed the photovoltaic array, and continues operation and maintenance efforts. In addition, Nellis AFB signed a power purchase agreement with MMA Renewable Ventures, effectively agreeing to buy all power produced by the solar array for a fixed price for the 20 year lease period.

For this analysis, the amount of power delivered from the solar array to the grid is based on actual data received from Nellis AFB energy archives. For the June time period, the array begins to generate power just before 7:00 AM and stops generating shortly after 7:00 PM. Power production peaks around noon each day, with most of the daylight hours producing between 10 and 12 megawatts of power. Due to the structuring of the contract by base energy and contracting officials, the cost for the solar array at Nellis AFB is $0.023 per kilowatt-hour, and this is below the industry average. Staffing and support for the array is minimal, and no additional costs are added. The array is connected directly to the electrical grid without battery backup. In the event of a power failure, the array is shut down until the grid is functioning properly again. Thus, in the system's current state, the solar array cannot provide electrical power to Nellis AFB during any scenario resulting in power failure to Nellis AFB. This is typical of most installation energy projects across the Department of Defense.

Installation Generators – Diesel and Natural Gas

In AFI 32-1062, the Air Force authorizes emergency or standby generators when needed in order to support mission-critical functions. Furthermore, MAJCOM/A7 staffs have the authority to approve additional generators not listed as long as they support mission-critical functions. The Air Force has typically purchased generators that are sized beyond the maximum capacity of an individual facility, and the generator is connected to the building via an automatic transfer switch. Generators are usually placed outside the facility within a generator storage house. Fuel storage tanks are attached to the generator and are sized to allow for three to five days worth of continuous generation capacity.

Air Force Instruction 32-1062 (AFI 32-1062), Electrical Power Plants and Generators, focuses on power generation for real property installed equipment (RPIE) prime, standby, and emergency generators. This document instructs acquisition, operation, and maintenance requirements for all generation and power plants on Air Force installations. AFI 32-1062 also rescinds Air Force Instruction 32-1063 (AFI 32-1063), Electrical Power Systems. AFI 32-1062 requires that every generator is tested semi-annually at full facility load, and that technicians check the operability of all its components. Furthermore, every time the generator operates, whether for emergency or maintenance, the event is detailed on AF Form 487, *Emergency Generator Operating Log* and AF Form 719, *Historical Record – Diesel-Electric Generator and System*. With such stringent testing and documentation requirements, generator reliability is high. Operating, maintaining, and testing generators falls within the Power Production element of base Civil Engineering Squadrons. These teams are typically on-call 24 hours a day in order to respond to power failure. The Civil Engineering Squadron is authorized a number of billets for its power production team, and it is not uncommon with current global operations that one-third are deployed at any given time. At the time the model was created, the Nellis AFB team operated a system comprised of 41 fixed generators across the base with an average age of 5.5 years. They also held 25 mobile generators used for contingency and emergency operations, and most of those assets were deployed. Standard life expectancy of the generators is 20 years.

There are two basic types of generators used on Air Force installations: diesel generators and natural gas generators. Diesel generators can be sized small enough to power individual equipment in offices and housing, or can also be large enough to provide megawatts of power. Diesel engines have been built for ships for providing power for main propulsion in addition to the ship's electrical power demand. As seen in Chapter Two, modern diesel generators can operate on a variety of fuels including alcohols, gasoline, and biomass-derived fuels in addition to the commonly used diesel derived from crude oil.

Natural gas generators operate similarly to diesel generators, though these generators are often larger in size. Whereas diesel generators have storage tanks of diesel fuel, natural gas generators typically are connected to the installation's fixed natural gas lines. On the one hand, this connects the generator to a larger supply of fuel than the limited supply diesel has through storage tanks. However, in scenarios where infrastructure is damaged, the fixed natural gas lines are as susceptible to failure as are the transmission and distribution power lines.

Capital costs for generators can be found from various venders, including Caterpillar, Cummins, Detroit Diesel, and Kohler. Prices are dependent on size and make of generator, size and make of automatic transfer switch, location of the installation, and other installation cost. This analysis uses a total installation cost of $0.80 per watt of power provided for generators smaller than 30 kilowatts and $0.60 per watt of power provided for generators greater than 30 kilowatts. Thus, a 100 kilowatt generator would cost around $60,000 for the complete installation, and this includes the price of the automated transfer switch. These prices are comparable to those estimated by the Real Property Office and the Power Production team at Nellis AFB. For modeling purposes, these prices are only applied to new or replacement generators; generators already installed on the installation do not incur capital costs.

Operating costs are driven by fuel consumption, and a modern diesel plant will typically consume around 1 gallon of fuel per 10 kilowatt-hours of power generated. The efficiencies used below are representative of industry averages. Increasing the efficiency of an engine or generator increases the amount of energy delivered per unit of fuel, as seen in Equations (4.1) and (4.2) below.

Eq. (4.1): 30% Engine Efficiency: $$\frac{2{,}545 Btu}{hp-hr} * \frac{Gal}{134{,}885 Btu} * \frac{1}{0.30 Eng.Efficiency} = \frac{0.0629 Gal}{hp-hr}$$

Eq. (4.2): 85% Generator Efficiency: $$\frac{0.0629 Gal}{hp-hr} * \frac{1}{0.85 Gen.Efficiency} * \frac{1 hp}{0.746 kw} = \frac{0.0992 Gal}{kwh}$$

With average bulk commercial diesel prices of $1.70 per gallon at the time of the analysis (EIA, "Annual Electric Generator Report"), fuel costs are estimated around $0.17 per kilowatt-hour generated from a diesel generator. Operating costs of natural gas follow a similar calculation, as seen in Equations (4.3) and (4.4) below.

Eq. (4.3): 24% Engine Efficiency: $\frac{2{,}545 Btu}{hp-hr} * \frac{MCF}{1{,}000{,}000 Btu} * \frac{1}{0.24 Eng.Efficiency} = \frac{0.0106 MCF}{hp-hr}$

Eq. (4.4): 85% Generator Efficiency: $\frac{0.0106 MCF}{hp-hr} * \frac{1}{0.85 GenEfficiency} * \frac{1 hp}{0.746 kw} = \frac{0.0167 MCF}{kwh}$

Though wellhead natural gas prices were quite low in June 2009 at $3.45 per thousand cubic feet, residential and commercial prices were $13.81 and $9.24 per thousand cubic feet. Using a natural gas price of $10.00 per thousand cubic feet, natural gas fuel costs for this analysis are estimated at $0.167 per kilowatt-hour generated from a natural gas generator.

Consistent with Air Force policy and AFI 32-1061, Providing Utilities to U.S. Air Force Installations, system operations and maintenance costs are included in the total cost of power generation assets. System operations and maintenance costs include routine maintenance and repair. Replacing the distribution system with a newer system which "adds value or capacity" falls into a different category of replacement cost. Thus, purchasing new generators is not included in system operations and maintenance costs. For routine maintenance, the manpower costs need to be estimated as well. Table 16 estimates the daily cost for employing a standard 25 person team using Table A-19.2 of Air Force Instruction 65-503, FY 2009 Military Annual Standard Composite Pay.

Table 16: Estimated Manpower Costs

Rank	Total Annual Composite Rate	Number Employed	Total Annual Cost	Daily Rate
E-6	$84,194	2	$168,388	$461
E-5	$71,608	2	$143,216	$392
E-4	$59,998	10	$599,980	$1,644
E-3	$48,809	4	$195,236	$535
E-2	$40,028	7	$313,173	$858
		Total Cost	$932,531	$3,890

The total estimated manpower cost will be added to the total energy costs for each scenario, and represents the manpower costs of operating, maintaining, and repairing all of the fixed and mobile generators on the installation. Note, for operation of generators it is assumed that they are used solely for emergency generation. Requirements allowing for emergency generators to be used for utility tariff control or for base power are stringent and unlikely to be met in ordinary operations.

Options for Nellis AFB Energy Generation

Due to the success of the photovoltaic array, Nellis AFB has become not only a model for implementation of alternative energy, but it also stands at the forefront of continued development of installation energy solutions. The energy manager at Nellis AFB also oversees energy projects for Creech AFB and sites within the Nevada Test and Training Range, both of which cover significant areas of land in the Nevada desert. Potential projects for these locations include additional solar energy and geothermal. This dissertation will specifically analyze four energy options at Nellis AFB. Due to the proprietary nature of on-going projects, the options listed here are not to be considered official projects at Nellis AFB. Instead, they should be viewed as alternatives vetted by Nellis AFB energy officials as realistic options.

The first energy option is the addition of a diesel powered generator to an operational category building. A generator, an automatic transfer switch, and a fuel tank are purchased for this option. Though the building has an electrical demand peaking during the summer day at over 110 kilowatt-hours, the critical load of the building is listed at 12.5 kilowatts. Consistent with Air Force practices, the generator is sized at least twice the critical load at 25 kilowatts. Using an estimate of $0.80 per watt of power for total installation, the cost for this energy option is $20,000. Operating costs are assumed to be similar to the costs of current installation generators, and the addition of one generator does not increase the manpower costs associated with operating and maintaining power production equipment.

The second energy option is the addition of a photovoltaic solar array covering a parking lot. Directly connected to the Nellis AFB network, the array will be sized at 30 kilowatts. The net installation cost for the 30 kilowatt array will be $114,000 at a price of $3.80 per watt. The net installation cost per watt follows a 2009 report from the Lawrence Berkeley National Laboratory, which details photovoltaic costs from 1998-2007. The report takes into account state and federal investment tax credits as well as state and utility after-tax incentives (Wiser, Barbose, and Peterman, “Tracking the Sun”).

The third energy option is a rooftop solar array at the same location as the first energy option, but with the additional goal of providing backup power via an automatic transfer switch and a battery system. With a critical load of 12.5 kilowatts, the battery bank should be sized to provide power through night hours without sunlight. Assuming 14 hours as a maximum number of hours without sunlight and a system loss factor of 0.8, the total capacity of a battery will need to be just shy of 220 kilowatt-hours.

Though the Department of Energy has a goal of $500 per kilowatt-hour of energy storage, current costs are closer to the range of $750 to $1,000 per kilowatt-hour (Wald, "A Quest for Batteries to Alter the Energy Equation"). Using $750 as an estimate, the upfront cost of the backup battery will be $165,000. A 25 kilowatt solar array at $3.80 per watt is $95,000. As is consistent with backup battery systems, a battery more than doubles the installation cost of the solar powered system. A battery bank of this capacity will be physically large, though assuming there is available space around the perimeter of the building is reasonable.

The fourth energy option is a biomass integrated gasification combined cycle which will burn mainly from both on-base and local construction debris. The proposed generator will produced 5 megawatts of delivered power. The generator will be able to provide electrical power to a set of 50 buildings when electrical power to the installation fails. Assuming a capital cost of $1,500 per kilowatt, the initial cost will be $7,500,000. Including the cost of transporting, storing, and supplying fuel to the generator, the operating costs will be $0.09 per kilowatt-hour. This cost to the installation includes the staff and engineering costs of operating a power plant. The site will be located at the perimeter of the installation, such that truckloads of off base debris will not have access to the rest of the installation.

Power Failure Scenarios

The next step is to create and model failure scenarios. These scenarios give the base energy officials the ability to not only calculate the cost implications of energy options, but also to assess quantitatively how the energy options affect the installation's energy security. In this example, there are four power failure scenarios which will be used to assess how the various sources of electrical energy supply on an Air Force installation respond to power failure. After any power failure on an installation, base engineers responsible for providing electrical power are required to submit an outage response notification which details the type, effect, and duration of power failure as well as the response by base officials. The base and command retain records of past failures.

The first three scenarios discussed in this section are power failures that have occurred at an Air Force installation and are derived from outage response notifications. Though the details are generalized, the first three power failure scenarios provide different types and durations of power failure that are likely to occur at an Air Force installation. The fourth scenario represents a prolonged power failure in which base functions and missions are limited, and the local community is likely to be without domestic grid power as well. The probability of this scenario occurring at an Air Force installation is low, though potential effects can include loss of the installation's ability to operate highly critical missions.

Scenario One – Temporary Voltage Drop

An incoming voltage drop generally occurs because the electrical load in the domestic grid is higher than the total electrical generation. This type of failure, also known as a brownout, can also occur when a three-phase electric power system has one or more of the phases incorrectly phased. Brownouts are characterized by the dimming of lights as resistive devices such as household incandescent lamps vary heat output based on supplied voltage. In some electric and in three-phase motors, a brownout causes the motor to draw more current to compensate for the drop in voltage, which can cause serious overheating and damage of the motors.

Voltage drops typically last for a short period of time, with some dropouts lasting seconds or less and other longer brownouts lasting upwards of an hour. Because of the potential damage that can be incurred due to a voltage drop, some electrical systems are designed to compensate for varying voltage. However, common practice is to protect against voltage drop before the drop affects an appliance or electric motor. Analogous to relays and fuses in households, a segment of an electric circuit will automatically disconnect itself from the grid once a voltage drop is detected.

Air Force installations are protected from varying voltages in this way. A drop in the voltage can be detected at the substation serving the installation, and the circuits respond by opening and cutting all power to the loads. Automatic transfer switches connected to individual buildings can also be used to protect equipment within a building from a voltage drop. These systems disconnect the building from the grid and switch the power supply over to backup power if local backup generation exists. Restoring power occurs when the utility and power stations can correct the voltage differential by either generating additional power to match the demand or by cutting electrical demand. Then, at the Air Force installation level, equipment like the automatic transfer switches detect the rise in voltage and revert from backup generation to the grid.

This scenario assumes the total duration of the voltage drop lasts 15 minutes and is large enough that all power to the base from the domestic grid is disconnected. No equipment is damaged during the scenario, and the local switches transfer the demand to backup power where available. Power restoration occurs automatically, with buildings reconnecting to power without electronic equipment failure. To capture variability in electrical power demand during the day and during the week, the scenario will be run at six different times. The average power used and cost will be used for comparison. The *Day-Hour* combinations are shown in Table 17.

Table 17: Day-Hour Combinations Where Scenario 1 is Applied (Day-Hour)

Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00

Scenario Two – Distribution Line Failure

After entering a substation, power is delivered to the base through numerous distribution lines. Typically, multiple circuits will extend from a single substation and the individual circuits will provide electrical power to groups of buildings. These distribution lines can fail in numerous ways; bad weather can knock down distribution poles or the circuits can be damaged due to overuse or thermal overloading. Because circuits are often interconnected, a failure at one point in a distribution line may not cause power failure in the buildings it is connected to. Instead, if properly switched, power can reroute through the rest of the grid and buildings can operate normally. However, some locations in the localized grid may not have this flexibility, and building power failure will occur when the distribution line fails.

Once a distribution line has failed, power restoration involves many steps. The first step involves finding the location of the failure. Once the failure has been found, the repair team must then determine the cause of failure. Before actual repairs can begin, the team must disconnect electrical power to the area, which may involve disconnecting power to nearby buildings not directly impacted by the line failure. Restoration times can vary considerably, as demonstrated in Figure 15.

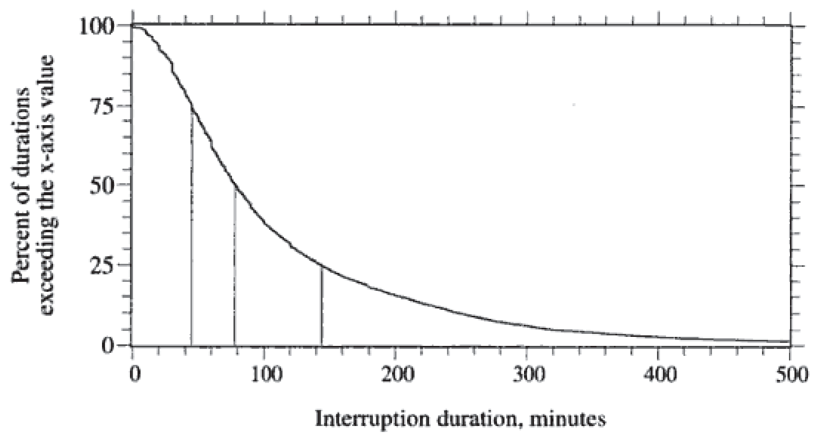


Figure 15: Line Failure Interruption Durations
(Short, "Distribution Reliability and Power Quality")

For this analysis, the power failure will last two hours. The two hour time period begins with the failure of the individual edge and concludes with the successful restoration of electrical power. According to Nellis AFB electrical systems engineers, a time period of two hours is consistent with previous distribution line failures at Nellis AFB. Instead of choosing various locations on Nellis AFB for power failure and analyzing the results from those select locations, this scenario models a two hour failure for each edge in the adjacency matrix. The impact of each failure is computed separately and the cost and the number of buildings without power are output for the each of 426 edges modeled for Nellis AFB.

The network is analyzed for connected components using a depth-first search algorithm. The algorithm begins at the substation node, and explores as far along each circuit until either it reaches the substation again or hits a node that has no further connections. Then, the search backtracks to the most recent node which it has not explored. All connected nodes are added to a visited array, and the array of visited nodes serves to show which nodes are connected to the network.

Each edge represents a connection between two nodes in the model. In order to implement the power failure scenario, each edge is disconnected from the network by replacing its value with a zero in the adjacency matrix. The depth first search algorithm is then run again, and the output shows a new set of connected nodes. If the result is the same as the original case, then the network has built in redundancy and the nodes remain connected to the electric grid through a different set of distribution lines, or edges. If the result indicates that fewer nodes are connected, then the disconnected nodes have no access to electric power.

The histogram below in Figure 16 summarizes the frequency of the number of buildings disconnected from the Nellis AFB electrical grid based on the failure of a single edge. As can be seen, the mode is zero and the median is one. There are 160 edges that do not result in a node losing power when the edge is modeled as failed, assuming automated switching functions properly. The maximum in the model is 75 nodes, implying that the removal of one edge results in 75 nodes being disconnected from the electrical grid. After further research, all of the edges resulting in greater than 15 buildings disconnected from the network are located on the same circuit on Nellis AFB.

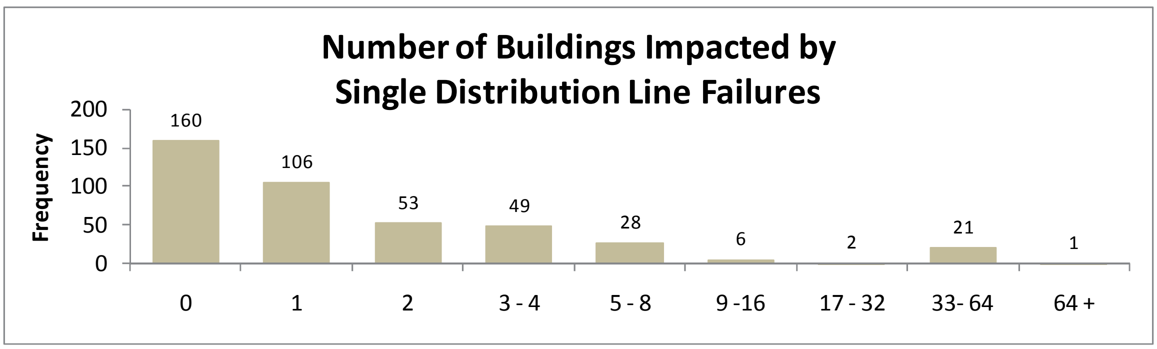


Figure 16: Number of Buildings Impacted By Distribution Line Failure on Nellis AFB

Analyzing the impact to the grid based on a single node failure illustrates two key conclusions. First, dependent on where the distribution line failure exists on the installation, power may not be lost. If the failure occurs in an area where it is not detected or apparent, a potentially dangerous situation can develop during power restoration by the utility or local base power technicians. In this case, a power line could be assumed to be energized when it is not, or vice-versa, and technicians could inadvertently be electrocuted. Standard procedures implemented by the technician can reduce the risk of electrocution. For example, the technician should always assume all lines are energized unless he or she personally verified the line had a visible open point between the load and the supply side or personally opened a fused switch or disconnect.

Second, it is critical that installations establish backup plans and procedures, and train personnel against these plans. Highly trained personnel, knowledgeable of their installation's strengths and weaknesses, can decrease the impacts of the disruption and the amount of time their installation suffers from power loss. Nellis AFB officials were told about the circuit with multiple failure modes and implemented two solutions. The first was a near term solution of training personnel against the risk and adding road barriers at the base of distribution lines at road intersections. The second solution was to add distribution lines and switching to the circuit in order to increase redundancy in the local network. Conversely, a poorly trained team without knowledge of their installation will likely take longer to restore power in the event of a failure, and the installation may suffer mission degradation that could have been prevented.

Scenario Three – Substation Failure

Distribution substations transfer electrical power from the transmission system to a distribution system. These substations typically serve to transform the voltage from high to low voltage and they also serve to isolate faults in the transmission or distribution system. One or more input lines feed a distribution substation, and the output is a larger number of feeders at lower voltage. Failure at an electrical substation can occur for a variety of reasons, though these are quite rare.

Planned substation outages are controlled and power can be restored quickly to the distribution system. Unplanned failures at a substation, however, can be dramatic as repair crews have to isolate the substation from locations in other parts of the grid before performing repair work. Some components of a substation can be hard to replace, and some components may not have a reliable backup available at all. A past event at the Nellis AFB substation caused a power failure for the entire base for 12 hours.

For the analysis, this scenario will be a failure at the substation lasting 12 hours. Only equipment at the substation is damaged, and switches transfer power supply to local backup generation where available. A repair crew of engineers and utility employees are able to restore power at the conclusion of the time period. The failure will take place on workday from 1000 hours to 2200 hours, thus encompassing workday and post-work evening demand characteristics.

Scenario Four – Extended Failure to the Domestic Grid

Although far less common, the last scenario to be modeled is the case where the electrical grid has gone down for an extended period of time. Natural disasters such as hurricanes, earthquakes, tornados, and floods are the primary causes of those that have occurred. Though the probability is low, the threat of an extended power failure caused by a terrorist or by other groups with malicious intent is real.

The final scenario for this analysis represents an extended power failure that lasts for a period of 168 hours. Damage to the installation's distribution network is assumed to be absent, as well as damage to on-base generation equipment. Essentially, the electrical failure is limited to an event resulting only in failure to the external electric grid. Other local commercial, residential, and industrial areas are assumed to be without power. Officials from the local utility are busy attending to the domestic grid failure, so base power production is left solely to the care of base engineers, technicians, and contractors.

Summary

Table 18 below depicts a summary view of the power failure scenarios.

Table 18: Scenario Overview

Scenario	Duration	Location	Description
1) Temporary Voltage Drop	15 minutes	Substation	Circuits automatically open to protect equipment; buildings are reconnected when voltage recovers
2) Distribution Line Failure	2 hours	All Edges	Failure occurs at individual distribution line locations; on duty engineers respond and fix failure after two hours
3) Substation Failure	12 hours	Substation	Power disconnected at substation to local distribution; coordinated recovery with local utility; 12 straight hours of backup / local generation only
4) Extended Failure to the Domestic Grid	1 week	Domestic Grid	Entire scenario experiences no electricity from the domestic grid; local generation only; external support unavailable

Each scenario is applied to the model with an indicator variable representing whether or not the domestic grid is supplying power to the installation at a particular hour. For each scenario, energy consumption and cost are reported. Additionally, the number of buildings without power and the duration of decreased power are determined. The results are reported in the next chapter.

As mentioned at the end of Chapter Three, though the data applied to this model is from Nellis AFB, the methodology itself is not installation specific and can be used by the Air Force across its installations. The scenarios in this study were developed to represent a spectrum of power failure scenarios, and modifying the failures to those common to the installation being analyzed would increase the applicability of the model to that installation. The energy options, as well, can be modified to the multitude of energy sources, sizes, locations, and specific implementations being considered. The unit of time presented here is in hours; if data exists at different time intervals the unit of time can be changed. Similarly, the period of time to run the model in order to analyze the installation's response is a simple modification, though longer durations correspond to increased computational requirements. Additionally, the model could be enhanced by including a probably of failure for the energy sources or switches.

A common thread across energy security working groups, panels, and conferences is the need to identify and document conceptual and analytical/methodological frameworks for assessing energy security. Furthermore, the methods and tools need to show decision-makers how to evaluate and prioritize mitigation measures. This dissertation assists that task by publicly detailing one, simple methodology for assessing energy options at the installation level. In particular, this chapter described a Power Failure Response Model that will show how an installation responds to power failure scenarios. The model allows the decision maker to evaluate energy options with the ultimate goal of informing investment decisions.

Chapter 5: Results from Data Analysis

The model, energy options, and failure scenarios were described in the previous chapter. The three outputs from running the model are energy used for each modeled facility and for the installation, the cost of that energy consumption, and a list of the modeled facilities that are without power for each scenario. Data is collected for each energy option considered. This chapter details the results from the model, and presents the data in ways useable by installation energy managers and decision makers.

As described in the specific scenarios in Chapter Four, this study modeled a seven-day period at Nellis AFB. The results are presented in three segments. The first segment is what most Air Force organizations begin with and serves as an initial baseline. It accounts for the cost of power delivered from the domestic grid and the number of facilities without power. For each of the power failure scenarios, because there is no on-site generation capacity, this represents the maximum number of modeled facilities without power. The second segment represents the current baseline of the installation and takes into account on-site generation and back-up sources. The value in having the two baselines is in being able to show the benefits and costs of current generating sources. The final segment represents the costs and modeled facilities without power for each of the energy options being considered.

For consistency, costs only include direct energy costs and those costs associated with energy use such as providing for and maintaining backup power supply, purchasing new power supply options, or purchasing new electrical grid components. One could imagine including costs such as lost productivity, monetized costs of mission failure, and others, but these are not included in this analysis. Each of the variables used in the cost calculations is defined below.

- $Cost_{subscript}$ = Total energy costs modeled, where the subscript describes the source of the cost
- $Price_{subscript}$ = Price, where the subscript defines the source (utility, solar, generator)
- $Kwh_{subscript}$ = Kilowatt-hours used during the time period, where the subscript defines the source

Previously, the facilities were categorized based on real property standard category codes, and then further grouped based on energy intensity. This was useful for energy use estimates. But for calculating impact to an installation, the base energy managers and installation leaders should come up with their own criteria for mission impact. The energy intensity for a facility could be used, but then certain buildings could be lumped together that do not have the same mission impact. For example, administrative buildings could get lumped with operational support buildings and presumably, if these facilities lost power, they would have different levels of impact to the installation. The category codes could be used, or a binary critical/non-critical grouping could be used. As described in Chapter Three, this study breaks down the modeled facilities into four categories: operational/critical facilities, office/administration facilities, support/service facilities, and all other facilities.

During interactions with installation energy officials, it became apparent that some facilities are more critical than others. Reporting a metric in terms of number of facilities without power or duration of power failure implies equal weights for facilities. In order to properly report on the criticality of different facilities, there are two simple ways the mission critical aspect can be implemented in the model. The first would be to categorize buildings according to how critical they are to the mission of the installation. This categorization is already formally reported through the Air Force Critical Asset Risk Management program, and could be simply implemented using already established data. Though this analysis did not use the exact list of critical assets on Nellis AFB, it did analyze a group of facilities categorized as Operational/Critical. Secondly, and what is shown at the end of this chapter, facilities or groups of facilities can be given a weight. Though subjective, the weight can be applied consistently across the analysis in a way that the installation decision maker can observe the effect of the power failure scenarios more clearly in terms of critical missions impacted.

Domestic Grid Results

The domestic grid results account for the costs and impacts associated with supplying power to the network of distribution lines and loads on the installation using only energy provided by the domestic grid. In this case, the total energy used equals 2,721,652 kwh. Since the domestic grid functions for the entire scenario, the cost is a simple multiple of the price. In equation form, domestic grid costs are defined in Eq. (5.1) below.

Eq. (5.1): $Cost_{DomesticGrid} = Kwh_{Utility} * Price_{Utility}$

The total cost indirectly includes normal operational and maintenance costs associated with the system of supplying power via a substation and transmission lines to base infrastructure. Implicit in this is the assumption that any maintenance or repairs are part of the price of energy.

The assumption that maintenance and repairs are part of the price of energy is implemented because beyond tree trimming, the practices of maintaining distribution circuits vary widely. Most equipment such as transformers, capacitors, insulators, wires, and cables do not need maintenance. Other equipment such oil-filled switches and reclosers need only occasional maintenance (Short, 2006). Failure rates for electrical equipment vary significantly, and often the same equipment fails repeatedly. Weather often drives maintenance, storms knock down power lines and equipment, and as crews restore this equipment they often assess its quality.

Thus, maintenance costs are not a separately listed cost, and this holds for the entire analysis when costs are applied to power supplied from the domestic grid. Table 19 below shows the total cost for five price options if all power were provided from the domestic grid. During the rest of the analysis, the domestic grid price will be set to $0.10 per kilowatt-hour unless otherwise noted.

Table 19: No Power Failure Costs for Domestic Grid Working Scenario

Price	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Total Cost	$217,732	$244,949	$272,165	$299,382	$326,598

For the first case where the Air Force installation is powered only from the domestic grid, the results from the model are summarized in Table 20 below. The results for each scenario are explained in further detail following the table.

Table 20: Results from Analysis for Domestic Grid Power

Scenario	1 No Power Failure	2 Temporary Voltage Drop	3 Distribution Line Failure	4 Substation Failure	5 Extended Failure
Electricity Used (*Kwh*)	2,721,652	2,717,392	2,721,263	2,493,266	0
$\text{Cost}_{\text{DomesticGrid}}$	$272,165	$271,739	$272,126	$249,327	$0
Facilities Without Power – Operational/Critical	0	26	0.17	26	26
Facility-Hours Without Power – Operational/Critical	0	6.5	0.34	312	4,368
Facilities Without Power – Admin/Office	0	108	0.80	108	108
Facility-Hours Without Power – Admin/Office	0	27.08	1.60	1,298	17,450
Facilities Without Power – Support/Service	0	110.33	2.51	111	111
Facility-Hours Without Power – Support/Service	0	27.75	5.02	1,332	17,892
Facilities Without Power – Other	0	90	0.77	90	90
Facility-Hours Without Power – Other	0	22.5	1.54	1,080	15,120

The highest domestic grid cost is seen in the case where there is no power failure because all of the other scenarios result in less total electrical power used for some period of time. Because there are no backup power systems modeled, the number of buildings without power and the total hours without power for each scenario are the maximum that will be seen for the analysis.   The average cost for the first power failure scenario is $271,739, and the costs per each sub-scenario are seen in Table 21 below.

Table 21: Scenario 1 (Temporary Voltage Drop) Costs

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Cost	$271,768	$271,666	$271,810	$271,829	$271,591	$271,771

As mentioned, the impact on the installation in terms of facilities without power is a maximum since there are no modeled secondary power sources to provide power when the grid is down. The reason the number of facilities without power is 110.33 and not the full 111 facilities for the support/service group is due to the fact that one node under this category accounts for the airfield parking apron lights, and these lights do not require electricity during two of the six sub-scenarios occurring during daylight hours.

The kilowatt-hours and costs for the second scenario are averages from the complete set of possible distribution line failures. The maximum failure occurs once and it results in 75 modeled facilities losing access to the base electrical grid, with three of those facilities considered mission critical, as depicted in Table 22 below. The maximum failure also corresponds with the minimum cost, in that the most buildings are without power for the scenario. The minimum failure occurs 160 times, and this represents the set of distribution edges in which its failure does not result in electrical power loss to a modeled facility or node on the installation. As seen in the third column of Table 22 below, when these 160 "unaffected" edges are removed from the analysis the average number of facilities without electrical power increases. Thus, the differences in the two averages for the second scenario are reflective of removing the distribution edges which do not result in infrastructure power loss.

Table 22: Results for Power Failure Scenario 2 (Distribution Line Failure) of Domestic Grid Only

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Affected Nodes	Scenario 2 – Maximum
Electricity Used (*Kwh*)	2,721,652	2,721,263	2,721,034	2,714,810
$Cost_{DomesticGrid}$	$272,165	$271,739	$272,126	$271,481
Facilities Without Power – Operational/Critical	0	0.17	1.14	3
Facility-Hours Without Power – Operational/Critical	0	0.34	2.28	6
Facilities Without Power – Admin/Office	0	0.80	2.61	15
Facility-Hours Without Power – Admin/Office	0	1.60	5.23	30
Facilities Without Power – Support/Service	0	2.51	7.63	45
Facility-Hours Without Power – Support/Service	0	5.02	15.26	90
Facilities Without Power – Other	0	0.77	3.29	12
Facility-Hours Without Power – Other	0	1.54	6.58	24

For the third and fourth scenarios, the number of facilities without power is the maximum that will be seen throughout the entire analysis, as this represents a case where all of the facilities are without power due to lack of any secondary or backup generation capacity. Likewise, the reported number of hours without power is a maximum as well. There is no electricity used in the fourth scenario as the electrical grid is non-functional.

Baseline Costs – Current Nellis AFB Infrastructure

With the last section representing costs associated solely with the domestic grid and without consideration of on-site power generation, this section factors in the current installation infrastructure and calculates the total costs and impacts associated with power use across the same scenarios. Additions to the previous section include the costs from operating the photovoltaic plant at Nellis AFB, as well as an estimate of the total costs of operating and maintaining the electric power generation backup systems.

The Nellis AFB photovoltaic plant provides power to the installation when the domestic grid is functioning. This is accomplished by providing power through the substation to the installation distribution system. As implemented at Nellis AFB and as reflected in the model, when the domestic grid fails the photovoltaic plant is turned off and it does not provide power to the installation. Since the costs of energy from the photovoltaic plant are lower than those purchased from the local utility, the main effect of the photovoltaic plant will be to reduce costs when it is operating. In itself, this is a useful method to show cost comparisons for implementing the photovoltaic plant or any similarly implemented energy source.

Since backup generation exists for this and future scenarios, it is important to remember a few key assumptions. The generators are assumed to operate normally when called upon, and they continue to operate through the remainder of the scenario. Furthermore, generators are strictly limited to providing power to the facility they are attached to. Even if a generator has excess capacity, it is not capable of providing power to surrounding demands. Lastly, with generators consuming approximately 0.1 gallons per kilowatt-hour, it is assumed that both local storage and total installation capacity are large enough to allow continued operations. Storage tanks at Nellis are sized from 100 gallons for small generators rated at 8 kilowatts to 10,000 gallons for larger generators.

In equation form, the baseline costs are defined in Eq. (5.2) below.

Eq. (5.2): $Cost_{Baseline} = Cost_{DomesticGrid} + Cost_{Generators} + Cost_{Solar}$

Where

Eq. (5.3): $Cost_{DomesticGrid} = Kwh_{Utility} * Price_{Utility}$
Eq. (5.4): $Cost_{Generators} = Kwh_{Generators} * Price_{Generators} + Cost_{Manpower}$
Eq. (5.5): $Cost_{Solar} = Kwh_{Solar} * Price_{Solar}$

When the domestic grid is fully functioning, the complete seven day cost is $238,631 for a total power consumption of 2,721,652 kilowatt-hours. The total costs for the baseline are broken down to its components in the four equations below.

Eq. (5.3): $Cost_{DomesticGrid} = Kwh_{Utility} * Price_{Utility}$
$= 1{,}932{,}469\ kwh * \$0.10 / kwh$
$= \$193{,}247$
Eq. (5.4): $Cost_{Generators} = Kwh_{Generators} * Price_{Generators} + Cost_{Manpower}$
$= 0 * \$0.17 / kwh + \$27{,}233$
$= \$27{,}233$
Eq. (5.5): $Cost_{Solar} = Kwh_{Solar} * Price_{Solar}$
$= 789{,}182\ kwh * \$0.023 / kwh$
$= \$18{,}151$
Eq. (5.2): $Cost_{Baseline} = Cost_{DomesticGrid} + Cost_{Generators} + Cost_{Solar}$
$= \$193{,}247 + \$27{,}233 + \$18{,}151$
$= \$238{,}631$

At a domestic grid utility energy cost at $0.10 per kilowatt-hour, the total cost which includes current infrastructure is nearly $35,000 less than the case where the installation only received power from the domestic grid. Furthermore, as seen in Table 23 below, for a range of domestic grid costs up to 20% above and below that used in the analysis, the total cost factoring in current infrastructure remains lower than total domestic grid only costs. Thus, the photovoltaic plant operational at Nellis AFB provides the installation with considerable energy bill savings.

Table 23: No Power Failure Costs for the Domestic Grid and Baseline Cases

Price (Domestic Grid)	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Domestic Grid Only	$217,732	$244,949	$272,165	$299,382	$326,598
Baseline Nellis AFB	$199,982	$219,306	$238,631	$257,956	$277,281

The electrical power used, the costs, and the impacts of the power failure scenarios for the Nellis AFB baseline case are summarized in Table 24 below. The values and constants used in the baseline case are the same as those used in the analysis when the power is provided from the domestic grid only. Specifics for each scenario are discussed below the table.

Table 24: Results from Analysis for the Nellis AFB Baseline Case

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Electricity Used (*Kwh*)	2,721,652	2,718,131	2,721,363	2,531,222	480,276
$Cost_{DomesticGrid}$	\$238,631	\$238,570	\$238,605	\$228,910	\$108,811
Facilities Without Power – Operational/Critical	0	3	0.007	3	3
Facility-Hours Without Power – Operational/Critical	0	0.75	0.014	36	504
Facilities Without Power – Admin/Office	0	93	0.64	93	93
Facility-Hours Without Power – Admin/Office	0	23.08	1.28	1106	14944
Facilities Without Power – Support/Service	0	109.33	2.51	110	110
Facility-Hours Without Power – Support/Service	0	27.5	5.02	1320	17724
Facilities Without Power – Other	0	88	0.75	88	88
Facility-Hours Without Power – Other	0	22	1.51	1056	14784

The highest cost for the baseline case occurs when there is no power failure. Again, each failure scenario results in enough power loss that the costs are lower than the no power failure scenario. With backup power systems present, the number of facilities without power across the four categories decreases. These baseline results will be used for comparing the different energy options at Nellis AFB.

The average cost for the first scenario is \$238,570, and the prices for the different failure times are seen in Table 25 below. Due to the low price of acquiring energy from the solar farm, this baseline price is dramatically less than the domestic grid only case. The average cost is also less than the cost for the scenario where there is no power failure, but only by 0.025%. Thus, even though less power is being drawn from the domestic grid, the generators are being used at a higher marginal cost, effectively pushing the price up.

Table 25: Scenario 1 (Temporary Voltage Drop) Costs and Regret - Baseline

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Domestic Grid Only	$271,768	$271,666	$271,810	$271,829	$271,591	$271,771
Baseline Nellis AFB	$238,488	$238,632	$238,542	$238,520	$238,556	$238,685

For the first scenario that the number of modeled facilities listed as being without power has decreased in all of the categories as compared to the case where no generators were present. When the differences in the total number of facilities without power are added up, it equals the total number of generators modeled for Nellis AFB. The largest category change is within the operational/critical facility category, and for these facilities the backup generators provide emergency power to 23 of the 26 facilities when voltage drop occurs. However, there are still three facilities within the operational/critical category that do not have generators and thus operational/critical missions cannot be executed from these facilities when electrical power is lost.

For the distribution line failure scenario, the maximum failure occurs once and results in 71 modeled facilities losing access to the base electrical grid. For this specific distribution edge failure, there are three operational/critical category buildings which lose access to the installation grid but are powered by generators. With the generators functioning, the maximum number of operational category facilities without power during this scenario is equal to one building, and this occurs for three of the 426 edges. The minimum failure occurs 180 times, an increase of 20 from the domestic grid only case. The values for the second scenario are summarized in Table 26 below.

Table 26: Results for Power Failure Scenario 2 (Distribution Line Failure) of Baseline Case

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Affected Nodes	Scenario 2 – Maximum
Electricity Used (Kwh)	2,721,652	2,721,363	2,721,187	2,714,810
$Cost_{DomesticGrid}$	$238,631	$238,604	$238,589	$237,947
Facilities Without Power – Operational/Critical	0	0.007	0.011	1
Facility-Hours Without Power – Operational/Critical	0	0.014	0.022	2
Facilities Without Power – Admin/Office	0	0.64	1.03	13
Facility-Hours Without Power – Admin/Office	0	1.28	2.05	26
Facilities Without Power – Support/Service	0	2.51	4.01	45
Facility-Hours Without Power – Support/Service	0	5.02	8.03	90
Facilities Without Power – Other	0	0.75	1.21	12
Facility-Hours Without Power – Other	0	1.51	2.41	24

For the substation failure scenario, the total cost drops by $9,721 or 4.07% when compared to the scenario where there is no power failure, while the total energy use drops by 190,430 kilowatt-hours or 7.00%. The difference in percentages is due to the higher cost of generating electricity from backup generators. Table 27 breaks down these costs in more detail.

Table 27: Baseline Case: Energy Use and Cost for Scenario 3 (Substation Failure)

Scenario 3 – Substation Failure	Baseline – No Power Failure	Baseline – Scenario 3
Total Electricity Used	2,721,652 kwh	2,531,222 kwh
Domestic Grid Electricity Used	1,932,469 kwh	1,790,713 kwh
Photovoltaic Electricity Used	789,183 kwh	702,553 kwh
Base Generators Electricity Used	0 kwh	37,956 kwh
Total Cost	$238,631	$228,910
Domestic Grid Cost	$193,247	$179,071
Photovoltaic Cost	$18,151	$16,159
Base Generators Cost	0	$6,447

For the extended power failure scenario there is no electricity delivered from the domestic grid, nor is there any delivered from the photovoltaic array. All energy delivered is from the on-site generators. This scenario assumes that the generators successfully operate for the full seven days without failure and that their fuel supply is sufficiently restored. Additionally, this assumes no additional generation capacity is added, either trucked in from nearby commercial or industrial companies or flown in from other military installations. The total cost reflects fixed manpower costs and the fuel costs of operating the installation generators.

Energy Option 1 – Diesel Backup Generator

The first energy option aims to provide backup power capacity to a facility in the operational/critical category. Total installation cost for the generator is estimated at $20,000. For the no power failure scenario, the seven day operational costs are the same for the baseline case and the first energy option, as seen in Table 28.

Table 28: No Power Failure Costs for Energy Option 1

Price (Domestic Grid)	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Baseline Nellis AFB	$199,982	$219,306	$238,631	$257,956	$277,281
Energy Option 1	$199,982	$219,306	$238,631	$257,956	$277,281

The results for the analysis with the first energy option included are summarized in Table 29 below. Specifics for each scenario are discussed below the table.

Table 29: Results from Analysis for the Nellis AFB Energy Option 1

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Electricity Used (Kwh)	2,721,652	2,718,138	2,721,268	2,531,522	484,476
$Cost_{DomesticGrid}$	$238,631	$238,571	$238,601	$228,961	$109,525
Facilities Without Power – Operational/Critical	0	2	0.005	2	2
Facility-Hours Without Power – Operational/Critical	0	0.5	0.009	24	336
Facilities Without Power – Admin/Office	0	93	0.64	93	93
Facility-Hours Without Power – Admin/Office	0	23.08	1.28	1106	14944
Facilities Without Power – Support/Service	0	109.33	2.51	110	110
Facility-Hours Without Power – Support/Service	0	27.5	5.02	1320	17724
Facilities Without Power – Other	0	88	0.75	88	88
Facility-Hours Without Power – Other	0	22	1.51	1056	14784

The average cost for the temporary voltage drop failure scenario is $238,571, which is negligibly different as seen in Table 30. The power failure lasts only 15 minutes and the additional generator averages around nine extra kilowatt-hours. At a price of $0.17, the average increase in price is around $1.50. Thus, for the temporary voltage drop scenario, the increase in operational costs is less than one thousandths of a percent and negligible. The number of facilities listed as being without power has decreased from three to two in only the category of buildings labeled operational/critical. This is comforting knowing that only one generator was added at a critical operations building to the baseline Nellis AFB network.

Table 30: Scenario 1 (Temporary Voltage Drop) Costs and Impact – Energy Option 1

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Baseline Nellis AFB	$238,488	$238,632	$238,542	$238,520	$238,556	$238,685
Energy Option 1	$238,489	$238,633	$238,543	$238,521	$238,557	$238,686

For the distribution line failure scenario, the maximum failure remains at 71 modeled facilities losing access to the base electrical grid. The difference between this case and the baseline is that the building with the generator now receives power even though it becomes disconnected from the base electrical network. Additionally, the minimum failure occurs 180 times, an increase of 1 from the baseline Nellis AFB analysis. The data is reported in Table 31 below.

Table 31: Results for Power Failure Scenario 2 (Distribution Line Failure) of Energy Option 1

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Affected Nodes	Scenario 2 – Maximum
Electricity Used (Kwh)	2,721,652	2,721,268	2,721,129	2,696,974
$\mathbf{Cost}_{\mathbf{DomesticGrid}}$	$238,631	$238,601	$238,583	$237,947
Facilities Without Power – Operational/Critical	0	0.005	0.007	1
Facility-Hours Without Power – Operational/Critical	0	0.009	0.015	2
Facilities Without Power – Admin/Office	0	0.64	1.03	13
Facility-Hours Without Power – Admin/Office	0	1.28	2.05	26
Facilities Without Power – Support/Service	0	2.51	4.01	45
Facility-Hours Without Power – Support/Service	0	5.02	8.03	90
Facilities Without Power – Other	0	0.75	1.21	12
Facility-Hours Without Power – Other	0	1.51	2.41	24

For the substation failure scenario, the total operating cost increases by $51 or 0.022% when compared to the baseline Nellis AFB case. Table 32 breaks down these costs in more detail.

Table 32: Baseline Case: Energy Use and Cost for Scenario 3 (Substation Failure)

Scenario 3 – Substation Failure	Baseline – Scenario 3	Energy Option 1 – Scenario 3
Total Electricity Used	2,531,222 kwh	2,531,522 kwh
Domestic Grid Electricity Used	1,790,713 kwh	1,790,713 kwh
Photovoltaic Electricity Used	702,553 kwh	702,553 kwh
Base Generators Electricity Used	37,956 kwh	38,256 kwh
Total Cost	$228,910	$228,961
Domestic Grid Cost	$179,071	$179,071
Photovoltaic Cost	$16,159	$16,159
Base Generators Cost	$6,447	$6,498

For the extended power failure scenario, all electricity is delivered from on-site generators. Compared to the baseline cost of $108,811 for 480,276 kilowatt-hours of power, the added generator increases the total energy to 484,476 kilowatts-hours of power at a price of $109,525. The change in costs is equal to a 0.87% increase.

Using data provided from Nellis AFB on past fiscal year generator use, the average time a generator is used per year is 48.8 hours, with a range of 9.6 to 175.6 hours. It can be assumed that future generator use will be nearly equal to past use. Assuming the purchased generator has a lifespan of 20 years, the life cycle costs are computed using the following equation. The table following the equation displays the total lifecycle costs for a variety of interest rates and generator operating costs, using Eq. (5.6).

Eq. (5.6): *Present Value (Costs)* = $\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$

Table 33: Present Value Costs for a 25 Kilowatt Diesel Generator

Interest Rate	**\$0.11 / kwh**	**\$0.14 / kwh**	**\$0.17 / kwh**	**\$0.20 / kwh**	**\$0.23 / kwh**
1.0%	\$2,445.93	\$3,113.00	\$3,780.07	\$4,447.15	\$5,114.22
2.8%	\$2,090.93	\$2,661.19	\$3,231.44	\$3,801.70	\$4,371.95
4.0%	\$1,896.77	\$2,414,08	\$2,931.28	\$3,447.68	\$3,965.98
7.0%	\$1,521.24	\$1,936.12	\$2,351.00	\$2,765.89	\$3,180.77

The lifecycle costs are quite small in comparison to the upfront capital cost of the generator and its accessories, assuming the additional generator places no additional constraints on manpower. Furthermore, across the scenarios, the results indicate a less than 1% increase in operational costs for a reduction of one operational/critical category facility without power. Due to this small change, the operational fuel costs should not be heavily considered when deciding whether or not to add a generator to a specific facility. Instead, the two main factors should be the initial installation cost and the value of having a secure power source for the facility being considered.

Energy Option 2 – Parking-Lot Solar

The second energy option places a 30 kilowatt photovoltaic array over a parking lot for a total installation cost of \$114,000. The operational cost of power delivered from the solar array is assumed to be zero. Since the solar array does not provide any backup function, the only difference between this analysis and the baseline is in the cost for the scenario. Data results for this section will only display the costs, since the impact on the number of facilities without power for each scenario is the same as the baseline case.

During normal operations, or no power failure, the operational costs are less than the baseline by 0.067% when utility prices are at \$0.08 per kilowatt-hour and 0.072% when utility prices are at \$0.10 per kilowatt-hour, as seen in Table 34.

Table 34: No Power Failure Costs for Energy Option 2

Price (Domestic Grid)	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Baseline Nellis AFB	$199,982	$219,306	$238,631	$257,956	$277,281
Energy Option 2	$199,848	$219,156	$238,464	$257,772	$277,080

The results for the analysis with the second energy option included are summarized in Table 35 below. The analysis assumes $0.10 per kilowatt-hour for energy delivered from the domestic grid.

Table 35: Results from Analysis for Energy Option 2

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Electricity Used (Kwh)	2,721,652	2,718,131	2,721,326	2,531,222	480,276
$\mathrm{Cost}_{\mathrm{DomesticGrid}}$	$238,464	$238,404	$238,438	$228,762	$108,811

As seen in Table 36 below, the average cost for the temporary voltage drop scenario is $238,404, which is 0.070% less than the baseline costs. The decrease in price is due to the power generated by the new solar array, which operates most of the scenario.

Table 36: Scenario 1 (Temporary Voltage Drop) Costs – Energy Option 2

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Baseline Nellis AFB	$238,488	$238,632	$238,542	$238,520	$238,556	$238,685
Energy Option 1	$238,322	$238,466	$238,375	$238,353	$238,390	$238,519

For the distribution line failure scenario, total cost has again decreased. The proposed location of the photovoltaic array is near an area where removing a transmission edge has little impact on the functionality of the Nellis AFB electrical network. Specifically, the parking lot photovoltaic array will be supplying electrical power for 424 of the 426 edge failures. Thus, the costs displayed in Table 37 below are going to be close to the largest decreases in cost possible. Had the proposed location of the array been in a different location, it is possible that distribution line failure would have more frequently impacted the ability of the parking lot photovoltaic array to provide power to the base network.

Table 37: Results for Power Failure Scenario 2 (Distribution Line Failure) of Energy Option 2

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Non-Zeroes	Scenario 2 – Maximum
Electricity Used (Kwh)	2,721,652	2,721,326	2,721,128	2,714,810
$Cost_{DomesticGrid}$	$238,464	$238,438	$238,420	$237,784

For the substation failure scenario, the total operating cost decreases by $148 or 0.065% when compared to the baseline Nellis AFB case. Table 38 breaks down these costs in more detail.

Table 38: Baseline Case: Energy Use and Cost for Scenario 3 (Substation Failure)

Scenario – Substation Failure	Baseline – Scenario 3	Energy Option 2 – Scenario 3
Total Electricity Used	2,531,222 kwh	2,531,222 kwh
Domestic Grid Electricity Used	1,790,713 kwh	1,789,229 kwh
Photovoltaic Electricity Used	702,553 kwh	704,037 kwh
Base Generators Electricity Used	37,956 kwh	37,956 kwh
Total Cost	$228,910	$228,762
Domestic Grid Cost	$179,071	$178,923
Photovoltaic Cost	$16,159	$16,159
Base Generators Cost	$6,447	$6,447

For the extended power failure scenario, the solar array does not provide any power to the Nellis AFB network. Thus the costs are the same as for the baseline case.

As the photovoltaic array is directly connected to the grid, there are no benefits with respect to additional facilities receiving power when the domestic grid fails. Across the scenarios, the results indicate operational costs which are less than or equal to the costs associated with the baseline scenario. These savings, however, are small in comparison to a total installation cost of $114,000. An important question to ask is whether or not the energy savings justify the purchase of the solar array. There are two ways to answer the question.

The first answer applies a benefit-cost approach in which the total lifetime savings are compared to the total cost. An energy output value for the 30 kilowatt solar array energy option is estimated hourly for the entire year using actual data on energy delivered for the 14.2 MW photovoltaic array at Nellis AFB. The ratio of nameplate capacity to delivered power is applied to the 30 kilowatt solar option, and the total energy per hour is calculated and summed for the entire year equaling approximately 71,700 kilowatt-hours. At $0.10 per kilowatt-hour, this saves the Air Force $7,170 per year. If we assume the solar array lasts for twenty years, then the following present value equation will calculate the net benefits of the array for the twenty year time period.

Eq. (5.7): *Present Value (Benefits)* = $\sum_{t=0}^{n} \frac{B_t}{(1+i)^t}$

The cells in Table 39 below show the net present value of the photovoltaic array investment, with the rows representing four different interest rates and the columns representing five utility energy prices. The colored cells represent the interest rate and utility price pair which have net present values greater than the initial cost of $114,000 for the solar array. Note the cost side assumes that maintenance, repair, and general upkeep costs are zero or included in the initial cost of $114,000.

Table 39: Present Value Benefits for 30 Kilowatt Photovoltaic Array

Interest Rate	**$0.08 / kwh**	**$0.09 / kwh**	**$0.10 / kwh**	**$0.11 / kwh**	**$0.12 / kwh**
1.0%	$104,529	$117,595	$130,662	$143,728	$156,794
2.8%	$89,358	$100,528	$111,698	$122,867	$134,037
4.0%	$81,060	$91,193	$101,326	$111,458	$121,591
7.0%	$65,012	$73,138	$81,264	$89,391	$97,517

If the assumptions from this analysis of $0.10 per kilowatt-hour and 2.8% as the standard Air Force discount rate are applied, then the present value calculation of the benefits does not cover the initial installation cost.

The second answer takes into consideration that there are much more creative ways to finance an energy project than paying full cost upfront. It is important to remember that the model analyzes the Nellis AFB grid with an operational cost of zero for the parking lot photovoltaic array. Therefore the net benefits are exactly equal to the cost of energy produced by the array that the installation does not have to purchase from the local utility. However, it is possible that a commercial entity can front the installation cost of the array and then charge the installation for the energy produced by the array. From a financial standpoint, this type of financing would be attractive at a cost per kilowatt-hour that is less than the expected long-term utility price of electricity.

Though the cost for photovoltaic electricity is much higher than $0.10 per kilowatt-hour, often a commercial entity will take into consideration the various renewable energy credits available and be able to offer a competitive price. This type of financing has already occurred at Nellis AFB with the 14.2 megawatt photovoltaic array and elsewhere in the Department of Defense, and has significantly decreased the utility bill for those installations.

Energy Option 3 – Rooftop Solar with Battery Backup

The third energy option has similar elements to the first two. The purpose of the third option is to provide a backup power supply to a facility categorized as operational/critical, but to provide this power through solar energy coupled with a battery. Total installation cost for the photovoltaic array and battery system is $260,000, which includes $95,000 for the array and $165,000 for the batteries, as described in Chapter Four. To remain consistent, operational costs are assumed to be zero. Without power failure, the solar array provides power to the Nellis AFB network and the costs drop from the baseline as seen in Table 40 below.

Table 40: No Power Failure Costs for Energy Option 3

Price (Domestic Grid)	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Baseline Nellis AFB	$199,982	$219,306	$238,631	$257,956	$277,281
Energy Option 3	$199,871	$219,181	$238,492	$257,803	$277,114

Complete results for the four scenarios are summarized in Table 41 below.

Table 41: Results from Analysis for the Nellis AFB Energy Option 3

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Electricity Used (Kwh)	2,721,652	2,718,135	2,721,326	2,531,372	481,676
$\text{Cost}_{\text{DomesticGrid}}$	$238,492	$238,432	$238,462	$228,794	$108,811
Facilities Without Power – Operational/Critical	0	2	0.005	2	3
Facility-Hours Without Power – Operational/Critical	0	0.5	0.009	24	393
Facilities Without Power – Admin/Office	0	93	0.64	93	93
Facility-Hours Without Power – Admin/Office	0	23.08	1.28	1106	14944
Facilities Without Power – Support/Service	0	109.33	2.51	110	110
Facility-Hours Without Power – Support/Service	0	27.5	5.02	1320	17724
Facilities Without Power – Other	0	88	0.75	88	88
Facility-Hours Without Power – Other	0	22	1.51	1056	14784

Costs for the temporary voltage drop scenario are shown in Table 42, and the average cost of $238,432 is $138 or 0.058% less than the baseline scenario. The decrease in price is due to the solar array generating electrical power for the seven days of the scenario. As with the first energy option, the number of facilities listed as being without power has decreased in only the category labeled operational/critical.

Table 42: Scenario 1 (Temporary Voltage Drop) Costs – Energy Option 3

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Baseline Nellis AFB	$238,488	$238,632	$238,542	$238,520	$238,556	$238,685
Energy Option 3	$238,350	$238,494	$238,403	$238,381	$238,418	$238,547

The average failure again decreases for operational/critical category facilities, with the minimum failure occurring 181 times. The operational costs for the scenario have all decreased, as seen in Table 43 below.

Table 43: Results for Power Failure Scenario 2 (Distribution Line Failure) of Energy Option 3

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Affected Nodes	Scenario 2 – Maximum
Electricity Used (Kwh)	2,721,652	2,721,326	2,721,129	2,714,810
$Cost_{DomesticGrid}$	$238,492	$238,462	$238,444	$237,808
Facilities Without Power – Operational/Critical	0	0.005	0.007	1
Facility-Hours Without Power – Operational/Critical	0	0.009	0.015	2
Facilities Without Power – Admin/Office	0	0.64	1.03	13
Facility-Hours Without Power – Admin/Office	0	1.28	2.05	26
Facilities Without Power – Support/Service	0	2.51	4.01	45
Facility-Hours Without Power – Support/Service	0	5.02	8.03	90
Facilities Without Power – Other	0	0.75	1.21	12
Facility-Hours Without Power – Other	0	1.51	2.41	24

For the substation failure scenario, the total operating cost decreases by $116 or 0.051% when compared to the baseline Nellis AFB case. Table 44 breaks down these costs in more detail. During the 12 hour failure, the solar array and the battery are able to provide backup power for the entire time period. The decrease in cost reflects the use of power from the photovoltaic array and not the domestic grid during the rest of the scenario.

Table 44: Energy Option 3: Energy Use and Cost for Scenario 3 (Substation Failure)

Scenario 3 – Substation Failure	Baseline – Scenario 3	Energy Option 3 – Scenario 3
Total Electricity Used	2,531,222 kwh	2,531,372 kwh
Domestic Grid Electricity Used	1,790,713 kwh	1,789,476 kwh
Photovoltaic Electricity Used	702,553 kwh	703,898 kwh
Base Generators Electricity Used	37,956 kwh	37,956 kwh
Total Cost	$228,910	$228,794
Domestic Grid Cost	$179,071	$178,955
Photovoltaic Cost	$16,159	$16,159
Base Generators Cost	$6,447	$6,447

For the extended power failure scenario, electricity is delivered from on-site generators including the photovoltaic array/battery option. Compared to the baseline of $108,811 for 480,276 kilowatt-hours of power, the third energy option increases the total power used to

481,676 kilowatts-hours at the same price of $108,811 since the operational costs were modeled to be zero. The key difference for this energy option is that the battery pack cannot provide enough power in the long run when the sun goes down in the evenings. Table 45 below outlines the total number of hours out of 168 that the facility goes without power for the fourth scenario for a range of battery bank sizes.

Table 45: Energy Option 3: Cost & Hours Without Power (Extended Power Failure)

Battery Bank Size	0 kwh	30 kwh	110 kwh	220 kwh	330 kwh	440 kwh
Estimated Cost	$95,000	$117,500	$177,500	$260,000	$342,500	$425,000
Hours Without Power	61	59	54	47	40	33

For the extended power failure scenario, the photovoltaic array and battery pack for a range of battery sizes are not capable of providing continual power to the building. As the model progresses, a 25 kilowatt array has the ability to charge the battery and provide emergency power, though it can only charge upwards of 60 kilowatt-hours per day. Thus, in the night the power is drained from the battery at a modeled constant rate of 12.5 kilowatts per hour. A larger battery lasts longer but at a very steep cost. As seen in the previous scenarios, the savings never exceed 0.06%. A 25 kilowatt photovoltaic array reducing annual costs by 0.06% saves an estimated $5,974 per year in energy costs. Table 46 summarizes the net present value benefits from the solar array and battery pack in terms of energy saved, assuming a life of twenty years. The yellow cells represent those where the net present value of the benefits exceed the present value of the cost of the photovoltaic array only. For the solar option with the battery, the benefits only exceed costs when the smallest battery is used and when domestic grid costs are $0.11 and $0.12 per kilowatt-hour.

Table 46: Present Value Benefits for 25 Kilowatt Photovoltaic Array and 220 Kwh Battery

Interest Rate	**$0.08 / kwh**	**$0.09 / kwh**	**$0.10 / kwh**	**$0.11 / kwh**	**$0.12 / kwh**
1.0%	$87,108	$97,996	$108,884	$119,773	$130,662
2.8%	$74,465	$83,773	$93,081	$102,389	$111,698
4.0%	$67,550	$75,994	$84,438	$92,882	$101,326
7.0%	$54,176	$60,948	$67,720	$74,492	$81,264

Energy Option 4 – Biomass Generating Plant

With the addition of a biomass generating plant, there are an additional 5,000 kilowatt-hours of energy produced per hour at Nellis AFB. The plant has a high capital cost of $7,500,000 with a moderately low operating cost of $0.09 per kilowatt-hour. The plant runs for the entire duration of the 168 hour scenario. When power fails, an electrical switch automatically opens and the plant and 50 facilities are sectioned off from the rest of the base and domestic grid. In the scenario where there is no power failure, the seven day costs are shown in Table 47 below.

Table 47: No Power Failure Costs for Energy Option 4

Price (Domestic Grid)	$0.08 / kwh	$0.09 / kwh	$0.10 / kwh	$0.11 / kwh	$0.12 / kwh
Baseline Nellis AFB	$199,982	$219,306	$238,631	$257,956	$277,281
Energy Option 4	$208,382	$219,306	$230,231	$241,156	$252,081
Percent Change in Price	4.20%	0.00%	-3.52%	-6.51%	-9.09%

Complete results for the four scenarios are summarized in Table 48 below.

Table 48: Results from Analysis for the Nellis AFB Energy Option 4

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Electricity Used (Kwh)	2,721,652	2,717,262	2,721,313	2,543,863	647,970
$Cost_{DomesticGrid}$	$230,231	$230,092	$230,200	$222,403	$123,614
Facilities Without Power – Operational/Critical	0	2	0.005	2	2
Facility-Hours Without Power – Operational/Critical	0	0.5	0.009	24	336
Facilities Without Power – Admin/Office	0	87	0.34	87	87
Facility-Hours Without Power – Admin/Office	0	21.58	0.69	1034	14022
Facilities Without Power – Support/Service	0	75.33	0.57	76	76
Facility-Hours Without Power – Support/Service	0	19	1.15	912	12260
Facilities Without Power – Other	0	80	0.44	80	80
Facility-Hours Without Power – Other	0	20	0.88	960	13440

The average cost for the temporary voltage drop scenario is $230,092, which is $8,478 or 3.55% less than the baseline scenario. This decrease in cost is reflective of the fact that the biomass generator is producing large amounts of electricity at $0.01 less than the local utility rate, which is held constant at $0.10 per kilowatt-hour. One of the 50 facilities connected to the biomass generator already has a generator, therefore the number of facilities without power during the voltage drop decreases by 49. The costs for this scenario are in Table 49 below.

Table 49: Scenario 1 (Temporary Voltage Drop) Costs – Energy Option 4

Scenario	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 1.4	Scenario 1.5	Scenario 1.6
Time	Day 1-18:00	Day 2-12:00	Day 3-06:00	Day 4-23:00	Day 5-16:00	Day 7-09:00
Baseline Nellis AFB	$238,488	$238,632	$238,542	$238,520	$238,556	$238,685
Energy Option 4	$230,017	$230,145	$230,072	$230,069	$230,026	$230,221

For the distribution line failure scenario, there are far fewer facilities which are disconnected from the grid across the categories than the baseline case. The minimum failure now occurs 215 times, the highest of the four energy options. The results for the second power failure are shown in Table 50 below.

Table 50: Results for Power Failure Scenario 2 (Distribution Line Failure) Energy Option 4

Scenario 2 – Distribution Line Failure	Scenario 2 – Minimum	Scenario 2 – Average	Scenario 2 – Average for Affected Facilities	Scenario 2 – Maximum
Electricity Used (Kwh)	2,721,652	2,721,313	2,721,107	2,714,810
$Cost_{DomesticGrid}$	$230,231	$230,200	$230,180	$229,547
Facilities Without Power – Operational/Critical	0	0.005	0.011	1
Facility-Hours Without Power – Operational/Critical	0	0.009	0.022	2
Facilities Without Power – Admin/Office	0	0.34	0.55	7
Facility-Hours Without Power – Admin/Office	0	0.69	1.10	14
Facilities Without Power – Support/Service	0	0.57	0.92	11
Facility-Hours Without Power – Support/Service	0	1.15	1.84	22
Facilities Without Power – Other	0	0.44	0.71	7
Facility-Hours Without Power – Other	0	0.88	1.41	14

For the substation failure scenario, the total operating cost decreases by $6,507 or 2.84% when compared to the baseline Nellis AFB case. Table 51 breaks down these costs in more detail. During the 12 hour failure, the biomass plant is able to provide backup power for the 50 modeled facilities on its circuit. There is a decrease in the amount of energy from base backup generators as power to these facilities is delivered from the biomass plant during the failure. Note, one cost savings to the installation and government not anticipated by this model is that the generators connected to the same circuit as the biomass plant could likely be removed and used as backup at a different location or disposed of through Defense Logistics Agency Disposition Services.

Table 51: Energy Option 4: Energy Use and Cost for Scenario 3 (Substation Failure)

Scenario 3 – Substation Failure	Baseline – Scenario 3	Energy Option 4 – Scenario 3
Total Electricity Used	2,531,222 kwh	2,545,863 kwh
Domestic Grid Electricity Used	1,790,713 kwh	1,010,713 kwh
Photovoltaic Electricity Used	702,553 kwh	702,553 kwh
Base Generators Electricity Used	37,956 kwh	37,642 kwh
Base Biomass Used	0 kwh	794,955 kwh
Total Cost	$228,910	$222,403
Domestic Grid Cost	$179,071	$101,071
Photovoltaic Cost	$16,159	$16,159
Base Generators Cost	$6,447	$6,394
Base Biomass Cost	$0	$67,571

For the extended power failure scenario, the biomass generator is able to provide electrical power to the facilities located in its area of the installation. Facilities on the other side of the electrical switch do not have electricity unless they are powered by their own backup generator. The cost for Energy Option 4 for this scenario increases 13.6%.

Assuming that the generator operates 360 days out of the year, the annual total energy produced by the biomass generator will be 1.8 million kilowatt-hours. Table 52 summarizes the net present benefits of this biomass plant using the parameters listed. Shaded green cells represent the pair of interest rate and utility price where the benefits exceed the cost of the biomass plant.

Table 52: Present Value Benefits for a 5 Megawatt Biomass Plant

	\$0.09 / kwh	**\$0.095 / kwh**	**\$0.10 / kwh**	**\$0.105 / kwh**	**\$0.11 / kwh**
$Price_{Utility} - Price_{Biomass}$	\$0.00 / kwh	\$0.005 / kwh	\$0.01 / kwh	\$0.015 / kwh	\$0.02 / kwh
1.0%	\$0	\$3,936,818	\$7,873,636	\$11,810,454	\$15,747,271
2.8%	\$0	\$3,365,435	\$6,730,871,	\$10,096,306	\$13,461,742
4.0%	\$0	\$3,052,931	\$6,105,862	\$9,158,793	\$12,211,724
7.0%	\$0	\$2,448,489	\$4,896,977	\$7,345,466	\$9,793,954

Using Results to Inform Decisions

The data analysis from previous sections showed the total power used, the total cost, and the number of buildings, categorized by importance, without power across a number of scenarios. A base commander or infrastructure manager can use this information to make decisions on his or her best option or options of installation-based electrical energy generators. This section shows one method of quantifying the analysis in order to inform that decision.

When a base commander or an infrastructure manager needs to make a decision on additional energy generation options, he or she considers two main criteria: cost and the impact on mission measured by how the energy option reduces power failure to the facilities on the installation. Costs have two main components. The first measures the change from the baseline in operational costs of the installation. The installation has a good understanding of its current total energy costs. These costs can be reasonably forecasted by a number of different methods, and the costs can be broken down into varying time periods. The delta cost (Eq. (5.8)), *ΔCost*, is the difference between the baseline cost and the estimated cost for each energy option, and this value is what the decision-maker is considering.

Eq. (5.8): $\Delta Cost(Energy\_Option, Scen) =$
$Total\_OpsCost(Baseline, Scen) - Total\_OpsCost(Energy\_Option, Scen)$

In each scenario, the *ΔCost* variable is measured by taking the specific *Energy_Option* cost and subtracting it from the baseline cost. This is a simple calculation and can also be expressed in terms of a percentage, as seen in Eq. (5.9).

Eq. (5.9): $\Delta Cost(\%) = \frac{Total\_OpsCost(Energy\_Option,Scen) - Total\_OpsCost(Baseline,Scen)}{Total\_OpsCost(Baseline,Scen)}$

The percent change in operational costs for each of the modeled energy options is reported in Table 53 below.

Table 53: Percent Change in Operational Costs

Scenario	1	2	3	4	5
	No Power Failure	Temporary Voltage Drop	Distribution Line Failure	Substation Failure	Extended Failure
Baseline	$238,631	$238,570	$238,605	$228,910	$108,811
Energy Option 1	0.0000%	0.0004%	-0.0017%	0.0223%	0.6562%
Energy Option 2	-0.0700%	-0.0696%	-0.0700%	-0.0647%	0.0000%
Energy Option 3	-0.0582%	-0.0578%	-0.0599%	-0.0507%	0.0000%
Energy Option 4	-3.5201%	-3.5537%	-3.5226%	-2.8426%	13.6043%

These costs represent only the operational costs associated with the particular scenario. The reported savings across most of the scenarios are a reflection of the fact that the prices assumed for the energy options are less than the price charged for domestic grid energy at $0.10 per kilowatt-hour. The higher costs are a result of the fact that the energy options are providing power when there was no power delivered in the baseline case.

The second cost component represents the upfront capital costs associated with constructing and setting up an energy option. The decision-maker can take these one-time acquisition costs and incorporate them in a number of ways. The first method could be to take the initial cost (present value) and break it into a stream of future costs (future value) over a finite time period, and incorporate those costs into the time period of the model. In this case, those costs could be included in the *Total_OpsCost(Energy_Option, Scen)* However, funding of government projects typically do not occur that way. Most funding comes through long acquisition timelines and processes, in which the funding requirement is compared across a myriad of other requirements. The requirement with the largest operational impact is funded. Additionally, energy projects are often funded through end of year fallout funds, at which the decision process is similar in that requirements are ranked against others and a decision is made based on availability of funds and ranking of requirements, or through congressionally mandated funds. In either of the cases relating the costs to other requirements, the capital upfront costs are often incorporated through a separate decision process than the one listed above.

Measuring the impact of power failure begins with how the installation defines its facilities. Some installations use the critical/non-critical binary approach to categorizing their installation's facilities. Other installations might find it useful to categorize the facilities per the nine Real Property codes. The previous section defined facility categories as operational/critical, administration/office, support/service, and all other. No matter how the facilities are grouped, it is important to allow the decision maker a quantitative way for ranking the importance of each category of facility against the other. Eq. (5.10) allows each category of facility to be given a weight relative to the other categories. Note, in some cases it is reasonable to expect operational or critical facilities to be rated with a weight of unity, and all other categories to carry a weight of zero.

Eq. (5.10): $Impact(Energy\ Option, Scen) =$

$$\sum_{i=1}^{M} wt(Facilities)_i * Without\_Power(Facilities, Source\_Func, Scen)_i \, ;$$

The *Impact* measure is the weighted sum of the number of *Facilities* without power across for the particular *Scenario*. *M* is the number of categories of facilities. In order to have meaning, *Impact* for each energy option is compared to the baseline, as seen in Eq. (5.11).

Eq. (5.11): $\Delta Impact(Energy\_Option, Scen) = \frac{Impact(Energy\_Option, Scen)}{Impact(Baseline, Scen)}$

A value of *ΔImpact* that is less than unity means that the particular energy option reduced the impact of the power failure.

Table 54 below summarizes the hours without power for the modeled baseline case at Nellis AFB.

Table 54: Facility-Hours Without Power - Baseline Case

BASELINE	**FACILITY-HOURS WITHOUT POWER**				
	No Failure	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power
Ops / Critical	0	0.75	0.014	36	504
Admin / Office	0	23.08	1.28	1106	14944
Support / Service	0	27.5	5.02	1320	17724
Other	0	22	1.51	1056	14784

As an example, the Operational / Critical category of buildings is given a weight 100 times more important than the other three categories, and the other three categories have the same weight, as seen in Table 55.

Table 55: Weighted Score - Baseline Case

BASELINE	**WEIGHTED SCORE**					
	No Failure	Scenario 1 – Temporary Voltage Drop	Scenario 2 – Distribution Line Failure	Scenario 3 – Substation Failure	Scenario 4 – Extended Power Failure	
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	WEIGHTS
Ops / Critical	0	75	1.4	3600	50400	100
Admin / Office	0	23.08	1.28	1106	14944	1
Support / Service	0	27.5	5.02	1320	17724	1
Other	0	22	1.51	1056	14784	1
Sum	0	147.58	9.21	7082	97852	

The same weight is applied to the first energy option, and is shown in Table 56. As reported, the first energy option reduces the impact of the power failure by these weighted values.

Table 56: Weighted Score – Energy Option 1

ENERGY OPTION 1	**WEIGHTED SCORE**					
	No Failure	Scenario 1 – Temporary Voltage Drop	Scenario 2 – Distribution Line Failure	Scenario 3 – Substation Failure	Scenario 4 – Extended Power Failure	
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	WEIGHTS
Ops / Critical	0	50	0.9	2400	33600	100
Admin / Office	0	23.08	1.28	1106	14944	1
Support / Service	0	27.5	5.02	1320	17724	1
Other	0	22	1.51	1056	14784	1
Sum	0	122.58	8.71	5882	81052	
ΔImpact		0.8306	0.9457	0.8306	0.8283	

The same weight is applied to the second energy option, and is shown in Table 57 below. Because this energy option was connected to the domestic grid and provided no power backup capacity greater than the current baseline, the impact value remains unchanged from the baseline.

Table 57: Weighted Score – Energy Option 2

ENERGY OPTION 2	**WEIGHTED SCORE**					
	No Failure	Scenario 1 – Temporary Voltage Drop	Scenario 2 – Distribution Line Failure	Scenario 3 – Substation Failure	Scenario 4 – Extended Power Failure	
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	WEIGHTS
Ops / Critical	0	75	1.4	3600	50400	100
Admin / Office	0	23.08	1.28	1106	14944	1
Support / Service	0	27.5	5.02	1320	17724	1
Other	0	22	1.51	1056	14784	1
Sum	0	147.58	9.21	7082	97852	
⊿Impact		1	1	1	1	

The same weight is applied to the third energy option, and is shown in Table 58 below. This rooftop solar option is the same as the first option in that it was able to provide power for the first three energy failure scenarios, but it differs since it was not able to supply power for the long-term outage modeled in Scenario 4.

Table 58: Weighted Score – Energy Option 3

ENERGY OPTION 3	**WEIGHTED SCORE**					
	No Failure	Scenario 1 – Temporary Voltage Drop	Scenario 2 – Distribution Line Failure	Scenario 3 – Substation Failure	Scenario 4 – Extended Power Failure	
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	WEIGHTS
Ops / Critical	0	50	0.9	2400	39300	100
Admin / Office	0	23.08	1.28	1106	14944	1
Support / Service	0	27.5	5.02	1320	17724	1
Other	0	22	1.51	1056	14784	1
Sum	0	122.58	8.71	5882	86752	
⊿Impact		0.8306	0.9457	0.8306	0.8866	

The same weight is applied to the fourth energy option, and is shown in Table 59 below

Table 59: Weighted Score – Energy Option 4

ENERGY OPTION 4	**WEIGHTED SCORE**					
	No Failure	Scenario 1 – Temporary Voltage Drop	Scenario 2 – Distribution Line Failure	Scenario 3 – Substation Failure	Scenario 4 – Extended Power Failure	
	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	Hrs W/out Power	WEIGHTS
Ops / Critical	0	50	0.9	2400	33600	100
Admin / Office	0	21.58	0.69	1034	14022	1
Support / Service	0	19	1.15	912	12260	1
Other	0	20	0.88	960	13440	1
Sum	0	110.58	3.62	5306	73322	
⊿Impact		0.7493	0.3931	0.7492	0.7493	

Given the operational costs and impact scores, the decision maker can assess how the energy options influence installation costs and susceptibility to power failure. The data can also be presented graphically. Figure 17 below shows the baseline costs for the five power failure scenarios. Each arrow represents a different scenario, and the units of the axes are not to scale.

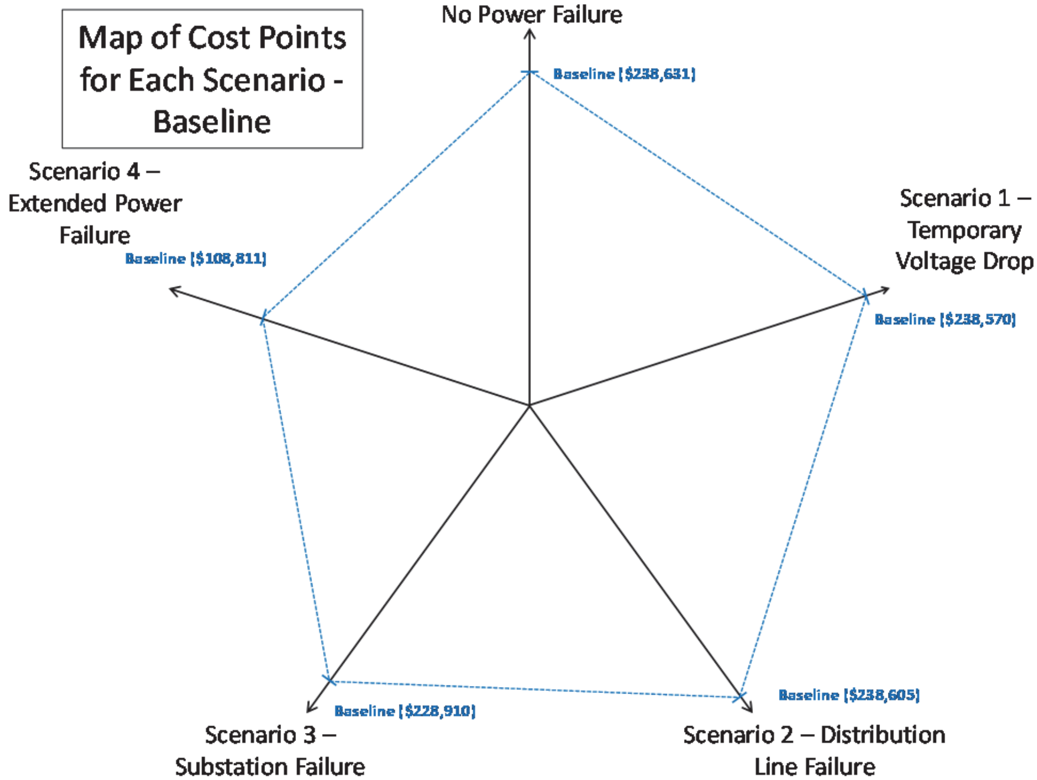


Figure 17: Baseline Costs

Figure 18 shows the costs for third energy option compared to the baseline costs. The third energy option decreased costs across all the power scenarios except the extended power failure scenario.

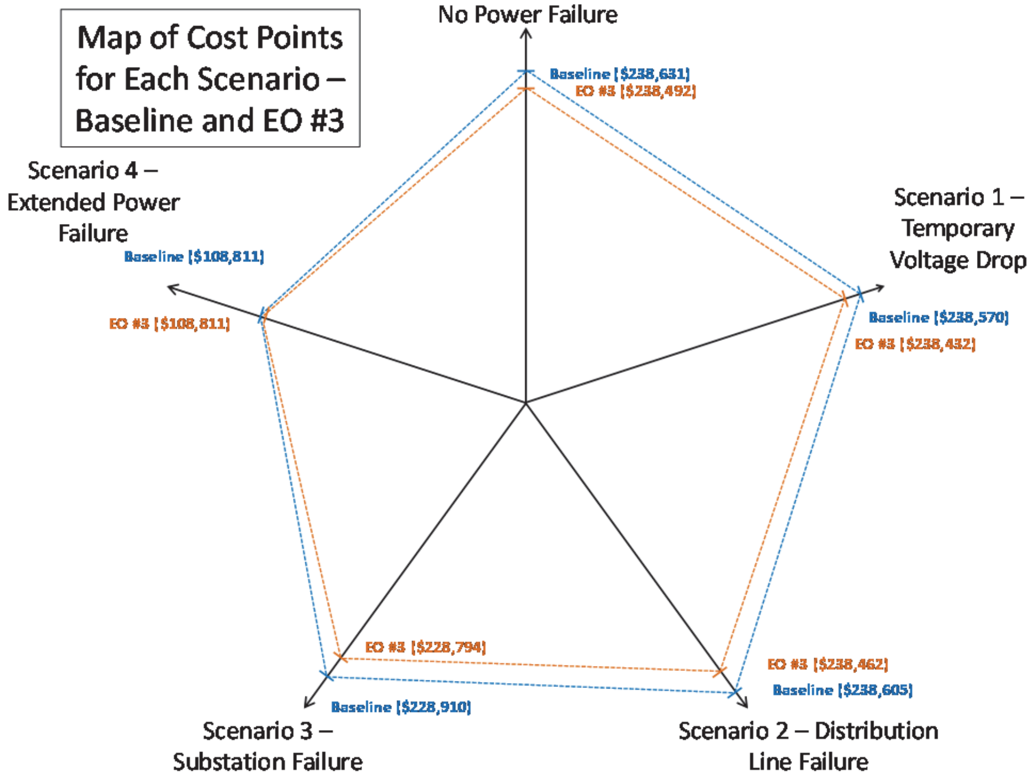


Figure 18: Baseline and Energy Option 3 Costs

Next, the impact scores are added to the figure, as seen in Figure 19 below. The decision maker can now holistically assess the third energy option. To summarize, for an initial price of $260,000 the installation will build a 25 KW parking lot solar array with battery backup. The array and battery bank is co-located with a critical / operational category building, and can provide power to that building during installation power outages. During normal operations, the installation saves an estimated $5,974 annually. The operational costs to the installation during the scenarios is lower, except for Scenario 4, which is a reflection of the solar array providing power during the non-failure hours of the scenario. For each of the power failure scenarios, the parking lot solar array provides benefit to the installation in that it powers the facility during those outages.

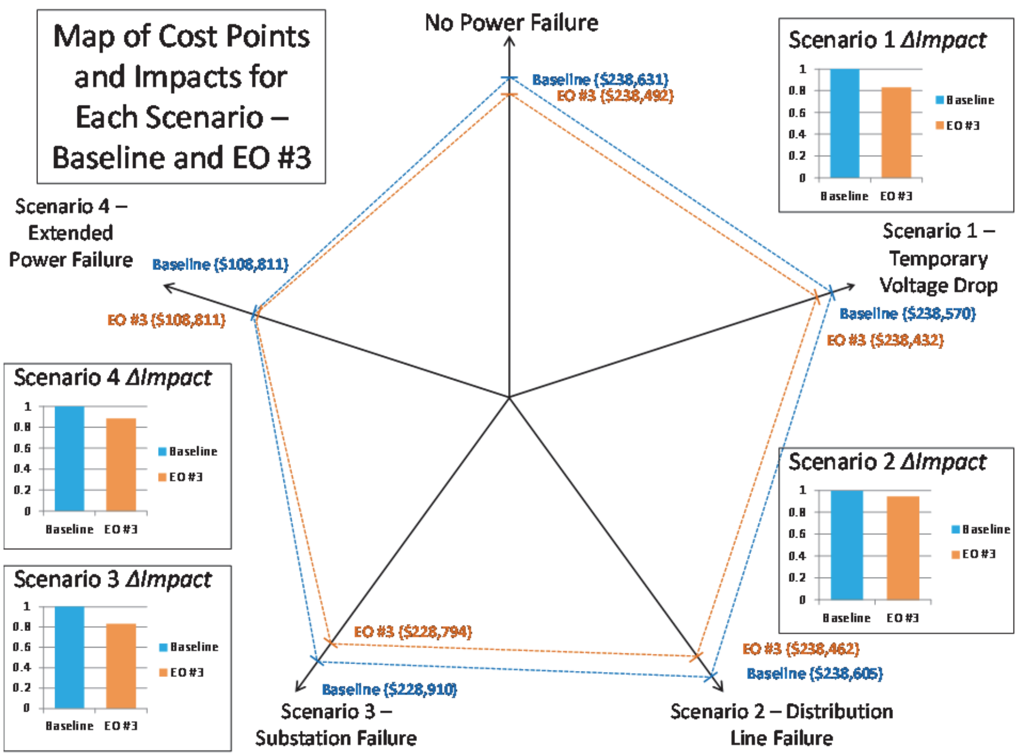


Figure 19: Baseline and Energy Option 3 Costs and Impacts

Figure 20 shows all of the energy options on a single chart. The important visual from the figure is the location of the energy option cost relative to the baseline.

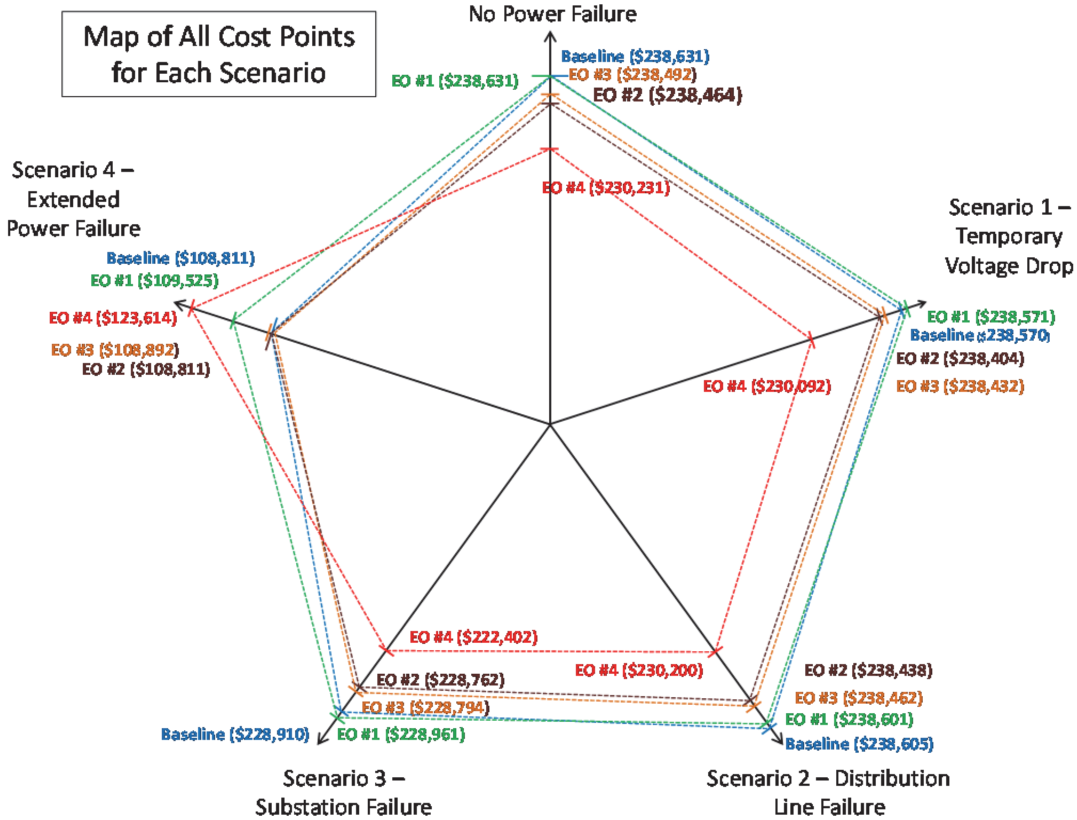


Figure 20: Baseline and All Energy Options Costs

Lastly, Figure 21 shows all of the costs and impact scores on the same chart.

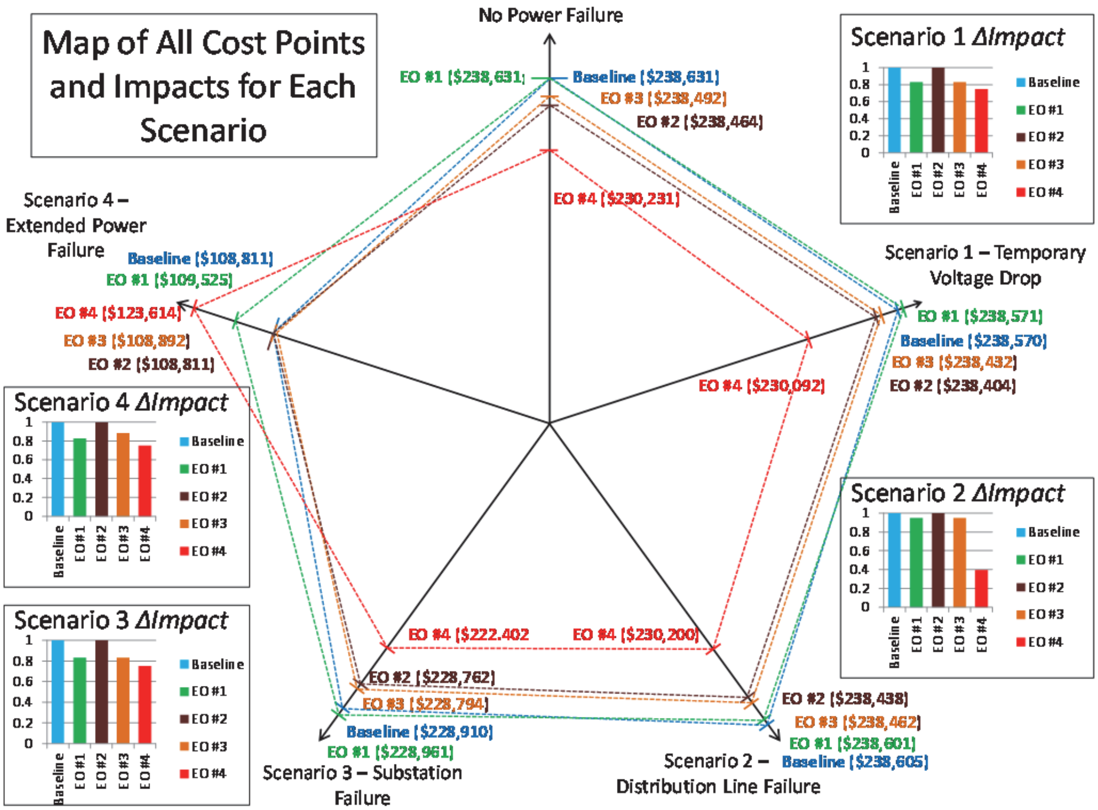


Figure 21: Baseline and All Energy Options Costs and Impacts

This analysis indicates that there is some form of cost versus energy security trade-off when looking at energy security solutions for installations. The first way to increase energy security at a base lies in the multitude of local generating options available for an installation. As seen through this chapter, the options have an initial capital cost, an operation and maintenance cost, an energy cost or saving, and some impact on energy security. The decision maker is given his/her initial conditions, or baseline energy infrastructure. Any energy option that improves upon the initial conditions in terms of decreased total cost or increased number of facilities with power during failure, or both, is preferable to the decision maker. The data presented can be tailored to an installation's energy options, and it allows the decision maker to assess the options related to local failure scenarios.

Energy demand reduction is another way to help increase an installation's energy security. In terms of energy security, energy demand reduction can be considered "free," and can even save money. By Fiscal Year 2013, through its energy savings initiatives, the Air Force had reduced its energy intensity 22.3 percent compared to its 2003 baseline (AF Civil Engineer Center, "Talking Points"). This has been accomplished through reducing its physical footprint in terms of declining military end strength numbers and through consolidating into fewer facilities. Other low cost efforts in reducing demand include replacing older lighting and equipment with newer energy efficient products. Energy awareness campaigns have contributed to this decreased demand as well, by encouraging employees to turn off computers, lights, and other equipment when not in use. All of these efforts are "free" to energy security in that any reduction in energy consumed decreases reliance on the domestic grid and/or on-base generating capability, and this is at least as good as the baseline. A portfolio approach with different energy generation and efficiency technologies, combined with demand reduction campaigns, is a good way to enhance energy security. These various approaches can and are being implemented across the Air Force and Department of Defense to achieve greater energy security. In the example discussed earlier, Fort Knox implemented a portfolio approach over a multi-year period, incrementally adding energy generation and efficiency technologies while also reducing demand across its users.

The third way to enhance an installation's energy security is in the strengthening of the distribution system. At its most base level, the smaller the distribution system, the more secure it is in terms of vulnerable nodes. For example, high value facilities use power from the domestic grid but can island off the grid in the event of a failure through an automatic transfer switch. This facility will have one or more backup generation capabilities attached at the transfer switch so the mission can continue in the event of power failure. By islanding off from the rest of the grid, the facility essentially becomes a distribution network with one (or more) generating sources and one user. This comes at a higher cost than normal operations, which includes the initial capital investment in the backup generation capability, the operation and fuel costs, and the logistics trail of maintaining and servicing the unit. An island of one facility with a backup generator is thus the simplest form of a microgrid. Larger microgrids take this concept to the next step by providing energy from one or more energy generating systems to one or more users across a network using a control system. Microgrids come at a higher cost for energy security due to the capital investment in the automated switching hardware, control systems, and the logistics trail of maintaining, servicing, and operating the capability. In theory, larger microgrids can be more cost efficient than a similar number of facilities each having their own backup generation capability.

In expeditionary environments like smaller United States and coalition forward operating bases across Afghanistan during Operations Enduring Freedom and Resolute Support, the microgrid structure was simply implemented and effective. Reliable power is not common from the Afghanistan domestic grid, so these bases had to generate their own power, which is typically done using petroleum based generators. As opposed to running one generator per facility, a group of geographically co-located facilities were powered by a single generator, with mobile generators available as backup. The main draw of power for these units was the large demand for cooled air, meaning the demand for electricity was highly variable throughout the day but predictable. Implementation of microgrids on military installations in the United States is less prevalent since the external grid is relatively reliable.

Fort Bliss is an example of a domestic installation that has a microgrid prototype in place. Its microgrid consists of onsite backup generation, a 120 kilowatt solar array, a 300 kilowatt energy storage system, and utility grid interconnection (Ferdinando, "Fort Bliss Unveils Army's First Microgrid"). More of these permanent installations could be used for experimenting with and implementing microgrids along with various energy options. Not only could the development and implementation benefit the fixed domestic sites, but ultimately, the system could be delivered to the warfighter, saving dollars and reducing demand for the critical supply of petroleum in the wartime environment.

The military could consider completely islanding its installations from the domestic grid, which could be seen as highly secure in terms of energy security. This is more complex than it seems, since at this point the installation would then be acting as its own utility, which the military is not designed to do. That said, this is a possible solution, and at the right incentive a utility could be brought in to provide such capability. In the context of a conventional utility system that produces power from a large source and distributes the energy to a large network of users, implementation of microgrid systems was opposed by most utilities. Microgrids bring interconnection issues, expensive distribution system upgrades, customer needs for utility rights-of-way, increased demand for expensive energy storage systems, and cost uncertainties (Masiello, "Microgrids Introduce Issues for Utilities"). However, recent evidence suggests microgrid implementation is gaining traction within the utility community, especially as they explore various business cases for increased reliability, capacity, use of renewable energy sources, generation diversity, as well as grid independence (Nelder, "Microgrids: A Utility's

Best Friend or Worst Enemy?”). Furthermore, in 2013 Utility Dive polled over 200 utility executives, and 97 percent responded that they believed “microgrids present them with a viable business opportunity within the next decade,” while only 24 percent of the respondents believed “microgrids pose a significant threat to grid stability” (Hales, “What Do Utilities Think About Microgrids?). In the near term, the cost of an installation level microgrid would likely be fairly high, and would include the difference between normal operations with backup capability and the costs of adding energy sources, load matching, power monitoring, and all the continual costs associated with energy generation, distribution, and management. Various challenges still need to be overcome, and implementing microgrids on Air Force installations will require close coordination with the local utility.

What the analysis in this chapter showed is the ability to assess specific instances of energy options and their impact on energy security, measured in units of facilities without power, and the associated costs of those options. Run individually, the decision maker can make stepwise decisions based on his available funding and desire to increase the installation’s energy security. Ultimately, the trade-off between cost and energy security varies depending on location, specific state and local regulations and policies, and the mission behind the energy demand. The analysis and tools developed here can aid the decision maker in addressing his or her specific cost versus energy security tradeoff.

Formatting the material in this structure for installation decision making is important for three primary reasons. First, when installation leaders and energy officials are approached with energy generation ideas or concepts, they often do not have an understanding of the energy security implications. Modeling the installation’s network and applying the energy option to that model allow for a quantifiable and repeatable approach for assessing its impact on reducing power failure. Second, the energy generation ideas are typically accompanied with good estimates for costs, but often they are not coupled with the installation’s actual network. By using facility level, actual and estimated energy use and cost data in the model, initial and operational costs for the energy option can be clearly articulated and assessed.

Lastly, by presenting failure scenarios and applying weights to different categories of facilities for use in the model, it enhances the understanding and discussion among installation leaders, base energy officials, and all other stakeholders as to the importance of energy security and the cost at which they are willing to pay for it. Another way to frame the results of the analysis would be to show the positive impact on operations from the energy investment. For example, with the addition of a particular energy source or generator, airfield operations can continue across the scenarios even though the rest of the installation is without power. This dialogue is imperative for continuing progress toward the 25 percent renewable energy goal by 2025 while simultaneously increasing energy security.

Chapter 6: Recommendations for an Energy Secure Force

As weapon systems and their support infrastructure become more complex, the requirement they place on energy input is typically higher than less complex systems and infrastructure. A higher requirement for energy comes with a higher energy bill, especially as the price of energy rises with the economy. In a government budget environment of high and rising operational costs, the Air Force must continue achieving its energy priorities of improving resiliency, reducing demand, assuring supply, and fostering an energy aware culture. Per the most recent *Air Force Energy Strategic Plan*, the Air Force is committed to diversifying energy sources and securing sufficient quantities to perform its missions. There are a number of energy options available to the Air Force at competitive costs, and the Air Force has been successful in implementing many of these options. From an installation energy perspective, diversification of energy sources is the first step and one where the Air Force is in the process of obtaining positive results. Continuity of operations, on the other hand, is dependent on the reliability of the energy source and on how it is implemented at the installation. The Air Force must continue to emphasize selection of energy sources that are reliable so that installations can be insulated from grid failure or other supply disruptions.

This research began by describing what current and projected energy sources can be developed and operated efficiently and reliably on an Air Force installation. Various energy supply options were characterized with respect to their power supply reliability, their complexity of integration to the grid and on Air Force installations, and their cost. The consumption side was then assessed, and a method for calculating energy use at facilities without metering was described. Next, a model illustrating how the Air Force can assess potential energy generation options and their impacts on installation vulnerability to power failure was developed. Given notional failure scenarios and energy options, this model was then applied to Nellis AFB data. By analyzing how the installation infrastructure responded to the power failure scenarios, the energy options were evaluated with respect to their impact to the installation's response and cost to operations. In total, this process illustrated a method for Air Force installation leaders and base energy managers to assess how various energy options affect their risk to mission failure due to electrical energy disruption, and at what cost.

Recommendations

In order to help inform Air Force decision-makers on their policy options for alternative energy use in the increasingly important context of energy security, the study concludes with the following recommendations.

Recommendation 1 – Air Force energy policy should require an assessment of the impacts to installation energy security for all new energy generation projects at an Air Force installation. The Air Force needs to address how the technologies being implemented affect the extent to which their installations are impacted by power failure. Systematic focus should be placed on choosing technologies and energy generation options that improve resiliency and assure supply, which are two key priorities in the *Air Force Strategic Energy Plan.* As illustrated in the analysis and results from the Power Failure Response Model, the trade-off between costs and energy security should be addressed specific to location, specific state and local regulations and policies, and the mission driving the energy demand. A variety of tools, models, and techniques can be used for this assessment, and this study illustrates the process for one method to integrate mission assurance into infrastructure investment decisions.

Recommendation 2 – In the next 10 years, the Air Force should posture itself to be open to and flexible regarding diversification of energy sources. In order to assure energy security, one must have energy diversity. Significant research has been performed on a variety of energy generation sources; the Air Force as an organization and at the installation level must be ready and flexible to implement a variety of energy sources. At the installation level, installation leaders should assess the power supply reliability, the complexities associated with integrating the source into the grid and their installation, and the lifecycle costs when deciding which options to implement. At the enterprise level, the Air Force should understand that reaching the goal of 25% renewable energy generation by the year 2025 will require alternative energy sources at nearly every Air Force installation.

As illustrated in Chapter Two, military installations can be successful employing a portfolio approach when addressing their installation energy needs. Base leaders can combine energy sources in order to take advantage of cheaper technologies while still investing in the more reliable and more secure energy solutions. Similarly, the base leader can choose a portfolio of small and large options, further diversifying the sources of energy used which minimizes risk to the installation. This portfolio approach should also take into consideration energy efficiency upgrades and demand reduction initiatives.

Recommendation 3 – The Air Force can reduce risk to mission failure by investing in research and development of technologies that improve energy security. Air Force energy policy should emphasize the continual research, development, and evaluation of renewable energy generation sources and field those projects determined by analysis to be economically advantageous to the government. As mentioned in Chapter Two, the Air Force must bear in mind that it is not in the business of primary research and development of energy sources for infrastructure purposes, but that it can leverage external research. This does not preclude partnerships where the military can provide land, resources, or a large, stable customer for new technologies.

In particular, the Air Force should selectively choose investment opportunities and partnerships that are unique, but beneficial to the Air Force. For example, the Air Force should partner on further research regarding the benefits of an in-house, organic production facility for producing liquid fuels and on understanding how these fuels and their byproducts could be used to increase installation reliability. Additionally, the Air Force should focus on energy storage options for microgrids and islanding, advanced automation and switching technologies, non-UPS storage units, peaking power supplies, and power solutions that benefit both infrastructure and aircraft or space vehicle energy demand. All investment opportunities and partnerships should consistently adhere to an Air Force wide energy policy which pursues competitive renewable energy projects that improve energy security.

Recommendation 4 – The Air Force should verify its critical assets will not be impacted by power failure through the use of analysis, followed by exercises or audits. The Energy Security and Flexibility section of DoDI 4170.11 "Installation Energy Management" states that "The DoD Components shall take necessary steps to ensure the security of energy and water resources." The first two steps in the instruction for ensuring energy security are to evaluate the vulnerabilities of basic mission requirements to energy disruptions, and to nominate those critical nodes of systems with unacceptably high risk implications of mission achievement to the

Defense Critical Infrastructure Program (DoDI 4170.11, "Installation Energy Management", pg 15).

The Air Force, in meeting the requirements of DoDI 4170.11 and DoD Directive 3020.40, ensures each installation has the capacity or a viable plan in place to guarantee no disruption in electrical services for their facilities in the Defense Critical Infrastructure Program. Based on current energy sources available and results presented in Chapter Five, it is apparent that inexpensive solutions exist, such as adding dedicated fuel back-up generating capacity directly to the critical node, and these simple solutions can be implemented to provide single facility resiliency. By verification, the Air Force should ensure backup energy generation equipment, connectivity, and contingency plans are identified and operational for all facilities identified as task critical assets through its Critical Asset Risk Management Program. . Verification can be performed numerous ways: through analysis similar to that presented in Chapters Four and Five, through physical audits of the critical asset lists, or through exercises where power failure scenarios like those described Chapter Four are executed.

Conclusions

In 2009 an ice storm paralyzed an area of land from the Ozarks through Appalachia. At its height, 1.3 million people were left without power. The Kentucky National Guard was mobilized, and spent days aiding those without power. They replenished spent fuel tanks and brought mobile generators to provide power and heat to remote areas (Halladay and Bratton, pg 3). Though military installations, such as Fort Knox, were left without grid power and partially closed for operations, emergency preparedness plans and resources were sufficiently in place to allow the National Guard to extend its hand to the local community. Imagine if the Governor of Kentucky had turned to the National Guard for support and found an organization unprepared and struggling with its own problems. The military should be prepared and ready when called to serve, and this includes ensuring military installations have generation and contingency plans in place so they respond during any failure scenario. In particular, Fort Knox learned from this experience and invested in a portfolio approach to energy security, ensuring operations can continue when faced with domestic grid power outages.

The Air Force must also be prepared for uncertainties. The future could bring unknowns like rising energy costs, bankrupt utilities, or energy demand so high that rolling blackouts and outages are common. Facing this uncertainty, the installation decision maker must understand the impact to his or her mission in the event of power failure; the methodology described in this study provides one example of the necessary tools. At a minimum, every installation commander and base energy official should understand the status quo in terms of their baseline energy cost and impact to operations in the event of power failure. Modeling likely power failure scenarios and showing their effects to the installation commander are key first steps in encouraging an energy aware culture. Then, illustrating what different options do to the installation's operational posture during those failures is a simple way to empower the commander with decision making information.

Given the historical development and structure of the domestic energy grid, the assets and infrastructure that the Department of Defense relies upon for energy distribution lie outside the purview or authority of the Department. Thus, there is often little ability for the military to influence decisions with regard to enhancing their energy security. One solution for the Department of Defense is to work with the Department of Homeland Defense and the National Infrastructure Protection Plan to establish standards for military installations, but this solution relies heavily on the dynamic relationships in place among state and local governments, federal agencies, utilities, and private entities. Another solution is to internally develop policies that aim to accomplish energy security. The military departments, and especially the Air Force through its Energy Strategic Plan, are beginning to accomplish this. More importantly, though, is that local energy managers establish close relationships with local government and utility partners to understand the interdependencies of critical infrastructure systems, response options, and plans toward future development.

The Air Force "Installation of the Future" is diverse, provides global, networked power projection and command and control, and serves as a model of excellence for its surrounding community. The requirements for power reliability in such a future are high. By remaining committed to its energy priorities and advancing toward improved energy security through flexibility in sources, the Air Force will remain at the forefront within the Department of Defense for renewable energy implementation and energy security for its diverse mission set.

Abbreviations

AF – Air Force

AFB – Air Force Base

AFI – Air Force Instruction

AFPD – Air Force Policy Directive

AFPM – Air Force Policy Memorandum

CARM – Critical Asset Risk Management

CFR – Code of Federal Regulations

DARPA – Defense Advanced Research Projects Agency

DoD – Department of Defense

DoDI –Department of Defense Instruction

DOE – Department of Energy

DSB – Defense Science Board

DUERS – Defense Utility Energy Reporting System

EIA – Energy Information Administration

EO – Executive Order

EPA – Environmental Protection Agency

FAA – Federal Aviation Administration

GAO – Government Accountability Office

ICBM – Intercontinental Ballistic Missile

LCOE – Levelized Cost of Electricity

MW - Megawatts

NIPP – National Infrastructure Protection Program

NORAD – North American Aerospace Defense Command

OPR – The Office of Primary Responsibility

SAF/IE – Assistant Secretary of the Air Force for Installations, Environment, and Energy

UAV – Unmanned Aerial Vehicles

UFC – Unified Facilities Criteria

UPS – Uninterruptible Power Supply

USAF – United States Air Force

USC – United States Code

VAQ – Visiting Airman's Quarters

WTE – Waste-to-Energy

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