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Realizing energy security on a DoD installation using photovoltaics with a battery energy storage system

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THESIS

REALIZING ENERGY SECURITY ON A DOD INSTALLATION USING PHOTOVOLTAICS WITH A BATTERY ENERGY STORAGE SYSTEM

by

Cody W. Keesee

March 2018

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Energy security is a critical facet of installation energy management, which is a key focus of a base's Public Works Officer and Energy Manager. Providing full-time power to critical infrastructure loads on a base or facility during commercial grid disruptions is the definition of true energy security. Determining the most stable and efficient source of energy and means of storing the installation's power, whether it be renewable or not, is a key concern. For solar renewable energy, the climate is of utmost importance.

Weather and climate are two components that dictate the output of a photovoltaic array. Coupling the array with battery storage is a proven method to provide energy security. Capitalizing on currently installed energy generation systems and combining this with new construction infrastructure of new arrays and storage can make energy security realizable. In this thesis, we introduce a novel design tool that sizes solar arrays. When applied to a facility in Monterey, it is clear that relying upon solar arrays to provide complete energy security is not practical. The low average peak-sun hours and subsequent high-energy storage requirements do not support the installation of large-scale solar arrays for energy security purposes.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
BESS	battery energy storage system
CEC	Civil Engineering Corps
CNO	Chief of Naval Operations
DC	direct current
DoD	Department of Defense
DON	Department of the Navy
DOSE	Director of Shore Energy
DR	distributed resources
EMS	energy management system
FEAD	Facilities Engineering Acquisition Development
HESS	hybrid energy storage system
IEA	International Energy Agency
MCAS	Marine Corps Air Station
MOSES	Model of Short-Term Energy Security
MPP	maximum power point
NAS	Naval Air Station
NAVFAC	Naval Facilities Engineering Command
NPS	Naval Postgraduate School
NREL	National Renewable Energy Laboratory
NSAM	Naval Support Activity Monterey
OPNAV	Office of the Chief of Naval Operations
PSH	peak-sun hours
PV	photovoltaic
PWO	Public Works Officer
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SECNAV	Secretary of the Navy
UPS	uninterrupted power supply

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Dedicated to my mother, Genevieve A. Keesee. You are missed.

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I. INTRODUCTION

A. BACKGROUND

Civil Engineering Corps (CEC) officers are the public works professionals for the Navy and for the Naval Facilities Engineering Command (NAVFAC) and as such have several different roles and responsibilities relating to energy security and the infrastructure on the Navy and Marine Corps team. NAVFAC is responsible for construction and maintenance at all Navy and Marine Corps facilities around the globe. The professional life of the CEC officer is broken down into three distinct categories of construction and facilities management billets. These categories are Public Works Officer (PWO), Facilities Engineering Acquisition Development (FEAD) officer, and expeditionary. The PWO is concerned about all aspects of maintenance and upkeep of the base to which they are assigned, including maintaining existing energy projects. As a FEAD, the focus is on new construction and the development of new energy security projects. Finally, the expeditionary officer’s perspective is concerned with finding efficient methods to power forward operating bases in austere environments. These bases can be compared to a stateside base, which is islanding or operating independent of the commercial grid.

B. PREVIOUS WORK

Related work in this area is abundant as is previous research. A related thesis written by Major David Gustafson dealt with the use of an energy management system to provide energy security [1]. He found that while various energy storage methods were available on the commercial market, the technology was very expensive and did not meet the robust storage requirements of a large scale installation. Furthermore, he concluded that as energy costs rise, so would the cost effectiveness of energy security [1].

The process of designing of a solar array is discussed at length in the G.M. Masters book *Renewable and Efficient Electric Power Systems* [2]. The research in this thesis draws upon the design architecture introduced in the text but expands greatly to include several factors discussed in Chapters III and IV that were adapted from research conducted by Sandia National Laboratories and the National Renewable Energy Laboratory.

C. OBJECTIVE

The objective of this thesis is twofold. The first is to create a design tool that sizes an energy security system using photovoltaic panels and batteries based on a variety of factors. Next, the design tool is applied to a given installation in order to capitalize on the solar availability of a region. The end product is a representation of how feasible providing full energy security via solar energy and battery storage would be under various scenarios, including shifts in geographic location. The study also uses existing capability and installed renewable resources in a real-world design. A proposed infrastructure improvement plan, outlining new construction to provide energy security, is provided.

D. ORGANIZATION

A detailed energy security discussion in Chapter II provides an understanding of the research prepared in the following chapters and the importance of energy security from a top-down approach. In Chapter III, we feature the design of the model and the factors required to create an accurate system. The chapter culminates in a detailed sample solution using realistic but arbitrary numbers. In Chapter IV, the design tool is used to examine a specific installation on a military base and how geography and climate play a role is system design. A final scenario described in Chapter V involves new construction on a Navy installation and seeks to maximize the output of a proposed solar array with the goal of determining how much energy could be produced.

II. ENERGY SECURITY

A. INTRODUCTION

From the standpoint of the civilian marketplace, there exists a set of principles regarding energy security that is quite different from what the Navy definition and requirement is. The interesting point is how they are tied together. From a civilian standpoint, the focus is on both the short- and long-term availability of transportation, maintenance of energy infrastructure, and the economic and political aspects of providing energy. The International Energy Agency (IEA) definition of energy security is "the uninterrupted availability of energy sources at an affordable price" [3]. As mentioned, this is broken down into both long-term and short-term definitions of energy security from the viewpoint of what can be considered the market standpoint.

B. TRANSPORTATION OF ENERGY

Loss of transportation of energy can be both a long and short term problem. Historically, the most transported energy commodity is oil. For instance, a shipwreck today on the order of the *Exxon Valdez* could result in a short term loss of availability of oil that would most likely result in a short term increase in price that could be absorbed by the market in a relatively short amount of time. This category of interruption would be fairly inconsequential to the Navy. Another more recent interruption that was more impactful but still considered short term to the domestic production of petroleum were the hurricanes Harvey and Irma in the Gulf of Mexico. The loss of production resulting from these back to back natural disasters was felt across the nation, albeit for a relatively short time according to news agencies [4].

A loss of oil production or importation on a larger scale could result in a long term energy shortage that could be problematic for the Navy. The use of the word "problematic" suggests that the Navy could not perform its primary mission for an undetermined period of time. Navy ships operate on diesel fuel for the most part, nuclear ships notwithstanding. A loss in the availability of fuel would at a minimum tax the reserves of fuel and lead to a decrease in mission effectiveness.

C. INFRASTRUCTURE ORGANIZATION

From a shore standpoint, which is the basis for this research, a long-term loss in domestic energy availability would affect the readiness of the fleet. In addition, the discussion is focused mainly on electrical power and losses of electrical power from the grid. For the most part, domestic Navy bases are powered by the commercial grid. Navy infrastructure can be split into two basic categories for the sake of this research: operational and training. An example of an operational base is an airfield housing squadrons of aircraft such as Naval Air Station (NAS) Lemoore located in the Central Valley of California. The most recognizable training base is the Naval Support Activity Monterey (NSAM), the home of the Naval Postgraduate School (NPS). Obviously both of these types of bases are similar in that they receive electrical power from the local commercial grid and, as such, are dependent on the availability and directly affected by the energy security of the grid.

1. Operational Bases

The difference in the way operations on an airfield or other operational based are affected due to a long term loss of power is in a loss of capability. An airfield requires petroleum to fuel the airplanes. Less obvious, or perhaps less visible and taken for granted, are electrical loads such as runway lighting, radar systems, and communication centers vital to the safe and effective operation of what can be considered a small airport. Several other electrical loads that are less vital to runway operations are maintenance facilities for the aircraft and other base support services such as galley and barracks facilities for the sailors and airman stationed at the base. A base such as NAS Lemoore has fuel reserves to run generators that can power the ancillary systems for a short period of time of perhaps a few days to a few week before requiring a resupply. In the event of a long-term outage, those fuel reserves will run dry, leaving the base with no way to power its planes, airfields, or support the personnel conducting the work required to operate the base.

2. Training Bases

On the other hand, the power and energy security needs of a training base such as NSAM are not so different from that of the operational base. The mission is different in that there is not an operational airfield but several academic buildings supporting the mission of training mid-grade officers in various fields. The long-term loss of power here at NPS might, at worst, be a temporary setback for the higher education of a few thousand officers. The global situation that might lead to the long-term loss of power might also lead to the immediate deployment of many of the students and, thereby, reduce the immediate need for energy security on a base such as NSAM.

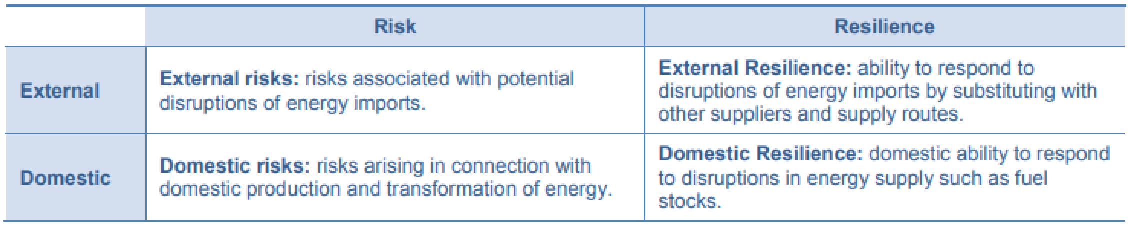
3. Loss of Supply

Without discussing the various geopolitical scenarios that could cause a long-term decrease or halt to the production or the delivery of energy in any form, it will prove to be important to forecast and prepare for the eventuality. The Navy infrastructure, and more importantly the mission and defense of the nation, will suffer from a long-term loss of petroleum or any domestic or imported source of energy. In short, these are but a sample of many scenarios that could lead to an inability of the Navy to conduct its mission.

D. IEA AND MOSES

The IEA created a tool that plays a part in bridging the gap between the Navy's energy security goals and its own. The Model of Short-term Energy Security (MOSES) is one of IEA's methods of putting qualitative data on what energy security is to the global members of IEA [5]. MOSES gives a combination of number scores and letter grades to regions based on many factors, most importantly, the ability to import energy and protect distribution. MOSES addresses four basic dimensions of energy security as shown in Table 1.

Table 1. Dimensions of Energy Security Addressed in MOSES. Source: [5].



	Risk	Resilience
External	**External risks:** risks associated with potential disruptions of energy imports.	**External Resilience:** ability to respond to disruptions of energy imports by substituting with other suppliers and supply routes.
Domestic	**Domestic risks:** risks arising in connection with domestic production and transformation of energy.	**Domestic Resilience:** domestic ability to respond to disruptions in energy supply such as fuel stocks.

There exist both internal (domestic) and external risks and resilience factors. The external dimension of risk deals with the previously mentioned possibility of the loss of energy imported from outside agencies such as the closing of a port of entry into the country or disruption of a pipeline. The resilience factor is how well the energy infrastructure is able to deal with such an event according to Jewell [5]. The domestic dimensions work in much the same way, and the real difference lies in the source of both the energy and the response. In the description of the model, illustrated in Figure 1, Jewell discussed how the idea of energy security applies to more than just oil production and transportation as discussed previously [5].

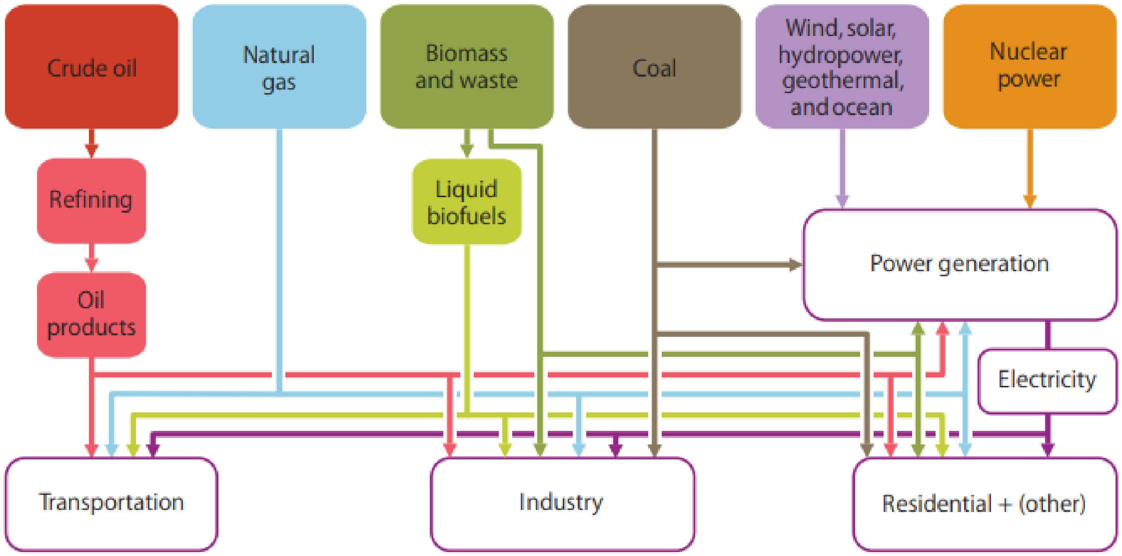


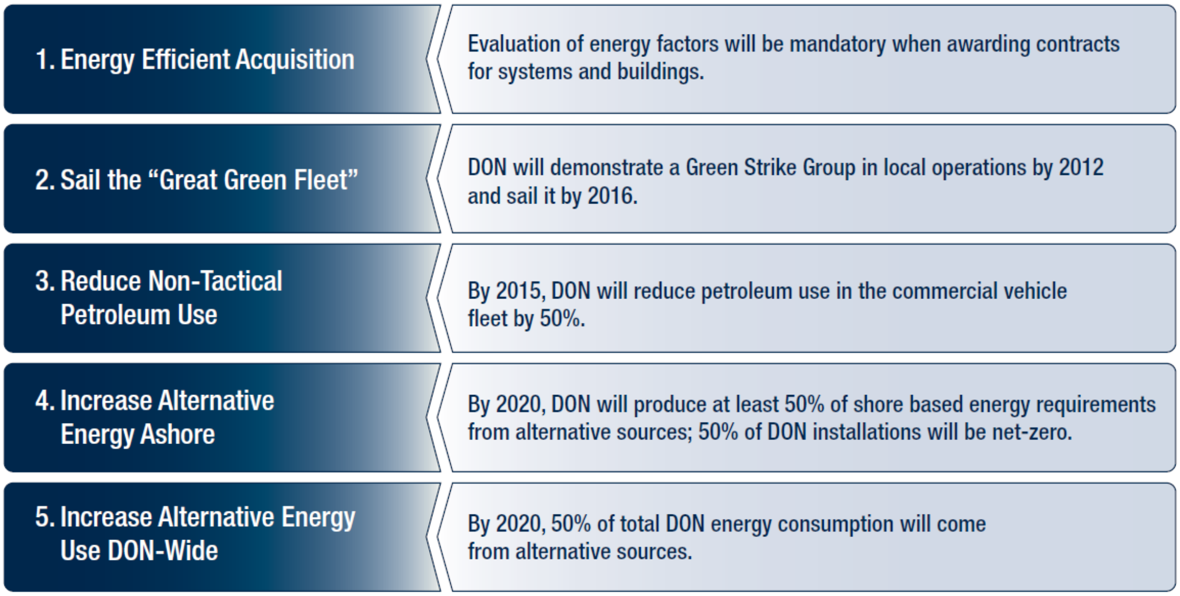
Figure 1. Energy Systems Approach. Source: [5].

The need to protect energy infrastructure as well as non-oil based forms of energy production are discussed at length; however, what Jewell and the IEA fail to discuss in any quantitative capacity in MOSES are renewable sources of energy such as wind and solar. The reason given for the seemingly dismissive attitude towards the abundant renewables is that renewables are subject to a lack of persistence or full time availability in that wind and solar power are dependent upon various climate factors; however, when looking at energy security from a local level such as a base or campus, renewables may be the only viable or realistic source of energy security available.

E. NAVY LEADERSHIP GUIDANCE

In 2010 the office of Secretary of the Navy (SECNAV) published the Department of the Navy's (DON) *Energy Program for Security and Independence*. In the publication, several goals were laid out that are seemingly in line with the IEA's research discussed in the previous pages. The goals of the two organizations are parallel if not the same: decrease consumption of energy overall and increase funding for renewable sources of energy while using less fossil fuels [6]. In order to meet these goals the SECNAV discusses two priorities. The first is very important to this research— energy security, and the second is energy independence. Again, while the IEA kept with the theme of energy security, the SECNAV splits the two, but the end goal remains the same.

To meet the priorities of the Secretary, five goals were laid out as shown in Figure 2. The five goals are laid out in a logical fashion and seemingly hit all the major points for the goals of reducing energy consumption and increasing the use of alternative and renewable forms of energy. It must be pointed out that while these go a long way in meeting the priorities, the goal of energy independence and true security are not met. The fourth goal prioritizes the use of alternative energy, going so far as to say that in two years 50% of shore energy should come from alternative sources and all Department of the Navy installations should be net-zero, meaning the base makes enough energy from alternative sources to offset the energy obtained from the commercial grid [6]. This sounds like a good plan, but as this research demonstrates, being net-zero is not nearly the same as being energy secure. Without some form of energy storage such as batteries or any of the other commercially viable forms of electrical energy storage, no base or facility can operate without backup generators and a dependence on petroleum and, therefore, cannot truly be energy secure.



1. Energy Efficient Acquisition	Evaluation of energy factors will be mandatory when awarding contracts for systems and buildings.
2. Sail the "Great Green Fleet"	DON will demonstrate a Green Strike Group in local operations by 2012 and sail it by 2016.
3. Reduce Non-Tactical Petroleum Use	By 2015, DON will reduce petroleum use in the commercial vehicle fleet by 50%.
4. Increase Alternative Energy Ashore	By 2020, DON will produce at least 50% of shore based energy requirements from alternative sources; 50% of DON installations will be net-zero.
5. Increase Alternative Energy Use DON-Wide	By 2020, 50% of total DON energy consumption will come from alternative sources.

Figure 2. The Secretary of the Navy's Energy Goals. Source: [6].

The Secretary of the Navy's *Strategy for Renewable Energy*, published in 2012, is more in line with this research in that the focus is on protection of critical infrastructure from a loss of the power due to natural disaster, cyber-attack, or a malfunction of the commercial grid [7]. The office of the SECNAV places an emphasis on the integration of microgrids and the power of being energy secure versus simply being net-zero.

> Being able to generate power independently is of strategic importance, but will not significantly improve an installation's security unless the power is available during blackouts or other incidents affecting grid reliability. It is not a requirement to provide power to each and every building on a base during grid outages; we must however be able to match generation to critical demand loads to support mission enabling infrastructure and to enable demand response techniques in response to requests from the local utility. To improve energy security, DON must evolve beyond simply providing emergency generators for individual buildings to being able to provide reliable, sustained power to designated substations with the capability to match sources to critical loads. [7]

From the standpoint of facility infrastructure, the Department of the Navy's Director of Shore Energy's (DOSE) benchmarks for energy security are reliability, resiliency, and efficiency. As discussed in the introduction, the research proposed is extremely relevant from a facility and installation standpoint. Commander Tetatzin developed a three pillar approach to installation energy security presented in Figure 3 [8]. In the brief, she proposed that without any of the three pillars, the goal of energy security is unobtainable, and she provides specific benchmarks for each of the three pillars. For reliability, the litmus test involves the system average interruption duration index and frequency index (SAIDI, SAIFI). SAIDI is an index representing the number of minutes a facility is without power during a year, while SAIFI is the number of sustained outages per year, which is discussed in depth in *Electrical Reliability Reports* [9]. According to Tetatzin, we find the baseline for DOSE is to keep the SAIFI index at less than 120 minutes per year and SAIDI at less than two outages per year. The resiliency benchmark given by DOSE is based on having multiple paths of power and up to a weeks' worth of storage. Finally, efficiency is measured as having quality metering of facilities and controls.

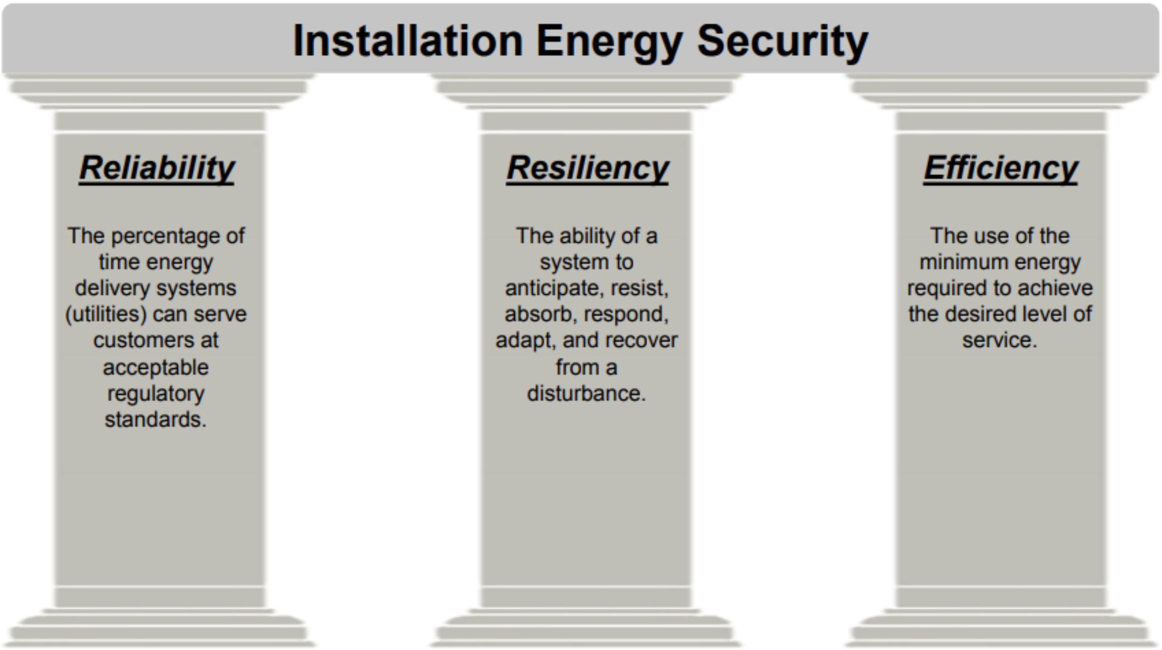


Figure 3. Installation Energy Security. Source: [8].

The discussion of energy security is important to this research because it is important to illustrate what energy security really is. Furthermore, it is equally important for the purpose of this research to show what the Navy's leadership's policies on energy security are from multiple levels. The difference between what the SECNAV dictates as his energy security policy to how the DOSE implements the policy from an installation level should match quite closely. Next, it is important to look at how to implement energy security on an actual installation.

III. DESIGN TOOL CONSTRUCTION

A. INTRODUCTION

For the purpose of this research, a design tool was created to streamline the calculation for sizing both photovoltaic (PV) arrays and battery banks to meet given energy needs. The output of the calculator for the sizing of the array is given in number of individual panels in series and in parallel to meet the system voltage requirements. The tool also calculates the nominal battery size required to meet the needs of the system and is delivered in ampere-hours. The usefulness of the tool is in the fact that it requires just three inputs. There are several other factors at play in the calculator, however, for a given geographical region. The additional factors do not change, and as such, they are labeled design constants. A detailed description of the tool follows.

B. ISLANDING VS. PEAK SHAVING

1. Peak Shaving

When designing a system with the goal of providing energy security for a building or facility, peak shaving and islanding are two primary functions to consider. From a basic point of view, peak shaving is a method of saving money by purchasing electricity at night, when it is cheaper, and storing it for use when peak demand is high and energy rates are also higher. This way the “peak” electricity usage is “shaved” because it is being augmented with stored electricity from batteries. Another way to achieve this is to use an array of PV panels to charge the batteries to augment the power bought from the commercial grid. Optimally, a system where both peak-shaving methods are used is preferred. From an energy security standpoint, utilizing a bank of batteries to offset consumption is a step in the right direction but ultimately falls short of having any real commercial grid independence.

2. Islanding

Islanding is a term used to describe a system where the entirety of a building’s electrical load is provided from a local microgrid and is the primary focus of this research as it pertains to energy security [10]. Islanding is most often used for short durations such as during power outages or other types of grid disruption. The supply of power from an islanding system can be as basic as an uninterruptable power supply (UPS) for a computer that allows for safe shutdown and mitigates the loss of data. It can also be as robust as having the ability to power a building for an indefinite period of time. A forward operating base is a good example of a facility that requires a system to provide power for a long period of time without being attached to a commercial grid. On NPS there is a system of generators installed at Herrmann Hall that provides emergency power. This is a type of islanding that is dependent upon a source of diesel fuel to operate. As discussed in a previous chapter, this does not meet the definition of energy security because of the need for refueling.

3. Energy Storage

In order to have a system capable of islanding in the most basic sense, a few elements must be present. First, a source of energy generation is required, and in this case, PV panels are used to capture solar energy. There are other viable sources of renewable energy such as wind and hydroelectric, but none are more suited for the design of a system in this location than solar. Second, a form of electrical energy storage is needed. There are several forms of energy storage available on the market today. The most readily available storage medium are lead-acid batteries. Batteries exist in many different varieties and differences exist in the energy density, depth of discharge, power rating; these are but a few of the differences. There are mechanical forms of storage as well to include high-power flywheels and even hydroelectric storage. Again for the sake of this design, the focus is on calculations in terms of required battery storage and not the type of battery to be used.

4. Case Study

An interesting case study is using hydroelectric energy as a mechanical form of storage in the tiny island in the Canary chain called El Heirro. The island has a population of about 7,000 and is historically dependent on diesel brought in by boat on a daily basis. The island is a textbook example of requiring a redundant form of power and ultimately energy security. Several wind turbines were installed to make good use of the island's location in a prime spot to capture the trade winds. In order to provide power for the residents when the wind is not blowing, an ingenious hydroelectric system was installed to make further use of the island's geography. Basically, during times of steady wind, the turbines make more than enough electricity to power the island. The excess power is used to pump water to two reservoirs high on the island as depicted in Figure 4.

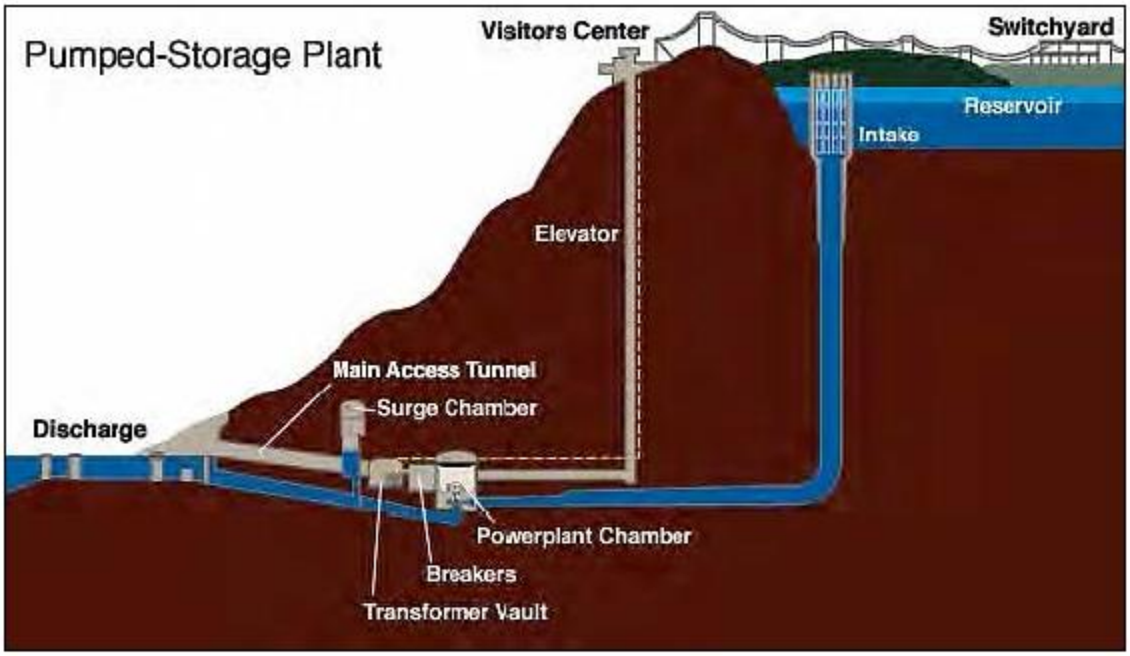


Figure 4. Cutaway Diagram of a Typical Pumped Hydro Plant. Source: [12].

In times of less than ideal wind, the water is released from the reservoirs, and power for the island is maintained via the hydroelectric generators installed. This ingenious system obviously takes advantage of the El Hierro's natural geography. This sort of system cannot be installed everywhere, but it serves as an example that energy security is achievable in many different ways [12].

C. ASSUMPTIONS

In order to properly design a system for full time islanding, several factors are taken into consideration. A simplified diagram is shown in Figure 5. As mentioned previously, this design requires three inputs, the first of which is the AC load required to be supported. Estimating the load can be done several ways and this is discussed in a following section. For the calculations that follow, the load is either a test load used for the purpose of demonstrating a sample system design or the actual load being modeled that is discussed in depth in a following section. The remaining two factors are the peak-sun hours and the days of usable storage required. These data points are available in several different resources, and the numbers used in this research were taken from charts created by Sandia National Laboratories and the National Renewable Energy Library [10], [11].

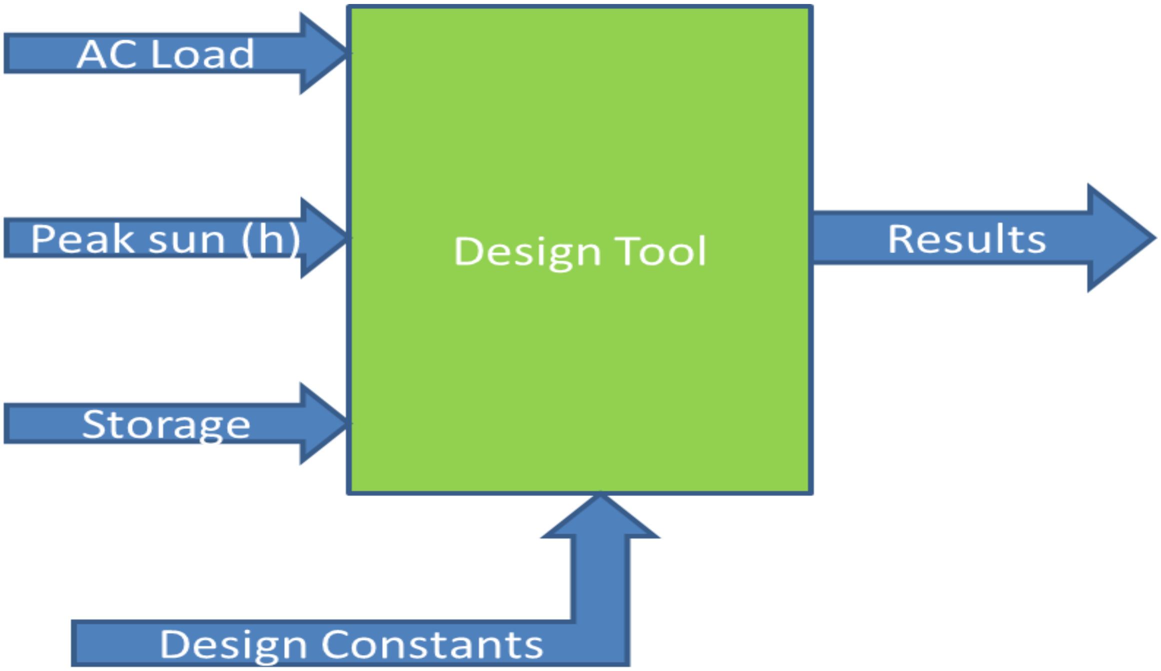


Figure 5. Block Diagram of Design Tool

D. DESIGN CONSTANTS

"Design constants" is used to describe the calculation factors that do not change for the design in a certain geographical area. They are considered constant because they are independent of the three inputs to the design tool, and this is discussed at length. In the following section, we explain the design process and the different elements taken into account when designing a photovoltaic system. Keep in mind that this will be a robust system capable of islanding a facility for an indefinite period of time. The design starts with the calculation of the required nominal battery capacity, followed by the sizing of the solar panels.

1. Inverter Efficiency

The first design constant to be considered is the inverter efficiency. The inverter is a critical part of the design as it converts the DC current to AC. A battery stores electricity in DC, and to size the batteries to meet the AC load requirement, the AC load is divided by the inverter efficiency to calculate the DC load. For the purposes of the design, the same inverter is used throughout the system, which is also why it is considered a design constant that does not change throughout the design. In this case the inverters currently installed on NSAM are the PowerGate Plus 75 kW. This inverter is a widely used commercial-sized inverter. The manufacturer's rated efficiency of the inverter is 96.6% when the load is above 30% pf the rated power level and is within the range of an efficient inverter [13].

2. System Voltage

The system voltage is another design constant. For a microgrid of this size, it is kept constant at 480 VDC. The system voltage can be adjusted to any voltage that the inverter can accept. For instance, the PowerGate inverter has an input voltage range of 315 to 600 VDC. Currently on NSAM, there are three PowerGate inverters installed and they operate at a voltage range from 300 to 480 VDC. Again, the system voltage is kept constant at 480 VDC to make it a design constant and not an input variable for the sake of this research.

3. Battery Depth of Discharge

Battery depth of discharge is another variable that is kept constant as it is an intrinsic characteristic of the batteries themselves. As mentioned previously, the results of the design tool for nominal battery size are given in ampere—hours, and a specific battery size is not given as it is with the PV panels. Even for lead-acid batteries, the depth of discharge for the temperatures expected in either of the two design environments are well above the range where it is a fact to be considered. When temperatures are at or below freezing combined with a discharge of greater than 90%, lead-acid batteries begin to degrade. A standard value of 0.90 is used for the depth of discharge. This means that during the time when the battery is supporting the load, the battery is never discharged more than 90% of its rated capacity. At certain low temperatures, lead-acid batteries can be damaged if drained to less than 10%.

4. Maximum Power Points

The next two design constants are qualities of the solar panels themselves and are the maximum power point voltage and maximum power point (MPP) current. These are more often than not expressed in terms of the overall wattage rating of the photovoltaic panel or in the efficiency of the panel, which is simply the MPP values multiplied per Ohm’s Law as power is the voltage multiplied by the current. The panels used in the design for this research are the ones currently installed on NSAM, the Sharp 216 W modules. They are still commercially available, and since some of the calculations include the installed panels, it makes sense to standardize the panels as done with the inverters.

The size of the panels in wattage is the multiplication of the MPP voltage times the MPP current using Ohm’s law. In this way we see that the 216 W is calculated from the MPP voltage of 28.9 V multiplied by the MPP current of 7.48 A for a total of 216.17 W. The panels on NSAM were installed in 2011. These were perhaps the most efficient at the time; however, PV panel technology has improved over the last several years. In fact every day new and more efficient panels are in the news. It is common to see PV panels in the 315 W to 345 W range with MPP voltage well above 50 V. Due to the nature of the design tool, it is easy to adjust the values of the MPP characteristics in the calculations of the PV panels used in a particular design. The current and voltage curves from the Sharp 216 W panels are included as a reference in Figure 6.

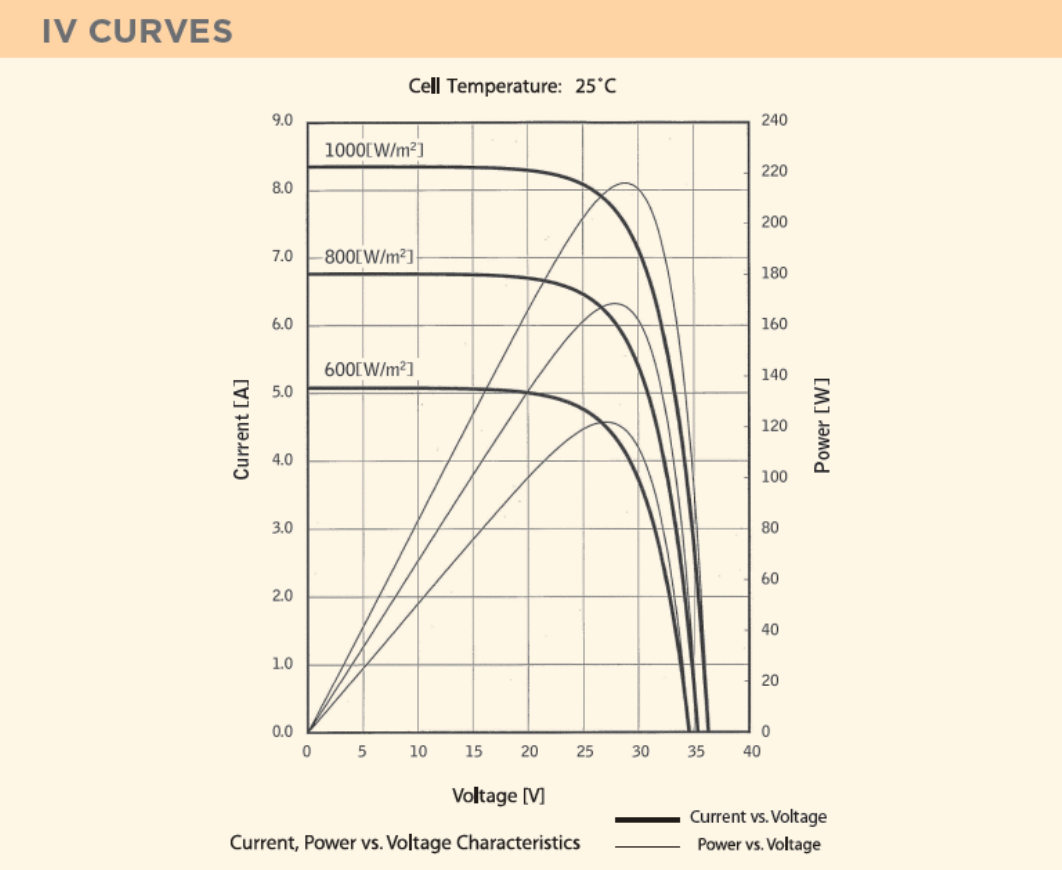


Figure 6. IV Curves for Sharp 216 W Panel. Source: [14].

The array orientation and tilt are factors that must be taken into account when designing a PV array as well, especially when using non-tracking, fixed, PV panels. The currently installed panels are fixed, and for the purposes of these calculations, the same orientation and tilt are assumed for any new installation.

5. System Efficiency

Moving on to the next design constant, the overall system efficiency is another important aspect to consider when designing a PV system. The factors influencing this number are not as clearly defined as the previous design factors in that several actors are at play here. In making this estimate, the NREL PVWatts user’s manual was consulted in order to maintain the integrity of the design tool [15]. NREL’s list of system losses include soiling, shading, snow, mismatch, wiring, connections, and age among others [15]. Some of these factors are obvious in that it is easy to see how a dusting of pollen in the spring on the PV panels would affect the output of the panels. Snow is not a factor in either of the climates considered for this study. In general, the losses that cannot be mitigated are due to the installation of the system in the wiring and connections. NREL estimates total losses in system efficiency to be on the order of 14%, and that number is used in this design tool [15].

E. INPUTS

Over the course of the last few pages, the design constants of the design tool were discussed. As mentioned, for a particular geographic area, these do not change. The three main factors that change and are the main inputs for the design tool are the AC load, the peak-sun hours, and the required number of days of usable storage.

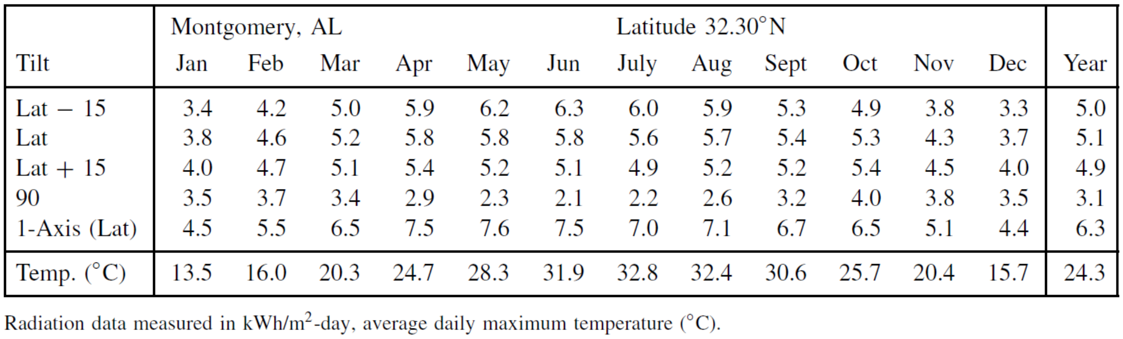
1. AC Load

The AC load is fairly straightforward to find. For the specific case of this research and the use of Spanagel Hall in NSAM, the load data came directly from the base energy manager and the meter for the building. Another load can be calculated by simply adding up the appliances that have to be powered and the hours of the day that they are in use. The design tool is flexible in that it can work for large commercial scale loads as well as smaller household type loads. Some of the design constants have to change, but as shown previously, that does not require a significant effort.

2. Peak-Sun Hours

The peak-sun hours (PSH) figure come from insolation tables published by Sandia National Laboratories among others. These data tables are the result of years of collecting solar radiation and various other weather factors including wind and temperature to determine how many hours per day a given solar panel will produce useable electricity in a given location [11]. A sample insolation table is shown in Table 2.

Table 2. Sample Insolation Table. Source: [2].



Tilt	Montgomery, AL						Latitude 32.30°N						
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	3.4	4.2	5.0	5.9	6.2	6.3	6.0	5.9	5.3	4.9	3.8	3.3	5.0
Lat	3.8	4.6	5.2	5.8	5.8	5.8	5.6	5.7	5.4	5.3	4.3	3.7	5.1
Lat + 15	4.0	4.7	5.1	5.4	5.2	5.1	4.9	5.2	5.2	5.4	4.5	4.0	4.9
90	3.5	3.7	3.4	2.9	2.3	2.1	2.2	2.6	3.2	4.0	3.8	3.5	3.1
1-Axis (Lat)	4.5	5.5	6.5	7.5	7.6	7.5	7.0	7.1	6.7	6.5	5.1	4.4	6.3
Temp. (°C)	13.5	16.0	20.3	24.7	28.3	31.9	32.8	32.4	30.6	25.7	20.4	15.7	24.3

Radiation data measured in kWh/m^2-day, average daily maximum temperature (°C).

When designing a PV system, an important design strategy is to use the worst month. This is the most conservative approach because if the highest PSH, sunniest month, was used for the design of the system, then in the cloudier months, the design would not allow for the charging of the batteries and a potential outage is probable. For example, if the PSH from Table 2 was used to design a system of any size using the data from one of the summer months with a value of 5.8 hours per day, there is little reason to believe the system would be capable of charging the batteries in December with a PSH of 3.7 hours.

3. Usable Storage

Once a suitable AC load is obtained and the PSH is found, the required days of usable storage can be estimated. Sandia National Laboratories created a figure, recreated in the Masters book [2], shown in Figure 7, that estimated the numbers of days of battery storage is required based on the PSH from the insolation tables [2]. The graph has two curves, one for 95% availability, and the other for 99% availability. What this means is that for a load to be supported 99% of the time, that curve is the one to use for calculations. It is obvious that it requires a much larger storage system to provide the 99% availability, but that is the cost for energy security.

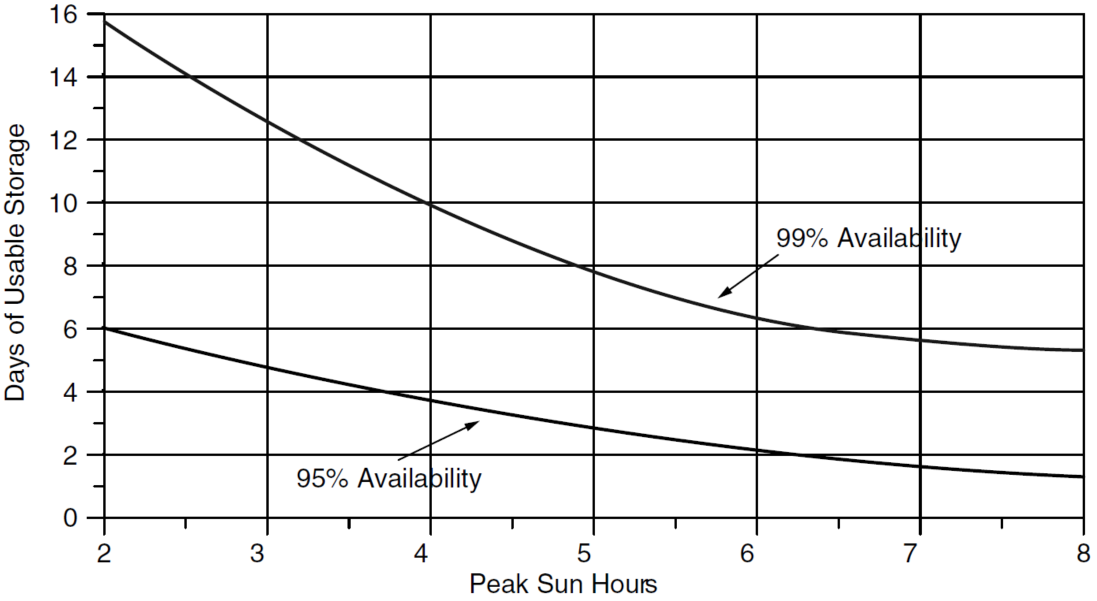
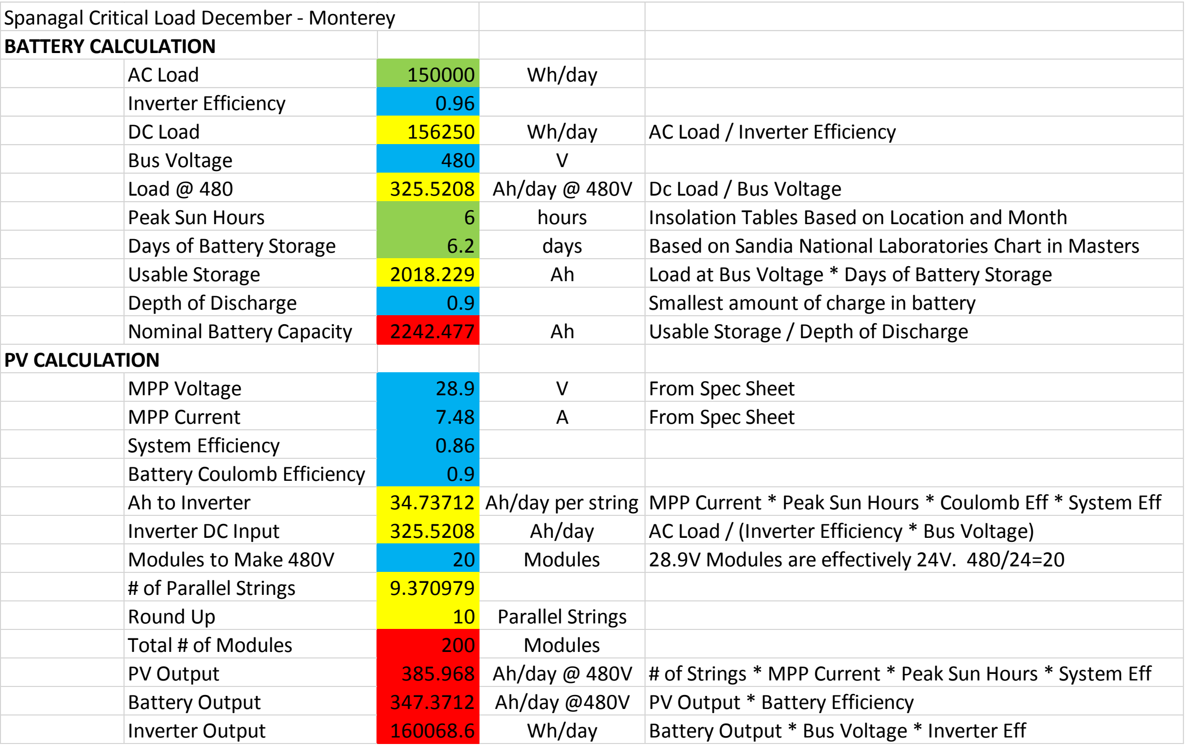


Figure 7. Usable Storage. Source: [2].

F. SAMPLE CALCULATION

Now that the necessary factors are known, a sample calculation is in order to demonstrate the usefulness of the tool. Table 3 is a copy of the design tool created for this research. The green cells are the user inputs: AC load, PSH, and days of usable storage. The blue cells are all the design constants discussed in the previous section. Yellow cells denote interim calculations that are required to find the red cells, and red cells are the outputs of the design tool. The last column in the chart defines the mathematical operations used to calculate the values for the particular row or defines where the number was derived from.

Table 3. Sample Calculation



Spanagal Critical Load December - Monterey				
BATTERY CALCULATION				
	AC Load	150000	Wh/day	
	Inverter Efficiency	0.96		
	DC Load	156250	Wh/day	AC Load / Inverter Efficiency
	Bus Voltage	480	V	
	Load @ 480	325.5208	Ah/day @ 480V	Dc Load / Bus Voltage
	Peak Sun Hours	6	hours	Insolation Tables Based on Location and Month
	Days of Battery Storage	6.2	days	Based on Sandia National Laboratories Chart in Masters
	Usable Storage	2018.229	Ah	Load at Bus Voltage * Days of Battery Storage
	Depth of Discharge	0.9		Smallest amount of charge in battery
	Nominal Battery Capacity	2242.477	Ah	Usable Storage / Depth of Discharge
PV CALCULATION				
	MPP Voltage	28.9	V	From Spec Sheet
	MPP Current	7.48	A	From Spec Sheet
	System Efficiency	0.86		
	Battery Coulomb Efficiency	0.9		
	Ah to Inverter	34.73712	Ah/day per string	MPP Current * Peak Sun Hours * Coulomb Eff * System Eff
	Inverter DC Input	325.5208	Ah/day	AC Load / (Inverter Efficiency * Bus Voltage)
	Modules to Make 480V	20	Modules	28.9V Modules are effectively 24V. 480/24=20
	# of Parallel Strings	9.370979		
	Round Up	10	Parallel Strings	
	Total # of Modules	200	Modules	
	PV Output	385.968	Ah/day @ 480V	# of Strings * MPP Current * Peak Sun Hours * System Eff
	Battery Output	347.3712	Ah/day @480V	PV Output * Battery Efficiency
	Inverter Output	160068.6	Wh/day	Battery Output * Bus Voltage * Inverter Eff

For the basis of this sample calculation, it was determined that an AC load of 150,000 W-hours per day is required to be supplied. Dividing by the inverter efficiency of 96%, we calculate the DC load. To find the bus voltage, assuming a 480 VDC system voltage, the DC load is divided by 480 V to get the load in A-hours per day at the bus voltage. From there, the load is multiplied by the required days of usable storage and finally divided by the battery depth of discharge to find the nominal battery capacity. It should be noted here that the driving factor in the nominal battery capacity is the required days of usable storage.

Moving on to the calculation of the number of PV panels required, we find that the design steps are slightly more complicated. The first step is to find the current delivered to the inverter measured in ampere - hours per string of panels. From there, the DC input to the inverter is calculated as shown above. Now the number of modules required to make the 480 VDC system voltage is found by dividing the system voltage by the nominal MPP voltage rating of the panel; in this case the 28.9 V panels are nominally 24 V, so 20 modules in series are required to make 480 VDC. Solar panels add in the same fashion as batteries, and that fact makes the calculations more familiar. From Table 3, in order to meet the required AC load at 99% availability for the sample location and usable storage needs, a nominal battery capacity of 2242 ampere-hours per day is needed. Following the design again, we see that 200 individual Sharp 216 W panels are needed to meet the load requirements.

IV. APPLYING THE DESIGN

A. NSAM MONTEREY CALCULATIONS

Naval Support Activity Monterey is located on the Central California Coast. Monterey's weather is influenced by its proximity to the ocean and the bay as seen in Figure 8 and the cool temperatures, especially on the coast. The average high temperature for the year ranges from the low 50s to the mid-60s and the lows in the winter range from the mid-30s to the low 50s [17]. From the insolation tables, the peak-sun hours range from just 3.01 hours in the worst month of December to more than double that figure in the best month of June at 6.32 hours. In the design month of December at 99% availability, this equates to a requirement of 12.5 days of usable storage. When compared to requiring just six days of required usable storage for the month of June, it is apparent that there exists a wide PSH variability in Monterey. The design rules are very specific in that the design month needs to be the worst month, so the calculations are based on the 12.5 days of usable storage.

Figure 8. Central Coast of California. Source: [16].

NSAM currently has 868 installed photovoltaic panels installed on the rooftops of three academic buildings. Building 245 is Watkins Hall and has 350 Modules installed followed by building 234, Halligan Hall, which has 364 modules. The Dudley Knox Library, building 339, has the smallest number of panels at 154. The installed PV panels on the roofs of Watkins and Halligan Hall are shown in Figure 9.

Figure 9. Watkins and Halligan Halls

The installed panels on all three facilities are non-tracking modules. This means that they are fixed and do not track or follow the sun throughout the day. As mentioned previously, all the installed panels on NSAM are the Sharp 216 Watt polycrystalline silicon multipurpose modules. They have a maximum power point voltage of 28.9 V, a MPP current of 7.48 A, and are rated as being 13.3% efficient. The panels on all the buildings are installed at an azimuth of 230 degrees at a tilt of 15 degrees. For the following designs, except where noted, we use these same panel specifications, including installation characteristics, for the basis of comparison. The installed PV panels have a monitoring website, and real-time data is available [18]. As of now, the installed system on NSAM is not being stored in any fashion. The only benefit to having the panels is a reduction in peak electricity costs.

With the power created using the currently installed panels, there are possible loads that can be supported with the addition of a Battery Energy Storage System (BESS). The system is rated to provide 187.4 kW; this can provide power to a small bank of servers, providing a very small amount of energy security. For instance, the panels installed on NSAM in the last month generated an average of 595.7 kWh of power per day, and the last year's average was 598.9 kWh per day [18]. To put this amount of energy into perspective, it is beneficial to look at a specific load on NSAM.

B. CRITICAL LOAD

A critical load for the purposes of this research is one that is vital to the operation of a base. In a previous chapter on energy security, the discussion focused on the differences between training bases and operational bases. In much the same fashion, there are loads on a base or facility that require power even during times of an outage, and these are considered critical. Typically, infrastructure that is life supporting is always considered critical, and that a main reason why hospitals always have redundant power supplies and generators to keep life-support devices operating. NSAM does not have critical infrastructure such as that; however, the lodging facilities on base do have backup generator power in the form of diesel generators.

The 4th floor of Spanagel Hall was selected to be the critical load on NSAM for the purposes of the following calculations and discussion. Because this base is a training base, there is not a critical operational load that necessitates a building or function that is critical to the mission of training junior officers. If the commercial grid were to go down for any reason, classes would cease until the grid came back on line, and the mission would continue. There may be some small loads associated with the information technology aspect of the base, and those are more than likely provided with small uninterruptable power systems to allow for a graceful shutdown so as to mitigate any loss of data.

On an operational base, there are critical loads that must be powered indefinitely even in the event of a loss of the commercial grid. In this case Spanagel Hall is considered the building-of-interest on NSAM. It is modeled as a fleet headquarters facility with critical loads. Instead of being a building full of classrooms, laboratories, and offices, it is now modeled as an operational headquarters. The classrooms are considered briefing rooms, the laboratories are considered watch floors full of computers and communication equipment, and the offices remain offices.

Spanagel is a large building, on the order of 220,000 square feet over its five floors, excluding the basement and rooftop spaces. The actual building electrical usage data was obtained from the NSAM Energy Manager, and that is why it is used in this research [19]. The average daily usage by month for the last several years is shown in Figure 10. It is plain to see that Spanagel uses a large amount of electricity on a daily basis. Aside from the two months in 2016, February and March, most of the usage is fairly consistent throughout the year from an examination of the data. A deeper look shows that the largest load month is June, with an average usage of 5.15 MWh of energy used daily. The December average used for calculations is 4.75 MWh per day. In the previous section, it was shown that the average generation was just under 600 kWh per day, a difference of over 4 MWh [19]. An important question to ask is why does Spanagel use so much power?

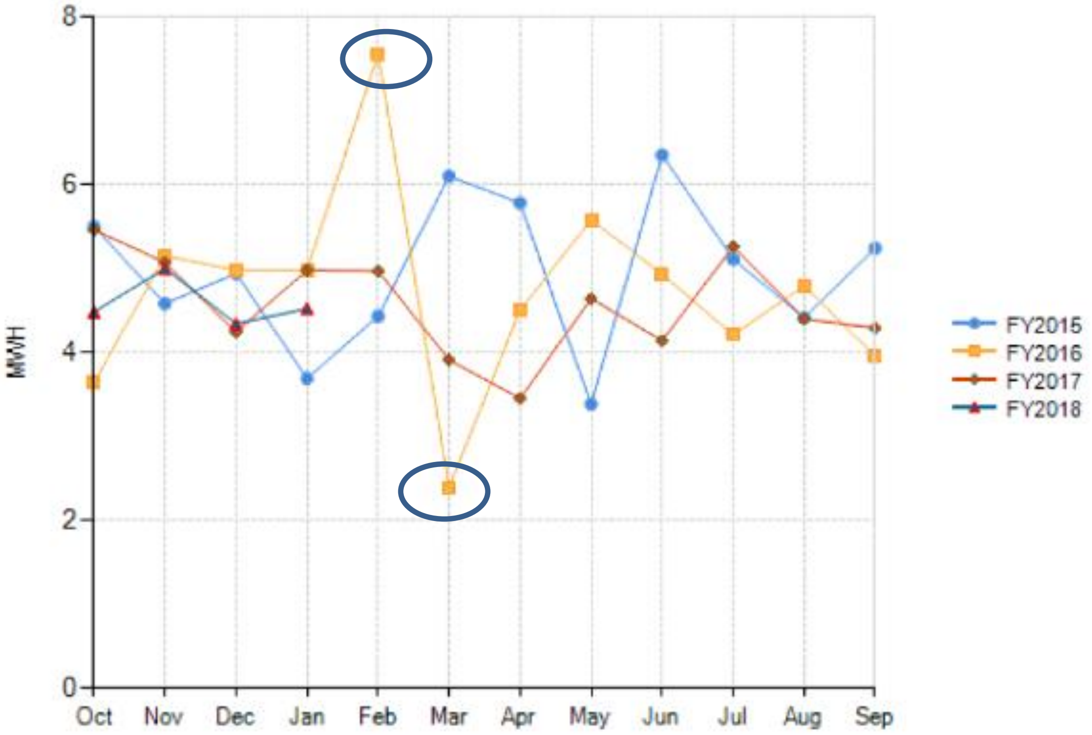


Figure 10. Spanagel Load Profile. Source: [19].

The critical load for the purposes of this research is the 4th floor of Spanagel. This was chosen because it is the Electrical and Computer Engineering (ECE) department floor and access for an independent estimate of the load was available. The load for this floor is 935 kWh per day. Energy usage in commercial buildings is divided into several categories. It is not difficult to understand what many of the factors in calculating the load are since they are similar to household loads but on a much larger scale. The U.S. Energy Information Administration (EIA) conducts research on various topics related to energy. In Figure 11, we see the largest energy draws for commercial buildings, and Spanagel is considered to be a commercial building.

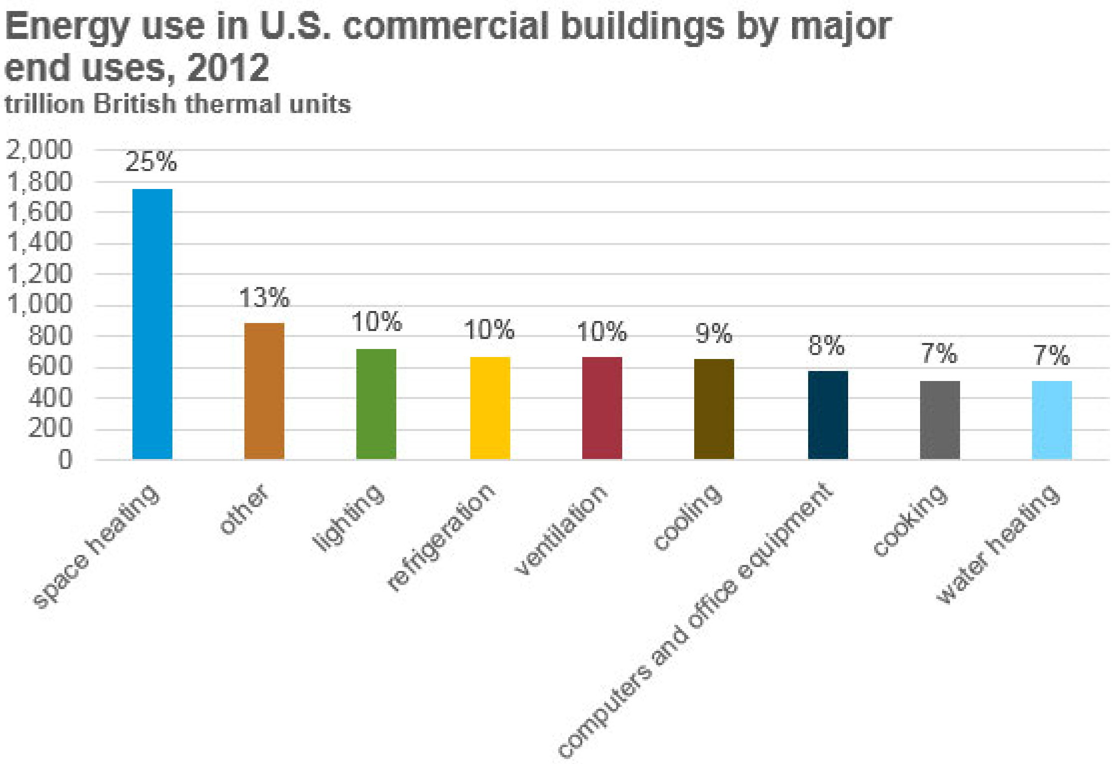


Figure 11. Energy Use in Commercial Building. Source: [20].

An estimate of the load on the fourth floor of Spanagel was conducted by counting the number of electrical devices plugged in and drawing current. The main devices counted were computers with monitors and overhead lights. An estimate as to how many hours per day these devices were plugged in was made, and the nameplate data was used to calculate the load. The rough estimate of the load based solely on consumer electronics and overhead lighting was 618.3 kWh. When taking into account that the heating and ventilation numbers are not known, the estimate is reasonable. Adding a factor of 25% to account for space heating brings the estimate up to 772 kWh. The main load on the fourth floor of Spanagel is the lights and computer monitors. The lights use a lot of power because they are in use for many hours of the day, and the computer monitors in the laboratories, even though not used all day, consume a large amount of power even in standby mode.

C. RESULTS OF MONTEREY CALCULATIONS

After the discussion on how to design and size a solar array for energy security use, the logical next step is to apply that power to a DoD facility, Naval Support Activity Monterey. First, the installed PV panels on NSAM are discussed. Using December's historical peak-sun hours of 3.01 hours per day and the associated and required usable storage days of 12.5, we see that the installed PV panels on NSAM are capable of supporting a load of 340 kWh per day with a nominal battery capacity of 10.25 kAh as shown in Figure 12.

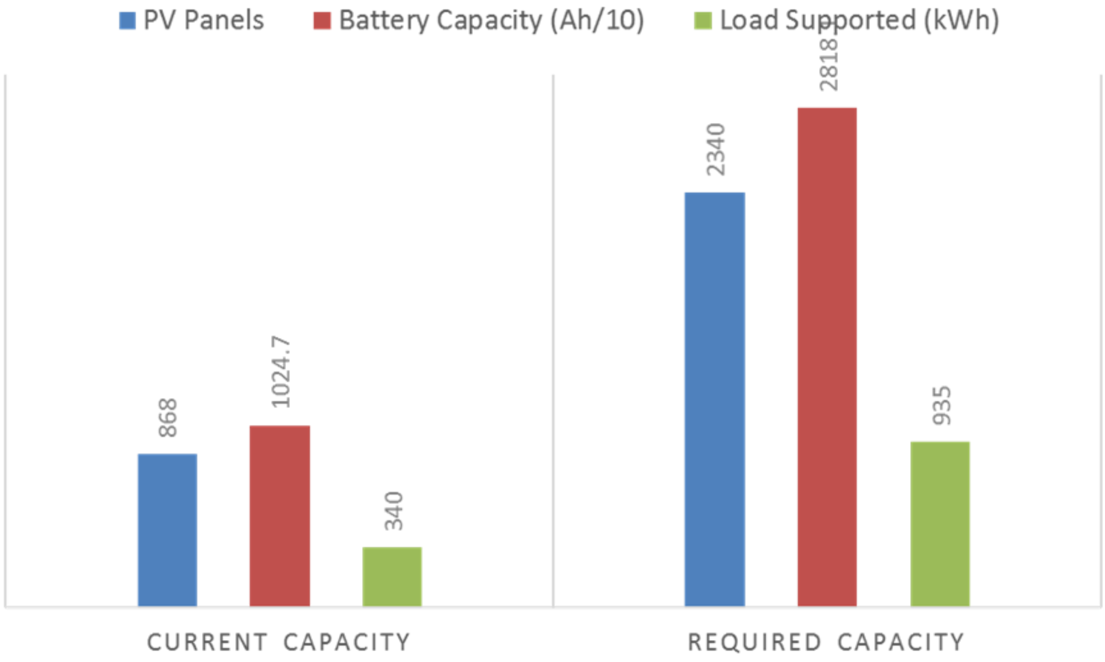


Figure 12. Currently Installed PV on NSAM

From the historical data provided, the load for the 4th floor of Spanagel, the critical load, requires 935 kWh per day, so there is a deficit of 495 kWh. The currently installed PV system falls well short of the goal to provide energy security to just one floor of one building on NSAM. Furthermore, the currently installed system lacks a method to store this energy such as an installed Battery Energy Storage System. In order to support the load of the 4th floor of Spanagel, 2340 panels need to be available, an increase of 1472 panels. To provide energy security, a nominal battery capacity of 28.181 kAh is required.

D. SAN DIEGO WEATHER

To understand the effects climate and available sun has on a given solar energy security system, the design was moved from Monterey to Southern California in the vicinity of San Diego and, specifically, MCAS Miramar (MCAS). The MCAS location was chosen as an alternate site to the more central San Diego Naval bases because MCAS is located inland and has a sunnier climate than coastal San Diego. MCAS Miramar is located on the Southern California Coast. The climate influence caused by the coast is not nearly as severe as in Monterey. The location of MCAS near the city of Poway, CA is free from such impact. The average high temperature in the summer is in the mid-80s, and the lows in the winter are in the high 40s [21].

Not only is the climate warmer in southern California, the sun shines more as well. The warmer temperatures have their own problems as will be shown shortly. Peak-sun hours range from 4.47 hours per day in December to 7.22 hours per day in June. For the critical load to be supported 99% of the year, 8.9 days of usable storage are required [2]. This is using the December figures in order to ensure the load is supported throughout the year. When compared to 5.5 days of usable storage using June's peak-sun hours, the Monterey numbers pale in comparison as far as peak-sun hours are concerned. The MCAS weather requires 70% of the usable storage required in Monterey.

Without accounting for an increase in the load, the following results are shown in Figure 13. Due to the peak-sun hours of 4.47 hours and the required 8.9 days of nominal battery capacity storage, the PV system produces more power and requires much less storage; however, the shift alone to the more favorable climate is not enough to make up the deficiency. The 868 solar modules are still not enough to power the critical load, and 712 additional PV panels are required in the more favorable solar climate to make up the deficiency of 420 kWh. In order to meet the storage demand to support the critical load, and additional 9.12 kAh of nominal battery capacity is needed.

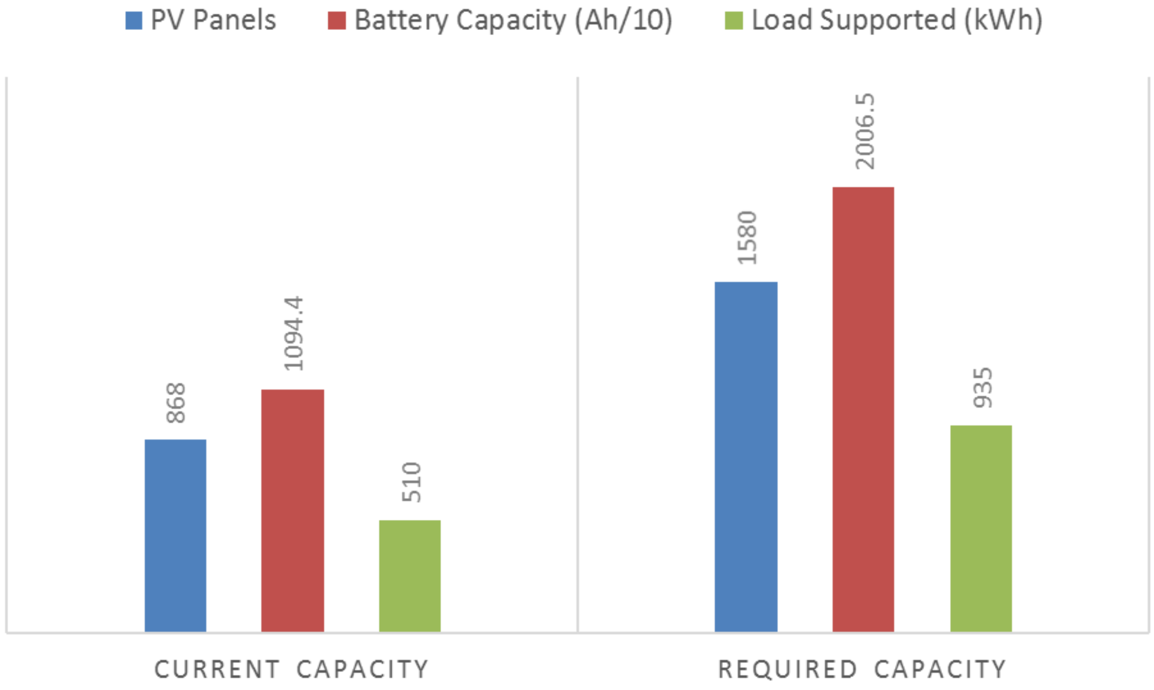


Figure 13. Critical Load MCAS without HVAC

E. NEED FOR HVAC IN SAN DIEGO

In order to properly capture the load in a geographic shift to San Diego, an increase in the load to account for additional heating, ventilation, air conditioning (HVAC) must be considered. The warmer climate requires an additional infrastructure load that is air conditioning. The increase in sunlight does not come without additional expense for creature comforts and safety of the population. As illustrated in Figure 11, the EIA estimates that cooling accounts for 9% of energy use in commercial buildings, so an increase in the load by 10% is reasonable [20]. In order to account for this, the load increased by 10% from 935 kWh to 1.03 MWh as illustrated in Figure 14. Also, an additional 160 PV panels are required due to the increase in load and a supported load deficit of 518 kWh. It is important not to make light of just 160 panels. These particular panels are 40 inches wide, 65 inches long, and weigh 44.1 pounds each without the mounting racks and hardware. Adding the extra panels adds at least 7,000 pounds of weight, and the additional battery capacity will weigh even more.

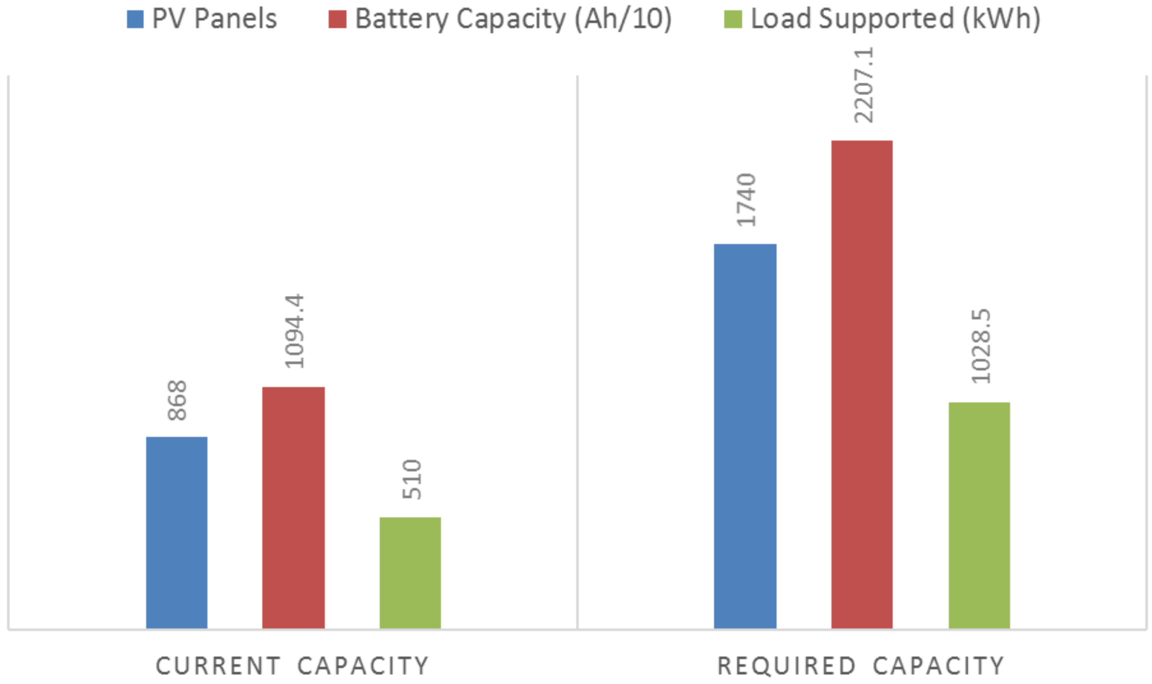


Figure 14. MCAS with HVAC

F. NSAM VS. MIRAMAR EXISTING

In order to gain a better understanding of how the change in location and more favorable solar climate affects the results and size of the PV system despite the increased load, it makes sense to look at the results side by side. The first scenario to compare and contrast is the existing situation with the currently installed 868 panels. The result of the comparison of NSAM vs. MCAS is illustrated in Figure 15 and shows that the required nominal battery capacity between the two locations is within 6.5%. The relatively small difference in battery capacity is due to the fact that one of the largest factors in the calculation of battery capacity is the days of usable storage. In the case of the December months in the two locations, the usable storage requirement is 12.5 days on NSAM and 8.9 days on MCAS; however, a bigger difference is the supportable load. NSAM’s solar panels can support 33% less load than in MCAS. The larger difference in peak-sun hours is the driving force behind this disparity. What this illustrates is that while the peak-sun hours play a large role in the power output of the solar panels, the nominal battery capacity is driven to a great extent by the usable storage requirement independent of the peak-sun availability.

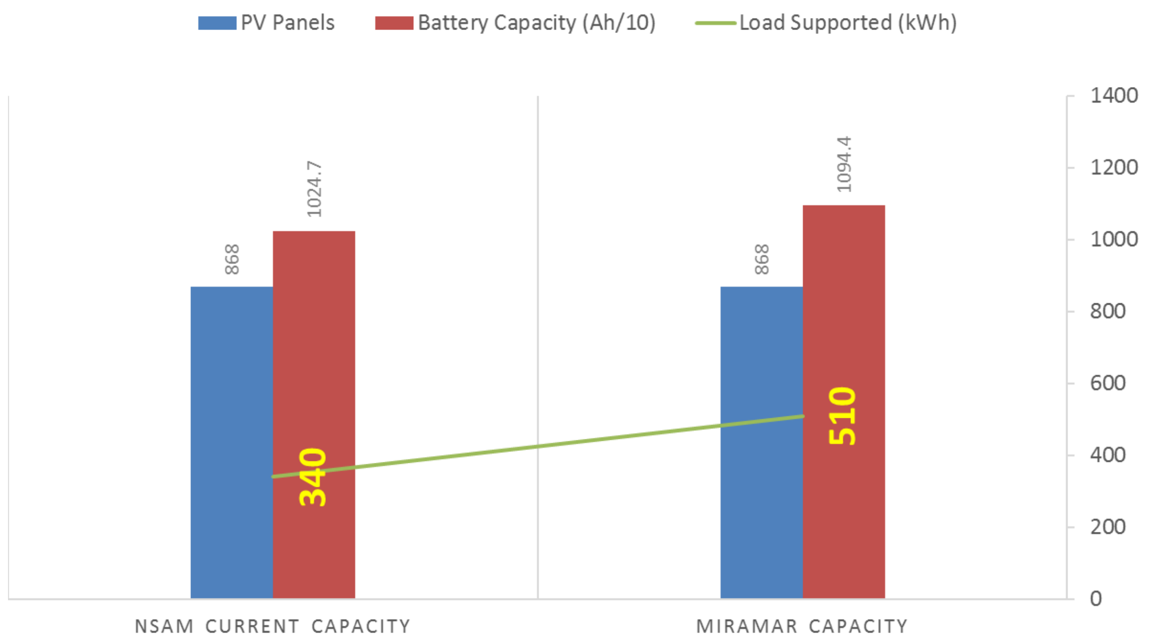


Figure 15. NSAM vs. MCAS Currently Installed Capacity

Another comparison worth looking at is the difference between the two locations when the number of solar panels required to meet the critical load values are seen side by side with HVAC included for MCAS. Consider the difference the peak-sun hours and required storage values accomplish on a larger scale: the full demand of the critical load. Here the increase of the load is the green trend line in Figure 16. The 10% increase in the load is only just observable unless inspected closely; however, the disparity in both of the PV and battery columns is easily recognized. To serve the load in Monterey, an additional 600 panels are needed. Again, to add a metric to this value, that is nearly 27,000 pounds of panels and 978 square meters of dedicated property without taking into account installation or spacing of the panels.

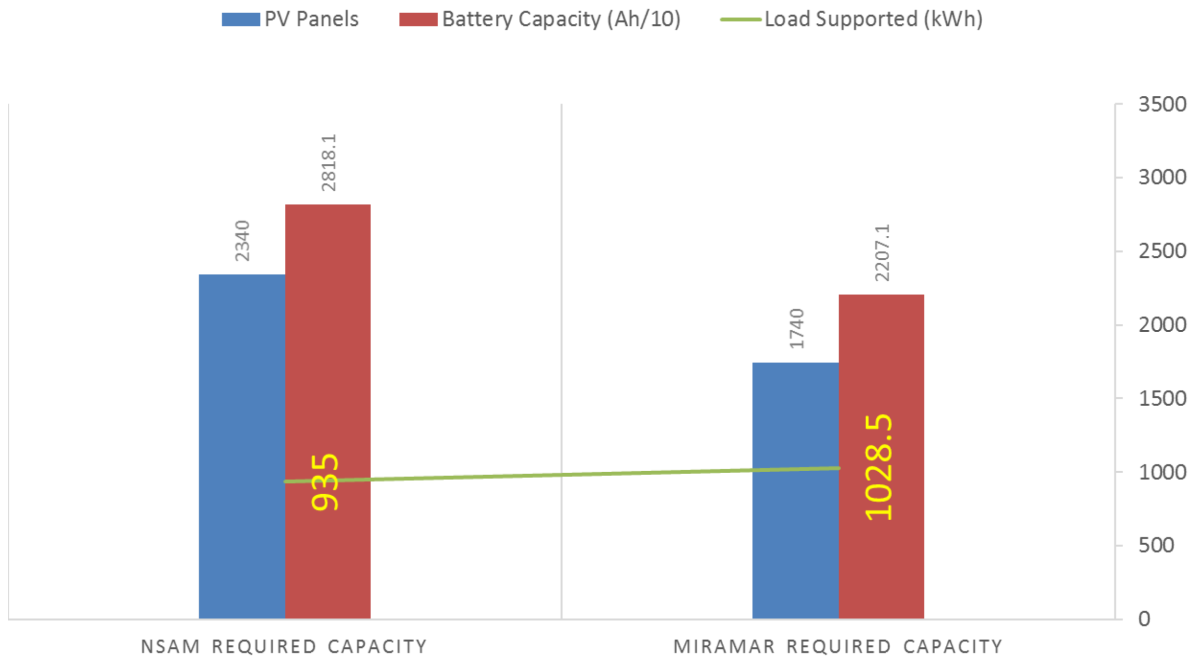


Figure 16. Required Panels to Meet Capacity

V. NEW CONSTRUCTION

A. PROPOSED INSTALLATION

The final facet of this research is to use the design tool created to develop a plan to maximize the use of solar panels on NSAM. The ultimate goal is to see how much energy can theoretically be produced on the campus by installing PV panels on all realistic open spaces. This is not a wholesale project to cover every building but a realistic approach to design that can be used by decision makers if such a project were ever considered. All available rooftops on non-historic buildings were considered as candidates for a potential PV installation. Availability in this sense takes into account flat rooftop surfaces similar in structure to the currently installed PV arrays on Watkins, Halligan, and the Dudley Knox Library. Sloped roof buildings were not considered, and no demolition of structures to make room for panels was considered. In addition, open parking lots in the student spaces were considered for the installation of PV carports where feasible.

The NREL PVWatts website has a tool that can aid in the estimate of terrestrial object sizes for the installation of solar panels. This was used to augment the design tool in order to get a rough order-of-magnitude size along with Google Maps. An overhead of the NSAM is shown in Figure 17. Circled in red are the proposed locations for the installation of PV panels. A detailed breakdown of the additional installations follows the map of the proposed installation sites. Although more efficient panels are available on the commercial market today, for the sake of consistency, the Sharp 216 W panels used in the previous analysis are used in the design of the proposed system.

Figure 17. Proposed Installation Sites

Table 4. Proposed Installation Details

Building	Size (m^2)	Power Supplied (kWh)	# of Panels
Root Hall	3144	471600	1180
Bullard Hall	789	118300	300
Ingersoll Hall	2059	308800	780
Glasgow Hall	931	139600	360
King Hall	765	114800	300
Watkins Hall	389	58300	160
PV1	858	128700	340
PV2	389	58400	160
PV3	617	92600	240
PV4	346	51900	140
PV5	577	86500	220
PV6	381	57200	160
PV7	519	77900	200
PV8	514	77200	200
PV9	853	128000	320
PV10	762	114300	300
PV11	381	57200	160
Totals	**14274**	**2141300**	**5520**

In Table 4, we see a detailed breakdown of the proposed installation of PV panels on NSAM, with the calculated power each building can theoretically deliver using the same model of panel currently installed. The largest available single site for new panels is Root Hall. The building's long narrow shape and favorable orientation make it a prime candidate for a PV installation. The PV1 through PV11 buildings are proposed carport installations in the available staff and student lots on campus. The carport installations alone account for 6,200 square meters, or room for 2,440 additional PV panels. The total new installation area is calculated at 14,274 square meters, or imagine a land area of 120 m by 120 m. An additional 5,540 PV modules can be added to the campus with an estimated power delivery of 2,141,300 Wh per day. Since Spanagel Hall consumes an average of 4.75 MWh per day, the proposed installation does not deliver enough to power even half of the building. The proposed installation compared to the current installation is shown in the last chart, Figure 18. Keep in mind that the data displayed on the right hand side of the chart is the number of the current panels and the proposed panels combined.

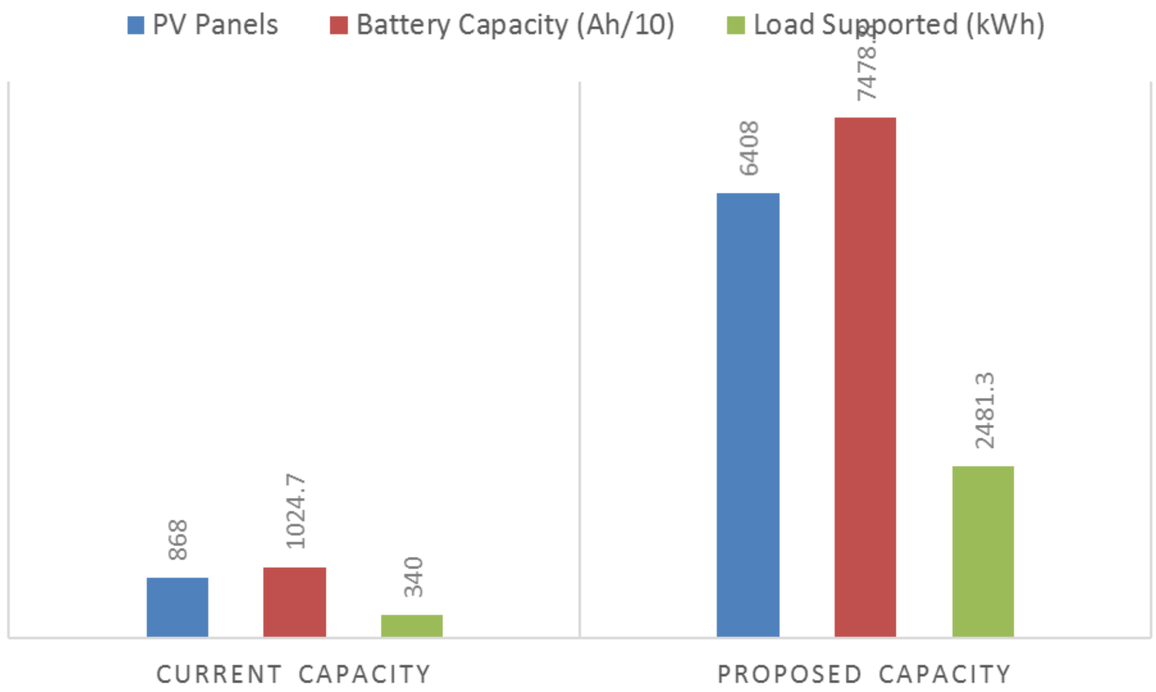


Figure 18. Current vs. Proposed Installation

Finally, technology has increased in the eight years since the current NSAM panels were installed, and commercial and residential solar panels have increased in efficiency. While the Sharp 216 W panel is still on the market, newer panels are rated with a nominal power of greater than 300 W. The efficiency ratings have increased to greater than 20%. On a newer panels, the maximum power point voltage for a 320 W panel can be as large as 55 V. This is much higher than the MPP of the installed panels, which is 28.9 V. The higher numbers were plugged into the design tool to see what the difference would be given the same design constants. To meet the same supported load of 2,481 kWh, only 3,950 panels are required. The nominal battery capacity remains unchanged. Furthermore, if the new infrastructure proposal were to use the modern panels, the supported load is calculated as nearly 3,500 kWh for the same number of panels. This is a large increase in the capacity of the proposed infrastructure improvements; however, the delta of the output when compared to the anticipated load remains untenable.

VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

Navy leaders, at multiple levels, have made it clear that progressing towards energy security on naval installations is of great importance [6]. The differences between being energy secure versus what is energy sustainable, or net-zero, is quite different. When the commercial grid is impacted due to unforeseen acts of nature or perhaps due to a malicious attack on energy transportation infrastructure, the difference becomes clear. Energy security is the ability to function at a level of operations appropriate to the tasked mission for an indefinite period of time [7]. Airplanes must keep flying and communications must continue uninterrupted to support the warfighter and the mission. Anything less is not energy security.

The currently installed PV system on NSAM does not provide for islanding of any critical infrastructure due mainly to lack of storage and, therefore, does not increase the energy security of the facility. If a BESS were installed and coupled with the existing PV panels and inverters on the facility, a small-scale level of energy security can be achieved through islanding a small load related to critical infrastructure. Peak shaving can also be used during times of high demand and increased commercial grid energy costs as demonstrated by Gustafson [1].

Coastal Monterey’s climate does not provide adequate peak-sun hours in either the winter or summer months to justify large scale solar installations for energy security purposes. It was shown that by taking advantage of all available NSAM areas suitable for PV installation, the critical load that can be sustained electrically is small compared to the rest of the base. The proposed microgrid can provide energy security for some critical loads on NSAM but at a large cost. Peak shaving, using the previously designed EMS, could offset the cost of the installation. Energy security is the professed goal of key leaders in the organization and is realizable to some extent using PV arrays and BESS enclosures; however, it is clear that NSAM is not a viable candidate for such a system.

B. FUTURE WORK

Future work along the lines of infrastructure development and cost analysis would be beneficial to the Navy and to the academic community. A relationship was started with the base PWO and the Energy Manager, and those lines of communication can pay dividends through the sharing of energy usage data and research funding between the two entities. The base can serve as a testbed for future research in energy security and storage through collaboration between motivated students, engaged faculty, and an amenable facilities officer.

Specific projects related to this research could include the development of a thorough cost analysis of a new PV installation. This work could be completed, possibly in conjunction with a professional in the business school to leverage the knowledge base of a different NPS department. The goal would be to determine the true financial cost of energy security and complete a cost benefit analysis. Exploring other methods of renewable power generation that can be more efficient in this region or for another base in a more favorable location is another topic. Finally, other forms of storage besides lead-acid batteries can be examined. This research focused on the generation of the electricity and the storage was given in terms of required capacity instead of number and type of batteries. Lithium-ion batteries are becoming cheaper and have a higher energy density than lead-acid ones, and that could be a focus of continuing research.

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