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THESIS

MODELING AND OPTIMIZING GREEN MICROGRIDS AT REMOTE U.S. NAVY ISLANDS

by

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December 2017

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MODELING AND OPTIMIZING GREEN MICROGRIDS AT REMOTE U.S. NAVY ISLANDS

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ABSTRACT

This thesis builds upon existing research involving energy microgrid solutions and applies the findings to isolated U.S. Navy locations, specifically, San Nicolas Island. This includes accurately building power system models for U.S. Navy remote and disparate island facilities total power-system microgrids and providing vital information for decision makers. Multifactor optimization and analysis conducted in this thesis led to enhancement of the proposed models and can aid in development of efficient control solutions. These solutions would allow the U.S. Navy to efficiently manage power systems at facilities worldwide. Ultimately, these optimizations can lead to net-zero energy solutions. The experimental and analytical methods presented in this thesis detail the technical simulations from the EnergyPLAN software model. By implementing these plans, the models and approaches developed in this thesis can be applied to other locations, as well.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAES	compressed air energy storage
DNI	direct normal irradiance
DON	Department of the Navy
DOD	Department of Defense
ESTEP	Energy Systems Technology Evaluation Program
FIDE	Finding and Inputting Data into EnergyPLAN
FIDE-USN	Finding and Inputting Data into EnergyPLAN – U.S. Navy
HOMER	Hybrid Optimization Model for Multiple Energy Resources
INCOSE	International Council on Systems Engineering
NPS	Naval Postgraduate School
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NREL	National Renewable Energy Laboratory
ONR	Office of Naval Research
PESWG	Power and Energy Working Group
PSM	Physical Solar Model
PV	photovoltaics
RE	renewable energy
RSWG	Resilient Systems Working Group
SE	systems engineering
SNI	San Nicolas Island
SoS	system of systems

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EXECUTIVE SUMMARY

U.S. Navy personnel operate globally, employ ships across all oceans, and conduct mission vital to national security on a daily basis. A major piece of successfully doing so is relying on efficient and effective facilities that are capable of supporting the warfighter at all times. Many of these locations are disparate and remote, often "islanded" from other power grids, if not actual islands in the middle of vast oceans. To continually operate these facilities, requires massive amounts of natural resources for reliable energy production. Taking advantage of microgrid technology may greatly enhance the U.S. Navy's energy security, energy resilience, and overall mission accomplishment.

This thesis produced the following:

- A fully modeled analysis of energy capacity, demand, balancing, and cost at San Nicolas Island (SNI).
- A step-by-step guide in the form of the FIDE-USN to replicate the analysis at other locations.
- Various technical simulations and analysis of the SNI total energy balance, including a net-zero solution using solar and a storage battery.
- Systems-level thinking in terms of the strategic (mission assurance), technical (efficiencies of microgrid), and financial considerations.

There are multiple tools that are used in this thesis to analyze microgrid technology and the applicability to SNI. These include EnergyPLAN energy grid management software, MATLAB, Microsoft Excel, multifactor optimizations, and analytical systems level thinking and proposals. By comparing the EnergyPLAN results at the Samsø Island in Denmark, Isle of Eigg in Scotland and also considering the success of renewable energy at El Hierro in the Canary Islands, it may be possible to enable decision makers to create the first 100% renewable energy (RE) military facility at SNI. According to Anderson and Yakimenko (2017, 2), both Samsø and El Hierro are 100% RE, supporting 3,700 and 11,000 people, respectively. Also, there are many similarities between the Isle of Eigg and

SNI, to that point that what has been accomplished on the Isle of Eigg has a great opportunity to be replicated at SNI. Land mass, max elevation, average temperatures, average wind speed, and average rainfall are all very comparable.

This thesis adds to two previous National Renewable Energy Laboratory studies (1996 and 2008) and a recent NAVFAC EXWC study in 2017 regarding energy management on SNI. The energy opportunity at SNI is both unique and significant. It was shown that the location, operations, and energy requirements of SNI provide a great opportunity for the DOD to achieve a tremendous benefit as a first of its kind net-zero facility at SNI. Figure 1 shows the net-zero model for SNI. Annual load is red, annual generation for the diesel is black and for the wind turbines is blue, and the total energy balance is green.

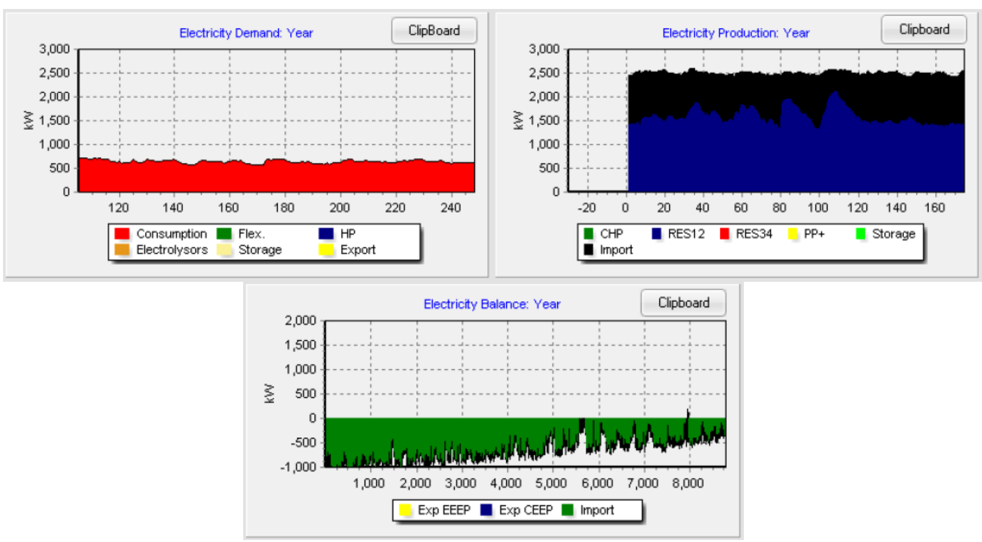

Figure 1. SNI Net-Zero Model Results.

Reference

Anderson, William W., and Oleg A. Yakimenko. “Comparative Analysis of Two Microgrid Solutions for Island Green Energy Supply Sustainability.” IEEE International Conference on Renewable Energy Research and Applications. San Diego, CA, 2017.

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To my wife, Devon, and our 19-month-old daughter, Alexandria May, thank you for your unwavering love and support during this time, which has allowed me to devote an all-out effort to this thesis.

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I. INTRODUCTION

A. BACKGROUND AND PROBLEM STATEMENT

Microgrids are small-scale power systems located closer to the load than typically found in conventional power plants. A traditional microgrid typically includes three core components: hybrid generation, energy storage, and controls. All of these components work together as a system solution to serve a nearby load, such as a wind turbine and a storage battery. The key difference with green microgrids is that they leverage an alternative energy source in the power generation phase. These sources can include wind (on shore or off shore), solar, hydrodynamic, pumped hydrodynamic, river, wave, compressed air energy storage (CAES), and a number of other emerging technologies.

The processes required of the U.S. Navy to procure, move, store, and utilize various forms of energy are fraught with security vulnerabilities and massive costs. Simply put, the U.S. Navy spends much human and monetary capital on supplying its ever-growing energy demands and physical footprints around the world. This essential national security resource is in need of optimization and simplification in the way that it is used by our military, especially in isolated and disparate island facilities. As a specific example, energy usage on San Nicolas Island (SNI) will be modeled and analyzed for optimization in this thesis.

The ability to secure the energy supply and decrease vulnerabilities is of high interest and crucial in the ever-changing world. Threats from ill-intentioned actors are continually increasing and costs due to manpower and transportation play a hefty role in the bottom line. Traditionally, our government has to coordinate complex shipments of oil and gas to the far reaches of the world where our military has a presence. These island locales are responsible not only for their own needs for energy on island, but for the resupply and support of our nation's Navy when present.

The International Council on Systems Engineering (INCOSE) believes that power, energy, and resilient systems are of such high importance that they currently have two working groups that focus their efforts on improving the body of knowledge in these globally key, vital areas. These working groups are the Power and Energy Working Group

(PESWG) and the Resilient Systems Working Group (RSWG). The INCOSE working groups' efforts are directly applicable to the proposals in this thesis regarding remote island locations under control of the U.S. Navy. These critical locations can definitely benefit from improvements and optimizations in the area of resilient power and energy systems.

According to INCOSE (2017), the PESWG seeks to organize experts from within the ranks of INCOSE as well as other professionals in the energy sector of the economy to facilitate a "systems approach" to the analysis and future development of effective energy solutions. The purpose of the PESWG is to direct expertise and a "systems" focus to support decision makers in the critical challenges of developing future energy systems. This is directly applicable to the fields of energy and microgrids in terms of their application to the U.S. Navy.

The use of microgrids with varying combinations of traditional and renewable energy sources on the grids can deliver these results for the U.S. Navy. Microgrids are small-scaled power systems located closer to the load (item using the power) than is typically found in conventional power plants. A microgrid normally includes three core components: hybrid generation, energy storage, and controls. All of these components work together as a system solution to serve a nearby load. Green microgrids leverage an alternative energy source in the power generation.

For the U.S. Navy, achieving an outlook similar to this for energy systems can lead to several overall enhancements:

- all aspects of energy security, especially at remote and disparate island facilities
- energy system resiliency against threats
- cost savings from energy logistics
- cost savings from decreased manpower requirements
- scalability as needed for other remote and isolated U.S. Navy installations worldwide

In his thesis regarding system of systems (SoS) life cycle security architecture and design, Harley (2016) stated that with the increasing complexity of systems and the attacker’s improving ability to conduct multiple unpredictable, non-linear, multi-domain attacks, the ability of any system to survive and accomplish its designed objectives greatly depends upon its security quality. Transitioning the U.S. Navy’s most remote and vulnerable key locations to a more energy-secure posture can greatly enhance total fleet readiness and reliability.

This thesis contributes to the existing research of optimizing renewable energy microgrids to enhance energy security for remote island naval installations. The U.S. Navy is a traditional energy consumer, on a massive scale. The requirement to operate worldwide, all days of year, and all hours of the day places enormous demands on the amount and types of energy required to sustain the force. Efficiency in costs is not at the forefront of concerns as much as availability and capability.

Disparate locations often require extenuating circumstances and heavy demands to be able to continually man and operate those forces necessary to support the U.S. Navy in a continually sustained manner around the world. Vulnerabilities exist all along the supply chain, the transportation process, the manpower footprint, and the overall total energy system. These facilities and critical operations centers are increasingly vulnerable to power disruptions such as power outages. Thus, a dependable and self-sufficient energy solution is of the utmost importance. Currently, critical facilities heavily rely upon diesel generators. Challenges to this stated problem include ad-hoc micro grid integration, grid stability management, developing modular approach, and battery technology selections.

This thesis suggests the U.S. Navy can benefit from transitioning to advanced energy system microgrid technology while maximizing use of renewable resources as an energy supply. This is especially applicable and vital at the most isolated locations where the mentioned risks to the system are inherently higher than in a more protected location on the mainland in the continental United States.

B. PROPOSED SOLUTIONS

The Department of the Navy (DON) needs to increase energy security to ensure mission assurance of critical infrastructure primarily through microgrids at remote islanded sites. This thesis intends to provide four contributions to the fields of systems engineering and energy. The PESWG and RSWG may also benefit from the findings presented here. Specifically, the following will be provided:

- a fully modeled analysis, as a SoS, of installed energy capacity, demand, balancing, and cost at SNI that can be replicated for other similar U.S. Navy locations
- technical simulations and analysis of the SNI total energy balance
- technical multifactor optimizations of the generation and storage models
- microgrid architecture design analysis and proposals to enhance future microgrid energy security and resiliency at U.S. Navy isolated island locations
- systems-level thinking in terms of the strategic (mission assurance), technical (efficiencies of microgrid), and financial considerations. This is one step beyond the optimizations and considers the holistic factors that should be integrated into the systems engineering (SE) design approach

More importantly, the models, analyses, and optimizations presented herein can be replicated at other U.S. Navy island locales. Appendix A details the step-by-step process used here that can easily be applied at other installations. This thesis utilizes raw data collected from installed equipment at SNI and analytical simulations run by EnergyPLAN energy software.

Renewable energy can be a major advantage in terms of energy security, resiliency to vulnerabilities, costs, and manpower requirements. There is much opportunity for the U.S. Navy to apply microgrid architecture to all existing applicable technology at each of its isolated locations to improve overall combat effectiveness by enhancing energy security and resiliency. Microgrids are small-scale power systems located closer to the load than those typically found in conventional power plants. Some small-scale power systems, specifically green microgrids, leverage an alternative energy source in the power generation process.

The recommendations presented here suggest viewing an island microgrid energy system as an SoS that can all be monitored, controlled, operated through an internet of things approach. The Department of the Navy needs to increase energy security to ensure mission assurance of critical infrastructure primarily through microgrids at remote islanded sites.

C. RESEARCH QUESTIONS

This thesis aims to investigate four key questions:

- Is it possible to accurately model and apply power system microgrid technology at U.S. Navy remote and disparate island facilities?
- Can the derived model lead to a more efficient total system energy balance for San Nicolas Island and other U.S. Navy islands?
- Can multifactor optimizations enhance the proposed models and lead to enhanced control solutions for the power system microgrids?
- Can U.S. Navy bases become more energy self-sufficient to the point of increasing energy security and resiliency?

D. RESEARCH APPROACH AND THESIS ORGANIZATION

The work presented in this thesis builds upon existing research and ongoing analysis of microgrid solutions for island green energy supply and sustainability. Experimental and analytical SE approaches were used to create an EnergyPLAN model for SNI. Data was collected from the existing SNI energy grid and modeled in the EnergyPLAN software to compare all existing energy aspects and optimize the results. Technical simulations were also conducted and analyzed.

The Academic Associate Energy Academic Group seminars and the Office of Naval Research (ONR) Energy Systems Technology Evaluation Program (ESTEP) presentations were both utilized to the full extent possible to contribute to this thesis. Both events were conducted on campus at the Naval Postgraduate School (NPS) in June and July 2017. Energy and academic research experts and professionals from across the country presented a varying field of topics, many of which are applicable to the subject matter in this thesis. Also, a site survey of SNI was performed in September 2017 with Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) personnel to fully understand and capture the aspects of the existing energy infrastructure at SNI. This greatly enhanced the energy model in EnergyPLAN.

This thesis is organized as follows. Chapter II introduces microgrids and tools for their analysis, such as HOMER and EnergyPLAN. Chapter III describes the details of the complete SNI energy system. Chapter IV contains the data collection process and modeling efforts. Chapter V contains the modeling results, conclusions, and recommendations.

II. MICROGRIDS AND TOOLS FOR THEIR ANALYSIS

This chapter introduces microgrids, their architectures and components, and provides a brief review of software packages most applicable to microgrid analysis and optimization.

A. MICROGRID COMPONENTS

Microgrids are directly applicable to the U.S. Navy's interest to optimize whole system energy plants at isolated locations. Through doing so, the U.S. Navy can become more energy secure, especially at remote and disparate island facilities. Utilizing optimized green microgrids can also lead to energy system resiliency against threats and cost savings from energy logistics and decreased manpower.

A microgrid, as shown in Figure 1, is a small-scaled power systems located closer to the load than typically found in conventional power plants. A microgrid normally includes three core components: hybrid generation, energy storage, and controls.

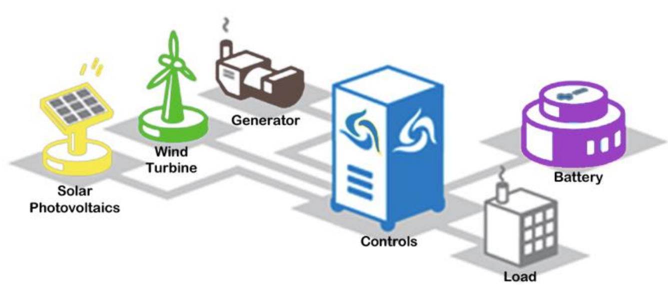

Figure 1. Microgrid Components. Source: Anderson and Yakimenko (2017).

All of these components work together as a system solution to serve a nearby load. Most microgrids are designed and installed to meet a specialized need not ideally served by the utility company. Often this need is dictated by the remoteness and dislocation of the load from a utility company such as a remote island or by loads that are deemed critical infrastructure. For remote island communities, the microgrids have been used to provide greater independence, reliability and sustainability from off-island power services. As a result, these green microgrids have rather creative and complex designs.

Microgrid deployment relies on fast and real time control, adequate capacity and robust communications. Modular, building level controls can alleviate information assurance issues of information technology interconnections. Modular power control can be sized to meet specific needs. With power storage, available renewables can be fully utilized. With correctly sized, dispatchable generation, seamless grid to off-grid operation for power resiliency is possible. Though ideal for mission critical facilities, adoption may be slow. However, for mission essential facilities application of non-dispatchable power sources can be utilized to form a microgrid and limit the dependency on backup generation. These facilities can provide an intelligent, scalable, microgrid power system designed to distribute, manage and control AC and DC power generated and consumed in a grid connected or stand-alone environment.

For U.S. Navy installations, microgrids have been used and considered primarily to serve critical infrastructure typically employed in remote locations to include SNI. Military installations certainly have very specific energy needs that also vary slightly from location to location. The U.S. Department of Energy classifies a microgrid as a complex system, not so much for its characteristics of emergent behavior or nonlinear dynamics, rather simply because of its use of advanced distributed energy resources components. According to Sugiyama (2017), microgrids can include

- small, local and stand-alone power systems integrated with a larger distribution feeder
- energy storage and distributed generation (DG) within a small control area
- variety of DG
- plug-and-play functionality not dependent upon communications
- single interface to power system to have seamless power transition between parallel to grid and islanded

Although there has been a steady push into architecting “smart microgrids” by optimizing the entire system, this approach has not effectively leveraged complex systems tools, such as agent-based modeling. However, for remote islands and U.S. Navy installations the primary benefit is energy security and mission assurance, not economic (Anderson and Yakimenko, 2017). A microgrid should be interconnected to the installation's grid as well as be considered interconnected as a networked system with other systems. This leads to optimization of control systems to factor in the dynamics of weather, utilities commodity pricing, and real-time loads.

Microgrids consist of parts that are numerous, diverse, interdependent, connected, and adaptive. They deal with systems that are not normal in that the probabilities of outcomes are not described by normal distributions. Power law distributions are the norm. Given the variability of renewable energy generation serving small and disparate loads coupled with the system operation of a microgrid, these microgrids can conceivably be considered a complex system by virtue of their interrelated, heterogeneous elements (agents and objects) (Anderson and Yakimenko 2017). Control Systems are used in microgrids to primarily match generation to the load. Control systems for microgrids vary from simple inverter controls to more complex controls systems using programmable logic controllers.

B. HOMER

The NREL hybrid optimization model for multiple energy resources (HOMER) has been the gold standard for energy grid analysis and optimizations. It is used worldwide and has been very successful. However, using EnergyPLAN to model microgrids, especially green microgrids, has distinct advantages over HOMER in the following areas.

- EnergyPLAN is free. There is free account access, free software download, free reference models from around the world, and a free discussion board and forum or share ideas and learn about issues.

- The user interface is designed as a series of tab sheets and stacked side columns. Therefore, jumping between sections and inputting data is very quick and easy. Also, there is online training available from the EnergyPLAN website.

- Renewable energy systems, such as wind energy, tend to fluctuate greatly throughout any measured time period. Connolly (2015, 4) states that EnergyPLAN considers the three primary sectors of an energy system to be electricity, heat, and transport, integration of these fluctuating sectors becomes more of an issue. This is even more pronounced when these renewable sources come to achieve more penetration in the grid. EnergyPLAN allows all of this to occur.

- EnergyPLAN has been used to simulate a 100% renewable energy system for Denmark. (Anderson and Yakimenko 2017, 4)

- HOMER does not account for transients of equipment and can lead to the output showing certain pieces of equipment, such as a diesel generating set (genset), being switched on and off more often than may be realistic. This can lead to errors in the outputs.

- EnergyPLAN, when compared to many other energy-planning tools, includes the ability to add a plethora of renewable energy options to the traditional energy grid. The result is a fully analyzed, both technical and economic, hybrid microgrid for decision makers to choose the best course of action.

- HOMER will always optimize for cost first, not the best technical solution.

- EnergyPLAN, while offering the option to maximize the technical solution, can also simulate the costs of an energy system in four areas as stated by Lund and Connolly:

    - Fuel costs: purchasing, handling, and taxes for each fuel as well as CO_2 costs.

    - Investment costs: capital required, the lifetime of each unit, and the interest rate on repayments.

- Operation costs: the variable and fixed operation and maintenance costs for each production unit.

- Additional costs: any extra costs not already accounted for, such as the cost of insulating houses for increased energy efficiency. (2017, 28)

C. ENERGYPLAN

The computer software EnergyPLAN: Advanced Energy Systems Analysis Computer Model version 12.0 was designed by Henrik Lund (2016) at the Sustainable Energy Planning Research Group at Aalborg University in Denmark. It is intended to simulate energy systems, specifically green microgrids, by taking user inputs and running selected simulations on an energy system. The overall structure consists of demand, supply, balancing and storage, cost, simulation, and output. The user inputs control the demand, supply, balancing and storage, cost, and desired selection of simulation options. Major components of the user inputs include supply data, demand data, renewable energy sources, energy plant capacities, and costs. Outputs include energy balances, annual productions, fuel consumption, and total costs. Using an SE approach and viewing a microgrid as a SoS, it assists the "design of energy planning strategies based on technical and economic analyses of the consequences of different energy system options and investments" (EnergyPLAN 2017). This system has thus far been most directly applicable to European nations but is now, for the sole purpose of this thesis, being analyzed for use at U.S. Navy installations. It is a deterministic, hour-simulation model, aggregated in a systems description through optimizing operations and using analytical programming. The simulations provide an opportunity to include technical simulations and market-economic simulations. For these reasons, it appears to be a good fit for research regarding energy usage at disparate and remote U.S. Navy facilities.

Figure 2 shows a typical energy system block diagram in EnergyPLAN. The overall structure consists of demand, supply, balancing and storage, cost, simulation, and output. The user input controls the demand, supply, balancing and storage, cost, and desired selection of simulation options. Major components of the user inputs include renewable energy sources and energy plant capacities. Outputs include energy balances, annual productions, fuel consumption, and total costs. The advantages to using EnergyPLAN, when compared to many other energy-planning tools, include the ability to add a plethora of renewable energy options to the traditional energy grid. The result is a fully analyzed, both technical and economic, hybrid microgrid for decision makers to choose the best course of action. EnergyPLAN has already been used to simulate a 100% renewable energy system on Samsø Island in Denmark. (Anderson and Yakimenko 2017, 4)

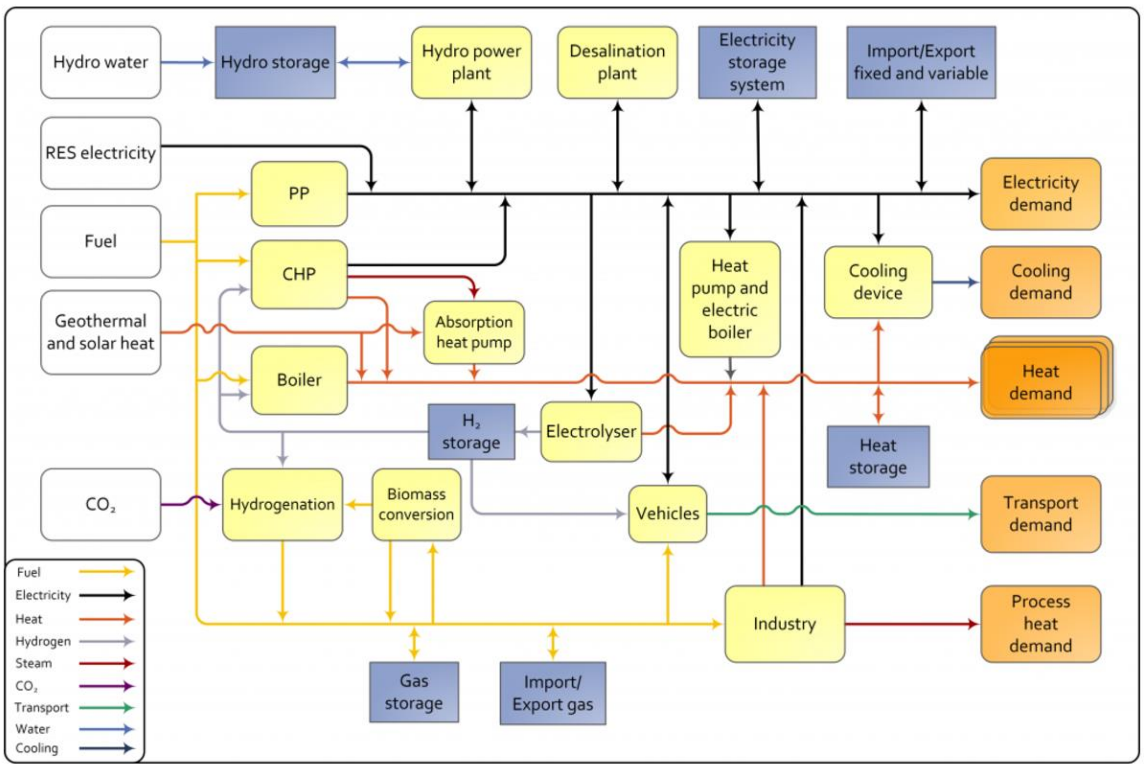

Figure 2. Typical Energy System in EnergyPLAN. Source: EnergyPLAN (2017).

Through the path of his doctoral research, David Connolly (2015) of Aalborg University created *Finding and Inputting Data into EnergyPLAN (the FIDE Guide)*. As the data collection process can be time consuming and difficult, the FIDE paper was relied upon heavily to form the basis for my SNI data collection strategy. One contribution of this thesis is the creation of a Finding and Inputting Data into EnergyPLAN for the U. S. Navy

(FIDE-USN) by using the original FIDE as a guide along with my research. This can be found in Appendix A. While EnergyPLAN can be simple to use, the reference model requires a focused effort to find and input the correct data. Once the set of reference data is obtained, the model can be adjusted to account for any U.S. Navy system with varying combinations of energy generation, loads, and storage.

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III. SAN NICOLAS ISLAND ENERGY SYSTEM

This chapter describes in detail all aspects of the existing SNI energy system and past energy system reviews conducted by the National Renewable Energy Lab (NREL).

A. ISLAND PROFILE

San Nicolas Island is one of the eight islands that comprise the California Channel Islands, as shown in Figure 3. The others include Anacapa, San Clemente, Santa Barbara, Santa Catalina, San Miguel, Santa Cruz, and Santa Rosa. The total land mass is approximately 54 square miles (14,500 acres) with the highest peak being 905 feet as shown in the topographical map in Figure 4. Temperatures range from 56 F to 69 F with annual rainfall just over 7.9" (Weather Underground 2017). Winds on SNI are from the northwest and strong most of the year. The average wind speed is 7.2 m/s (14 knots) and only varies slightly throughout the year (Weather Underground 2017). NREL (1996, 2) states that, during the windiest months, March through July, wind speeds average 8.2 m/s (16 knots), whereas during the least windy months, August through February, wind speeds average 6.2 m/s (12 knots). No freezing temperatures have ever been recorded on SNI.

San Nicolas Island is the most remote and farthest from the California coast of the group, 61 miles, and is solely used for U.S. Navy purposes. Figure 5 details the government and military footprint and installations on the island.

San Nicolas Island is not served by a mainland utility company and the only existing energy infrastructure and generation at SNI includes five diesel generators of varying capacities and seven 100kW wind turbines. The diesel genset specifics are shown in Table 1. They typically run at only 30% of nominal capacity, while they are most efficient at 70% (Anderson et al. 2017). The wind turbines are all Northwind 100 kW models and waste much of their capacity as heat in a load bank due to a lack of storage capability on island.

Table 1. SNI Diesel Gensets.

Unit (year installed)	Rated Capacity	Type
diesel genset #1 (1990)	750 kW	CAT 3512
diesel genset #2 (2002)	1250 kW	Cummins QSK-45
diesel genset #3 (2002)	750 kW	Cummins QST-30
diesel genset #4 (?)	900 kW	Cummins QST-30
diesel genset #5 (1960)	1000 kW	EMD 645

The diesel gensets use JP-5 fuel and produce the vast majority of the power for the island. The fuel is barged in and pumped up from the beach to the airfield, then up to the generating plant. As for the power plant infrastructure, the building was constructed in 1960 and expanded in 1990. The distribution panel was installed in 1988. The average load ranges from 550 kW to 950 kW with a 150 kW to 200 kW peak over the average occurring in the morning, noon and evening (Anderson et al. 2017, 1). The power factor is currently 0.7-0.75. Power is distributed around the island by 4160 V distribution system, much of it underground. There are also 32 emergency back-up diesel generators on buildings and range operations.

From both the NREL (1996 and 2008) studies, the Defense Energy Supply Center (DESC) covers the cost to transport JP-5 fuel to SNI. As of October 1, 2017, the cost to purchase JP-5 from DESC is $2.18/gallon (Roth 2017, 2). According to NREL (2008, 20), barge shipments costs $40,000 each, are able to transport 250,000 gallons of JP-5 fuel, and are run on average three and a half times per year. These barges must also be run alongside a standby ship, which costs $15,000 per barge trip.

The SNI transportation fleet is comprised of trucks, vans, and a bus. All vehicles on the island operate on either gasoline or JP-5. According to NREL (2008, 21), the annual gasoline demand on the island is 32,000 gallons. This is shipped on a different vessel than the JP-5 fuel. Regular unleaded gas costs $2.10/gallon to purchase from DESC (Roth 2017, 2), and costs an additional $1.50/gallon to transport to the island. This shipment cost is not covered by DESC.

Figure 3. California Channel Islands. Source: Google Maps (2017).

Figure 4. San Nicolas Island Topographical Map. Source: Google Maps (2017).

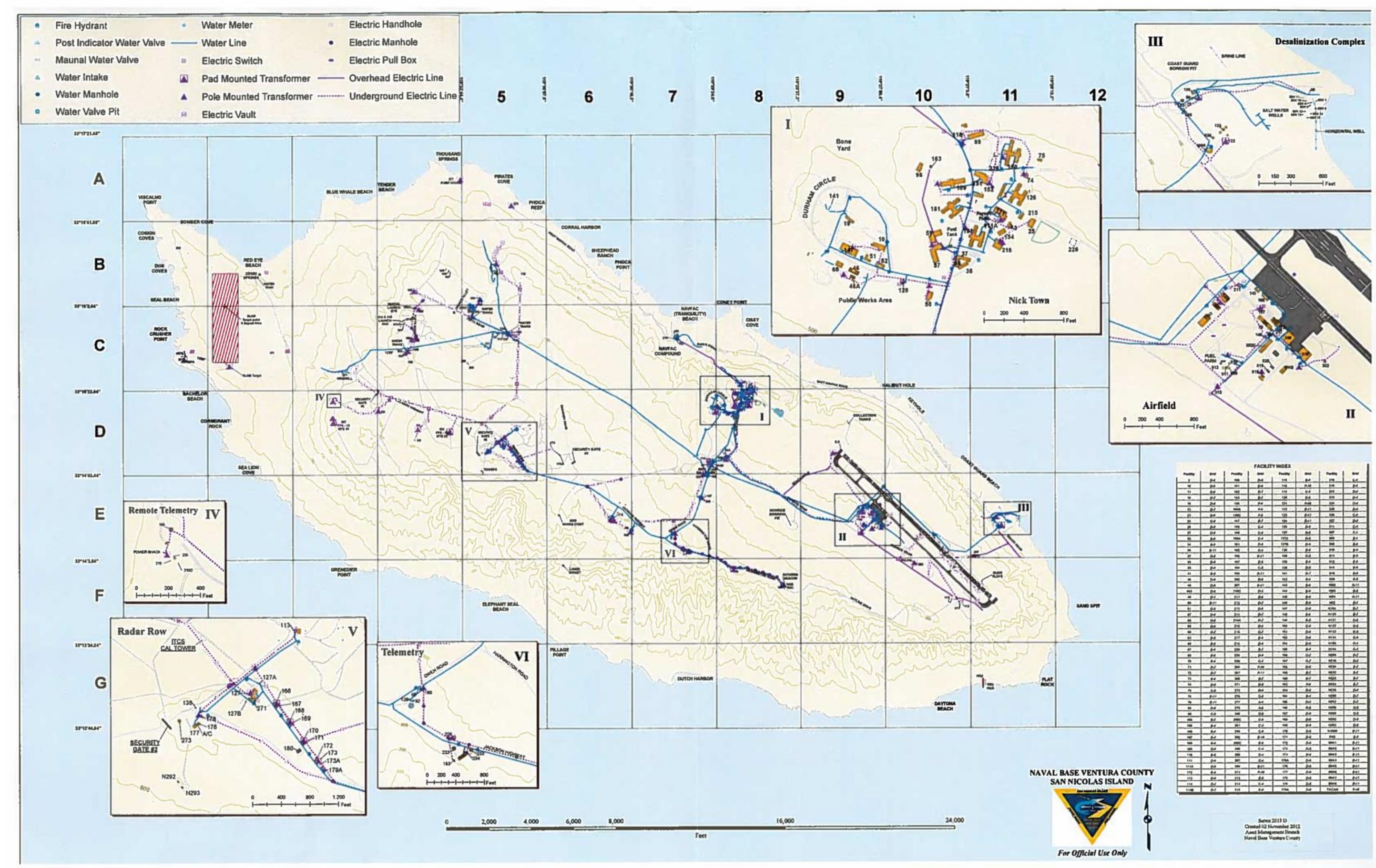


Figure 5. Official U.S. Navy SNI Infrastructure Map. Source: NAVFAC EXWC, Port Hueneme, CA. (2017).

B. 1996–2017 STUDIES

1. NREL 1996 Study

In 1996, NREL conducted the first of two energy studies regarding energy usage at SNI. This first study was designed to determine if wind energy could be used to decrease overall energy costs on the island. The goal was to institute a wind-diesel hybrid system. At the time, the major energy cost drivers on SNI were capital and installation costs, diesel fuel costs, and diesel operating and maintenance costs. Due to the generally favorable environmental conditions to use wind energy at SNI, this goal had a solid chance of success to deliver the proper amount of energy and to be cost effective. Any excess generation would not be wasted but could instead be used for reverse osmosis (RO) units, water heating, or space heating. The major hurdle to the excess energy utilization was the lack of an existing storage capability in 1996. As a result of the study, other, more detailed, analyses were recommended. Specifically, dynamic load management was recommended using load and wind data at shorter intervals than the 1-hour average used in the study (less than or equal to two minutes recommended).

According to Timothy Olsen and Ed McKenna of NREL (1996, 14), the assumptions made in 1996 included the following.

> First, at least 200 kW must always be generated by the existing diesel generators even if there is excess wind capacity. Second, it is assumed that only the necessary number of turbines will be generating power at any given time, with the remaining turbines idled. Third, a minimum diesel time is required to hold the number of diesel starts on the order of 100.

The 1996 proposed solution, stated by Olsen and McKenna (1996, 22) included a hybrid system of diesel and wind.

> Between one and four commercially available wind turbines (each with a capacity of 225 kW) would be combined with the existing 3500 kW diesel generation capacity. Of note, SNI would later add additional diesel genset capacity to 4650 kW, which is where it currently stands. With a demand peak of 1230 kW, no more than 1500 kW of diesel is on line at any time. Therefore, wind penetration of on-line capacity with four wind turbines is 900/1500 = 60%. Based on instantaneous power, wind penetration can range from 0% when there is no wind to 250% when peak wind power of 900 kW is combined with a minimum load of 360 kW.

Power storage, photovoltaic generation, dump load, and advanced load management were not included in the 1996 analysis.

The wind and diesel hybrid system produces favorable energy and economic results. The Olsen and McKenna (1996, 27) NREL report concludes, "the hybrid case using four 225 kW wind turbines is $0.338/kWh versus $0.358/kWh for the baseline case. This would create a savings of 5.6%. The payback period is 6.97 years, the internal rate of return of 13.1%".

2. NREL 2008 Study

Still interested in how renewable energy may enhance the Department of Defense (DOD) mission, Alicen Kandt and Andy Walker of NREL (2008) developed the method used in this study to calculate a hybrid energy system aimed at minimizing life cycle costs. This renewable assessment and optimization was done to support this determination and to lay a foundation for the planning of a future "Net Zero Energy Installation." The DOD funded this study to provide: "(1) a plan outline for transitioning Navy Outlying Landing Field SNI into a renewable community; and, (2) a current energy, water and waste baseline of SNI" (NREL 2008, 6). To take the 1996 study a few steps further, the team collected data for a baseline of energy, water, and waste.

As stated by the U.S. Energy Information Administration, the Energy Independence and Security Act, passed in December 2007, defines zero-net energy buildings as "a building that is designed, constructed and operated to

- require a greatly reduced quantity of energy to operate
- meet the balance of energy needs from sources of energy that do not produce greenhouse gases
- result in no net emissions of greenhouse gases
- are economically viable" (2017)

Proving that a net-zero facility is possible at SNI is one of the main goals of this thesis. Additionally, according to NREL (2008, 7),

> an optimization analysis was done to determine the combination of renewable energy technologies that could replace the use of JP-5 fuel to heat and power the stationary loads at San Nicolas Island, first with batteries and then without batteries. The technologies evaluated include photovoltaics, wind power, solar ventilation air preheating, solar water heating, solar thermal steam and solar thermal electric, biomass thermal steam and biomass electric, and daylighting. Results indicate that solar water heating, solar ventilation air preheating and daylighting can be integrated directly into buildings to reduce both electric and heating use. The remaining electrical requirements can be reduced by wind power connected to the central plant. Remaining heat uses at some buildings would continue to be supplied by oil since there is no renewable energy technology considered that can serve those loads. However, this remaining load could easily be served by bio-diesel purchased and delivered in the same way that JP-5 is currently delivered. Also, these oil-fired loads could be converted to electricity which could be provided by renewables, although this would not reduce life cycle cost under current conditions.

3. NAVFAC EXWC 2017 HOMER Study

As recently as earlier this year, the SNI microgrid was modelled using HOMER simulation software. According to Anderson et al. (2017, 1),

> various technologies were investigated as potential solutions to increase RE penetration and resiliency of the SNI microgrid, while reducing reliance on costly diesel generators. These technologies include solar, wind, battery, fuel cell, flywheel, and supercapacitor. The results show a solar and battery installation to be the most cost effective method to increase renewable penetration, reduce diesel reliance, and increase resiliency of the SNI microgrid at minimal cost.

This study concluded that there were two worthy configurations that deserved further analysis. First is the solar with battery storage option. Second, and the most efficient net-zero solution, is the solar with fuel cell configuration (Anderson et al. 2017, 10).

C. ARCHITECTURE OF ENERGYPLAN MODELS

Based upon the results and conclusions of the 1996 and 2008 NREL studies, as well as the 2017 NAVFAC EXWC HOMER study of SNI, the following EnergyPLAN models were created and run to serve as a comparison for further analysis:

Reference (current SNI configuration) model: This model serves as the SNI reference model, to which all below models will be compared. The SNI EnergyPLAN reference model shows the island’s energy microgrid as it is currently established on site. The diesel gensets carry the vast majority of the total island load and operate at very inefficient frequencies due to the constant nature of cycling them up and down. As shown in the reference model section of Appendix B, the island’s daily load remains fairly constant throughout the year, averaging about 500 kW daily. One glance at the production graphs reveals that there is a great opportunity not only to decrease diesel genset production, but also to capture, store, and use wind turbine energy production on demand. Thus, a better model must be possible.

The nominal SNI energy microgrid is depicted in Figure 6. The five diesel gensets and seven wind turbines can be seen, connected with switchgear.

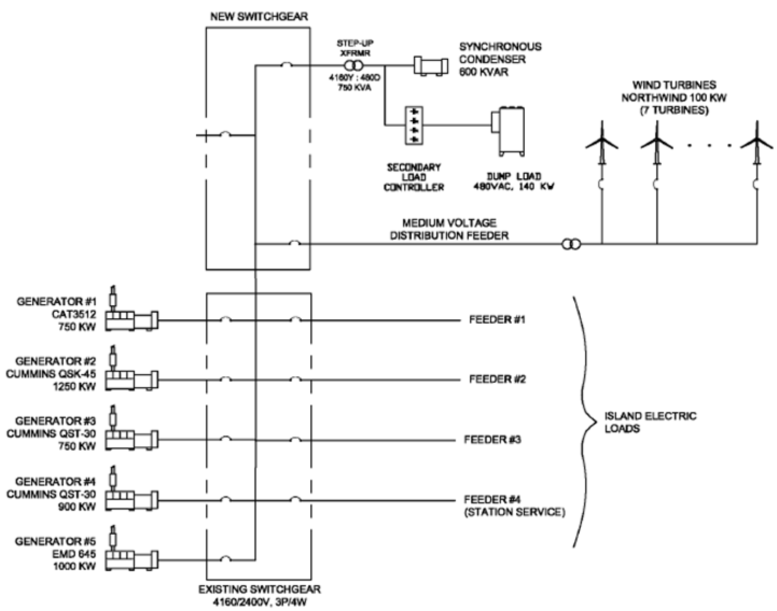


Figure 6. San Nicolas Island Energy Grid. Source: Anderson et al. (2017).

Optimized model. This model adds a storage battery to the base model, decreases the contribution of the diesel gensets to the SNI energy grid, and increases the RE penetration.

Net-Zero model. This model adds solar PV and a storage battery to the base model and shows that SNI can become a 100% RE U.S. Navy installation.

IV. DATA COLLECTION AND MODELING

This chapter describes the data collection process, the preprocessing that was required for the data, and the energy system modeling efforts.

A. SYSTEMS ENGINEERING ELEMENTS

Scott (2016, 4) states that insight is the goal of Law #3 in the "9 Laws of Effective Systems Engineering." Through the data obtained from SNI, many insights can be formed about energy usage and opportunities for improvement on the island. Good information feeding a good process leads to insight, and insight leads to better choices. Otherwise, "garbage in yields garbage out." This is the one of the powers of applying systems engineering principles to complex systems. Models allow us to capture and communicate our understanding unambiguously. According to Scott, "models enable us to coherently reason about the problem and the solution in a way that is not possible in the abstract" (2016, 4). The applicability of this research to the field of systems engineering is in the research and solutions to power systems for mission assurance of critical infrastructure. This is accomplished by expanding the system boundary to best ensure SE tools create more value through greater efficiency, resiliency, and mission assurance.

Other classic SE process elements that are presented in this thesis include an operational concept, an effective need, system boundaries, an input-output model, a functional architecture design, a physical architecture design, and systems analysis methodology. Figure 7 depicts the SNI energy ecosystem in a high-level operational concept graphic, or an OV-1.

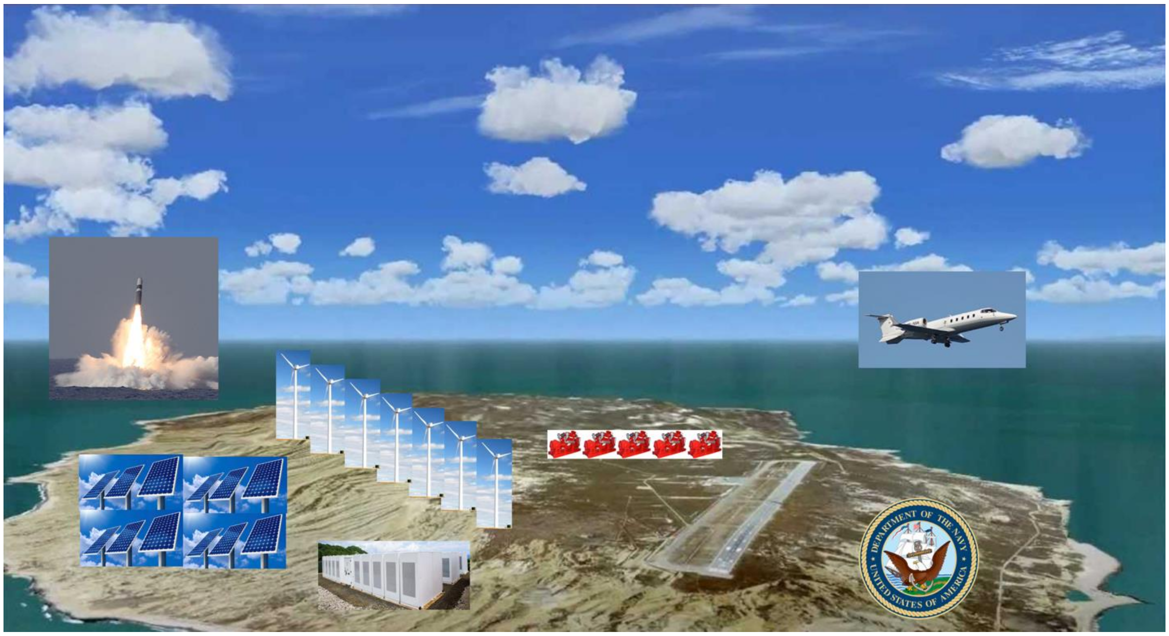


Figure 7. San Nicolas Island OV-1. Adapted from Google Maps (2017).

As shown, SNI currently receives energy from five diesel gensets and seven 100kW Northwind wind turbines. Most realistic short-term energy solutions, including those plans that can result in a net-zero energy solution on the island, add in solar photovoltaics (PV) and storage batteries. Small island usage of storage batteries has already proven to be successful with Tesla's venture to American Samoa (Science Alert 2016).

B. DATA COLLECTION AND PROCESSING

In terms of data collection, three sets of data were obtained to create the SNI reference model. These sets include diesel generator production (island demand), wind turbine production, and solar PV. The solar PV data was needed in order to analyze enhanced models, so direct normal solar irradiance (DNI) data was obtained. Monetary data, such as investments, operations, fuel, and maintenance costs were estimated based on the three previous reports conducted on SNI discussed in Chapter III. LCDR Kyle Kobold and Professor Oleg Yakimenko of the Naval Postgraduate School (NPS) visited NAVFAC EXWC in Port Hueneme, CA on September 6, 2017. They were accompanied on the site visit by Bill Anderson of NAVFAC EXWC. During the visit, they surveyed the facilities and downloaded actual island demand data from a standalone computer that has access to the energy system on the island.

1. Diesel Gensets

The three sets of annual SNI demand data were downloaded and exported to a text file for processing. MATLAB code was written to filter out every hourly data point from the three files. Since EnergyPLAN requires 8784 data points for the distribution files that are called in the software, the data processing was a vital step to the creation of the model. Data preprocessing includes:

- Raw data was obtained from the storage medium of the desired energy source. Diesel generator demand data was collected on site at Port Hueneme at NAVFAC EXWC. Wind turbine data was obtained on SNI. Solar PV data was downloaded from NREL. Existing energy capacities were obtained from past NREL reports.

- Diesel generator demand data required the most effort to process. Three separate files, containing 10-minute data for a year were obtained at NAVFAC EXWC. In order to feed EnergyPLAN the required distribution, this data needed to be filter to hourly data for a year, or 8784 data points. MATLAB code was written to extract the data points in this manner. A sample of the MATLAB code is provided in Appendix A.

- Wind data did not require as much work as it arrived in larger time intervals and was filtered to hourly data using MS Excel.

- Solar PV data was simply downloaded from NREL and average direct normal irradiance. From there, the sunrise and sunset times were calculated and used to arrive at an average hourly value for solar PV capability at SNI. Since SNI currently does not have solar PV installed, this is an estimated value.

Obtaining raw data and converting it into usable data for EnergyPLAN can require a considerable amount of effort. Preprocessing of the data is a vital step in the process though if realistic results are desired.

2. Wind

Wind data was provided by Nicolas DeMarco, one of the authors of the NAVFAC EXWC HOMER study that was recently conducted on SNI. This data must be acquired on island, as there is no way to access it remotely. Weather prohibited a trip to the island for the purposes of this thesis. For accuracy, this data was compared to downloadable wind speed data from a couple websites – NREL and Weather Underground. As with the diesel generator data, 8784 data points that represent a full year of hourly data were obtained. This also required filtering due to arriving as 10-minute wind speed data. The index method, described in Appendix A, was used to create this distribution file for EnergyPLAN. That is, the fastest recorded wind speed was set to one, and the rest of the data points were referenced from there.

3. Solar

Solar PV data was obtained from the NREL Geospatial Data Science website. Once on the site, one can either select or query a specific data point from the graph, shown in Figure 8. Or, one can download data by filling in the requested information as shown in Figure 9 in the Download Wizard. This provides National Solar Radiation Database (NSRDB) information.

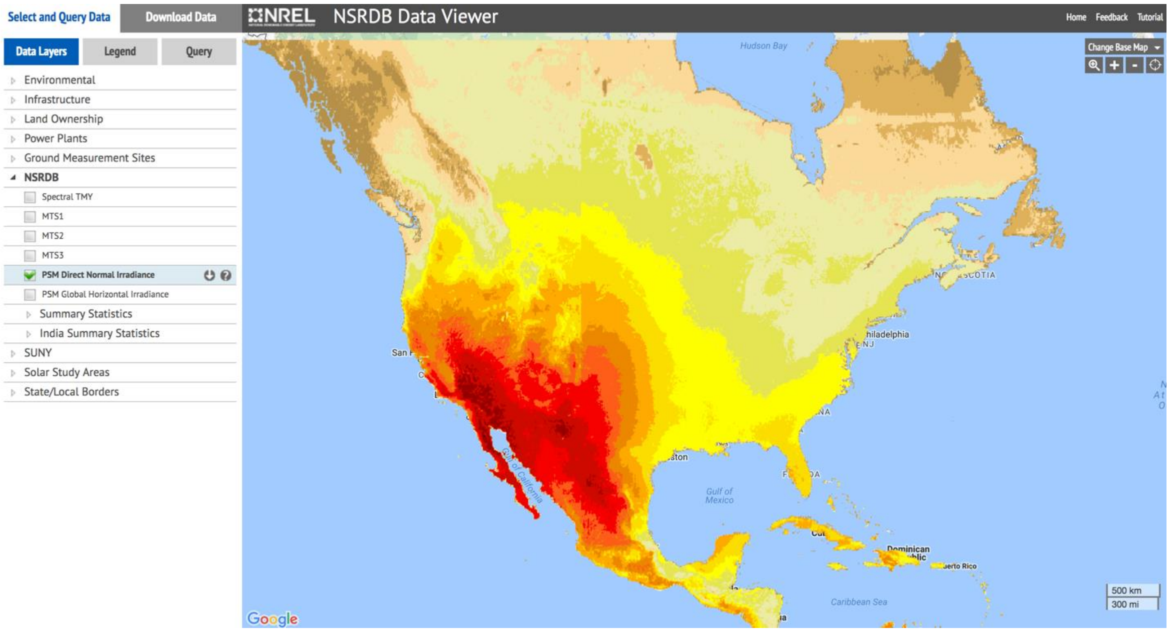


Figure 8. Direct Normal Irradiance Graph. Source: NSRDB Data Viewer (2017)

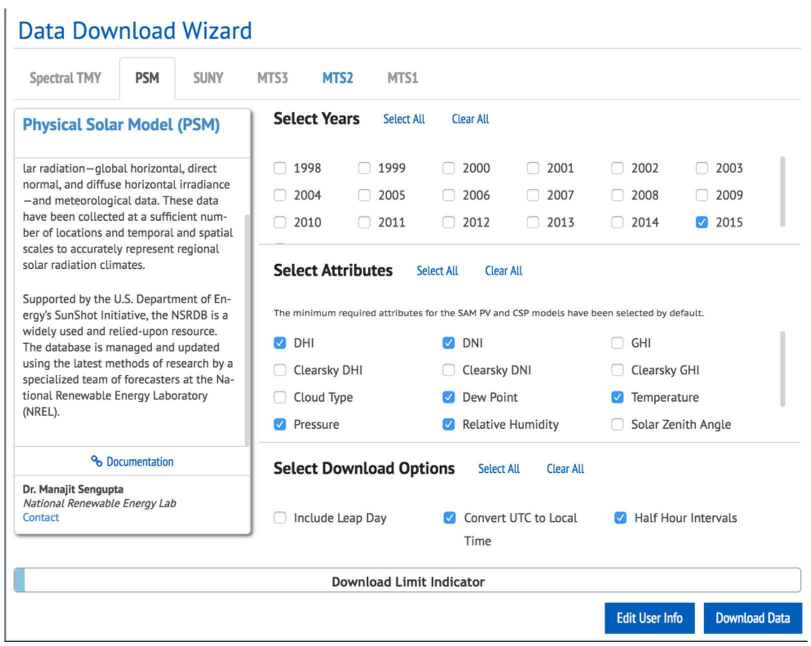


Figure 9. NREL Physical Solar Model (PSM) Data Download Options. Source: NSRDB Data Viewer (2017).

According to NREL (2017), this data provides monthly average and annual average daily total solar resource averaged over surface cells of 0.038 degrees in both latitude and longitude, or nominally 4 km in size. The solar radiation values represent the resource available to solar energy systems. The data was created using cloud properties which are generated using multiple NREL proprietary models. The data are averaged from hourly model output over 17 years (1998-2014).

4. Cost

Information regarding the cost inputs proved difficult to obtain but was found scattered throughout the three previous detailed reports regarding SNI's energy system. For the energy prices used in the multifactor MS Excel optimization model, the Roth (2017, 2) OSD Memo was referenced.

C. MS EXCEL OPTIMIZATION

Since EnergyPLAN requires user inputs to derive the output, it is vital to feed EnergyPLAN accurate information. Otherwise, the output will be worthless. So, the first step to creating the most accurate SNI output model as possible is to derive the actual required numbers of the different types of energy sources on the island. This was accomplished with MS Excel.

MS Excel optimizations were used to arrive at the specific numbers used in the optimized and net-zero models found in Chapter V. The optimization of the microgrid components relied on a formulation that is multi-objective, mixed-integer, and nonlinear. The feasibility of the recommended configurations was established through constraints governing the requirements for the load and the capabilities of both the generation, storage and overall SNI energy system. There are two objective functions that maximize penetration of renewables onto grid and minimize overall costs. Figure 10 shows the SNI energy architecture as currently installed while Figure 11 shows an example of an enhanced model with solar PV and a storage battery. This architecture could serve as the net-zero solution as long as the diesel gensets are maintained off the grid unless needed for an emergency situation.

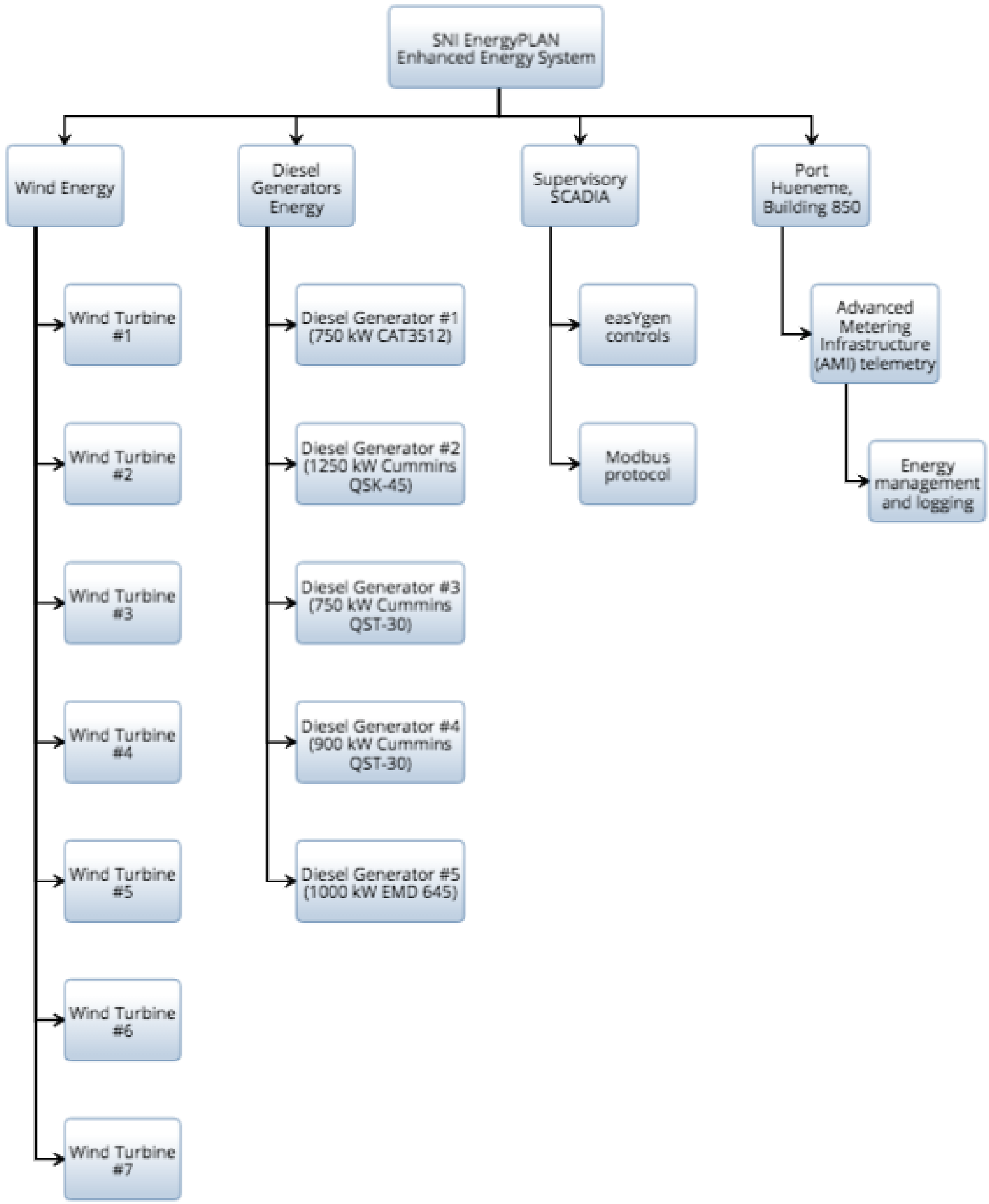


Figure 10. Current SNI Energy Structure.

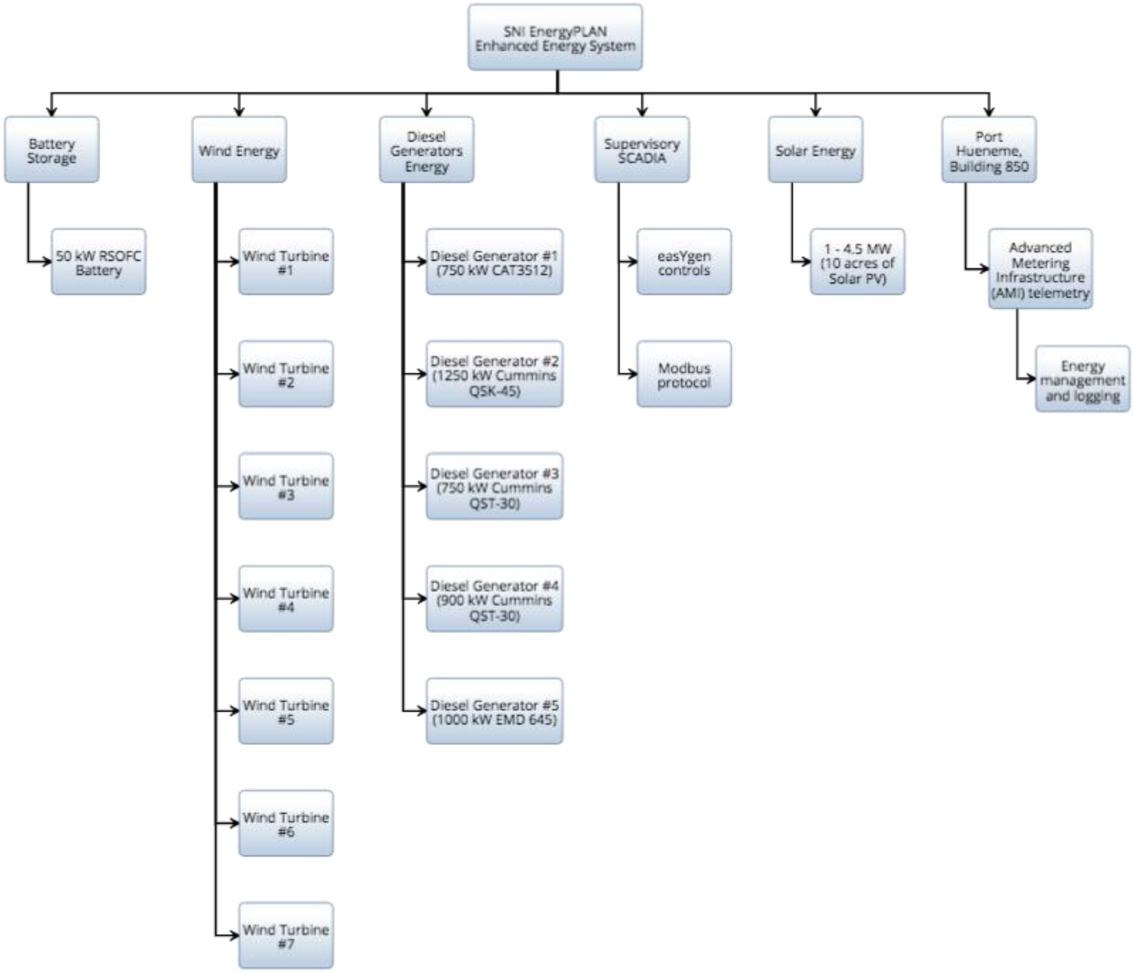


Figure 11. Optimized and Net-Zero SNI Energy Structure.

Figure 12 represents a user interface for the MS Excel optimization. In this model, black numbers are user defined, green displays MS Excel Solver calculated solutions, and red are the constraints. Segment 1 represents the SNI energy sources in the rows and SNI load locations in the columns. The actual distances between them are estimated from the infrastructure map shown in Figure 5. Segment 2 represents potential capacities of the current and proposed energy sources on SNI. Segment 3 provides the estimates of the total cost (such as investment, operation, maintenance) required to deliver energy to the loads. This requires calculations based on generation source, distance from the load, efficiencies, losses, and more. While the exact numbers are not known, this study used a simple approach to estimate them. This approach was based on a simple relationship (Duke, 2017):

$$R = \frac{\rho L}{A}$$

relating the resistance R (in ohms), resistivityρ is (in ohms*m), the distance between the source and the load L (in meters), and the cross-sectional area of the transmission wire A (in m^2).

Segment 1.	distances from the loads (miles)				
	Nick Town	Airfield	Desal	Telemetry	Radar
Diesel	0.1	1	1.7	0.9	3
Wind	2	1.1	1.5	1	2.8
Solar	2.2	0.8	1	1.4	1.7
Battery	0.1	1	1.2	1.6	1.9

Segment 2.	capacity (kW)
Diesel	10
Wind	7
Solar	2
Battery	0.5

Segment 3.	Cost per source ($kUSD)				
	Nick Town	Airfield	Desal	Telemetry	Radar
Diesel	1	10	17	9	30
Wind	0.1	0.2	0.2	0.2	0.2
Solar	0.5	0.75	0.75	0.75	0.75
Battery	0.01	0.02	0.02	0.02	0.02

Segment 4.	Number of sources assigned					Solution sums
	Nick Town	Airfield	Desal	Telemetry	Radar	
Diesel	0	0	0	0	0	0
Wind	4	1	1	2	1	9
Solar	1	1	0	0	0	2
Battery	1	1	0	0	0	2

Constraints		
current	optimized	net-zero
5	2	0
7	7	14
0	1	2
0	2	2

Segment 5.	Power Demand					Solution sums
	Nick Town	Airfield	Desal	Telemetry	Radar	
req	24	5	3	10	5	47
actual	30.5	9.5	7	14	7	68
RE fraction	1.00	1.00	1.00	1.00	1.00	1

Total cost ($kUSD)	2.68

configuration	Diesel	Wind	Solar	Battery	cost index	% RE
current	2	7	0	0	3.2	41%
optimized	1	7	1	2	4.2	58%
net-zero	0	9	2	2	2.68	100%

Figure 12. MS Excel SNI Optimization Interface.

Obviously, the greater the distance of the load from the energy generation source, the greater the resistivity. The greater the resistivity, the greater the losses in the transmission from source to load. The greater the losses from source to load, the more it costs to deliver a unit of energy. Assuming $\rho A^{-1}$is constant, the cost is therefore inversely proportional to the distance, i.e. $C \sim \frac{1}{L}$. Segment 4 shows the maximum number available of each source in the “current,” “optimized,” and “net-zero” cells. Additional configurations can be added in columns that follow, if needed. These cells are calculated and constrained as integers by the MS Excel Solver. The operating hours (per day) of the load at each location appear in “req” line. These were estimated based on a typical day of operations at SNI. For example, Nick Town is continuously manned, so there needs to be reliable power delivered there 24 hours per day. However, the airfield, radar, and telemetry sites are not always in operation as often as Nick Town and thus have a lower power requirement. Segment 4 contains the variable cells that displays the number of energy sources required to meet a specific configuration. For this thesis, the three configurations are shown in yellow shaded Constraints box. Segment 5 contains the required hours of operation where energy supply is required, the actual hours obtained through the selected simulation (to ensure the need is being met), and the percent RE of the model. The values in Segment 2 are again used as part of the calculation for the actual and RE fraction rows in Segment 5.

To operate the developed model, the user needs to select the MS Excel Data tab, then the Solver button. The blue objective function, “total cost,” is minimized by changing the green variable cells. Constraints include the red “actual” cells being greater than or equal to the black “req” cells and the red “Solution sums” cells being less than or equal to the black “current” “optimized,” or “net-zero” cells on a case by case basis. That is, the model must be run three times to solve each current, optimized, and net-zero case by changing the constraint as appropriate in Solver to match the model being run. In this case, the model was run three times for the three different configurations and Figure 12 displays the results from the net-zero model. More can be added as desired. Ensure that the box for “Make Unconstrained Variables Non-Negative” is checked and that the “Solving Method as Simplex EP” is chosen.

Running the model three times, once for each configuration (current, optimized, and net-zero), produces the results shown at the bottom of Figure 12. The numbers of required energy sources, total cost, and % RE are displayed. It should be noted that the terms “current” and “reference” are used interchangeably in terms of these models and in

EnergyPLAN. In terms of capacities, wind turbines are 100 kW each, solar PV is 1 MW each, and batteries are 250 kWh each.

As shown, the net-zero model yields the lowest relative cost as compared to the current and optimized configurations. This calculation does not reflect the investment cost to achieve a net-zero status. That will need to be considered based on the needs of the facility and then a break-even point can be calculated. The main cost driver in the current and optimized configurations is the use of the diesel gensets. This is the reason for the cost increase for the optimized model as compared to the reference model. Here, both the traditional diesel genset source and the RE sources are being used, but not to optimal efficiency, thus the cost is increased. It is important to note that the loads on SNI can be fully carried in all three models. The choice for which model to employ will be up to the decision maker based on a number of factors, most importantly being the budget for investment.

D. ENERGYPLAN REFERENCE MODEL

Next, EnergyPLAN was used to take the MS Excel optimized outputs for each model and derive total system, annual energy balances for each configuration as shown in Table 2. That is, the results for each model from Figure 12 were used as direct inputs into EnergyPLAN as the number of each source of energy. The results of these configurations are shown graphically in Chapter V. Again, all three configurations meet the current SNI demand. Also, all five diesel gensets are not required in any of the models to meet the SNI demand. This correlates with the manner in which the diesel gensets are currently operated on the island, which also happens to not be the most efficient method.

Table 2. Reference, Enhanced, and Net Zero Model Configurations.

	number of units | capacity			
Model	Diesel	Wind	Solar	Storage
Current	2 | 1000 kW	7 | 700 kW	-	-
Optimized	2 | 1000 kW	7 | 700 kW	1 | 1 MW	2 | 500 kWh
Net-Zero	-	9 | 900 kW	2 | 2 MW	2 | 500 kWh

A few assumptions for these models include:

- At any given time, power available from generated and stored energy sources must meet or exceed total SNI demand.

- Excess power generated will be converted to stored energy via lithium ion batteries in the optimized and net-zero configurations.

Given a mix of generators and storage capacity, the goal of the EnergyPLAN simulation and optimization is to minimize fuel consumption by managing the mix of generators running at a particular time and by managing the batteries charging and discharging times.

While EnergyPLAN is fully capable of complex energy system modeling solutions, the steps provided in Appendix A outline the basic required steps to construct a reference model. It is the hope of the author of this thesis that the steps outlined in Appendix A will be taken to optimize energy grids at other isolated and disparate U.S. locations and achieve as close to a net-zero solution as possible at those sites.

If the data is more than hourly, some type of filtering will be required in order to meet the 8784 points required by EnergyPLAN. MATLAB is the best solution for this processing. Another option, but much more labor intensive, is using MS Excel. If MATLAB is the method of choice, this will also afford the opportunity to be able to run certain optimizations later in the analysis by using the MATLAB wrapper for EnergyPLAN. This was designed by Pedro J. Cabrerra of the University of Las Palmas de Gran Canaria and can be used to call EnergyPLAN directly from MATLAB. This is a powerful extension of an already capable energy analysis software package and is free to download from the EnergyPLAN website.

If annual data is unable to be obtained or there are fewer than the required 8784 data points, the data that is on hand can simply be replicated with knowing some amount of error and uncertainty has been introduced. While this is not ideal and will lead to a less than an optimal solution, it will provide a solid starting point to assess the energy situation and way forward.

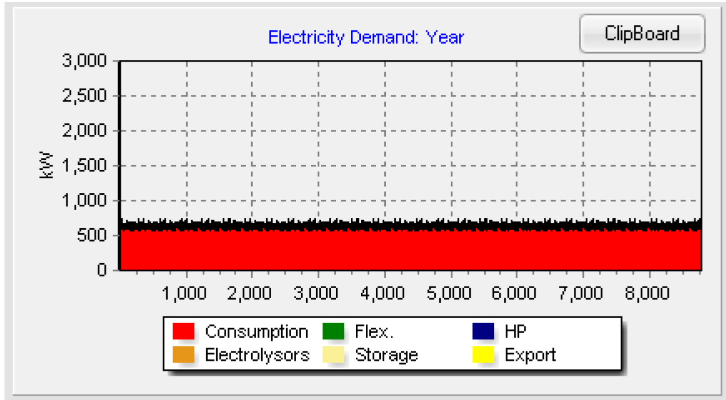
V. ANALYSIS

This chapter presents the analyses of the SNI reference, optimized, and net-zero models as well as an energy source sensitivity analysis.

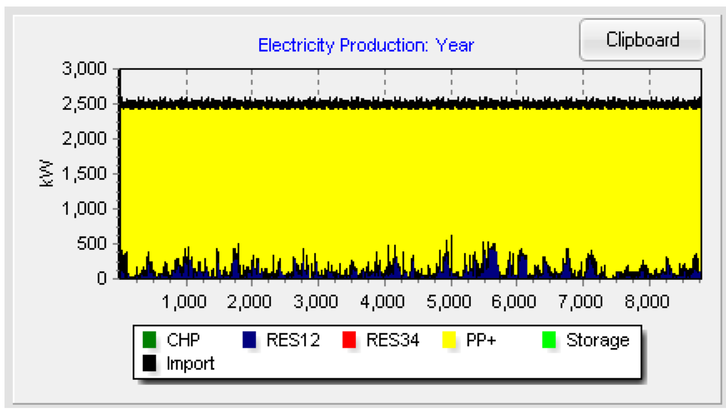
A. REFERENCE MODEL

The results of the EnergyPLAN simulation on the reference (current) model configuration are shown in Figure 13. This model serves as the SNI reference model, to which the optimized and net-zero models will be compared. This model represents the island as it is today, with only diesel generators and wind turbines supplying the island loads. The red area in Figure 13a, labeled Consumption, depicts SNI demand over a full year. The x-axis shows hourly data points (8784) for a full year. As seen, average daily demand (~525 kW) is relatively constant throughout the year. Note that the plot appearance in EnergyPLAN is not editable. Hence, the other entries shown in the legend box refer to non-existing data entries for these models.

Due to the heavy reliance on diesel gensets, this is the least efficient and most costly of the three models under analysis in this thesis. As shown in Figure 13b, production (shown in yellow) far exceeds demand (shown in red in Figure 13a) and much opportunity to send energy to storage is lost. As shown in Figure 6 of Chapter III, much of this production is simply directed to a dump load due to no storage capability at SNI. Yellow, labeled PP+ (power plant), represents the diesel gensets and the dark blue, labeled RES12 (renewable energy source), represents wind turbine production. Data points were collected from August to July; therefore, the wind production appears to peak midyear, but that is actually the winter months that fall in the middle of the data collection period. These are the windiest months at SNI and yield the most productive results for the wind turbines. The lost opportunity is shown in Figure 13c. The goals for the subsequent models will be to find a more optimal solution for the total SNI energy balance and attempt to achieve a net-zero solution. As noted before, it should be noted that all of the other colors are not editable and are built into the EnergyPLAN software. These are default EnergyPLAN assignments and cannot be changed by the user.



a)



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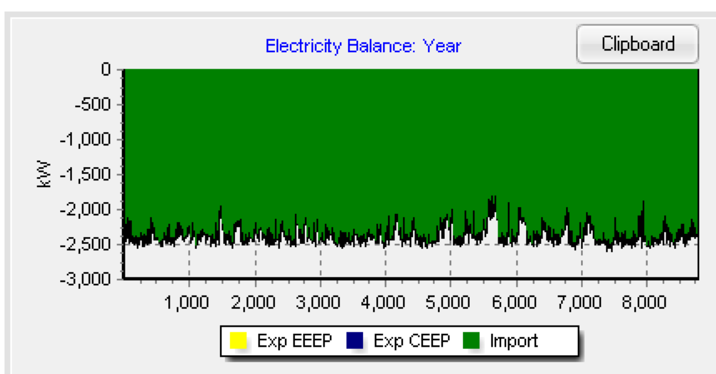


c)

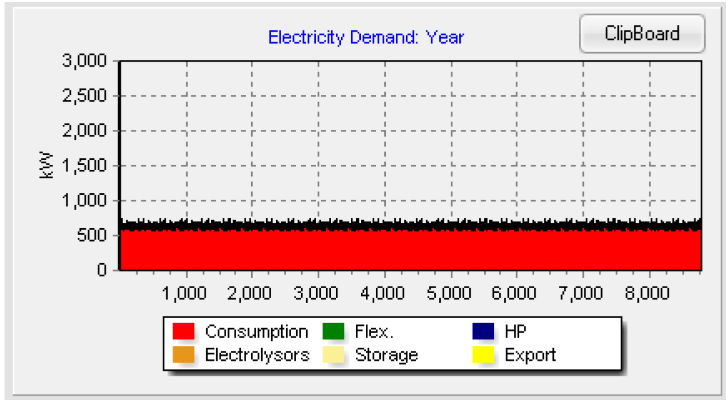
Figure 13. SNI Reference Model Annual Energy Balance.

B. OPTIMIZED MODEL

The results of the EnergyPLAN simulation on the optimized model configuration are shown in Figure 14. From Figure 12 and Table 2 in Chapter IV, this model adds a 1MW solar PV farm and a 500-kWh Tesla storage battery to the reference model. The SNI demand graph, the red area in Figure 14b remains the same, at ~525 kW per day. As shown in Figure 14b, this model depicts a lower reliance on the diesel gensets, again shown in yellow under PP+, than the reference model due to the solar PV and the storage battery (shown in dark blue under RES12) carrying more of the total SNI load. However, as shown in Figure 14c, total production again exceeds demand, and there is still an opportunity to refine the configuration.

This model is not the recommended solution for SNI energy needs, but is shown as a step between the current SNI configuration and the possibility of a net-zero solution on the island. Other forms of RE can be explored here as well, such as wave power, compressed air energy storage, hydrogen fuel cells.

See Appendix A for a step-by-step guide on how to enter data in EnergyPLAN and achieve these and the other output graphs.



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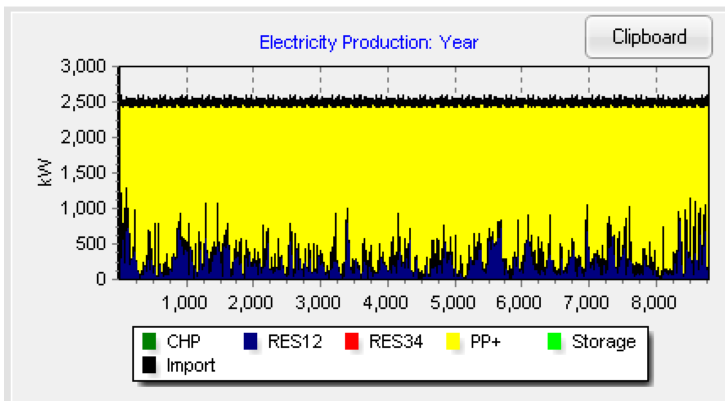

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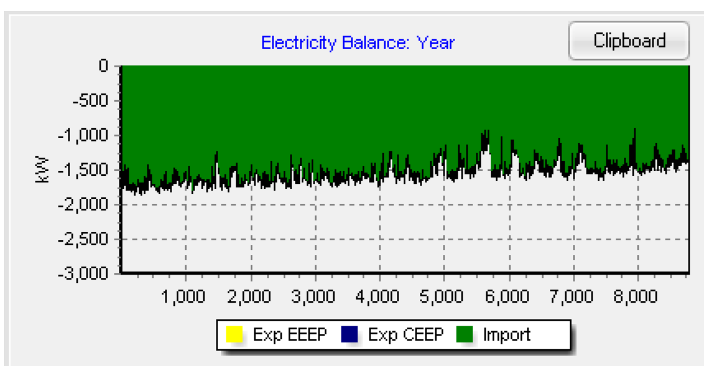


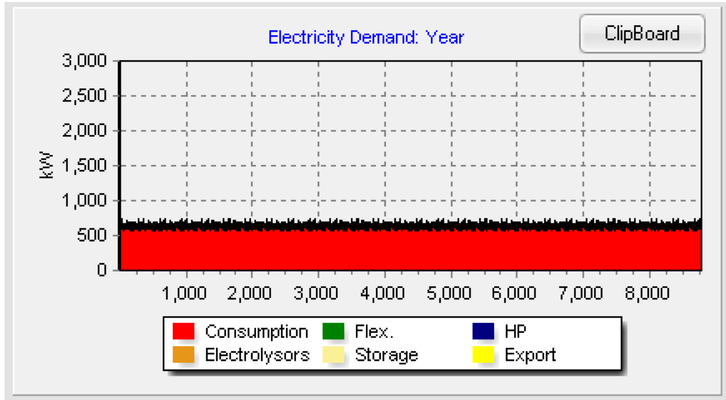
c)

Figure 14. SNI Optimized Model Annual Energy Balance.

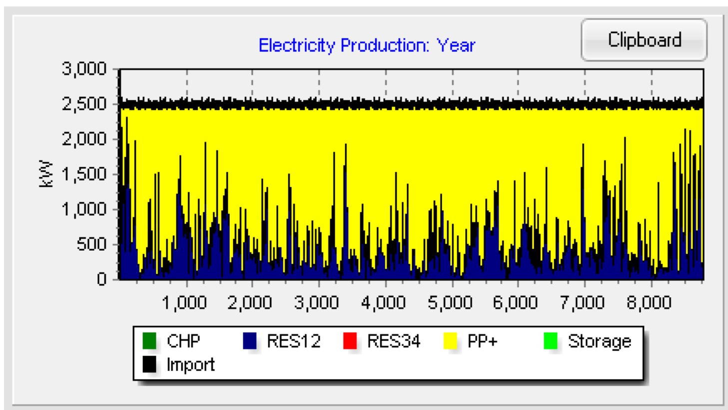
C. NET-ZERO MODEL

Again, from Figure 12 and Table 2 in Chapter IV, the net-zero model represents SNI with 2 MW of solar PV, 900 kW of wind turbines (a 200 kW increase over the currently installed wind capacity), and a 500-kWh Tesla storage battery. Nine 100 kW wind turbines, 2MW of solar PV, 500 kWh Tesla storage battery, and zero diesel gensets is the full solution to a net-zero SNI. The average daily SNI demand (~525 kW) is again shown in red in Figure 15a for analysis. As shown, this model is fully capable of meeting the average daily demand with excess to account for any surge demand times. Figure 15b shows the RE generation exceeding the demand in Figure 15a at many times throughout the year. Where there is excess production, this is sent to battery storage and subsequently used when the production falls below demand. The yellow PP+ portion of the plot is maintained for comparison purposes only.

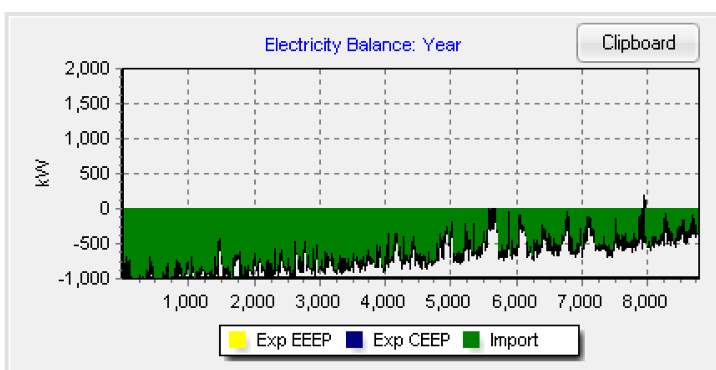
Figure 15c shows the SNI total energy balance achieving a net-zero solution, several times throughout the year. If the storage battery was preloaded with a decent charge, this solution would have been achieved even sooner. This SNI model is also able to increase the stabilization of the grid due to the large percentage of RE share. The exact numbers of installed components can be increased or decreased with the MS Excel optimization tool in order to allow for more or less overshoot to properly balance the grid and the storage battery. Or, perhaps, the excess can somehow be exported as a source of revenue.



a)



b)



c)

Figure 15. SNI Net-Zero Model Annual Energy Balance.

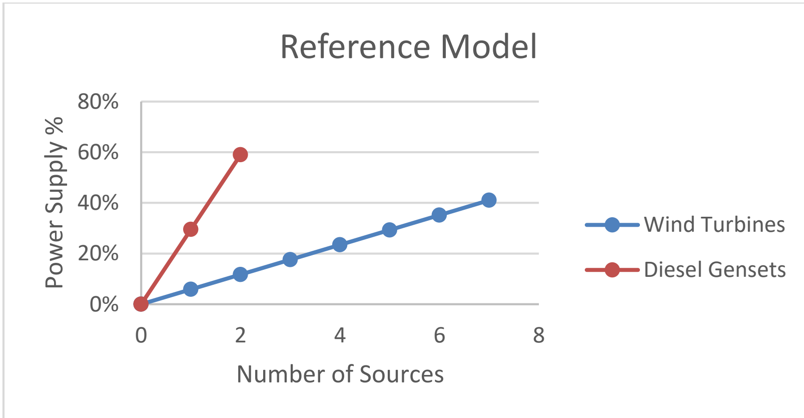
D. SENSITIVITY ANALYSIS

This section completes the discussion with a sensitivity analysis of the three proposed energy models. Since some months afford more of an opportunity to harvest more RE production than others, it is appropriate to consider the effects of not fully employing all of the proposed configurations from the MS Excel optimization. The winter months tend to be the windiest at SNI and will therefore be more reliable for wind turbine employment. As for solar PV, and not considering cloud cover, the island is nearly completely treeless and should be an optimal spot for year-round solar irradiance.

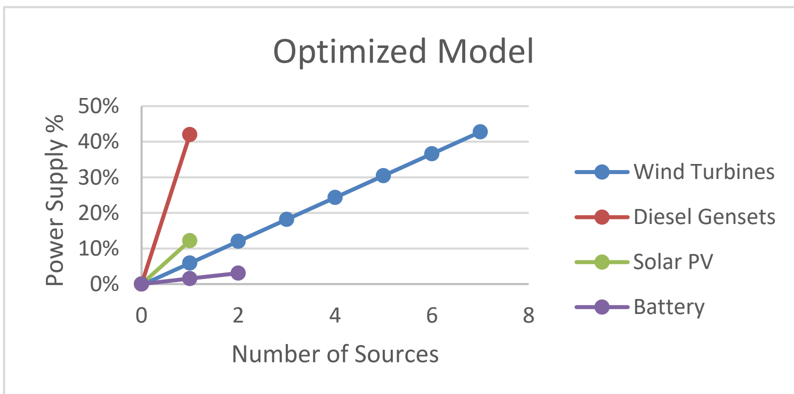
As seen from Figure 16a, representing the reference model, the diesel gensets comprise the majority of the energy production capacity. While SNI has five diesel gensets (Table 1), only two of them are in operation at any given time. Therefore, losing one diesel genset would account for a 30% drop in SNI power supply. This would be a drastic situation for the island and the energy needs would be severely impacted. For comparison, losing a single wind turbine accounts for only a 5.9% drop in supply. Hence, not all of the reference model is flawed, it is just not robust enough to account for a loss of a diesel genset.

As seen from Figure 16b, for the optimized model, the diesel gensets and the wind turbines are nearly identical in share of supply at 42% and 42.7% respectively. Here, losing a diesel geneset is even more drastic due to the MS Excel optimization only allowing one diesel genset to operate on the grid at a time. Losing a single wind turbine though is still only a 5.9% drop in supply. Solar PV carries 12.2% and the storage battery shows a 3.1% share. The diesel genset is still vital to SNI energy needs in this model.

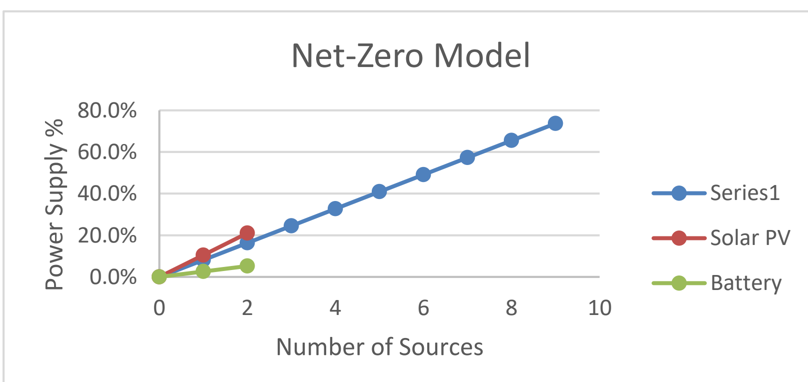
Finally, for the net-zero model, shown in Figure 16c, the diesel gensets are completely removed from the grid and the wind turbines are now carrying 73.7% of the load. Since there are now nine wind turbines, losing a single turbine accounts for an 8.2% drop in supply. This could be significant in the summer months which typically feature weaker winds. Solar PV carries 10.5% and the storage battery shows a 2.6% share. Additional solar PV or battery storage can be considered to lessen the potential impact of a loss of multiple wind turbines in the summer months.



a)



b)



c)

Figure 16. Sensitivity Analysis for Reference, Optimized, and Net-Zero Energy Models

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis resulted in the following elements:

- a fully modeled analysis of installed energy capacity, demand, balancing, and cost at SNI,
- a step-by-step guide in the form of the FIDE-USN that can be used to replicate this analysis at similar U.S. Navy locations,
- varying technical simulations and analysis of the SNI total energy balance,
- technical multifactor optimizations of the generation and storage models,
- microgrid architecture design analysis and proposals, and
- systems level thinking in terms of the strategic (mission assurance), technical (efficiencies of microgrid), and financial considerations.

It was shown that the location, operations, and energy requirements of SNI provide a unique opportunity for the DOD to achieve a tremendous benefit as a first of its kind net-zero facility. The current day-to-day costs associated with maintaining SNI are measurably higher than similarly sized facilities in the continental United States. All fuel and food are transported to the island, and waste is transported off the island. This supply chain also results in an island community that is very vulnerable to supply interruptions and is completely dependent on outside supplies for survival. The baseline use of resources and strategies for reducing energy use and providing energy from on-site renewable energy systems have been described. Findings indicate that not only could on-site systems provide much of the island requirements, but also that it may be cost effective to do so. It would be possible to make the island self-sufficient, or nearly so, in terms of energy use.

The opportunity at SNI is both unique and significant. The realization of energy security and resilience is enormous for the U.S. Navy and SNI provides that opportunity.

One of the main goals of this thesis was to show and demonstrate that a military installation can be 100% RE. From there, it is possible to scale and adjust the solution to other sites, as appropriate. If a 100% RE solution is achieved at SNI, it would be the first know instance in the DOD. As mentioned in Anderson and Yakimenko (2017, 2), other notable global locations with high levels of RE include El Hierro in the Canary Islands (Spain) at 100% penetration with 10,000 people on the island. Isle of Eigg (Scotland) at 94% penetration with 94 total people on the island. And, Samsø (Denmark) at 100% penetration with an estimated 3,000 to 4,000 inhabitants.

The modeling and analysis efforts allowed the four key research questions to be addressed as presented in Table 3.

Table 3. Research Questions and Conclusions

Research Question	Conclusion
Is it possible to accurately model and apply power system microgrid technology at U.S. Navy remote and disparate island facilities?	Yes, this was proven to be possible for SNI with a step-by-step guide created for use at other locations.
Can the derived model lead to a more efficient total system energy balance for San Nicolas Island and other U.S. Navy islands?	Yes, the proposed models can lead to a more efficient and potentially net-zero U.S. Navy installation at SNI. This would be a first for the DOD.
Can multifactor optimizations enhance the proposed models and lead to enhanced control solutions for the power system microgrids?	Yes, but more work is needed to further refine the optimizations.
Can U.S. Navy bases become more energy self-sufficient to the point of increasing energy security and resiliency?	Yes, if a facility is able to achieve a net-zero situation.

B. RECOMMENDATIONS

The goal for future work is to optimize microgrids for remote islands even further by using complex systems tools. EnergyPLAN, MATLAB, Solver and Agent Based

Modelling (either through NetLogo or MATLAB) and applying these tools to isolated U.S. Navy locations could be a discrete tool and valuable to the DOD. Through modeling facilities with these tools, synthesizing the results, and then revising the control system solution in MATLAB, a greater efficiency can be gained approaching a 100% RE solution.

The following areas offer opportunities for further research in the important field of U.S. Navy energy microgrids:

- Apply the analysis presented in this thesis to the following U.S. Navy locations: Diego Garcia, Guantanamo Bay, San Clemente, Camp Lemonnier (Djibouti).
- Monitor SNI electricity demand and supply in real-time, similar to Canary Islands (Real Time Demand and Generation, 2017).
- Use agent-based modeling (ABM) through MATLAB or NetLogo.
- Employ control systems dynamics modeling.
- Apply non-linear energy system modeling.
- Construct a predictive control model based on weather.

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APPENDIX A. FINDING AND INPUTTING DATA INTO ENERGYPLAN—UNITED STATES NAVY (FIDE-USN)

The goal of the FIDE-USN is to assist others working on green energy solutions for U.S. Navy installations on the processes required to maximize the EnergyPLAN software model. I hope that my lessons learned in modeling SNI will help others more efficiently find the correct data and enter it efficiently into EnergyPLAN. This appendix will assist in the creation of a reference model for any U.S. Navy facility's energy system from which it can then be compared to alternatives by adding in renewable green energy solutions to the model. While EnergyPLAN is fully capable of complex energy system modeling solutions, the steps below outline the basic required steps to construct a reference model.

1. Sign up for a free account at http://www.energyplan.eu/.

2. Download and install the EnergyPLAN software. This only works on a PC. If you are working on a Mac, you will need to download and install some form of virtual machine. I recommend VMware Fusion.

3. Acquire the following technical data regarding the specific site or facility:

Note: The following data collection steps may require local data collection or, if available, downloading data from a remote networked computer. You will need 8784 data points to build the reference diesel genset data file for EnergyPLAN. This, as with wind and solar data, is equivalent to hourly data for a year. If you have less data than this, you may need to simply replicate the data to meet the 8784 data point requirement. Work with what data is available but strive for 8784 unique data points in order to construct the most accurate model.

- diesel genset hourly data for a year
- wind turbine hourly data for a year
- solar photovoltaic hourly data for a year

4. The total annual production/demand (TWh/year).

5. Find the installed supply capacities (MW) of all supply sources at the site.

6. Find or best estimate the following costs at the site in $USD:

- Overall machine and material investments
- Fixed operations and maintenance
- Variable operation and maintenance
- Fuel(s)
- Transportation (vehicles)

7. Collect a year of weather data. To get a full report:

- I recommend using https://www.wunderground.com/ and search for the target location
- Go to the historical data as follows: History → Custom → enter dates → Get History
- Export this data to MS Excel. This may require select all, copy, and paste.

8. Enter all of the above data into EnergyPLAN as follows:

- Total annual production/demand: Demand tab → Electricity demand field.
- Diesel Genset distribution: Enter the 8784 data point distribution in the line next to the Electricity demand box by selecting the "Change distribution" button.
- Wind 8784 data point distribution: Supply → Electricity Only → Intermittent Renewable Electricity → select the appropriate dropdown. Be sure to enter the Capacity kW and enter the distribution by selecting the "Change" button to the right.
- Follow the same process for Solar PV as for Wind.

9. Run the reference model by going to the Output Tab and then selecting Graphics. Use the embedded page buttons to achieve your desired graphical result.

10. Select the Run (Screen) button from the navigation bar to acquire the numerical report.

11. Start adding in proposed RE energy sources and analyzing how your model changes in terms of both technical outputs and economic outputs. If unable to accurately determine the correct number of RE sources to add to the model, consider using the MS Excel Optimization techniques presented in Chapter IV.

Notes:

1. It is vital to save all distribution files as Windows Formatted Text (.txt). This is the file type required for EnergyPLAN. The distribution is inputted as a text file and stored in the "Distributions" folder of EnergyPLAN.

2. Specifically for the annual distributions files that contain 8784 data points, Connolly (2017, 5) states in the FIDE Guide:

> The data points are usually between 0 and 1, representing 0–100% of production or demand. However, if a distribution is entered with values greater than 1, EnergyPLAN will automatically index the distribution. This is done by dividing each entry in the distribution by the maximum value in the distribution. One exception is the price distribution under the 'Regulation' tab, which does not index the inputs.

3. Prior to adding battery storage capacity, make sure to understand how EnergyPLAN treats storage batteries. Connolly (2017, 38) states in the FIDE Guide:

> In EnergyPLAN, electricity storage is described in the form of pumped hydroelectric energy storage (PHES) as this is the largest and most common form of electricity storage in use today. However, this can be used to define any type of electricity storage which has a charging capacity (pump/compressor), discharge capacity (turbine), and a storage capacity. When defining the electricity storage capacities available, it is also possible to define an electricity storage operation strategy.

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APPENDIX B. DATA PREPROCESSING MATLAB CODE

```
%% Read in data
load DemandData
%% Check each data set individually
figure
DT=diff(T1); DTs=datenum(DT);           % see if there are gaps
subplot(311), plot(DT); hold
MDT=mean(DTs); STDDT=std(DTs);
OInd=find(DTs>MDT+10*STDDT|DTs<MDT-10*STDDT)';
plot(OInd,DT(OInd),'or')
text(OInd+10,DT(OInd),num2str(OInd))    % dropout
No=length(OInd);
for i=1:No, T1(OInd(i):OInd(i)+1)', end
    DT=diff(T2); DTs=datenum(DT);       % see if there are gaps
    subplot(312), plot(DT); hold
    MDT=mean(DTs); STDDT=std(DTs);
    OInd=find(DTs>MDT+10*STDDT|DTs<MDT-10*STDDT)';
    plot(OInd,DT(OInd),'or')
    text(OInd+10,DT(OInd),num2str(OInd))    % dropout
    No=length(OInd);
    for i=1:No, T2(OInd(i):OInd(i)+1)', end
DT=diff(T3); DTs=datenum(DT);           % see if there are gaps
subplot(313), plot(DT); hold
MDT=mean(DTs); STDDT=std(DTs);
OInd=find(DTs>MDT+10*STDDT|DTs<MDT-10*STDDT)';
plot(OInd,DT(OInd),'or')
text(OInd+10,DT(OInd),num2str(OInd))    % dropouts (missing data)
No=length(OInd);
for i=1:No, T3(OInd(i):OInd(i)+1)', end
%% Check all three date sets alltogether
ComInd=intersect(T1,intersect(T2,T3)); % find common dates for all 3 sets
DT=diff(ComInd); DTs=datenum(DT);       % see if there are gaps
figure
plot(DT); hold
MDT=mean(DTs); STDDT=std(DTs);
OInd=find(DTs>MDT+10*STDDT)
plot(OInd,DT(OInd),'or')
text(OInd+10,DT(OInd),num2str(OInd))    % dropout
ComInd(OInd:OInd+1)'
%%
[~,iT,~]=intersect(T1,ComInd); % find indices of common date points for Set 1
Demand1=[SNIdemand1{iT,4}];
    [~,iT,~]=intersect(T2,ComInd); % find indices of common date points for Set 2
    Demand2=[SNIdemand2{iT,4}];
[~,iT,~]=intersect(T3,ComInd); % find indices of common date points for Set 3
Demand3=[SNIdemand3{iT,4}];
%% Plot data
figure
subplot(311)
plot(ComInd,Demand1,'.-.'), grid
xlabel('Time'), ylabel('Power, Units?')
subplot(312)
plot(ComInd,Demand2,'.-.'), grid
xlabel('Time'), ylabel('Power, Units?')
subplot(313)
plot(ComInd,Demand3,'.-.'), grid
xlabel('Time'), ylabel('Power, Units?')
```

Figure 17. MATLAB Code Used to Process SNI Energy Demand Data Files. Source: Yakimenko (2017).

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   Ft. Belvoir, Virginia

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