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MONTEREY, CALIFORNIA

THESIS

**ESTIMATING THE LIFE CYCLE COST
OF MICROGRID RESILIENCE**

by

Joshua P. Hildebrand

December 2020

Thesis Advisor:

Douglas L. Van Bossuyt

Co-Advisor:

Daniel A. Nussbaum

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ESTIMATING THE LIFE CYCLE COST OF MICROGRID RESILIENCE

Joshua P. Hildebrand
Lieutenant, United States Navy
BS, U.S. Naval Academy, 2014

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December 2020**

Approved by: Douglas L. Van Bossuyt
Advisor

Daniel A. Nussbaum
Co-Advisor

Ronald E. Giachetti
Chair, Department of Systems Engineering

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ABSTRACT

The Department of Defense has placed significant emphasis on the importance of a stable and secure energy infrastructure system. The Department of the Navy (DoN) defines energy security as consisting of three components, namely reliability, efficiency, and resilience. One of the ways the DoN improves resilience in installation electrical energy systems is by using microgrids. The relationship between microgrid resilience and cost is not well explored in existing research. This thesis develops a seven-step process to estimate the cost of microgrid resilience using design of experiments and regression analysis. The process is designed to be used by installation energy managers when considering the installation or upgrade of a microgrid. The process is demonstrated in a case study using net present value to quantify life cycle cost and expected life cycle mission impact to quantify resilience. The case study analyzes a microgrid representative of a portion of the electrical distribution system at the Naval Postgraduate School in Monterey, CA, which is made up of multiple diesel generators, a large photovoltaic array, an energy storage system, several loads, and a utility grid connection. The case study demonstrates the effectiveness of the process developed in this thesis and the importance of understanding the cost of microgrid resilience to inform decisions about the necessary distributed energy resources that make up a specific microgrid architecture.

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List of Acronyms and Abbreviations

DoD	Department of Defense
NAVFAC	Naval Facilities Engineering Command
AEMRR	Annual Energy Management and Resilience Report
DoN	Department of the Navy
SECDEF	Secretary of Defense
NSETTI	Navy Shore Energy Technology Transition and Integration
NSAM	Naval Support Activity Monterey
UPS	uninterruptible power supply
DER	distributed energy resources
PV	photovoltaic
DG	diesel generator
AC	alternating current
DC	direct current
ESS	energy storage system
NPS	Naval Postgraduate School
UAV	unmanned aerial vehicle
IEEE	Institute of Electrical and Electronics Engineers
USN	U.S. Navy
LBNL	Lawrence Berkeley National Laboratory
LCOE	levelized cost of energy
LCC	life cycle cost
LCCE	life cycle cost estimation
LCCA	life cycle cost analysis
DOE	design of experiments

ESAT	Energy Security Assessment Tool
MIT	Massachusetts Institute of Technology
ERA	Energy Resilience Assessment
RE	renewable energy
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
NREL	National Renewable Energy Laboratory
ELMI	Expected Life Cycle Mission Impact
CO	Commanding Officer
MDI	Mission Dependency Index
CNIC	Commander, Navy Installations Command
NASA	National Aeronautics and Space Administration
DER-CAM	Distributed Energy Resources Customer Adoption Model
DERGOS	Distributed Energy Resource Grid Optimization Services
CONOPS	Concept of Operations
MDT	Microgrid Design Toolkit
GAO	Government Accountability Office
ICE	independent cost estimate
ROM	rough order of magnitude
EAC	estimates at completion
FEMP	Federal Energy Management Program
NPV	net present value
CBA	cost-benefit analysis
SE	systems engineering
NIST	National Institute of Standards and Technology
O+S	operating and support
NATO	North Atlantic Treaty Organization

Executive Summary

The Department of Defense (DoD) has placed increased emphasis on achieving and maintaining a secure and stable energy infrastructure to support a growing reliance on technology and the prospect of revolutionary platforms such as directed energy weapons [1]. Energy security is defined as “having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet mission essential requirements” [2]. Installation energy managers within the DoD are required to strive to maximize energy security at the minimum cost when conducting cost-benefit analysis (CBA) and traditional life cycle cost analysis (LCCA) [3]. The Department of the Navy (DoN) measures energy security using three pillars of energy security: reliability, efficiency, and resilience [4]. The DoN develops a more reliable, resilient, and efficient energy infrastructure through the use of microgrids (the electrical energy system of interest to this thesis) on naval installations [5].

The systems engineering (SE) community has generally focused on reliability and efficiency when conducting cost analysis of microgrids. Further, there is limited research available on microgrid resilience and the relationship between the resilience and cost, especially when applied to microgrids [6]. To support the DoD’s goal of considering resilience and cost when procuring and upgrading energy infrastructure, the link between microgrid resilience and microgrid cost is one area on which the SE community needs to focus research.

This thesis develops a seven-step process to estimate the cost of microgrid resilience that an installation energy manager can use to assist with design decisions when installing a new microgrid or upgrading an existing system. The steps are as follows:

1. Conduct a design of experiments (DOE) to identify possible microgrid architectures.
2. Simulate microgrid performance for each microgrid architecture to determine the resilience score.
3. Estimate the life cycle cost (LCC) for each microgrid architecture.
4. Analyze results of DOE for both resilience score and LCC.
5. Generate a plot of cost versus resilience for all microgrid architectures identified in Step 1.
6. Conduct regression analysis of the plotted data to identify potential relationships

between cost and resilience.

7. Analyze results for sensitivities and make budget and microgrid design recommendations.

The above outlined steps are intended to be used on microgrids of various designs and sizes. An installation energy manager can choose the metric that they feel is most appropriate to quantify LCC and microgrid resilience. This thesis determined that net present value (NPV) is most appropriate to quantify the LCC of a microgrid because it covers the entire life cycle of the microgrid and accounts for both positive and negative cash flows. This thesis determined that Expected Life Cycle Mission Impact (ELMI), as developed in [7] is the most appropriate metric to quantify microgrid resilience because it accounts for both the probability of a disturbance occurring and the impact the disturbance has to mission completion. This thesis slightly modifies step four of the process developed in [7] and quantifies the impact to mission using the Mission Dependency Index (MDI) score for each load the microgrid serves rather than having the installation energy manager assign an arbitrary value. The regression equation(s) developed in step 6 of the process developed in this thesis can be used to allow base energy managers to understand how much it costs to achieve a specific improvement in ELMI or achieve a desired ELMI threshold.

The process for estimating the cost of microgrid resilience is demonstrated in a case study, using a microgrid representative of a portion of the energy distribution system at Naval Postgraduate School (NPS) located at Naval Support Activity Monterey (NSAM). The microgrid used in the case study had five loads, up to two diesel generators (DGs), an energy storage system (ESS), a photovoltaic (PV) array, and can operate in grid connected and islanded modes. Due to the specific architecture and load profiles of the microgrid used in the case study, a total of 18 regression equations are developed to estimate the cost of microgrid resilience. Each equation correlates to specific microgrid characteristics such as fuel capacity, total DG capacity, and ESS efficiency. The method developed in this thesis is one of several tools that installation energy managers can use to assist with the design of a microgrid. The methodology developed helps identify the factors that significantly impact cost of microgrid resilience and allows installation energy managers to determine the desired level of microgrid resilience. After working through the method developed, installation energy managers are more prepared to work directly with Naval Facilities Engineering Command (NAVFAC) to further analyze and determine the best microgrid

design for the installation under consideration.

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CHAPTER 1:

Introduction

As society has become more reliant on technology to accomplish daily tasks, the existence of a stable and reliable energy grid has become extremely important over the last fifty years. In particular the Department of Defense (DoD) has emphasized the importance of stable energy to support the introduction of revolutionary platforms and capabilities such as directed energy weapons and smart technology [1]. Driven by the increased importance of energy, as defined in the 2017 Annual Energy Management and Resilience Report (AEMRR), the DoD has made the pursuit of a secure and resilient energy infrastructure its top energy policy in order to ensure mission readiness [2]. Energy security is defined by 10 U.S.C.§2924 as “having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet mission essential requirements” [3]. To assist in implementation energy security throughout the DoD, the Secretary of Defense (SECDEF) is given the authority under U.S. law to “authorize the use of energy security and energy resilience, including the benefits of on-site generation resources that reduce or avoid the cost of backup power, as factors in the cost-benefit analysis (CBA) for procurement of energy” [4]. Therefore, DoD energy managers must maximize energy security while minimizing costs and conducting traditional life cycle cost analysis (LCCA) and CBA [5].

One of the DoD’s most important types of energy infrastructure is electrical energy which it requires for nearly every mission set [2]. The Department of the Navy (DoN) defines the three pillars of energy security as reliability, efficiency, and resilience [6]. The DoN uses electrical energy systems such as microgrids (the electrical energy system of interest to this thesis) on military installations (of which naval installations is a subset) to develop a more reliable, resilient, and efficient energy infrastructure. Energy efficiency and reliability are well defined and thoroughly studied principles. The systems engineering (SE) community has historically placed less focus on the study of resilience and relied on traditional reliability, availability, and maintainability metrics [7]. Given the DoD’s requirement to consider energy security and resilience, as well as cost, when procuring energy systems to update existing infrastructure, or building a new military installation, the SE community will need to analyze cost versus resilience performance and understand the estimated life cycle cost (LCC) of

various microgrid architectures.

1.1 Research Objective

This thesis's primary objective is to develop a process to quantify the cost of resilience when applied to a microgrid on a naval installation. Understanding this cost helps support decision makers in making informed decisions when implementing or upgrading a current installation's energy grid. The process developed in this thesis to quantify the cost of resilience is then applied to a baseline microgrid architecture as a case study to demonstrate how installation energy managers can use the process.

The research conducted as part of this thesis is in support of a Navy Shore Energy Technology Transition and Integration (NSETTI) research project focused on the modeling, analysis, and design of electrical energy systems (a subset of the portfolio of energy systems used by the DoD) for naval installations. The NSETTI research project is a collaborative effort between the Naval Postgraduate School (NPS), University of Wisconsin-Milwaukee, and Naval Facilities Engineering Command (NAVFAC) Engineering and Expeditionary Warfare Center that aims to maximize energy security.

1.2 Microgrids

The U.S. Department of Energy defines a microgrid as “a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode” [8]. Using this definition as a baseline, Giachetti et al. define the four main functions a microgrid must perform: generate power, store energy, distribute power, and provide system control [7]. The specific architectures of a microgrid varies; however, the concept and components remain consistent regardless of the size and application. An example of a simple microgrid is shown in Figure 1.1. While on a small scale, it accomplishes the four functions of a microgrid. High-voltage power is received from the utility grid and stepped down to between 7 and 13 kV and is then stepped down further at loads, two of which are represented at the bottom left and right corners of Figure 1.1. photovoltaic (PV) arrays and the battery produce direct current (DC) power while the loads all operate on alternating current (AC) so the microgrid

requires AC/DC converters with those systems. The system is controlled by varying the positions of the six switches on the electrical bus, changing the source and destination of the power on the microgrid.

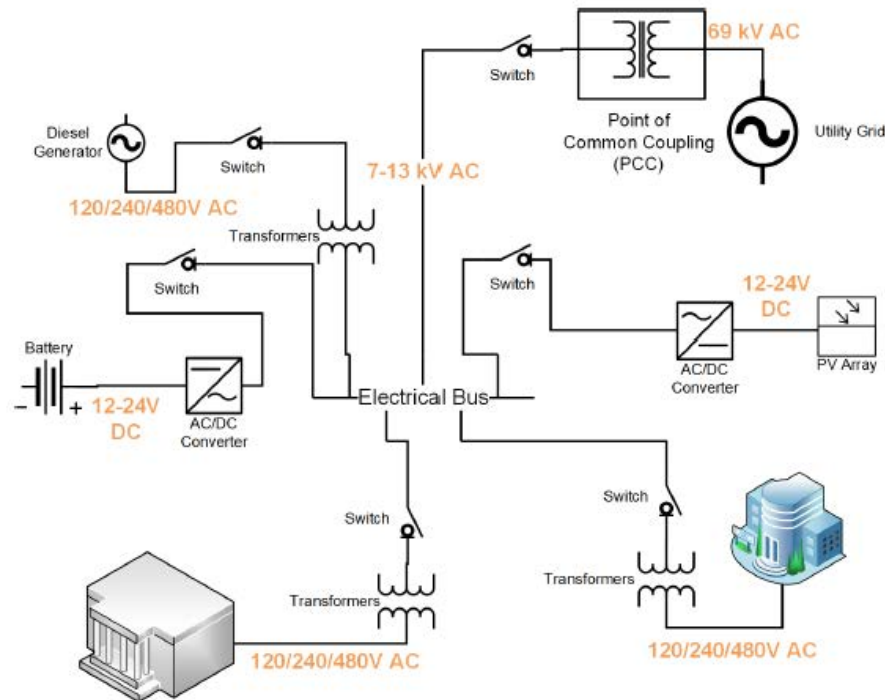


Figure 1.1. Diagram of a Basic Microgrid. Source: [9].

DERs commonly found in a typical military microgrid are PV cells, wind turbines, diesel generator (DG)s, or small combined/heat power generators that all can either be at a central power plant facility or distributed across the microgrid [10]. Microgrids that include renewable energy (RE) resources often include an energy storage system (ESS) that allows for load balancing to offset the unpredictability in electricity generation caused by variable cloud cover and winds [11]. Power can flow both into and out of the ESS, so when the DERs in a microgrid are generating excess power, the microgrid can replenish the state of ESS charge. If the DERs provide insufficient power, then the ESS can provide supplemental power to support the loads. The most common ESS consists of chemical batteries to store DC power. However, flywheels, thermal storage, and pumped-storage hydropower can also be used within microgrids [12]. The distribution system of a microgrid is made

of up the physical lines that move power from the generation/storage location to where it is consumed [13]. These lines can be buried in conduit or strung overhead from utility poles [14]. Power delivered through a microgrid can be either AC or DC power depending on the source, so it is common to find AC/DC converters within a microgrid because the electrical distribution lines transfer AC power. The microgrid controller fulfills the vital role of controlling the flow of power throughout the microgrid. A microgrid controller manages the amount of power each DER provides, the flow of power into or out of the ESS, and the microgrid's connection to the utility grid [15]. The controller uses load priorities and load shedding to manage which loads are receiving power based on the microgrid's operational state. NAVFAC defines loads as either total load, priority loads, or critical loads [6]. When the microgrid is operating connected to the utility grid, all loads receive power (total load). If the microgrid is forced to operate in islanded mode, then the total loads drop off and only priority and critical loads receive power. If the microgrid is islanded and operating under reduced capacity, then the priority loads are also dropped, and only critical loads receive power. A summary of this prioritization is shown in Figure 1.2.

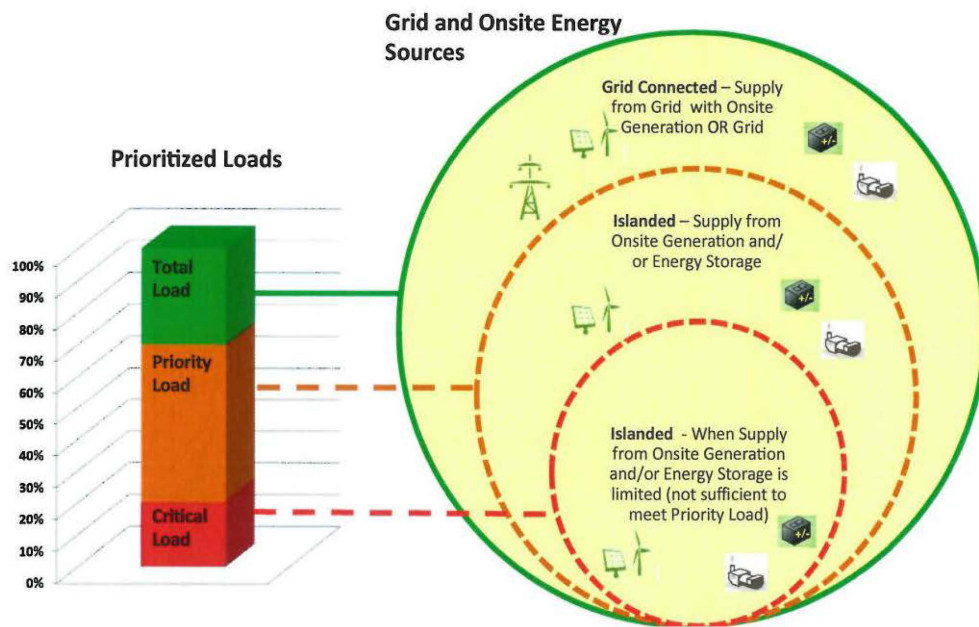


Figure 1.2. Load Priority Categories Used by NAVFAC. Source: [9].

A microgrid can be implemented to increase energy security, reduce energy infrastructure

LCC, increase use of RE sources, or provide power to areas without the infrastructure to access the main power grid among other potential uses [10]. The primary reason that the DoN has begun to implement microgrids is to improve overall energy security [16]. Moreover, DoD policy requires installations must have at least 25% of installation energy provided by RE resources by fiscal year 2025 [2]. The requirement for increased RE use makes microgrids a logical choice to replace stand-alone generators and uninterruptible power supply (UPS) for individual buildings.

Despite their benefits, designing and implementing microgrids does not come without significant challenges. Complex controllers are necessary to ensure that multiple DERs' power is in phase and stable with each other and with the utility grid [17]. Combining a variety of DERs and loads creates the potential for conflicting control and communication protocols that must be addressed by installing additional components to allow for system integration [18]. The Institute of Electrical and Electronics Engineers (IEEE) has made several efforts in the last few years to develop multiple standards to address this issue [19]–[21]. However, many existing microgrid control systems were built and installed before these standards were developed. Additional complexity created by a lack of standards will decrease as older systems are replaced over the next several years.

1.3 DoD Energy Security

The U.S. Navy (USN) currently focuses on a combination of reliability, resilience, and efficiency when assessing energy security. NAVFAC defines energy system reliability as “the percentage of time energy delivery systems can serve customers at acceptable regulatory standards” and includes four critical attributes for reliable electrical systems in Pub-602 [6]. These attributes include proper maintenance, prompt power restoration, and system monitoring/control functions. Pub-602 also defines energy efficiency as “the use of minimal energy required to achieve the desired level of service,” stating that inadequate maintenance and outdated equipment are possible contributors to an inefficient system. Aging energy infrastructure is vulnerable to failure due to components reaching the end of life, accidents, natural disasters, or deliberate attacks. The third NAVFAC pillar of energy security is resilience and is defined as “the ability of a system to anticipate, resist, absorb, respond, adapt, and recover from a disturbance” [6]. The threats the USN considers as possible causes for a disturbance are “weather events, accidents, geo-magnetic storms, terrorism,

fire, cyber-attack, and the effects of climate change” [6].

There are several examples of disruptions to civilian electrical grids due to deliberate attacks, whether physical attacks or cyber-attacks. Physical attacks can target specific substation components, high voltage transmission lines, or distribution line towers themselves [22]–[24]. A specific example occurred in 1974 when 14 transmission towers in Oregon were bombed by extortionists [25]. Two successful cyber attacks in Ukraine resulted in widespread power loss in 2015 and 2016 [26]. Successful cyber attacks against power systems have caused several countries to consider the cyber defense of critical infrastructure, a significant facet of their overall national defense strategy [27]. There have also been several large-scale blackouts throughout the world, such as the blackout in the United States and Canada on August 14, 2003, and a Moscow blackout on May 25, 2005 [28]. Failures of the microgrid and its components can also create a substantial threat to energy security. While there are not widespread examples of damage to microgrids by a deliberate attack, microgrids are still vulnerable to deliberate. There are examples of damage to microgrid components or above-ground transmission lines caused by significant weather events such as hurricanes [29].

Due to military installations’ functions, attacking either the primary utility grid or an installation microgrid can be an attractive target for state actors or terrorists. Maintaining a constant flow of electricity to military installations is critical to national security, specifically as command and control systems become more advanced and reliant on power. As an example of the critical nature of maintaining constant flow of electrical energy to critical loads on military installations, unmanned aerial vehicles (UAVs) flying in theater are often controlled and piloted from thousands of miles away in United States; an interruption to power to the UAV control station could in theory result in a complete loss of an aircraft. Military installations are home to critical functions to maintain mission readiness. They also host organizations that conduct critical research, development, and testing of new technology. All these roles the installation fulfills require stable and reliable electrical power [30]. This makes military installations a higher value target compared to civilian facilities [31]. The distribution components on several DoD installations are not well protected and very close to the fenced perimeter [9]. The proximity to unsecure areas makes these components vulnerable to deliberate sabotage, similar to the Metcalf incident. In 2013 a gunman opened fire on the Metcalf Transmission Substation in Santa Clara, CA, damaging 17 transformers [32]. Although this incident did not cause a significant loss of power due

to the ability to reroute service from other transmission substations, it does demonstrate creative ways to damage a distribution system. DoD installation energy security must be addressed in “a systematic and systemic way to assure mission accomplishment” [7].

1.4 Cost Estimation

Any large-scale government acquisition project requires a complete cost estimate before procurement, and a microgrid is no different. Cost estimates are critical to government programs because they support budget decisions, long-term planning, and assist in analyzing alternatives [33]. As required in [34], cost estimation and analysis must consider the entire life cycle for federal energy programs and buildings. A LCC includes the totality of resources necessary from initial conceptual design through the project’s disposal. A life cycle is typically broken down into four main phases, research and development, investment, operating and support (O+S), and disposal [33]. RE resources are often compared using the metric “levelized cost of energy (LCOE),” which “measures lifetime costs divided by energy production” [35]. LCOE can be used as a benchmarking tool to compare energy technology with different life spans and energy capacity [36]. It is a useful metric to estimate cost and compare alternatives when the goal is to minimize the cost over a product lifetime. However, it is an inadequate metric if the goal is to maximize resilience or estimate the cost of resilience in a specific microgrid application.

1.5 Research Method

The research conducted for this thesis is both experimental and analytic as defined in [37]. A simulation microgrid model was further developed using linear programming to quantify the resilience of a specific architecture based on various failure modes. A cost model is then developed to estimate each architecture’s LCC. A design of experiments (DOE) is used to ensure all potential microgrid architectures are included in the analysis. By conducting a regression analysis of cost versus resilience, the relationship of cost to resilience is quantified to inform the design decisions for a naval installation microgrid. The relationship between cost and resilience can be analyzed to determine how sensitive the outcome is to input variables.

Cost estimates play a critical role in the SE process. The systems engineer uses LCC

to influence design decisions and trade-off analysis when determining contracting and production schedules [38]. Throughout DoD acquisition, SE is used to “influence the balance between, performance, risk, cost, and schedule” [39]. The information output from the methodology developed in this thesis will be critical to trade studies conducted during microgrid acquisition and design, which is a core knowledge area of the systems engineer [7]. This research utilized a microgrid model developed using linear programming to quantify the resilience of a specific architecture based on various failure modes. A DOE is used to ensure all potential microgrid architectures are analyzed for both cost and resilience.

1.6 Chapter Summary

This chapter has discussed the objective of this research as well as the method that is used to answer that objective. It outlines the basic principles discussed in this thesis and how the research fits into SE. The remaining chapters include a review of prior and related work, outline the process to quantify the cost, and conduct a case study. Chapter 2 consists of a literature review to define similar work that has been conducted on microgrid resilience and resilience cost estimation. It identifies gaps and discrepancies within that work that are be filled by this research. Chapter 3 outlines the process to quantify what resilience costs. The process is demonstrated in Chapter 4 by applying the process to a case study with a small-scale microgrid, representative of a portion of Naval Support Activity Monterey (NSAM). Chapter 5 provides a conclusion for the research and recommendations for future study.

CHAPTER 2: Literature Review

The purpose of this chapter is to review relevant prior research into microgrids, energy security, and cost estimation. This chapter identifies gaps or deficiencies in the current methods for quantifying resilience and estimating the cost of a microgrid.

2.1 Microgrids

This section reviews the design process for a microgrid and review the basic principles of energy security related to the U.S. military. The systems and software used to assist in the design of microgrids are reviewed to understand the objective of each tool.

2.1.1 Overview and Design

The U.S. Department of Energy and IEEE define a microgrid as “a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid” [8], [20]. A microgrid generally has a single interconnect point with the utility grid to feed offsite power to the microgrid and allows the microgrid to operate in islanded mode if desired [20]. When a microgrid connects to the utility grid, the microgrid either draws power from the grid, supplements grid power using microgrid DERs, or if a microgrid generates more energy than the microgrid needs to support internal microgrid loads, a microgrid can supplement the utility grid with the excess power if it is economically advantageous [16]. Since microgrids are a relatively new and still maturing technology, standards for microgrid design and interface with the overall utility grid are limited and continually being updated and improved. IEEE Standard 1547 series covers the interconnection and interoperability of DERs and associated systems, while IEEE Standard 2030 series covers microgrid controllers [19]–[21].

NAVFAC P-601 provides an overview of a three-phase process to design and implement a microgrid on a naval installation [16]. During the pre-design phase, designers conduct a site evaluation to determine specific system boundaries and building classification. The pre-design step will also utilize NAVFAC’s Distributed Energy Resource Grid Optimization

Services (DERGOS) to conduct computer model analysis for the proposed microgrid. The next phase required in [16] is a concept design, where design options still under consideration are selected and a cost estimate is completed. The concept design phase also includes a detailed Concept of Operations (CONOPS) for the microgrid. The process ends with the delivery method phase where a final build design is approved, and the request for proposal is submitted [16]. An analysis of energy security and microgrid resilience is important to consider during the concept design phase. It is especially important for decision makers to understand the cost of system resilience.

Several design tools exist to determine the optimum microgrid architecture for a specific application. Many of these design tools minimize cost or carbon emissions of the microgrid but do not focus on the ability to accomplish the mission in the event of a disturbance. The Lawrence Berkeley National Laboratory (LBNL) has been developing the Distributed Energy Resources Customer Adoption Model (DER-CAM) since the early 2000s, focusing on the cost-effective design of on-site generation and combined heat and power systems, with the objective of minimizing the total system cost [40]. A goal of DER-CAM is to develop “resilient microgrids that reduce energy costs and CO_2 emissions” [40]. However, resilience is not an objective function. Sandia National Laboratory developed the Microgrid Design Toolkit (MDT) and is intended to support decisions made early in the design of a microgrid, focusing on minimizing cost and maximizing system reliability [40]. National Renewable Energy Laboratory (NREL) has developed both REopt and REopt Lite to assist with the implementation of RE technology. REopt is only available to organizations directly working with NREL, so it could not be fully assessed as a part of this research. REopt Lite is a straightforward web-based interface that assesses a single load but can provide a probability of the system to meet critical load requirements depending on the length of an outage. HOMER Pro is a software product developed to provide an hourly assessment of all possible design combinations based on user input, focusing on optimizing economic impact [41]. While these design tools all provide detailed information on microgrid performance, none of the existing design tools focus on assessing or optimizing the microgrid’s resilience. The only microgrid design tool currently available that specifically focuses on microgrid resilience is developed by Peterson when proposing Expected Life Cycle Mission Impact (ELMI) as a metric to define resilience [9].

2.1.2 Energy Security

NAVFAC is the organization that is primarily responsible for Energy Security on naval installations. NAVFAC, in alignment with 10 USC 2924, defines energy security as “having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet mission essential requirements” [3], [6]. Energy security is implemented through three distinct pillars: reliability, resilience, and efficiency. These pillars of energy security are shown in Figure 2.1. Reliability can be measured using System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and availability which are three metrics commonly used by electric power utilities to indicate system reliability [6], [42]. Efficiency is achieved and improved by optimized load management and demand response programs. A list of energy security benchmarks is outlined throughout [6] that all naval facilities must meet or exceed. In terms of resilience, P-602 calls for the widespread use of redundant emergency generators, UPSs, and fuel storage capacity [6]. A list of installation best practices is included in P-602 to outline ways building and installation energy managers can improve their installation’s overall energy security.

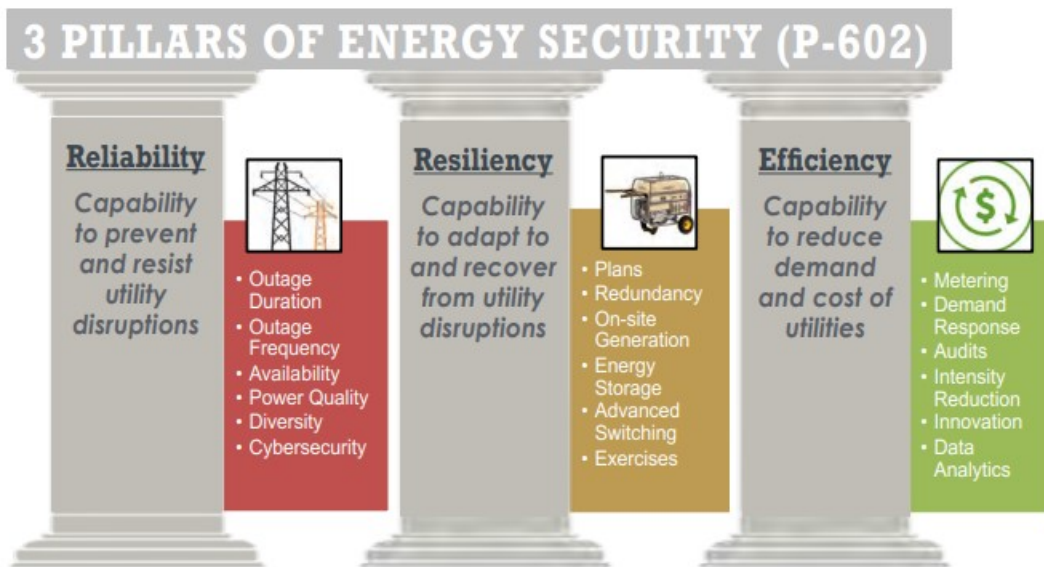


Figure 2.1. Three Pillars of Energy Security as defined by NAVFAC P-602. Source: [1].

In addition to the benchmarks installations must meet, each military service has its own

standards for how long an organization should be capable of operating without utility power. The Army must have the power capacity and water on hand to maintain critical missions for a period of at least 14 days [43]. The Marine Corps should be prepared to “stay mission operable off of the grid for at least 14 days” [44]. The Navy has less-specific guidance for the length of time an installation should be expected to operate without connection to the utility grid. The Navy is required to ensure each installation has a minimum of seven days of fuel storage, but fuel storage requirements can be met through a confirmed delivery source [6], [45]. The Navy does not provide a standard for how long an UPS should be able to provide power to a building or piece of equipment. This research considers resilience throughout a 14-day outage to remain consistent with the worst-case scenario presented by the Army and Marine Corps.

2.2 Resilience

This section focuses on reviewing the literature covering resilience definitions, metrics, and the factors that influence microgrid resilience.

2.2.1 Definitions

Before estimating the cost of, or quantifying resilience, a definition for resilience must be agreed-upon. The terms resilience and resiliency are used interchangeably throughout the literature. This research uses resilience for consistency. Several organizations define resilience differently depending on their preferred application, but in its simplest form, resilience refers to the ability to function in the presence of a disturbance [46]. This section reviews definitions of resilience, focusing on energy and infrastructure applications. A 2013 White House Presidential Policy Directive on Critical Infrastructure defines resilience as

the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents. [47]

U.S. Code §101(e)(6) defines energy resilience as

Energy Resilience means the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements. [48]

U.S. code also defines energy resilience of military installations, stating that the installation as a whole must be able to maintain the ability to execute the mission in the presence of a disturbance [48]. The DoD defines energy resilience as “the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations” [5]. NAVFAC P-602 defines resilience as a facility’s ability to “anticipate, resist, absorb, respond, adapt, and recover from a disturbance” [6]. This definition continues by listing the types of disturbances that a naval installation could encounter, such as extreme weather, terrorism, or cyber attack. Researchers from the University of Virginia used a more general definition for resilience as, “an ability to withstand, adapt to, and recover from a disruption” [49], when analyzing scenario-based resilience of energy microgrids. After conducting a thorough review of all resilience literature, Peterson concluded that a definition that closely aligned with DoD resilience objectives, and the system functions of a microgrid is “the ability of the system to maximize functionality in the event of a disruption” [9]. He continues to state that resilience must consider both the impact and likelihood of a disruption across the entire set of potential disruptions.

After reviewing the definitions above, the author has determined that the Peterson definition of resilience is the most useful for electrical energy applications and it is used throughout the remainder of this thesis. While all definitions discussed in this section discuss the how a system responds to a disruption, the definition developed by Peterson focuses specifically on the importance of understanding impact and likelihood of a disruption occurring. Peterson’s definition is also broad enough to ensure that the possible disruptions can be tailored based on the specific area being assessed. It also is in alignment with the definitions defined by both the DoD [5] and NAVFAC [6] so it can be used for applications to electrical energy resilience of naval installations.

2.2.2 Metrics

It is critical to have a quantifiable metric to measure the level of resilience a specific installation energy system or microgrid possesses. This section covers a review of the various metrics used throughout the energy community to measure and define resilience. Metrics for quantifying resilience is an active field of study within the energy community with no agreed-upon standard in widespread use [50]. This section reviews the literature on several methods used and identify the best metric to use as part of this research.

The DoN uses the Energy Security Assessment Tool (ESAT) to assess DoN shore-based installations for energy security scores. ESAT is a qualitative assessment of reliability, resilience, and efficiency based on the generation facilities available and the utility grid infrastructure. ESAT scores each of the three pillars between 0 and 100 and then sums these pillar scores [51], [52]. A radar plot is then used to show the overall scores, as shown in Figure 2.2. The resilience score is based purely on a set of questions about the number of buildings with backup power sources and mission redundancy. The metric used in ESAT does not align with the Navy's resilience definition because it doesn't account for system behavior after a disturbance. The ESAT score is mostly based on a qualitative assessment rather than a quantitative evaluation of system performance.



Figure 2.2. Summary of Energy Security Assessment Tool for a Navy Shore-Based Facility. Source: [51].

After identifying the flaws in ESAT’s resilience score, researchers at Massachusetts Institute of Technology (MIT)’s Lincoln Laboratory developed the Energy Resilience Assessment (ERA) tool to help determine the best arrangement of electrical generation and storage on military installations that is resilient but at the lowest cost [53]. The ERA follows an eight-step process. The ERA tool provides insight into the types of energy system architectures to cost-effectively pursue with more detailed system design tools. ERA considers the unmet load to be a metric for resilience [54]. The ERA utilizes a MATLAB Monte Carlo simulation to calculate various microgrid architectures’ performance utilizing a year of load profiles and resource availability and implementing random failures based on component reliability data. The model is repeated several thousand times to find the average unmet loads, but the model output does not provide information about variability about the data. Each architecture is also input into a financial model to develop a life cycle cost estimation (LCCE). The cost vs. unmet load can then be compared to understand the architectures that are worth further study. Because the tool is only available in MATLAB, it is not available for widespread

use by energy managers throughout the DoD [55]. A critical input to the ERA is reliability data, and ERA therefore provides a relationship between reliability and cost rather than resilience.

The use of reliability or availability data to quantify resilience is common. An increase in operational availability was used to quantify improved resilience for adding a solar PV and battery at a Southern California telecommunications facility [56] using REOpt. The REOpt tool developed by NREL to compare the length of an outage a DG-only microgrid had a 90% probability of surviving to the outage a RE microgrid could withstand. SAIDI and SAIFI are used by utility companies to quantify reliability and have been used to analyze resilience [28], [57].

Several researchers have proposed methods to model resilience as system performance over time. The first method used was developed by Bruneau to plot infrastructure performance after a seismic event [58]. This method proposes a resilience triangle plotting the quality of the infrastructure as a function of time, with an immediate reduction due to the seismic event, and linear improvement until returning to full capacity. Figure 2.3 shows an example of a basic resilience triangle.

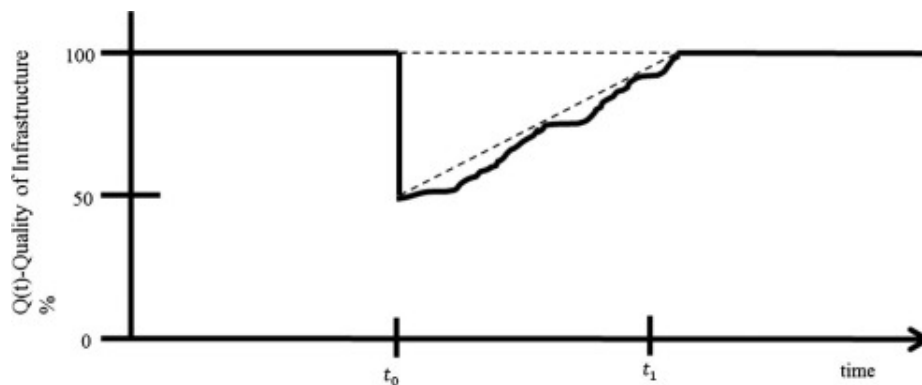


Figure 2.3. Resilience triangle of infrastructure performance as a function of time, based on a significant failure event. Source: [59].

The resilience triangle has been paired with modeling and simulation to analyze the performance of several systems such as infrastructure after natural disasters or the number of passengers that the London Underground can service in 24 hours [59], [60]. Henry and Ramirez-Marquez propose a resilience trapezoid that monitors a steadily degraded state

after the disruptive event until a system reaches its steady disrupted state. They assert that a specific resilience action must occur before the system steadily improves performance until returning to a fully recovered state [61]. Yodo and Wang expand the resilience triangle and trapezoid to identify five specific stages a system goes through that all influence resilience: reliability, unreliability, disrupted, recovery, and recovered [62]. Analysis of the five stages of failure creates a “resilience curve.” Resilience triangles or curves for various systems designed can be compared to analyze the overall system performance. A critical component to either plot is understanding the system performance plotted on the y-axis and how to quantify the system performance. While these methods capture the dynamic behavior, they are not be used in this research. In order to analyze system resilience against cost it is important to have a single one-dimensional metric for resilience. Having a single resilience and cost number for each microgrid architecture allows for the comparison of multiple architectures and facilitate regression analysis.

Peterson examined the metrics reviewed above and proposed a new resilience metric, ELMI [9]. The ELMI metric focuses on the impact an outage has on the installation’s ability to complete its mission. The impact is based on the total number of hours a microgrid is unable to support the load. Equation 2.1 shows Peterson’s method for calculating ELMI where M_s is the mission impact for a specific failure scenarios, s , and $Pr(S = s)$ is the probability of that specific scenario occurring.

$$ELMI \equiv \sum_{s \in S} Pr(S = s)M_s \quad (2.1)$$

Peterson’s seven step process to quantify resilience is quoted below. These steps are intended to be used by installation energy managers to assist in understanding resilience of a proposed microgrid architecture.

1. Define the critical load and contribution of mission achievement from each facility served by the microgrid
2. Generate the list of scenarios, S , and estimate the probability of each, $Pr(S = s)$, for each scenario s .
3. Determine the recovery time to restore lost functionality from the impacts identified in the previous step.

4. Map the dependency of mission impact against loss of critical load.
5. Simulate the microgrid system for each scenario s to determine the mission impact under that scenario.
6. Calculate the total expected mission impact.
7. Analyze the results. [9]

Peterson developed a model to simulate the performance of a microgrid installed in Monterey, CA, representing a portion of NSAM where NPS is located. Peterson’s model is dependent on the duration of an outage but does not differentiate the difference in resilience between one extended outage or many short outages. Additionally, the proposed method to quantify the mission impact in step four remains subjective based on the installation energy manager or Commanding Officer (CO)’s perspective. Utilizing Mission Dependency Index (MDI) to quantify mission impact rather than the subjective value for M_s proposed by Peterson would significantly improve the ELMI model. Commander, Navy Installations Command (CNIC) uses MDI to “capture the operational mission impacts of facility degradation or outage” [63]. MDI survey assessments are conducted for every naval installation on a five-year cycle and rely on qualitative input from mission experts. The mission interdependencies (MD_B) and intra-dependencies (MD_W) are assessed through four questions and scoring matrices. The MDI is calculated for each building and then aggregated to provide a total MDI score for the installation. This information can be used to support decisions on where to allocate limited security and infrastructure resources [63]. Equation 2.2 shows how the total MDI is calculated for a specific naval installation.

$$MDI = 16.5[MD_w + \frac{MD_{bAvg}}{8} + 0.1 \ln N] - 15.5 \quad (2.2)$$

The U.S. Air Force, Army, and National Aeronautics and Space Administration (NASA) have their own similar versions of MDI that they use to understand risk to mission [64]–[66]. While used throughout the government, MDI is not a perfect metric for quantifying the mission impact [67]. Kujawski and Miller propose five fallacies and misuses of MDI taking issue with the answers’ subjectivity, questioning the coefficients used in Equation 2.2, and calling the system overly complex. Despite these issues, MDI data is readily available for every naval installation, making it a useful metric to input into Peterson’s ELMI model.

In addition to the literature reviewed above, two NPS students are developing their own

models and metrics for estimating resilience. Bill Anderson, an SE PhD candidate, is developing a microgrid resilience model that quantifies resilience as the relationship between invulnerability and recoverability from an unanticipated disturbance. His model is developed to focus on installations' resilience, utilizing a microgrid with no connection to the utility grid [68]. LT Dan Beaton, an SE student, is developing a model to capture the dynamic behaviors of resilience, utilizing a similar model developed by Peterson [69].

The most complete metric for quantifying resilience is Peterson's ELMI. This thesis utilizes ELMI with the slight modification of using MDI to quantify mission impact. By using MDI to quantify mission impact, the ELMI metric is improved. ELMI has also been selected because it was developed with the sole purpose of quantifying the resilience as Peterson defined and was selected in Section 2.2.1. ELMI accounts for both the probability of a disturbance occurring and the impact of the disturbance. ELMI allows the installation energy manager to consider all possible microgrid failure modes and model the performance for each of them to determine the impact to mission. ELMI is also a one-dimensional number that allows for direct comparison to cost for each architecture as proposed in this thesis. The case study conducted in Chapter 4 of this thesis utilizes ELMI to quantify resilience of each microgrid architecture.

2.2.3 Factors that Affect Resilience

Microgrid resilience can be affected by any component of the microgrid or connected infrastructure that has the potential to fail. By reviewing the resilience metrics above, and several microgrid design models, a list of factors that affect resilience is presented in this section. Table 2.1 summarizes the microgrid design parameters that contribute to system resilience.

Table 2.1. Summary of Factors that affect microgrid resilience.

No.	Factor that Affects Resilience
1	Size of ESS*
2	Layout of distribution cables (above or below ground)
3	On hand fuel storage capacity*
4	Distributed for centralized DERs*
5	Size of DERs*
6	Level of investment in system maintenance
7	System redundancy
8	Reliability and maintainability of all microgrid components
9	Rate and probability of fuel resupply

Note: Items annotated with an * are the factors that are controlled variables in the ELMI model developed by Peterson [9].

The size of the ESS and DERs directly impact a microgrid's ability to provide power when the utility is lost. The ability to provide power in the absence of a utility grid makes them critical to maintaining system performance [16], [31]. If DERs are centralized, there is a risk for a single event to damage multiple components [32]. If an installation runs out of fuel or is unable to be refueled during the utility outage, distributed DGs will not provide the necessary backup power [70]. The use of redundant systems improves reliability and enhances a microgrid's ability to withstand an outage or component failure [71]. The configuration of distribution lines plays a significant, but conflicting role in resilience. A distribution line that is buried is less susceptible to damage in a windstorm but takes longer to repair if it is damaged [72]. Alternatively, an above-ground power distribution line is more vulnerable to damage but can be repaired in less time [72], [73]. The metrics annotated with an * in Table 2.1 are the only factors considered in this thesis as they are controlled variables in the ELMI model selected for quantifying microgrid resilience. While improving the ELMI model developed by Peterson to include all nine factors listed in Table 2.1 is important, it is outside the scope of this research. Therefore, the only factors that are modeled in this thesis

are those annotated with an *.

2.3 Cost Estimation

A critical metric in the decision-making process is the development of cost estimates. The Government Accountability Office (GAO) Cost Estimating Guide [74] defines cost estimating as “the summation of individual cost elements, using established methods and valid data, to estimate the future costs of a program, based on what is known today.” A reasonable and credible cost estimate is critical to assist in budgeting and long-term planning [33], [74]. The most detailed type of cost estimate is an LCC, which covers the system’s entire life cycle and can be developed by either a program office or an independent entity. Less common cost estimates used throughout [74] are independent cost estimate (ICE)s, budget estimates, rough order of magnitude (ROM) estimates, and estimates at completion (EAC)s. The less common types of cost analysis (ICE, EAC) are not reviewed in this research as they are not used for microgrid and energy applications. This section covers common methods for obtaining a LCC and specific application to microgrids. Various types of costs can be used in cost estimation, and this section identifies the most applicable to microgrid resilience. A review of literature attempting to quantify the cost of resilience is also included.

2.3.1 Traditional LCC

Four distinct phases are considered when developing a system LCC: research and development, investment, O+S, and disposal. The majority of money is typically spent in upfront investment and operation and support. Figure 2.4 shows the relative relationships between the four phases. The research and development phase includes all costs associated with a systems design, fabrication, building, as well as test and evaluation [33]. Investment costs include all costs associated with procurement, installation, training, and related support equipment [33]. Operations and support costs are any cost necessary to operate and maintain the system, including personnel and sustainment [33]. Disposal costs typically make up the smallest portion of costs but can be considerable depending on any significant long-term waste storage or environmental restoration costs. [33]. Both [33] and [74] provide insight as to possible data sources and methods for gaining cost data.

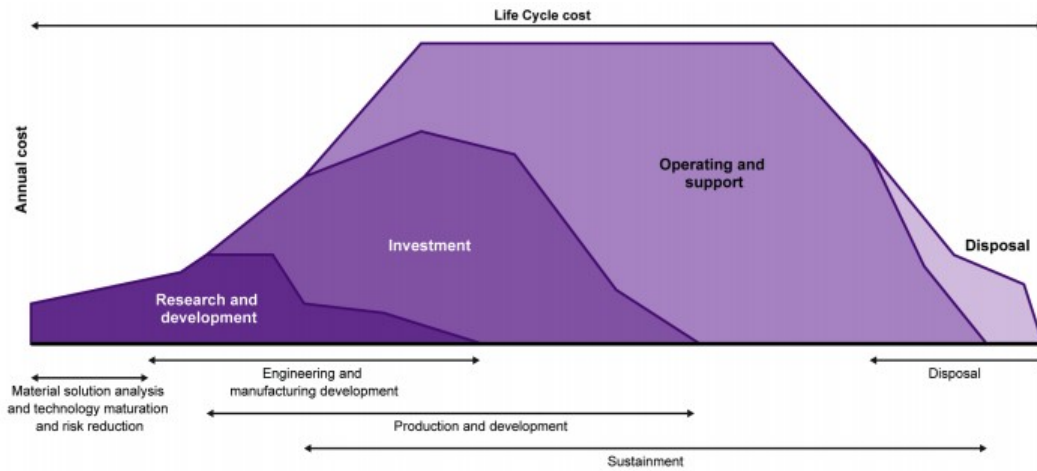


Figure 2.4. Phases of a System LCC and the relationship between annual cost and LCC. Source: [74].

Three methods typically used to develop a cost estimate are analogy, parametric, and engineering build-up. An analogy estimate uses a single historical data point to compare the current system [33]. Despite being the most straightforward method, there are several potential error sources due to only relying on a single data point. A parametric cost estimate uses several historical data points to determine the relationship between cost and technical characteristics using regression [33]. The most complex and time-consuming of the three is an engineering build-up estimate, where an itemized price for each component is developed using cataloged labor and material costs [33]. The specific advantages and disadvantages of these methods are covered in detail in [33].

2.3.2 Application to Microgrids

Microgrid LCCs are typically listed as either a net present value (NPV), LCOE, or LCCE. This section discusses the benefits and drawbacks of each type of cost. NPV accounts for the time value of money to compare the present value of costs and benefits that occur spread out over a system's life cycle [33]. NPV is valuable when conducting CBA to determine which microgrid design should be selected from a group of proposed architectures. An LCCE does not consider positive cash flow but discounts future costs to account for inflation using a discount factor [75]. Both NPV and LCCE are used throughout the cost estimating field, for analyzing all kinds of projects, including energy systems [33], [75], [76]. LCOE

is similar to an NPV however, LCOE is used solely for energy applications. By dividing the NPV by the energy systems generating capacity (could be individual DER or the combination of DERs in a microgrid), system designers can compare different energy sources on an equivalent scale, typically described in \$/kWh [75]. National Institute of Standards and Technology (NIST) Handbook 135 [76] and the annual supplement [77] provide the guidance for calculating LCCE and NPV for all buildings and facilities that fall under the Federal Energy Management Program (FEMP). The annual supplement specifically includes energy price indices and discount factors to be used for “all energy and water conservation and RE projects in federal facilities” [77]. The steps outlined in [76] are the basis for microgrid cost estimation conducted within this research.

2.3.3 Application to Microgrid Resilience

The application of cost estimating to microgrid resilience is relatively limited. Two recent studies have modeled microgrid performance and analyzed the microgrid cost to determine the added cost necessary to achieve a more resilient microgrid. A 2017 paper that studied the added resilience provided by an RE utilized the difference in NPV of the three systems to determine the increased investment required for more resilient microgrid [56]. The research used the REopt model to optimize the microgrid architecture to achieve the desired performance while minimizing system cost. The 2017 paper only compared three microgrid architectures and could have neglected to include the most resilient solution. The metric for resilience in [56] paper was the length of grid outage the microgrid could survive. The cost estimate in [56] used a 25-year life cycle and compared both LCCE and NPV. The paper did not include the cost of lost performance in the model. Hamilton [49] attempted to include the cost of lost mission in the cost estimation by considering the labor costs of downtime as a proxy. She assumed this based on the assumption that there is a loss of productivity when the system cannot operate. This assumption is application-specific and does not work across all scenarios. Other than considering the additional cost of lost load, the two frames studied in [49] are mostly independent and the analysis did not relate the resilience scores to cost. Hamilton’s research used a ten-year life cycle to determine the NPV. The process developed in this thesis aims to more thoroughly define how to determine how much it costs to improve system resilience. NPV is the best metric to use to quantify the LCC of microgrid resilience because it covers the microgrids entire life cycle and accounts for both positive and negative cash flows while scaling all costs to constant year dollars. NPV is the

only metric used in the limited literature available when dealing specifically with microgrid resilience and is therefore used throughout this thesis.

2.4 Chapter Summary

This chapter reviewed the relevant literature that forms the basis for the research conducted in this thesis. The various tools used to design microgrids were discussed and a fundamental review of what makes up a microgrid. Multiple definitions and metrics for quantifying resilience were discussed, identifying strengths and weaknesses. The chapter closed with a review of cost estimating as applied to microgrids and resilience. Chapter 3 proposes a process for estimating the cost of resilience in a microgrid.

CHAPTER 3: Resilience Cost Estimation Process

This chapter synthesizes the background information discussed in Chapters 1 and 2 and develops a process to estimate the cost of resilience in a microgrid. Chapter 2 of this thesis determined the most appropriate metric to quantify microgrid resilience and the best metric to describe LCC. If new information or metrics become available to quantify resilience and LCC base energy managers must verify the selections made in Chapter 2 are still applicable. If not, then the analysis should be conducted with the metrics the installation energy manager deems most appropriate for their situation. The case study conducted in Chapter 4 of this thesis utilizes ELMI and the associated modeling program to quantify microgrid resilience and NPV to describe microgrid cost. This research proposes seven steps to quantify the cost of resilience:

1. Conduct a DOE to identify possible microgrid architectures.
2. Simulate microgrid performance for each microgrid architecture to determine the resilience score.
3. Estimate the LCC for each microgrid architecture.
4. Analyze results of DOE for both resilience score and LCC.
5. Generate a plot of cost versus resilience for all microgrid architectures identified in Step 1.
6. Conduct regression analysis of the plotted data to identify potential relationships between cost and resilience.
7. Analyze results for sensitivities and make budget and microgrid design recommendations.

The remainder of this chapter elaborates on each step's goal and discuss assumptions and recommendations for each.

3.1 Steps to Estimate Cost of Microgrid Resilience

3.1.1 Step 1: Conduct DOE

The first step to quantifying the cost of microgrid resilience is to identify the different ways the microgrid can be configured, that is, the possible combinations of microgrid components that make up the microgrid being studied. Before conducting this step, installation energy managers will need to have assessed the buildings and loads the microgrid will service. Using the load assessment as a baseline, installation energy managers should utilize a DOE to determine all possible combinations of DERs and ESSs to make up the microgrid. The number of factors to be included in the DOE is dependent on the number of controlled variables in the microgrid performance model that will be used. To be included in the DOE, each factor must have at least two levels (a high and low value) but may include additional levels if desired. The high and low values for each factor should be dependent on the service requirements for total and critical loads and data that influences system performance, such as solar incidence data for the geographical location under evaluation. If possible, it is important to execute a full factorial DOE to ensure all interactions between various sizes of DERs and ESSs are analyzed.

3.1.2 Step 2: Simulate Microgrid Performance

Using the selected microgrid performance simulation tool, determine each microgrid architecture's resilience score. It is useful to simulate microgrid performance under the worst-case scenario to evaluate the lowest possible resilience score. It is up to the installation energy manager to identify the worst-case scenario for the specific application. In general, the worst-case scenario is likely the most prolonged period the microgrid will need to perform in islanded mode. The worst-case scenario would also occur during the time of the year with the worst expected PV performance. This research assumes that a 14-day outage from the main utility grid is the longest the microgrid is expected to operate. The worst-case scenario is defined as the 14-day period with the lowest daily average solar incidence for the geographical area under evaluation.

3.1.3 Step 3: Estimate Microgrid LCC

After gathering the necessary resilience data, the installation energy manager develops (or obtains) an estimate for LCC for each microgrid architecture. A critical factor in the LCC of a microgrid is the length of time that should be considered the microgrid's life. As discussed in Section 2.3.3 there is no agreed-upon life cycle for a microgrid. NAVFAC proposes the period of assessment to be 40 years or the lifespan of the energy system, whichever is lower [78]. This research recommends that the energy system lifespan be the same as the component with the lowest expected useful life. The following list includes all of the components to consider when determining a microgrid's LCC.

- Layout and design of DERs
- Layout and design of the ESS
- Distribution Lines
- Transformers
- Microgrid controller
- AC/DC converters
- Switches and breakers
- Average annual DG fuel consumption
- Infrastructure required to tie microgrid into the main utility

This research recommends that the cost estimate developed in this process only includes the cost of components that change in each architecture. A reasonable assumption is that the cost to install distribution lines, switches, AC/DC, transformers, and the microgrid controller is constant regardless of the microgrid architecture. The costs to tie the microgrid into the main utility grid can also be treated as a constant cost regardless of microgrid architecture. The constant costs are ignored because they would have the same impact on the overall LCC regardless of architecture being evaluated, equally increasing the LCC of each architecture. These costs are known in cost-benefit analysis as “wash costs” [79].

3.1.4 Step 4: Analyze DOE Results

The installation energy manager must use the results from steps two and three to ensure the DOE conducted in step one includes the full range of microgrid architectures are being analyzed. This is done by analyzing the main effects plots for both resilience and LCC. Any

factors that do not have a significant impact on either resilience or LCC can be considered to be removed from the DOE. If any of the factors show they have significant impact on resilience or LCC the installation energy manager should consider adding more levels to the DOE. If the base energy manager determines that the DOE needs to be expanded to include more microgrid architectures, they must repeats steps one through three.

3.1.5 Step 5: Plot Data

The installation energy manager then takes the resilience score and LCC for each microgrid architecture and generates a scatter plot. The x values are microgrid resilience, and the y values will be the microgrid LCC. This plot is utilized to identify potential relationships between the two factors.

3.1.6 Step 6: Conduct Regression Analysis

Then appropriate regression analysis of the cost versus resilience plot to identify the potential relationship between the two values is conducted. Several regression models may be relevant to consider before determining the best way to quantify the relationship. There is also the potential to need to separate the data into separate clusters depending on specific microgrid architecture traits to allow for a more accurate regression estimate.

3.1.7 Step 7: Analyze Results

Finally, the installation energy manager should utilize the regression equation to determine how much an incremental resilience improvement will cost. This understanding can be used early in the microgrid design process to justify requested funding and determine the point where improved resilience is no longer worth the increased cost.

3.2 Chapter Summary

This chapter identifies a seven-step process that can be applied by installation energy managers to estimate the cost of resilience for a specific microgrid application. This thesis proposes the use of ELMI as the resilience metric and NPV to describe LCC to implement these steps, but it could theoretically be applied using any resilience metric and LCC value. If another resilience metric or LCC are used the installation energy manager will need

to justify these by conducting a thorough review of applicable literature as conducted in Chapter 2 of this thesis. The output of this process is critical to helping to justify the design of a microgrid with improved resilience and understanding the impacts to the overall system cost. The process developed in this chapter is demonstrated by applying it to a case study utilizing a representative of a portion of NSAM in Chapter 4.

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CHAPTER 4: Case Study Analysis

This chapter applies the process developed in Chapter 3 to a case study on a microgrid that is representative of a microgrid at NSAM in Monterey, CA. NPS is the primary tenant command at NSAM. The electrical distribution system is shared between both NPS and NSAM buildings. This case study uses ELMI as the resilience metric, using the process developed in [9], and NPV as the LCC cost metric for each architecture. The case study is conducted to demonstrate how an installation energy manager could use the process to guide decisions when designing and/or upgrading an installation microgrid. The baseline microgrid used in this thesis is the same microgrid used in [9], however each load was assigned to a specific building at NPS/NSAM.

Figure 4.1 shows the one-line diagram for the case study microgrid, including all loads, DERs, AC/DC converters, switches, and transformers. It is made up of five loads of varying sizes, one PV array, one ESS, two DGs, and a tie in to the utility. The loads are labeled EP1, EP3, EP4, EP5, and EP6. EP1 is representative of the Flag Admin Building at NPS. EP3 is representative of the U.S. Post Office on NSAM. EP4 is representative of NPS's Bullard Hall. EP5 is representative of NPS's Ingersoll Hall. EP6 is representative of the Hazardous Gas Storage facility on NSAM. The distribution system is made up two electrical busses, BUS1 and BUS2. BUS1 is energized by GENSET1 and GENSET2 or the utility grid. Loads EP1, EP5, and EP6 receive power through BUS1. BUS2 provides power to EP3 and EP4. BUS2 is energized from by the PV array and ESS. A single distribution line is used to connect BUS1 to BUS2 with a breaker to isolate the buses if desired. When the breaker is closed any DER can provide power to any load. While this is not an actual microgrid being considered for installation, the modeled microgrid is a realistic microgrid design that could be installed on NSAM to improve energy security. Analyzing microgrid shown in Figure 4.1 provides a realistic demonstration for the process developed in this thesis.

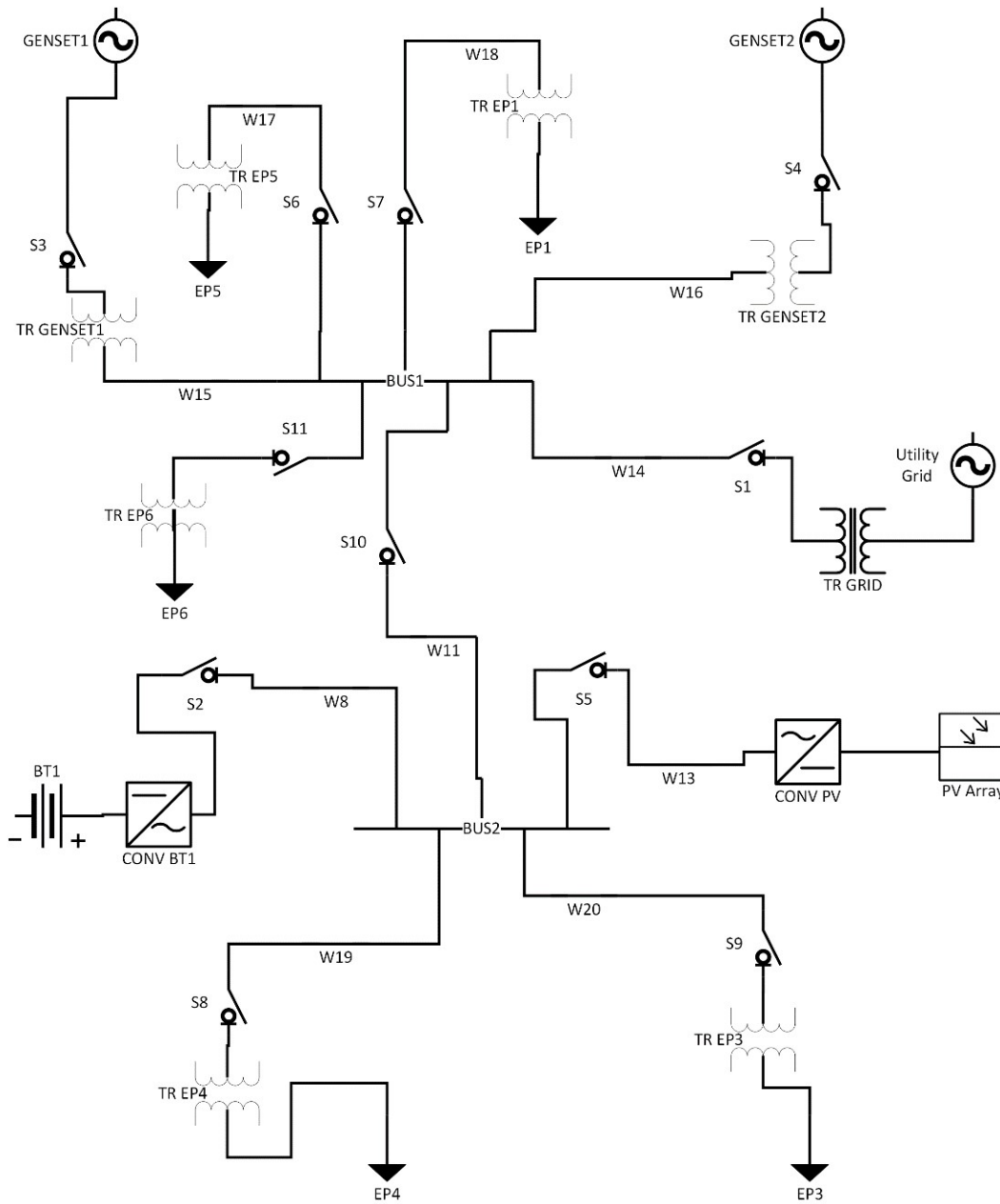


Figure 4.1. Baseline Microgrid System One-Line Diagram used for ELMI case study. Source: [9].

4.1 Microgrid Resilience Cost Estimate

4.1.1 Step 1: Conduct DOE

The model used to simulate microgrid performance allows for a total of seven factors to be included in the DOE:

- Fuel Capacity
- Number of DGs
- Total DG capacity
- PV array efficiency
- Size of PV array
- ESS charge/discharge efficiency
- ESS capacity

After analyzing the expected load profiles for all five buildings, and using the analysis conducted in [9] as a guide, a DOE was developed to include 192 different combinations of the seven factors listed above. A summary of the factors, number of levels, and the values for each level are shown in Table 4.1. The full DOE listing all 192 architectures is shown in Appendix A for reference.

Table 4.1. Summary of Initial DOE to determine microgrid architectures for case study.

Factor	No. of Levels	Values		
Fuel Capacity	2	3,000 gal.	5,000 gal.	N/A
Number of DGs	2	1	2	N/A
Total DG Capacity	3	200 kW	400 kW	600 kW
PV Array Efficiency	2	0.1865	0.2001	N/A
Size of PV Array	2	1,000 m ²	3,000 m ²	N/A
ESS Efficiency	2	0.8	0.95	N/A
ESS Capacity	2	1,000 kWh	3,000 kWh	N/A

The size of PV array and DER capacities were selected based on the expected total critical

load the microgrid needs to support, while operating in islanded mode. The PV array efficiencies were selected using the advertised efficiency of two monocrystalline PV cells available that represent the upper and lower bounds of typical PV cell efficiencies [80], [81]. The ESS efficiencies were selected based on typical efficiencies for sealed lead-acid battery banks and lithium iron phosphate batteries that are typically used in microgrids. Lithium batteries provide significant efficiency improvements but are more expensive, while flooded lead-acid batteries are cheaper and but have lower efficiency [82].

4.1.2 Step 2: Simulate Microgrid Performance

The microgrid performance for each architecture was simulated using the MATLAB model developed in [9]. Minor adjustments were made to the model code to allow for simultaneous simulation of multiple failure modes, and to incorporate all 192 microgrid architectures could be simulated in one run. The full code is included in Appendix B. The only change implemented to Peterson’s ELMI process was to use MDI to define mission impact in step four. The MDI scores for the five microgrid loads are shown in Table 4.2. The average normal and critical loads, in kW, are also listed in 4.2.

Table 4.2. Summary of Microgrid Loads. Adapted from [9], [83].

Load Number	Facility Name	Avg Critical Load (kW)	Avg Normal Load (kW)	MDI
EP1	Flag Admin	2.8	6.95	46
EP3	Post Office	2.8	6.95	45
EP4	Bullard Hall	32.3	75.9	73
EP5	Ingersoll Hall	267	679	95
EP6	Hazardous Gas Storage Facility	10.9	26.6	60

The model simulated a total of 22 possible failure scenarios including a failure of each distribution line, and all possible combinations of DER failures. A summary of these failure scenarios is shown in Table 4.3. The columns represent the different components that could fail. BT1 is the microgrid ESS. B1_B2 is the distribution line connecting BUS1 to BUS2.

Each load (EP) failure refers to a failure of the distribution line connecting the load to its associated bus. GEN1/GEN2 refers to a failure of either the DG itself or the distribution line connecting the DG to BUS1. All 22 failure scenarios assume that the utility grid has failed. Each failure scenario, s , is modeled to determine the M_s . Each simulated M_s was combined with the P_f used in [9] to calculate the ELMI for each microgrid architecture. The model simulates and calculates ELMI for all microgrid architectures identified in step one of this process.

Table 4.3. Microgrid Failure Modes. 0 represents line/component failed, 1 represents line/component operational.

Failure Scenario	BT1	B1_B2	EP1	EP3	EP4	EP5	EP6	GEN1	GEN2	PV
1	0	1	1	1	1	1	1	0	0	0
2	1	1	1	1	1	1	1	0	0	0
3	0	1	1	1	1	1	1	1	0	0
4	1	1	1	1	1	1	1	1	0	0
5	0	1	1	1	1	1	1	0	1	0
6	1	1	1	1	1	1	1	0	1	0
7	0	1	1	1	1	1	1	1	1	0
8	1	1	1	1	1	1	1	1	1	0
9	0	1	1	1	1	1	1	0	0	1
10	1	1	1	1	1	1	1	0	0	1
11	0	1	1	1	1	1	1	1	0	1
12	1	1	1	1	1	1	1	1	0	1
13	0	1	1	1	1	1	1	0	1	1
14	1	1	1	1	1	1	1	0	1	1
15	0	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	0	1	1	1	1	1	1	1	1
18	1	1	0	1	1	1	1	1	1	1
19	1	1	1	0	1	1	1	1	1	1
20	1	1	1	1	0	1	1	1	1	1
21	1	1	1	1	1	0	1	1	1	1
22	1	1	1	1	1	1	0	1	1	1

4.1.3 Step 3: Estimate Microgrid LCC

The NPV for each architecture was determined by finding the initial investment cost and annual maintenance costs for each microgrid component included in the DOE. These costs were obtained through conversations with subject matter experts, sales representatives, and reviewing product catalogs. The cost of fuel was calculated using the average fuel burned across a 14-day utility grid outage for each architecture. If a specific failure scenario resulted in zero fuel burn, this value was not included in the average. Including zero fuel burn failure scenarios in the average results in a smaller average burn but higher variability. Ignoring the zero burn values gives a higher average with lower variability. The higher average is in line with the worst-case scenario assumptions used throughout this thesis. A summary of component costs are listed in Tables 4.4, 4.5, and 4.6.

Table 4.4. Summary of DG Costs. Adapted from [84]–[86].

DG Costs		
Capacity (kW)	Investment Cost	Annual O+S
100	-\$32,000	-\$1,550
200	-\$48,000	-\$3,100
300	-\$62,000	-\$4,650
400	-\$82,000	-\$6,200
600	-\$124,000	-\$9,300
Fuel Costs		
-\$2.39/gal.		

Table 4.5. Summary of ESS Costs. Adapted from [85]–[88].

ESS Costs					
Charge/Discharge Efficiency=0.8			Charge/Discharge Efficiency=0.95		
Capacity (kWh)	Investment Cost	Annual O+S	Capacity (kWh)	Investment Cost	Annual O+S
1000	-\$214,678	-\$1,500	1000	-\$1,034,280	-\$1,500
3000	-\$644,034	-\$1,500	3000	-\$3,102,841	-\$1,500

Table 4.6. Summary of PV Array Costs. Adapted from [80], [81], [85], [86].

PV Array Costs					
Efficiency=0.1865			Efficiency=0.2001		
Size (m²)	Investment Cost	Annual O+S	Size (m²)	Investment Cost	Annual O+S
1000	-\$467,509	-\$18,300	1000	-\$451,239	-\$18,300
3000	-\$1,402,527	-\$54,900	3000	-\$1,353,717	-\$54,900

NPV is calculated using a ten-year life cycle and a discount factor of 3.0% as defined in [77]. Sensitivity analysis is conducted using 2.0% and 4.0% in Step 6. The sealed lead acid batteries used in the ESS with a charge/discharge efficiency of 0.8 require replacement every five years [87]. An example 10-year cash flow and NPV is shown in Table 4.7. The NPV was calculated for all 192 microgrid architectures using a Microsoft Excel model.

Table 4.7. Example Microgrid NPV Cash Flow

Year	DG Invest.	DG O+S	ESS Invest.	ESS O+S	PV Invest.	PV O+S	Total
1	-\$64,000	-\$7,720	-\$214,678	-\$1,500	-\$451,239	-\$18,300	-\$757,437
2	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
3	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
4	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
5	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
6	\$0	-\$7,720	-\$214,678	-\$1,500	\$0	-\$18,300	-\$242,198
7	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
8	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
9	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
10	\$0	-\$7,720	\$0	-\$1,500	\$0	-\$18,300	-\$27,520
NPV=							-\$1,123,202

4.1.4 Step 4: Analyze DOE Results

With both ELMI and NPV calculated for each of the microgrid architectures, the results of the DOE were analyzed to determine if more architectures need to be considered. The main

effects plot for ELMI and NPV are shown in Figure 4.2. Analyzing these plots it is clear that the DG capacity, ESS capacity, and size of PV array all had significant impacts on both ELMI and NPV. Based on how steep the slopes of the lines for DG Capacity, size of PV array, and ESS capacity are it is important to also increase the maximum values modeled for each of them. It is clear from these results that an additional DOE is required. The main effects plots also show that both the number of generators and the PV efficiency had little to no impact on either ELMI or NPV. In the revised DOE these two factors are not considered. Omitting them from the DOE allows for more detailed analysis of the other factors. The fuel capacity had a relatively significant impact on ELMI in the initial DOE. Because there is a 1,000 gal. difference in the fuel capacities modeled, an additional level can be added just in case there is any nonlinear impact on ELMI.

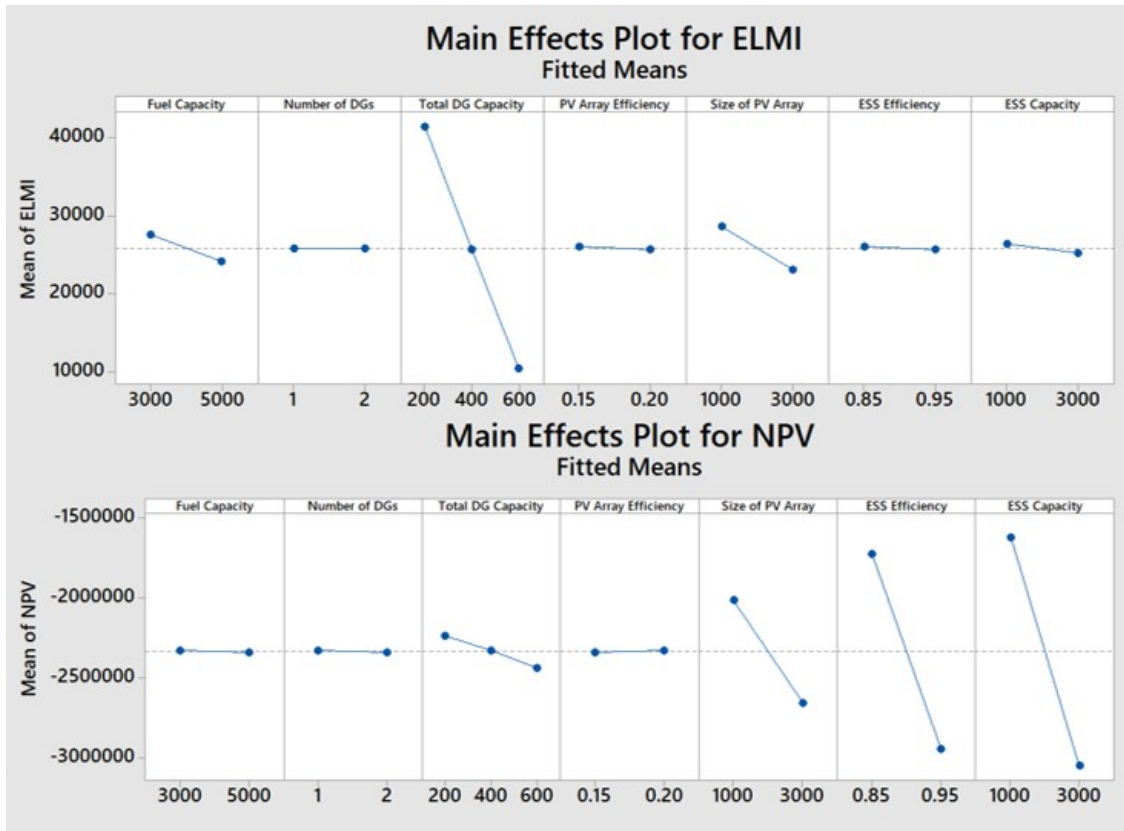


Figure 4.2. Initial DOE Analysis Main Effects Plots.

4.1.5 Step 1: Conduct Revised DOE

The results of the initial DOE indicated that two factors could be removed, and three factors required additional levels to be analyzed. A revised DOE was developed to model these five factors and additional levels for a total of 1,470 microgrid architectures. The factors and levels included in the DOE are summarized in Table 4.8

Table 4.8. Summary of Revised DOE to Determine Microgrid Architectures for Case Study.

Factor	No. of Levels	Values						
Fuel Capacity	2	3,000 gal.	4,000 gal.	5,000 gal.	N/A	N/A	N/A	N/A
Total DG Capacity	5	200 kW	400 kW	600 kW	800 kW	1,000 kW	N/A	N/A
Size of PV Array	7	1,000 m ²	2,000 m ²	3,000 m ²	4,000 m ²	5,000 m ²	6,000 m ²	7,000 m ²
ESS Efficiency	2	0.8	0.95	N/A	N/A	N/A	N/A	N/A
ESS Capacity	7	1,000 kWh	2,000 kWh	3,000 kWh	4,000 kWh	5,000 kWh	6,000 kWh	7,000 kWh

4.1.6 Step 2: Simulate Revised Microgrid Performance

ELMI for all 1,470 microgrid architectures were calculated as described in Section 4.1.2.

4.1.7 Step 3: Estimate Revised Microgrid LCC

The NPV for each architecture was calculated as described in Section 4.1.3. Updated components costs are summarized in Tables 4.9, 4.10, and 4.11.

Table 4.9. Summary of DG Costs for Revised DOE. Adapted from [84]–[86].

DG Costs		
Capacity (kW)	Investment Cost	Annual O+S
100	-\$32,000	-\$1,550
200	-\$48,000	-\$3,100
300	-\$62,000	-\$4,650
400	-\$82,000	-\$6,200
500	-\$90,000	-\$7,750
600	-\$124,000	-\$9,300
800	-\$175,000	-\$12,400
1000	-\$225,000	-\$15,100
Fuel Costs		
-\$2.39/gal.		

Table 4.10. Summary of ESS Costs for Revised DOE. Adapted from [85]–[88].

ESS Costs					
Charge/Discharge Efficiency=0.8			Charge/Discharge Efficiency=0.95		
Capacity (kWh)	Investment Cost	Annual O+S	Capacity (kWh)	Investment Cost	Annual O+S
1000	-\$214,678	-\$1,500	1000	-\$1,034,280	-\$1,500
2000	-\$429,356	-\$1,500	2000	-\$2,068,561	-\$1,500
3000	-\$644,034	-\$1,500	3000	-\$3,102,841	-\$1,500
4000	-\$858,712	-\$1,500	4000	-\$4,137,121	-\$1,500
5000	-\$1,073,390	-\$1,500	5000	-\$5,171,402	-\$1,500
6000	-\$1,288,068	-\$1,500	6000	-\$6,205,682	-\$1,500
7000	-\$1,502,746	-\$1,500	7000	-\$7,239,962	-\$1,500

Table 4.11. Summary of PV Array Costs for Revised DOE. Adapted from [80], [81], [85], [86].

PV Array Costs		
Efficiency=0.2001		
Size (m²)	Investment Cost	Annual O+S
1000	-\$451,239	-\$18,300
2000	-\$902,478	-\$36,600
3000	-\$1,353,717	-\$54,900
4000	-\$1,804,956	-\$73,200
5000	-\$2,256,195	-\$91,500
6000	-\$2,707,434	-\$109,800
7000	-\$3,158,673	-\$128,100

4.1.8 Step 4: Analyze Revised DOE Results

The main effects plots for both ELMI and NPV are shown in Figure 4.3. The added levels provide additional insight and greater granularity into the microgrid performance. NPV interactions show that all factors result in a linear cost increase as the size/efficiency increases. The effects for total DG capacity, size of PV array, and ESS capacity that were linear in Figure 4.2 now show nonlinear changes. It is clear that a DG capacity of over 600 kW does not result in significant ELMI improvement. The size of PV array also appears to be flattening out so a larger PV array does not need to be studied. The results of this DOE analysis are satisfactory to move on to Step 5.

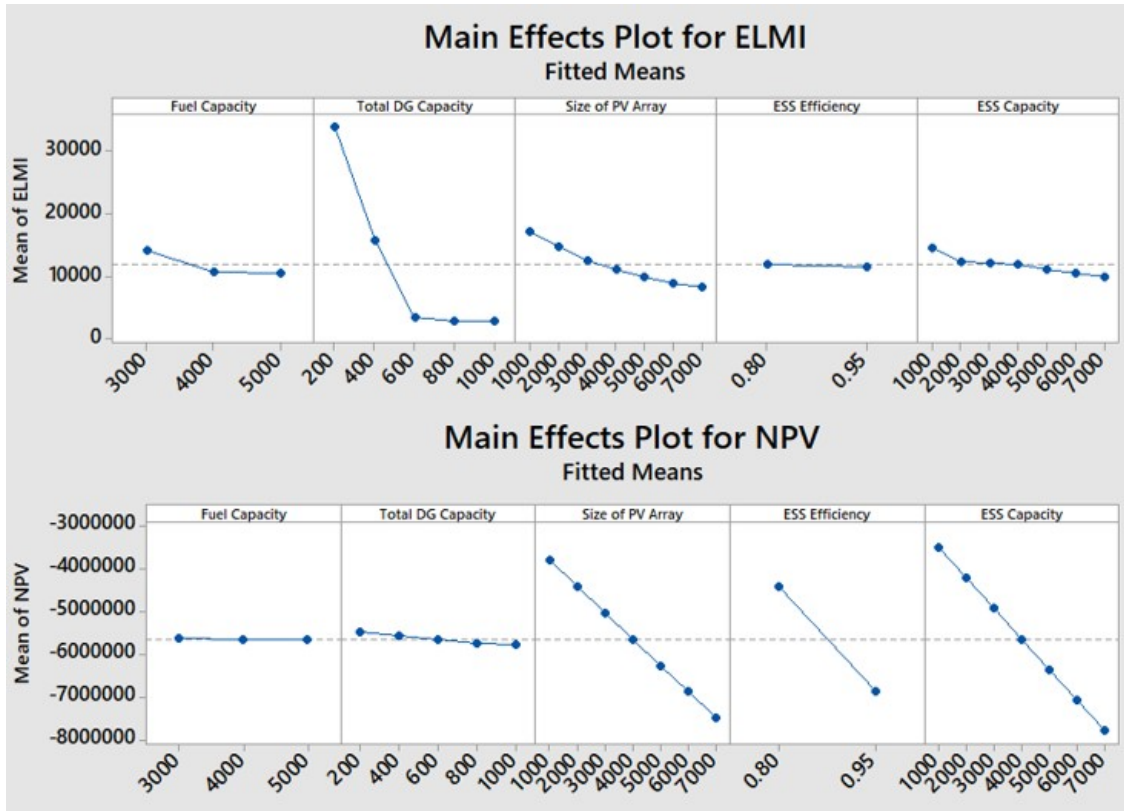


Figure 4.3. Revised DOE Analysis Main Effects Plots.

4.1.9 Step 5: Plot Data

A plot of NPV vs. ELMI is shown in Figure 4.4. This plot is automatically generated in the Microsoft Excel model developed to calculate NPV as part of this thesis. Data and regression analysis is conducted in Step 6.

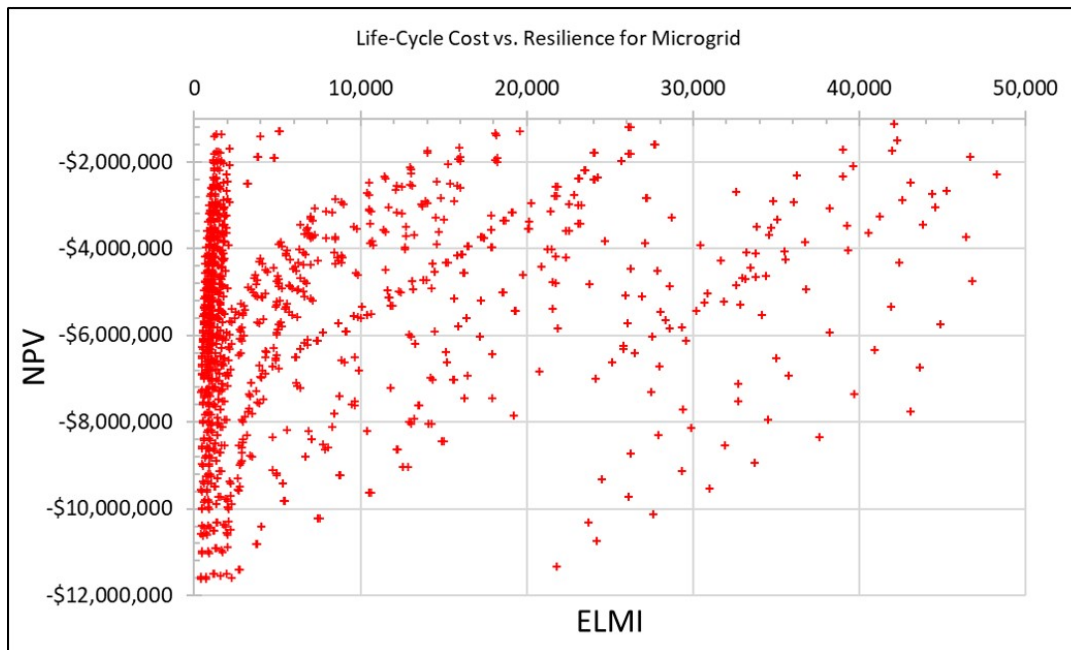


Figure 4.4. Scatter Plot of NPV vs. ELMI.

4.1.10 Step 6: Conduct Regression Analysis

The scatter plot developed in Step 5 shows four clusters of data that can be analyzed further as shown in Figure 4.5. A linear regression of the non-clustered data results in an R^2 value of 0.05. This is nearly useless to the installation energy manager so further analysis is required. The data points that are outlined in the purple box are all microgrid architectures with a total DG capacity of 200kW. The best performing architecture with a 200 kW only provided a resilience score of ELMI=21,797. Because the goal of implementing a microgrid is to minimize ELMI these microgrid architectures are not analyzed further. The yellow box primarily consists of microgrid architectures with a total DG capacity of 400 kW. The green box consists of microgrid architectures with a total DG capacity of at least 600 kW and a fuel capacity of 3,000 gal. The red box consists of microgrid architectures that have at least 600 kW of total DG capacity and at least 4,000 gal. of fuel capacity. Detailed regression analysis is conducted for microgrid architectures with these characteristics to be used for analysis in Step 7. Sensitivity analysis is conducted for NPV using discount rates of 2% and 4% [79].

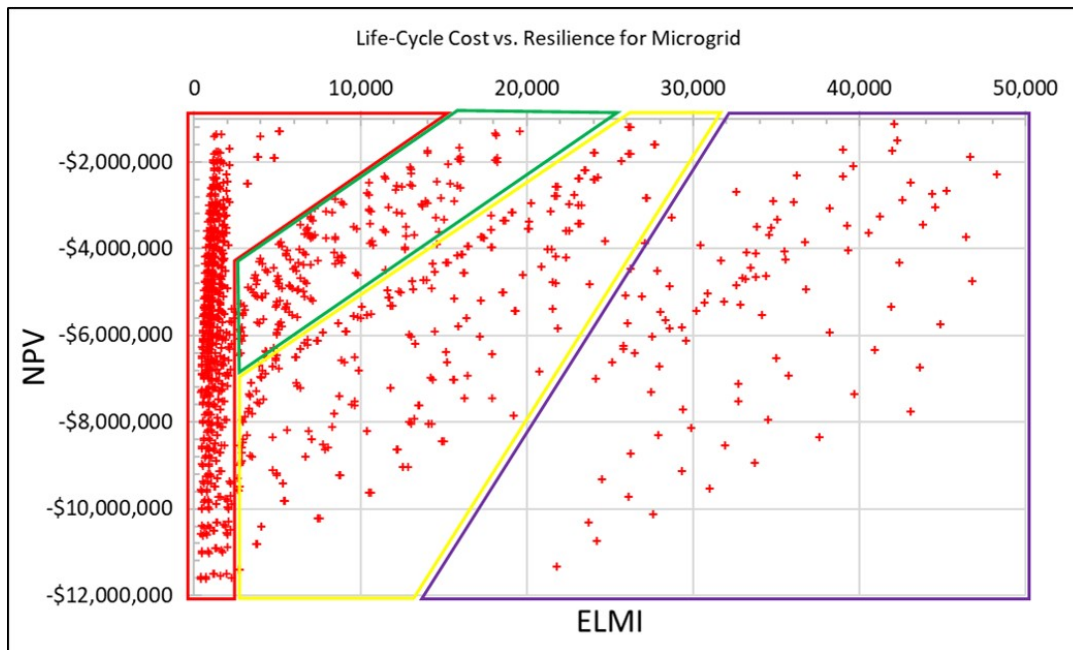


Figure 4.5. Scatter Plot of NPV vs. ELMI with four clusters outlined for further analysis. Purple box consists of microgrid architectures with a total DG capacity of 200 kW. Yellow box primarily consists of microgrid architectures with a total DG capacity of 400 kW. Green box consists of microgrid architectures with a fuel capacity of 3,000 gal. and a total DG capacity of at least 600 kW. The red box consists of microgrid architectures with a total DG capacity of at least 600 kW and at least 4,000 gal. of fuel capacity.

The regression equations identified for each cluster allow the installation energy manager to understand the cost of increased resilience within the microgrid shown in Figure 4.1. If they have a desired ELMI value the microgrid needs to meet then they can estimate the NPV for that level of resilience. Furthermore, the installation energy manager can use the slope of the linear regression equation developed to estimate the cost of each unit of resilience improvement. This can help decision-makers determine if increasing the microgrid's resilience is worth the additional investment. While the following sections develop several different equations, as long as the installation energy manager has made some initial decisions about microgrid architecture, they are able to estimate the cost of microgrid resilience.

Regression Analysis of Microgrid Architectures with 400 kW of Total DG Capacity.

A plot of NPV vs. ELMI for all microgrid architectures with 400 kW of total DG capacity is shown in Figure 4.6. A linear regression was conducted to estimate the NPV for a desired ELMI. The red dashed line is the linear regression of NPV vs. ELMI using a 3% discount rate and blue and green dashed lines show how the regression changes if 2% or 4% discount rates were used. It is clear that the discount rate does not have a major impact on the regression.

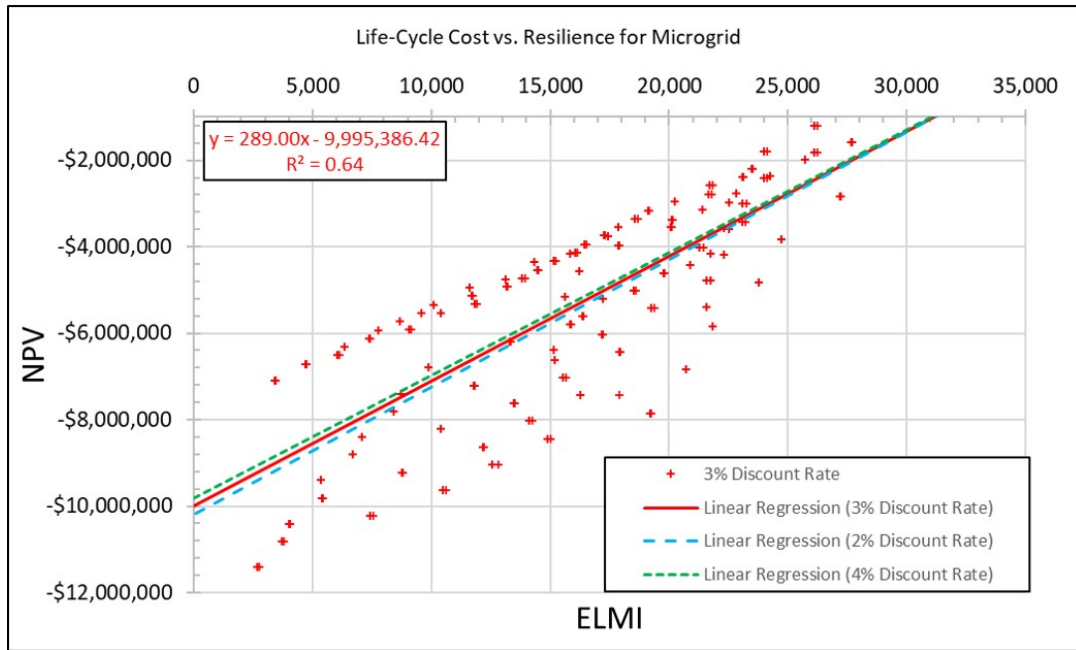


Figure 4.6. Linear Regression of Microgrid Architectures with 400 kW of Total DG Capacity.

Equation 4.1 shows the relationship between NPV and ELMI for a microgrid with 400 kW of total DG capacity. It has an R^2 value of 0.64 which indicates there is some uncertainty but it does provide a good estimate for NPV given a desired ELMI.

$$NPV = 289(ELMI) - 9995386.42 \quad (4.1)$$

Further analyzing the plot in Figure 4.6 shows two smaller clusters of data, one above and one below the regression lines. The data above represents architectures that had an ESS efficiency of 0.8 while those below are microgrid architectures with an ESS efficiency of

0.95. Two separate linear regressions can be done on this data to further refine the NPV estimate if the installation energy manager knows which type of batteries they intend to use in the ESS. Equation 4.2 shows the regression equation for an ESS made of up sealed lead-acid batteries with an efficiency of 0.8. Equation 4.2 has an R^2 value of 0.91. Equation 4.3 is the regression equation for an ESS consisting of lithium batteries with an efficiency of 0.95. Equation 4.3 has an R^2 value of 0.83.

$$NPV = 221.37(ELMI) - 7777512.04 \quad (4.2)$$

$$NPV = 326.86(ELMI) - 11694265.95 \quad (4.3)$$

Regression Analysis of Microgrid Architectures with 3,000 gal. Fuel Capacity and at Least 600 kW of Total DG Capacity.

A plot of NPV vs. ELMI for all microgrid architectures with 3,000 gal. fuel capacity and at least 600 kW of total DG capacity is shown in Figure 4.7. The red dotted line is the linear regression for NPV as a function of ELMI. The blue and green dotted lines show that the data remains mostly unchanged with a $\pm 1\%$ change in the discount rate used to calculate NPV.

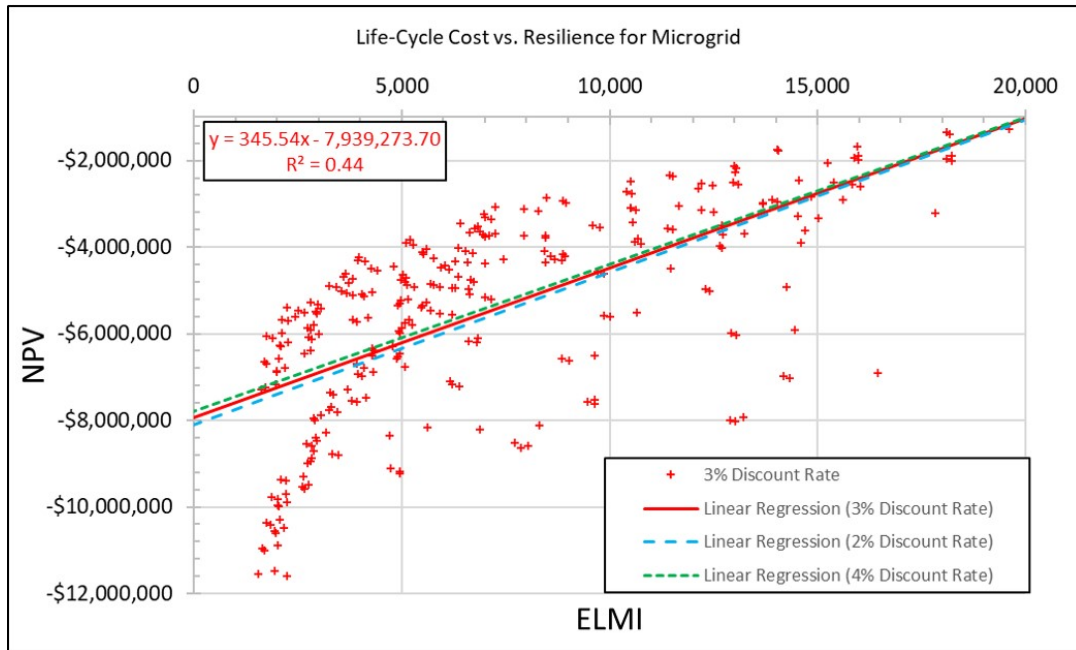


Figure 4.7. Linear Regression of Microgrid Architectures with 3,000 gal. of fuel capacity and at least 600 kW of total DG capacity.

Equation 4.4 can be used to estimate the NPV for a microgrid with a total DG capacity of 600 kW and 3,000 gal. of fuel capacity, with an R^2 value of 0.44. This is not as accurate of an estimate as the estimate for microgrid architectures with 400 kW of total DG capacity.

$$NPV = 345.54(ELMI) - 7939273.7 \quad (4.4)$$

Similar to the regression conducted for the microgrids with 400 kW of total DG capacity, this plot can be separated into two separate regression lines. One line to describe the microgrid architectures with an ESS efficiency of 0.8 and the other regression line to describe the microgrid architectures with an ESS efficiency of 0.95.

Equation 4.5 shows the equation for microgrid architectures with sealed lead-acid batteries in the ESS, a fuel capacity of 3,000 gal., and a total of 600 kW of DG capacity, with an R^2 value of 0.79.

$$NPV = 281.45(ELMI) - 6287176.68 \quad (4.5)$$

Equation 4.6 shows the equation for microgrid architectures with lithium batteries in the ESS, a fuel capacity of 3,000 gal., and a total of 600 kW of DG capacity, with an R^2 value of 0.55.

$$NPV = 401.87(ELMI) - 9524936.53 \quad (4.6)$$

Regression Analysis of Microgrid Architectures at Least 4,000 gal. Fuel Capacity and at Least 600 kW of Total DG Capacity.

Figure 4.8 shows a plot of NPV vs. ELMI for microgrid architectures with at least 4,000 gal. of fuel capacity and at least 600 kW of total DG capacity. A linear regression of this data results in an R^2 value of 0.18 so it is clear it needs to be separated further before it can be used to estimate the relationship between ELMI and NPV. As was conducted in previous regressions, the data is separated by total DG capacity, ESS efficiency, and fuel capacity to estimate the relationship between ELMI and NPV for the remaining microgrid architectures. There are nine microgrid architectures in Figure 4.8 that have an ELMI greater than 3,000 that do not fit with the rest of the data. They are ignored in further regression analysis.

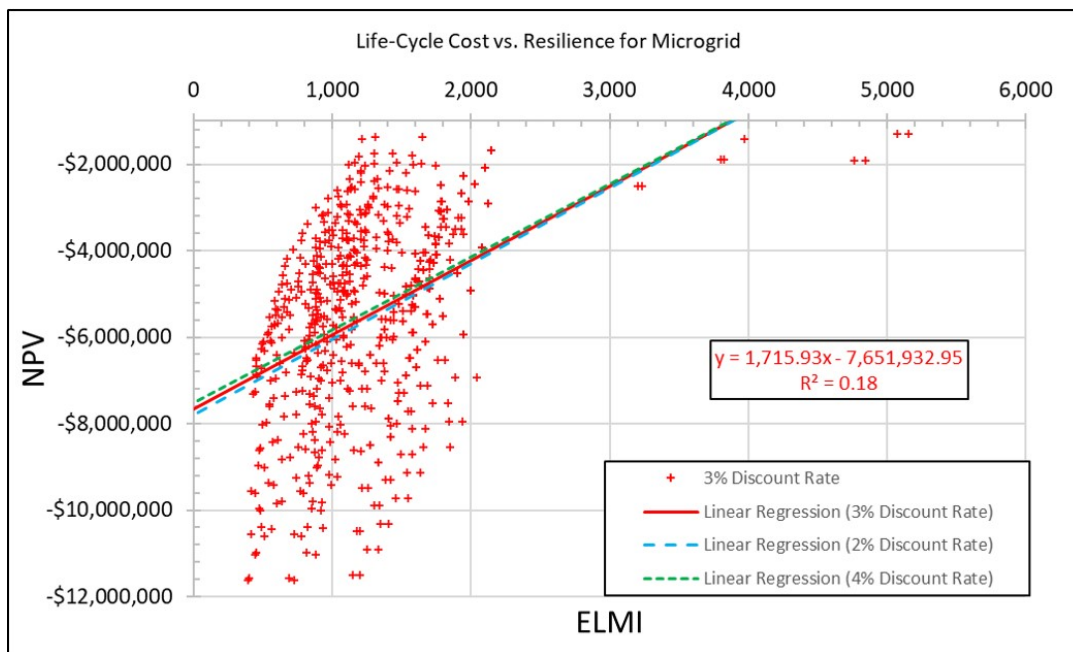


Figure 4.8. Linear Regression of Microgrid Architectures with at least 4,000 gal. of fuel capacity and at least 600 kW of total DG capacity.

Equation 4.7 estimates NPV as a function of ELMI for microgrids with 600 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.88.

$$NPV = 5799.28(ELMI) - 14031394.60 \quad (4.7)$$

Equation 4.8 estimates NPV as a function of ELMI for microgrids with 600 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.54.

$$NPV = 6950.10(ELMI) - 18309278.18 \quad (4.8)$$

Equation 4.9 estimates NPV as a function of ELMI for microgrids with 600 kW of total DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.93.

$$NPV = 5813.83(ELMI) - 13921378.57 \quad (4.9)$$

Equation 4.10 estimates NPV as a function of ELMI for microgrids with 600 kW of total DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.69.

$$NPV = 7833.32(ELMI) - 19510614.72 \quad (4.10)$$

Equation 4.11 estimates NPV as a function of ELMI for microgrids with 800 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.89.

$$NPV = 6072.04(ELMI) - 10942933.65 \quad (4.11)$$

Equation 4.12 estimates NPV as a function of ELMI for microgrids with 800 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.65.

$$NPV = 8111.87(ELMI) - 15566552.10 \quad (4.12)$$

Equation 4.13 estimates NPV as a function of ELMI for microgrids with 800 kW of total DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.89.

$$NPV = 5490.72(ELMI) - 9061285.85 \quad (4.13)$$

Equation 4.14 estimates NPV as a function of ELMI for microgrids with 800 kW of total

DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.71.

$$NPV = 7566.38(ELMI) - 13164656.59 \quad (4.14)$$

Equation 4.15 estimates NPV as a function of ELMI for microgrids with 1,000 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.80.

$$NPV = 5573.65(ELMI) - 10909782.85 \quad (4.15)$$

Equation 4.16 estimates NPV as a function of ELMI for microgrids with 1,000 kW of total DG capacity, 4,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.67.

$$NPV = 7732.89(ELMI) - 15710468.61 \quad (4.16)$$

Equation 4.17 estimates NPV as a function of ELMI for microgrids with 1,000 kW of total DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.8; with an R^2 value of 0.88.

$$NPV = 5913.68(ELMI) - 8996163.44 \quad (4.17)$$

Equation 4.18 estimates NPV as a function of ELMI for microgrids with 1,000 kW of total DG capacity, 5,000 gal. fuel capacity, and an ESS efficiency of 0.95; with an R^2 value of 0.71.

$$NPV = 8360.32(ELMI) - 13219323.96 \quad (4.18)$$

The equations and insights developed in this step can be used by the base energy manager to make informed design decisions about how microgrid architecture impacts ELMI and NPV.

4.1.11 Step 7: Analyze Results

Regression analysis from the four clusters of data can be used to estimate the NPV of a microgrid given the desired ELMI score of the installation energy manager and various stakeholders. The biggest take away from this process is that the total DG capacity, fuel capacity, and ESS efficiency play a major role in the relationship between ELMI and NPV for the modeled microgrid. If the installation energy manager has decided on the values for total DG capacity, fuel capacity, and ESS efficiency, the energy manager is able to use the

equations developed in Step 6 to estimate the NPV for a desired ELMI. This process also identified that the microgrid studied in this case study requires a total DG capacity of at least 400 kW to result in an ELMI of less than 20,000.

4.2 Chapter Summary

This chapter applied the process developed in Chapter 3 to a base line microgrid. By executing each step of the process, it demonstrated how the process can be used to inform the decisions made by an installation energy manager. Chapter 5 summarizes the findings of this thesis and discuss future work.

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CHAPTER 5: Conclusion and Future Work

This chapter presents a summary of the research conducted in this thesis and an overview of how the research can be used by installation energy managers. This chapter closes by discussing several potential topics for future work to improve upon the process for estimating the cost of microgrid resilience developed in this thesis and the overall study of microgrid resilience and cost estimation.

5.1 Conclusion

Microgrids are way the DoD implements energy security on military bases throughout the world. Energy security is described by the DoN by three separate areas of study, namely reliability, resilience, and efficiency. Reliability and efficiency are well established fields, while resilience is more complex and less understood. Currently, the research into the cost of implementing resilience for electrical energy applications is very limited. The objective of this research was to develop a process to quantify the cost of resilience when applied to a microgrid on a naval installation. Prior to developing this process, a review of microgrids, microgrid resilience, and microgrid cost estimation was conducted. The resilience metric developed in [9], ELMI, was determined to be the most appropriate to use when quantifying the cost of resilience. The review of cost estimation determined that NPV is the most appropriate cost metric to describe LCC for a microgrid with a variety of DERs. This thesis developed a seven-step process for installation energy managers to implement as part of the decision-making process when designing a microgrid. The process was demonstrated using a microgrid representative of a portion of the electrical distribution system at NSAM. The case study resulted in several equations to estimate the NPV of a microgrid for a desired ELMI. These equations allow an installation energy manager to estimate the additional cost of achieving a certain level of resilience for the proposed microgrid. Each equation requires that the installation energy manager has made decisions on the fuel capacity, total DG capacity, and type of batteries used in the ESS. The process developed in this thesis is one of several tools that can be used by installation energy managers to influence their decision for the best way to implement resilience to the electrical energy system. In helping

narrow down the factors of microgrid architecture that significantly impact cost of microgrid resilience, installation energy managers can work with NAVFAC to conduct more detailed analysis and identify the best microgrid design to install.

5.2 Guidance for Installation Energy Managers

The process for estimating cost of microgrid resilience developed in this thesis is intentionally broad/generic. It is designed to be applied to a wide variety of microgrids and leave room for the installation energy manager to make decisions that specifically apply to their application. While this thesis recommends the use of ELMI and NPV to quantify resilience and LCC neither are perfect metrics. The only requirement for resilience and LCC metrics used in this method are that they are one dimensional numbers that can be plotted on a scatter plot for regression analysis. Any multidimensional vectors to quantify resilience or LCC would require more complex computers and machine learning to understand the relationship between cost and resilience.

Installation energy managers should be aware that there is the potential conduct several iterations of steps one through four of this process before understanding the full scope of microgrid architectures that should be studied to understand the cost of microgrid resilience. Installation energy managers are encouraged to understand the constraints of the loads and installation being analyzed. The components selected for inclusion in the DOE should be realistic given the installation. For example, a 7000 m² PV array might not be realistic on an installation in a major metropolitan area where there is limited, or no space available for a large PV array. However, the microgrid components should be selected allow for at least one microgrid architecture to result in the lowest possible resilience score, regardless of cost.

5.3 Future Work

This section discusses possible topics related to the cost of microgrid resilience that have to potential for continued research. The topics for future work are separated into two categories: 1) microgrid resilience simulation model, and 2) factors that affect cost of microgrid resilience.

5.3.1 Microgrid Resilience Simulation Model

The simulation model used in this thesis is an adaptation of the model developed in [9]. In the final chapter of [9], the author proposes several concepts for improvement such as a more complex load shedding algorithm, dynamic mapping of lost load to mission impact, and additional analysis to quantify the probability of failure scenarios to include deliberate attack. In addition to those improvements already proposed, this research has identified other avenues for further research. This thesis did not include any variability in the ELMI for each microgrid architecture because all failures occurred at the same time of year and day. This results in the same solar irradiance data load profiles being used to calculate energy flow within the microgrid. While the time period used in this thesis was identified as the worst case scenario, conducting a Monte Carlo simulation to allow for the failure scenario to occur at a different time each iteration would provide installation energy managers with a greater understanding as to the variability of the results and improve sensitivity analysis. The microgrid resilience simulation model used in this thesis could also be improved to include all of the factors that affect resilience as described in Table 2.1. Only four of the nine factors identified in this research were included in the simulation model developed in [9]. Including all identified factors would result in a more in depth understanding of microgrid resilience as well as how each factor influences microgrid performance. The case study effectively demonstrated the process and considerations associated with each step so that it can be repeated for real world applications and assist in the decisions made by installation energy managers. The process developed is able to be applied regardless of the metrics for resilience and LCC the installation energy manager chooses. The literature review conducted in this thesis determined that ELMI is the most appropriate resilience metric currently available to use when quantifying the cost of microgrid resilience.

5.3.2 Factors that Affect Cost of Resilience

The case study conducted in this research identified total DG capacity, fuel storage, and ESS efficiency as the biggest factors that affect the cost of microgrid resilience. In order to confirm that these factors truly do play a major role in cost of resilience it is important to repeat the process developed in this thesis on additional microgrids. By studying several microgrids located in various geographic locations, researchers could confirm the impact of these factors and identify other factors that could potentially play a significant role in microgrid resilience.

The results of this case study showed that increasing DG capacity had significant impact on resilience for a relatively small increase in cost, while increasing capacity of RE DERs combined with a low capacity DG resulted in a significant cost increase associated with a less drastic resilience improvement. This trend shows that from a cost perspective, increasing RE generating capacity to improve resilience does not make sense given the current costs. Further research into quantifying the benefits of RE DERs could potentially change these results. This research did not include any potential carbon credits available for the use of RE technology over carbon-based fuel. When a microgrid is connected to the utility grid, the excess energy generated from PV arrays can typically be sold back to the energy company resulting in a positive cash flow. These positive costs could lead to the conclusion that RE DERs result in a better cost-benefit relationship than DGs.

The case study further identified that fuel capacity played a significant role in the relationship between cost of microgrid resilience. The cost of fuel used in this case study utilized the cost of fuel per gallon as published by the Defense Logistics Agency. Fuel costs were included in the NPV estimate based on the average fuel burn per microgrid architecture, but the cost of fuel storage was not evaluated. This research could be improved by studying the fully burdened cost of fuel for a microgrid and the influence that has on the cost of microgrid resilience. Including fully burdened cost of fuel allows for the cost of transportation to the microgrid to be considered as well as the cost associated with excess fuel capacity on hand. This research also assumes that a fuel delivery occurs every seven days and the logistics supply chain remains fully operational. This assumption is not guaranteed to be the case, especially in the event of a conflict with a major fuel provider. Currently the United States relies on North Atlantic Treaty Organization (NATO) allies to procure fuel throughout Europe and Asia, it is estimated that around 40% of European petroleum is imported from Russia [89]. If a conflict were to arise between the United States and Russia, this fuel supply would likely be cut off resulting in a significant decrease in installation energy resilience. A comparison of microgrid resilience between storing large quantities of fuel on site or conducting frequent refueling with varying probabilities of arrival could also provide insight into how fuel influences the cost of microgrid resilience. In addition to analyzing the impact of logistics interruptions on resilience, the safety and security requirements for large fuel supplies compared to large ESSs is a useful field of further study. Both are susceptible to attack and could reduce overall resilience if they are damaged but also pose safety concerns

such as fire or explosion to a lithium battery bank. Overall, there are several potential areas of study regarding fuel storage and delivery around microgrids.

This research focused on the cost of achieving resilience, with the goal of maximizing resilience at the minimum cost. The process developed in this thesis calculates cost based on the components that make up a particular microgrid architecture. Resilience was measured as a function of the impact to mission by losing the electrical load to a particular building. One area of study that could be useful to study further is the quantifying the cost of not having achieved a particular level of resilience. For example, what is the cost to the naval installation if they lose power to the control tower at a naval air station and are no longer able to launch or recover aircraft.

5.4 Summary

This chapter summarized the research conducted in this thesis and outlines the key findings of the research. The process developed in this thesis can be replicated across any naval installation considering a new or upgraded microgrid to improve overall resilience. This chapter also describes several areas of research that can be studied further to gain better insight into the cost and resilience of microgrids as used throughout the DoD.

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APPENDIX A:

Full DOE of Microgrid Architectures

Table A.1 shows the complete DOE results for the case study. All 1,470 microgrid architectures modeled as part of the case study conducted in Chapter 4 are listed for reference.

Table A.1. Full List of Microgrid Architectures Modeled in Case Study.

Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1	3000	200	1000	0.8	1000
2	3000	200	1000	0.8	2000
3	3000	200	1000	0.8	3000
4	3000	200	1000	0.8	4000
5	3000	200	1000	0.8	5000
6	3000	200	1000	0.8	6000
7	3000	200	1000	0.8	7000
8	3000	200	1000	0.95	1000
9	3000	200	1000	0.95	2000
10	3000	200	1000	0.95	3000
11	3000	200	1000	0.95	4000
12	3000	200	1000	0.95	5000
13	3000	200	1000	0.95	6000
14	3000	200	1000	0.95	7000
15	3000	200	2000	0.8	1000
16	3000	200	2000	0.8	2000
17	3000	200	2000	0.8	3000
18	3000	200	2000	0.8	4000
19	3000	200	2000	0.8	5000
20	3000	200	2000	0.8	6000
21	3000	200	2000	0.8	7000
22	3000	200	2000	0.95	1000
23	3000	200	2000	0.95	2000
24	3000	200	2000	0.95	3000
25	3000	200	2000	0.95	4000
26	3000	200	2000	0.95	5000
27	3000	200	2000	0.95	6000
28	3000	200	2000	0.95	7000
29	3000	200	3000	0.8	1000
30	3000	200	3000	0.8	2000
31	3000	200	3000	0.8	3000
32	3000	200	3000	0.8	4000
33	3000	200	3000	0.8	5000
34	3000	200	3000	0.8	6000
35	3000	200	3000	0.8	7000
36	3000	200	3000	0.95	1000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
37	3000	200	3000	0.95	2000
38	3000	200	3000	0.95	3000
39	3000	200	3000	0.95	4000
40	3000	200	3000	0.95	5000
41	3000	200	3000	0.95	6000
42	3000	200	3000	0.95	7000
43	3000	200	4000	0.8	1000
44	3000	200	4000	0.8	2000
45	3000	200	4000	0.8	3000
46	3000	200	4000	0.8	4000
47	3000	200	4000	0.8	5000
48	3000	200	4000	0.8	6000
49	3000	200	4000	0.8	7000
50	3000	200	4000	0.95	1000
51	3000	200	4000	0.95	2000
52	3000	200	4000	0.95	3000
53	3000	200	4000	0.95	4000
54	3000	200	4000	0.95	5000
55	3000	200	4000	0.95	6000
56	3000	200	4000	0.95	7000
57	3000	200	5000	0.8	1000
58	3000	200	5000	0.8	2000
59	3000	200	5000	0.8	3000
60	3000	200	5000	0.8	4000
61	3000	200	5000	0.8	5000
62	3000	200	5000	0.8	6000
63	3000	200	5000	0.8	7000
64	3000	200	5000	0.95	1000
65	3000	200	5000	0.95	2000
66	3000	200	5000	0.95	3000
67	3000	200	5000	0.95	4000
68	3000	200	5000	0.95	5000
69	3000	200	5000	0.95	6000
70	3000	200	5000	0.95	7000
71	3000	200	6000	0.8	1000
72	3000	200	6000	0.8	2000
73	3000	200	6000	0.8	3000
74	3000	200	6000	0.8	4000
75	3000	200	6000	0.8	5000
76	3000	200	6000	0.8	6000
77	3000	200	6000	0.8	7000
78	3000	200	6000	0.95	1000
79	3000	200	6000	0.95	2000
80	3000	200	6000	0.95	3000
81	3000	200	6000	0.95	4000
82	3000	200	6000	0.95	5000
83	3000	200	6000	0.95	6000
84	3000	200	6000	0.95	7000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
85	3000	200	7000	0.8	1000
86	3000	200	7000	0.8	2000
87	3000	200	7000	0.8	3000
88	3000	200	7000	0.8	4000
89	3000	200	7000	0.8	5000
90	3000	200	7000	0.8	6000
91	3000	200	7000	0.8	7000
92	3000	200	7000	0.95	1000
93	3000	200	7000	0.95	2000
94	3000	200	7000	0.95	3000
95	3000	200	7000	0.95	4000
96	3000	200	7000	0.95	5000
97	3000	200	7000	0.95	6000
98	3000	200	7000	0.95	7000
99	3000	400	1000	0.8	1000
100	3000	400	1000	0.8	2000
101	3000	400	1000	0.8	3000
102	3000	400	1000	0.8	4000
103	3000	400	1000	0.8	5000
104	3000	400	1000	0.8	6000
105	3000	400	1000	0.8	7000
106	3000	400	1000	0.95	1000
107	3000	400	1000	0.95	2000
108	3000	400	1000	0.95	3000
109	3000	400	1000	0.95	4000
110	3000	400	1000	0.95	5000
111	3000	400	1000	0.95	6000
112	3000	400	1000	0.95	7000
113	3000	400	2000	0.8	1000
114	3000	400	2000	0.8	2000
115	3000	400	2000	0.8	3000
116	3000	400	2000	0.8	4000
117	3000	400	2000	0.8	5000
118	3000	400	2000	0.8	6000
119	3000	400	2000	0.8	7000
120	3000	400	2000	0.95	1000
121	3000	400	2000	0.95	2000
122	3000	400	2000	0.95	3000
123	3000	400	2000	0.95	4000
124	3000	400	2000	0.95	5000
125	3000	400	2000	0.95	6000
126	3000	400	2000	0.95	7000
127	3000	400	3000	0.8	1000
128	3000	400	3000	0.8	2000
129	3000	400	3000	0.8	3000
130	3000	400	3000	0.8	4000
131	3000	400	3000	0.8	5000
132	3000	400	3000	0.8	6000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
133	3000	400	3000	0.8	7000
134	3000	400	3000	0.95	1000
135	3000	400	3000	0.95	2000
136	3000	400	3000	0.95	3000
137	3000	400	3000	0.95	4000
138	3000	400	3000	0.95	5000
139	3000	400	3000	0.95	6000
140	3000	400	3000	0.95	7000
141	3000	400	4000	0.8	1000
142	3000	400	4000	0.8	2000
143	3000	400	4000	0.8	3000
144	3000	400	4000	0.8	4000
145	3000	400	4000	0.8	5000
146	3000	400	4000	0.8	6000
147	3000	400	4000	0.8	7000
148	3000	400	4000	0.95	1000
149	3000	400	4000	0.95	2000
150	3000	400	4000	0.95	3000
151	3000	400	4000	0.95	4000
152	3000	400	4000	0.95	5000
153	3000	400	4000	0.95	6000
154	3000	400	4000	0.95	7000
155	3000	400	5000	0.8	1000
156	3000	400	5000	0.8	2000
157	3000	400	5000	0.8	3000
158	3000	400	5000	0.8	4000
159	3000	400	5000	0.8	5000
160	3000	400	5000	0.8	6000
161	3000	400	5000	0.8	7000
162	3000	400	5000	0.95	1000
163	3000	400	5000	0.95	2000
164	3000	400	5000	0.95	3000
165	3000	400	5000	0.95	4000
166	3000	400	5000	0.95	5000
167	3000	400	5000	0.95	6000
168	3000	400	5000	0.95	7000
169	3000	400	6000	0.8	1000
170	3000	400	6000	0.8	2000
171	3000	400	6000	0.8	3000
172	3000	400	6000	0.8	4000
173	3000	400	6000	0.8	5000
174	3000	400	6000	0.8	6000
175	3000	400	6000	0.8	7000
176	3000	400	6000	0.95	1000
177	3000	400	6000	0.95	2000
178	3000	400	6000	0.95	3000
179	3000	400	6000	0.95	4000
180	3000	400	6000	0.95	5000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
181	3000	400	6000	0.95	6000
182	3000	400	6000	0.95	7000
183	3000	400	7000	0.8	1000
184	3000	400	7000	0.8	2000
185	3000	400	7000	0.8	3000
186	3000	400	7000	0.8	4000
187	3000	400	7000	0.8	5000
188	3000	400	7000	0.8	6000
189	3000	400	7000	0.8	7000
190	3000	400	7000	0.95	1000
191	3000	400	7000	0.95	2000
192	3000	400	7000	0.95	3000
193	3000	400	7000	0.95	4000
194	3000	400	7000	0.95	5000
195	3000	400	7000	0.95	6000
196	3000	400	7000	0.95	7000
197	3000	600	1000	0.8	1000
198	3000	600	1000	0.8	2000
199	3000	600	1000	0.8	3000
200	3000	600	1000	0.8	4000
201	3000	600	1000	0.8	5000
202	3000	600	1000	0.8	6000
203	3000	600	1000	0.8	7000
204	3000	600	1000	0.95	1000
205	3000	600	1000	0.95	2000
206	3000	600	1000	0.95	3000
207	3000	600	1000	0.95	4000
208	3000	600	1000	0.95	5000
209	3000	600	1000	0.95	6000
210	3000	600	1000	0.95	7000
211	3000	600	2000	0.8	1000
212	3000	600	2000	0.8	2000
213	3000	600	2000	0.8	3000
214	3000	600	2000	0.8	4000
215	3000	600	2000	0.8	5000
216	3000	600	2000	0.8	6000
217	3000	600	2000	0.8	7000
218	3000	600	2000	0.95	1000
219	3000	600	2000	0.95	2000
220	3000	600	2000	0.95	3000
221	3000	600	2000	0.95	4000
222	3000	600	2000	0.95	5000
223	3000	600	2000	0.95	6000
224	3000	600	2000	0.95	7000
225	3000	600	3000	0.8	1000
226	3000	600	3000	0.8	2000
227	3000	600	3000	0.8	3000
228	3000	600	3000	0.8	4000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
229	3000	600	3000	0.8	5000
230	3000	600	3000	0.8	6000
231	3000	600	3000	0.8	7000
232	3000	600	3000	0.95	1000
233	3000	600	3000	0.95	2000
234	3000	600	3000	0.95	3000
235	3000	600	3000	0.95	4000
236	3000	600	3000	0.95	5000
237	3000	600	3000	0.95	6000
238	3000	600	3000	0.95	7000
239	3000	600	4000	0.8	1000
240	3000	600	4000	0.8	2000
241	3000	600	4000	0.8	3000
242	3000	600	4000	0.8	4000
243	3000	600	4000	0.8	5000
244	3000	600	4000	0.8	6000
245	3000	600	4000	0.8	7000
246	3000	600	4000	0.95	1000
247	3000	600	4000	0.95	2000
248	3000	600	4000	0.95	3000
249	3000	600	4000	0.95	4000
250	3000	600	4000	0.95	5000
251	3000	600	4000	0.95	6000
252	3000	600	4000	0.95	7000
253	3000	600	5000	0.8	1000
254	3000	600	5000	0.8	2000
255	3000	600	5000	0.8	3000
256	3000	600	5000	0.8	4000
257	3000	600	5000	0.8	5000
258	3000	600	5000	0.8	6000
259	3000	600	5000	0.8	7000
260	3000	600	5000	0.95	1000
261	3000	600	5000	0.95	2000
262	3000	600	5000	0.95	3000
263	3000	600	5000	0.95	4000
264	3000	600	5000	0.95	5000
265	3000	600	5000	0.95	6000
266	3000	600	5000	0.95	7000
267	3000	600	6000	0.8	1000
268	3000	600	6000	0.8	2000
269	3000	600	6000	0.8	3000
270	3000	600	6000	0.8	4000
271	3000	600	6000	0.8	5000
272	3000	600	6000	0.8	6000
273	3000	600	6000	0.8	7000
274	3000	600	6000	0.95	1000
275	3000	600	6000	0.95	2000
276	3000	600	6000	0.95	3000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
277	3000	600	6000	0.95	4000
278	3000	600	6000	0.95	5000
279	3000	600	6000	0.95	6000
280	3000	600	6000	0.95	7000
281	3000	600	7000	0.8	1000
282	3000	600	7000	0.8	2000
283	3000	600	7000	0.8	3000
284	3000	600	7000	0.8	4000
285	3000	600	7000	0.8	5000
286	3000	600	7000	0.8	6000
287	3000	600	7000	0.8	7000
288	3000	600	7000	0.95	1000
289	3000	600	7000	0.95	2000
290	3000	600	7000	0.95	3000
291	3000	600	7000	0.95	4000
292	3000	600	7000	0.95	5000
293	3000	600	7000	0.95	6000
294	3000	600	7000	0.95	7000
295	3000	800	1000	0.8	1000
296	3000	800	1000	0.8	2000
297	3000	800	1000	0.8	3000
298	3000	800	1000	0.8	4000
299	3000	800	1000	0.8	5000
300	3000	800	1000	0.8	6000
301	3000	800	1000	0.8	7000
302	3000	800	1000	0.95	1000
303	3000	800	1000	0.95	2000
304	3000	800	1000	0.95	3000
305	3000	800	1000	0.95	4000
306	3000	800	1000	0.95	5000
307	3000	800	1000	0.95	6000
308	3000	800	1000	0.95	7000
309	3000	800	2000	0.8	1000
310	3000	800	2000	0.8	2000
311	3000	800	2000	0.8	3000
312	3000	800	2000	0.8	4000
313	3000	800	2000	0.8	5000
314	3000	800	2000	0.8	6000
315	3000	800	2000	0.8	7000
316	3000	800	2000	0.95	1000
317	3000	800	2000	0.95	2000
318	3000	800	2000	0.95	3000
319	3000	800	2000	0.95	4000
320	3000	800	2000	0.95	5000
321	3000	800	2000	0.95	6000
322	3000	800	2000	0.95	7000
323	3000	800	3000	0.8	1000
324	3000	800	3000	0.8	2000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
325	3000	800	3000	0.8	3000
326	3000	800	3000	0.8	4000
327	3000	800	3000	0.8	5000
328	3000	800	3000	0.8	6000
329	3000	800	3000	0.8	7000
330	3000	800	3000	0.95	1000
331	3000	800	3000	0.95	2000
332	3000	800	3000	0.95	3000
333	3000	800	3000	0.95	4000
334	3000	800	3000	0.95	5000
335	3000	800	3000	0.95	6000
336	3000	800	3000	0.95	7000
337	3000	800	4000	0.8	1000
338	3000	800	4000	0.8	2000
339	3000	800	4000	0.8	3000
340	3000	800	4000	0.8	4000
341	3000	800	4000	0.8	5000
342	3000	800	4000	0.8	6000
343	3000	800	4000	0.8	7000
344	3000	800	4000	0.95	1000
345	3000	800	4000	0.95	2000
346	3000	800	4000	0.95	3000
347	3000	800	4000	0.95	4000
348	3000	800	4000	0.95	5000
349	3000	800	4000	0.95	6000
350	3000	800	4000	0.95	7000
351	3000	800	5000	0.8	1000
352	3000	800	5000	0.8	2000
353	3000	800	5000	0.8	3000
354	3000	800	5000	0.8	4000
355	3000	800	5000	0.8	5000
356	3000	800	5000	0.8	6000
357	3000	800	5000	0.8	7000
358	3000	800	5000	0.95	1000
359	3000	800	5000	0.95	2000
360	3000	800	5000	0.95	3000
361	3000	800	5000	0.95	4000
362	3000	800	5000	0.95	5000
363	3000	800	5000	0.95	6000
364	3000	800	5000	0.95	7000
365	3000	800	6000	0.8	1000
366	3000	800	6000	0.8	2000
367	3000	800	6000	0.8	3000
368	3000	800	6000	0.8	4000
369	3000	800	6000	0.8	5000
370	3000	800	6000	0.8	6000
371	3000	800	6000	0.8	7000
372	3000	800	6000	0.95	1000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
373	3000	800	6000	0.95	2000
374	3000	800	6000	0.95	3000
375	3000	800	6000	0.95	4000
376	3000	800	6000	0.95	5000
377	3000	800	6000	0.95	6000
378	3000	800	6000	0.95	7000
379	3000	800	7000	0.8	1000
380	3000	800	7000	0.8	2000
381	3000	800	7000	0.8	3000
382	3000	800	7000	0.8	4000
383	3000	800	7000	0.8	5000
384	3000	800	7000	0.8	6000
385	3000	800	7000	0.8	7000
386	3000	800	7000	0.95	1000
387	3000	800	7000	0.95	2000
388	3000	800	7000	0.95	3000
389	3000	800	7000	0.95	4000
390	3000	800	7000	0.95	5000
391	3000	800	7000	0.95	6000
392	3000	800	7000	0.95	7000
393	3000	1000	1000	0.8	1000
394	3000	1000	1000	0.8	2000
395	3000	1000	1000	0.8	3000
396	3000	1000	1000	0.8	4000
397	3000	1000	1000	0.8	5000
398	3000	1000	1000	0.8	6000
399	3000	1000	1000	0.8	7000
400	3000	1000	1000	0.95	1000
401	3000	1000	1000	0.95	2000
402	3000	1000	1000	0.95	3000
403	3000	1000	1000	0.95	4000
404	3000	1000	1000	0.95	5000
405	3000	1000	1000	0.95	6000
406	3000	1000	1000	0.95	7000
407	3000	1000	2000	0.8	1000
408	3000	1000	2000	0.8	2000
409	3000	1000	2000	0.8	3000
410	3000	1000	2000	0.8	4000
411	3000	1000	2000	0.8	5000
412	3000	1000	2000	0.8	6000
413	3000	1000	2000	0.8	7000
414	3000	1000	2000	0.95	1000
415	3000	1000	2000	0.95	2000
416	3000	1000	2000	0.95	3000
417	3000	1000	2000	0.95	4000
418	3000	1000	2000	0.95	5000
419	3000	1000	2000	0.95	6000
420	3000	1000	2000	0.95	7000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
421	3000	1000	3000	0.8	1000
422	3000	1000	3000	0.8	2000
423	3000	1000	3000	0.8	3000
424	3000	1000	3000	0.8	4000
425	3000	1000	3000	0.8	5000
426	3000	1000	3000	0.8	6000
427	3000	1000	3000	0.8	7000
428	3000	1000	3000	0.95	1000
429	3000	1000	3000	0.95	2000
430	3000	1000	3000	0.95	3000
431	3000	1000	3000	0.95	4000
432	3000	1000	3000	0.95	5000
433	3000	1000	3000	0.95	6000
434	3000	1000	3000	0.95	7000
435	3000	1000	4000	0.8	1000
436	3000	1000	4000	0.8	2000
437	3000	1000	4000	0.8	3000
438	3000	1000	4000	0.8	4000
439	3000	1000	4000	0.8	5000
440	3000	1000	4000	0.8	6000
441	3000	1000	4000	0.8	7000
442	3000	1000	4000	0.95	1000
443	3000	1000	4000	0.95	2000
444	3000	1000	4000	0.95	3000
445	3000	1000	4000	0.95	4000
446	3000	1000	4000	0.95	5000
447	3000	1000	4000	0.95	6000
448	3000	1000	4000	0.95	7000
449	3000	1000	5000	0.8	1000
450	3000	1000	5000	0.8	2000
451	3000	1000	5000	0.8	3000
452	3000	1000	5000	0.8	4000
453	3000	1000	5000	0.8	5000
454	3000	1000	5000	0.8	6000
455	3000	1000	5000	0.8	7000
456	3000	1000	5000	0.95	1000
457	3000	1000	5000	0.95	2000
458	3000	1000	5000	0.95	3000
459	3000	1000	5000	0.95	4000
460	3000	1000	5000	0.95	5000
461	3000	1000	5000	0.95	6000
462	3000	1000	5000	0.95	7000
463	3000	1000	6000	0.8	1000
464	3000	1000	6000	0.8	2000
465	3000	1000	6000	0.8	3000
466	3000	1000	6000	0.8	4000
467	3000	1000	6000	0.8	5000
468	3000	1000	6000	0.8	6000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
469	3000	1000	6000	0.8	7000
470	3000	1000	6000	0.95	1000
471	3000	1000	6000	0.95	2000
472	3000	1000	6000	0.95	3000
473	3000	1000	6000	0.95	4000
474	3000	1000	6000	0.95	5000
475	3000	1000	6000	0.95	6000
476	3000	1000	6000	0.95	7000
477	3000	1000	7000	0.8	1000
478	3000	1000	7000	0.8	2000
479	3000	1000	7000	0.8	3000
480	3000	1000	7000	0.8	4000
481	3000	1000	7000	0.8	5000
482	3000	1000	7000	0.8	6000
483	3000	1000	7000	0.8	7000
484	3000	1000	7000	0.95	1000
485	3000	1000	7000	0.95	2000
486	3000	1000	7000	0.95	3000
487	3000	1000	7000	0.95	4000
488	3000	1000	7000	0.95	5000
489	3000	1000	7000	0.95	6000
490	3000	1000	7000	0.95	7000
491	4000	200	1000	0.8	1000
492	4000	200	1000	0.8	2000
493	4000	200	1000	0.8	3000
494	4000	200	1000	0.8	4000
495	4000	200	1000	0.8	5000
496	4000	200	1000	0.8	6000
497	4000	200	1000	0.8	7000
498	4000	200	1000	0.95	1000
499	4000	200	1000	0.95	2000
500	4000	200	1000	0.95	3000
501	4000	200	1000	0.95	4000
502	4000	200	1000	0.95	5000
503	4000	200	1000	0.95	6000
504	4000	200	1000	0.95	7000
505	4000	200	2000	0.8	1000
506	4000	200	2000	0.8	2000
507	4000	200	2000	0.8	3000
508	4000	200	2000	0.8	4000
509	4000	200	2000	0.8	5000
510	4000	200	2000	0.8	6000
511	4000	200	2000	0.8	7000
512	4000	200	2000	0.95	1000
513	4000	200	2000	0.95	2000
514	4000	200	2000	0.95	3000
515	4000	200	2000	0.95	4000
516	4000	200	2000	0.95	5000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
517	4000	200	2000	0.95	6000
518	4000	200	2000	0.95	7000
519	4000	200	3000	0.8	1000
520	4000	200	3000	0.8	2000
521	4000	200	3000	0.8	3000
522	4000	200	3000	0.8	4000
523	4000	200	3000	0.8	5000
524	4000	200	3000	0.8	6000
525	4000	200	3000	0.8	7000
526	4000	200	3000	0.95	1000
527	4000	200	3000	0.95	2000
528	4000	200	3000	0.95	3000
529	4000	200	3000	0.95	4000
530	4000	200	3000	0.95	5000
531	4000	200	3000	0.95	6000
532	4000	200	3000	0.95	7000
533	4000	200	4000	0.8	1000
534	4000	200	4000	0.8	2000
535	4000	200	4000	0.8	3000
536	4000	200	4000	0.8	4000
537	4000	200	4000	0.8	5000
538	4000	200	4000	0.8	6000
539	4000	200	4000	0.8	7000
540	4000	200	4000	0.95	1000
541	4000	200	4000	0.95	2000
542	4000	200	4000	0.95	3000
543	4000	200	4000	0.95	4000
544	4000	200	4000	0.95	5000
545	4000	200	4000	0.95	6000
546	4000	200	4000	0.95	7000
547	4000	200	5000	0.8	1000
548	4000	200	5000	0.8	2000
549	4000	200	5000	0.8	3000
550	4000	200	5000	0.8	4000
551	4000	200	5000	0.8	5000
552	4000	200	5000	0.8	6000
553	4000	200	5000	0.8	7000
554	4000	200	5000	0.95	1000
555	4000	200	5000	0.95	2000
556	4000	200	5000	0.95	3000
557	4000	200	5000	0.95	4000
558	4000	200	5000	0.95	5000
559	4000	200	5000	0.95	6000
560	4000	200	5000	0.95	7000
561	4000	200	6000	0.8	1000
562	4000	200	6000	0.8	2000
563	4000	200	6000	0.8	3000
564	4000	200	6000	0.8	4000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
565	4000	200	6000	0.8	5000
566	4000	200	6000	0.8	6000
567	4000	200	6000	0.8	7000
568	4000	200	6000	0.95	1000
569	4000	200	6000	0.95	2000
570	4000	200	6000	0.95	3000
571	4000	200	6000	0.95	4000
572	4000	200	6000	0.95	5000
573	4000	200	6000	0.95	6000
574	4000	200	6000	0.95	7000
575	4000	200	7000	0.8	1000
576	4000	200	7000	0.8	2000
577	4000	200	7000	0.8	3000
578	4000	200	7000	0.8	4000
579	4000	200	7000	0.8	5000
580	4000	200	7000	0.8	6000
581	4000	200	7000	0.8	7000
582	4000	200	7000	0.95	1000
583	4000	200	7000	0.95	2000
584	4000	200	7000	0.95	3000
585	4000	200	7000	0.95	4000
586	4000	200	7000	0.95	5000
587	4000	200	7000	0.95	6000
588	4000	200	7000	0.95	7000
589	4000	400	1000	0.8	1000
590	4000	400	1000	0.8	2000
591	4000	400	1000	0.8	3000
592	4000	400	1000	0.8	4000
593	4000	400	1000	0.8	5000
594	4000	400	1000	0.8	6000
595	4000	400	1000	0.8	7000
596	4000	400	1000	0.95	1000
597	4000	400	1000	0.95	2000
598	4000	400	1000	0.95	3000
599	4000	400	1000	0.95	4000
600	4000	400	1000	0.95	5000
601	4000	400	1000	0.95	6000
602	4000	400	1000	0.95	7000
603	4000	400	2000	0.8	1000
604	4000	400	2000	0.8	2000
605	4000	400	2000	0.8	3000
606	4000	400	2000	0.8	4000
607	4000	400	2000	0.8	5000
608	4000	400	2000	0.8	6000
609	4000	400	2000	0.8	7000
610	4000	400	2000	0.95	1000
611	4000	400	2000	0.95	2000
612	4000	400	2000	0.95	3000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
613	4000	400	2000	0.95	4000
614	4000	400	2000	0.95	5000
615	4000	400	2000	0.95	6000
616	4000	400	2000	0.95	7000
617	4000	400	3000	0.8	1000
618	4000	400	3000	0.8	2000
619	4000	400	3000	0.8	3000
620	4000	400	3000	0.8	4000
621	4000	400	3000	0.8	5000
622	4000	400	3000	0.8	6000
623	4000	400	3000	0.8	7000
624	4000	400	3000	0.95	1000
625	4000	400	3000	0.95	2000
626	4000	400	3000	0.95	3000
627	4000	400	3000	0.95	4000
628	4000	400	3000	0.95	5000
629	4000	400	3000	0.95	6000
630	4000	400	3000	0.95	7000
631	4000	400	4000	0.8	1000
632	4000	400	4000	0.8	2000
633	4000	400	4000	0.8	3000
634	4000	400	4000	0.8	4000
635	4000	400	4000	0.8	5000
636	4000	400	4000	0.8	6000
637	4000	400	4000	0.8	7000
638	4000	400	4000	0.95	1000
639	4000	400	4000	0.95	2000
640	4000	400	4000	0.95	3000
641	4000	400	4000	0.95	4000
642	4000	400	4000	0.95	5000
643	4000	400	4000	0.95	6000
644	4000	400	4000	0.95	7000
645	4000	400	5000	0.8	1000
646	4000	400	5000	0.8	2000
647	4000	400	5000	0.8	3000
648	4000	400	5000	0.8	4000
649	4000	400	5000	0.8	5000
650	4000	400	5000	0.8	6000
651	4000	400	5000	0.8	7000
652	4000	400	5000	0.95	1000
653	4000	400	5000	0.95	2000
654	4000	400	5000	0.95	3000
655	4000	400	5000	0.95	4000
656	4000	400	5000	0.95	5000
657	4000	400	5000	0.95	6000
658	4000	400	5000	0.95	7000
659	4000	400	6000	0.8	1000
660	4000	400	6000	0.8	2000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
661	4000	400	6000	0.8	3000
662	4000	400	6000	0.8	4000
663	4000	400	6000	0.8	5000
664	4000	400	6000	0.8	6000
665	4000	400	6000	0.8	7000
666	4000	400	6000	0.95	1000
667	4000	400	6000	0.95	2000
668	4000	400	6000	0.95	3000
669	4000	400	6000	0.95	4000
670	4000	400	6000	0.95	5000
671	4000	400	6000	0.95	6000
672	4000	400	6000	0.95	7000
673	4000	400	7000	0.8	1000
674	4000	400	7000	0.8	2000
675	4000	400	7000	0.8	3000
676	4000	400	7000	0.8	4000
677	4000	400	7000	0.8	5000
678	4000	400	7000	0.8	6000
679	4000	400	7000	0.8	7000
680	4000	400	7000	0.95	1000
681	4000	400	7000	0.95	2000
682	4000	400	7000	0.95	3000
683	4000	400	7000	0.95	4000
684	4000	400	7000	0.95	5000
685	4000	400	7000	0.95	6000
686	4000	400	7000	0.95	7000
687	4000	600	1000	0.8	1000
688	4000	600	1000	0.8	2000
689	4000	600	1000	0.8	3000
690	4000	600	1000	0.8	4000
691	4000	600	1000	0.8	5000
692	4000	600	1000	0.8	6000
693	4000	600	1000	0.8	7000
694	4000	600	1000	0.95	1000
695	4000	600	1000	0.95	2000
696	4000	600	1000	0.95	3000
697	4000	600	1000	0.95	4000
698	4000	600	1000	0.95	5000
699	4000	600	1000	0.95	6000
700	4000	600	1000	0.95	7000
701	4000	600	2000	0.8	1000
702	4000	600	2000	0.8	2000
703	4000	600	2000	0.8	3000
704	4000	600	2000	0.8	4000
705	4000	600	2000	0.8	5000
706	4000	600	2000	0.8	6000
707	4000	600	2000	0.8	7000
708	4000	600	2000	0.95	1000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
709	4000	600	2000	0.95	2000
710	4000	600	2000	0.95	3000
711	4000	600	2000	0.95	4000
712	4000	600	2000	0.95	5000
713	4000	600	2000	0.95	6000
714	4000	600	2000	0.95	7000
715	4000	600	3000	0.8	1000
716	4000	600	3000	0.8	2000
717	4000	600	3000	0.8	3000
718	4000	600	3000	0.8	4000
719	4000	600	3000	0.8	5000
720	4000	600	3000	0.8	6000
721	4000	600	3000	0.8	7000
722	4000	600	3000	0.95	1000
723	4000	600	3000	0.95	2000
724	4000	600	3000	0.95	3000
725	4000	600	3000	0.95	4000
726	4000	600	3000	0.95	5000
727	4000	600	3000	0.95	6000
728	4000	600	3000	0.95	7000
729	4000	600	4000	0.8	1000
730	4000	600	4000	0.8	2000
731	4000	600	4000	0.8	3000
732	4000	600	4000	0.8	4000
733	4000	600	4000	0.8	5000
734	4000	600	4000	0.8	6000
735	4000	600	4000	0.8	7000
736	4000	600	4000	0.95	1000
737	4000	600	4000	0.95	2000
738	4000	600	4000	0.95	3000
739	4000	600	4000	0.95	4000
740	4000	600	4000	0.95	5000
741	4000	600	4000	0.95	6000
742	4000	600	4000	0.95	7000
743	4000	600	5000	0.8	1000
744	4000	600	5000	0.8	2000
745	4000	600	5000	0.8	3000
746	4000	600	5000	0.8	4000
747	4000	600	5000	0.8	5000
748	4000	600	5000	0.8	6000
749	4000	600	5000	0.8	7000
750	4000	600	5000	0.95	1000
751	4000	600	5000	0.95	2000
752	4000	600	5000	0.95	3000
753	4000	600	5000	0.95	4000
754	4000	600	5000	0.95	5000
755	4000	600	5000	0.95	6000
756	4000	600	5000	0.95	7000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
757	4000	600	6000	0.8	1000
758	4000	600	6000	0.8	2000
759	4000	600	6000	0.8	3000
760	4000	600	6000	0.8	4000
761	4000	600	6000	0.8	5000
762	4000	600	6000	0.8	6000
763	4000	600	6000	0.8	7000
764	4000	600	6000	0.95	1000
765	4000	600	6000	0.95	2000
766	4000	600	6000	0.95	3000
767	4000	600	6000	0.95	4000
768	4000	600	6000	0.95	5000
769	4000	600	6000	0.95	6000
770	4000	600	6000	0.95	7000
771	4000	600	7000	0.8	1000
772	4000	600	7000	0.8	2000
773	4000	600	7000	0.8	3000
774	4000	600	7000	0.8	4000
775	4000	600	7000	0.8	5000
776	4000	600	7000	0.8	6000
777	4000	600	7000	0.8	7000
778	4000	600	7000	0.95	1000
779	4000	600	7000	0.95	2000
780	4000	600	7000	0.95	3000
781	4000	600	7000	0.95	4000
782	4000	600	7000	0.95	5000
783	4000	600	7000	0.95	6000
784	4000	600	7000	0.95	7000
785	4000	800	1000	0.8	1000
786	4000	800	1000	0.8	2000
787	4000	800	1000	0.8	3000
788	4000	800	1000	0.8	4000
789	4000	800	1000	0.8	5000
790	4000	800	1000	0.8	6000
791	4000	800	1000	0.8	7000
792	4000	800	1000	0.95	1000
793	4000	800	1000	0.95	2000
794	4000	800	1000	0.95	3000
795	4000	800	1000	0.95	4000
796	4000	800	1000	0.95	5000
797	4000	800	1000	0.95	6000
798	4000	800	1000	0.95	7000
799	4000	800	2000	0.8	1000
800	4000	800	2000	0.8	2000
801	4000	800	2000	0.8	3000
802	4000	800	2000	0.8	4000
803	4000	800	2000	0.8	5000
804	4000	800	2000	0.8	6000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
805	4000	800	2000	0.8	7000
806	4000	800	2000	0.95	1000
807	4000	800	2000	0.95	2000
808	4000	800	2000	0.95	3000
809	4000	800	2000	0.95	4000
810	4000	800	2000	0.95	5000
811	4000	800	2000	0.95	6000
812	4000	800	2000	0.95	7000
813	4000	800	3000	0.8	1000
814	4000	800	3000	0.8	2000
815	4000	800	3000	0.8	3000
816	4000	800	3000	0.8	4000
817	4000	800	3000	0.8	5000
818	4000	800	3000	0.8	6000
819	4000	800	3000	0.8	7000
820	4000	800	3000	0.95	1000
821	4000	800	3000	0.95	2000
822	4000	800	3000	0.95	3000
823	4000	800	3000	0.95	4000
824	4000	800	3000	0.95	5000
825	4000	800	3000	0.95	6000
826	4000	800	3000	0.95	7000
827	4000	800	4000	0.8	1000
828	4000	800	4000	0.8	2000
829	4000	800	4000	0.8	3000
830	4000	800	4000	0.8	4000
831	4000	800	4000	0.8	5000
832	4000	800	4000	0.8	6000
833	4000	800	4000	0.8	7000
834	4000	800	4000	0.95	1000
835	4000	800	4000	0.95	2000
836	4000	800	4000	0.95	3000
837	4000	800	4000	0.95	4000
838	4000	800	4000	0.95	5000
839	4000	800	4000	0.95	6000
840	4000	800	4000	0.95	7000
841	4000	800	5000	0.8	1000
842	4000	800	5000	0.8	2000
843	4000	800	5000	0.8	3000
844	4000	800	5000	0.8	4000
845	4000	800	5000	0.8	5000
846	4000	800	5000	0.8	6000
847	4000	800	5000	0.8	7000
848	4000	800	5000	0.95	1000
849	4000	800	5000	0.95	2000
850	4000	800	5000	0.95	3000
851	4000	800	5000	0.95	4000
852	4000	800	5000	0.95	5000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
853	4000	800	5000	0.95	6000
854	4000	800	5000	0.95	7000
855	4000	800	6000	0.8	1000
856	4000	800	6000	0.8	2000
857	4000	800	6000	0.8	3000
858	4000	800	6000	0.8	4000
859	4000	800	6000	0.8	5000
860	4000	800	6000	0.8	6000
861	4000	800	6000	0.8	7000
862	4000	800	6000	0.95	1000
863	4000	800	6000	0.95	2000
864	4000	800	6000	0.95	3000
865	4000	800	6000	0.95	4000
866	4000	800	6000	0.95	5000
867	4000	800	6000	0.95	6000
868	4000	800	6000	0.95	7000
869	4000	800	7000	0.8	1000
870	4000	800	7000	0.8	2000
871	4000	800	7000	0.8	3000
872	4000	800	7000	0.8	4000
873	4000	800	7000	0.8	5000
874	4000	800	7000	0.8	6000
875	4000	800	7000	0.8	7000
876	4000	800	7000	0.95	1000
877	4000	800	7000	0.95	2000
878	4000	800	7000	0.95	3000
879	4000	800	7000	0.95	4000
880	4000	800	7000	0.95	5000
881	4000	800	7000	0.95	6000
882	4000	800	7000	0.95	7000
883	4000	1000	1000	0.8	1000
884	4000	1000	1000	0.8	2000
885	4000	1000	1000	0.8	3000
886	4000	1000	1000	0.8	4000
887	4000	1000	1000	0.8	5000
888	4000	1000	1000	0.8	6000
889	4000	1000	1000	0.8	7000
890	4000	1000	1000	0.95	1000
891	4000	1000	1000	0.95	2000
892	4000	1000	1000	0.95	3000
893	4000	1000	1000	0.95	4000
894	4000	1000	1000	0.95	5000
895	4000	1000	1000	0.95	6000
896	4000	1000	1000	0.95	7000
897	4000	1000	2000	0.8	1000
898	4000	1000	2000	0.8	2000
899	4000	1000	2000	0.8	3000
900	4000	1000	2000	0.8	4000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
901	4000	1000	2000	0.8	5000
902	4000	1000	2000	0.8	6000
903	4000	1000	2000	0.8	7000
904	4000	1000	2000	0.95	1000
905	4000	1000	2000	0.95	2000
906	4000	1000	2000	0.95	3000
907	4000	1000	2000	0.95	4000
908	4000	1000	2000	0.95	5000
909	4000	1000	2000	0.95	6000
910	4000	1000	2000	0.95	7000
911	4000	1000	3000	0.8	1000
912	4000	1000	3000	0.8	2000
913	4000	1000	3000	0.8	3000
914	4000	1000	3000	0.8	4000
915	4000	1000	3000	0.8	5000
916	4000	1000	3000	0.8	6000
917	4000	1000	3000	0.8	7000
918	4000	1000	3000	0.95	1000
919	4000	1000	3000	0.95	2000
920	4000	1000	3000	0.95	3000
921	4000	1000	3000	0.95	4000
922	4000	1000	3000	0.95	5000
923	4000	1000	3000	0.95	6000
924	4000	1000	3000	0.95	7000
925	4000	1000	4000	0.8	1000
926	4000	1000	4000	0.8	2000
927	4000	1000	4000	0.8	3000
928	4000	1000	4000	0.8	4000
929	4000	1000	4000	0.8	5000
930	4000	1000	4000	0.8	6000
931	4000	1000	4000	0.8	7000
932	4000	1000	4000	0.95	1000
933	4000	1000	4000	0.95	2000
934	4000	1000	4000	0.95	3000
935	4000	1000	4000	0.95	4000
936	4000	1000	4000	0.95	5000
937	4000	1000	4000	0.95	6000
938	4000	1000	4000	0.95	7000
939	4000	1000	5000	0.8	1000
940	4000	1000	5000	0.8	2000
941	4000	1000	5000	0.8	3000
942	4000	1000	5000	0.8	4000
943	4000	1000	5000	0.8	5000
944	4000	1000	5000	0.8	6000
945	4000	1000	5000	0.8	7000
946	4000	1000	5000	0.95	1000
947	4000	1000	5000	0.95	2000
948	4000	1000	5000	0.95	3000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
949	4000	1000	5000	0.95	4000
950	4000	1000	5000	0.95	5000
951	4000	1000	5000	0.95	6000
952	4000	1000	5000	0.95	7000
953	4000	1000	6000	0.8	1000
954	4000	1000	6000	0.8	2000
955	4000	1000	6000	0.8	3000
956	4000	1000	6000	0.8	4000
957	4000	1000	6000	0.8	5000
958	4000	1000	6000	0.8	6000
959	4000	1000	6000	0.8	7000
960	4000	1000	6000	0.95	1000
961	4000	1000	6000	0.95	2000
962	4000	1000	6000	0.95	3000
963	4000	1000	6000	0.95	4000
964	4000	1000	6000	0.95	5000
965	4000	1000	6000	0.95	6000
966	4000	1000	6000	0.95	7000
967	4000	1000	7000	0.8	1000
968	4000	1000	7000	0.8	2000
969	4000	1000	7000	0.8	3000
970	4000	1000	7000	0.8	4000
971	4000	1000	7000	0.8	5000
972	4000	1000	7000	0.8	6000
973	4000	1000	7000	0.8	7000
974	4000	1000	7000	0.95	1000
975	4000	1000	7000	0.95	2000
976	4000	1000	7000	0.95	3000
977	4000	1000	7000	0.95	4000
978	4000	1000	7000	0.95	5000
979	4000	1000	7000	0.95	6000
980	4000	1000	7000	0.95	7000
981	5000	200	1000	0.8	1000
982	5000	200	1000	0.8	2000
983	5000	200	1000	0.8	3000
984	5000	200	1000	0.8	4000
985	5000	200	1000	0.8	5000
986	5000	200	1000	0.8	6000
987	5000	200	1000	0.8	7000
988	5000	200	1000	0.95	1000
989	5000	200	1000	0.95	2000
990	5000	200	1000	0.95	3000
991	5000	200	1000	0.95	4000
992	5000	200	1000	0.95	5000
993	5000	200	1000	0.95	6000
994	5000	200	1000	0.95	7000
995	5000	200	2000	0.8	1000
996	5000	200	2000	0.8	2000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
997	5000	200	2000	0.8	3000
998	5000	200	2000	0.8	4000
999	5000	200	2000	0.8	5000
1000	5000	200	2000	0.8	6000
1001	5000	200	2000	0.8	7000
1002	5000	200	2000	0.95	1000
1003	5000	200	2000	0.95	2000
1004	5000	200	2000	0.95	3000
1005	5000	200	2000	0.95	4000
1006	5000	200	2000	0.95	5000
1007	5000	200	2000	0.95	6000
1008	5000	200	2000	0.95	7000
1009	5000	200	3000	0.8	1000
1010	5000	200	3000	0.8	2000
1011	5000	200	3000	0.8	3000
1012	5000	200	3000	0.8	4000
1013	5000	200	3000	0.8	5000
1014	5000	200	3000	0.8	6000
1015	5000	200	3000	0.8	7000
1016	5000	200	3000	0.95	1000
1017	5000	200	3000	0.95	2000
1018	5000	200	3000	0.95	3000
1019	5000	200	3000	0.95	4000
1020	5000	200	3000	0.95	5000
1021	5000	200	3000	0.95	6000
1022	5000	200	3000	0.95	7000
1023	5000	200	4000	0.8	1000
1024	5000	200	4000	0.8	2000
1025	5000	200	4000	0.8	3000
1026	5000	200	4000	0.8	4000
1027	5000	200	4000	0.8	5000
1028	5000	200	4000	0.8	6000
1029	5000	200	4000	0.8	7000
1030	5000	200	4000	0.95	1000
1031	5000	200	4000	0.95	2000
1032	5000	200	4000	0.95	3000
1033	5000	200	4000	0.95	4000
1034	5000	200	4000	0.95	5000
1035	5000	200	4000	0.95	6000
1036	5000	200	4000	0.95	7000
1037	5000	200	5000	0.8	1000
1038	5000	200	5000	0.8	2000
1039	5000	200	5000	0.8	3000
1040	5000	200	5000	0.8	4000
1041	5000	200	5000	0.8	5000
1042	5000	200	5000	0.8	6000
1043	5000	200	5000	0.8	7000
1044	5000	200	5000	0.95	1000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1045	5000	200	5000	0.95	2000
1046	5000	200	5000	0.95	3000
1047	5000	200	5000	0.95	4000
1048	5000	200	5000	0.95	5000
1049	5000	200	5000	0.95	6000
1050	5000	200	5000	0.95	7000
1051	5000	200	6000	0.8	1000
1052	5000	200	6000	0.8	2000
1053	5000	200	6000	0.8	3000
1054	5000	200	6000	0.8	4000
1055	5000	200	6000	0.8	5000
1056	5000	200	6000	0.8	6000
1057	5000	200	6000	0.8	7000
1058	5000	200	6000	0.95	1000
1059	5000	200	6000	0.95	2000
1060	5000	200	6000	0.95	3000
1061	5000	200	6000	0.95	4000
1062	5000	200	6000	0.95	5000
1063	5000	200	6000	0.95	6000
1064	5000	200	6000	0.95	7000
1065	5000	200	7000	0.8	1000
1066	5000	200	7000	0.8	2000
1067	5000	200	7000	0.8	3000
1068	5000	200	7000	0.8	4000
1069	5000	200	7000	0.8	5000
1070	5000	200	7000	0.8	6000
1071	5000	200	7000	0.8	7000
1072	5000	200	7000	0.95	1000
1073	5000	200	7000	0.95	2000
1074	5000	200	7000	0.95	3000
1075	5000	200	7000	0.95	4000
1076	5000	200	7000	0.95	5000
1077	5000	200	7000	0.95	6000
1078	5000	200	7000	0.95	7000
1079	5000	400	1000	0.8	1000
1080	5000	400	1000	0.8	2000
1081	5000	400	1000	0.8	3000
1082	5000	400	1000	0.8	4000
1083	5000	400	1000	0.8	5000
1084	5000	400	1000	0.8	6000
1085	5000	400	1000	0.8	7000
1086	5000	400	1000	0.95	1000
1087	5000	400	1000	0.95	2000
1088	5000	400	1000	0.95	3000
1089	5000	400	1000	0.95	4000
1090	5000	400	1000	0.95	5000
1091	5000	400	1000	0.95	6000
1092	5000	400	1000	0.95	7000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1093	5000	400	2000	0.8	1000
1094	5000	400	2000	0.8	2000
1095	5000	400	2000	0.8	3000
1096	5000	400	2000	0.8	4000
1097	5000	400	2000	0.8	5000
1098	5000	400	2000	0.8	6000
1099	5000	400	2000	0.8	7000
1100	5000	400	2000	0.95	1000
1101	5000	400	2000	0.95	2000
1102	5000	400	2000	0.95	3000
1103	5000	400	2000	0.95	4000
1104	5000	400	2000	0.95	5000
1105	5000	400	2000	0.95	6000
1106	5000	400	2000	0.95	7000
1107	5000	400	3000	0.8	1000
1108	5000	400	3000	0.8	2000
1109	5000	400	3000	0.8	3000
1110	5000	400	3000	0.8	4000
1111	5000	400	3000	0.8	5000
1112	5000	400	3000	0.8	6000
1113	5000	400	3000	0.8	7000
1114	5000	400	3000	0.95	1000
1115	5000	400	3000	0.95	2000
1116	5000	400	3000	0.95	3000
1117	5000	400	3000	0.95	4000
1118	5000	400	3000	0.95	5000
1119	5000	400	3000	0.95	6000
1120	5000	400	3000	0.95	7000
1121	5000	400	4000	0.8	1000
1122	5000	400	4000	0.8	2000
1123	5000	400	4000	0.8	3000
1124	5000	400	4000	0.8	4000
1125	5000	400	4000	0.8	5000
1126	5000	400	4000	0.8	6000
1127	5000	400	4000	0.8	7000
1128	5000	400	4000	0.95	1000
1129	5000	400	4000	0.95	2000
1130	5000	400	4000	0.95	3000
1131	5000	400	4000	0.95	4000
1132	5000	400	4000	0.95	5000
1133	5000	400	4000	0.95	6000
1134	5000	400	4000	0.95	7000
1135	5000	400	5000	0.8	1000
1136	5000	400	5000	0.8	2000
1137	5000	400	5000	0.8	3000
1138	5000	400	5000	0.8	4000
1139	5000	400	5000	0.8	5000
1140	5000	400	5000	0.8	6000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1141	5000	400	5000	0.8	7000
1142	5000	400	5000	0.95	1000
1143	5000	400	5000	0.95	2000
1144	5000	400	5000	0.95	3000
1145	5000	400	5000	0.95	4000
1146	5000	400	5000	0.95	5000
1147	5000	400	5000	0.95	6000
1148	5000	400	5000	0.95	7000
1149	5000	400	6000	0.8	1000
1150	5000	400	6000	0.8	2000
1151	5000	400	6000	0.8	3000
1152	5000	400	6000	0.8	4000
1153	5000	400	6000	0.8	5000
1154	5000	400	6000	0.8	6000
1155	5000	400	6000	0.8	7000
1156	5000	400	6000	0.95	1000
1157	5000	400	6000	0.95	2000
1158	5000	400	6000	0.95	3000
1159	5000	400	6000	0.95	4000
1160	5000	400	6000	0.95	5000
1161	5000	400	6000	0.95	6000
1162	5000	400	6000	0.95	7000
1163	5000	400	7000	0.8	1000
1164	5000	400	7000	0.8	2000
1165	5000	400	7000	0.8	3000
1166	5000	400	7000	0.8	4000
1167	5000	400	7000	0.8	5000
1168	5000	400	7000	0.8	6000
1169	5000	400	7000	0.8	7000
1170	5000	400	7000	0.95	1000
1171	5000	400	7000	0.95	2000
1172	5000	400	7000	0.95	3000
1173	5000	400	7000	0.95	4000
1174	5000	400	7000	0.95	5000
1175	5000	400	7000	0.95	6000
1176	5000	400	7000	0.95	7000
1177	5000	600	1000	0.8	1000
1178	5000	600	1000	0.8	2000
1179	5000	600	1000	0.8	3000
1180	5000	600	1000	0.8	4000
1181	5000	600	1000	0.8	5000
1182	5000	600	1000	0.8	6000
1183	5000	600	1000	0.8	7000
1184	5000	600	1000	0.95	1000
1185	5000	600	1000	0.95	2000
1186	5000	600	1000	0.95	3000
1187	5000	600	1000	0.95	4000
1188	5000	600	1000	0.95	5000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1189	5000	600	1000	0.95	6000
1190	5000	600	1000	0.95	7000
1191	5000	600	2000	0.8	1000
1192	5000	600	2000	0.8	2000
1193	5000	600	2000	0.8	3000
1194	5000	600	2000	0.8	4000
1195	5000	600	2000	0.8	5000
1196	5000	600	2000	0.8	6000
1197	5000	600	2000	0.8	7000
1198	5000	600	2000	0.95	1000
1199	5000	600	2000	0.95	2000
1200	5000	600	2000	0.95	3000
1201	5000	600	2000	0.95	4000
1202	5000	600	2000	0.95	5000
1203	5000	600	2000	0.95	6000
1204	5000	600	2000	0.95	7000
1205	5000	600	3000	0.8	1000
1206	5000	600	3000	0.8	2000
1207	5000	600	3000	0.8	3000
1208	5000	600	3000	0.8	4000
1209	5000	600	3000	0.8	5000
1210	5000	600	3000	0.8	6000
1211	5000	600	3000	0.8	7000
1212	5000	600	3000	0.95	1000
1213	5000	600	3000	0.95	2000
1214	5000	600	3000	0.95	3000
1215	5000	600	3000	0.95	4000
1216	5000	600	3000	0.95	5000
1217	5000	600	3000	0.95	6000
1218	5000	600	3000	0.95	7000
1219	5000	600	4000	0.8	1000
1220	5000	600	4000	0.8	2000
1221	5000	600	4000	0.8	3000
1222	5000	600	4000	0.8	4000
1223	5000	600	4000	0.8	5000
1224	5000	600	4000	0.8	6000
1225	5000	600	4000	0.8	7000
1226	5000	600	4000	0.95	1000
1227	5000	600	4000	0.95	2000
1228	5000	600	4000	0.95	3000
1229	5000	600	4000	0.95	4000
1230	5000	600	4000	0.95	5000
1231	5000	600	4000	0.95	6000
1232	5000	600	4000	0.95	7000
1233	5000	600	5000	0.8	1000
1234	5000	600	5000	0.8	2000
1235	5000	600	5000	0.8	3000
1236	5000	600	5000	0.8	4000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1237	5000	600	5000	0.8	5000
1238	5000	600	5000	0.8	6000
1239	5000	600	5000	0.8	7000
1240	5000	600	5000	0.95	1000
1241	5000	600	5000	0.95	2000
1242	5000	600	5000	0.95	3000
1243	5000	600	5000	0.95	4000
1244	5000	600	5000	0.95	5000
1245	5000	600	5000	0.95	6000
1246	5000	600	5000	0.95	7000
1247	5000	600	6000	0.8	1000
1248	5000	600	6000	0.8	2000
1249	5000	600	6000	0.8	3000
1250	5000	600	6000	0.8	4000
1251	5000	600	6000	0.8	5000
1252	5000	600	6000	0.8	6000
1253	5000	600	6000	0.8	7000
1254	5000	600	6000	0.95	1000
1255	5000	600	6000	0.95	2000
1256	5000	600	6000	0.95	3000
1257	5000	600	6000	0.95	4000
1258	5000	600	6000	0.95	5000
1259	5000	600	6000	0.95	6000
1260	5000	600	6000	0.95	7000
1261	5000	600	7000	0.8	1000
1262	5000	600	7000	0.8	2000
1263	5000	600	7000	0.8	3000
1264	5000	600	7000	0.8	4000
1265	5000	600	7000	0.8	5000
1266	5000	600	7000	0.8	6000
1267	5000	600	7000	0.8	7000
1268	5000	600	7000	0.95	1000
1269	5000	600	7000	0.95	2000
1270	5000	600	7000	0.95	3000
1271	5000	600	7000	0.95	4000
1272	5000	600	7000	0.95	5000
1273	5000	600	7000	0.95	6000
1274	5000	600	7000	0.95	7000
1275	5000	800	1000	0.8	1000
1276	5000	800	1000	0.8	2000
1277	5000	800	1000	0.8	3000
1278	5000	800	1000	0.8	4000
1279	5000	800	1000	0.8	5000
1280	5000	800	1000	0.8	6000
1281	5000	800	1000	0.8	7000
1282	5000	800	1000	0.95	1000
1283	5000	800	1000	0.95	2000
1284	5000	800	1000	0.95	3000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1285	5000	800	1000	0.95	4000
1286	5000	800	1000	0.95	5000
1287	5000	800	1000	0.95	6000
1288	5000	800	1000	0.95	7000
1289	5000	800	2000	0.8	1000
1290	5000	800	2000	0.8	2000
1291	5000	800	2000	0.8	3000
1292	5000	800	2000	0.8	4000
1293	5000	800	2000	0.8	5000
1294	5000	800	2000	0.8	6000
1295	5000	800	2000	0.8	7000
1296	5000	800	2000	0.95	1000
1297	5000	800	2000	0.95	2000
1298	5000	800	2000	0.95	3000
1299	5000	800	2000	0.95	4000
1300	5000	800	2000	0.95	5000
1301	5000	800	2000	0.95	6000
1302	5000	800	2000	0.95	7000
1303	5000	800	3000	0.8	1000
1304	5000	800	3000	0.8	2000
1305	5000	800	3000	0.8	3000
1306	5000	800	3000	0.8	4000
1307	5000	800	3000	0.8	5000
1308	5000	800	3000	0.8	6000
1309	5000	800	3000	0.8	7000
1310	5000	800	3000	0.95	1000
1311	5000	800	3000	0.95	2000
1312	5000	800	3000	0.95	3000
1313	5000	800	3000	0.95	4000
1314	5000	800	3000	0.95	5000
1315	5000	800	3000	0.95	6000
1316	5000	800	3000	0.95	7000
1317	5000	800	4000	0.8	1000
1318	5000	800	4000	0.8	2000
1319	5000	800	4000	0.8	3000
1320	5000	800	4000	0.8	4000
1321	5000	800	4000	0.8	5000
1322	5000	800	4000	0.8	6000
1323	5000	800	4000	0.8	7000
1324	5000	800	4000	0.95	1000
1325	5000	800	4000	0.95	2000
1326	5000	800	4000	0.95	3000
1327	5000	800	4000	0.95	4000
1328	5000	800	4000	0.95	5000
1329	5000	800	4000	0.95	6000
1330	5000	800	4000	0.95	7000
1331	5000	800	5000	0.8	1000
1332	5000	800	5000	0.8	2000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1333	5000	800	5000	0.8	3000
1334	5000	800	5000	0.8	4000
1335	5000	800	5000	0.8	5000
1336	5000	800	5000	0.8	6000
1337	5000	800	5000	0.8	7000
1338	5000	800	5000	0.95	1000
1339	5000	800	5000	0.95	2000
1340	5000	800	5000	0.95	3000
1341	5000	800	5000	0.95	4000
1342	5000	800	5000	0.95	5000
1343	5000	800	5000	0.95	6000
1344	5000	800	5000	0.95	7000
1345	5000	800	6000	0.8	1000
1346	5000	800	6000	0.8	2000
1347	5000	800	6000	0.8	3000
1348	5000	800	6000	0.8	4000
1349	5000	800	6000	0.8	5000
1350	5000	800	6000	0.8	6000
1351	5000	800	6000	0.8	7000
1352	5000	800	6000	0.95	1000
1353	5000	800	6000	0.95	2000
1354	5000	800	6000	0.95	3000
1355	5000	800	6000	0.95	4000
1356	5000	800	6000	0.95	5000
1357	5000	800	6000	0.95	6000
1358	5000	800	6000	0.95	7000
1359	5000	800	7000	0.8	1000
1360	5000	800	7000	0.8	2000
1361	5000	800	7000	0.8	3000
1362	5000	800	7000	0.8	4000
1363	5000	800	7000	0.8	5000
1364	5000	800	7000	0.8	6000
1365	5000	800	7000	0.8	7000
1366	5000	800	7000	0.95	1000
1367	5000	800	7000	0.95	2000
1368	5000	800	7000	0.95	3000
1369	5000	800	7000	0.95	4000
1370	5000	800	7000	0.95	5000
1371	5000	800	7000	0.95	6000
1372	5000	800	7000	0.95	7000
1373	5000	1000	1000	0.8	1000
1374	5000	1000	1000	0.8	2000
1375	5000	1000	1000	0.8	3000
1376	5000	1000	1000	0.8	4000
1377	5000	1000	1000	0.8	5000
1378	5000	1000	1000	0.8	6000
1379	5000	1000	1000	0.8	7000
1380	5000	1000	1000	0.95	1000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1381	5000	1000	1000	0.95	2000
1382	5000	1000	1000	0.95	3000
1383	5000	1000	1000	0.95	4000
1384	5000	1000	1000	0.95	5000
1385	5000	1000	1000	0.95	6000
1386	5000	1000	1000	0.95	7000
1387	5000	1000	2000	0.8	1000
1388	5000	1000	2000	0.8	2000
1389	5000	1000	2000	0.8	3000
1390	5000	1000	2000	0.8	4000
1391	5000	1000	2000	0.8	5000
1392	5000	1000	2000	0.8	6000
1393	5000	1000	2000	0.8	7000
1394	5000	1000	2000	0.95	1000
1395	5000	1000	2000	0.95	2000
1396	5000	1000	2000	0.95	3000
1397	5000	1000	2000	0.95	4000
1398	5000	1000	2000	0.95	5000
1399	5000	1000	2000	0.95	6000
1400	5000	1000	2000	0.95	7000
1401	5000	1000	3000	0.8	1000
1402	5000	1000	3000	0.8	2000
1403	5000	1000	3000	0.8	3000
1404	5000	1000	3000	0.8	4000
1405	5000	1000	3000	0.8	5000
1406	5000	1000	3000	0.8	6000
1407	5000	1000	3000	0.8	7000
1408	5000	1000	3000	0.95	1000
1409	5000	1000	3000	0.95	2000
1410	5000	1000	3000	0.95	3000
1411	5000	1000	3000	0.95	4000
1412	5000	1000	3000	0.95	5000
1413	5000	1000	3000	0.95	6000
1414	5000	1000	3000	0.95	7000
1415	5000	1000	4000	0.8	1000
1416	5000	1000	4000	0.8	2000
1417	5000	1000	4000	0.8	3000
1418	5000	1000	4000	0.8	4000
1419	5000	1000	4000	0.8	5000
1420	5000	1000	4000	0.8	6000
1421	5000	1000	4000	0.8	7000
1422	5000	1000	4000	0.95	1000
1423	5000	1000	4000	0.95	2000
1424	5000	1000	4000	0.95	3000
1425	5000	1000	4000	0.95	4000
1426	5000	1000	4000	0.95	5000
1427	5000	1000	4000	0.95	6000
1428	5000	1000	4000	0.95	7000

Continuation of Table A.1					
Architecture Number	Fuel Capacity (gal.)	DG Capacity (kW)	Size of PV Array (m ²)	ESS Efficiency	ESS Capacity (kWh)
1429	5000	1000	5000	0.8	1000
1430	5000	1000	5000	0.8	2000
1431	5000	1000	5000	0.8	3000
1432	5000	1000	5000	0.8	4000
1433	5000	1000	5000	0.8	5000
1434	5000	1000	5000	0.8	6000
1435	5000	1000	5000	0.8	7000
1436	5000	1000	5000	0.95	1000
1437	5000	1000	5000	0.95	2000
1438	5000	1000	5000	0.95	3000
1439	5000	1000	5000	0.95	4000
1440	5000	1000	5000	0.95	5000
1441	5000	1000	5000	0.95	6000
1442	5000	1000	5000	0.95	7000
1443	5000	1000	6000	0.8	1000
1444	5000	1000	6000	0.8	2000
1445	5000	1000	6000	0.8	3000
1446	5000	1000	6000	0.8	4000
1447	5000	1000	6000	0.8	5000
1448	5000	1000	6000	0.8	6000
1449	5000	1000	6000	0.8	7000
1450	5000	1000	6000	0.95	1000
1451	5000	1000	6000	0.95	2000
1452	5000	1000	6000	0.95	3000
1453	5000	1000	6000	0.95	4000
1454	5000	1000	6000	0.95	5000
1455	5000	1000	6000	0.95	6000
1456	5000	1000	6000	0.95	7000
1457	5000	1000	7000	0.8	1000
1458	5000	1000	7000	0.8	2000
1459	5000	1000	7000	0.8	3000
1460	5000	1000	7000	0.8	4000
1461	5000	1000	7000	0.8	5000
1462	5000	1000	7000	0.8	6000
1463	5000	1000	7000	0.8	7000
1464	5000	1000	7000	0.95	1000
1465	5000	1000	7000	0.95	2000
1466	5000	1000	7000	0.95	3000
1467	5000	1000	7000	0.95	4000
1468	5000	1000	7000	0.95	5000
1469	5000	1000	7000	0.95	6000
1470	5000	1000	7000	0.95	7000

End of Table A.1

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APPENDIX B: ELMI Simulation MATLAB Code

The Matlab code used to simulate microgrid performance is included below. The code was generated as part of [9] and modified for this thesis to automatically import failure scenarios and microgrid architectures from a Microsoft Excel spreadsheet. The model was also modified to automatically calculate the ELMI for each architecture and export results to Microsoft Excel.

```
% JH_MG_LP_test_v10_1
%Removed selection boxes at initial run. Always runs off "Import State",
% "TY", and "No Random Failure"
% ts is constant at worst case scenario starting at 0100 13Jan (ts=289)
% Best case scenario would be 0100 2Aug (ts=5137)
% Create Separate plots for loads and DERs
% When excess solar power exists during load shedding and GENs are not in
% use send solar to charge batteries
% Import Failure Mode from Failure_Mode_Input.xlsx
% v10_2
% Run a loop for all 22 Failure Modes and record results in new row of
% "Results" variable
% Import Probability of Failures from 'Prob_Failure.csv'
% Calculate ELMI for architecture
% Record MI for each failure mode in MI variable
% Import Architecture from MicrogridArchitectureImport.xlsx
% Run loop for all architectures

% v10_3
% Update to use MDI rather than CP numbers
% Import comes from 'MG1v10 Report.xlsx'
% Export Results and Fuel Burn Data to Excel
```

```

%% Clear Workspace
clear all
clc
%% Import Microgrid Architectures
run ImportArchitecture2
numarch=numel(MicrogridArchitecture.FuelCapacity);
failuremodes=22;
MI(1:numarch,1:failuremodes+1)=0;
FuelBurn.Gen1(1:numarch,1:failuremodes)=0;
FuelBurn.Gen2(1:numarch,1:failuremodes)=0;
fuelburn(1:numarch,1:failuremodes)=0;
%% Set Model Options
for arch=1:numarch
    Set Number of Failure Modes

    Set ploton=1 if you want to plot results of each failure mode and pause
    the model for viewing (must hit "continue" button to resume model).
    ploton=0 will skip plot section
ploton=0;
    Set Scenario Name for Settings Summary Output File
MGSettings = {'Scenario', 'Two week Islanded Operation. Total Loss of GEN1. Priority Sort.'};
    year.sel = "TY";
    year.run = "TY";

if ~isnan(str2double(year.run))
    year.run = str2double(year.run);
end

Set Grid Mode
MG_Mode="Import State";

Set if random failure mode is used for Monte Carlo simulation
failure.mode=false;

PV Data

```

```
PV.Area = MicrogridArchitecture.SizePV(arch); %area in m^2
PV.eff = MicrogridArchitecture.PVEfficiency(arch); %PV efficiency
```

Generator Data

```
if MicrogridArchitecture.NumGens==2
    Gens(1).Capacity = MicrogridArchitecture.GenCap(arch)/2; %kW
    Gens(1).Storage = MicrogridArchitecture.FuelCapacity(arch)/2; %Gal
    Gens(1).Efficiency = 1/13; %(GPH/kW)
    Gens(1).Refuel = 7*24; % # of hours between refueling
    Gens(1).PrRefuel = 0.95; % Pr of Refueling each time
    Gens(1).RefuelTogether = true; %Set if refueling is together or independent
    Gens(2) = Gens(1); % Identical Generators
else
    Gens(1).Capacity = MicrogridArchitecture.GenCap(arch); %kW
    Gens(1).Storage = MicrogridArchitecture.FuelCapacity(arch); %Gal
    Gens(1).Efficiency = 1/13; %(GPH/kW)
    Gens(1).Refuel = 7*24; % # of hours between refueling
    Gens(1).PrRefuel = 0.95; % Pr of Refueling each time
    Gens(1).RefuelTogether = true; %Set if refueling is together or independent
    Gens(2).Capacity = 0; %kW
    Gens(2).Storage = 0; %Gal
    Gens(2).Efficiency = 1/13; %(GPH/kW)
    Gens(2).Refuel = 7*24; % # of hours between refueling
    Gens(2).PrRefuel = 0.95; % Pr of Refueling each time
    Gens(2).RefuelTogether = true; %Set if refueling is together or independent
end
```

Battery Storage Capacity in kW*hr, Output in kW

```
BT1.Capacity = MicrogridArchitecture.BattSize(arch);
    BT1.Output = BT1.Capacity*0.20;
    Test with battery output override to test impact
BT1.Output = BT1.Capacity/10;
BT1.Efficiency = sqrt(MicrogridArchitecture.BattEfficiency(arch)); % One way efficiency.
```

Record Summary of Settings for Output File

```

MGSettings = [MGSettings;...
    {'PV Area', PV.Area;...
    'PV Eff', PV.eff; 'Gen Capacity', Gens(1).Capacity;...
    'Gen Storage' , Gens(1).Storage; 'Gen Refueling', Gens(1).Refuel;...
    'Refueling Pr' , Gens(1).PrRefuel;...
    'Same Fuel Supply' , Gens(1).RefuelTogether
    'BT1 Capacity' , BT1.Capacity; 'BT1 Output' , BT1.Output}];

%% Import A and b Matrix Values
run Import_A_b

% Import Solar Data

if strcmp(year.run, "TY")
    disp("Run Simulation for Typical Year")
    run ImportTY_NPS
elseif isnumeric(year.run)
    disp("Run Simulation for year "+year.run);
    run Import2000_NPS
end

%% Import Load Data and Mission Importance
run ImportLoads
run ImportMission

%% Import Probabilities of Failure
run Import_Pf
Pf=ProbFailure.Pfail;
%% Setup Results Variables
Results = table();
Mission Impacted (lost)
Results.MI(1:failuremodes) = 0;
Time that Battery was Exhausted
Results.BatteryExhausted(1:failuremodes) = 0;
Time that GEN1 was out of fuel
Results.GEN1_Fuel_Empty(1:failuremodes) = 0;

```

```

Time that GEN2 was out of fuel
Results.GEN2_Fuel_Empty(1:failuremodes) = 0;
Load Shedding
Results.LoadShed(1:failuremodes,:) = zeros(failuremodes,5);
Time Load Not Met
Results.ShedHours(1:failuremodes,:) = zeros(failuremodes,5);

for failmode = 1:failuremodes
    %% Setup the microgrid initial conditions

MG_State=importfailuremode(failmode);
steps = height(MG_State);
MG_State_Initial = MG_State;
    If a failure simulation, set MG_State for each run stochastically
if failure.mode
    run MG_Failure_State
end
number of hours in a year. Used to loop to start of year if end reached
loop = 365*24;
choose random time of year to start time step, unless ts is specified
    ts = randi([1,loop]);
ts=289;
Assume Battery at full capacity at the start of the simulation
BT1_Charge = zeros([1,steps]);
BT1_Charge(1) = BT1.Capacity*MG_State.B2_BT1(ts);
Capture charge lost when battery capacity limit is reached
BT1_lost = zeros([1,steps]);
Setup Fuel Calc
Gens(1).Fuel = zeros([1,steps]);
Gens(1).Fuel(1) = Gens(1).Storage;
Gens(2).Fuel = zeros([1,steps]);
Gens(2).Fuel(1) = Gens(2).Storage;
Gens(1).NextFuel = Gens(1).Refuel;
Gens(2).NextFuel = Gens(2).Refuel;

```

```

Reset Gen Fuel Burn Numbers
gen1fuelburn=0;
gen2fuelburn=0;
Table to Capture Load Shedding
LoadShed = table;
LoadShed.Overload([1,steps]) = false;
LoadShed.EP1(:) = 0;
LoadShed.EP3(:) = 0;
LoadShed.EP4(:) = 0;
LoadShed.EP5(:) = 0;
LoadShed.EP6(:) = 0;
If the year is random, then import solar data for the year
if year.sel == "Random"
    year.run = randi([2000,2009]);
    run Import2000_NPS;
end
Skip Failure Mode if there is only 1 Gen and GEN2 "Failed"
if MicrogridArchitecture.NumGens(arch)==1 && MG_State.B1_GEN2(1)==0
    continue
end

%% Run Linear Solver to find flows
Initialize x with size of array
x = zeros(numel(b),steps);

Bus balances
b(1:3) = 0;

Find Variable Positions of Loads in Data
pos.EP = contains(LoadVars,'EP');
pos.Gens = contains(LoadVars, 'GEN');
pos.GEN1 = nodes == 'GEN1';
pos.GEN2 = nodes == 'GEN2';
pos.B2B1 = contains(LoadVars, 'B2_B1');
pos.B1B2 = contains(LoadVars, 'B1_B2');

```

```

pos.BT1 = contains(nodes,'BT1');
Run Loop
for n=1:steps
    Overload.BT1 = false;
    Overload.Gens = false;

    % If fuel exhausted, then generators are nonoperational
    MG_State.B1_GEN1(n) = MG_State.B1_GEN1(n) * (Gens(1).Fuel(n) > 0);
    MG_State.B1_GEN2(n) = MG_State.B1_GEN2(n) * (Gens(2).Fuel(n) > 0);

    if MG_State.B1_UG(n) == false
        %Islanded mode occurred during some point of simulation
        IM_sim = true;
        %Reset A to IM Defaults
        A2 = A_IM;

        %No grid connection
        b(4) = 0;
        %Generators are equally sized
        b(5) = 0;
        %Islanded, battery used as little as possible to maximize charge to
        %maximize resiliency
        b(6) = 0;

        %Calculated building loads
        b(7) = RefSmallOfficeLoads.Critical(ts); %EP1 Load is Small Office
        b(8) = RefSmallOfficeLoads.Critical(ts); %EP3 Load is Small Office
        b(9) = RefMedOfficeLoads.Critical(ts); %EP4 Load is Medium Office
        b(10) = RefLargeOfficeLoads.Critical(ts); %EP5 Load is Large Office
        b(11) = RefWarehouseLoads.Critical(ts); %EP6 Load is Warehouse
    end

    %Calculated PV output. Output is zero if line failure occurred
    b(12)= (-1/1000) * PV.Area * PV.eff * solar(ts) * MG_State.B2_PV(n);

```

```

%Determine if any load paths have failed
if ~all(MG_State{n,pos.EP})
    % Capture Load Shed as Result of Failure
    LoadShed{n,2:6} = ~MG_State{n,pos.EP}.*b(7:11)';
    %If load paths has failed, then set load to zero on that path
    b(7) = b(7)*MG_State{n,'B1_EP1'};
    b(8) = b(8)*MG_State{n,'B2_EP3'};
    b(9) = b(9)*MG_State{n,'B2_EP4'};
    b(10) = b(10)*MG_State{n,'B1_EP5'};
    b(11) = b(11)*MG_State{n,'B1_EP6'};

end

%Modify A if there is a loss of B2_B1/B1_B2 Line
if MG_State.B2_B1(n) == false
    A2(1,pos.B1B2) = 0;
    A2(2,pos.B2B1) = 0;
    A2(6,:) = pos.B2B1;
end

%Modify A for loss of generator
%Only applies if UG is not connected
if MG_State.B1_UG(n) == false
    if MG_State.B1_GEN1(n) == false
        A2(5,:) = pos.GEN1;
        b(5) = 0;
    end
    if MG_State.B1_GEN2(n) == false
        A2(5,:) = pos.GEN2;
        b(5) = 0;
    end
end
if (MG_State.B1_GEN1(n) == false && MG_State.B1_GEN2(n) == false)
    A2(5,:) = pos.GEN1;
    b(5) = 0;
    A2(6,:) = pos.GEN2;
end

```

```

        b(6) = 0;
    end
end

%Initial Solve
x(:,n) = linsolve(A2,b);

%Determine if generator demand exceeds generator capacity
Gen_Demand = -x(pos.Gens,n);

if any(Gen_Demand > [Gens.Capacity]')
    %If the B2 to B1 Buss line or BT1 line is failed, or battery is
    %exhausted cannot utilize ESS to make up generator capacity
    if MG_State.B2_B1(n) == false || MG_State.B2_BT1(n) == false ...
        || BT1_Charge(n) < 0
        % Below line was useful for debugging in single runs. Commented out
        % disp("Gens Overloaded at time step "+n)
        Overload.Gens = true;
    else
        %Otherwise set Generators at full output, use battery to
        %make up unmet demand
        A2(6,:) = pos.Gens & MG_State{n,:};
        b(6) = -MG_State{n,{'B1_GEN1' 'B1_GEN2'}}*[Gens.Capacity]';
        x(:,n) = linsolve(A2,b);
    end
    %If Generator demand is negative, then generator output is zero,
    %charge batteries with excess PV generation
elseif any(Gen_Demand < 0)
    A2(6,:) = pos.Gens;
    b(6) = 0;
    x(:,n) = linsolve(A2,b);
end

% Check for Battery Output Exceeded
% Add 0.1 Due to Rounding Errors in Linear Solver

```

```

if -x(contains(LoadVars,'BT1'),n) - 0.01 > BT1.Output * (BT1_Charge(n) > 0)
    Overload.BT1 = true;
    % Below line was useful for debugging in single runs. Commented out
    % disp("Battery Output Exceeded at time step "+n)
end

% Check if load shedding is required.
bShed = b;
x0 = zeros(numel(b),numel(Mission.LoadName)+1);
x0(:,1) = x(:,n);
for i=1:numel(Mission.LoadName)
    % Enumerate through loads until no overload is present
    if ~any([Overload.BT1 Overload.Gens])
        break
    end
    % Set Load i to 0
    % Sheds one load at a time, and turns on any previously shed load
    % that did not remove generator or battery overload.
    LoadShed.Overload(n) = true;
    bShed(7) = bShed(7)*~(Mission.LoadName(i) == 'EP1');
    bShed(8) = bShed(8)*~(Mission.LoadName(i) == 'EP3');
    bShed(9) = bShed(9)*~(Mission.LoadName(i) == 'EP4');
    bShed(10) = bShed(10)*~(Mission.LoadName(i) == 'EP5');
    bShed(11) = bShed(11)*~(Mission.LoadName(i) == 'EP6');

    x0(:,i+1) = linsolve(A2,bShed);
    % If load shedding resulted in no change to overload, then skip
    % to next load. Prevents shedding unnecessary loads when busses are
    % seperated or load was shed due to a failed line
    if (Overload.Gens && all(x0(pos.Gens,i) == x0(pos.Gens,i+1)))...
        || (Overload.BT1 && (x0(pos.BT1,i) == x0(pos.BT1,i+1)))
        bShed(7:11) = bShed(7:11) + b(7:11) .* (Mission.LoadName(i) == {'EP1' 'EP3' 'EP4' 'EP5''EP6'})
        continue
    end
end

```

```

% If load sheds to the point that the generators are now charging
% the battery, set battery charging to zero
if Overload.BT1 && (x0(pos.BT1,i+1) > 0) && ...
    any(x0(pos.Gens,i+1) > 0)
    A2(6,:) = pos.BT1;
    bShed(6) = 0;
    x0(:,i+1) = linsolve(A2,bShed);
    % And if that leads to the generators now running in reverse...
    Gen_Demand = -x0(pos.Gens,i+1);
    if any(Gen_Demand < 0)
        A2(6,:) = pos.Gens;
        x0(:,i+1) = linsolve(A2,bShed);
    end
end

end

% Capture Load Shed
LoadShed{n,Mission.LoadName(i)} = x(nodes == Mission.LoadName(i),n);

% Check if overload is clear
Gen_Demand = -x0(pos.Gens,i+1);
if all(Gen_Demand <= [Gens.Capacity]')
    Overload.Gens = false;
end

if ~(-x0(pos.BT1,i+1) - .01 > BT1.Output * (BT1_Charge(n) > 0))
    Overload.BT1 = false;
end

x(:,n) = x0(:,i+1);
% Iterate to next load if additional shedding is required
end
if x(9,n)>0 || x(10,n)>0
    x(1,n)=-1*(x(11,n)+x(4,n)+x(5,n)+x(6,n)+x(7,n)+x(8,n));
    x(9,n)=0;
    x(10,n)=0;
end

```

```

end
if x(1,n)==(-1*(x(9,n)+x(10,n))) && x(1,n)~=0
    x(1,n)=0;
    x(2,n)=0;
    x(3,n)=0;
    x(9,n)=0;
    x(10,n)=0;
end

%Calculate battery state
if MG_State{n,pos.BT1}
    if x(1,n)>0 % charging
        %Decrease charge by efficiency
        BT1_Charge(n+1) = BT1_Charge(n)+x(1,n)*BT1.Efficiency;
    else
        %Increase demand by efficiency
        BT1_Charge(n+1) = BT1_Charge(n)+x(1,n)/BT1.Efficiency;
    end
elseif ~MG_State{n,pos.BT1}
    BT1_Charge(n+1) = BT1_Charge(n);
end

%Prevent Overcharging
if BT1_Charge(n+1) > BT1.Capacity
    %Capture lost charge
    BT1_lost(n) = BT1_lost(n) + BT1_Charge(n+1) - BT1.Capacity;
    %Set the charge capacity to limit to 100%
    BT1_Charge(n+1) = BT1.Capacity;
end

%Generator Refueling
if Gens(1).NextFuel == n
    % Pr of Refueling each day
    if rand() > Gens(1).PrRefuel
        Gens(1).NextFuel = Gens(1).NextFuel + 24;
    end
end

```

```

        if Gens(2).RefuelTogether
            Gens(2).NextFuel = Gens(2).NextFuel + 24;
        end
    else
        % Reset Fuel Level for GEN1
        Gens(1).Fuel(n) = Gens(1).Storage;
        Gens(1).NextFuel = Gens(1).NextFuel + Gens(1).Refuel;
        if Gens(2).RefuelTogether
            % And also for GEN2 if supplied together
            Gens(2).Fuel(n) = Gens(2).Storage;
            Gens(2).NextFuel = Gens(2).NextFuel + Gens(2).Refuel;
        end
    end
end
end
if Gens(2).RefuelTogether == false && Gens(2).NextFuel == n
    % Pr of Refueling each day
    if rand() > Gens(2).PrRefuel
        Gens(2).NextFuel = Gens(2).NextFuel + 24;
    else
        % Reset Fuel Level for GEN2
        Gens(2).Fuel(n) = Gens(2).Storage;
        Gens(2).NextFuel = Gens(2).NextFuel + Gens(2).Refuel;
    end
end
end

% Update Fuel Levels
Gens(1).Fuel(n+1) = Gens(1).Fuel(n) + x(pos.GEN1,n).* Gens(1).Efficiency;
Gens(2).Fuel(n+1) = Gens(2).Fuel(n) + x(pos.GEN2,n).* Gens(2).Efficiency;
% Calculate Total Fuel Burned
gen1fuelburn=gen1fuelburn+(-1*((x(pos.GEN1,n).* Gens(1).Efficiency)));
gen2fuelburn=gen2fuelburn+(-1*((x(pos.GEN2,n).* Gens(2).Efficiency)));
% loop iteration to next time step
ts=ts+1;
if ts > loop
    ts=1;
end

```

```

end

end

%% Calculate Results of Each Failure Mode

Calculate Mission Impacted (lost)
TN = (sortrows(Mission,'LoadName'));
TN is temporary Table to reorder based on name so both vectors for below
calculation are ordered by load name in ascending order
Results.MI(failmode) = sum(LoadShed{:,2:end}>0) * TN.Critical;
MI(arch,failmode)=sum(LoadShed{:,2:end}>0) * TN.Critical;
fuelburn(arch,failmode)=gen1fuelburn+gen2fuelburn;
FuelBurn.Gen1(arch,failmode)=gen1fuelburn;
FuelBurn.Gen2(arch,failmode)=gen2fuelburn;
Time that Battery was Exhausted
Results.BatteryExhausted(failmode) = sum(BT1_Charge < 0);
Time that GEN1 was out of fuel
Results.GEN1_Fuel_Empty(failmode) = sum(Gens(1).Fuel < 0);
Time that GEN2 was out of fuel
Results.GEN2_Fuel_Empty(failmode) = sum(Gens(2).Fuel < 0);
Load Shedding
Results.LoadShed(failmode,:) = sum(LoadShed{:,2:end}) ;
Results.ShedHours(failmode,:) = sum(LoadShed{:,2:end} > 0);

%% Plot Results of Each Failure Mode
if ploton==1
    disp("Plots shown for failure mode "+failmode);
    figure(1)
    plot(transpose(x([1,9:11],:)))
    title("DER Power Flows");
    legend(LoadVars([1,9:11]),'Interpreter','none');
    xlabel("hrs");
    ylabel("kW");
    set(gca,'FontSize',20);

```

```

% Plot Load Flows
figure(2)
plot(transpose(x(4:8,:)));
title("Load Power Flows");
legend(LoadVars(4:8), 'Interpreter', 'none');
xlabel("hrs");
ylabel("kW");
set(gca, 'FontSize', 20);
if IM_sim == true
    %Plot Battery State Data
    figure(3)
    yyaxis left
    plot(BT1_Charge)
    title("Battery Charge Level");
    legend("BT1");
    xlabel("hrs")
    ylabel("Battery Charge (kW*h)")
    % refline(0,0)
    yyaxis right
    plot(x(1,:))
    ylabel("Battery Power Flow (kW)")
    legend("BT1", "B2_BT1", 'Interpreter', 'none')
    set(gca, 'FontSize', 20)
    %Plot Generator Fuel
    figure(4)
    plot([Gens(1).Fuel; Gens(2).Fuel]')
    title("Generator Fuel Level");
    xlabel("hrs")
    ylabel("Fuel Level (gal)")
    set(gca, 'FontSize', 20)
    pause(1)
end
end
end

```

```
%% Calculate Results
ELMI for Microgrid Architecture
ELMI(arch, 1)=dot(Results.MI,Pf);
MI(arch,failuremodes+1)=dot(Results.MI,Pf); %stores ELMI in final column of MI data

fprintf('ELMI for architecture %i is %.2f.\n', arch, ELMI(arch));
end
Write ELMI Data to Excel
writematrix(ELMI,'JHcostresilmodel_1.3.xlsm','Sheet','ELMI','Range','B3');
writematrix(fuelburn,'JHcostresilmodel_1.3.xlsm','Sheet','Fuel Burn Data','Range','B3');
% Done
beep;
```

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