2022-09

EXPERIMENTAL VALIDATION OF RESILIENCE MODELS FOR ISLANDED MICROGRIDS FOR MILITARY OPERATIONS

He, Jiawei J.

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/71012

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EXPERIMENTAL VALIDATION OF RESILIENCE MODELS FOR ISLANDED MICROGRIDS FOR MILITARY OPERATIONS

by

Jiawei J. He

September 2022

Thesis Advisor:	Douglas L. Van Bossuyt
Co-Advisor:	Anthony G. Pollman

Approved for public release. Distribution is unlimited.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2022	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE EXPERIMENTAL VALIDATION OF RESILIENCE MODELS FOR ISLANDED MICROGRIDS FOR MILITARY OPERATIONS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Jiawei J. He	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Modern warfighters rely heavily on fast, accurate information to conduct all forms of military operations. It is critical that deployed Command and Control centers have reliable power for conduct of military operations and serve as a central node for information relay. For military deployments outside areas with prepared infrastructure for utility power, or in locations with no reliable utility power, stable power supply from microgrids for operations will be required. Such operations range from peacekeeping to humanitarian aid and disaster relief operations. Although such microgrids are generally reliable at providing stable power, their resilience to disruption is poor. Common interruptions include natural disasters like earthquakes, and man-made causes like cyber or physical attacks. Previous research into microgrid resilience evaluation efforts center on theoretical modeling of total electrical microgrid loading, critical electrical load prioritization, assumed capacity of renewable energy sources and their associated energy storage systems, and assumed availability of emergency generators. Experimental data from a scaled microgrid system was collected and assessed against the results from two simulation models by Peterson and Anderson. The results validate the simulation models and highlight some areas for model improvement.

14. SUBJECT TERMS islanded microgrid, resilience modelling for microgrid, microgrid, validation of microgrid resilience	**15. NUMBER OF PAGES** 67
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

THIS PAGE INTENTIONALLY LEFT BLANK

EXPERIMENTAL VALIDATION OF RESILIENCE MODELS FOR ISLANDED MICROGRIDS FOR MILITARY OPERATIONS

Jiawei J. He
Military Expert 5, Republic of Singapore Air Force
BEE, Nanyang Technological University, 2012

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2022

Approved by: Douglas L. Van Bossuyt
Advisor

Anthony G. Pollman
Co-Advisor

Oleg A. Yakimenko
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Modern warfighters rely heavily on fast, accurate information to conduct all forms of military operations. It is critical that deployed Command and Control centers have reliable power for conduct of military operations and serve as a central node for information relay. For military deployments outside areas with prepared infrastructure for utility power, or in locations with no reliable utility power, stable power supply from microgrids for operations will be required. Such operations range from peacekeeping to humanitarian aid and disaster relief operations. Although such microgrids are generally reliable at providing stable power, their resilience to disruption is poor. Common interruptions include natural disasters like earthquakes, and man-made causes like cyber or physical attacks. Previous research into microgrid resilience evaluation efforts center on theoretical modeling of total electrical microgrid loading, critical electrical load prioritization, assumed capacity of renewable energy sources and their associated energy storage systems, and assumed availability of emergency generators. Experimental data from a scaled microgrid system was collected and assessed against the results from two simulation models by Peterson and Anderson. The results validate the simulation models and highlight some areas for model improvement.

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

THIS PAGE INTENTIONALLY LEFT BLANK

List of Figures

THIS PAGE INTENTIONALLY LEFT BLANK

Executive Summary

Energy security is important to modern military installations and the use of microgrids in military installations have widely been accepted as an effective way to improve resilience. Beyond military applications, microgrids have also been deployed to support critical infrastructure like hospitals, water treatment and sanitation plants. To better understand and further develop military microgrid solutions for energy resilience, research into measures for energy resilience specific to military and defense applications have resulted in the development of simulation models to conduct analysis. These models have not been validated against real-world hardware data and this research conducts an experimental validation to match reality with simulated results to build trust in the models.

This research contributes a comparison of experimental and simulation data for military microgrid resilience, and identifies areas where two simulation models of interest could be modified to better represent the real world. In refining the simulation models, the respective model result output for cost and architecture optimisation could also be improved to better represent reality. General take aways are that the simulation model results match experimental data but that there are recommendations for improving microgrid control algorithms in the simulation model input parameters.

The analysis of Peterson's simulation model battery charge shows a positive trend line for the residuals when compared against the experimental results. It was found that the model was not able to utilize generator power to charge the batteries when excess power was available in the microgrid. Therefore the simulated batteries continued to be depleted. This difference in battery charge conditions is assessed to only have an impact on specific conditions where there is a need to draw power from the batteries due to fluctuations in power generation in the model. This comparison is shown in Figure 1.

Anderson's simulation model power rating comparison matches closely and residuals trend flat. The resilience measure computed from the simulation model and the experimental results was also computed to have a difference of only 0.7% showing that Anderson's model power rating results are similar to the experimental results. The power rating comparison and residuals are shown in Figure 2.

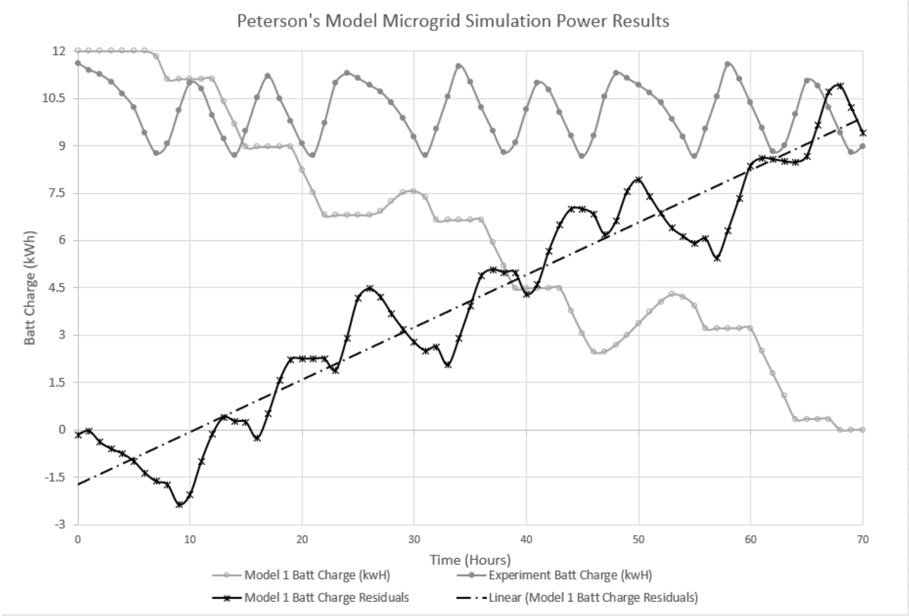

Figure 1. Peterson's Simulation Model battery charge results show a positive trend because the model batteries were not charged by excess diesel generator power.

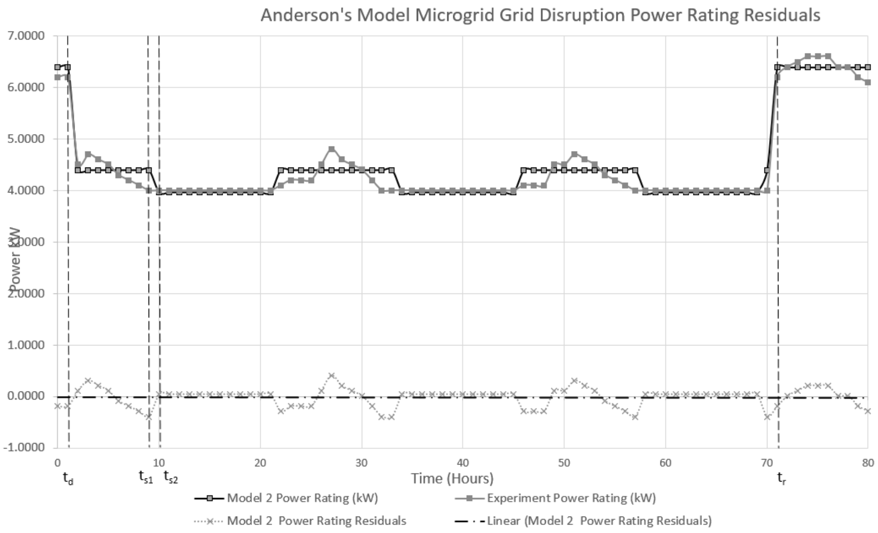

Figure 2. Anderson's Simulation Model power rating residuals trend flat and close to 0.

In conclusion, the experimental microgrid results were useful in helping to validate the simulation models used for microgrid resilience research. It supports the effort to improve energy resilience in the increasing risk environment from extreme weather events and adversarial threats. It is also important to recognize that both Peterson’s simulation model and Anderson’s Simulation model are systems engineering tools to analyze cost and design when making large architectural decisions. As this experiment was conducted on a scaled microgrid with commercial-off-the shelf components, it may not be able to highlight issues that may be present in the operation of larger microgrid systems. The recommendation for future work includes repeating the experiment on a scaled up physical microgrid system, or to collect power disruption data from deployed microgrid systems during scheduled downtime.

Acknowledgments

The research journey for this thesis has been challenging and I have to thank quite a team of people who have supported me in this journey. The most important person I would like to thank is my wife who supported me through late nights and always encouraging me on in this journey. Professor Douglas and Professor Pollman who have been very patient and they provided the steady hand in advising me on research work and were always present to guide me whenever I encountered a roadblock. Fellow student, Chris Frackell, that helped me in getting up to speed quickly with the literature review ground work after deciding to pursue another research area. Apart from the research and writing I am also grateful for the assistance from Brandon Naylor and Robert Lindstrom who helped with the experimental lab test set up and adjustments to enable collection of the microgrid data.

This research work would not have been possible without the strong support I received from them.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 1:
Introduction

Energy security is important to the military as modern combat systems rely on electrical power to operate. Microgrids have widely been accepted as an effective way to improve resilience for a defined area functioning as a single controllable entity which military installations conveniently fit within. Microgrids improve resilience by having interconnected distributed energy resources, energy storage systems, and loads. This is an improvement from typical redundant power generator architectures where a backup diesel generator or similar supports critical system loads, can only support the single system it is connected to, and cannot draw on nearby resources that may be available should the redundant system fail. To better assess the level of resilience, several novel models have previously been developed to determine some measure of resilience for military installations supported by a microgrid. This thesis reviews two models previously developed to measure resilience of military microgrids, and develops an experimental methodology to validate the models.

This chapter provides some background on the increasing need for resilient power supply for operations and threats to military installation power security. Thereafter, the thesis aims to utilize a scaled experimental microgrid set up to validate some of the existing simulation models used for analyzing microgrid resilience. Two microgrid resilience simulation models are discussed and the scaled experimental microgrid parameters are used as simulation inputs. The results of the models are then compared with data obtained from the experimental setup.

1.1 Military Systems Reliance on Electrical Power

Military installations require resilient and reliable electrical power to ensure operations, and meet operational and mission requirements. Such requirements support a very wide range of critical functions which include projecting hard capabilities for national defense and upholding national policies to providing aid and disaster relief to advance national interests. While the power grid is cost effective in providing power for the Department of Defense (DOD), it is susceptible to disruptions which may impact operations. Weather events are a major contributor to power disruptions in the United States [1] and were found to cost billions annually [2]. Beyond cost, disruptions risk exposing the DOD's operational and strategic capabilities to interruption [3]. When computing the potential loss due to electrical power disruption, it is possible for civilian commercial entities to use lost revenue, power restoration costs and other associate costs [4]. For the military, however, the potential implications for power disruptions have consequences that are beyond monetary value. Examples include the risk of adversarial entities exploiting the identified vulnerability for an attack and the leak of damaging information to undermine public confidence [5]. Such potential impacts and risk are difficult to quantify, and make it difficult to justify the additional investment needed to improve military power systems.

1.2 Threats to Military Power Supplies

The Russian invasion of Ukraine and its efforts to disrupt energy supplies to neighboring European countries that are supporting Ukraine is a clear example of an adversarial threat to power security [6]. Cyber-threats, accidents, and weather-related disruptions also threaten to disrupt electrical supply to military installations [7]. Although military installations are more attractive targets for deliberate disruption actions, most recent power disruptions have been caused by natural disasters and extreme weather. Recent extreme weather events have exposed critical vulnerabilities in centralized grid power generation to lengthy disruptions where users were left without power due to extreme cold weather and wildfire risk. Examples include the Texas blackouts due to gas power plant shutdowns in the extremely cold winter storms in Feb 2021 [8], and the California 'Public Safety Power Shut-Offs' during periods of severe wildfire risk in 2019 [9].

There is sustained interest by the DOD in improving military installation energy resilience [10]. The DOD also aims to consume more energy from renewable sources to substitute current strategies of using backup generators and battery banks for backup power. Microgrids utilizing renewable energy sources have been an emerging system of interest to improve resilience. In the event of grid power interruption, a microgrid is often able to continue to provide power in islanded mode operations using distributed energy resources [11]. As such, there has been sustained interest in the analysis of military microgrid resilience.

Although there are several commercial tools available for microgrid design optimization where the main focus of the tools is to optimize the microgrid for cost [12], [13], many of these tools do not address resilience or address it from a cost perspective. To address this gap in assessment, several simulation models have been developed to assess system design, cost and level of maintenance. This thesis compares two simulation models with data from a small research microgrid at the Naval Postgraduate School. The results help to build confidence in the models and identify where model improvements must occur.

This thesis is written using the "manuscript option" and has the following structure: Chapter 1 provides a military context to and objective of the thesis; Chapter 2 presents a journal manuscript prepared for submission to *MDPI Systems Journal* for peer review; and Chapter 3 provides a summary of the research and potential future work from a military perspective.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 2:
Manuscript Submission

2.1 Experimental Validation of Resilience Models for Islanded Microgrids for Military Operations

A version of this chapter was prepared for submission to the MDPI journal *Systems* as: J.H. Jiawei, A. Pollman, and D. L. Van Bossuyt, “Experimental Validation of Resilience Models for Islanded Microgrids for Military Operations.”

2.2 Introduction

Civilian and national defense installations require resilient and reliable electrical power to ensure operations, and meet operational and mission requirements. While the power grid is cost effective in providing power for hospitals, ports, food storage facilities, water treatment and sanitation plants, the Department of Defense (DOD), and others, it is susceptible to disruptions which may impact operations. Weather events are a major contributor to power disruptions in the United States [1] and were found to cost billions annually [2]. Within the realm of national defense, disruptions risk exposing operational and strategic capabilities to interruption which are challenging to attach a monetary value to [3]. Recent extreme weather events have also exposed critical vulnerabilities in centralized grid power generation to lengthy disruptions where users were left without power due to extreme cold weather and wildfire risk. Examples include the Texas blackouts due to gas power plant shutdowns in the extremely cold winter storms in February 2021 [8] and the California ’Public Safety Power Shut-Offs’ during periods of severe wildfire risk in 2019 [9].

There is sustained interest by the DOD and other national defense organizations in improving military installation energy resilience [10]. The DOD also aims to consume more energy from renewable sources to substitute current strategies of using backup generators and battery banks for backup power. Microgrids utilizing renewable energy sources have been an emerging system of interest to improve resilience. In the event of power interruption, the microgrid is able to continue to provide power in islanded mode operations using distributed energy resources [11]. As such there has been sustained interest in the analysis of military microgrid resilience. Although there are several commercial tools available for microgrid design optimization where the main focus of the tools is to optimize the microgrid for cost [12], [13], these tools do not fully address resilience analysis in national defense contexts. Recent research into measures of microgrid resilience for national defense and military installations has resulted in the development of simulation models to conduct analysis. However, these models have not been validated against real-world hardware data. To validate that the models closely match reality and build trust in the model results, experimental validation can be useful.

This article aims to utilize a scaled experimental microgrid setup to validate some of the simulation models used for analyzing microgrid resilience in national defense applications. Two microgrid resilience simulation models are discussed and the scaled experimental microgrid parameters are used as simulation inputs. The results of the models are then compared with data obtained from the experimental setup. A close result after comparison of the experimental model and the simulation model will be used to validate the simulation models.

2.3 Background and Related Research

Advanced military defense systems require electrical and computing power to support all of the complex system functions. The importance of electricity cannot be overemphasized as the lack of electrical power could disable all modern communications, radar defenses, and sever military command lines. Title 10, section 101 within the United States Code, which outlines the role of the armed forces defines energy resilience as the "... 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” [14]. Key points in the quote include the ability to minimize energy disruption and to recover from it. Microgrids can support the military resilience requirements and this section will discuss microgrid architecture and microgrid resilience measures.

2.3.1 Microgrids

Electric utilities, regardless of ownership type (public or private), have been found to have similar performance and only differ slightly in pricing structure and reliability [15]. Regardless of the utility ownership, utilities must provide a reliable supply of power to customers at a reasonable cost to be viable. This balance between reliability and cost compels utilities to build infrastructure to operate under typical historical conditions. As such, occasional interruptions occur during abnormal weather which may inconvenience civilian customers and lead to some monetary loss to corporate customers [16]. Power interruptions at military installations may impact national security and the consequences may be a lot more severe, and hard to quantify monetarily. National security requirements and the increasing number of abnormal weather events have elevated interest in improving electrical resilience though the deployment of microgrids. Recent publications have also asserted that microgrids were successful and practical in improving resilience [17]–[19].

The U.S. Department of Energy has adopted the widely cited definition of a microgrid which was developed by the Microgrid Exchange Group. It defines a microgrid as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts 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” [20]. Crucially, the microgrid acts as a single controllable entity that can function regardless of whether it is connected to another grid. It requires the microgrid to be distinctly identifiable from the grid, locally interconnected and controlled, and lastly, functionally independent [21]. For the microgrid to be distinctly identifiable, it must have clear physical and functional boundaries. This is defined by the hardware and functional components that form the external interface for coupling to the utility grid, also known as the Point of Common Coupling (PCC) [22]. The microgrid controller and its local interconnection fulfils the requirement of being locally interconnected and controlled to balance power availability with load demands [23]. Finally, the requirement of being independent is fulfilled by the microgrid's capacity to sufficiently cater to load demands within its boundaries. Therefore, to meet the functional requirements of a microgrid, the basic components include (1) Distribution System, (2) Distributed Generation Resources, (3) Energy Storage Systems, and (4) a Control and Communication System [24]. The basic microgrid system is presented in Figure 2.1.

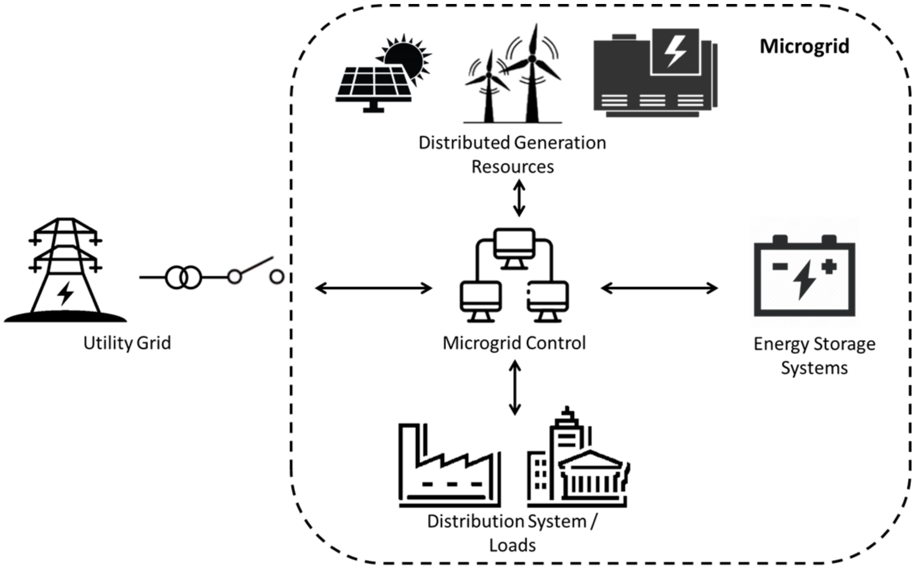

Figure 2.1. Components of a basic microgrid architecture. Adapted from [24].

Microgrid Distribution System

Microgrids typically utilize AC and DC distribution systems that match with the connected loads and generation sources. DC distribution systems have some advantages in certain cases by providing lower losses and higher transmittable power, while AC distribution has been a standard and is widely used. DC distribution advantages include that DC power need not be converted to AC for Distributed Generation sources like PV to the ESS like batteries. Therefore, research work on standardizing DC distribution and control is ongoing and, in the meantime, hybrid AC/DC microgrids are generally used [25].

Distributed Generation Resources

There are a range of technologies that are available for microgrid power generation. Widely used systems includes diesel generators, solar photovoltaic (PV) systems, wind turbines, and micro-hydro [21]. Diesel generators consume fuel to generate electrical power; however, it is not a renewable energy source and would need fuel for continued operations. Solar PV generates DC electricity from solar energy which is inexhaustible. The performance of the PV system is dependent on the location which will determine solar intensity and cloud cover. It is also not able to generate electricity after nightfall and its performance is degraded in winter months [26]. Wind Turbines harness kinetic energy from wind with rotor blades and transforms it into electric energy though a generator. Like the Solar PV system, its performance is also location dependent and can only generate electricity when the weather allows. The last common power generation technology is micro-hydro which generates electricity from the flow of water and is dependent on topography and rainfall of the area.

Energy Storage Systems

The rapid reduction in cost of energy storage systems (ESS) and its central role in many microgrids has driven the development and the successful operation of microgrids. ESS allows for the balancing of power and energy demands while providing uninterrupted transition from utility supply to the microgrid supply. Essentially the ESS main functions allow for some of the following within the microgrid:

- Handle load fluctuations and power transients, and provide some time for generation sources to respond to the fluctuations.
- Ensure power supply stability when the power source is unstable.
- Handle microgrid transition from utility connected to islanded operations.

There will be a slight change in the system AC frequency when loads are added or removed from the system. This must be handled by sufficient ESS capacity to ensure the microgrid with several power generation sources is able to ensure energy balance following the system loading adjustments. Common ESS for microgrids that are practical include batteries, fuel cells, flywheels, and super-capacitors. Batteries are the most common microgrid storage solution as it is the most affordable type of system. The most common type of battery deployed for microgrids are lead-acid batteries as they can support high currents in a very short period to handle power transients [27] during microgrid decoupling and it is capable of saving reserve energy for future demands. The next type of ESS, fuel cells, is rapidly rising in popularity [28] as the technology matures. Fuel cells provide high efficiency by directly converting chemical energy from a fuel into electricity through a chemical reaction. This improves the practical performance of the microgrid [29] by reducing cost, improving energy efficiency, and microgrid reliability. When a fuel cell is implemented with an electrolyser, it can supplement batteries for energy storage as it has a high specific energy that can be used to soak up spare energy generated on the microgrid [30]. The last two types of ESS, the flywheel and the super-capacitor, are usually employed to improve power quality and as uninterruptible power supply for small loads [31].

Control and Communication Systems

IEEE Std. 2030.7-20.7 [32] published in 2018 specifies the general functional requirements for microgrid control to allow for standardization. The core functions described in the standard are the "dispatch" and "transition" functions for the microgrid. The microgrid controller dispatch function ensures balancing power generation and load when the system is in islanded mode, rebalancing of generation and load when there are changes in profiles, and responding to external control orders to meet interconnection agreement requirements. The microgrid controller transition function enables the system to transit between grid-connected mode and islanded mode without delay or power supply disruption to connected loads.

To achieve dispatch control, Sun, Paquin, Al Jajeh, Joos, and Bouffard proposed a unified rule-based control strategy with separate rules for grid-connected mode and islanded mode operations [33]. In grid-connected mode, the reduction of power variation at the point of interconnection to the grid is prioritized to meet interconnection agreement requirements. For dispatch in islanded mode, the control objectives change to maintaining power balance while ensuring the microgrid components are operating within limits defined by the pre-defined rules. This ensures power balance, safe, and efficient operations of the microgrid. Transition between grid connected and islanded mode is initiated by one of the following 3 processes with steps described:

- Planned Islanding – the microgrid controller receives the islanding command, proceeds to balance load and generation, configure local controllers, disconnect point of interconnection, and achieve steady state islanded power dispatch on the microgrid.
- Unplanned Islanding – the microgrid detects islanded conditions, disconnect point of interconnection to create an island, configure local controllers, execute pre-configured control commands like load shedding and achieves steady state islanded power dispatch on the microgrid.
- Reconnection to the grid – the microgrid controller synchronizes to the grid power, configures local controllers, reconnects the point of interconnection, and achieves steady state grid-connected dispatch mode.

Microgrid controllers rely on a robust communication system to enable core control functions. Centralized communication architectures were initially developed for microgrid controls, implementation was straightforward, and it met the microgrid requirements [34].

2.3.2 Microgrid Resilience

Natural disasters which include flooding, earthquakes, and hurricanes can cause severe power disruptions. Although such events are rare, the disruptions are severe and continue to cause economic loss after the disaster. Power system resilience has been studied and defined to improve the design of power systems to be able to withstand external shock or damage events, and to recover quickly [35]. A recent review of microgrid resilience found that accurate and realistic simulations are needed to design microgrids with better resilience. The examination of more realistic and general simulation frameworks would enable accurate comparison of different microgrid design and employment strategies [36].

There are various performance measures for microgrids and Lu, Wang, Zhang and Cheng had proposed the following categories of reliability, economic (cost), practicality and environmental sustainability as performance indices [37]. The reliability index measures the ratio of total unmet load to total electric load demand. The economic index measures the system cost effectiveness by computing the ratio of annualized cost for power generation to the total electrical load demand. Next, the practicality index computes the ratio of the total microgrid system occupied area to the available area for the system. Finally, the environmental sustainability index is computed from percentage of load demands met by renewable sources. This may be a comprehensive matrix for microgrid performance which incorporates design architecture elements like space practicality and environmental sustainability. Most microgrid assessments optimize system performance by maximizing reliability to meet an objective reliability value and minimizing system cost. This is therefore done by computing a reliability-cost objective function with reliability as a constraint, or with a predetermined investment amount [38], [39]. Such methods focus on the reduction of operational cost for historical normal loads and do not focus on microgrid resilience [40].

Energy Resilience Definitions

Energy resilience must first be understood and measured before microgrid resilience can be analyzed. Various studies have reviewed quantitative measures of energy resilience from different perspectives that include design, identified threats to the system, and from different time periods. These measures typically use the resilience curve shown in Figure 2.2 where the disruption impacts the microgrid at time t_d [41]. Ideally, a resilient microgrid system would either have no or a small drop in performance at time t_d at the onset of the disruption event. The system would then need maintain a stabilized supply before it could recover and this period would be the recovery time. The invulnerability and recovery time form the key measures of the microgrid resilience. These measures are also depicted in Figure 2.2.

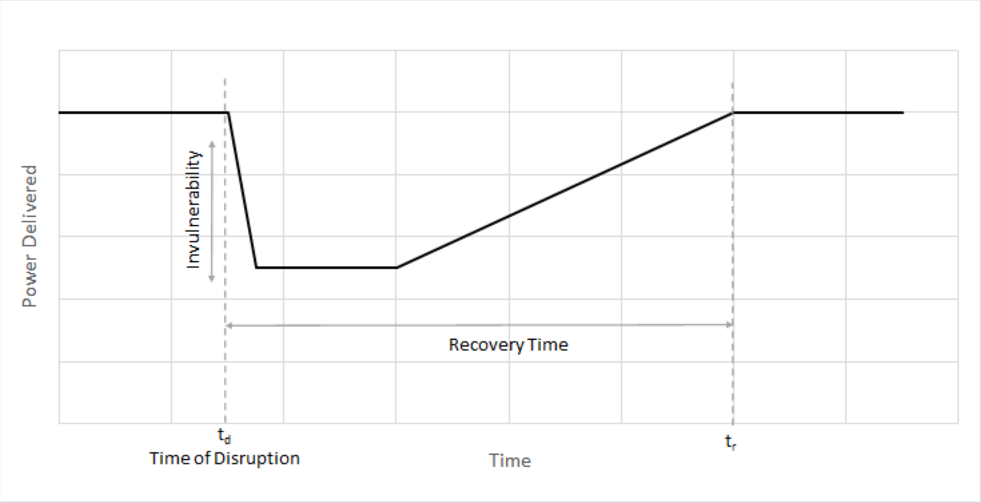

Figure 2.2. Typical resilience curve showing the phases of disruption, and the key measures of invulnerability and recovery time. Adapted from [42].

A common measure for resilience uses the ratio of the area under normal operational performance and the actual degraded performance after the disruption [43]. Other researchers included the definition of the components of resilience like absorption capacity or invulnerability, and the time taken to recover from the disruption [41], [44].

Resilience is also threat-dependent [45] and the threats can be widely categorized as intentional attacks, including physical and cyber-attacks, and low probability high impact events like extreme weather. As such some researchers have introduced operational resilience and infrastructural resilience to analyze the different operational and infrastructural resilience strategies [35]. This also highlights the difference between the reliability and resilience measures for the microgrid although both terms have frequently been used interchangeably [46].

Clark-Ginsberg uses a cyber incident to illustrate the difference between power reliability and resilience. When the cyber incident disrupts power supply, the system reliability is impacted as reliability is generally measured by the power supply ability to meet load demands. Resilience then measures how much the cyber incident disrupts (invulnerability measure) and how quickly the system is able to recover (recovery time). He then argues that by implementing rolling blackouts, the system maintains a high resilience while reliability continues to degrade. However, it seems that this views resilience from a single load perspective as the recovery in this instance is when the lights go back on and the system is considered to be ‘recovered’ prior to the next blackout in a rolling blackout scenario. However, should the resilience measure account for the grid system supply, rolling blackouts are considered as part of the stabilization and restoration phase [47]. To summarize, reliability provides a quantified metric for a system to function as specified and does not assess the system’s degraded functionality or ability to recover from failure or disruption. Resilience provides a measure of functionality of the system when degraded from a disruption event and the ability of the system to return to a state that is able to meet functional requirements of the system [46].

Military Energy Resilience

The deployment of microgrids in military installations can improve electrical power security, reduce energy costs by incorporating renewable energy generation, meet military mission objectives and provide supply in remote installations [48]. Therefore, military requirements differ from civilian microgrid application requirements which typically only define the value of resilience in financial terms and only account for low probability high impact events. The value of military microgrid resilience is national defense and this can make them attractive targets for intentional attacks [49]. This widens the range of threats to the military installation energy security and examples include grid disruptions, component failure, damage due to disaster, and intentional physical or cyber-attacks. Because national defense microgrids are unable to use just monetary value to measure microgrid resilience, there is no standard to define the value of energy resilience within the DOD [40]. Some examples of methods used include attempts to quantify resilience for military microgrids using the cost of implemented generators, the cost to relocate the mission for the duration of the disruption or developing a method to compute a damage function based on the disruption duration [50], [51]. Though there are differences in the computation for the value of energy resilience, researchers agree that the implementation of microgrids with distributed energy resources improves energy resilience [52], [53].

Resilience Improvement

This section reviews available research and technology that have been found to enhance energy resilience which is of direct relevance to the work presented in this article. Mahzarnia, Moghaddam, Baboli, and Saino conducted a study to review measures to enhance power system resilience and found that there was a lack of comprehensive studies that considered power system resilience holistically. Although the impact of the topology and employment of renewable systems on resilience needs to be better understood for power distribution, they found that the investment of distributed energy resources, development of smart grid technologies, and the employment of microgrids to be useful [54]. For distributed energy resources, a study for distributed energy storage systems has found considerable improvements to power resilience [55], while smart grid technologies for fault isolation and service restoration provide quick analysis and decision support [56] that also enhances resilience. Microgrids have shown to be invaluable in servicing connected critical loads in Tokyo after major disruption caused by a tsunami in 2011 and are able to support power restoration, network formation strategies, and power disruption preventive measures [17] .

Resilience Assessment Methodologies

There is keen research interest on military microgrids to enhance power resilience and the diverse studies have spanned from cost trade space, to assessing the impact of power resilience on mission operations and cyber security. [42], [57]–[59]. To conduct and assessment or analysis, simulation models are a common feature of most studies. This article focuses on two methods gaining traction within the US Navy's Naval Facilities Command (NAVFAC) and elsewhere that are used for analysis of military mission resilience impact, and the cost trade space for microgrids on islands, and is discussed next.

The Peterson's model developed for the analysis of military microgrid resilience computes an electrical disruption mission impact metric for a microgrid model by determining the power flow within the microgrid. The mission impact metric accounts for periods when the load demands are not met and load shedding occurs. This model uses reference building load models from the Department of Energy and solar radiation data from the National Renewable Energy Laboratory together with user input of the microgrid design parameters like energy storage and generation capacity to simulate the impact to mission when a disruption occurs [57]. Anderson's model computes islanded microgrid resilience using invulnerability and recoverability metrices [42]. Invulnerability is computed from the ratio of power delivered and load demand, and recoverability is the computed ratio of power demand that is not met after the disruption event. The model varies the power generation from three power sources (diesel, solar and wind) together with the energy storage system capacity to generate the metrices.

2.4 Methodology and Simulation

This section introduces the system engineering process and focus on the verification and validation methods used to validate the Peterson's and Anderson's military microgrid resilience models. The systems engineering methods for verification and validation is presented together with the strategy, identified inputs, activities and outputs [60]. The simulation models are first adapted to a scaled down experimental microgrid for direct comparison. Thereafter, the results from the experimental microgrid are collected and compared with the simulation model results. The simulation and experiment are set up to illustrate a 72 hour power disruption to allow for the microgrid to operate islanded mode. This validation effort focuses on validation of electrical energy resilience of the simulation models and does not assess the additional functions such as mission impact or cost effectiveness.

2.4.1 Validation Process

The system engineering process comprehensively describes the key activities for a structured development process to realize a successful system. It is an interdisciplinary approach to integrate various disciplines and specialisations that is initiated from system conception to operation. The system engineering V-Model which was developed in the 1970s has roots in software engineering and some early researchers used it as a tool to emphasise the importance of verification and validation [61]. The right side of the V-model depicts the integration phase of the system and consists of various verification and validation processes alongside the integration processes. A simplified V-model with the basic development processes is illustrated in Figure 2.3. The INCOSE Systems Engineering handbook describes both the verification and validation processes which have some similarities. Although both processes aim to provide objective evidence that the system meets requirements, the aims and scope differ. The verification process seeks to produce evidence that the system meets system and technical requirements and is generally at the lower right side of the V-model.

This phase consists of the development phase where the systems and sub-systems are tested for acceptance. The validation process then tests the system in its operational environment after the system has been verified to meet system requirements. This validation process assesses if the system is suitable and meets operational need.

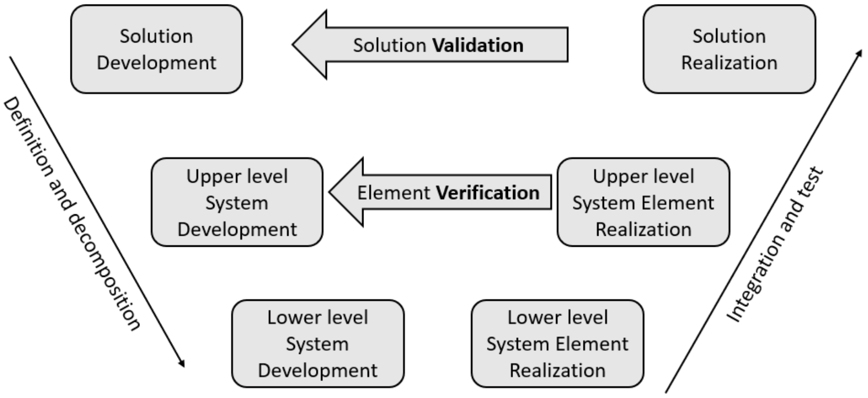

Figure 2.3. Systems Engineering Vee Model highlighting the verification and validation processes. Adapted from [60].

2.4.2 Peterson's Microgrid Resilience Simulation Model

Peterson's simulation model was developed to quantify microgrid resilience and investigate the impact to military installation missions [57]. It uses an expected electrical disruption mission impact metric to analyze mission impact and does not account for peripheral issues like power factor and phase imbalance. This allows for the model to explore the high level engineering trade space between power resilience and mission impact. For the simulation to mimic real scenarios as close as possible, hourly historical models for solar energy from the National Solar Radiation Data Base [62] and facility load demands from the US Department of Energy were used as model inputs [63]. The other user defined input variables include the mission impact assessment and the ratio of critical loads of each facility modelled, a set of power interruption scenarios and the assessed recovery time. The simulation could then be initiated to produce mission impact results for a single run or utilize a series of

Monte Carlo simulations to compute a mean for a more representative general result. The baseline microgrid system design used in the model consists of (1) Utility Grid Connection, (2) Diesel Generators, (3) Photovoltaic Solar Arrays, (4) Energy Storage Systems and (5) Multiple Facility loads [57]. To compute mission impact, the model then categorizes load priority based on assessed criticality and adds a mission impact figure if the microgrid was unable to meet critical loads for the simulation. The summation of the mission impact measure will then be the result of one simulation. It was assessed that carrying out an experiment to generate results for computing mission impact was not feasible as part of this article because failure distributions for distribution line components and generating systems were used in the Monte Carlo simulations. The experiment in this article instead focus on the validation of power flow and system battery charge results which is used by the simulation to compute mission impact. The power flow and battery charge status graphs will be compared with experimental result graphs for an assessment. This baseline model is shown in Figure 2.4, where loads are indicated as EP with the respective power sources shown.

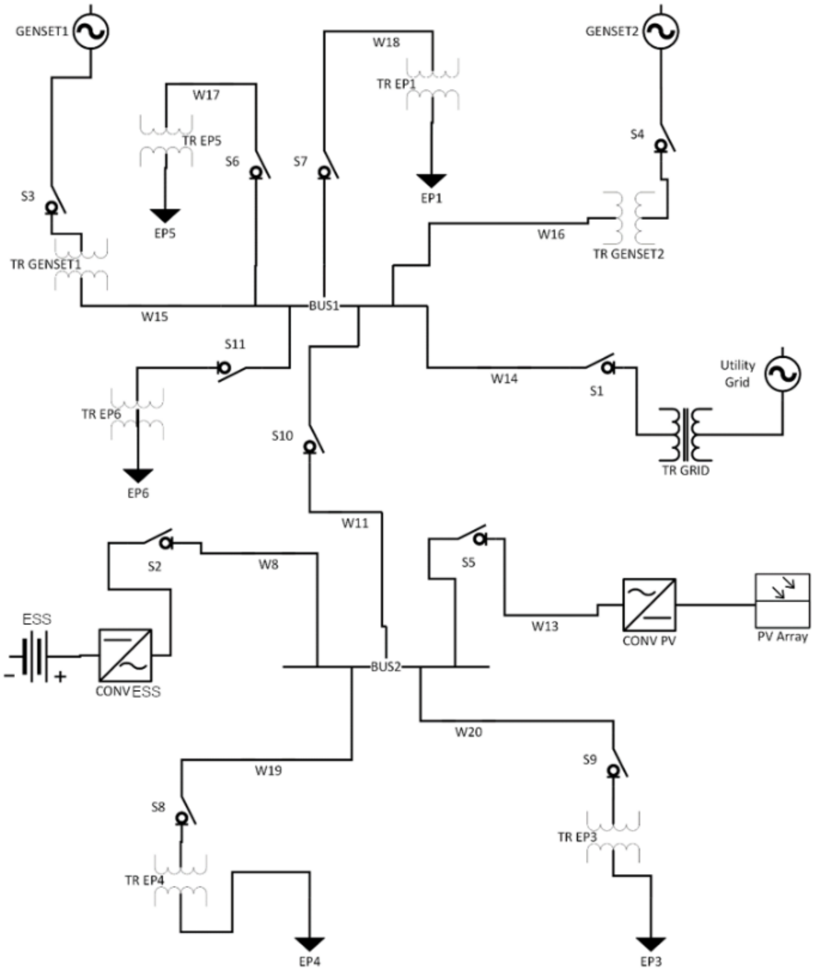

Figure 2.4. Peterson's Simulation model 1 baseline architecture with full array of generators and loads. Source: [57].

This baseline model was adjusted to match the scaled down experimental set up on Figure 2.5 and was used to produce data to for assessment with the experiment system. To facilitate a direct comparison, switches to loads and source components were not used in the experiment model and were set open, a constant AC load was used, and the power generation and storage system ratings were changed to match the experimental microgrid.

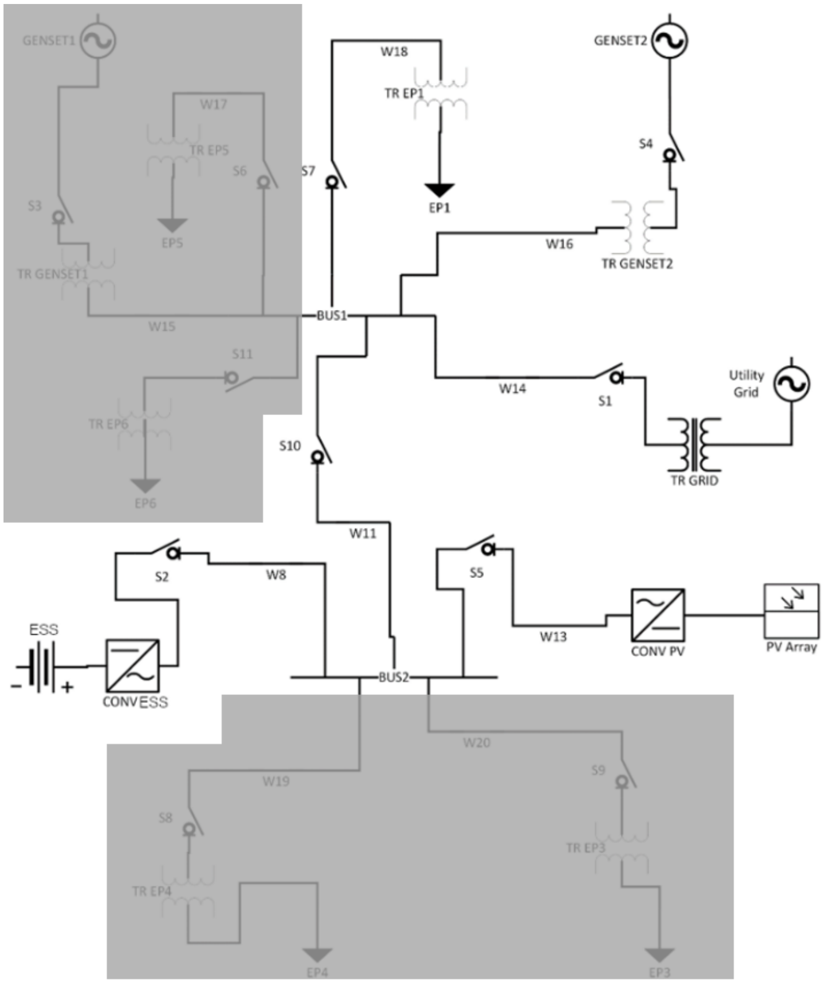

Figure 2.5. Peterson's Simulation model adjusted architecture with excess components removed in grey to match scaled experiment generators and loads. Adapted from [57].

A simple power disruption scenario with indefinite utility grid power loss and with a 20 hour loss of the diesel generator was simulated. This produced the simulated baseline result graph for the model that mimics the experiment microgrid shown in Figure 2.6. The result is consistent with expected power delivery behavior as the load has to draw from the battery once the microgrid is islanded. In the initial 20 hours with no diesel generator, the battery charge is consumed until there is sufficient solar power to meet power demands. After the diesel generator is recovered, demand is supplied by the diesel generator and does not further drain battery charge. When solar energy is available in the day, the photovoltaic solar system supplies power to the load and negative value power indicates power flow to the batteries for charging. However, it is noted that in this model, although there was surplus power from the 2kW diesel generator after hour 20, the battery charge only increased when there was solar power in excess of the load of 0.7kW. In other words, the model does not allow for ESS charging from the diesel generator. This becomes important in a subsequent section with experiments conducted on the physical microgrid.

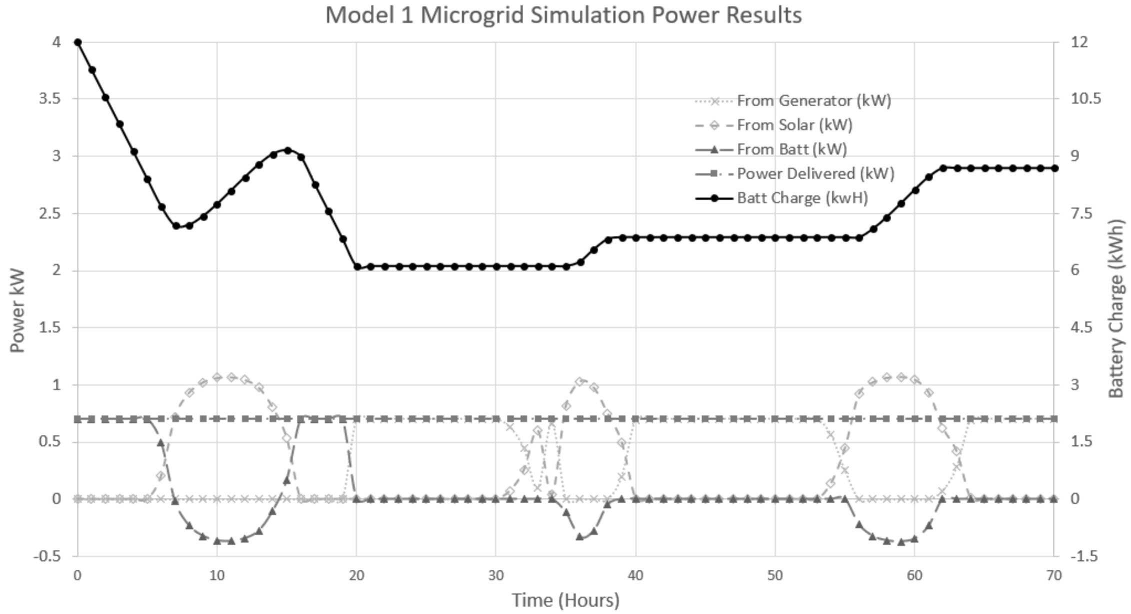

Figure 2.6. Peterson's Simulation Model adjusted architecture results for battery state of charge and power flow.

2.4.3 Anderson's Microgrid Resilience Simulation Model

Anderson's microgrid resilience simulation model was developed to model resilience and system cost assessment to provide a resilience and cost trade space for a high level decision making [42]. The simulation model computes the microgrid invulnerability and recoverability metrics to determine the resilience measure, and uses the cost model to estimate the cost of the modelled microgrid architecture. The model for resilience is stochastic and includes distributions for probability of damage to the microgrid components and resources. The recovery duration is also stochastic and based on the available repair resources generated in the simulation [64].

Anderson's simulation resilience model equation is studied for verification in this article. The model it includes an equal weight for both invulnerability and recovery measures. The measures are computed as positive ratios shown in Equation 2.1. The simulated microgrid resilience curve function is shown in Figure 2.7 and it includes annotations for the invulnerability and recovery measures.

$$resilience = 0.5(invulnerability + recovery) \tag{2.1}$$

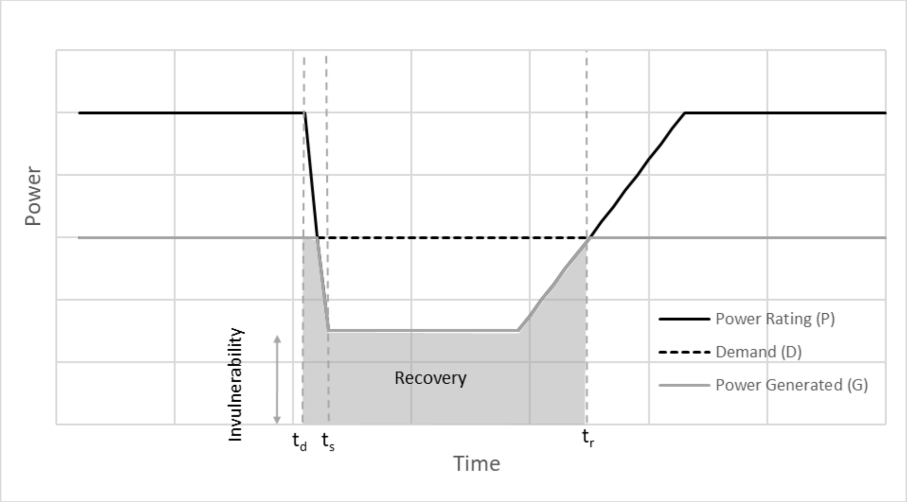

Figure 2.7. Anderson's Simulation model resilience curve function for a power disruption with annotations for invulnerability and recovery measures.

The invulnerability measure is computed with the reduction in power delivered immediately after the disruption. The invulnerability measure is constructed by the ratio of power delivered to load demands shown in Equation 2.2. This is also described in various research work by Francis and Bekra as absorptive capacity and by Yodo and Wang as lost performance [41], [65].

$$invulnerability = \frac{P_{t_s}}{P_{t_d}} \tag{2.2}$$

Recoverability is defined as the ratio of the area bounded by the demand and the reduced post disruption power delivered shown in Equation 2.3. This method provides an accurate indication of the microgrid's ability to rapidly recover as it accounts for time after the disruption until it is recovered.

$$recoverability = 1 - \frac{\sum_{t=t_d}^{t=t_r} D_t - G_t}{\sum_{t=t_d}^{t=t_r} D_t} \tag{2.3}$$

The simulation resilience model requires 12 input variables which include energy generation resource parameters, energy storage capacity, probability of damage, and demand profile. Random variables like damage to the generation resource and component mean time to repair will be generated by the simulation to be used in the resilience model. The model then computes the resilience metrics of recovery, invulnerability, and time to recover. The simulation model developer had used an existing microgrid at Naval Station Rota, Spain which has a diesel generator, a solar array and an energy storage system to demonstrate the simulation model. This demonstration utilized historical demand data and utilized the model to generate a simulation of the loss of both solar and diesel generators in a tsunami event. Results of the system demand, system power rating, and power delivered is shown in Figure 2.8. As both the diesel generator and the solar generators have been damaged by the disruption, power demands could only be supplied by the energy storage system for the initial 24 hours. Thereafter, the recovery of the solar and diesel generators allowed the microgrid to meet demands at time step 65 hours.

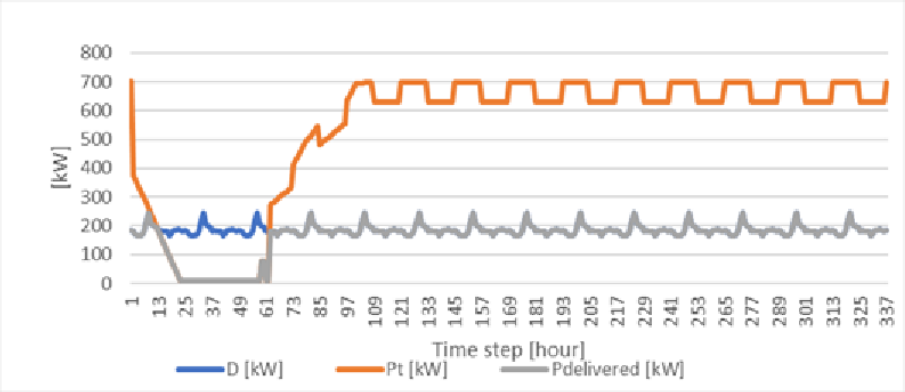

Figure 2.8. Anderson's Simulation model resilience curve showing simulation of diesel generator and solar power disruption. Source: [64].

The baseline model inputs were then adjusted to match the scaled microgrid experiment and allowed to generate results with probabilistic random variable input for system damage and mean time to repair. This simulation model generates a 14 day scenario for the islanded microgrid and a sample result of the resilience curve is shown in Figure 2.8. The diesel generator in this scenario was damaged and was repaired at time 175 hour. The battery was able to sustain the load until hour 12 and was fully depleted at hour 19 while the solar panels was only able to support part of the load requirements during the day. This solar power cycling between day and night can be seen between hour 24 to 175 until the diesel generator was recovered.

2.5 Scaled Microgrid Experimental System

The validation experiment was done on a scaled microgrid system with commercial off the shelf systems consisting of an integrated controller, inverter, and charger system; a photovoltaic array; a bank of batteries; and a generator. The system monitors the microgrid power and generates an hourly log of the respective component power generation and demands. This data log is then used for the experiment and to verify against the simulated model data. Details of the main components of the system include:

- 2kW Integrated controller, inverter and charger system (FXR2524A, from OutBack

Power)

- 1.2kW Static array of twelve 100 watt solar panels are mounted on the roof with no obstruction to the light from the sun. (RNG-100D-R-BK, from Renology)
- 12kWh Battery bank (SLR500-2, from GS Battery (U.S.A.))
- 2kW Gasoline generator (Hybrid Series H03651, from Firman)

The integrated controller inverter and charger is central to the system with solar, grid, and generator power generation sources. The battery is also connected and can be charged by any available source, and can supply power when there is a disruption causing power generated to fall below the load demands. The experimental system set up diagram with power flow direction represented by arrows is shown in Figure 2.9 below.

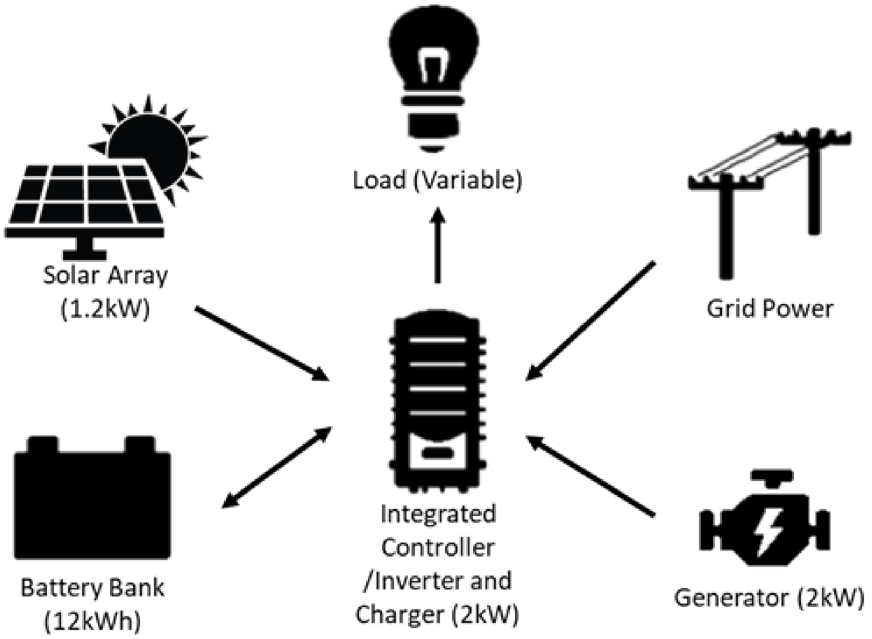

Figure 2.9. Scaled Experimental Microgrid Diagram showing connected power generation and demand components.

To mimic power disruption on the experimental microgrid, the system is configured to consume battery power when grid power and solar power is insufficient to support load power demands. the system will then attempt to utilize the generator to charge the battery when its state of charge falls below a set threshold. The experiment utilizes a grid power disruption and hourly logs of system power are used to assess the Peterson's and Anderson's resilience models.

2.6 Experimental Results

The scaled microgrid experimental system was integrated and tested in the configuration discussed in the methodology and simulation section above. This section discusses the results from the experimental system described in the previous section, and assesses the two microgrid resilience analysis models against the experimental system. The baseline microgrid operational performance without any power disruptions is be discussed before it is configured to simulate a power disruption. Key system parameters like the battery state of charge and power within the microgrid is presented.

2.6.1 Experimental Microgrid Baseline Results

Initially, the microgrid is connected to the utility grid and uses grid power to meet power demands when grid power is available. With renewable energy resources connected, the microgrid controller utilizes power generated by the renewable resource and supplements it with utility grid power if power delivered by the renewable resource is not sufficient to meet load demands. The baseline scenario was set up with a 0.7kW load demand over 32 hours as shown in Figure 2.10. This experiment was conducted between 23 and 24 July, 2022 in Monterey, California.

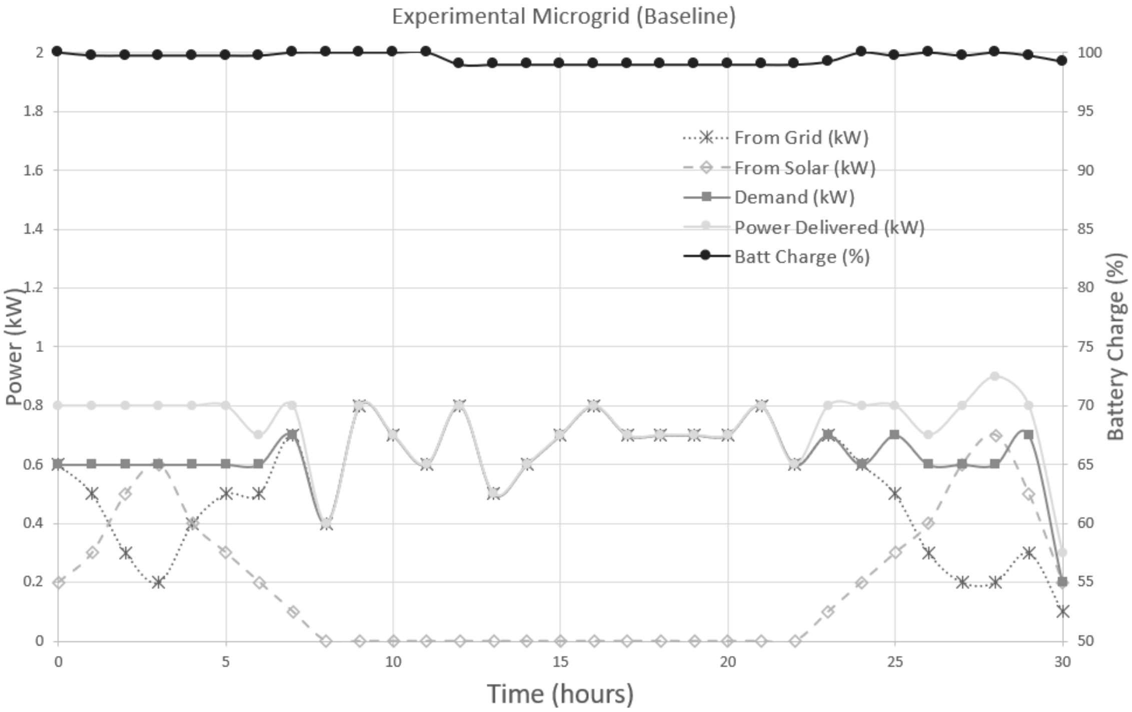

Figure 2.10. Experimental microgrid baseline result for a clear day with no power disruption is shown in this figure. It shows power delivered from energy resources, and power delivered to load demands.

As there were no power disruptions, the battery state of charge (SOC) was maintained close to the full level and load demand was supplied by the renewable resource and the utility grid. In this baseline scenario, the power delivered matches or exceeds the power demands. It can be examined from the data graph in Figure 2.10 that the power delivered from the utility grid is reduced when there is available power from the solar panels. In addition, total power delivered exceeds load demands when solar power is available. This small difference is due to inverter efficiency loss. This behavior of the microgrid under normal power conditions is within expectations and consistent with deployed systems [66].

2.6.2 Experimental Microgrid Simulated Disruption Results

As the experimental microgrid system is installed in Monterey, California, U.S.A., with benign weather and a reliable utility grid, a simulated disruption is next conducted to carry out the experiment to examine microgrid resilience and power behavior. The test scenario used for the experiment was a power disruption of the utility grid power. To simulate the scenario on the microgrid, the system was configured to prioritise power from the batteries, and grid power was limited to 2kW to simulate generator power. Data was collected over a 70 hour utility supply disruption with the microgrid operating within battery charge constraints, with available solar power, and within simulated diesel generator constraints. The test was carried out on 15 July, 2022. The microgrid maintained delivery of power to meet load demands for the whole test and charged the batteries when it fell below the 70% (8.4kWh) threshold. Solar power during daylight hours was able to support load demands and reduce the rate of battery discharge, and this can be clearly seen in the results graph on Figure 2.11. The battery charge takes a longer time compared to night hours to fall below the threshold.

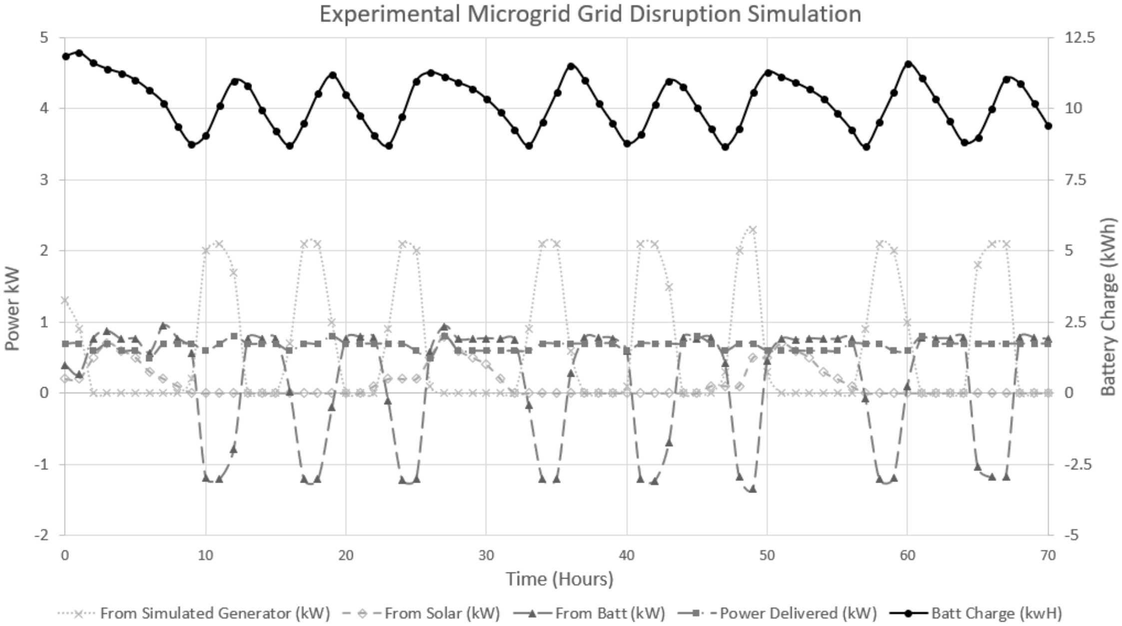

Figure 2.11. Experimental microgrid simulated loss of utility grid disruption results.

To assess the resilience curve of this simulated utility grid power disruption on the experimental microgrid, the overall power rating, demand and power delivered is illustrated in Figure 2.12. Power demands were met for the length of the disruption as there was sufficient power capacity from the batteries, solar power, and the simulated diesel generator. The system power rating shows the available microgrid power capacity during the power disruption. This differs from the component power graph shown in Figure 2.11 as the microgrid controller balances power delivery to meet demands and only depicts the power transferred within the system. The system resilience matrix can be computed from the results between t_d and t_r, and this will be presented in the model result discussion sections. The minor differences between the power delivered and the constant 0.7kW load was also noted and this was assessed to be attributed to component power efficiency losses.

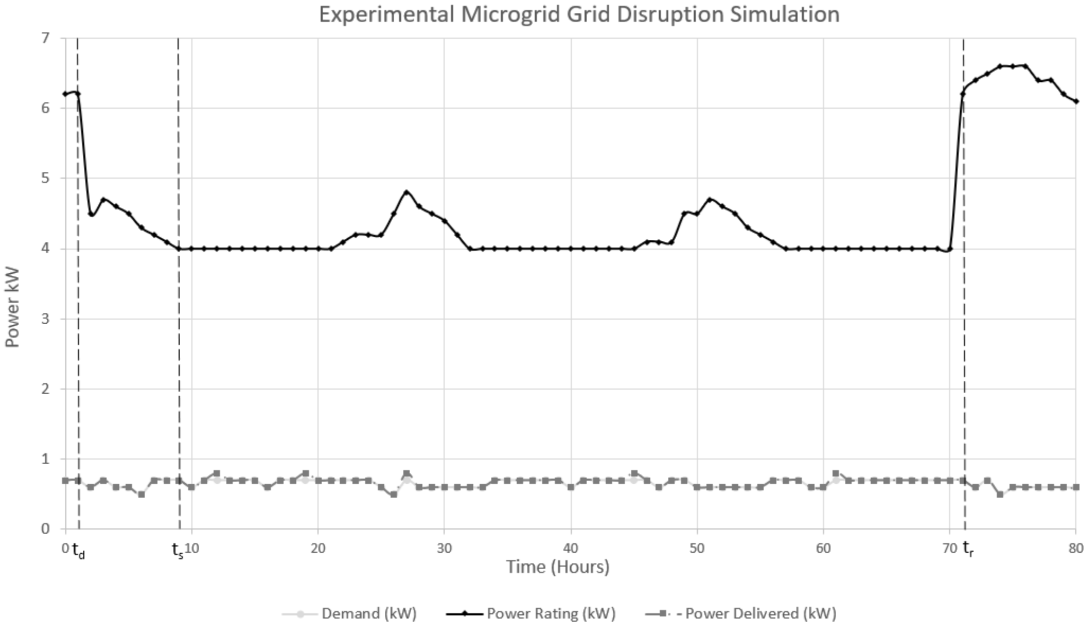

Figure 2.12. Experimental microgrid simulated loss of utility grid disruption resilience curve results.

The parameters used for the experimental microgrid are next used on Peterston's and Anderson's simulation models for a comparison of results. The generator power is controlled to toggle on and off in the same time interval as the experiment, and the load demand is kept constant at 0.7kW. This aims to generate simulations on the two models to mimic the experimental results for assessment.

2.6.3 Peterson's Simulation Model Results

Using the experiment parameters, the results of Peterson's simulation model show that the system was not able to meet load demands 3 out of 71 hours. This simulation result was not expected as the simulated microgrid was assessed to have more than sufficient remaining power resources to meet power demands. The battery charge results were plotted and they showed that the battery continued to deplete even after diesel generator power was available. Unlike the experimental results in Figure 2.11, where the battery charges on excess power of the diesel generator, Peterson's Simulation Model limits diesel generator power delivery to load demands. Therefore, as shown in Figure 2.13 the battery charge continues to deplete and at time 68 hours, the system was not able to meet load demands until solar power was available.

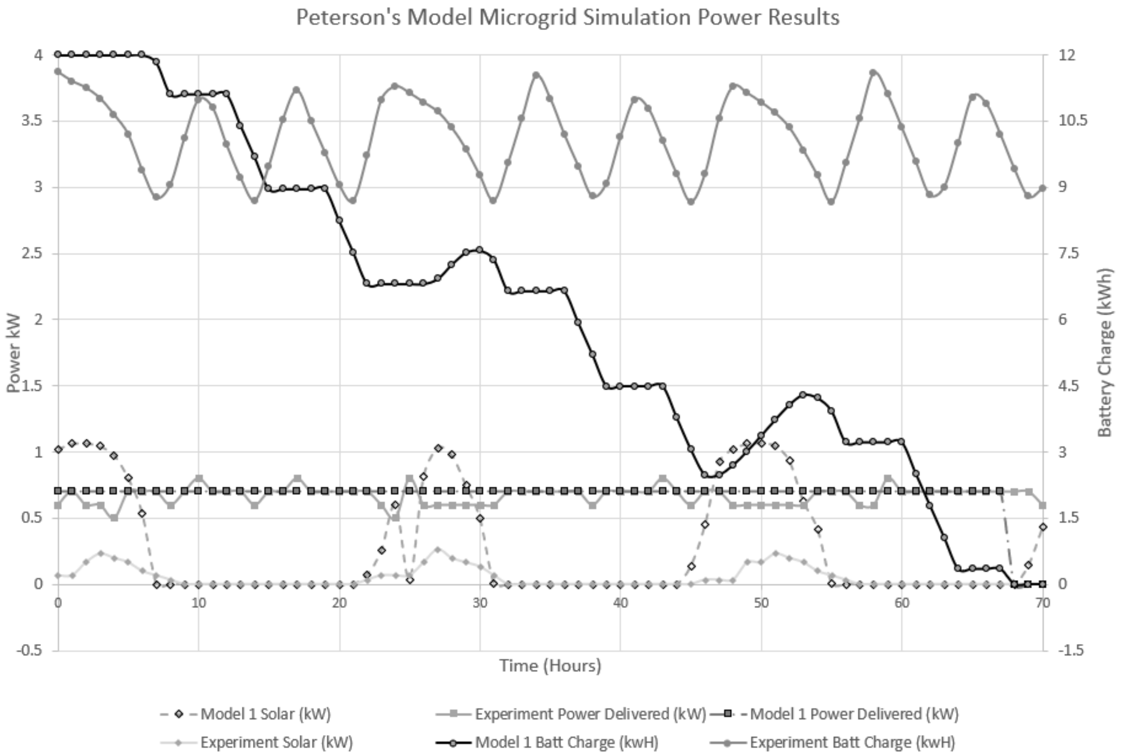

Figure 2.13. Peterson's Simulation Model battery charge and component power over length of simulation.

2.6.4 Anderson's Simulation Model Results

The experiment parameters was also applied to Anderson's Simulation Model and it showed that power generated was able to support the load for the duration of the test. This result is similar to the experimental results. As this was a high level, low-fidelity simulation, minor effects like power loss within the system was not included and the power delivered matches the demand as shown in Figure 2.14. With the overlay of the experimental data, it can be seen that the simulation model results is similar to the experimental data.

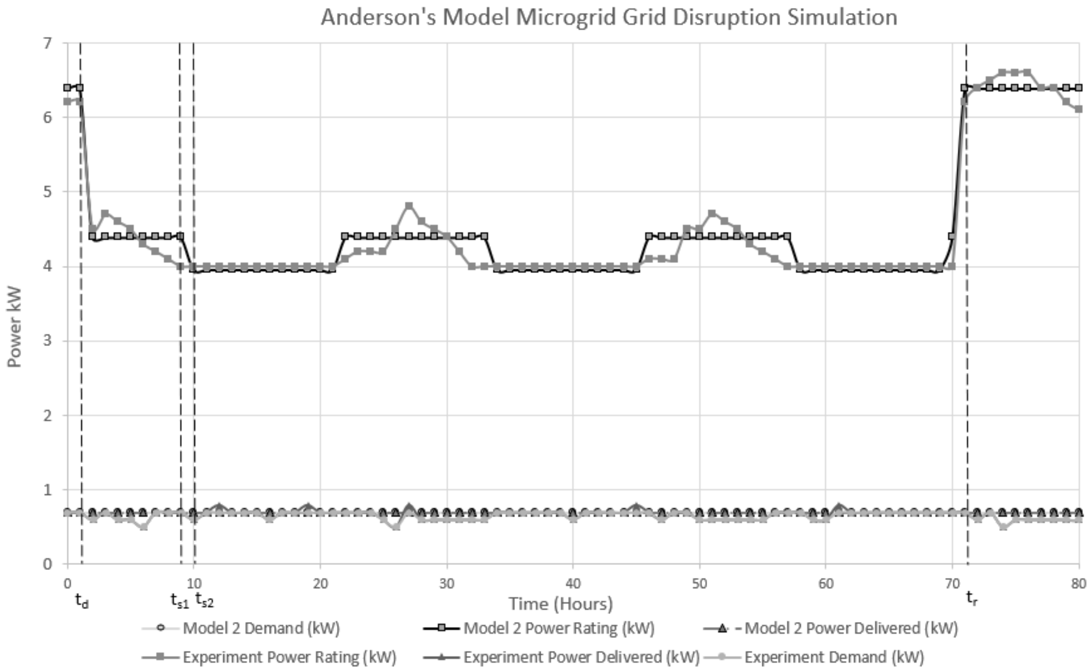

Figure 2.14. Anderson's Simulation Model power rating, power demands and power delivered over length of simulation overlaid with experimental data.

2.7 Result Analysis

The microgrid resilience simulation results from Peterson's and Anderson's Simulation Models is now compared with the experimental results for assessment. Apart from comparing the computed metrics, the results for the identified parameters are also computed and presented. This validates and highlight areas where the respective simulation model results differ from the experimental results.

2.7.1 Peterson's Simulation Model Result Analysis

Peterson's Simulation Model is able to simulate the utility power disruption of 70 hours. The results report that the system was not able to handle load requirements for 3 hours which is not congruent with the experimental results where the experimental microgrid was able to support load requirements for the duration of the disruption. Two observations of the results are now discussed: the reducing battery charge level in Peterson's model compared to the ability of the experimental microgrid to maintain battery charge, and the higher solar power generation in the simulation model. The results for Peterson's Simulation Model battery charge were computed and it shows a clear positive trend as shown in Figure 2.15. Upon investigation, it was found that Peterson's Simulation Model was not able to utilize generator power to charge the batteries and this continued to deplete the battery charge.

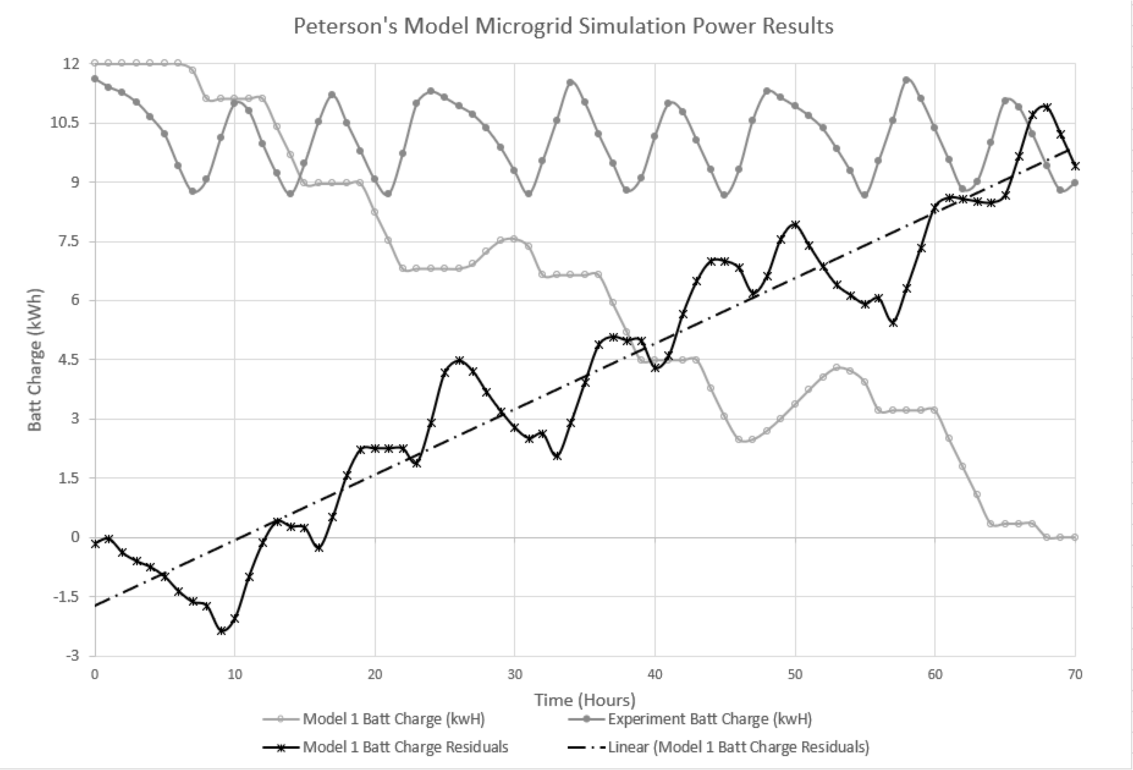

Figure 2.15. Peterson's Simulation Model battery charge results show a positive trend because the model batteries were not charged by excess diesel generator power.

The peaks for Peterson's model solar power generation was also found to be higher than the experimental microgrid. The trend line for the residuals of Peterson's model solar power as shown in Figure 2.16 is below 0, showing that the solar generation in Peterson's model was higher than the experimental results. This was is because of lower solar power generation efficiency due to the position of the static solar panels and weather conditions during the experiment versus the solar data used in Peterson's model. However, the residuals trend line is flat, and close to 0, showing that the model results for solar power generation is similar to the experiment results.

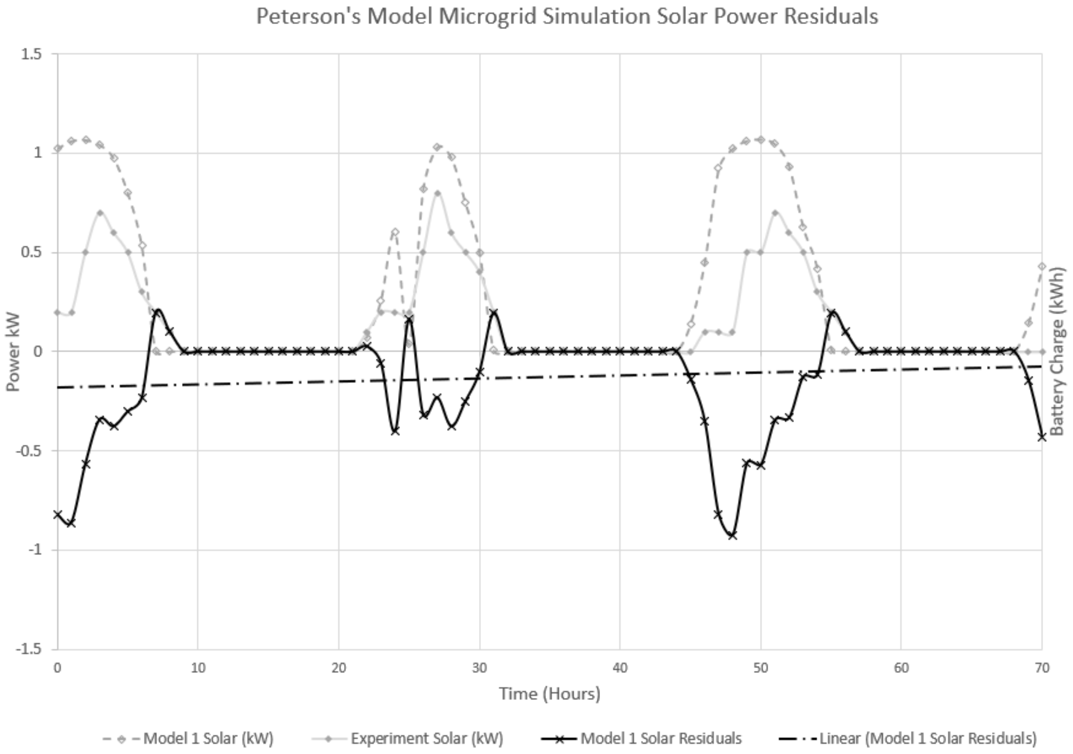

Figure 2.16. Peterson's Simulation Model solar power residuals trend flat and slightly below 0 due to difference in assumptions for solar efficiency and weather conditions.

The difference in battery charge conditions for Peterson's Simulation Model is assessed to only have an impact on specific conditions where there is a periodic need to draw power from the batteries due to fluctuations in power generation. Although there are various configuration schemes for the microgrid to ensure power delivery to meet demands, the microgrid controller would be able to monitor the system conditions and maximise available power generation resources to meet demand. In the event that the batteries are unable to charge, the controller would have allowed the diesel generator to run continuously to meet power demands.

2.7.2 Anderson's Simulation Model Result Analysis

The resilience measure for both the experiment and Anderson's Simulation Model was computed using equation 2.1 and the results were 0.816 for the experimental microgrid and 0.809 for Anderson's Simulation Model. The difference of 0.7% in resilience measure is assessed to be small and power demands are fully met in both the experiment and Anderson's Simulation Model results. The results for Anderson's Simulation Model power rating were also computed and the trend line is flat and close to zero as shown in Figure 2.17. This shows that Anderson's model power rating results are similar to the experimental results.

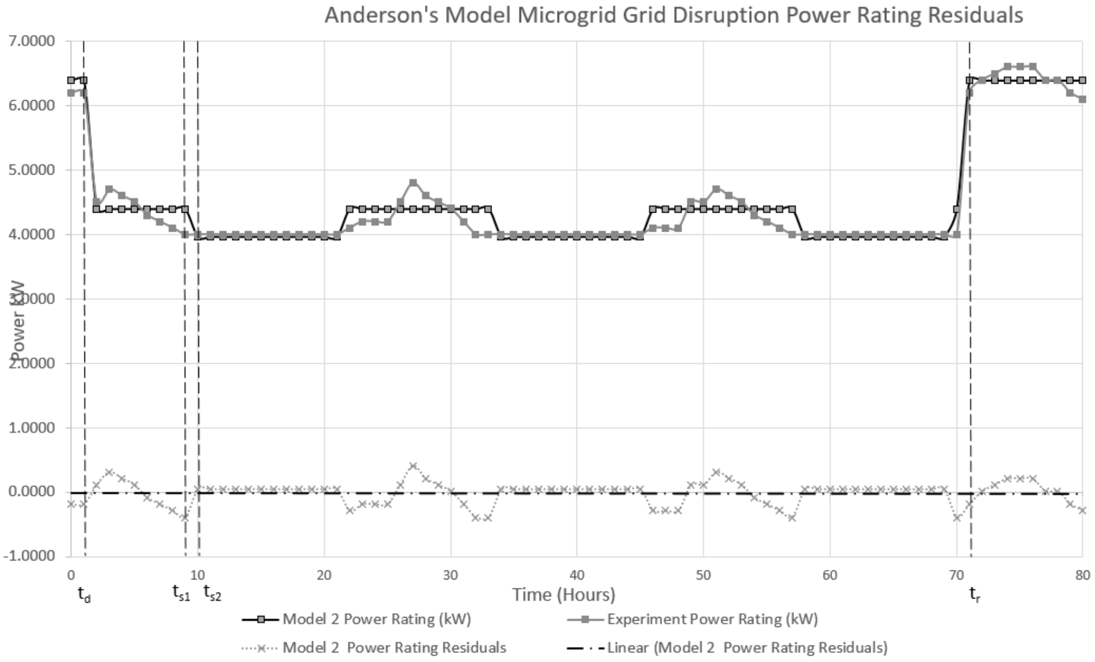

Figure 2.17. Anderson's Simulation Model power rating residuals trend flat and close to 0.

2.8 Conclusion

The experimental microgrid results were useful in helping to validate the simulation models used for microgrid resilience research. This validation effort for the microgrid resilience models supports the effort to improve energy resilience in the increasing risk environment from extreme weather events and adversarial threats. The two microgrid resilience models (Peterson's and Anderson's) studied in this research were used in exploring tradeoff between energy resilience versus resource distribution and cost.

Although there were some minor differences in the power control for battery charging between Peterson's Simulation Model and the experimental microgrid, other aspects of the model were found to be similar. One option to fix this variance is to include in the model input an option to allow the user to indicate if the system is designed to allow for diesel generator power to charge the batteries. In larger capacity systems where connected energy resources run continuously, the impact to the simulation results would be minimal as the battery charge is utilized for bridging gaps in power delivery early in the disruption phase. Thereafter, standby generators would supply power with minimal fluctuations in supply. The model input parameters could also be improved to include the system solar panel position and orientation to improve computation of solar power efficiency.

Anderson's Simulation Model resilience results and associated metrics were found to be similar to experimental results. This provides physical evidence that validates resilience, invulnerability and recoverability used in Anderson's model. These experimental results support the high level microgrid architecture assessment simulation model that Anderson developed to be used for design and cost trade off analysis.

It is important to note that both Peterson's Simulation Model and Anderson's Simulation Model are systems engineering tools. While they do analyze microgrids, they are not detailed electrical engineering models. They are meant to be used early in a system design process when making large architectural decisions about a microgrid. Later design efforts can use models such as Fish's electrical microgrid simulation tool [67] are more appropriate for detailed design and simulation work.

2.8.1 Future work

While this article investigated one scenario to validate Peterson's and Anderson's model, there is a need for future studies to continue to utilize real world data to improve microgrid resilience simulation models. As this research was conducted on a scaled microgrid with commercial-off-the-shelf components, it may not be able to highlight issues that may be present in the operation of larger microgrid systems. Some recommendations for future work include repeating the experiment on a scaled up physical microgrid system with a power capacity close to deployed microgrid system, or to collect power disruption data from deployed systems when there is scheduled downtime.

For a mode holistic result, more system factors could be included for the design of this experiment. Possible factors include the number of renewable energy resources, energy storage systems, and several repetitions with measured environment data. This will help refine simulation models and identify significant factors that influence microgrid resilience. The next experimental microgrid could also explore including different power generation systems and topology design for assessment with the simulation model results.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 3:
Conclusion

Based on the results of this research, military installation systems reliant on electrical power are able to better fulfil missions and objectives with a highly resilient power supply system. Although the implementation of microgrids has been widely shown to improve power reliability and availability, the impact to resilience measure is not as well established. Resilience measures were introduced in several simulation models to address the gap in resilience assessment during disruption events. This is to better characterise the ability of the microgrid to continue supplying power for the operation of critical mission systems.

Several military mission types that will benefit greatly from the research to improve energy resilience include humanitarian aid and disaster relief missions, islanded military installations, and rapidly deployed military command centers to coordinate deployed forces. Such military mission deployments have limited access to utility grid power and rely on stable power to enable modern mission systems to function optimally.

For humanitarian aid and disaster relief, the responding deployment of military personnel will have to be self-sufficient as power to the operational area would likely have been disrupted. Further, the risk of a subsequent disaster that disrupts deployed power systems is also present. Islanded military installations are usually located in remote areas where there is little commercial incentive to build infrastructure to provide the facility with utility grid power. Lastly, rapidly deployed forward command centers are usually situated in less than friendly locations and access to utility grid is denied. Improving power resilience will allow these deployments and facilities to fulfil their operational mission and ensure planners have the appropriate tools to develop appropriately sized power system plans for the respective missions.

The results from the experiment were able to highlight significant factors that could be used to refine the simulation models. In addition, user input parameters could be included to adjust assumptions for solar power generation and battery use behavior for the modeled systems. These were found to have an impact to resilience measure in certain disruption scenarios. Implementing the changes will allow the simulation models to be applied for a wider range of designs and provide better results.

This experiment helps to validate the two simulation models that utilize resilience measures for analysis. It supports high level microgrid cost and resilience trade space analysis, and defined mission impact for the respective simulation models. Implementing recommended changes would allow for more granular assessment and more precise optimisation results. Such results will better inform decision makers on utility of investment in microgrid resilience and help scope implementation optimally to support facility mission.

List of References

[1] S. A. Shield, S. M. Quiring, J. V. Pino, and K. Buckstaff, "Major impacts of weather events on the electrical power delivery system in the United States," *Energy*, vol. 218, p. 119434, 2021, publisher: Elsevier.

[2] R. J. Campbell and S. Lowry, *Weather-related power outages and electric system resiliency* (CRS Report No. R42696). Washington, DC: Congressional Research Service, Library of Congress Washington, DC, 2012. Available: https://crsreports.congress.gov/product/pdf/R/R42696/4

[3] D. L. Sagunsky, "Risk on the Horizon, Rig for Dark: Solutions to Mitigate DoD's Reliance on the Fragile Electric Grid," Master's thesis, Joint Advanced Warfighting School, 2013.

[4] M. Sullivan, J. Schellenberg, and M. Blundell, "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States," Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States), Tech. Rep. LBNL-6941E, Jan. 2015. Available: https://www.osti.gov/biblio/1172643

[5] W. Wang, F. Di Maio, and E. Zio, "Adversarial Risk Analysis to Allocate Optimal Defense Resources for Protecting Cyber–Physical Systems from Cyber Attacks," *Risk Analysis*, vol. 39, no. 12, pp. 2766–2785, 2019, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.13382. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/risa.13382

[6] C. Steitz and N. Chestney, "Russia cuts gas flows further as Europe urges energy saving," *Reuters*, July 2022. Available: https://www.reuters.com/business/energy/physical-flows-through-nord-stream-1-pipeline-dip-2022-07-27/

[7] C. Samaras, W. J. Nuttall, and M. Bazilian, "Energy and the military: Convergence of security, economic, and environmental decision-making," *Energy Strategy Reviews*, vol. 26, p. 100409, Nov. 2019. Available: https://www.sciencedirect.com/science/article/pii/S2211467X19301026

[8] E. Douglas, "Texas largely relies on natural gas for power. It wasn't ready for the extreme cold." Feb. 2021. Available: https://www.texastribune.org/2021/02/16/natural-gas-power-storm/

[9] M. Goss, D. L. Swain, J. T. Abatzoglou, A. Sarhadi, C. A. Kolden, A. P. Williams, and N. S. Diffenbaugh, "Climate change is increasing the likelihood of extreme

autumn wildfire conditions across California," *Environmental Research Letters*, vol. 15, no. 9, p. 094016, 2020, publisher: IOP Publishing.

[10] D. of Defense, *Department of Defense Annual Energy Management and Resilience Report (AEMRR) Fiscal Year 2020* (8-BC91200). Department of Defense, Sep. 2021. Available: https://www.acq.osd.mil/eie/Downloads/IE/FY%202020%20AEMRR.pdf

[11] P. Sanjeevikumar, *Microgrids*, 2021, oCLC: 1226504835. Available: https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=2627266

[12] M. Stadler, G. Cardorso, S. Mashayekh, and N. DeForest, "Distributed Energy Resources Customer Adoption Model Plus (DER-CAM+), Version 1.0.0," Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States), Tech. Rep. DER-CAM+; 004669MLTPL00, Mar. 2016. Available: https://www.osti.gov/biblio/1245449-distributed-energy-resources-customer-adoption-model-plus-der-cam+-version

[13] "XENDEE | Microgrid Design and Decision Support Platform." Available: https://xendee.com/

[14] C. House of Representatives, "10 U.S.C. 1 - DEFINITIONS," Dec. 2020, publication Title: govinfo.gov Type: Government. Available: https://www.govinfo.gov/app/details/USCODE-2020-title10/https%3A%2F%2Fwww.govinfo.gov%2Fapp%2Fdetails%2FUSCODE-2020-title10%2FUSCODE-2020-title10-subtitleA-partI-chap1

[15] J. Pazzalia, "Sparking Debate: Private or Public? The Effect of Ownership on Electric Utility Performance," PhD diss., West Chester University, 2022. Available: https://digitalcommons.wcupa.edu/all_doctoral/138

[16] K. P. Schneider, F. K. Tuffner, M. A. Elizondo, C.-C. Liu, Y. Xu, and D. Ton, "Evaluating the feasibility to use microgrids as a resiliency resource," *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 687–696, 2016, publisher: IEEE.

[17] A. A. Bajwa, H. Mokhlis, S. Mekhilef, and M. Mubin, "Enhancing power system resilience leveraging microgrids: A review," *Journal of Renewable and Sustainable Energy*, vol. 11, no. 3, p. 035503, May 2019, publisher: American Institute of Physics. Available: https://aip.scitation.org/doi/full/10.1063/1.5066264

[18] S. Van Broekhoven, N. Judson, J. Galvin, and J. Marqusee, "Leading the charge: Microgrids for domestic military installations," *IEEE Power and Energy Magazine*, vol. 11, no. 4, pp. 40–45, 2013, publisher: IEEE.

[19] A. Hussain, V.-H. Bui, and H.-M. Kim, “Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience,” *Applied energy*, vol. 240, pp. 56–72, 2019, publisher: Elsevier.

[20] D. T. Ton and M. A. Smith, “The US department of energy’s microgrid initiative,” *The Electricity Journal*, vol. 25, no. 8, pp. 84–94, 2012, publisher: Elsevier.

[21] A. Hirsch, Y. Parag, and J. Guerrero, “Microgrids: A review of technologies, key drivers, and outstanding issues,” *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 402–411, July 2018. Available: https://www.sciencedirect.com/science/article/pii/S136403211830128X

[22] R. E. Giachetti, C. J. Peterson, D. L. Van Bossuyt, and G. W. Parker, “Systems Engineering Issues in Microgrids for Military Installations,” *INCOSE International Symposium*, vol. 30, no. 1, pp. 731–746, 2020, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/j.2334-5837.2020.00751.x. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2334-5837.2020.00751.x

[23] T. Caldognetto, P. Tenti, A. Costabeber, and P. Mattavelli, “Improving Microgrid Performance by Cooperative Control of Distributed Energy Sources,” *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3921–3930, Nov. 2014, conference Name: IEEE Transactions on Industry Applications.

[24] L. Mariam, M. Basu, and M. F. Conlon, “Microgrid: Architecture, policy and future trends,” *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 477–489, Oct. 2016. Available: https://www.sciencedirect.com/science/article/pii/S1364032116302635

[25] E. Planas, J. Andreu, J. I. Gárate, I. Martínez de Alegría, and E. Ibarra, “AC and DC technology in microgrids: A review,” *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 726–749, Mar. 2015. Available: https://www.sciencedirect.com/science/article/pii/S1364032114010065

[26] J. D. Mondol, Y. Yohanis, M. Smyth, and B. Norton, “Long term performance analysis of a grid connected photovoltaic system in Northern Ireland,” *Energy Conversion and Management*, vol. 47, no. 18, pp. 2925–2947, Nov. 2006. Available: https://www.sciencedirect.com/science/article/pii/S0196890406001051

[27] G. Venkataramanan and M. Illindala, “Microgrids and sensitive loads,” in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309)*, Jan. 2002, vol. 1, pp. 315–322 vol.1.

[28] E. Wood, “The Rise of Fuel Cell Microgrids: Special Report,” Apr. 2017, section: Distributed Energy. Available: https://microgridknowledge.com/fuel-cell-microgrids-fuelcell-energy/

[29] Z. Li, Z. Zheng, L. Xu, and X. Lu, “A review of the applications of fuel cells in microgrids: opportunities and challenges,” *BMC Energy*, vol. 1, no. 1, p. 8, Oct. 2019. Available: https://doi.org/10.1186/s42500-019-0008-3

[30] D. Akinyele, E. Olabode, and A. Amole, “Review of Fuel Cell Technologies and Applications for Sustainable Microgrid Systems,” *Inventions*, vol. 5, no. 3, p. 42, Sep. 2020, number: 3 Publisher: Multidisciplinary Digital Publishing Institute. Available: https://www.mdpi.com/2411-5134/5/3/42

[31] J. B. Ekanayake, N. Jenkins, K. Liyanage, J. Wu, and A. Yokoyama, *Smart grid: technology and applications*. John Wiley & Sons, 2012.

[32] “IEEE Standard for the Specification of Microgrid Controllers,” *IEEE Std 2030.7-2017*, pp. 1–43, Apr. 2018, conference Name: IEEE Std 2030.7-2017.

[33] C. Sun, J. N. Paquin, F. Al Jajeh, G. Joos, and F. Bouffard, “Implementation and CHIL Testing of a Microgrid Control System,” in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2018, pp. 2073–2080, iSSN: 2329-3748.

[34] X. Fang, S. Misra, G. Xue, and D. Yang, “Smart Grid — The New and Improved Power Grid: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 944–980, 2012, conference Name: IEEE Communications Surveys & Tutorials.

[35] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou, “Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems,” *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4732–4742, Nov. 2017, conference Name: IEEE Transactions on Power Systems.

[36] Y. Wang, A. O. Rousis, and G. Strbac, “On microgrids and resilience: A comprehensive review on modeling and operational strategies,” *Renewable and Sustainable Energy Reviews*, vol. 134, p. 110313, Dec. 2020. Available: https://www.sciencedirect.com/science/article/pii/S1364032120306018

[37] J. Lu, W. Wang, Y. Zhang, and S. Cheng, “Multi-Objective Optimal Design of Stand-Alone Hybrid Energy System Using Entropy Weight Method Based on HOMER,” *Energies*, vol. 10, no. 10, p. 1664, Oct. 2017, number: 10 Publisher: Multidisciplinary Digital Publishing Institute. Available: https://www.mdpi.com/1996-1073/10/10/1664

[38] T. Adefarati and R. C. Bansal, "Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources," *Applied Energy*, vol. 236, pp. 1089–1114, Feb. 2019. Available: https://www.sciencedirect.com/science/article/pii/S0306261918318671

[39] S. Wang, Z. Li, L. Wu, M. Shahidehpour, and Z. Li, "New Metrics for Assessing the Reliability and Economics of Microgrids in Distribution System," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2852–2861, Aug. 2013, conference Name: IEEE Transactions on Power Systems.

[40] F. Rusco, B. J. Lepore, J. Ludwigson, L. Durland, T. Barnes, E. Biskup, L. Ettaro, E. Gerken, T. Guinane, T. Hanford, A. Leff, A. O'Neill, J. Sandel, K. Theodoropoulos, and M. Willems, "DOD Renewable Energy Projects: Improved Guidance Needed for Analyzing and Documenting Costs and Benefits," U.S. Government Accountability Office Washington United States, Tech. Rep., Sep. 2016, section: Technical Reports. Available: https://apps.dtic.mil/sti/citations/AD1016617

[41] R. Francis and B. Bekera, "A metric and frameworks for resilience analysis of engineered and infrastructure systems," *Reliability Engineering & System Safety*, vol. 121, pp. 90–103, Jan. 2014. Available: https://www.sciencedirect.com/science/article/pii/S0951832013002147

[42] R. E. Giachetti, D. L. Van Bossuyt, W. Anderson, and G. Oriti, "Resilience and Cost Trade Space for Microgrids on Islands," *IEEE Systems Journal*, pp. 1–11, 2021, conference Name: IEEE Systems Journal.

[43] A. Gholami, T. Shekari, M. H. Amirioun, F. Aminifar, M. H. Amini, and A. Sargolzaei, "Toward a Consensus on the Definition and Taxonomy of Power System Resilience," *IEEE Access*, vol. 6, pp. 32 035–32 053, 2018, conference Name: IEEE Access.

[44] E. D. Vugrin, A. R. Castillo, and C. A. Silva-Monroy, "Resilience Metrics for the Electric Power System: A Performance-Based Approach." Sandia National Lab. (SNL-NM), Albuquerque, NM (United States), Tech. Rep. SAND2017-1493, Feb. 2017. Available: https://www.osti.gov/biblio/1367499

[45] Y. Y. Haimes, "On the Definition of Resilience in Systems," *Risk Analysis*, vol. 29, no. 4, pp. 498–501, 2009, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1539-6924.2009.01216.x. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.2009.01216.x

[46] M. N. Albasrawi, N. Jarus, K. A. Joshi, and S. S. Sarvestani, "Analysis of Reliability and Resilience for Smart Grids," in *2014 IEEE 38th Annual Computer Software and Applications Conference*, July 2014, pp. 529–534, iSSN: 0730-3157.

[47] A. Clark-Ginsberg, *What's the Difference between Reliability and Resilience?*, Mar. 2016.

[48] S. B. A. Kashem, S. De Souza, A. Iqbal, and J. Ahmed, "Microgrid in military applications," in *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*, Apr. 2018, pp. 1–5, iSSN: 2166-9546.

[49] V. Venkataramanan, A. K. Srivastava, A. Hahn, and S. Zonouz, "Measuring and Enhancing Microgrid Resiliency Against Cyber Threats," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6303–6312, Nov. 2019, conference Name: IEEE Transactions on Industry Applications.

[50] W. Rickerson, J. Gillis, and M. Bulkeley, *The Value of Resilience for Distributed Energy Resources: An Overview of Current Analytical Practices*, Apr. 2019.

[51] J. Giraldez, S. Booth, K. Anderson, and K. Massey, "Valuing Energy Security: Customer Damage Function Methodology and Case Studies at DoD Installations," National Renewable Energy Lab. (NREL), Golden, CO (United States), Tech. Rep. NREL/TP-7A30-55913, Oct. 2012. Available: https://www.osti.gov/biblio/1055367

[52] S. Mishra, K. Anderson, B. Miller, K. Boyer, and A. Warren, "Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies," *Applied Energy*, vol. 264, p. 114726, 2020, publisher: Elsevier.

[53] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked Microgrids for Enhancing the Power System Resilience," *Proceedings of the IEEE*, vol. 105, no. 7, pp. 1289–1310, July 2017, conference Name: Proceedings of the IEEE.

[54] M. Mahzarnia, M. P. Moghaddam, P. T. Baboli, and P. Siano, "A Review of the Measures to Enhance Power Systems Resilience," *IEEE Systems Journal*, vol. 14, no. 3, pp. 4059–4070, Sep. 2020, conference Name: IEEE Systems Journal.

[55] D. T. Beaton, "Testing Whether Distributed Energy Storage Results in Greater Resilience of Microgrids," Master's thesis, Monterey, CA; Naval Postgraduate School, Mar. 2021, accepted: 2021-05-14T03:50:34Z. Available: https://calhoun.nps.edu/handle/10945/67104

[56] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, "Toward a resilient distribution system," in *2015 IEEE Power & Energy Society General Meeting*, July 2015, pp. 1–5, iSSN: 1932-5517.

[57] C. J. Peterson, D. L. Van Bossuyt, R. E. Giachetti, and G. Oriti, "Analyzing Mission Impact of Military Installations Microgrid for Resilience," *Systems*, vol. 9, no. 3, p. 69, Sep. 2021, number: 3 Publisher: Multidisciplinary Digital Publishing Institute. Available: https://www.mdpi.com/2079-8954/9/3/69

[58] C. A. S. Castelo Branco, F. P. Moraes, H. A. Oliveira, P. B. L. Neto, O. R. Saavedra, J. G. de Matos, C. B. M. Oliveira, L. A. d. S. Ribeiro, A. C. Oliveira, M. F. A. Júnior, L. d. P. A. Pinheiro, and R. M. Cazo, "Mission Critical Microgrids: The Case of the Alcântara Space Center," *Energies*, vol. 15, no. 9, p. 3226, Jan. 2022, number: 9 Publisher: Multidisciplinary Digital Publishing Institute. Available: https://www.mdpi.com/1996-1073/15/9/3226

[59] P. S. Sarker, V. Venkataramanan, D. S. Cardenas, A. Srivastava, A. Hahn, and B. Miller, "Cyber-Physical Security and Resiliency Analysis Testbed for Critical Microgrids with IEEE 2030.5," in *2020 8th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems*, Apr. 2020, pp. 1–6.

[60] INCOSE and Wiley, *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. New York: John Wiley & Sons, Incorporated, 2015, publication Title: INCOSE Systems Engineering Handbook.

[61] T. Weilkiens, J. G. Lamm, S. Roth, and M. Walker, *Model-Based System Architecture*. Newark, NJ, UNITED STATES: John Wiley & Sons, Incorporated, 2015. Available: http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=4436159

[62] S. M. Wilcox, "National Solar Radiation Database 1991-2010 Update: User's Manual," National Renewable Energy Lab. (NREL), Golden, CO (United States), Tech. Rep. NREL/TP-5500-54824, Aug. 2012. Available: https://www.osti.gov/biblio/1054832

[63] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenberg, M. Yazdanian, J. Huang, and D. Crawley, "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock," National Renewable Energy Lab. (NREL), Golden, CO (United States), Tech. Rep. NREL/TP-5500-46861, Feb. 2011. Available: https://www.osti.gov/biblio/1009264-pitlfN/

[64] J. Anderson, William, "Resilience Assessment of Islanded Renewable Energy Microgrids," Ph.D. dissertation, Calhoun, 2020. Available: https://calhoun.nps.edu/handle/10945/66574

[65] N. Yodo and P. Wang, “Engineering Resilience Quantification and System Design Implications: A Literature Survey,” *Journal of Mechanical Design*, vol. 138, no. 11, Sep. 2016. Available: https://doi.org/10.1115/1.4034223

[66] M. E. Khodayar, M. Barati, and M. Shahidehpour, “Integration of High Reliability Distribution System in Microgrid Operation,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1997–2006, Dec. 2012, conference Name: IEEE Transactions on Smart Grid.

[67] N. Anglani, G. Oriti, R. Fish, and D. L. Van Bossuyt, “Design and optimization strategy to size resilient stand-alone hybrid microgrids in various climatic conditions,” *IEEE Open Journal of Industry Applications*, vol. 3, pp. 237–246, 2022.

Initial Distribution List

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California