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DEFENSE INSTALLATION ENERGY RESILIENCE FOR CHANGING OPERATIONAL REQUIREMENTS

by

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A process is proposed to determine the impact of different potential mission scenarios upon energy resilience for mission-critical loads attached to a military base's microgrid infrastructure. This process applies to any institution with changing operational states whose energy resilience requirements necessitates redundant electrical supply. The methodology may be used by energy managers to account for potential mission scenarios that a base may be part of, followed by assessing the microgrid energy resilience to supply the critical loads for said mission scenarios, especially where external grid power may be unavailable and/or damage to facility microgrid systems may be present. In the event a microgrid design is unable to provide sufficient electrical energy, distributed energy resources (DERs), including energy storage systems and renewable energy resources, may be added to improve energy resilience. A case study is conducted with a fictitious military base, microgrid design, and changing operational demands to demonstrate the application of the methodology. This paper contributes a method for energy managers to evaluate energy resilience using microgrids by accounting for potential mission operations, their energy requirements, resulting energy preparedness, and recommendations for improvement as necessary.

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DEFENSE INSTALLATION ENERGY RESILIENCE FOR CHANGING OPERATIONAL REQUIREMENTS

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ABSTRACT

A process is proposed to determine the impact of different potential mission scenarios upon energy resilience for mission-critical loads attached to a military base's microgrid infrastructure. This process applies to any institution with changing operational states whose energy resilience requirements necessitates redundant electrical supply. The methodology may be used by energy managers to account for potential mission scenarios that a base may be part of, followed by assessing the microgrid energy resilience to supply the critical loads for said mission scenarios, especially where external grid power may be unavailable and/or damage to facility microgrid systems may be present. In the event a microgrid design is unable to provide sufficient electrical energy, distributed energy resources (DERs), including energy storage systems and renewable energy resources, may be added to improve energy resilience. A case study is conducted with a fictitious military base, microgrid design, and changing operational demands to demonstrate the application of the methodology. This paper contributes a method for energy managers to evaluate energy resilience using microgrids by accounting for potential mission operations, their energy requirements, resulting energy preparedness, and recommendations for improvement as necessary.

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List of Acronyms and Abbreviations

ACX	Asia Container Express
BESS	battery energy storage system
DER	distributed energy resource
DOD	Department of Defense
DOE	Department of Energy
EEDMI	expected electrical disruption impact
EMS	energy management system
ERA	Energy resilience Analysis
ESS	energy storage system
FPCON	Force Protection Conditions
FY	fiscal year
IEEE	Institute of Electrical and Electronics Engineers
LCS	Littoral Combat Ships
MCAGCC	Marine Corps Air and Ground Combat Center
MCAS	Marine Corps Air Station
MDI	Mission Dependency Index
MEA	mission engineering and analysis
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MWR	morale, welfare, and recreation
NASA	National Aeronautics and Space Administration
NBGTS	Naval Base Guam Telecommunications Site
ORFMEA	Operational Risk Failure Modes and Effects Analysis
PMRF	Pacific Missile Range Facility

PV	photovoltaic
RIMPAC	Rim of the Pacific
SOI	system of interest
SOP	Standard Operating Procedures
SOS	system of system
UFC	United Facilities Criteria
USNS	United States Naval Ship
USS	United States Ship

Executive Summary

In today's age of technology, there are many uses for electronics equipment in defense systems. As defense acquisitions increasingly require electricity power supplies, the importance of energy resilience also increases. Microgrids are a successful method for increasing energy resilience on a military base when properly designed. Identification and prioritization of critical loads must be made to ensure the microgrid capability meets demands during worst-case failure scenarios and unplanned increases in operational load demands for changing mission requirements.

The military has many different capabilities and objectives. Global events affect mission priorities, which changes the operations conducted by individual units differently throughout the military. While one command's operations are heavily impacted by an inbound or impacted hurricane, another unit's operations on the opposite coast remain unchanged. These unplanned events may unexpectedly increase the load demanded upon the microgrid. The resilience of the energy supply system must be analyzed for these increased, unplanned periods of high electrical demand coupled with a damaging event to the utility and/or microgrid components to ensure there are no or minimal energy supply gaps.

This thesis identifies and analyzes the current literature and background information available for U.S. government requirements, energy resilience, microgrids, and mission engineering topics. The current related research includes military base microgrid resilience models, nanogrids as a military electrical power resilience resource, microgrid life cycle costs, microgrid resilience and cost tradespace, renewable energy sources, energy storage methods, among others. This thesis contributes a systems engineering method with a mission engineering perspective for the military base to account for changing mission requirements and the resulting operational critical load demands to ensure the microgrid design is prepared to meet resilience requirements.

The methodology is demonstrated with a case study for a fictitious representative military base and microgrid. The potential different mission scenarios that the military base may support are first identified as well as the operational load demands for those mission scenarios. The loads are then sorted based on their intended uses and timeline requirements into

four priority levels. These levels are used to determine which loads are critical and the order that loads will be shed in the event insufficient energy supply is available. This prioritization will minimize the consequences of insufficient energy and potential mission degradation. Once the critical load requirements for the mission scenario are identified, the microgrid is analyzed for energy hazards and resilience verification. If the microgrid resilience proves insufficient, iterative improvements are conducted until all hazards are analyzed and meet resilience requirements. This process is repeated for each different identified mission scenario, until all identified scenarios are shown resilient for all identified microgrid damaging events.

This careful critical load analysis will enable microgrid acquisition at increased military bases without unnecessary microgrid oversizing costs. By ensuring the critical loads are analyzed early in the design process, only the necessary microgrid capability to support critical loads need be required. For military bases with currently installed microgrids, the analysis will inform stakeholders of the capabilities and/or limitations of the microgrid. If the currently installed microgrid is determined to be insufficiently resilient, the energy manager may use the analysis as support to request microgrid improvements.

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CHAPTER 1:
Introduction

Energy resilience continues to be increasingly more important at military bases as current and new operational system functions rely on electrical power. Microgrids are an effective method to realize electrical resilience for critical loads through redundant power supplies via various power generation and storage sources. This thesis specifically considers the impact of changing mission priorities and the resulting operational load demands upon energy resilience at military bases. A systems engineering method is used to identify potential mission scenarios a military base may be required to support and their critical loads to analyze and improve microgrid resilience during damaging events. This method uses modeling and simulation to help ensure that the microgrid will continuously supply electrical power to critical loads for mission accomplishment.

This chapter provides additional background to supplement the journal manuscript work in Chapter 2. In this chapter, applications of changing military mission priorities are discussed, and the resulting importance of critical load identification. This chapter provides military, specifically U.S. Navy, context for the work performed in Chapter 2.

1.1 Changing Mission Requirements

The military has changing mission requirements affecting local operations. Each local operation may result in different energy loads. Energy usage by location, using general quantitative information, is shown in Figure 1.1 [1]–[10]. Variation in historical power usage among different locations is shown within the same year as well as the variation of power usage at the same location across different years. For smaller military base locations with less variable mission potential, the annual energy estimation is more stable whereas the larger military base locations' energy requirements may be more significantly impacted by current mission events. Also shown on Figure 1.1, the spikes in higher and lower energy consumption do not occur in the same year across every installation. Each installation has its own variable missions and are affected by global events differently. Where some facilities may be highly impacted by a specific local event, others are not affected at all in their energy usage. In addition, Department of Defense (DOD) facilities have less tolerance for power service interruptions as outages may impact mission accomplishment and national security, therefore requiring all potential mission scenarios to be accounted for during energy estimation methods for microgrid design. When military efforts such as the response to the September 11 attacks or humanitarian aid and disaster relief missions occur, the military base electrical system supports the deployable assets through their pre-deployment maintenance and launch actions. These unplanned increases in electrical demand may incidentally reduce the energy resilience for a short time. After the deployable assets have departed on their missions, the military base demands less electrical load as fewer equipment assets and personnel remain at the location. When the military hosts training exercises with additional countries (e.g., Rim of the Pacific (RIMPAC) hosted out of Pearl Harbor, Hawaii, with exercises occurring between Hawaii and Southern California [11]), the overall military base energy demand may increase proportionally with the excessive increase of ships, vehicles, aircraft and personnel at the hosting locations.

The microgrid supplies energy to tenant commands, whose missions are affected differently by changes in the global operational environment. Warfighting priorities are made based upon global threat conditions. The supporting operations range from equipment maintenance availabilities, training exercises, deployment events, damage control responses, communications support, physical fitness, and civil activities. Naval Station Norfolk, for example, is a small city in and of itself that supports ships, airfields, medical clinics, housing infrastructure, galleys, a fire department, a security force, entertainment facilities, training facilities, as well as operational command and control centers. For a military base, the operational activities vary depending on the warfighting threats and priorities at the time, which may change quickly and without notice in response to global events. Following September 11, 2001, many deployable forces set out with little notice. The USS Theodore Roosevelt conducted a 189-day cruise just seven days following the attack, including 159 days straight at sea with air strikes over Afghanistan until March 2002 [12], [13]. In 2005, Hurricane Katrina hit the Gulf Coast, resulting in 18,000 active duty service members joined by 43,000 national guardsmen who focused on relief efforts while 21 Naval ships and 7 Coast Guard vessels were deployed for humanitarian aid and disaster relief efforts [14]. In June 2017, unplanned maintenance and recovery actions were necessary at the naval facility in Yokosuka, Japan, after the United States Ship (USS) Fitzgerald collided with Asia Con-

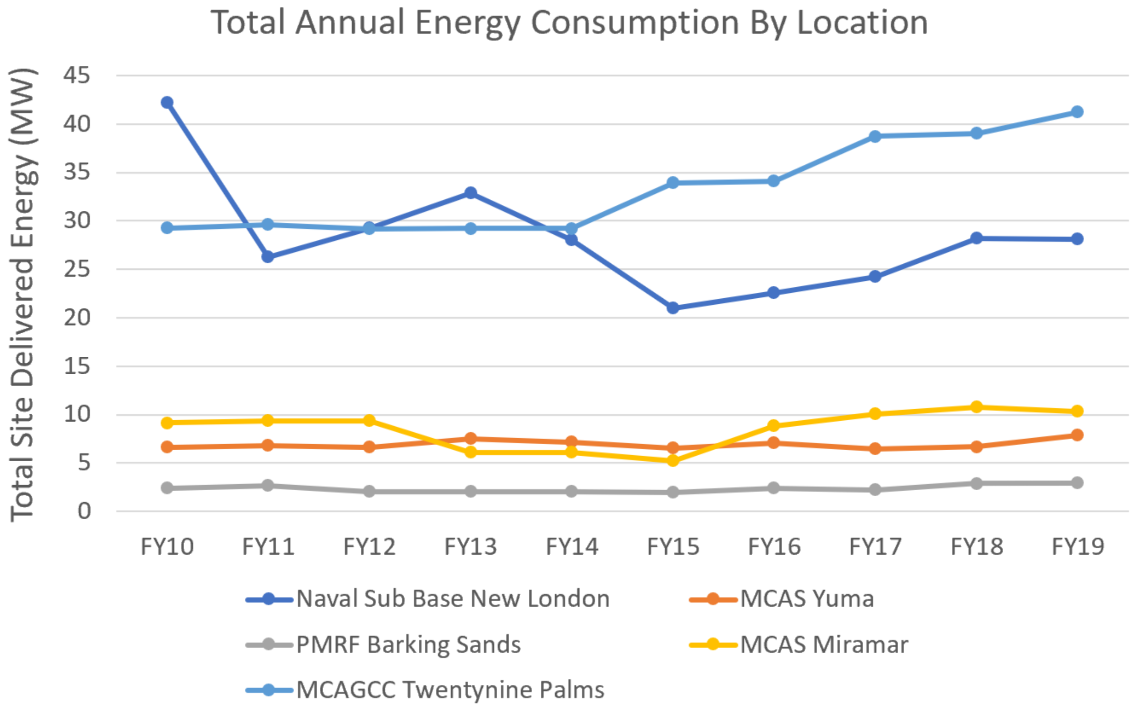

Figure 1.1. Total Annual Energy Consumption by Location. This graph demonstrates that the electrical loads vary each year at the same locations and do not vary at the same rate between locations.

tainer Express (ACX) Crystal [15]. Weather sortie operations occurred to evade hurricane damage at home ports. In September 2019, 2nd Fleet ordered 23 ships and nearly 120 aircraft to depart from Hampton Roads, Virginia, to avoid Hurricane Dorian [16], [17]. In March 2020, military bases in California, Texas and Georgia housed Grand Princess cruise passengers for COVID-19 virus tests and quarantine [18] while the hospital ships United States Naval Ship (USNS) Comfort and USNS Mercy prepared for unexpected operations in southern California and New York to support overtaxed hospitals fighting the virus [19]. The USNS Comfort was in Norfolk, Virginia, at the time undergoing maintenance actions that were required to be expedited in order to support the mission [19]. In July 2020, the USS Bonhomme Richard caught fire on a Sunday and burned for five days straight while alongside the pier in San Diego, resulting in additional firefighting efforts [20]. These unexpected or unplanned events resulted in equipment quickly being powered on and utilized to support deployment efforts, varying from the expected electrical load demanded of the military base's power supply at the time. These are examples of how mission priorities can quickly change local operations and their energy demands. These unplanned operational changes affecting load demand may significantly affect the resilience of the microgrid. If this is coupled with a microgrid and/or utility grid failure, the mission capability to may be degraded.

1.2 Critical Load Identification

Early identification of energy critical load requirements are necessary for system analysis with the use of simulations and modeling, as discussed and proposed by [21]. In order to verify the resilience of the microgrid, the critical load demands should first be considered as a requirement of the microgrid's capability, to mitigate the risk of physical systems built without functionality emphasis [21]. Failure to consider the variable operational energy requirements in support of different missions early in the microgrid design process results in the risk of a system that fails to be resilient in face of different hazards. Therefore, we stress the importance of identifying potential missions a base may be required to undertake to ensure the microgrid is designed to meet those energy performance requirements. The microgrid architecture should then be determined and modeled with the necessary electrical power to supply all critical loads. Microgrid hazards are then analyzed in operational simulations to determine if critical loads may still be met at a given time.

The current methods that are being used estimate the required load necessary to design the installed microgrids for individual U.S. DOD facilities, and their changing mission and energy needs are variable. Some DOD locations are using only islanded microgrid networks, where all energy supply is generated onsite. Other facilities are still connected to the utility power as their primary resource, while only using microgrids as a resilience measure to continue power for critical loads during a network power outage. Some islanded only networks are installed with microgrids capable of excessively supporting the load demand with the hope and assumption that the excessive energy capability will fulfill all future energy requirements. Using oversized microgrids puts less pressure on having accurate critical load estimations but may be more costly to install. Tailoring a microgrid design specifically to each locations' unique variable missions requires more accuracy to ensure the microgrids have low risk of being underrated for a future mission demand.

1.3 Government Resilience Requirements

A microgrid can improve reliability through power supply redundancy to ensure continuous power flows to the mission critical equipment in the face of any power interruption due to natural causes, accidents, or damaging events. Microgrid availability refers to its capability of supplying electrical power at an instant in time or over the specified period considering its reliability, maintainability, and maintenance support [22]. For support of critical systems, the acceptable failure rate of the microgrid power supply ranges between 9.5×10^{-7} and 9.5×10^{-6} [23], which is the equivalent to 30 seconds to 5 minutes of power delivery failure per year of demand. Power outages greater than 5 minutes are considered an energy reliability issue while any power outages less than 5 minutes are considered a momentary interruption [23]. System reliability describes preventing component failures, whereas resilience considers the recovery period in the event of a failure.

1.4 Journal Manuscript

While Chapter 1 provided naval context for this topic, the following chapter is a journal manuscript. This thesis follows the journal manuscript option, which includes a pending publication in Chapter 2 as the main content. Chapter 3 of this thesis includes a conclusion and future work with broader implications for military application.

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CHAPTER 2:
Manuscript Submission

2.1 Defense Installation Energy Resilience for Changing Operational Requirements

A version of this chapter was submitted for review as: Janice Mallery, Douglas L. Van Bossuyt, and Anthony Pollman, “Defense Installation Energy Resilience for Changing Operational Requirements,” Multidisciplinary Digital Publishing Institute’s (MDPI) special issue on Energy Storage for Grid Integration of Renewable Energy, *Energies*.

2.2 Introduction

In the modern technological age, the importance of electrical energy to successfully execute defense and national security missions is ever increasing. Operational units often require electronics equipment to complete their tasks. Lack of readily available power impacts the mission readiness and effectiveness of militaries and other organizations entrusted with defense and national security missions, such as the U.S. DOD. In order to ensure that electrical energy is available for the necessary systems, electricity supplies must be reliable, resilient, and secure. Of particular interest to this research is the resilience of electricity supplies.

10 U.S.C. §101(e)(6) defines energy resilience as "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 essential requirements" [24, (6)]. This research specifically examines energy resilience for national security and defense installations. Resilience for U.S. military installations is defined in 10 U.S.C. §101(e)(8) as "the capability of a military installation to avoid, prepare for, minimize the effect of, adapt to, and recover from extreme weather events...[that] have the potential to adversely affect the military installation" [24, (8)]. While the U.S. law focuses on the weather and the environment, we also include potential hostile human threats that disrupt energy supplies in our understanding of installation resilience.

A number of authors have recently focused on systems engineering approaches to improve energy resilience for national security and defense installations [25]–[28]. However, most exigent work assumes a constant operational environment with predictable loads. While the vast majority of missions a facility may perform can be predicted months or years in advance and operational environments rarely change significantly, this is not always the case. For instance, a facility with a port may conduct nominal operations with ships coming and going at regular intervals and on predictable schedules. However, a battle-damaged ship [29], or a ship that has suffered a significant collision [30] may drastically change the operating environment of the facility due to unplanned mission needs of stabilizing damaged vessels, treating wounded, housing additional personnel due to recovery efforts, and other activities. Such a rapid and unpredictable change in the operational environment of a facility can adversely impact the resilience of electrical energy sources due to insufficient preparation for load demand at the facility.

Many facilities involved with national security and defense have implemented electrical microgrids to improve resilience and reliability of electrical energy. A microgrid is a system of system (SOS) consisting of interconnected loads and distributed energy resources (DERs) within an established electrical boundary specifically designed to operate in either a grid-connected or islanded mode [27]. Generally, microgrids are sized to protect critical loads. Critical loads are defined as those supporting safety, process reliability, and operational requirements [31]. Critical loads for operational requirements are those which require continuous electrical power in the event of disruption [26]. With the use of microgrids, disruptions in electrical power sources are avoided through the use of redundant electrical inputs for anticipated critical loads. This minimizes any negative effect to mission accomplishment following a utility grid and/or microgrid component failure, and allows operational commanders and energy managers time to adapt and recover from the energy disruption. In a scenario such as a ship coming into a port after sustaining significant damage, the critical loads of the facility increase to include both the day-to-day critical loads and the transitory critical loads created by the change in operational environment. Thus, sometimes facility electrical energy resilience can decrease if additional loads are required to be rapidly supported with little warning or time available for proper preparation.

2.2.1 Specific Contribution

This paper contributes a systems engineering method for microgrid resilience analysis that specifically accounts for potential mission operations, their energy requirements, and verifies the microgrid design adequacy for system energy preparedness. A mission engineering perspective is used to ensure changing operational load demands are met, implemented with a modeling and simulation tool for verification of microgrid resilience in the face of damaging events, and with iterative design improvements conducted as necessary. This method enables energy managers to ensure their microgrid systems are prepared to provide electrical power for all potential critical loads for all foreseen mission scenarios.

2.3 Background and Literature Review

This section reviews several areas of background and related work that are necessary to develop the methodology and case study in later sections.

2.3.1 Government Requirements

Each nation or industry may have their own requirements or regulations to meet energy security objectives, which should be considered during analysis. For example, the U.S. DOD requires facilities to collaborate with tenants, mission owners, and operators to ensure power is continuously available for critical operations [32]. Collaboration is important as the facility energy manager may not know the specifics of what each mission entails. Identification of what missions are considered critical may not be readily apparent, furthering the importance of collaboration and discussion with stakeholders as seen in [33]. As required by the U.S. DOD, the priorities for energy supply during periods of electrical failure need to be established based upon critical missions identified at a facility [23]. Specific engineering requirements for the U.S. DOD are published through the United Facilities Criteria (UFC), which details the use of metered load profiles if available or conducting an energy load analysis in accordance with the Institute of Electrical and Electronics Engineers (IEEE) standard 1547.4 otherwise [34]–[36]. Documentation for specific stakeholder requirements should be verified and tailored to the analysis as necessary.

2.3.2 Energy Resilience

A continuous power supply is necessary for missions with operations that depend on electrical systems. While the reliability of the electrical power supply system is important for mission failure minimization, reliability itself is not a sufficient measure with military systems that may be purposely attacked. It is not enough to prevent normal component failure, as the systems need to be resilient in the face of adversity. Common definitions in the literature for resilience include withstanding the hazard, rapidly responding to and recovering from the damage, and adapting the systems for future preparedness [37]. A system's resilience can be determined in a number of ways. A resilient system may reduce failure probabilities, reduce the consequences when a failure occurs, and/or reduce the recovery rate to restore the system to normal operating parameters [38]. A resilient system minimizes the damage that occurs by decreasing its vulnerability to weather and hostile attacks while enabling quick recovery. Figure 2.1 depicts the general definition of resilience and its stages [38].

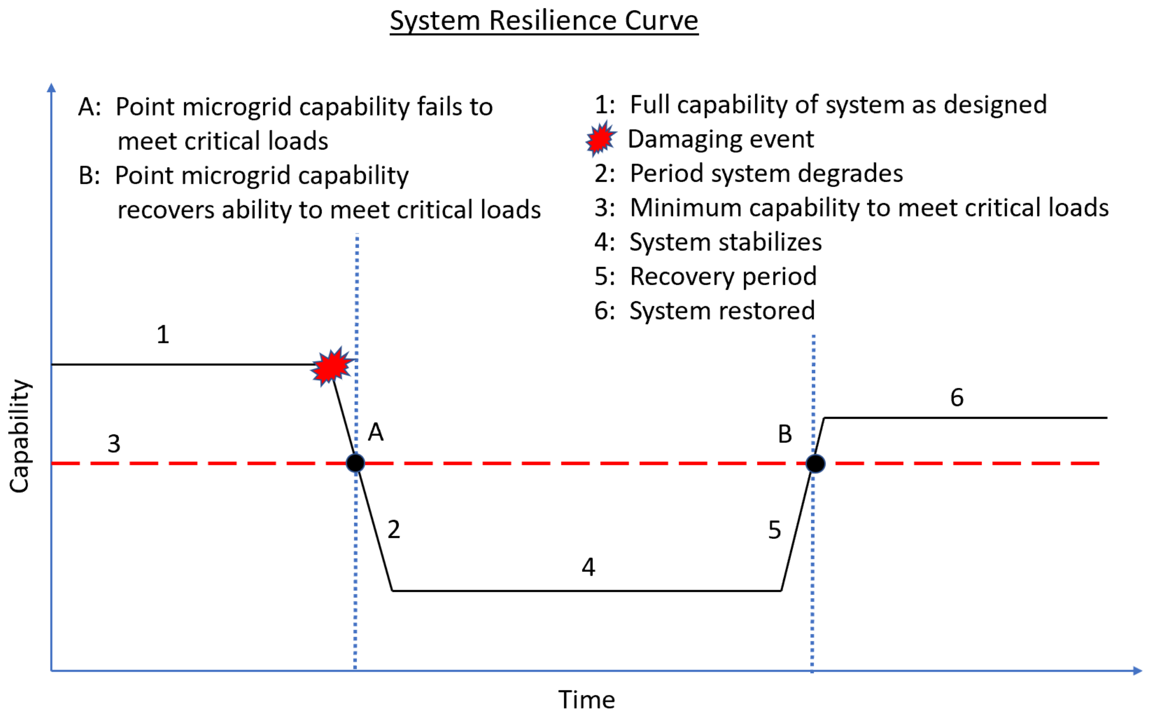

Figure 2.1. System Resilience Curve. This image describes the resilience definition of the system based upon the capability before and after a damaging event as well as the time the system is below the minimum capability to meet critical load demands [38].

The duration of installation resilience requirements vary per U.S. military branch, spanning from a required 7 days of autonomy for the U.S. Navy and up to 14 days of autonomy for the U.S. Army and Marines based upon the mission contingency timelines [26], [33]. For this paper, the resilience of the microgrid will be analyzed and assessed to ensure the total time that the microgrid fails to provide sufficient power (the time between points A and B in Figure 2.1) under specific circumstances to the identified critical systems is less than 5 minutes [23] for the duration of islanded microgrid operations spanning 2 weeks.

2.3.3 Microgrids

Many utility companies build and operate their electrical infrastructure based upon average historical conditions. This can result in any abnormal weather or environmental events or conditions causing service interruptions to the customer [39]. While civilian customers may be unhappy with the inconvenience of power interruptions, the potential consequences of a civilian power outage is relatively low compared to those of defense installation outages. Due to the national security necessity of a resilient electrical power supply on a defense installation, consumer interest, and renewable energy goals, there have been many recent publications demonstrating microgrids as a successful and practical electrical resilience measure [26], [37], [40]–[50].

The Department of Energy (DOE) definition of a microgrid is “a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid” [41]. Other definitions exist, but similarities include the power grid being independent and confined, with the ability to connect to the utility grid. When the microgrid is in islanded mode, the system is not connected to a utility grid and only the DERs and stored energy are used to supply power to the loads [40], [51]. The components of a microgrid include the power generation sources, electrical loads, energy storage, and interfaces [40]. Studies have verified that microgrids, when well designed, increase energy resilience for a local area as an independent source of power when the city grid is interrupted [37], [39], [40], [52]. When a weather-related anomaly or energy disruption to the utility grid occurs, the DOD facility can use a high speed switch to transition from a connected grid mode to the islanded mode with minimal interruptions and mission impact [52], [53], assuming the microgrid itself is not similarly degraded. The system studied in this article is scoped to one microgrid serving one military base while in islanded mode.

The successful implementation of microgrids for military facilities requires cooperation with local utilities [53]; comprehension of the load required for mission-critical functions [10]; and customization of the engineering design to support differing operational requirements, climate, and geography for various locations [33], [54]. Examples of successful microgrid installation for DOD facilities include Naval Base Guam Telecommunications Site (NBGTS) in Finegaya, Guam, and Marine Corps Air and Ground Combat Center (MCAGCC) in Twentynine Palms, CA [10]. Microgrids are accepted as a useful tool and method for increasing a power supply's resilience to support electrical demands in unusual or unexpected circumstances [10], [39], [40], [52].

The current variability of the DOD facilities load estimation per location is demonstrated by comparing the installed microgrid's capacity with the specific facility's energy consumption shown in Table 2.1. It is important to note that the energy consumption listed in the table is historical data that encompasses all types of energy consumption for the specific area in fiscal year (FY) 2019, and is not limited to only critical loads. Table 2.1 only displays historical data over year, which limits the location's representation of energy consumption in variable operational conditions. However, the size comparison in Table 2.1 makes for an interesting observation in scale difference between total energy consumed and the size of the microgrid that was installed. The installed microgrid capacity for Marine Corps Air Station (MCAS) Yuma, which has all of its power generated on-site [55], and Pacific Missile Range Facility (PMRF) Barking Sands, which cooperated with Kauai Island Utility for infrastructure on installation property [53], [56], are examples of overestimation to ensure supportability while Naval Submarine Base New London appears to be equipped to only support the critical loads at a quarter of the total location's historical power usage in FY 2019. The Miramar microgrid was designed to potentially power the entire installation for full facility capability at all times [57], not being constrained to only critical load capability. Miramar and Twentynine Palms are grid connected microgrids [55].

Table 2.1. Example DOD Microgrid Capacity and Facility Historical Energy Usage. This table displays currently installed military microgrids, their generation capacity, and how they compare to the total reported energy consumption at their respective locations. This comparison is limited to only one year's energy consumption data.

Facility	**Microgrid Capacity**	**FY19 Energy Consumption** [10]	**Comparison**
Naval Submarine Base New London	7.4MW fuel cell and microgrid [56], [58]	28.2MW	Approximately a quarter of resilience power generated that is demanded by the entire facility
Marine Corps Air Station (MCAS) Yuma	Ten 2.5MW diesel generators [53]	7.9MW	3.2 times the power generation capable as being demanded
Pacific Missile Range Facility (PMRF) Barking Sands	14MW AC plant including 19.3MW DC solar PV and 70MWh battery storage [53], [56]	2.9MW	6.6 times the power generation capable as being demanded
MCAS Miramar	4MW diesel generator, 3MW natural gas generator, landfill gas and solar photovoltaic power for a total of 11.2MW on-site power generation [10], [55], [57]	10.3MW	Approximately Equal
MCAGCC Twentynine Palms	10MW combined power generation microgrid, [59] two 16MW combined heat and power plants, chilled water plants, 5MW PV [55]	41.4MW	Approximately Equal

There are many ways electrical grid resilience has been measured and defined such as: the total degradation of service after an event; the time spent taking recovery actions; or the rate at which service is recovered [60]. A variety of tools and methods have been developed in the literature to study microgrid or energy resilience [25]–[27], [33], [61]–[64]. The Energy resilience Analysis (ERA) Tool, developed by the Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) [33], assesses energy resilience by focusing on comparison of life-cycle costs due to system availability and reliability to assist decision making of alternative energy designs [33]. In [33], the resilience measures are not quantitative but generalized with a scorecard to grade the reliability, resilience, and efficiency of the energy security and readiness system [33]. Studies that utilize modeling and simulation sometimes include the Mission Dependency Index (MDI) as a ranking scale from 1-100 for mission criticality which is quantified with various approaches [25], [61]–[63]. The MDI is a commonly used risk-based metric that links facilities to the mission [25]–[27], [64]. A method for measuring microgrid resilience with a military focus was defined in [26] and named the expected electrical disruption impact (EEDMI), which used MDI scores to quantify the mission impact of the load to the military base and to national security while considering the probability of a threat scenario occurring and its impact if power is not received. An alternative method called the Operational Risk Failure Modes and Effects Analysis (ORFMEA) was proposed by Kujawski and Miller after arguing that the MDI was oversimplified [61].

Distributed Energy Resources

Microgrids may also incorporate renewable energy resources [37], [65], which may increase resilience by withstanding disruptions due to fuel supply. The 2021 Colonial Pipeline cyberattack crippled fuel deliveries across its 5,500 mile length along the United States east coast and cost the affected company $5 million in ransom to resolve [66]. The literature includes methods for microgrid design to consider resilience as well as capacity, cost, reliability and sustainability with diesel generators, photovoltaic (PV) sources, battery energy storage system (BESS), and an energy management system (EMS) components [28], [67]. Other options for DER exist, but application of wind turbines, hydropower, compressed air caverns and others may not be feasible for all locations [68]. Natural location constraints should be considerations of DER feasibility, but may not necessarily hinder a type of energy technology from being used [33].

Energy Storage Systems

An energy storage system (ESS) is often found as a component in a microgrid [46] and is an effective method for improving energy resilience as a backup energy source to mitigate unexpected power loss or a shortage of energy available to meet the demand [68], [69]. There are multiple types of ESS (e.g., batteries, pumped hydro energy storage, compressed air, flywheels, and fuel cells) with different energy storage capacities, costs, and applications [68]. An ESS enhances power resilience by ensuring electrical equipment will still run in the event that microgrid power generation is lost or lacking, assuming the storage capacity enables usage through the repairs and restoration of the power generator. In the case of extended repairs, an ESS will allow time for operators to properly shut down affected equipment in the event of an unexpected power loss or discover alternative solutions for power supply. Following a power interruption event, the continued operation of critical loads is assured for a specified time interval if using an ESS [70]. An additional benefit of an ESS is the accumulation of excess generated energy during periods of low electrical power demand for use during periods of high demand, which may prevent stress on generators or potential load shedding during high power demand peaks [68]. An ESS is limited based upon potential issues associated with charging/discharging, safety, reliability, size, cost, and life cycle management requirements [71]. However, it has been shown that with PV solar energy and electrochemical storage, it is possible to increase electrical power resilience with better reliability than a backup diesel generator [72].

Load Prioritization

When there is insufficient power supply to meet all load demands, load shed begins to occur [31]. Energy loads have variable levels of importance associated with mission impact. Nonessential loads, those that do not adversely affect mission operations or safety if lost, supported by the power generation system are a low priority for distribution, whereas essential loads cannot be shed without risk to mission accomplishment and/or personnel and equipment safety [73].

Loads need to be prioritized so that nonessential loads are shed first. This will prevent mission critical loads from being shed or interrupted. In [74], load prioritization is discussed as congestion management, which is mitigated with load shedding algorithms to optimize the amount and location of electrical loads shed according to their priorities. However, [74] does not study how the loads are prioritized.

There are multiple methods an energy manager can use to establish load prioritization, but communication and input from all affected organizations is required to identify critical loads [32]. A case study conducted for Fort Bragg resulted in a year-long process to identify the mission-critical facilities, with results falling within four categories: life, health and safety; command and control; deployment; and life support [33].

On a U.S. naval vessel, there are three load shed categories: non-vital, semi-vital, and vital. In the event the ship's electrical system fails to supply all loads demanded upon it, non-vital loads are shed first, and whose loss will not adversely affect the operations of the ship or safety of the crew [73]. Semi-vital loads are considered important to ship operations, but may be dropped to prevent further damage to the ship's electrical system [73]. Vital loads are considered nonsheddable, as they affect the safety of the crew or the ship [73]. While non-vital loads on a ship include laundry and other conveniences, removing power from vital loads may result in personnel death or equipment destruction.

2.3.4 Mission Engineering

Mission engineering is a method of holistically focusing engineering efforts to ensure the overall intended mission a system or SOS performs may be successfully executed. This is different from the traditional engineering practices of ensuring each individual part of the system works while losing focus on the overall project intent. Mission engineering is defined as the application of SOS engineering, with deliberate planning, analyzing, and integrating of operational system capabilities to ensure achievement of desired mission effects [75]–[79]. A mission differs from operations in that a mission is an assigned actionable task with a designated purpose [76], while operations are used to accomplish the missions [75]. Mission engineering identifies new technologies that may be used in system development and acquisition to close identified mission capability gaps [76]. Systems engineering methods, to include customer needs statements, system boundary definitions, iterative processes to realize successful system scenarios, and verification and validation through modeling and simulation [22], may be useful to identify and close energy capability gaps for defense installation.

Mission engineering focuses the system design to ensure successful mission execution, and is achieved by understanding the operational context, the organizational capabilities, and military standards that must be followed [77]. Mission Engineering has been used by National Aeronautics and Space Administration (NASA) for the highest level of assurance of space launch mission achievement, and by government acquisitions processes to ensure individual engineering efforts will satisfy mission support [78]. A method for mission engineering and analysis (MEA) was developed by [75] and a simulated application of mission engineering was conducted by [79]. The simulated application included analytic support tools, where the system of interest (SOI) was the mission and the life cycle spanned from the introduction of the conflict until mission completion [79]. In this application, the weapon systems were the components of the SOI. The mission engineering method proposed by [80] includes a system definition, system model, and system analysis event sequence. Different approaches and uses for mission engineering occur, but all aim to ensure mission achievement with a holistic approach within the defined SOI.

Emergent behaviors may affect a system's ability to support the electrical demands of varied mission scenarios. Trained operational personnel and properly maintained equipment cannot execute their mission functions if they lack the necessary power to support them. Recently in Texas [81], consumers increased their heat during cold weather, while grid operators had to cut the amount of power distributed to prevent a months-long energy crisis. The wind power and coal plants themselves suffered damages due to the extreme cold (causing many to shut down), while consumers were increasing their power demand to heat their homes and businesses during the storm. The power demand from consumers overwhelmed the grid's remaining power generation capacity, resulting in grid operators taking actions that included load shed to prevent cascading physical damage to the grid infrastructure [81].

If a military base's microgrid drops a load, the mission capabilities that load supports will be limited or hindered until the microgrid capability is fully recovered. If a military microgrid has a mission scenario with a critical load that requires a greater power supply than a compromised or damaged microgrid can provide, then microgrid energy resilience is considered insufficient. This may result in critical loads being shed, loss of power throughout part or all of the facility, and potentially an overall failed or compromised mission scenario that the microgrid is required to support. Due to the more dangerous nature of missions in the defense industry, the outcome a of failed or compromised mission within a military base may potentially range from loss of monetary value to loss of human life. With DER in a microgrid, parallel reliability networks may exist to ensure vital equipment continues to receive power supplies, even in the event of individual component failures or damage [22]. In the event of a destructive scenario, the microgrid system needs to minimize its vulnerability to cascading damage events while increasing the system recoverability to provide adequate power for mission needs of the military base [82].

2.3.5 Related Research

This section reviews research of direct relevance to the work presented in this article: military microgrid resilience. The most salient work for military microgrids includes a variety of recent publications [26]–[28], [50], [62], [63], [83]–[85]. A method was recently developed to improve military base electrical resilience by introducing nanogrids (microgrids that support individual loads with one or more DER and an ESS) [25]. Systems architecture design and validation methods for microgrids was studied in [85], where a model was used to determine the resilience of a military facility's microgrid. The model determines the power flow within the microgrid according to the input load demand, what the microgrid is generating, and the battery discharge and charge rate while recording the demands not met and loads shed [26]. In the model, the loads are stochastic and time-dependent, spanning two weeks with hourly data, with the DER generation capability and ESS capacity input variables. A Monte Carlo simulation allows random time-dependent failures of microgrid components or the user may tailor specific failure scenarios. This model is used in further analysis for estimation of microgrid resilience life cycle cost, improved resilience energy storage methods, islanded grid renewable energy applications, and nanogrid resilience applications [25], [26], [62], [63], [84]. One study conducted analyses about the costs incurred by disruptions in energy supply and considered the trade space between the microgrid's resilience and cost [50]. Energy security for naval facilities is studied with renewable DERs and ESSs with a power-sizing design tool [83]. Military base microgrid resilience and mission impact is analyzed for accomplishment of mission objectives while operating two-weeks in the islanded mode [26]. Peterson et. al. defined the mission and associated loads using the existing MDI method and assumed that the mission impact is constant throughout a two-week grid outage. This usage of MDI fails to consider that different operational environments and missions may change a load's level of importance to national defense and its mission impact during islanded mode. We have found no literature that determines how a facility accounts for changing operational requirements based on different potential missions from an energy resilience perspective.

There have been many publications focusing on DOD energy strategy that mostly focus on minimizing energy use and cost while recognizing the necessity of energy security. Existing literature generally does not discuss how to define sufficient energy in order to meet operational needs. One paper discusses how DOD energy policy and research is organized into categories: energy research for reducing demand, expanding energy supplies, and building energy policy into the future force without a central mechanism to support strategic goals [86]. Hartranft focuses on U.S. Army installation energy security, and recognizes that there is a diverse range of missions with scalable energy requirements [87]. Without defining how to account for variable missions, Hartranft supports microgrid architectures that allow a mission commander to make changes in prioritization of facility loads to receive power as missions evolve through software and remote controls [87]. However, existing research does not include how the operational situation and different missions affect a DOD facility's energy requirements. Thus, a gap exists in the literature in understanding how unpredictable and rapidly changing missions a defense facility may perform can impact energy resilience.

2.4 Methodology

In this section, a novel method to analyze the potential different mission scenarios a base may be part of for load prediction is proposed. The method may be used for other applications of variable operational load analysis, but the process is designed specifically for military use. The critical loads for each military base need to be identified to conduct an energy resilience analysis for each location. This method can be used for either islanded or grid-connected microgrid assessments. The flow diagram for the methodology is shown in Figure 2.2. The methodology is iterative, studying the various mission scenario load requirements and the hazards the microgrid faces to ensure all critical loads are met. If the critical loads are not met, the microgrid design should be improved or altered until the microgrid is determined to be sufficiently resilient.

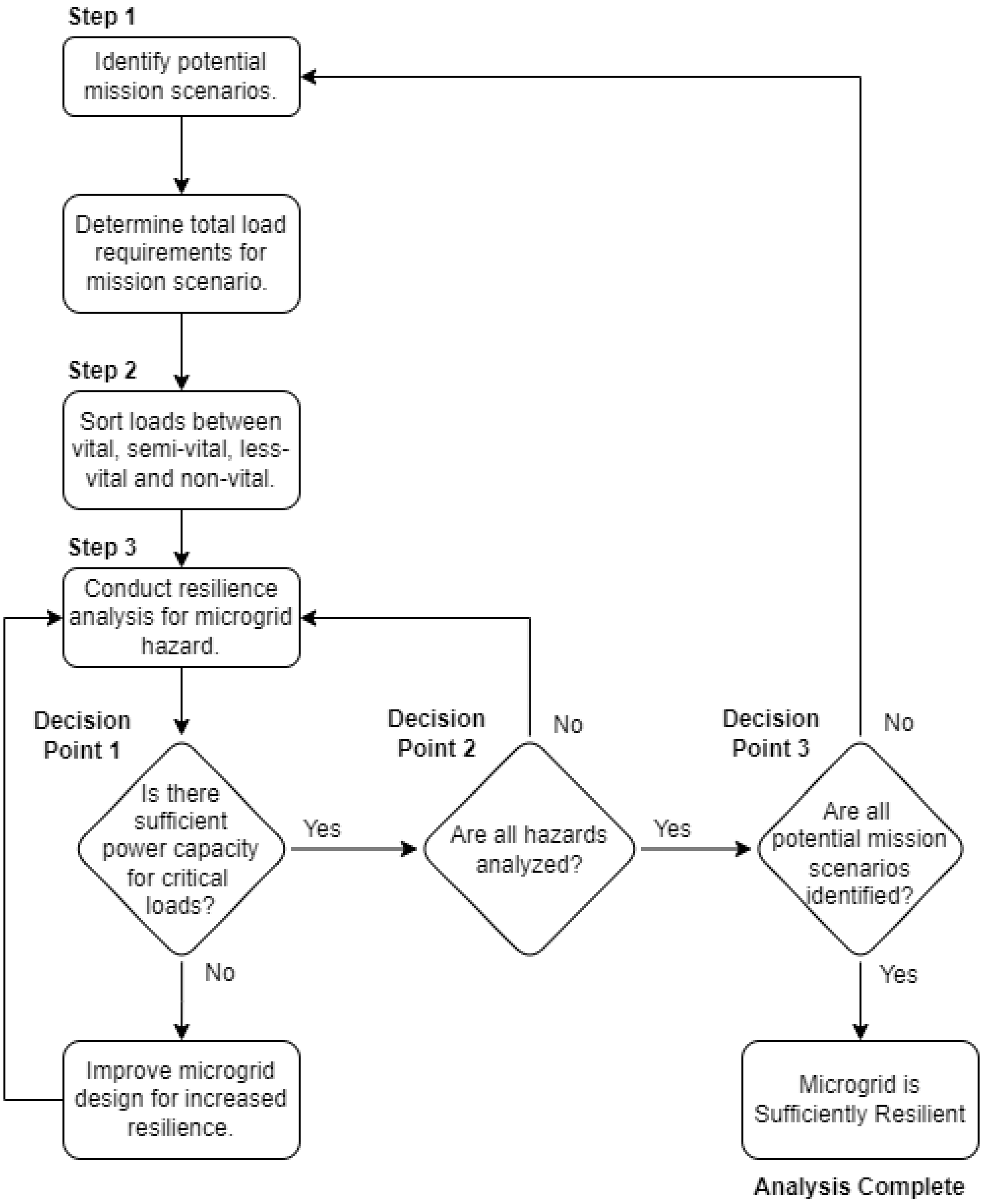

Figure 2.2. Methodology for Microgrid Resilience Load Planning and Verification. This flow chart may be followed by energy managers to ensure the designed or installed microgrid satisfies resilience requirements by identifying and modeling failure scenarios for all potential mission scenarios and their critical load supply needs.

2.4.1 Step 1: Identify Potential Different Mission Scenarios

To determine potential different mission scenarios that a military base will be responsible for providing electrical supplies, first all permanent fixtures on the military base need to be accounted for. In this paper, permanent fixtures are defined as those structures that do not easily move without major construction occurring. This includes, but is not limited to, the buildings and infrastructure that are held in place with concrete. The energy demanded from permanent fixtures is the least changing variable, as any changes to these facilities involve planned construction over a given period. Next, the support infrastructure for deployable forces needs to be accounted for. The energy demand by deployable forces will be variable depending on if the assets are located at the military base or deployed away from the energy system boundary. This electrical demand will be moderately variable depending on the capacity of the military base to host guest deployable forces (those that do not claim the location as their home port) and their required support. Deployable assets include equipment and personnel assigned aboard craft such as ships, aircraft, submarines, and vehicles that may require shore power services or maintenance support. Finally, the most changing variable that needs to be accounted for is personnel support. This will include the number of personnel on the base and the services requiring energy to support and provide for them. This may include, but not be limited to: medical support, food support, housing and hotel services, gym equipment operation, entertainment demands, personal transportation, and security demands. With an increased number of personnel present on the military base, there will be an increased number of energy demands.

If there are new equipment acquisitions or equipment updates affecting the predicted energy demand on the military base, then the energy resilience analysis will need to be conducted as part of the acquisition process to ensure the new expected electrical load demand can be met. Large equipment updates and acquisitions are a slow process that will allow for energy planning prior to the installation of the equipment. For example, when the Navy Freedom and Independent Class Littoral Combat Ships (LCS) were being built, the training support infrastructure needed to be developed and installed on the military bases that host those ships as their home port [88]. The ship operating simulators include large pieces of electronic equipment with an energy demand, and an energy resilience analysis needed to be conducted to verify the existing energy system and resilience methods can supply them.

The method we propose for accounting for all of the potential mission scenarios that a base may be a part of, and their load demands, is depicted in Figures 2.3 and 2.4, respectively. The method first considers mission scenarios that the baseline facility, such as the base command, within the microgrid system boundary is capable of supporting. Next, each additional facility that is supported within the microgrid system boundary is considered. On a military base, tenant commands have their own operational capabilities whose equipment draws power from the microgrid. The last mission consideration includes deployable assets. A military base deployable asset may include aircraft, ships, or submarines. Once the baseline facility, the additional facilities, and deployable facilities are accounted for, the mission scenarios may be generated from the combinations of operations being conducted by each unit. Following this, the potential loads need to be determined are shown in Figure 2.4 by considering all the possible building infrastructure, deployable equipment assets, and the personnel assigned to work within and upon these assets. The potential missions that may be accomplished within the system boundary account for what the infrastructure is capable of supporting. Once the list of required data is gathered, the loads are to be estimated using historical data usage values. If historical data is unavailable, then the load estimation analysis is conducted using similar facility historical data or technical specification calculations for unique equipment. Following the total load identification, the loads must then be sorted based upon their priority.

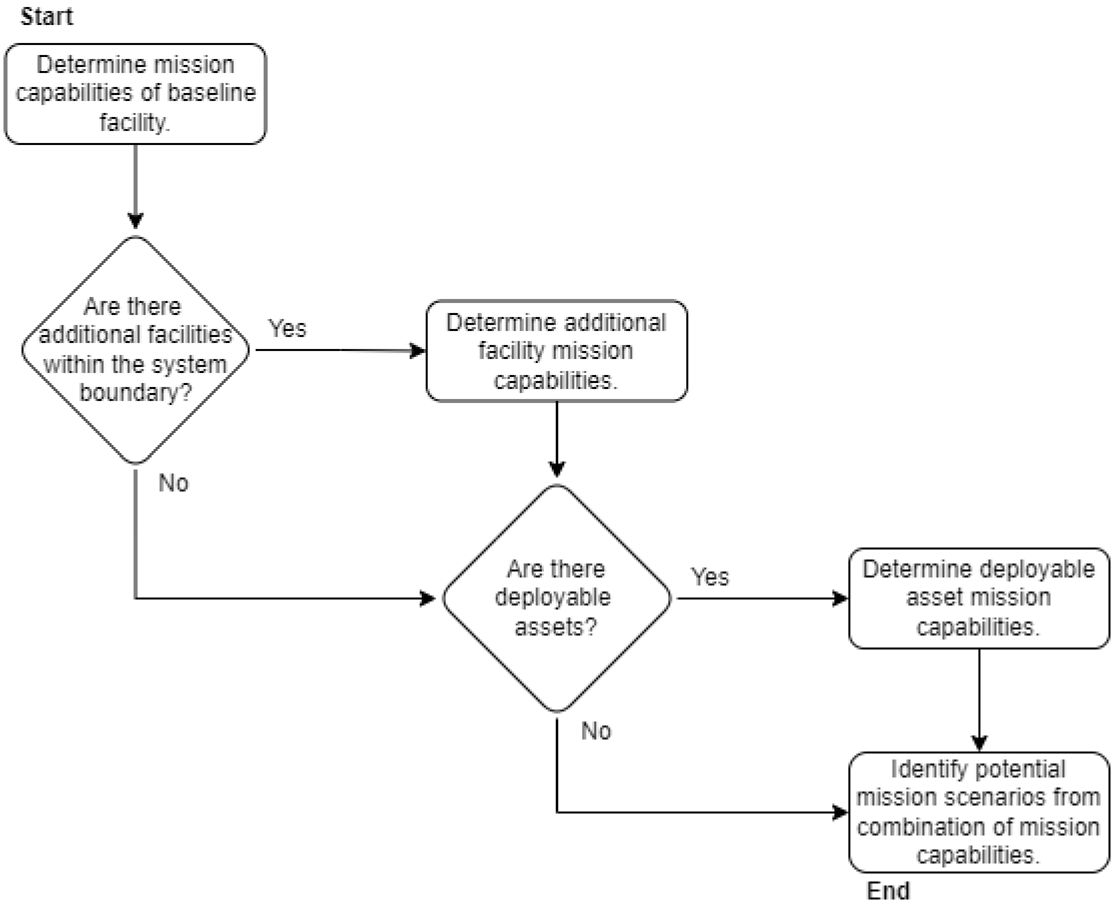

Figure 2.3. Identify Potential Capabilities. This flow chart adds detail to the first action in Step 1 of the methodology to ensure that all missions that the microgrid supplies are considered during the load analysis.

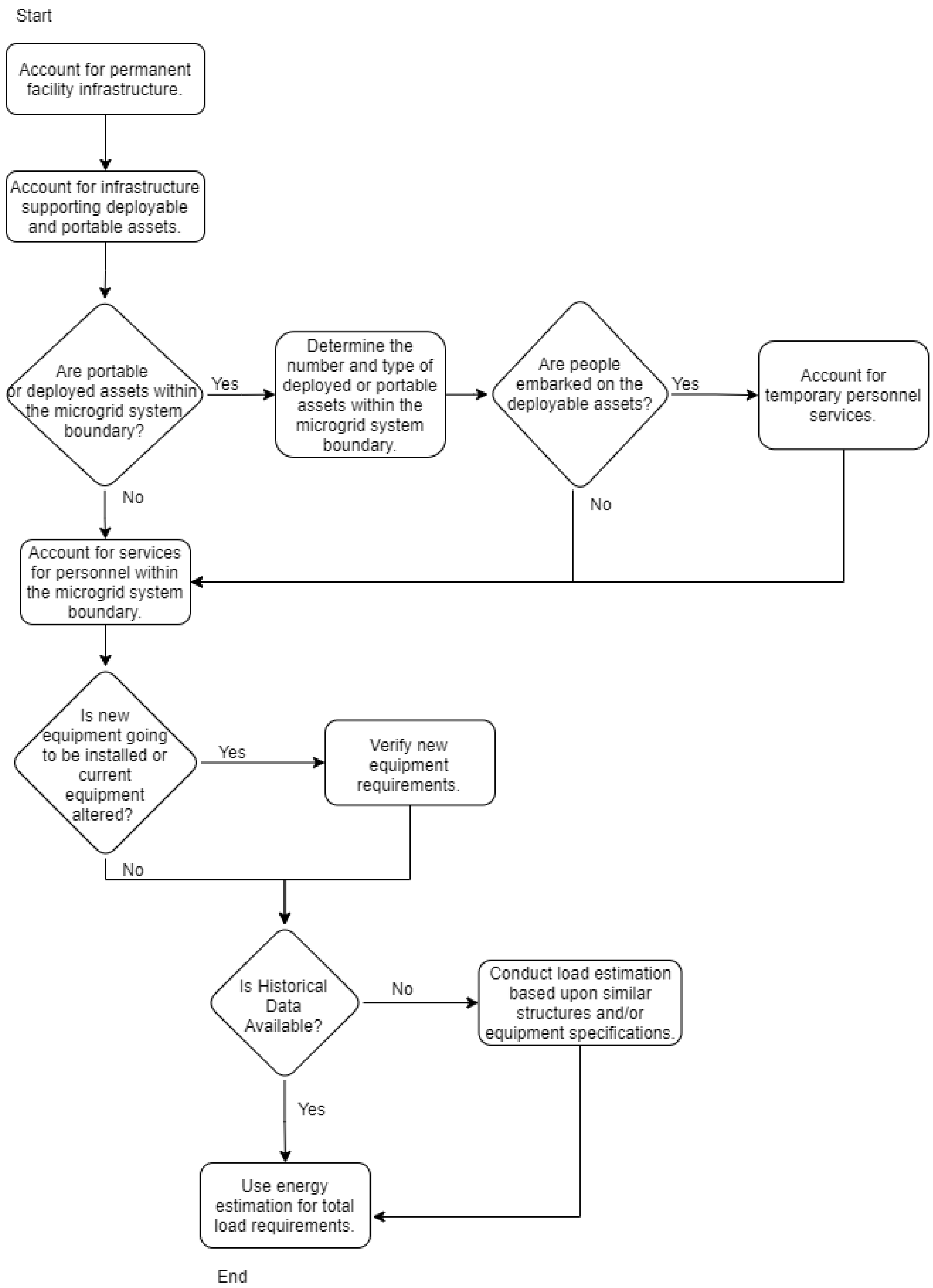

Figure 2.4. Determine Potential Load Demand. This flow chart adds detail to the second action in Step 1 of the methodology to ensure that the load demands of all equipment supplied within the electrical boundary are considered.

2.4.2 Step 2: Determine Critical Loads Within the Mission Scenarios

The determination of critical loads is subjective, as defined in the regulations and requirements discussed in Section 2.3.1. Our recommendation for the determination of critical loads on the military base is shown in Figure 2.5, which follows the findings in [33] as discussed in Section 2.3.3. Our electrical power demand prioritization for mission critical assessment includes four priority levels, which have been adapted and modified from the three levels of the naval vessel load shedding criteria [73] discussed in Section 2.3.3. As listed below, these loads are sorted to conduct load adjudication and prioritization when the electrical supplies fail to meet all electrical demands [23]. The times indicated within each prioritization level definition are estimated based upon the necessary response times to immediate threats to protect the military base, the necessary amount of time to launch the deployable assets, and the initial repair times. The timeline intent for equipment use and load prioritization is estimated upon the needed usage immediacy for mission actions following a microgrid casualty. These timelines should be tailored as necessary to meet the intent of each prioritization level for a specific location, and are only supplied here as a reference baseline. Example missions for each priority level are shown in Figure 2.5 where the first mission priority (vital equipment) is the immediate defense of people and equipment necessary for national security. The last priority (non-vital equipment) are morale, welfare, and recreation (MWR) type missions with potentially longer acceptable recovery periods. These mission type priorities are examples, and should be tailored for each military base depending on operational stakeholder input. Once the loads have been grouped, our recommendation for critical loads used for microgrid resilience analysis include all loads in the vital, semi-vital, and less-vital priority categories with power supply adjudication following the priority indications in the event critical loads must be shed.

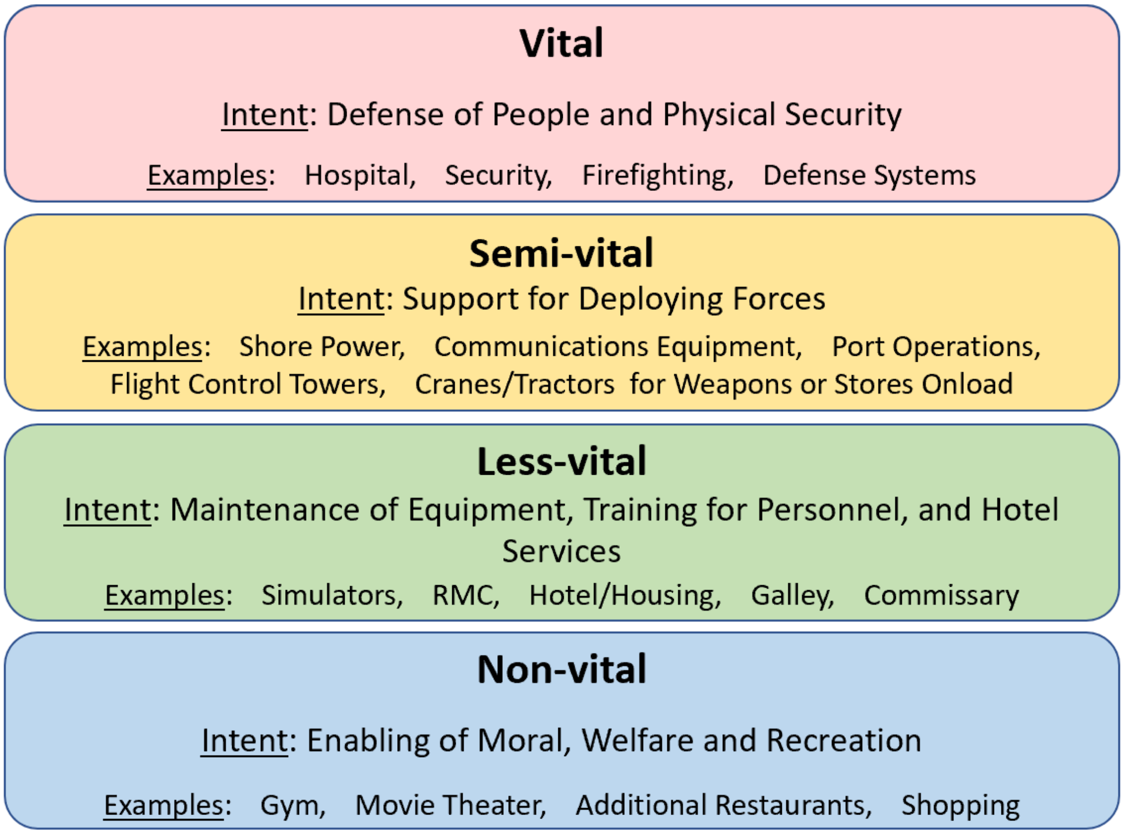

Figure 2.5. Recommended Mission Priorities for Critical Load Determination. This figure is created to visually demonstrate what loads are considered vital, semi-vital, less-vital, and non-vital.

1. Vital: Does this equipment affect the immediate defense and security of the installation against attack? If power is lost to this equipment for an extended period, could lives be lost or equipment important to national defense be destroyed? Examples include defense weapon systems, countermeasure systems, threat warning systems, medical operating rooms, security systems, and firefighting facilities. The timeline for the necessity of this equipment is measured in minutes to hours for immediate defense and life-saving.
2. Semi-vital: Is this equipment necessary for mission accomplishment? Does this mission immediately affect national security? The timeline for the necessity of this equipment is measured within 6–72 hours of immediate use. Examples include communications equipment, computer processing, cranes, aircraft tractors, equipment

elevators and hanger bay doors. This equipment is used to coordinate, launch, and deploy assets.

3. Less-vital: Is this equipment necessary for longer term recovery operations? Is this equipment necessary for long-term mission accomplishment? The timeline for this equipment is measured between days and weeks. Examples include the galley, sewer, water purification facilities, maintenance facilities, training facilities, and hotel services.
4. Non-vital: This includes all other electrical demand equipment that does not affect mission operations and the safety of equipment or personnel. The timeline for the necessity of this equipment is measured in months or longer. Examples include, but are not limited to laundry, scullery, gym equipment, entertainment equipment, and frivolous kitchen machines (vending machines, ice cream, popcorn, coffee, food court restaurants, etc.).

Depending on a hazard's predicted risk, actions may be taken to remove high value deployable assets from a threat scenario. Each asset will have a different timeline necessary to complete steps for safe deployment. These types of actions may occur as a result of events such as weather Sortie conditions [89] or changes in the Force Protection Conditions (FPCON). While ships are in port and conducting maintenance availabilities, they report to staff commands the time required to remove scaffolding and take other actions to deploy the craft. This information may be used to tailor the timeline estimations for equipment usage immediacy per location. The time required to launch naval aviation craft are often established through current Alert Postures, the requirements of which are established through *Naval Air Training and Operating Procedures Standardization Program* (NATOPS) manuals and local squadron Standard Operating Procedures (SOP) [90]. Ships will have underway checklists, with preparatory steps completed depending on the immediacy of the deployment [91]. Base energy managers should contact local commands to determine the specific timeline necessary to conduct procedures for emergency deployment.

2.4.3 Step 3: Conduct Resilience Analysis

The system operates per designed operating specifications prior to a damaging event. Following a damaging event, a period of system degradation occurs, which may or may not fall below the minimum system capability to meet the critical load demands. If the system degrades to a capability that meets or surpasses the necessary value for critical loads, then the nonessential loads may be dropped with little to no critical mission effect using load shed procedures. In this case, the critical missions may continue uninterrupted while full system capability recovery efforts are conducted. This is the ideal situation, but the greater risk occurs when the microgrid capability falls below what is necessary for critical loads. If the microgrid can no longer supply all critical load demands, load shed procedures begin negatively impacting critical mission execution. To minimize or prevent the mission degradation consequences, early consideration for the priorities of critical loads must occur. After initial response efforts to the microgrid hazard are completed, the microgrid will stabilize to prevent further loss of capability. Recovery efforts must then be made to return the microgrid to full specification capability.

Once the potential mission scenario energy demands are identified in Step 1, they are then prioritized in Step 2. To ensure that the military base has sufficient energy resilience, an analysis is conducted to verify that the installed or designed microgrid is resilient enough to provide power to the critical equipment as identified. To conduct this analysis, hazard and threat assumptions are made. This method does not focus upon the probability of the hazard occurring, but rather analyzes the resilience of the microgrid in the scenario that they occur. The energy manager can analyze the mission scenarios, the critical loads within their mission scenarios, and the supportability of their microgrid to meet energy demands throughout each specific hazard and threat scenario. The threat scenarios may be tailored as required to those possible threats anticipated by each individual location. The scenarios that are included in this methodology may serve as a baseline for consideration, as applicable to each facility.

Our analysis includes microgrid faults due to weather phenomenon, equipment component failure, and loss of fuel supply. Weather and environmental phenomenon such as fires, hurricanes, flooding, earthquakes, extreme hot and/or cold weather, can result in increase of electrical demand by users as well as component failure or degradation due to operating outside of the intended component specifications. Component failure in the microgrid may occur due to normal part reliability failure, accidental mishaps (e.g., plane crash, ship collision, or car crash), or malicious physical attacks (e.g., terrorist, active shooter, or insider threat equipment sabotage). If the fuel supply is interrupted, the microgrid may have to continue operations until the utility grid supply returns or additional fuel resources are found and delivered.

Once the failure scenarios are determined, the designed or installed microgrid should be modeled to assess its resilience in the face of each identified damaging event. In this article, we use the microgrid power flow model established in [26], tailoring the inputs with the appropriate energy load demands determined in Steps 1 and 2.

Following the requirement from the U.S. government stakeholder for the DOD microgrid to meet mission critical load demands, we measure the resilience of a military base's microgrid through its performance to meet or exceed the critical load capability requirement following a damaging event. After a damaging event occurs, the continued performance of the microgrid to meet or exceed mission critical loads demands should be maximized to minimize the impact to mission performance. In Figure 2.1, line four should remain above line three, and intersection points A and B never occur. As such, the time period during which the microgrid capability falls below its necessary value to support all critical loads is minimized.

Decision Point 1

Each failure scenario should be individually assessed to ensure the identified critical loads are not dropped for greater than the requirements allow. If there is sufficient power capacity for all critical loads, then the next identified hazard is assessed.

If a failure scenario indicates a critical load was dropped for greater than electrical resilient requirements allow, then the microgrid should be improved and reassessed for the same hazard. Once the improved microgrid has demonstrated sufficient power capacity for critical loads during the failure scenario, then the analysis continues with the following hazard.

Decision Point 2

Each hazard must be independently assessed until the microgrid design satisfies resilience requirements for the operational scenario for all identified hazards. Once the microgrid design has demonstrated its capability to supply critical loads for all hazards, the process continues for the varied mission scenarios.

Decision Point 3

In Step 1, there are different combinations of mission scenarios identified. Once the hazards are assessed for one combination of mission scenarios, further mission scenario combinations with high electrical demands should be tested. Once the operational scenario combination with maximum electrical demands has demonstrated no load shed for critical electrical loads for all identified hazards, the system has demonstrated it is sufficiently resilient.

2.5 Case Study

For this case study, a fictitious military base and microgrid have been developed to demonstrate the application of determining the mission capabilities a military base may have. The fictitious military base components are displayed in Figure 2.6, and include a pier, fire station, medical clinic, movie theater, fast food restaurant, gym, hotel, galley, five office buildings, and one large housing building. In this example application, the permanent fixtures include the buildings and the pier itself. The deployable forces include any vessels that are moored to the pier, with the energy demand fluctuating based upon the number of ships connected to shore power. To account for the potential deployable forces, the possible number of ships that can connect via shore power should be considered. This number may be larger than only considering the number of ships who call this base home port, and is limited by the length of the pier, the width of safe water along the pier (for nested vessels), and the number of shore power interfaces on the pier. The personnel support can be accounted for by inquiring into the number of personnel billets allowed to each command located on the base, the number of racks available on the possible ships, and the number of hotel beds. The barracks housing is not added to the personnel total, because they are accounted for via the command billets and ship racks. While this method of counting personnel is not perfect due to visitors potentially staying out in town and commuting or ships nesting together along the pier increase possible capacity, it should be a close estimation of the energy demanded from personnel through hotel services on the base.

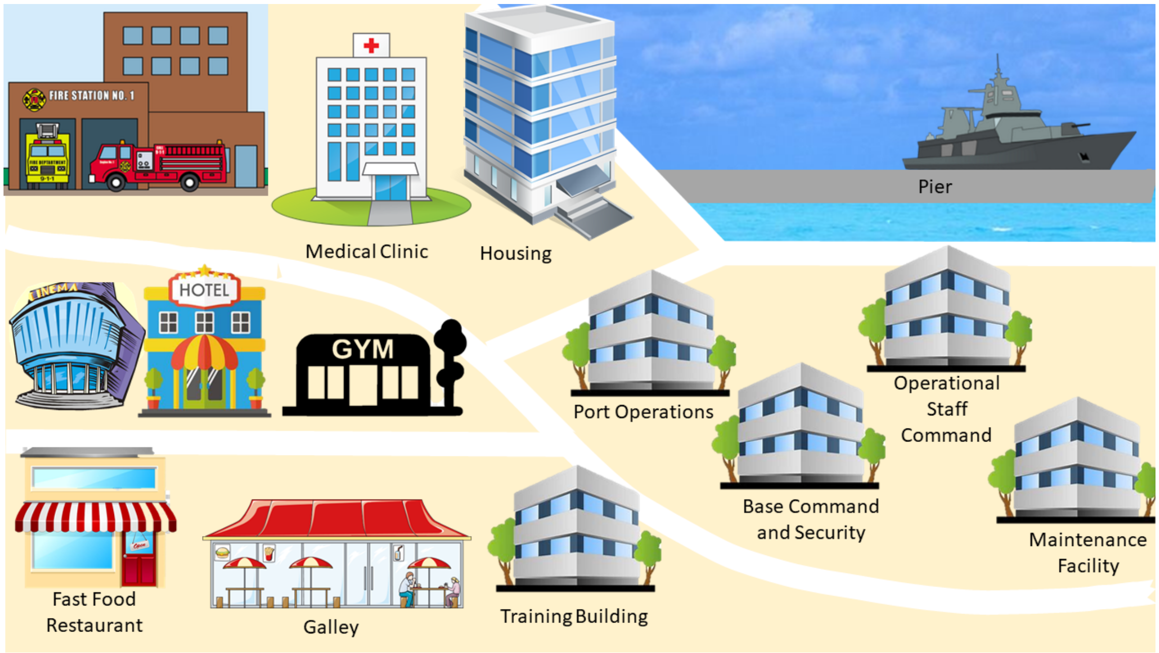

Figure 2.6. Fictitious Military Base Map. This image is used to demonstrate the possible mission combinations that may be determined.

The initial composition of the fictitious microgrid includes a utility grid connection, four diesel generators with 2.5MW capacity each, and a 90,000 gallon fuel storage supply split between the generators shown in Figure 2.7. This is an example of an installed microgrid with a power capacity chosen to meet historical load demands of the location, with realistic generators values as seen in Table 2.1. The fuel storage size was determined by fuel consumption over seven days, with refueling conducted to support the following seven days electrical generation. A resilience analysis of potential threats is then conducted using the identified mission capabilities of the location and the capability of the current microgrid composition. Following the discovery of critical loads being shed, iterative improvements of the microgrid are made with the addition of PV arrays and BESSs. Ideally, an assessment should be conducted for any location prior to microgrid installation, with early resilience and operational load demand analysis conducted to prevent additional time and costs spent building microgrid improvements. Rightsizing of the microgrid first occurs, with optimization as necessary for balancing energy supply components.

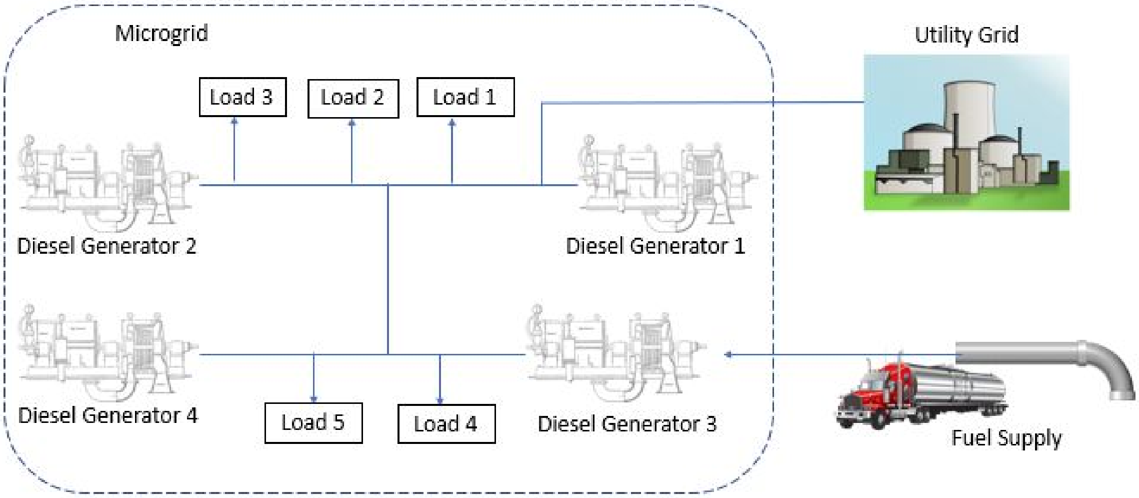

Figure 2.7. Initial Microgrid Composition. An initial microgrid design is developed based upon realistically installed equipment and initial energy load estimations.

2.5.1 Application of Step 1: Identify Potential Mission Scenarios

Following the flow chart in Figure 2.3, the mission capabilities are first identified for the base command. The military base command's mission is administrative in nature, and therefore their capabilities include mostly communication. The additional facilities for this base include the medical clinic, fire station, barracks housing, port operations, operational staff commands, maintenance facilities, training command, galley, and MWR services. The deployable assets include the ships on the pier. The mission capabilities for each identified operational stakeholder are listed in Table 2.2. Potential mission scenarios the military base may be required to support include any combination of the identified capabilities. Different operational stakeholders may have different mission priorities that coincide with one another. For instance, one ship may be undergoing maintenance, another ship may be conducting simulator training, while a third ship may be conducting regular underway movements for sea trial testing prior to deployment.

Table 2.2. Assumed Capabilities of Fictitious Base. The identified commands represent operational stakeholders with differing mission priorities. The mission capabilities are the possible missions for each stakeholder that the microgrid supplies.

Command	**Mission Capabilities**
Base Command	Administration and Communications
Fire Station	Emergency Response
Medical Clinic	Routine Healthcare and Emergency Response
Barracks Housing	Hotel Services
Movie Theater	Entertainment (MWR)
Hotel	Hotel Services
Gymnasium	Exercise (MWR)
Fast Food Restaurant	Food Options (MWR)
Galley	Provide Basic Sustenance
Training Command	Fleet Readiness: Inspections, and Classroom Training
Port Operations	Pilot, Tug, Security Operations
Security	Emergency Response, Gate Security
Operational Staff Command	Administration and Communications
Maintenance Facility	Equipment Maintenance, Overhaul, Scaffolding, Crane Operations
Ships	Pier Work, Sea and Anchor Detail, Crane Operations (on/off load), Refueling, Training, Maintenance, Deployment

Once the potential capabilities of the base have been identified, it becomes necessary to determine the total load requirements for each mission scenario. A list should be made for all of the energy demands upon the microgrid, following the steps outlined in Figure 2.4.

For an active military base, historical data may be used for analysis from the actual data usage reports of the facilities located on the base for each mission scenario. It is important to gather historical data that is represented of the mission scenario, no just general facility use. If this information is unavailable, estimated values from usage hours and specifications may be compared with historical data of similar structures. This case study utilizes the later option, following Figure 2.4 with no plan for new equipment installation.

The historical load data for each mission is approximated using similar structures from the DOE commercial reference buildings model [92]. To simulate high personnel capacity at the location, the largest consumption of electricity over a two-week period is used to account for load demand for each applicable building type. This is a risk decision to prevent underestimating the potential load, and therefore losing validity to the resilience analysis. While the deployed forces are out to sea and not connected to the grid, the minimal personnel usage is estimated with the smallest two week electrical consumption for each applicable structure type, and is used for operational electrical load demand variability comparison. For load demands not available in the DOE model, publicly disclosed point values are used to either generate an approximation of historical usage or apply specifications to hourly usage as required [93]–[95].

Mission Scenarios

For this case study, the first mission scenario for operations focuses solely on the missions of the permanent infrastructure, including the baseline and additional facilities within the electrical boundary, but no deployed forces or temporary support. This mission scenario occurs while all ships are deployed. The combination of potential mission scenarios are then analyzed for the highest electrical demand mission which includes the addition of the deployed assets within the electrical boundary. The location analyzed has a pier, with three vessels expected pier side in various operational phases: one ship conducting training, one ship conducting scheduled maintenance, and one ship conducting short underway movements in preparation for deployment. Unexpectedly, a fourth ship returns to port following a severe mishap on a Sunday and must undergo unplanned corrective maintenance. Hospital operations, galley output, and lodging are all increased to maximum capacity due to additional ships and supporting personnel at the location. All ships are connected to shore power. This section includes operational critical load graphs for the two different operational scenarios identified, shown in Figure 2.8.

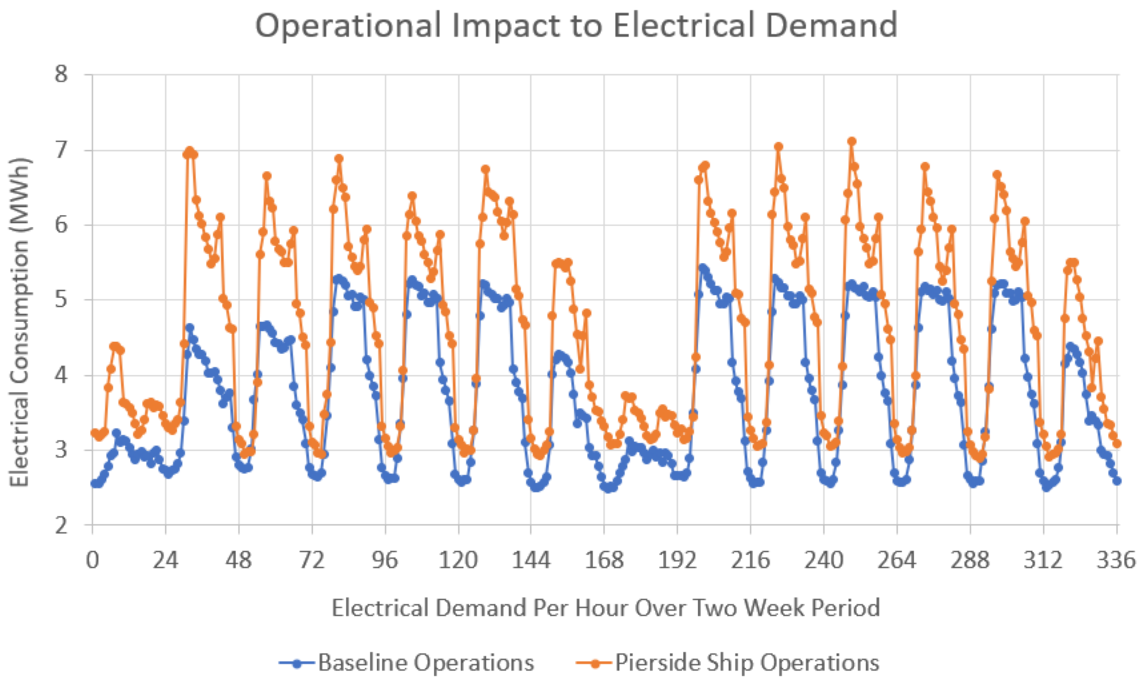

Figure 2.8. Identified Potential Mission Scenarios and Their Critical Load Demands. This graph shows the effect that the considered operational mission scenario has on the microgrid functional requirement to meet critical load demands within the system boundary. To ensure successful mission execution, higher operational mission load combinations must be verified to satisfy resilience standards.

2.5.2 Application of Step 2: Determine Critical Loads Within the Mission Scenarios

Once all of the potential mission loads have been identified, they must be sorted between vital, semi-vital, less-vital, and non-vital. This will ensure that the highest priority of loads are continuously fed electrical power, and the following loads have power within their necessitated time frame. The vital, semi-vital, and less-vital loads are all considered critical. Non-vital loads are not connected to the microgrid, and therefore shed in the event of failures resulting in the loss of the utility electrical grid. The critical loads are sorted to ensure equipment with the same priority level are connected to the same electrical panels, and therefore shed in the appropriate order according to mission time need. In this case study, prioritization loads have been identified consistently with Figure 2.5, and connected to electrical panels, as shown in Table 2.3. The electrical demands of the critical loads over the two week operating period are shown in Figure 2.8.

Table 2.3. Organization of Critical Loads within Microgrid System by Priority Level. This table shows how the identified critical loads are organized in the model to ensure any required load shed occurs in order of determined priority.

Load 1	**Load 2**	**Load 3**	**Load 4**	**Load 5**
Fire Station Medical Clinic	Pier Port Operations	Maintenance Training	Base Command Staff	Galley Housing Hotel

2.5.3 Application of Step 3: Conduct Resilience Analysis

In this case study, a resilience analysis was conducted using the microgrid power flow model established in [26]. The load demand input was identified in Step 1 for two mission scenarios, and sorted into electrical load shed priorities in Step 2. Since the input loads are not random and the failures are individually assessed, only a single run of the model is necessary to verify critical load power supplies. The failures are tailored as a worst-case scenario, as a system with verified resilience in low probability but high damage situations is more reliable for continuous critical electrical supplies in a wider spectrum of unanticipated situations. The worst-case scenario acts as a safety buffer to ensure other scenarios have sufficient energy supply to ensure mission success.

Often, worst-case scenarios occur during periods of anticipated low electrical demands such as on a Sunday. An unexpected increase in load demand during a normal low period may stress the electrical grid. Normal periods of complacency should be tested to ensure maximum readiness.

The model is first run without failures or damaging events, to verify the designed microgrid system meets predicted critical loads in both operational scenarios. As all analyzed loads connected to the microgrid are considered critical, and the model resolution is limited to hourly data, a satisfactory resilient system will have no loads shed for the duration of two weeks analysis.

The specific failures considered for this case study include component failure, excessive heat weather, and loss of fuel supply. A component failure scenario is tested to represent malicious physical attack, accidental incident, or reliability failure simulated with a loss of one diesel generator. In the excessive heat, there is potential for failures due to overheating generators and PV efficiency degradation. The weather failure scenario was tested for a loss of one diesel generator and PV efficiency to decrease by four percent. In the event that the fuel supply chain is interrupted, the microgrid continues to operate with the fuel currently stored available until the fuel supply is exhausted. With no available fuel, the resupply after seven days is interrupted and the microgrid continues to operate using other forms of installed DER and BESS.

Decision Point 1

While the initial microgrid system was sufficient to meet critical energy demands for both operational scenarios, it failed to meet all critical loads when failures were modeled. Therefore, iterative changes were made to improve the microgrid until no critical loads were shed in the model for the current analyzed failure.

Decision Point 2

Each of the three identified hazards was independently assessed against the most recent microgrid design in the first operational scenario being tested. If the microgrid was improved in the previous hazard, the improved design was tested against the new hazard within the operational scenario, until the microgrid demonstrated sufficient resilience for all hazards within the operational scenario.

Decision Point 3

After the first operational scenario is demonstrated supported with a resilient microgrid in all three identified hazards, the second operational scenario was analyzed and verified with the most recent improved microgrid design. The second operational scenario had different critical load inputs for the model as determined in Steps 1 and 2 previously, but was analyzed with the same failures. Following the verification that the final microgrid design satisfied resilience requirements for all three hazards in both operational scenarios, then the microgrid design may be determined sufficiently resilient.

2.5.4 Summary of Findings

The first hazard analyzed was component failure during the operational scenario with the ships out to sea and no deployable craft connected to the microgrid. With the original microgrid design shown in Figure 2.7, the power generation capacity was insufficient, resulting in critical loads shed for a total of 15 out of 336 hours analyzed. This is equivalent to 15 hours between points A and B on the System Resilience Curve in Figure 2.1. The microgrid design was then improved to include the addition of one 10,000 m^2 PV array at 18% efficiency and one BESS with 5MWh capacity with charge and discharge rate of 300kW/h, and reanalyzed with the same failure scenario. With this microgrid design, no loads were shed for component failure in the first operational scenario. The next failure scenario analyzed is the weather phenomenon of excessive heat in the operational scenario with the ships out to sea, where the improved microgrid design resulted in no loads shed.

The final hazard assessed was the loss of fuel supply, which failed the resilience analysis with loads shed over 39 out of 336 analyzed hours. The microgrid was then improved to the final design shown in Figure 2.9 of four 2.5MW diesel generators, five 9,600m^2 PV arrays at 18% efficiency, and five BESS with 50MWh capacity with charge and discharge rate of 1,600kW/h. While increasing the capacity of the BESS may be costly, it remains within the characteristics of lead-acid electrochemical energy storage technologies used in grids [71] while each PV array size approximates three football fields. While this seems like a large area for typically limited space, utilization of PV array placement on covered parking areas and building rooftops may result in feasible space for installation. After the final microgrid design satisfied resilience requirements in the first operational scenario, it was then verified against the increased critical load demands of the second operational scenario.

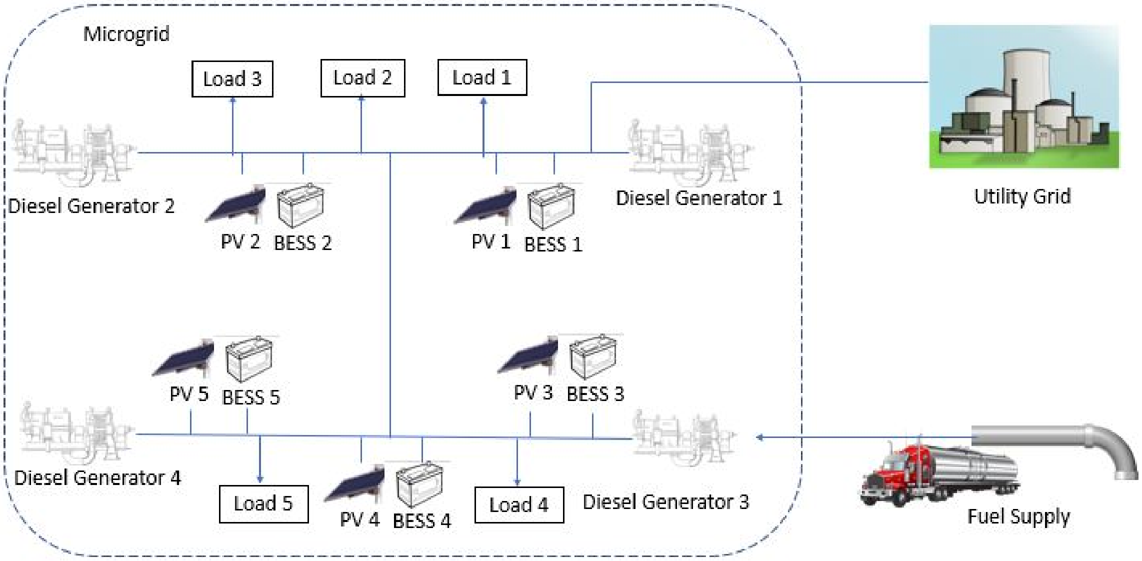

Figure 2.9. Final Microgrid Composition. This image displays the final microgrid composition, which includes four 2.5MW diesel generators, five 9,600m^2 PV arrays at 18% efficiency, and five BESS with 50MWh capacity with charge and discharge rate of 1,600kW/h.

The results of the load shed hours for all three microgrid designs, in all three hazards, for both operational scenarios are summarized for comparison and discussion in Table 2.4. As shown, the final microgrid design results in a satisfactorily resilient system with zero critical loads shed across all assessed hazards.

Comparing the load shed results directly between mission scenarios, it is readily apparent that the Ships in Port had higher electrical demand loads. For the Ships in Port scenario, load shed occurred for longer durations and for more failure scenarios. If fuel loss had not been considered, it would have been easy to assess that only a small PV and single BESS addition would have been sufficient while the ships were underway. Considering the loss of the diesel generation capability focuses electrical resiliency on renewable resources, causing a significant improvement upon the original design of only diesel generation. This early significant improvement was able to cover the additional critical load demand of the ships connected to the microgrid shore power.

Interesting trends shown in the data include much longer load shed times for loss of fuel supply than any other hazard. To satisfy load demands following loss of fuel, a large increase in microgrid capacity PV and BESS solutions was required to entirely compensate for the loss of diesel engine generation. While the addition of the single PV array and BESS was not enough to ensure a fully resilient solution, it did provide an additional 26 hours of critical load operation. This would increase the amount of time allotted to energy managers to find and have delivered an alternate fuel source solution to recover the microgrid without suffering load shed to critical equipment, and resulting loss of mission accomplishment.

Additionally, when load shed occurs it appears to be a large overload across the entire system for periods of time, causing all critical loads to be shed. This indicates that an increased number of smaller, dispersed DER may be the more resilient solution with a higher redundancy due to spare parts. Even if the total generation capability is the same, the loss of one DER would have a smaller effect on the microgrid resiliency. The microgrid designs were improved iteratively with trial and error solutions to demonstrate the need for operational load analysis. An energy manager may find cost effective, resilient solutions conducting an optimization analysis when improving the microgrid design in Step 3.

Table 2.4. Summary of Load Shed Analysis Results. This table includes the data for all three identified hazards analyzed with the different microgrid iterative designs, operational scenarios, and the resulting critical load shed hours.

Mission Scenario	**Failure Scenario**	**Microgrid Composition**	**Load Shed Hours** (Load 1/2/3/4/5)
No deployable assets, ships out to sea	Component Failure	Four 2.5MW Diesel Generators	5/9/9/9/15
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	0
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0
No deployable assets, ships out to sea	Weather Phenomenon	Four 2.5MW Diesel Generators	0
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	0
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0
No deployable assets, ships out to sea	Loss of Fuel Supply	Four 2.5MW Diesel Generators	81/81/81/81/81
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	39/39/39/39/39
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0
Ships In Port	Component Failure	Four 2.5MW Diesel Generators	22/36/40/28/40
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	30/31/31/30/35
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0
Ships In Port	Weather Phenomenon	Four 2.5MW Diesel Generators	38/38/38/38/38
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	12/25/25/17/28
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0
Ships In Port	Loss of Fuel Supply	Four 2.5MW Diesel Generators	136/136/136/136/136
		Four 2.5MW Diesel Generators, 10,000m^2 PV, 5MWh BESS	110/110/110/110/110
		Four 2.5MW Diesel Generators, Five 9,600m^2 PV, Five 50MWh BESS	0

2.6 Discussion and Future Work

Benefits of using microgrids as a resilience resource for defense facilities include maintaining power for critical loads while faults occur at one or more power sources among the DER, assuming sufficient microgrid functional capability and load prioritization is planned for. During the case study, a damaging event removed capability temporarily from one of the DERs but the system was able to manage the load until recovery was completed. Microgrids may also save fuel and resources by only running the generators or DER equipment required for current and estimated load demand. The microgrid power output never exceeded the electrical demand, and therefore during periods of lower electrical demand fewer DERs need to be used.

Military bases have different mission priorities and requirements at different times. The necessary power a base microgrid may have to provide for support to each state of readiness or operational tasking will vary, affecting the microgrid's resilience level at the time. Lower electrical demand requirements means the designed microgrid DER has additional redundancy and increased resilience. Higher power requirements may result in little to no redundancy in the DER and decreased resilience. Ships, aircraft, submarines, vehicles, or people may deploy to or from a military base, which must meet the changing mission needs and resulting load demand. The baseline mission load for the military base will include the power demand from constant, permanently affixed sources; while variable mission load demands need to be considered and accounted for.

This analysis is limited in the number of hazards and operational scenarios assessed, as it is only an example of the methodology application. The analysis is also limited with the use of assumed and generated historical data instead of actual values, and did not utilize rightsizing optimization techniques when improving the microgrid. Additionally, life-cycle costs where not a consideration in the model but are recognized as a hindrance to installation and improvement of microgrids. Without budgeted funds, energy managers may still analyze their system to ensure operational stakeholders are aware of the risks and limitations of the installed microgrid resilience system in the face of these hazards. This analysis and identification of resilience flaws in support of mission execution with proposed solutions may be useful in receiving allocated funds for microgrid installation or improvement efforts. Additional assumptions in the case study is that all loads assigned to each operational stakeholder have equal priority. More detailed critical load determination may be made based upon specific equipment, which may decrease load requirements.

Future work may include a more detailed study on the effects of fuel supply interruption for microgrid resilience. Installed diesel generators are used in most microgrid designs. With the loss of fuel, those DER become ineffective and result in not only a loss of invested acquisition funds, but also the inability to complete the mission in the event of disconnection from the utility grid.

2.7 Conclusion

This article presents a systems engineering method to analyze the impact on energy resilience of varied missions that a facility may be required to undertake on short notice due a changing operational environment. The method provides the ability to determine what the critical load requirements are and analyze the microgrids ability to supply them during damaging events affecting the islanded microgrid. This will allow energy managers to assess and prepare for changing missions before potential load shed occurs, preventing failed mission execution due to lack of electrical supplies to critical equipment.

Varied missions results in varied electrical load demands. An example case study was conducted with a fictitious, but representative, military base and microgrid design. By determining the mission capabilities of the operational stakeholders whose equipment interfaces with the microgrid, mission scenarios may be generated to account for potential electrical load demands. The early identification of critical loads ensures microgrids may be installed or updated to ensure satisfactory resilience before load shedding occurs. Any load shed of critical equipment negatively impacts the operational stakeholder's mission execution. Careful determination of critical loads enables resilient systems without having unnecessary costs due to oversizing the microgrid capacity. The addition of renewable energy resources, such as PV arrays and BESS, increases resilience to ensure mission execution during microgrid failure scenarios.

CHAPTER 3:
Conclusion

This chapter includes a summary of the work performed and the results of the analysis, supplementing the conclusion in Chapter 2 with larger implications of this research for the DOD. Research limitations and identified gaps are also discussed as potential subjects for future work.

3.1 Conclusion

Microgrids are a useful electrical energy resilience tool that may be utilized for military base applications if designed appropriately. Different locations have unexpectedly changing missions that must be analyzed for critical electrical load requirements to ensure proper resilience during various hazards. While average historical loads may be sufficient for most planned missions, if the microgrid suffers a damaging event concurrently with an unexpected increase in operational energy demand, the critical loads may not have enough power supplies for unhindered operations. Specific operational critical loads must be identified and analyzed to ensure an accurate minimum microgrid capability is determined.

The original microgrid design in the case study was able to supply critical loads for both mission scenarios as long as no damaging events to the microgrid occurred. However, as failures were added, the microgrid design proved insufficient. The microgrid model was first improved with one PV array and one BESS, and while the design enabled critical mission operations to continue for a longer period, the microgrid was unable to ensure operations through the entire fourteen day operations without load shed. Additionally, the microgrid design with the single PV array and BESS would continue critical load operations during component failure and weather phenomenon while the ships are out to sea, but showed insufficient resilience with those same failures if the ships were in port. This demonstrates that the microgrid resilience changes depending on the current mission scenarios and their operational load demands.

The case study also showed that the use of different types of DERs, including PV arrays and ESSs, increase resilience during damaging events. Different types of damaging events affect the microgrid system differently. With the loss of fuel supply, any number of additional of diesel generators added to the microgrid would still result in a resilience failure. Therefore, the PV arrays and BESSs were considered as the improvements. Other similar hazards for specific types of DERs may exist, and therefore various potential failures must be analyzed to ensure the microgrid resilience is sufficient for critical operations.

3.2 Future Work

This research is limited with the use of a fictional base and microgrid case study. Future work may include more detailed data analysis for specific locations and applications. The number and complexity of hazards and operational scenarios may also be increased, with optimization techniques used for microgrid rightsizing during improvements.

Weather hazard predictions and operational effects may also be tailored to geographic and diverse climate locations [96]. Emergent behavior predictions for safety and security assessments may also be incorporated for the microgrid hazards, instead of only focusing on mission gap capabilities [97]. This method focused on the energy resilience for one military base. Energy planning for complicated joint missions may also need to be conducted, through the use of tools or methods to improve communication between the operational stakeholders and the energy managers or systems design engineers [98].

Many industry power plants are designed, optimized, and installed with life cycle costs as the primary factor. While government budgets and acquisition projects are concerned with life cycle costs, the priority of minimizing operational risks with a resilient system is becoming increasingly more important. Future work on this topic may include incorporating microgrid design alternatives comparison for resilience improvements and life cycle costs into the iterative improvements.

Future work may include different DER component considerations for microgrid resilience improvement, such as liquid air energy storage systems [99]. As new technologies emerge or are studied, they should be considered as possible alternatives for energy resilience solutions.

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