2022-12

MICROGRID MODELING ASSESSMENT FOR CLIMATE TRENDS AND WEATHER EVENTS

Bell, Jacob M.; Berry, John L.; Bowers, Christian F.; Slagle, Charles D.

Monterey, CA; Naval Postgraduate School

https://hdl.handle.net/10945/71594

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

MICROGRID MODELING ASSESSMENT FOR CLIMATE TRENDS AND WEATHER EVENTS

by

Jacob M. Bell, John L. Berry, Christian F. Bowers,
and Charles D. Slagle

December 2022

Advisor:	Douglas L. Van Bossuyt
Co-Advisor:	Ronald E. Giachetti

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY
(Leave blank)

2. REPORT DATE
December 2022

3. REPORT TYPE AND DATES COVERED
Systems Engineering Capstone Report

4. TITLE AND SUBTITLE
MICROGRID MODELING ASSESSMENT FOR CLIMATE TRENDS AND WEATHER EVENTS

5. FUNDING NUMBERS

6. AUTHOR(S) Jacob M. Bell, John L. Berry, Christian F. Bowers, and Charles D. Slagle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

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

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

This report performs a gap analysis on microgrid models with respect to climate change risks at Naval installations. Six climate change risks are identified for the model analysis including drought, flooding, heat, cold, wildfires, and weather extremes. Each climate change risk is decomposed into ordered effects that inform the impacts that the climate risks may have on microgrids. The climate change risks, ordered effects, and the impacts on microgrids are used to analyze three microgrid models to determine if they adequately incorporate the six climate risks. A model analysis framework is developed to identify gaps in the approach of the models, the input parameters of the models, and the assumptions made in the models. The analysis demonstrates that gaps exist in each model when considering the climate change risks, the ordered effects, and the impacts to the microgrid. These gaps exist in all three models analyzed using the model analysis framework. The identified gaps are used to develop recommendations for ways to improve the incorporation of the climate change risks into microgrid models and the necessary research required to inform that data used in microgrid models.

14. SUBJECT TERMS
climate, weather, microgrid, model, resilience, energy, electrical power, power grid, climate trends, climate change, climate change, climate risks, extreme weather, weather effects, drought, temperature, flooding, fire, heat, cold, hurricane, Navy Shore Energy Technology Transition and Integration, NSETTI, Defense Climate Assessment Tool, DCAT, Distributed Energy Resource, DER, generator, environment, mission impact

15. NUMBER OF PAGES
91

16. PRICE CODE

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

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

MICROGRID MODELING ASSESSMENT FOR CLIMATE TRENDS AND WEATHER EVENTS

Jacob M. Bell, John L. Berry, Christian F. Bowers, and Charles D. Slagle

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
December 2022

Lead Editor: Jacob M. Bell

Reviewed by:

Douglas L. Van Bossuyt Advisor	Ronald E. Giachetti Co-Advisor

Accepted by:
Oleg A. Yakimenko
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This report performs a gap analysis on microgrid models with respect to climate change risks at Naval installations. Six climate change risks are identified for the model analysis including drought, flooding, heat, cold, wildfires, and weather extremes. Each climate change risk is decomposed into ordered effects that inform the impacts that the climate risks may have on microgrids. The climate change risks, ordered effects, and the impacts on microgrids are used to analyze three microgrid models to determine if they adequately incorporate the six climate risks. A model analysis framework is developed to identify gaps in the approach of the models, the input parameters of the models, and the assumptions made in the models. The analysis demonstrates that gaps exist in each model when considering the climate change risks, the ordered effects, and the impacts to the microgrid. These gaps exist in all three models analyzed using the model analysis framework. The identified gaps are used to develop recommendations for ways to improve the incorporation of the climate change risks into microgrid models and the necessary research required to inform that data used in microgrid models.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

CONUS	Contiguous United States
DCAT	DOD Climate Assessment Tool
DER	Distributed Energy Resource
DG	Diesel Generator
DOD	Department of Defense
DOE	Design of Experiments
DON	Department of the Navy
ELMI	Expected Life Cycle Mission Impact
EPA	Environmental Protection Agency
ESS	Energy Storage System
HILP	High Impact Low Probability
INI	Islanded Naval Installation
LCC	Life Cycle Cost
LCOED	Life Cycle Cost of Energy for Demand
LOE	Lines of Effort
MTTR	Mean Time To Repair
NDAA	The National Defense Authorization Act
NSETTI	Navy Shore Energy Technology Transition and Integration
PV	Photovoltaic
RE	Renewable Energy
UNDRR	United Nations Office for Disaster Risk Reduction
WOWA	Weighted Ordered Weighted Average
WT	Wind Turbine

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The Department of the Navy (DON) identifies climate change as a critical concern in the "Department of Navy Climate Action 2030." The DON states that climate change is "one of the most destabilizing forces of our time, exacerbating other national security concerns and posing serious readiness challenges" (Department of the Navy 2022). These readiness challenges include the risk to energy security at Naval installations. Microgrids have been installed to increase energy security at Naval installations to provide power when the Naval installation cannot rely on the power grid; however, the changes in climate pose risks to the long-term energy security at the Naval installation provided by microgrids. Understanding the impacts of climate change on microgrids is essential to ensure operations at the Naval installation can continue when the utility grid cannot be relied on. This understanding begins with analyzing microgrid models, which are used as a design tool, to determine if climate change has been accounted for.

The analysis of microgrid models with respect to climate change requires a thorough understanding of the risks associated with the changes in climate. The Defense Climate Assessment Tool (DCAT) is used as a baseline to understand the weather risks to each region the Navy operates in. The information provided in DCAT is used to identify six climate risks for the microgrid model analysis. These climate change risks include flooding, wildfires, drought, heat, cold, and weather extremes. Heat and cold includes the spikes in temperature along with the gradual increase or decrease in temperature over time. Each climate change risk is analyzed to determine the first, second, third, and in some cases fourth order effects of the climate change risk (Pinson 2021). These ordered effects are used to inform the impacts that the climate change risk may have on the microgrid. The climate change risks, ordered effects, and impacts to the microgrid are used to analyze three microgrid analysis models for gaps when considering the climate change risks.

Three models are analyzed with respect to the six climate change risks in this report. These models include the resilience and cost model developed by Dr. Bill Anderson (Anderson 2020), the mission impact model developed by Christopher Peterson (Peterson 2019), and the life cycle cost of resilience model developed by Joshua Hildebrand

(Hildebrand 2020). An analysis framework is developed to evaluate each model for gaps when considering the six climate change risks. This framework consists of examining the model's approach, the input parameters, and the assumptions.

The analysis of the three models indicates that gaps exist in each model when considering the six climate change risks. Each model's approach allows for the incorporation of climate data; however, the models do not allow for variation over time of the climate data. The inputs of the models also limit the user's ability to include climate data that may influence the model's output. The models have significant limitations in incorporating small incremental changes to the climate, such as gradual temperature rise. Additionally, the assumptions in the models also limit the incorporation of the climate change risks and could cause an inaccurate representation of the model output when considering the climate change risk.

This report identifies the limitations of microgrid models when considering the six primary climate change risks at Naval installations. If these climate change risks are not addressed in microgrid models, microgrids may not be able to meet the energy requirements of Naval installations which will limit the operational capabilities of Naval installations. Microgrid models must address the climate change risks in this report to ensure energy security at Naval installations. Ensuring energy security is fundamental to enabling Naval operations.

References

Anderson, William W. 2020. "Resilience Assessment of Islanded Renewable Energy Microgrids." Dissertation, Monterey, CA: Naval Postgraduate School.

Department of the Navy, Office of the Assistant Secretary of the Navy for Energy, Installations, and Environment. 2022. "Department of the Navy Climate Action 2030." Government Report, Washington, D.C.

Hildebrand, Joshua P. 2020. Estimating the Life Cycle Cost of Microgrid Resilience. Master's Thesis, Monterey, CA: Naval Postgraduate School.

Peterson, Christopher. 2019. Systems Architecture Design and Validation Methods for Microgrid Systems. Naval Postgraduate School

Pinson, A.O., K.D. White, E.E. Ritchie, H.M. Conners, and J.R. Arnold. 2021. DOD Installation Exposure to Climate Change at Home and Abroad. Technical Report, Washington, D.C.: U.S. Army Corps of Engineers.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

News of record-breaking temperatures (both high and low), record rainfall (both high and low), unprecedented flooding, drought, melting glaciers, rising sea levels, disappearing rivers, increased hurricane occurrences, and other weather trends all indicate that the climate is changing in different parts of the world. Many of these events and trends have an impact upon military installations of the United States. Due to the severity and frequency of these impacts, questions are being asked as to how to minimize these impacts.

It is common practice for the Navy to purchase electrical power from local providers. However, to mitigate the risk of a provider's inability to reliably provide the necessary power, the Navy installs microgrids at some shore installations to ensure continued critical operations. Prior to installing a microgrid, models are created as part of the design process to analyze the performance of the microgrid given the location and environment in which they will operate. Due to the impact of weather and climate, there is an interest in ensuring the models consider the effects of climate and weather events. As the climate changes, the assumptions and expectations that drive requirements and designs may not continue to be valid. More specifically, if weather events exceed design parameters, these microgrids can degrade and fail faster.

This capstone report captures the important weather and climate parameters as stated by the Department of the Navy (DON) and the Department of Defense (DOD) and identifies potential effects that may cause an impact to microgrids. This report then looks at a select number of microgrid models to identify the climate- and weather-related inputs included in the model, followed by recommendations as to which parameters may improve modeling results.

This report will utilize the research foundation established by Pinson et al. in their report for the Defense Climate Assessment Tool (DCAT). This report was created as part of Executive Order 14008 which charged the DOD with creating a plan of action in response to climate change. The Army Corps of Engineers produced the DCAT in response, which uses the most up-to-date and accurate information available to produce assessments that account for weather and climate effects. By utilizing this report's weather and climate information, this capstone report can assess other models considering modern climate change and weather trends (Pinson 2021) (Gade 2020).

A. PROBLEM DEFINITION

Climate change and weather extremes are impacting the operational capabilities of military installations. The examples of these impacts include increased cost, increased downtime, reduced security, diminishing readiness, and loss of the installation's capability to conduct its mission. Energy security is a critical element in ensuring the operations at a Naval installation can be supported. Microgrids enhance the energy security at Naval installations by providing a power generation and distribution capability when the Naval installation cannot rely on the utility grid. Climate change and weather extremes pose risks to the capability provided by microgrids. These risks and the potential impacts of the climate risks on microgrids have not been evaluated. Additionally, microgrid design tools, such as microgrid models, have not been analyzed to determine if changes in the climate are addressed. This report seeks to identify climate risks at Naval installations, the ordered effects of the climate risks, the impacts of climate risks to microgrids, and analyze models to determine if gaps exist in the models when considering the climate risks.

B. SCOPE

This report identifies Naval installation climate risks based on available climate data used in the DCAT. This report does not develop climate change trends or predictions for future regional climate; however, this report identifies ordered effects of climate events and the potential impacts to Naval microgrids.

The analysis is limited to the microgrid models and does not consider any specific microgrid design or location. Three models were chosen for the model gap analysis. The analysis only identifies gaps based on the Naval installation climate risks identified in DCAT and does not seek to identify all gaps that exist in the models. The analysis produces a list of gaps in the models related to the change in climate and weather.

C. ASSUMPTIONS

This report assumes that the information provided by DCAT accurately represents the climate concerns for Naval installations. The information provided by DCAT is used to inform the identification of the climate risks at Naval installations and the development of the ordered effects of the climate risk and the impacts to microgrids. Additionally, the three models analyzed are assumed to be validated and verified for their intended scope.

D. APPROACH

The goal of this report is to identify Naval installation climate risks, analyze models with respect to these climate risks, and determine the gaps that exist in the three models. The approach used to reach this goal begins with researching climate and weather data and documentation. The data and documentation are used to determine the regional climate risks for Naval installations. These climate risks are evaluated for ordered effects and the potential impacts to microgrids. The climate risks are used to analyze the three models to determine if the models address these concerns. After completing model analysis, any gaps in the models with respect to the climate risk are documented.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

Extreme weather and changes to regional climates have exposed vulnerabilities in infrastructure for both the public and the DOD. These vulnerabilities have led to the damage or loss of infrastructure, resulting in the loss of utilities such as electrical power. The Navy relies on electrical power at Naval installations to support critical operations. The loss of electrical power reduces the Navy's capability to perform its mission. DOD installations utilize microgrid systems to ensure installation operations can continue; however, these microgrids are exposed to the same risks that negatively impact the local power grids with regards to weather extremes and changes in the regional climate.

Microgrid models have been used in the design of microgrids; however, weather extremes and changes in regional climate may impact the design and must be addressed to ensure these vulnerabilities are mitigated. This effort seeks to identify gaps in microgrid models with respect to weather extremes and changes in regional climates. This section identifies the historic examples that have impacted both the public and DOD, the guiding doctrine with respect to weather extremes and changes in climate, stakeholders for the work performed, and a description of microgrids.

A. HISTORIC EXAMPLES OF WEATHER AND CLIMATE CHANGE

Weather extremes and changes in climate have impacted electrical power grids across the world. Weather is the "atmospheric condition at any given time or place" (Environmental Protection Agency (EPA) 2022). Weather events, and particularly extreme weather events, negatively impact the power grid by either damaging components of the power grid or requiring the power grid to limit output to ensure safe operations. The damage done to the power grid is costly to repair and the time required to repair the power grid increases the overall time of electrical power interruption. These weather events occur across the world; thus, examples can be found of weather events impacting power grids in various regions.

Heatwaves and drought are events and changes in climate that pose a risk to power grids as seen recently in China. The South China Morning Post reports that China's Sichuan province experienced the worst drought and record-breaking heatwave in more than 60 years during the summer of 2022 with sustained temperatures of more than 100 degrees F for over 70 days straight (Wong, 2022). The effect of such heat is detrimental to populated areas such as Sichuan and the surrounding provinces. The power grid of these areas is under increasing strain because of the increased energy demand from air conditioning usage to make the environment bearable or to ensure that important equipment is kept at an operational temperature. To compound the strain on the power grid, several rivers that supply hydroelectric power to these provinces were drying up due to the heat wave and subsequent drought that reduced their effectiveness in supplying the same level of power output (Gan 2022). In response to the grid crisis, power was suspended in those distressed regions. Further problems can be associated with the heat wave's havoc on a second order, such as drought, heat stroke, dehydration, wildfires, and all the associated dangers of their 3rd order issues, such as the death of people and livestock, failed staple crops, and destruction of property by fire (Gan 2022).

Flooding due to heavy storms poses a risk to critical infrastructure at Naval installations and the surrounding communities. For instance, Naval Station Rota is a critical installation that has seen major effects due to weather and changes in climate. Violent storms cause major flooding both at the base and in the surrounding area. In October of 2008, a single storm dropped over 15 inches of rainfall and brought 92 mph winds (Novak 2008). This led to massive power outages and standing water over 10 feet deep in some areas. The base sustained very little damage, but parts of the surrounding towns and housing areas were destroyed. The base provided relief and their efforts contributed to zero loss of life.

Coastal and riverine flooding have severely impacted military installation operations. In 2019, a record snowfall caused the Missouri river to overrun in Nebraska. These floodwaters submerged over a third of Offutt Air Force Base including over three thousand feet of runway. Everything from support structures to power generators were damaged (Losey 2020). This disaster was a major revelation for the Air Force. The Air Force called for a complete redesign of the base power grid. An emergency microgrid was built which includes three interconnected power stations at different locations to provide backup power to critical facilities for future outages.

Climate Change is a topic that is becoming more important to many people across the globe. The United Nations website states that “climate change refers to long-term shifts in temperature and weather patterns” (United Nations n.d.). The examples in this section suggest this shift may manifest in not only more extreme weather, but also more frequent weather events. Changes in regional climate are also a major issue for military operational capabilities. Sea level rise is a main concern for places such as Norfolk, the largest naval base in the world, because of the threat of loss to support structures such as homes or infrastructure related to base operations. Since the year 2000, onsite flooding has increased and intensified dramatically, with most climate models suggesting a sea level rise of five feet or more by the year 2100 (Farley 2021). If the current trends continue, Naval Station Norfolk will face major losses in capability and fleet support.

In February of 2021, Texas encountered three severe winter storms that brought record snowfall and extreme low temperatures causing almost the entire state’s power grid to fail (Wright 2021). These power grid failures and the effects they had on both emergency services and operations contributed to the deaths of over 700 people. The storms led to more than $195 billion in damages. It also drove massive shortages in water and food. Initial investigations showed that the Electric Reliability Council of Texas had failed to address previous warnings regarding the poor winterization of power generation machinery in both the coal and natural gas industries. These poor practices led to the power grid failure when the cold spell hit. During one storm, the Dallas/Fort Worth International Airport recorded its lowest temperature in 72 years of -2° F (Marfin, et. al 2021). Frozen natural gas lines and poor home insulation put a further strain on the power grid system by reducing the availability of energy resources and increasing the demand for heating (Adams-Heard 2021). With the limited number of tie-ins to other grids, fuel shortages, and frozen power generation equipment, the Texas power grid was unable to support the required power resulting in power outages across the state.

The combination of wildfires and high winds has resulted in electrical power interruptions on military installations. Vandenberg Air Force Base has experienced two major fires since 1977. The Honda Canyon fire, taking place in 1977, was fueled by hurricane-force winds with gusts of more than 100 mph causing power lines to fail (Minsky 2021). The fire that ensued led to the death of four individuals including the base commander. In 2016, the Canyon fire burned over 12 thousand acres and caused widespread power outages at the installation (Hamm 2016). These outages affected multiple facilities, including fire stations.

The United States eastern seaboard encounters multiple hurricanes annually. Hurricanes originate as tropical storms and are associated with extremely high winds and heavy rainfall. Homestead Air Force Base and Tyndall Air Force Base have both experienced Category 5 hurricanes. In 1992, Hurricane Andrew hit Homestead Air Force Base, causing widespread power outages (Tweten 2012). The storm destroyed the airbase and led to one of the larger cleanup and salvage operations in peacetime history. In 2018, Hurricane Michael hit Tyndall Air Force Base (Reeves 2019). Hurricane Michael caused over $4 billion in damages to infrastructure and made base housing uninhabitable. Cleanup efforts are still underway with the first batch of aircraft expected to return in 2023.

The examples above describe the results of extreme weather when not adequately mitigated. It is possible these risks were identified and determined to be acceptable at the time due to an estimate of low probability of occurrence and the high cost of implementing protective measures. These examples can be used in making future decisions about trade space and the cost of added protection versus the different costs of destruction.

B. FEDERAL GOVERNMENT DIRECTIVES TO ADDRESS CLIMATE CHANGE

The National Defense Authorization Act (NDAA) for fiscal year 2020 contains multiple sections addressing climate and resilience. It directs the DOD to prepare for climate and weather risks, calls for extreme weather vulnerability and risk assessment tools, directs the Secretary of Defense to assess every four years how climate impacts have affected and will affect the DOD's ability to accomplish missions, and requires language in unified facilities codes to address military construction implementation of these considerations.

The Fiscal Year 2020 NDAA was one of the first of several federal directives that focused on the impacts of climate change. On January 27, 2021, Executive Order 14008 was signed by President Joseph Biden which directs agencies and departments to identify approaches in addressing climate change. Executive Order 14008 states that the "Secretary of Defense…shall develop and submit to the President, within 120 days of the date of this order, an analysis of the security implications of climate change (Climate Risk Analysis) that can be incorporated into modeling, simulation, war-gaming, and other analysis" (Biden 2021). In response to Executive Order 14008, the DOD released the Climate Adaptation Plan on September 1, 2021. The DOD Climate Adaptation plan states that the purpose is to "ensure the military forces of the United States retain operational advantage under all conditions, leveraging efficiency and resilience to ensure our forces are agile, capable, and effective" (Department of Defense 2021). The DOD Climate Adaptation Plan establishes five lines of effort (LOE) to address climate change, two of which are supported by the work conducted in this report. The two lines of effort this report supports are LOE 1, climate-informed decision-making, and LOE 3, resilient built and natural installation infrastructure. The DON responded to the LOEs in the DOD Climate Adaptation Plan by highlighting initiatives in each LOE. As part of these initiatives, the DON states that they "will build on the successes of its microgrid program by incorporating a cyber-secure microgrid or comparable resilience technology to support all critical missions. This technology supports energy resilience by isolating critical missions from grid instabilities and outages whether they are natural or manmade" (Department of the Navy 2022). The research and analysis done throughout this report addresses the concerns of the Executive Office, DOD, and DON by identifying gaps in microgrid models with respect to climate risks to help ensure the Navy maintains resilient infrastructure.

C. MICROGRID SYSTEM DESCRIPTION

Microgrids are used by the DON to increase energy security at Naval installations. Allison Lantero from the Department of Energy defines a microgrid as "a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously" (Lantero 2014). Microgrids increase Naval installation energy security by providing a source of power and distribution mechanisms to support critical loads during events that disrupt the power grid. Bolen et al. states that once a grid disruption occurs, "island mode is initiated in which all loads on the base microgrid are shifted to be carried by the DER sources on base" (Bolen et al. 2021). Once the disruption event passes and the utility grid is restored, the microgrid enters a stand-by state while the utility grid provides power.

There is a difference between microgrids and distributed energy resources (DER). A microgrid is a localized energy system comprised of an energy source and its loads that can be isolated from the larger electrical utility grid. According to VECKTA, an energy resource and monitoring solution, "a distributed energy resource (DER) is any resource on the distribution system that produces electricity" (VEKTA 2020). Naval installation microgrids are commonly composed of multiple DERs. These DERs include diesel generators (DGs), wind turbines, photovoltaic (PV) panels, and other energy resources available for the Naval installation.

Microgrids are composed of various equipment for the generation, storage, and distribution of power to support the critical loads of the Naval installation. Christopher Peterson developed a microgrid overview diagram, provided in Figure 1 (Peterson 2019), which describes the electrical power generation, distribution, and storage systems that make up a microgrid (Peterson et al. 2021). Giachetti et al. identifies the top-level functions of a microgrid as "generate power, distribute power, control power distribution, and often a microgrid will also provide the function of storing power" (Giachetti et al. 2020). The power generation function of the microgrid is primarily met using diesel generators and is supplemented by other energy resources such as photovoltaic panels and wind turbines.

Figure 1 also helps explain the boundaries of a microgrid when determining which components to include in models and determining if and when they should be excluded. Two buildings are shown in the figure. During normal operations, the utility grid powers the installation. The other power generation systems shown may or may not be powering the electrical bus. In most cases, it is assumed that these other power generation systems are not powering the bus when the utility grid is connected. When the utility grid is disconnected by the switch closest to the point of common coupling, one or more other power sources provide power to the buildings. Note that the power lines to the buildings do not change. In most cases, everything on the opposite side of the point of common coupling from the utility grid is considered part of the microgrid even when connected to the utility grid. An issue to consider is properly capturing the impact to the power output if a microgrid power producer, like the photovoltaic array or battery, fails when the utility grid is still connected. This scenario should have no impact on the amount of power provided to these buildings. Other failures, such as a switch, converter, transmission lines, and transformers, will have an impact assuming they are constantly in the circuit with or without utility grid power.

Microgrids and buildings built by DOD are designed for lifespans of 36 to 50 years (GAO 2022). If the climate changes significantly over that period and these predicted changes are not incorporated into the building's design, the energy usage by that building may change. Both the loads on the microgrid and the microgrid itself should consider the respective design lifespan.

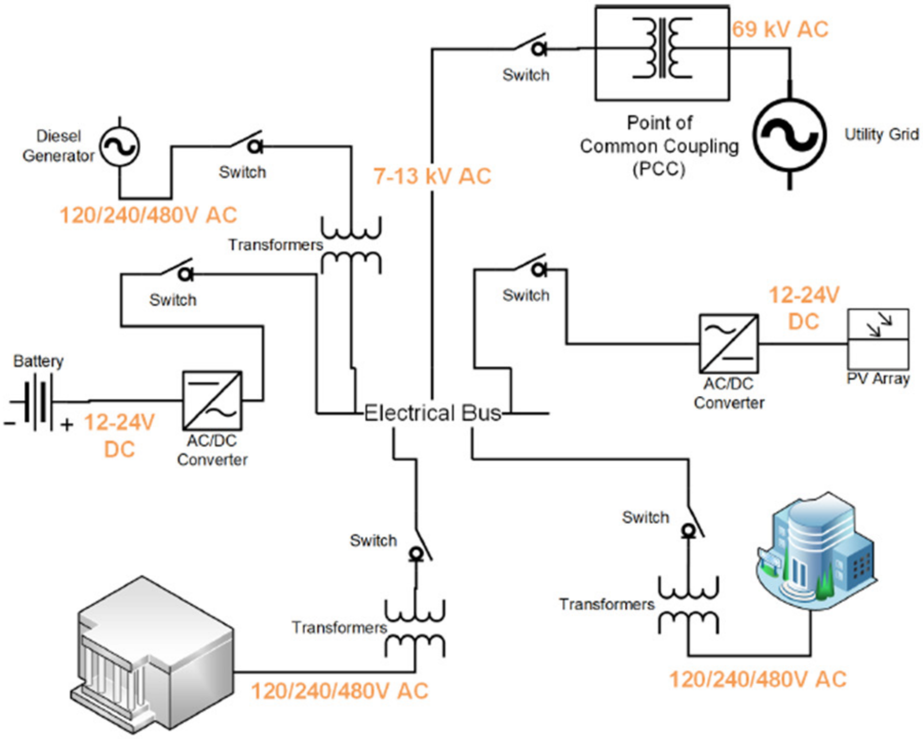


Figure 1. Microgrid Overview Diagram Source: Peterson (2019).

D. STAKEHOLDERS

The research and identification of gaps in microgrid models with respect to extreme weather events and the changes in regional climate benefits multiple Naval stakeholders. The Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) manages the Navy Shore Energy Technology Transition and Integration (NSETTI) program which funds research, development, test, and evaluation projects that address Naval installation energy capability needs. These needs include research into climate change impacts on Naval installations, projects that address Naval installation energy resilience, and other energy related topics. Previous work conducted by students and faculty at the Naval Postgraduate School focused on addressing the capability needs funded by the NSETTI program. This project builds off the previous work to identify gaps in microgrid models with respect to extreme weather and changes in climate. The research and analysis conducted in this report benefits the stakeholders listed in Table 1. This table focuses on Naval stakeholders and is not exhaustive.

Table 1. Stakeholders of Microgrid Modeling Analysis Report

Stakeholder	Goal/Need
Naval Facilities Engineering System Command (NAVFAC SYSCOM)	Receives information and/or recommendations on microgrid modeling with respect to the changing climate.
Chief of Naval Operations for Fleet Readiness and Logistics (OPNAV N4)	Funds the NSETTI program and other research, development, and improvements of microgrid models.
Commander, Naval Installations Command	Ensures microgrids installed at Naval Installations can withstand extreme weather events and climate threats.
Naval Postgraduate School	Informs current and future research topics on where models can be improved in respect to climate risks.
Commands located on Installations (i.e., SYSCOMS, HQs, etc.)	Receives confidence that military installations can support energy requirements to meet command operations.
Fleet Forces	Increases confidence that military installations can support Fleet sustainment during high-risk climate threats.

III. CLIMATE, WEATHER, AND EFFECTS

Merriam-webster defines climate as, “the average course or condition of the weather at a place usually over a period of years as exhibited by temperature, wind velocity, and precipitation” (Merriam-Webster Dictionary n.d.). Weather is defined as, “the state of the atmosphere with respect to heat or cold, wetness or dryness, calm or storm, clearness or cloudiness.” When looking closely at impacts, one realizes that it is the effects of climate and weather that have an impact.

To better classify the risks associated with changing climate and weather events, this report considers the impacts of the different orders of effects which must be addressed in models when considering resilience or the reliability of a microgrid. When attempting to incorporate metrics into a model, it is not always the cause that impacts the microgrid. There are occasions when an effect has an impact, and not the cause. An explanation of the difference between causes and effects is provided below.

Immediate results from causes are considered 1st order effects. Effects that result from 1st order effects are considered 2nd order effects, and so on.

A simple example of climate change is an increase in average precipitation in a localized area or region during a season. A significant weather event is rainfall in a relatively short period of time (i.e., hours, days, etc.) that exceeds expectations and preparation. The short-term 1st order effect is possible flooding from the excessive rain. A long-term 1st order effect is soil erosion.

An example of a short-term 2nd order effect of flooding due to rain is prevention of emergency personnel from accessing the first floor of the base hospital and/or prevention of access to the back-up generator building and use of equipment. A long-term 2nd order effect of the erosion due to rain would be the undermining of building foundations, concentration of flood waters, and removal of vegetation that would normally reduce future erosion.

A short-term 3rd order effect of the flooding due to rain would be destruction of power equipment in the hospital that disrupts power distribution throughout the hospital.

A long-term 3rd order effect of erosion due to rain and flooding could be necessary and costly investments in building foundation repair. In addition to repair and replacement costs of equipment, a 4th order effect of flooding could mean the loss of life.

Climate change may be viewed in at least two different manners. One view is that the general weather trend moderately changes over time, such as years. This might equate to the example of the frog in a beaker of water such that if the temperature of the water rises slowly, the frog does not notice and eventually may cook to death. Another view is with extreme weather events occurring more frequently. These events may be heat waves or cold snaps. In the case of the frog, a rapid change in temperature is noticeable and encourages the frog to change locations. Over multiple years, the average temperature may be the same in both examples, but the effects may be different. For example, extreme heat may cause components to melt while extreme cold may cause liquids to freeze, expand, and break pipes. However, a moderate temperature trend may not have a short-term, noticeable impact. Another example is extreme rainfall may cause flooding and erosion while a gradual increase in rainfall over time may produce an increase in humidity and vegetation. The effects of long-term climate trends, short-term weather events, and their effects must be considered.

Figure 2 shows an example of how first order effects can lead to second and third order effects over the course of 18 months during a drought.

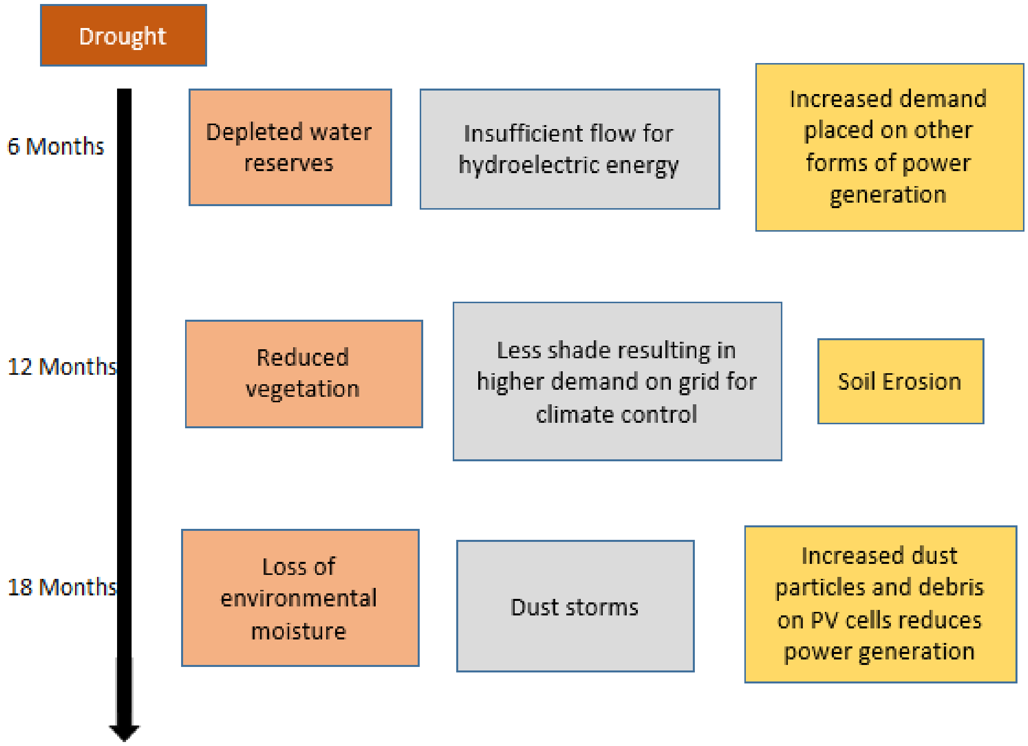


Figure 2. Example Timeline of Orders of Effect

A. CHANGES TO CLIMATE

For the past 20 years, weather events have been increasing steadily in severity and frequency, as pointed out by the United Nations Office for Disaster Risk Reduction (UNDRR), Yale School of the Environment, and others who echo those same sentiments. According to the Yale School of the Environment, “From 2000 to 2019, there were 7,348 major natural disasters around the world, killing 1.23 million people and resulting in $2.97 trillion in global economic losses.” (YaleEnvironment360 2020). The Environment School at Yale states that the weather in the previous 20 years (1980-1999) caused considerably less damage and fewer lives lost. It is unclear if the change in population is accounted for in these statements.

There is an observable trend in rising temperatures globally as seen in Figure 3 starting around 1970 and continuing to 2020. However, the averaging statistics show only part of the story with extreme temperatures playing a small role in the overall picture despite causing enormous problems during temperature spikes. According to NASA’s

Earth Observatory, “Nine of the ten hottest years or (sic) record have occurred in the past decade,” with the year 2021 the sixth hottest (NASA n.d.).

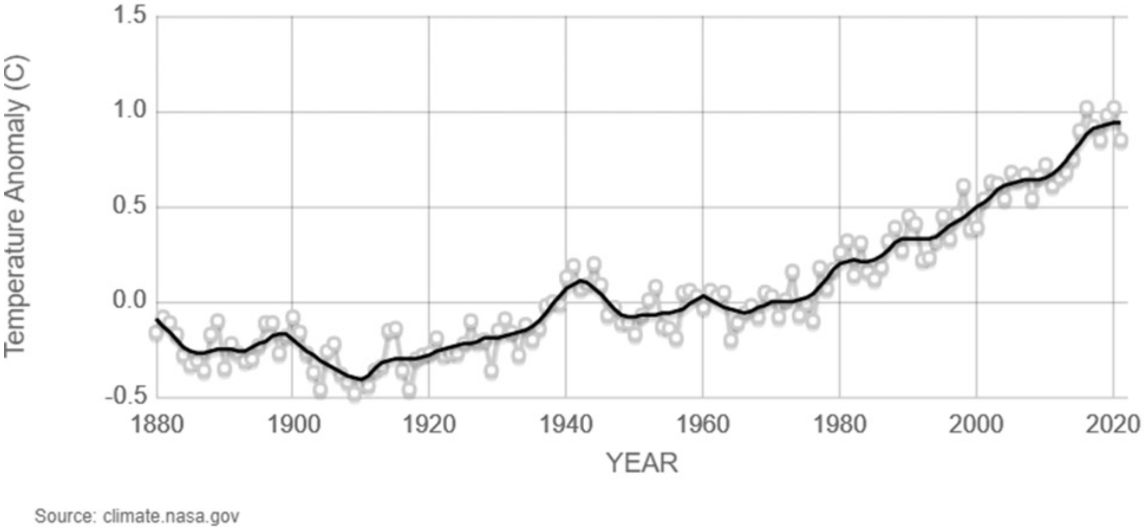
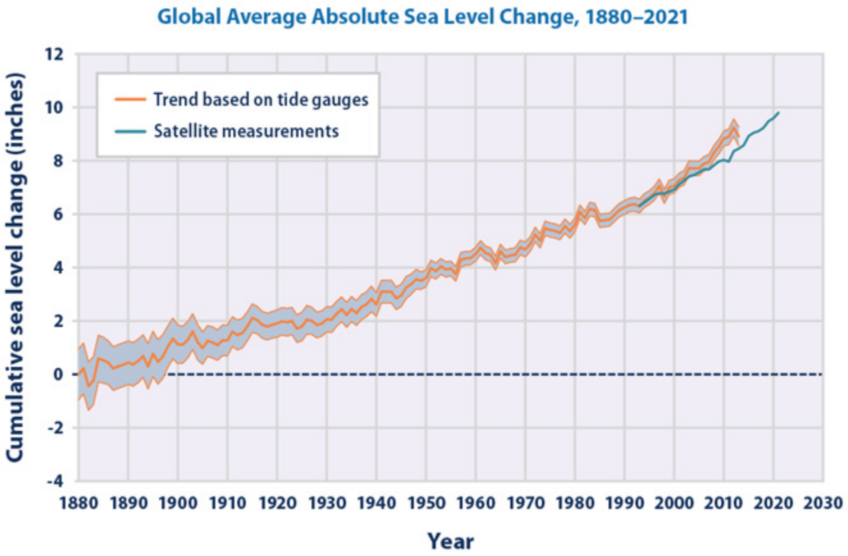


Figure 3. Yearly Global Temperature Average. Source: NASA (n.d.).

Another long-term problem associated with rising global temperature can be seen in the ice shelves breaking away from the larger masses in the two polar regions, which melt and cause sea levels to rise (Gudmundsson et al., 2022). This presents a particularly unique problem for U.S. Navy installations around the world because most of them require locations adjacent to the sea to both accomplish and support their missions. According to the EPA, global sea levels have increased almost 10 inches since 1880 as seen in Figure 4 with a steady increase in sea level.


Global Average Absolute Sea Level Change, 1880–2021

Data sources:

- CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2017 update to data originally published in: Church, J.A., and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys. 32:585–602. Accessed September 2017. www.cmar.csiro.au/sealevel/sl_data_cmar.html.
- NOAA (National Oceanic and Atmospheric Administration). 2022. Laboratory for Satellite Altimetry: Sea level rise. Accessed March 2022. www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 4. Global Average Sea Level Change. Source: EPA (2022).

B. WEATHER EVENTS

UNDRR reports that extreme weather has taken a significant lead in the topic of world-wide disasters. Most events are floods and storms, but also include drought, wildfires, and extreme temperatures according to UNDRR's report, "Human Cost of Disasters." Almost US$3 Trillion in global economic losses between 2000 and 2019 were attributed to extreme weather events. (United Nations Office for Disaster Risk Reduction 2020).

According to the EPA, "Rising global average temperature is associated with widespread changes in weather patterns" (Environmental Protection Agency (EPA) 2022), which likely means that regions will experience increased occurrences of weather with stronger effects as global temperature continues to rise (Pinson 2021). These events are witnessed in the form of increased flooding, wildfires, hurricanes, tornadoes, and longer periods of extreme temperature spikes.

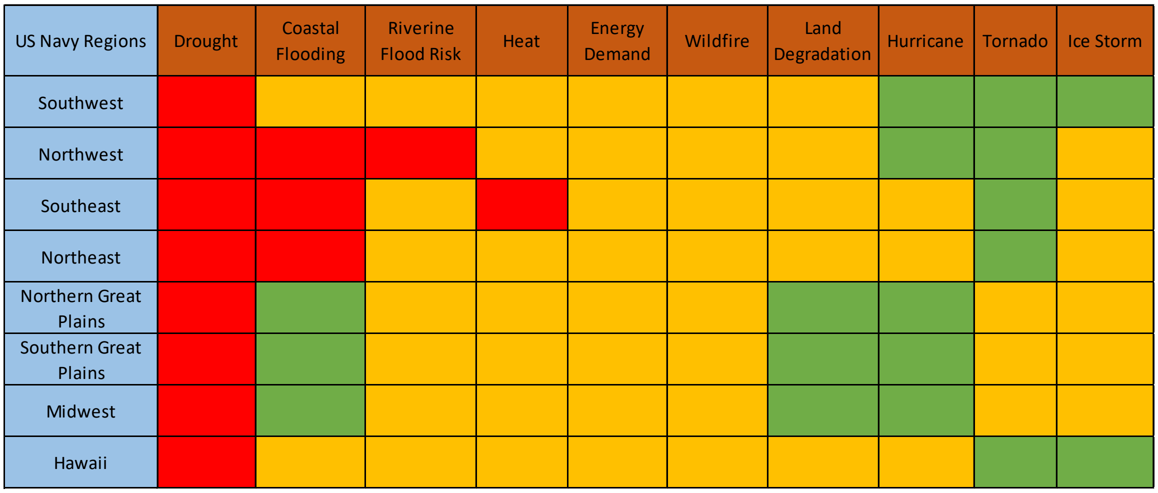
While it is easy for events such as these to garner the attention of the press, and therefore the world, it is important to make note of the slower evolutions regarding seasonal weather's increasingly destructive patterns. Events such as seasonal monsoons (or rainy seasons), tornados, hurricanes, and snowstorms have been observed to be occurring more frequently with greater severity. In Newport News, Virginia the seasonal floodings in the form of storm surges or overbank/riverine flooding have become commonplace, where standing orders and protocols are in place for the pattern to make its rounds every year (Newport News Government Information n.d.).

C. IMPACTS OF CLIMATE RISKS TO NAVAL INSTALLATIONS

Establishing what changes in climate and weather are currently emerging is important to understand where these trends will lead. When assessing the timeline of climate change, the DCAT uses two divisions of time, or epochs. Those two epochs are the years 2050 and 2085.

The tables below are based on the technical document for the DCAT, DOD Installation Exposure to Climate Change at Home and Abroad and use its predictions to identify the significant risks posed to CONUS naval installations (Pinson 2021).

Drought has been identified as the most significant weather risk for various contiguous United States (CONUS) regions as seen in Figure 5 which is accompanied by associated weather patterns for the large areas each region encompasses. Figure 5 is a graphic developed by the authors of this capstone report that visually represent data found in Pinson et al.'s DCAT report. Drought is be considered a dangerous aspect of climate change because it acts as a catalyst for many 2nd and 3rd order dangers to military installations; decreased water quality, loss of soil moisture which leads to vegetation die-off and soil erosion, and a significant chance of wildfire (Pinson 2021).



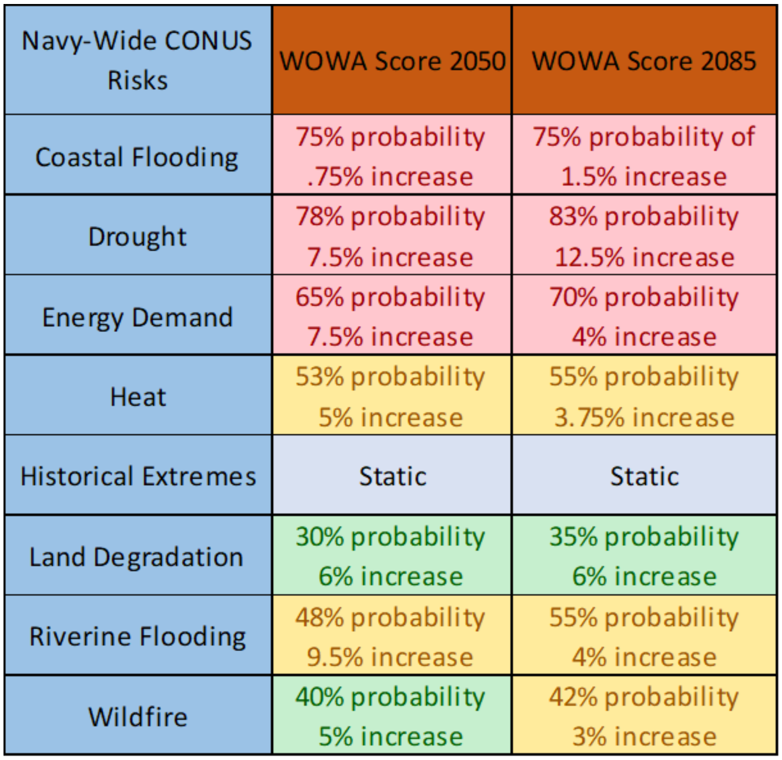
US Navy Regions	Drought	Coastal Flooding	Riverine Flood Risk	Heat	Energy Demand	Wildfire	Land Degradation	Hurricane	Tornado	Ice Storm
Southwest	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Northwest	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩	🟨
Southeast	🟥	🟥	🟨	🟥	🟨	🟨	🟨	🟨	🟩	🟨
Northeast	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟨
Northern Great Plains	🟥	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨
Southern Great Plains	🟥	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨
Midwest	🟥	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨
Hawaii	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩

Figure 5. Navy Regional Weather Risks (2050)

The second highest danger posed to naval installations, coastal flooding, is slightly more apparent when thinking of navy base locations, which require immediate access to bodies of water via wharfs, docks, and drydocks. As with the drought risks, coastal flooding presents its own set of greater-order effects such as soil/beach erosion or associated riverine flooding. In the year 2022, Thwaites Glacier was observed by scientists to be nearing a break-off point. This break-off could result in an expedited rise in sea level by 3 to 10 feet once melted and a permanent flooding of large portions of coastline (Lodewick 2022).

To determine how severe a weather event will affect a region, DCAT uses a Weighted Ordered Weighted Average (WOWA) to deliver a climate exposure score. It explains that these "WOWA score calculations require two steps that take into account (1) the contribution of individual indicators to aggregated exposure estimates and (2) the risk preference of the decision maker" (Pinson 2021).

Using the WOWA score across all navy installations and then comparing those scores to the weather risk, a valuable probability can be seen where the great risks to our bases reside over the two epochs in Figure 6. Figure 6 is a graphic developed by the authors of this capstone report that visually represent data found in Pinson et al.'s DCAT report. It can be observed that coastal flooding remains the most stable risk over the two stretches of time, with the most certain predictions comfortably situated in drought (Pinson 2021).

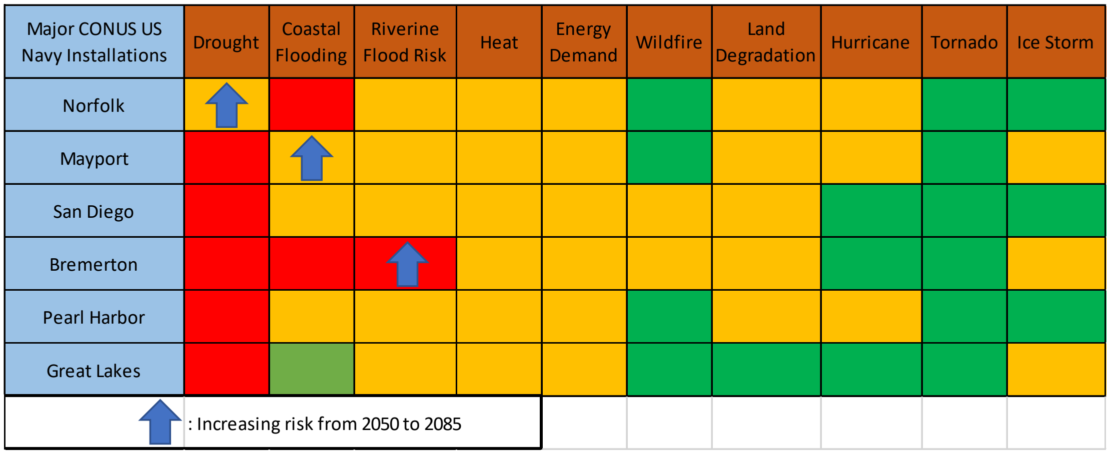


Navy-Wide CONUS Risks	WOWA Score 2050	WOWA Score 2085
Coastal Flooding	75% probability .75% increase	75% probability of 1.5% increase
Drought	78% probability 7.5% increase	83% probability 12.5% increase
Energy Demand	65% probability 7.5% increase	70% probability 4% increase
Heat	53% probability 5% increase	55% probability 3.75% increase
Historical Extremes	Static	Static
Land Degradation	30% probability 6% increase	35% probability 6% increase
Riverine Flooding	48% probability 9.5% increase	55% probability 4% increase
Wildfire	40% probability 5% increase	42% probability 3% increase

Figure 6. WOWA Scored Probabilities U.S. NAVY, CONUS.

While energy demand may not appear to be a weather risk, it is an effect of the weather that must be considered. Often, the x-ordered effects have the impact that the weather itself does not. To be discussed in more detail below, energy demand plays a large role in an installation's resiliency. A larger strain on the microgrid will consume more energy resources, which is expected to continue to increase over time in direct relation to rising or lowering temperatures and steady climate change in a holistic view. Energy requirements must be considered when we discuss an installation's resiliency, the sourcing, storage, and distribution where it concerns sustained and spiked demands of self-sustainment.

To better discern and identify specific risks to major CONUS naval installations, Figure 7 details predictions DCAT has found for future considerations. Figure 7 is a graphic developed by the authors of this capstone report that visually represent data found in Pinson et al.'s DCAT report. Though it has already been stated that drought poses a risk to all regions, it is apparent here that the associated installations within the region would be specifically affected as well. It should be stressed that Norfolk and Bremerton would both see coastal flooding as a highest-tier threat alongside drought and (Bremerton's) riverine flooding risk. From the 2050 to the 2085 epochs, there were three increases in risk for Norfolk, Mayport, and Bremerton for drought, coastal flooding, and riverine flood risks, respectively, if climate change continues its DCAT-predicted trend (Pinson 2021).



Major CONUS US Navy Installations	Drought	Coastal Flooding	Riverine Flood Risk	Heat	Energy Demand	Wildfire	Land Degradation	Hurricane	Tornado	Ice Storm
Norfolk	🟨 ⬆	🟥	🟨	🟨	🟨	🟩	🟨	🟨	🟩	🟩
Mayport	🟥	🟨 ⬆	🟨	🟨	🟨	🟩	🟨	🟨	🟩	🟨
San Diego	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Bremerton	🟥	🟥	🟥 ⬆	🟨	🟨	🟨	🟨	🟩	🟩	🟨
Pearl Harbor	🟥	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟩	🟩
Great Lakes	🟥	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨

⬆ : Increasing risk from 2050 to 2085

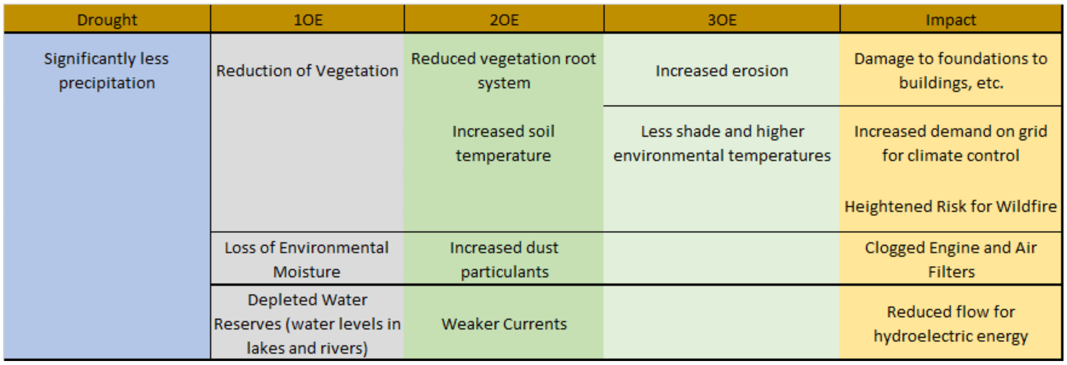
Figure 7. U.S. Navy CONUS Installation Weather Risks, derived from the DCAT Figure 28, Dominant Hazard (Lower) and (Upper)

D. THE EFFECTS OF CLIMATE AND WEATHER RISKS

To study a microgrid's resilience against climate and weather, an overview of how such events can affect installations and their operations is next discussed. DCAT provides an overview of the risks of select weather and climate events which this report expounds upon to reveal potential effects. Figure 8 through Figure 13 are graphics developed by the authors of this capstone report to show effects and impacts using climate risks found in Pinson et al.'s DCAT report (Pinson 2021). As the DCAT states

1. Drought: Drier soil means soil erosion, which usually ends up in the air as dust particles. Dust particles can cover photovoltaic (PV) arrays which can influence panel efficiency; the same particles can cause faster wear on air filters as well. Drought also has a direct effect on hydroelectric power source when river and lakes have a lower level of water that cannot

produce the same flow as when full. The drier vegetation environment stemming from a drought will increase wildfire risk at the installation. A higher demand should be expected on a microgrid due to energy costs associated with the heat of drought conditions and the demand for air conditioning. Examples of effects and impacts on microgrids caused by drought can be seen in Figure 8.



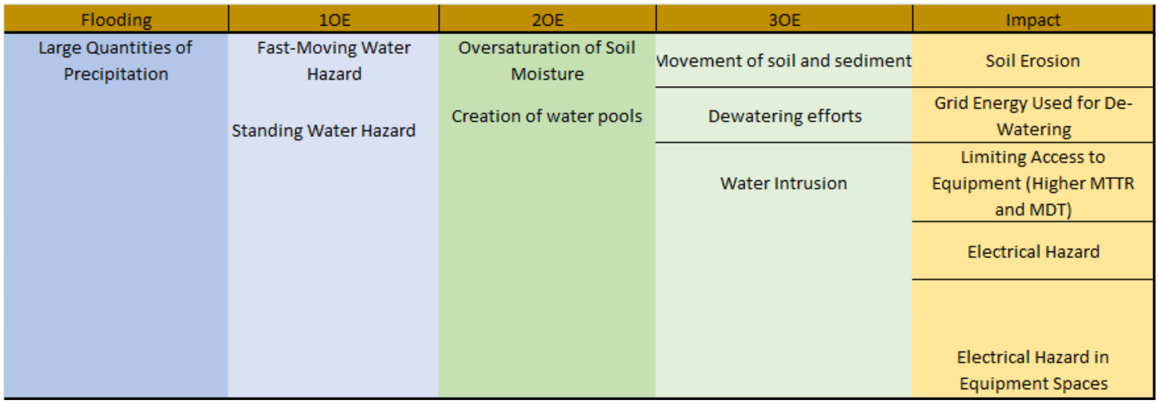
Drought	1OE	2OE	3OE	Impact
Significantly less precipitation	Reduction of Vegetation	Reduced vegetation root system	Increased erosion	Damage to foundations to buildings, etc.
		Increased soil temperature	Less shade and higher environmental temperatures	Increased demand on grid for climate control Heightened Risk for Wildfire
	Loss of Environmental Moisture	Increased dust particulants		Clogged Engine and Air Filters
	Depleted Water Reserves (water levels in lakes and rivers)	Weaker Currents		Reduced flow for hydroelectric energy

Figure 8. Examples of Drought Event Risks to Microgrids

2. Flooding: When flooding occurs where it has contact with facilities or equipment, there is a direct effect on a system where it could dimmish the expected life cycle, increase the Mean Time to Repair (MTTR) and Mean Down Time, and put a much higher strain on the microgrid for the duration of the flooding event from de-watering efforts. Flooding also presents a conductivity environment that can cause an electrical short within the system, taking parts of the microgrid offline until repairs can be made. Prolonged exposure may also result in corrosion that will require repair.

Flood waters can become contaminated if they reach diesel fuel supplies, which would diminish the effectiveness of the diesel generators or other system equipment relying on liquid fuel.

When flooding occurs, soil is disturbed as fast-moving water currents displace it along its path. The erosion that happens as a result can result in loss of land mass at the installation and could remove soil from around or under installation buildings and facilities. Fast-moving waters may also pick up and move debris which can clog rivers and damage equipment with the impact of the debris hitting that equipment. Examples of effects and impacts on microgrids caused by flooding can be seen in Figure 9.

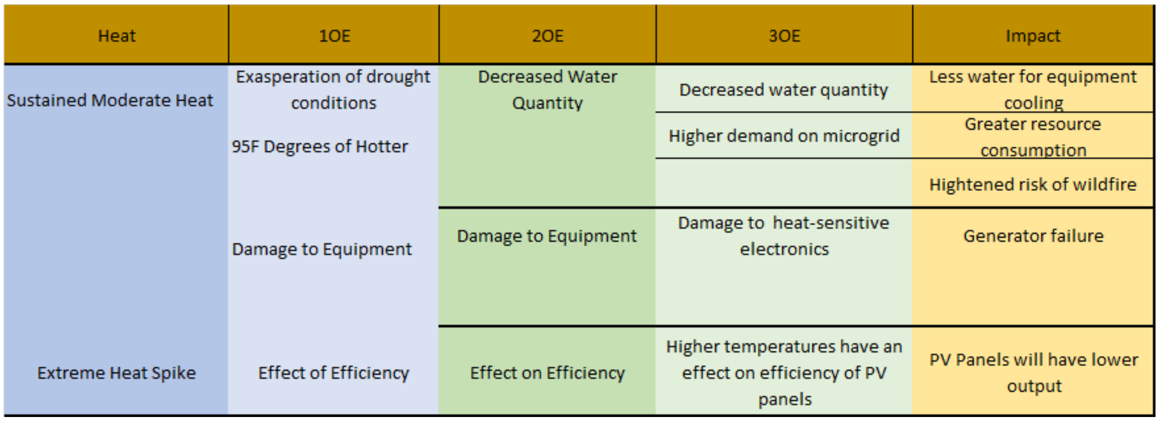


Flooding	1OE	2OE	3OE	Impact
Large Quantities of Precipitation	Fast-Moving Water Hazard	Oversaturation of Soil Moisture	Movement of soil and sediment	Soil Erosion
	Standing Water Hazard	Creation of water pools	Dewatering efforts	Grid Energy Used for De-Watering
			Water Intrusion	Limiting Access to Equipment (Higher MTTR and MDT)
				Electrical Hazard
				Electrical Hazard in Equipment Spaces

Figure 9. Examples of a Flooding Event Risks to Microgrids

3. Heat: In the event of rising temperatures, particularly prolonged periods of higher temperatures, we can expect to see direct impact to an installation’s readiness. The Photovoltaic Cells in solar generators are known to become less efficient at higher temperatures, at around 0.05% loss in efficiency for every Celsius degree (Glenn 2019). Heat also influences battery energy storage capacity, reducing its life cycle time in higher temperatures because of the material interactions within the battery (Bartlett 2019). Wind Turbine sensitive electronics must also be insulated and protected against higher temperatures to prevent failure.

Prolonged moderate heat waves can have a lasting and strenuous demand on an installation’s microgrid, which would require a higher sustained output from a system’s energy sources. Examples of effects and impacts on microgrids caused by heat can be seen in Figure 10.



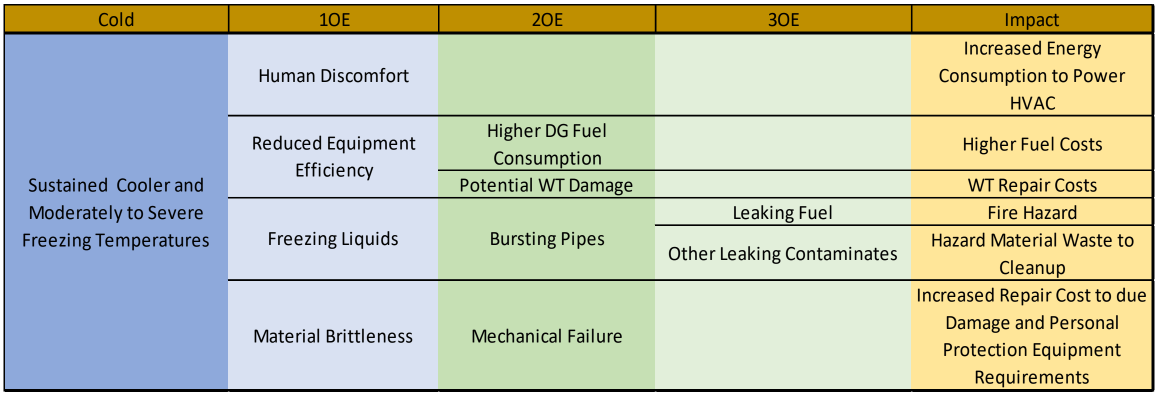
Heat	1OE	2OE	3OE	Impact
Sustained Moderate Heat	Exasperation of drought conditions	Decreased Water Quantity	Decreased water quantity	Less water for equipment cooling
	95F Degrees of Hotter		Higher demand on microgrid	Greater resource consumption
				Hightened risk of wildfire
	Damage to Equipment	Damage to Equipment	Damage to heat-sensitive electronics	Generator failure
Extreme Heat Spike	Effect of Efficiency	Effect on Efficiency	Higher temperatures have an effect on efficiency of PV panels	PV Panels will have lower output

Figure 10. Examples of Heat Event Risks to Microgrids

4. Cold: As with high heat environments, cold temperatures can result in an above average demand on the energy microgrid due to indoor climate control requirements. If not properly winterized, pipes and fixtures that transport liquids can be subject to freezing, which could potentially damage associated fixtures and valves. Burst pipes, valves, and other fittings could become a fire or hazardous material risk depending on the liquid being transported.

Though colder weather improves photovoltaic cell performance, there is a danger to wind turbine electronics and gears. As such, wind turbines should be properly winterized to prevent catastrophic damage that would reduce energy production on the microgrid.

Because proper Personal Protection Equipment is required by repair forces, an increase in MTTR can be expected in the event of damage to outdoor utilities. Examples of effects and impacts on microgrids caused by cold can be seen in Figure 11

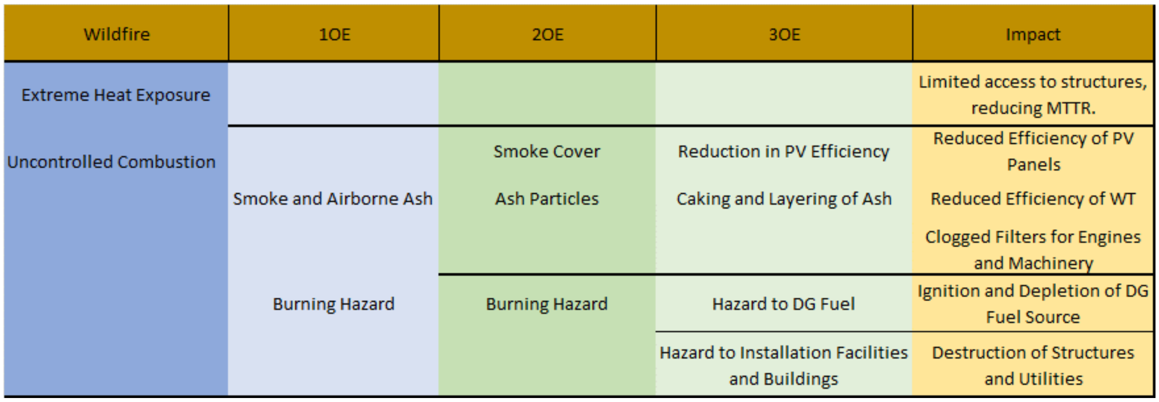


Cold	1OE	2OE	3OE	Impact
Sustained Cooler and Moderately to Severe Freezing Temperatures	Human Discomfort			Increased Energy Consumption to Power HVAC
	Reduced Equipment Efficiency	Higher DG Fuel Consumption		Higher Fuel Costs
		Potential WT Damage		WT Repair Costs
	Freezing Liquids	Bursting Pipes	Leaking Fuel	Fire Hazard
			Other Leaking Contaminates	Hazard Material Waste to Cleanup
	Material Brittleness	Mechanical Failure		Increased Repair Cost to due Damage and Personal Protection Equipment Requirements

Figure 11. Examples of Cold Event Risks to Microgrids

5. Wildfire: Fire poses a direct risk to an installation if located near vegetation and other fuel sources that can burn until those sources are exhausted, spreading to facilities and utilities within the installation. The path of the burn could limit access to certain structures or equipment and increase MTTR for any affected equipment. If precipitation follows wildfire damage, a landslide or mudslide scenario could cause damage to buildings and equipment as well.

   Ash particles carried by wind could also have an impact on energy generating equipment: settling on PV panels and blocking light, caking onto internal machinery and components of wind turbines, and clogging air filters for diesel generators. The ash particles are also acidic, which would react with seals and other vulnerable materials. Examples of effects and impacts on microgrids caused by wildfire can be seen in Figure 12.

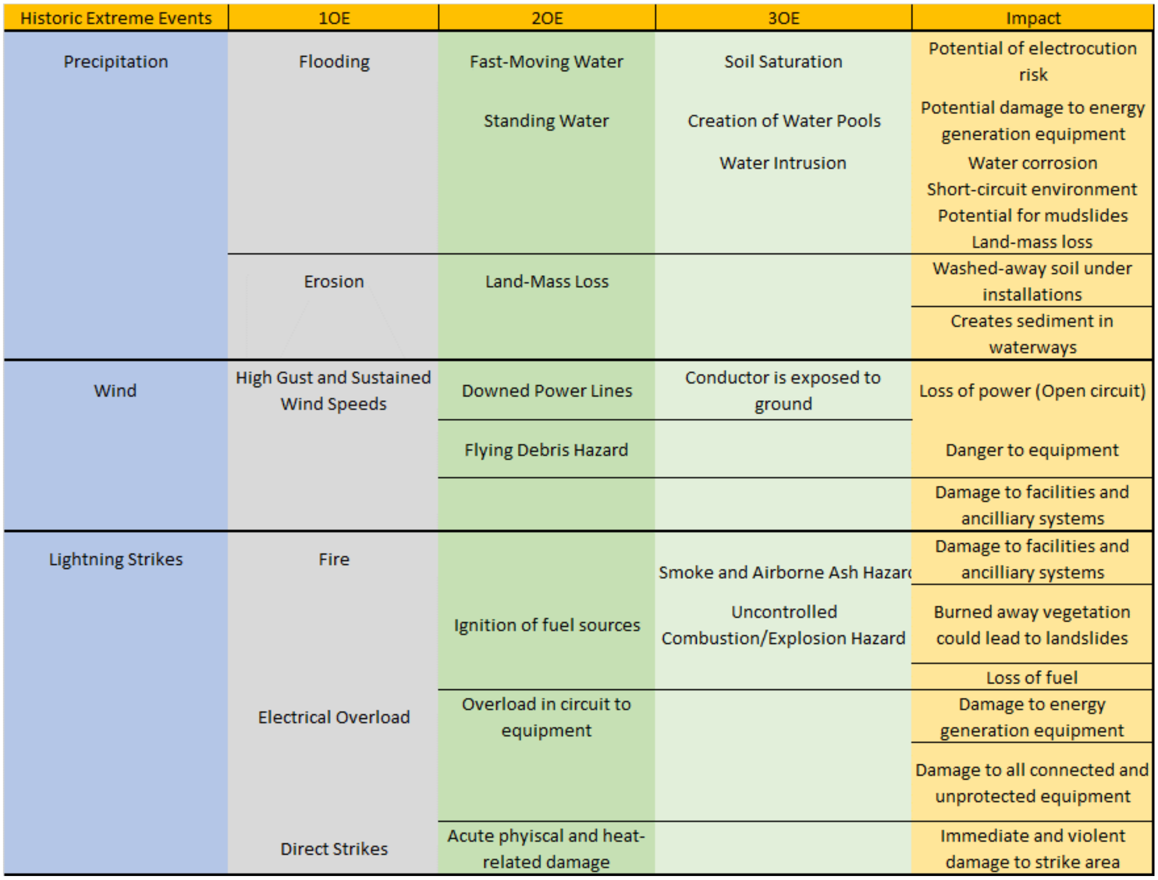


Wildfire	1OE	2OE	3OE	Impact
Extreme Heat Exposure				Limited access to structures, reducing MTTR.
Uncontrolled Combustion	Smoke and Airborne Ash	Smoke Cover	Reduction in PV Efficiency	Reduced Efficiency of PV Panels
		Ash Particles	Caking and Layering of Ash	Reduced Efficiency of WT
				Clogged Filters for Engines and Machinery
	Burning Hazard	Burning Hazard	Hazard to DG Fuel	Ignition and Depletion of DG Fuel Source
			Hazard to Installation Facilities and Buildings	Destruction of Structures and Utilities

Figure 12. Examples of Wildfire Event Risks to Microgrids

6. Weather Extremes: A common event on the east coast of the United States, extreme weather events present themselves as a hurricane originating in the Caribbean Sea and bring with them a host of other 2nd order effects such as flooding, high winds, and lightning strikes. The high winds are capable of much damage to exposed components of the microgrid. PV panels and wind turbine (WT) blades are easily carried by gusts and torn from their installations, possibly bringing down power lines. Though WTs can be brake-locked, there is little protection for PV panels. These high winds are also capable of blowing water into spaces or areas where water is not expected, which could also lead to further equipment damage.

   Wind borne debris presents a further risk to installations, hurling large objects into the air and causing damage to anything they strike. The airborne debris, wind, and flooding caused by these events pose a serious risk to installations by direct destruction and erosion of foundations through the simultaneous combination of 2nd order of effects. Examples of effects and impacts on microgrids caused by weather extremes can be seen in Figure 13.



Historic Extreme Events	1OE	2OE	3OE	Impact
Precipitation	Flooding	Fast-Moving Water	Soil Saturation	Potential of electrocution risk
		Standing Water	Creation of Water Pools	Potential damage to energy generation equipment
			Water Intrusion	Water corrosion
				Short-circuit environment
				Potential for mudslides
				Land-mass loss
	Erosion	Land-Mass Loss		Washed-away soil under installations
				Creates sediment in waterways
Wind	High Gust and Sustained Wind Speeds	Downed Power Lines	Conductor is exposed to ground	Loss of power (Open circuit)
		Flying Debris Hazard		Danger to equipment
				Damage to facilities and ancilliary systems
Lightning Strikes	Fire	Ignition of fuel sources	Smoke and Airborne Ash Hazar	Damage to facilities and ancilliary systems
			Uncontrolled Combustion/Explosion Hazard	Burned away vegetation could lead to landslides
				Loss of fuel
	Electrical Overload	Overload in circuit to equipment		Damage to energy generation equipment
				Damage to all connected and unprotected equipment
	Direct Strikes	Acute phyiscal and heat-related damage		Immediate and violent damage to strike area

Figure 13. Examples of Historic Extreme Event Risks to Microgrids

THIS PAGE INTENTIONALLY LEFT BLANK

IV. MICROGRID MODEL ANALYSIS

In this section, three microgrid models are reviewed and analyzed to determine the extent that climate change and extreme weather are incorporated into the models. The climate risks and weather extremes discussed in Section III.D are used to identify gaps in the model with respect to climate change.

A. MODEL OVERVIEW

Three models were selected for the analysis of the impacts due to the changing climate. All three models were developed by former NPS students. Each model is described to provide an understanding of the purpose of the model and the mathematics used to produce the model output. Dr. Anderson's model in Dr. Anderson's dissertation, "Resilience Assessment of Islanded Renewable Energy Microgrids," was chosen to analyze the effects that climate change has on the cost and resilience models used by the DON (Anderson 2020). Christopher Peterson's model in his thesis, "Analyzing Mission Impact of Military Installations Microgrid Resilience" (Peterson 2019) was chosen to demonstrate the impacts of climate change on the resilience measure used by the DON. Joshua Hildebrand's model in his thesis, "Estimating the Life Cycle Cost of Microgrid Resilience" (Hildebrand 2020) was chosen to identify the impacts of climate change on the life cycle cost of microgrid systems.

1. Resilience and Cost Modeling of Renewable Energy Microgrids

Dr. Anderson's dissertation focuses on the development of energy resilience and cost models for islanded microgrid systems. The objective of Dr. Anderson's work is to develop a resilience and cost trade space for islanded naval installation (INI) microgrids through the development of, what he states is "a methodology to choose renewable energy microgrid designs that maximize resilience and minimize costs on remote islands with applications for INIs" (Anderson 2020). The term islanded is described by Dr. Anderson as the disconnection from the external utility power. The method used to develop the resilience and cost trade space follows the path of establishing a baseline, simulating the baseline for resilience and cost measures, developing DER microgrid designs through microgrid optimization tools, selecting a design, simulating the design for the design's resilience and cost measures, and finally comparing the baseline to the various designs of interest.

Two separate models are used throughout Dr. Anderson's dissertation. These models include a resilience model and a cost model (Giachetti et al., 2021). Variables for both models include input variables, random variables, and decision variables. Figure 14 provides a description of the different inputs for the models. The values of each variable are determined by either the component specifications, the energy requirements of the installation of interest, or the available cost and disturbance data.

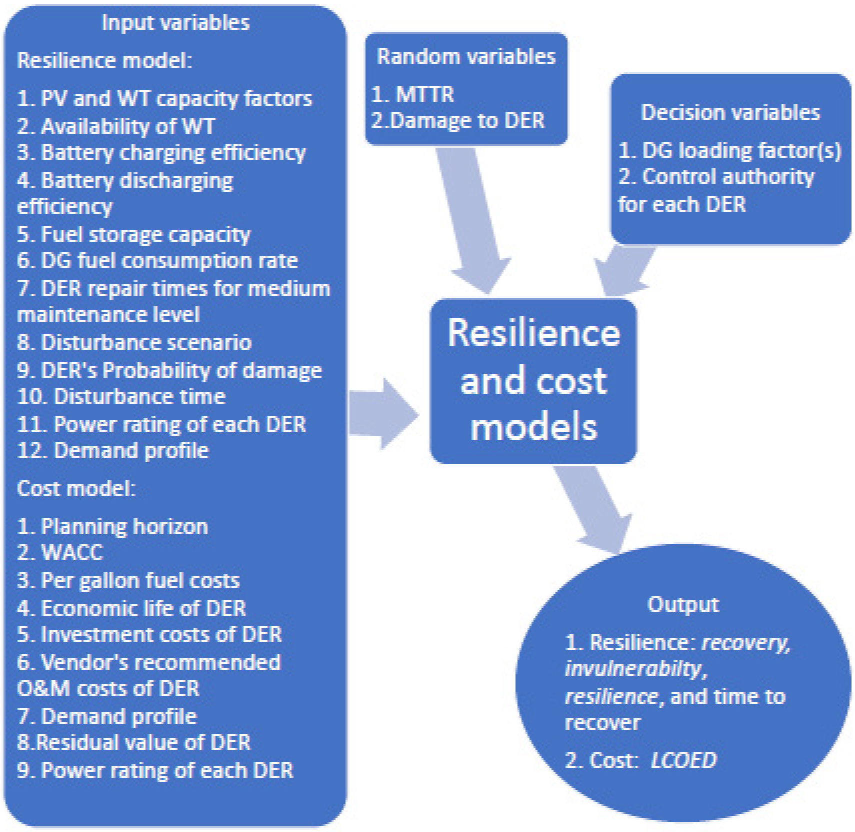


Figure 14. Model Inputs. Source: Anderson (2020).

The resilience model outputs the resilience of the modeled microgrid. The resilience measure includes the vulnerability and recovery of the microgrid after a disturbance occurs. Dr. Anderson defines invulnerability of the microgrid as "the ability of the microgrid system to resist power loss immediately following a disturbance" (Giachetti, Van Bossuyt et al. 2021). Additionally, Dr. Anderson defines recovery as the "microgrid system's ability to rapidly and completely return to the pre-disturbance performance level" (Anderson 2020). The cost model outputs the life cycle cost of energy for demand (LCOED) of the modeled microgrid. LCOED is defined as a cost measure for the life cycle cost of energy of a multi energy source microgrid to meet the installation demand. The outputs of the resilience model and cost model are combined to produce a 4-D trade space diagram shown in Figure 15.

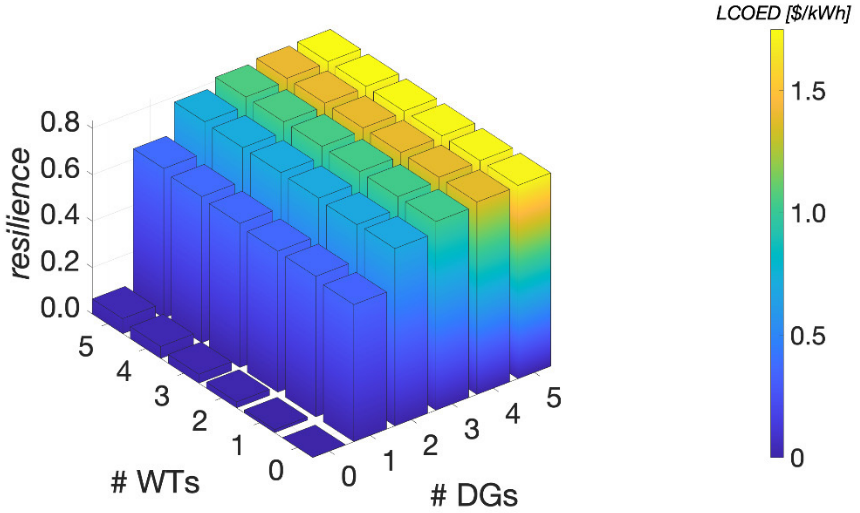


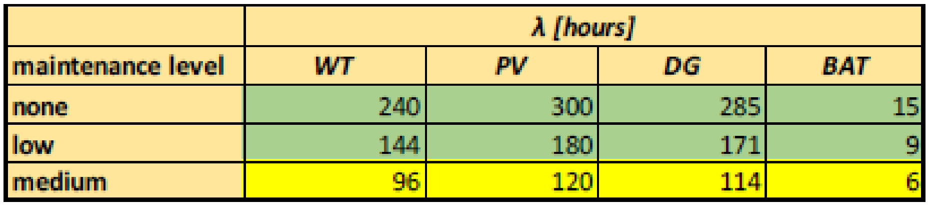
Figure 15. 4D Trade Space Graphic of Model Outputs. Source: Anderson (2020).

Dr. Anderson developed the resilience model to, as he stated, "model the behavior of a Renewable Energy (RE) microgrid over time while subjecting it to a disturbance" (Anderson 2020). These disturbances are categorized as High Impact Low Probability (HILP) disturbances. The HILP disturbances investigated in Dr. Anderson's dissertation include hurricanes, wildfires, earthquakes, and cyberattacks. Two simplifying assumptions were made in the resilience model. The first assumption states that, according to Dr. Anderson, “the disruptive event occurs at a point in time” (Anderson 2020). This assumption is made to simplify the resilience model for events that span a period, such as a hurricane or wildfire. Dr. Anderson’s second assumption states that “if damage occurs, it occurs immediately following the disruptive event” (Anderson 2020).

The resilience model makes several other assumptions that are necessary to appropriately model the resilience of a microgrid. The resilience model assumes that a DER will be restored. The resilience model assumes that the probability that a disturbance occurs is exclusive of the probability of damage, thus this creates the possibility of an event not causing damage to a microgrid component. The resilience model also assumes that the power demand does not drop below a specified power value (Anderson 2020).

Each component of the microgrid was provided a MTTR. The determination of the MTTR for each component assumes that there is a technician available and capable to make the repair and repair parts are located on-site and are available. Dr. Anderson determined the MTTR for each component through various technical documents. The time to repair a damaged DER (λ) values for each component are seen in Table 2.

Table 2. Mean Time to Repair DER Elements Adapted from Anderson (2020).

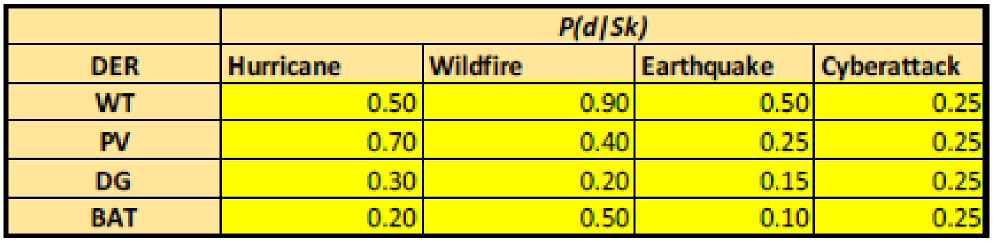


	λ [hours]			
maintenance level	***WT***	***PV***	***DG***	***BAT***
none	240	300	285	15
low	144	180	171	9
medium	96	120	114	6

The λ values for each component are separated into maintenance levels of none, low, and medium. The value of the DER maintenance level of none is calculated at 2.5 times the value of the maintenance level of medium. The value of a maintenance level of low is calculated at 1.5 times that of maintenance level medium. These values are used as inputs into an algorithm to determine the MTTR. The MTTR for each DER is the exponential of λ at the associated maintenance level. An additional algorithm is used to determine whether a DER is available by using the MTTR of the associated maintenance level for the DER as the required time input for the DER to become available.

The resilience model also uses conditional probabilities of damage to evaluate whether a DER is unavailable and requires a repair to become available. Dr. Anderson states that, "a DER will be damaged by a disturbance if it meets the conditional probability of damage given that a disturbance has occurred" (Anderson 2020). The resilience model uses an algorithm to generate a uniform random number. If the random number is less than the probability of damage for the DER, identified in Table 3, the DER is damaged and requires repair. If the random number is greater than the probability of damage, the DER is undamaged, thus the DER is available and generates power. For example, if the random number generator provides a value of 0.40 for the event of a hurricane, wind turbines and photovoltaic cells will be damaged and not provide power until restored.

Table 3. Probabilities of Damage. Adapted from Anderson (2020).



	P(d|Sk)			
DER	**Hurricane**	**Wildfire**	**Earthquake**	**Cyberattack**
WT	0.50	0.90	0.50	0.25
PV	0.70	0.40	0.25	0.25
DG	0.30	0.20	0.15	0.25
BAT	0.20	0.50	0.10	0.25

2. Mission Impact Model

Peterson develops a metric used to objectively measure the resilience of a microgrid design related to impacts to military missions. Peterson states, "the objective of this research is to optimize the system architecture to maximize mission achievement from the loads supplied by the microgrid" (Peterson 2019). The optimization of the system architecture requires an understanding of a quantitative measure for resilience. The metric developed in Peterson's thesis is called the expected life cycle mission impact (ELMI).

Peterson also found that cost is a significant consideration in most microgrid models. In addition to procurement and operational costs, costs may also be assigned to an inability to provide power to a load. He cites multiple authors and models that explore a variety of approaches to trade space that include some element and degree of cost. He observes that "metrics, methods, and tools used to optimize microgrids often focus on cost instead of energy security objectives" (Peterson 2019). In fact, he states, "This thesis concludes that a cost basis or load met are not appropriate metrics to develop microgrids that improve mission completion" (Peterson 2019). He points out that it is difficult to assign a cost to national security (Peterson et al. 2021).

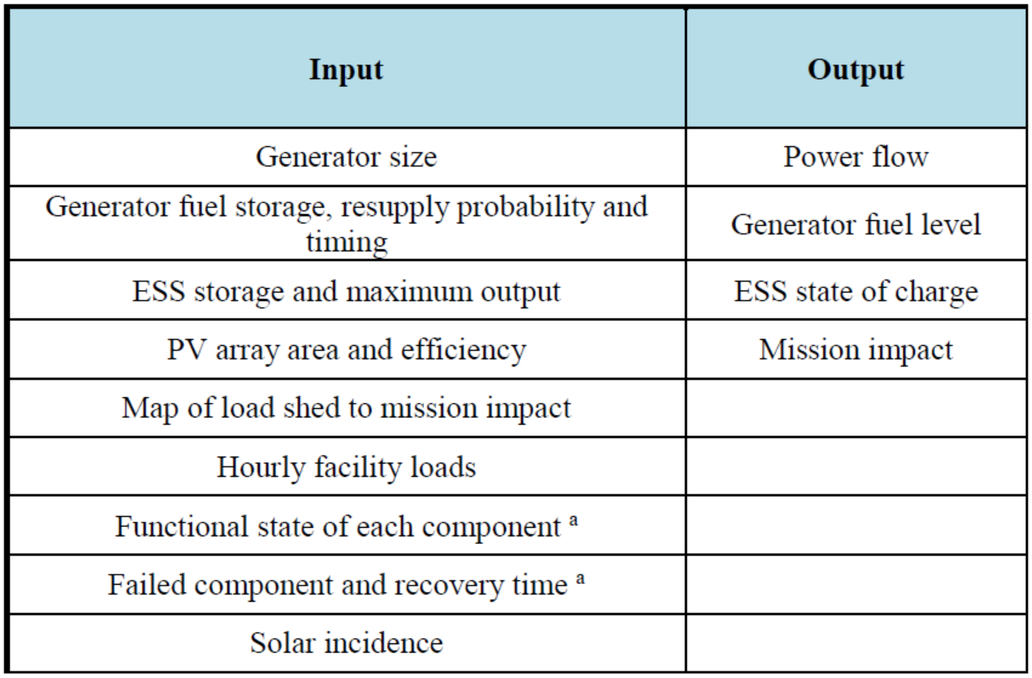
In developing his thesis, Peterson proposes a novel metric and method to determine the resiliency of a microgrid that prioritizes the importance of the mission objective while reducing the importance of cost. Based on his research, Peterson believes "that maximizing resiliency of a microgrid system is best achieved by minimizing the mission impact of threats to energy security" (Peterson et al. 2021). ELMI, which is given the name of expected electrical disruption mission impact (EEDMI) in the co-authored work titled "Analyzing Mission Impact of Military Installations Microgrid Resilience," is a calculation of the total impact of disruption events over all considered failure scenarios. Peterson's work includes the development of a model that simulates the resilience of an islanded microgrid for a two-week period. By comparing the results of different designs along with failure scenarios, the designer can maximize mission achievement through optimization of the architecture and show which equipment failures cause the biggest impact.

Peterson created a methodology to develop a design and determine the resilience of the microgrid. Peterson's 7-step method attempts to optimize microgrid architectures without considering phase imbalances, power factor issues, or energy flow direction (Peterson et al. 2021). This seven-step process defines the critical loads and mission for each facility, generates the set of scenarios the microgrid is simulated under, determines the recovery time for each scenario, maps the power lost to mission impacts, simulates the system under the scenarios, calculates the mission impact, and analyzes the results of the simulated system.

The first of the seven steps outlined is to determine the mission impact in terms of how the mission contributes to the load. This is done by associating each facility's load to the ability of mission accomplishment if the power was lost. The numerical range assigned to the mission impact variable is 0–100 for this model.

The second step is to determine a set of failures unique to the shore installation and the probably of annual occurrence. These failure modes should include maintenance issues and other events. The baseline is the scenario when the system is disconnected from the grid for a specified duration (e. g., 7 days, 14 days, etc.) without other failures. Table 4 is a summary of inputs and outputs used in this model. Adjusting the values of the inputs, the designer can simulate failure scenarios and determine how they impact the resiliency of the system (Peterson 2019). Peterson recommends that failure scenarios include equipment failure to include historical data, impacts of other systems and factors upon which the microgrid is reliant, and events outside the system boundary.

Table 4. Model Inputs and Outputs. Adapted from Peterson (2019).



Input	Output
Generator size	Power flow
Generator fuel storage, resupply probability and timing	Generator fuel level
ESS storage and maximum output	ESS state of charge
PV array area and efficiency	Mission impact
Map of load shed to mission impact	
Hourly facility loads	
Functional state of each component [a]	
Failed component and recovery time [a]	
Solar incidence	

[a] optional

The baseline system includes a pair of diesel generators, a photovoltaic array, and battery storage among other items. The model uses a decade of actual, hourly data showing electrical load. Peterson states that the user can “vary the failure rates and repair times to capture the sensitivity of the grid resilience to different factors” (Peterson 2019). A series of test scenarios are run to determine the best design. Scenarios start with the baseline condition of no equipment failures and result in no failures. Additional scenarios are created and run to simulate different annual failure rates and MTTR of each piece of equipment.

Scenarios that result in equipment failure are generated by the designer. Such scenarios may include a single piece of equipment failure in one scenario and the failure of multiple items in another scenario. The designer is expected to determine equipment failure probability and repair rates for each piece. Peterson et al. provides an example scenario of a natural disaster: a wildfire and the failure of two pieces of equipment and one connection. The designer would use external data sources to determine the probabilities and failure rates. Another example is an atmospheric debris flow where the designer assumes specific pieces of equipment fail in this event.

The third step is to determine the recovery time of each component in the system. Peterson proposes, “a probability distribution to account for the variation in repair times, and scenario dependent” (Peterson 2019). Peterson identifies that the repair times after a natural disaster has occurred will likely be higher than under normal repair conditions. The use of a probability distribution allows for the incorporation of differing repair times which can include low probability, but high impact events such as extreme weather events.

The fourth step is to map the power lost to the mission impact. Peterson states that this step requires the modeler to “map the disruption of power to an amount of mission impacted as a function of the amount and time of load shed. This mapping should be scenario based to capture the impact as a function of load shed and time” (Peterson 2019). Peterson cites examples where power lost for a few minutes can have a significant impact to days of production. One citation relates how a brief interruption to power can result in months of electron microscope recalibration (Cohn 2014).

The fifth step is to simulate the microgrid system using the model. Peterson states that the role of the model is to determine “the power flow within the system, the pertinent states of the equipment within the system such as the battery state, PV power being generated, and functional states of the components that make up the microgrid” (Peterson 2019). The model calculates the mission impact while determining the load shedding and behavior of the system and facilities. Peterson recommends a Monte Carlo simulation to iterate over each of the various scenarios.

The sixth step is to calculate the total mission impact of disruption events over all scenarios to determine the ELMI, which quantifies the resilience of the system. This starts with calculating the mission impact for a single scenario as,

$$M_s = \sum_{t=1}^{T} MI_s, t$$

, where MIs is the Mission Impact of the scenario for the entire duration (T) of the scenario. ELMI is

$$ELMI = \sum_{s \in S} Pr(S = s)\, M_s$$

, where Pr(S = s) is the estimated probability of a failure scenario (s) occurring from a set of failure scenarios (S) that could disrupt the power supply.

The seventh step of Peterson’s method is to analyze the results to identify significant contributors to the mission impact, potentially modifying inputs to explore improvement options. Peterson states that the analysis requires an “inspection of the contribution of each scenario to ELMI informs the manager which scenarios or probabilities contribute most” (Peterson 2019). The analysis is performed iteratively on the different microgrid architectures which results in ELMI measures for each design for comparison.

3. Cost of Resiliency Model

Joshua P. Hildebrand’s thesis, “Estimating the Life Cycle Cost of Microgrid Resilience,” focuses on the development and implementation of a seven-step process to estimate the cost of microgrid resilience using the design of experiments and regression analysis (Hildebrand 2020). Hildebrand demonstrates the use of Net Present Value (NPV) to quantify the life cycle cost. Hildebrand also determines that the ELMI is “the most appropriate metric to quantify microgrid resilience because it accounts for both the probability of a disturbance occurring and the impact the disturbance has to mission completion” (Hildebrand 2020). The use of both measures, NPV and ELMI, allow for the estimation of the cost of microgrid resilience.

The process is designed for use by installation energy managers when planning any installation or upgrades to base microgrid systems. In his study, Hildebrand analyzes a microgrid that is representative of a portion of the electrical distribution system at Naval Postgraduate School located in Monterey, CA. The study demonstrates the effectiveness of the process developed in his thesis and the importance of understanding the cost of microgrid resilience to make informed decisions about the necessary distributed energy resources that make up a specific microgrid architecture.

The seven-step process developed by Hildebrand is as follows:

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

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

The development of the DOE consists of identifying the different configurations of the microgrid and the various combinations of microgrid components to make up each configuration. This process starts by analyzing the loads the microgrid will support. The identified load is used to develop a DOE of microgrid configurations of various DERs and energy storage systems (ESSs). Hildebrand states that the "number of factors to be included in the DOE is dependent on the number of controlled variables in the microgrid performance model that will be used. To be included in the DOE, each factor must have at least two levels (a high and low value), but any include additional levels if desired" (Hildebrand 2020). The value for each factor is determined on the identified loads and the characteristics that affect system performance.

Resilience scores are determined for each microgrid configuration in the DOE. Hildebrand indicates that the microgrid should be simulated under the worst-case-scenario, which this scenario is "up to the installation energy manger to identify" (Hildebrand 2020). The simulations conducted in Hildebrand's research assumes a 14-day outage as the maximum operational time of the microgrid. Additionally, the worst-case-scenario used in the research assumes the lowest average solar incidence for the 14-day period.

The process includes the estimation of the LCC for each microgrid architecture used in the DOE. The life cycle is assumed to be 40 years, or the lifespan of the energy system if the lifespan is less than 40 years. The LCC is primarily influenced by the variations in microgrid architectures which includes the design of DERs, design of the ESS, distribution lines, transformers, microgrid controller, AC/DC converters, switches, breakers, and the average annual DG fuel consumption. It is assumed that the cost to install components and the cost to tie into the microgrid are constant regardless of the microgrid architecture.

Each DOE result is analyzed to ensure the full range of microgrid architectures are analyzed for both a resilience score and LCC. The main effects plots for each measure are analyzed for the impacts of each factor on both measures. Hildebrand states "if any of the factors show they have significant impact on resilience or LCC the installation energy manager should consider adding more levels to the DOE" (Hildebrand 2020). This portion of the step indicates an iterative step within the process. This ensures that the DOE accurately represents the impacts of each factor for each microgrid architecture. Once the DOE is finalized, the process utilizes the resilience and LCC measures to perform a regression analysis for the identification of potential relationships between the two measures. The identified relationships are used to quantify the cost of resilience increases.

The process was demonstrated using a model representative of a possible installation useable on site at Naval Postgraduate School (Hildebrand 2020). The model microgrid, as represented in Figure 16, consisted of five loads, two DGs, an ESS, a PV, and the ability to operate in both grid connected and islanded modes. The model allowed for generators and PV systems of different sizes to be simulated to produce meaningful results that allow for installation energy managers to customize their microgrid resiliency. A total of 18 different regression equations were used to estimate the cost of this specific microgrid's resilience, with each equation correlating to specific characteristics such as fuel capacity, total DG capacity, and ESS efficiency. From the results of the simulation, it was noticed that the number of generators and efficiency of the PV had little to no impact overall on ELMI or NPV, while the size and output capability of both played a much larger part.

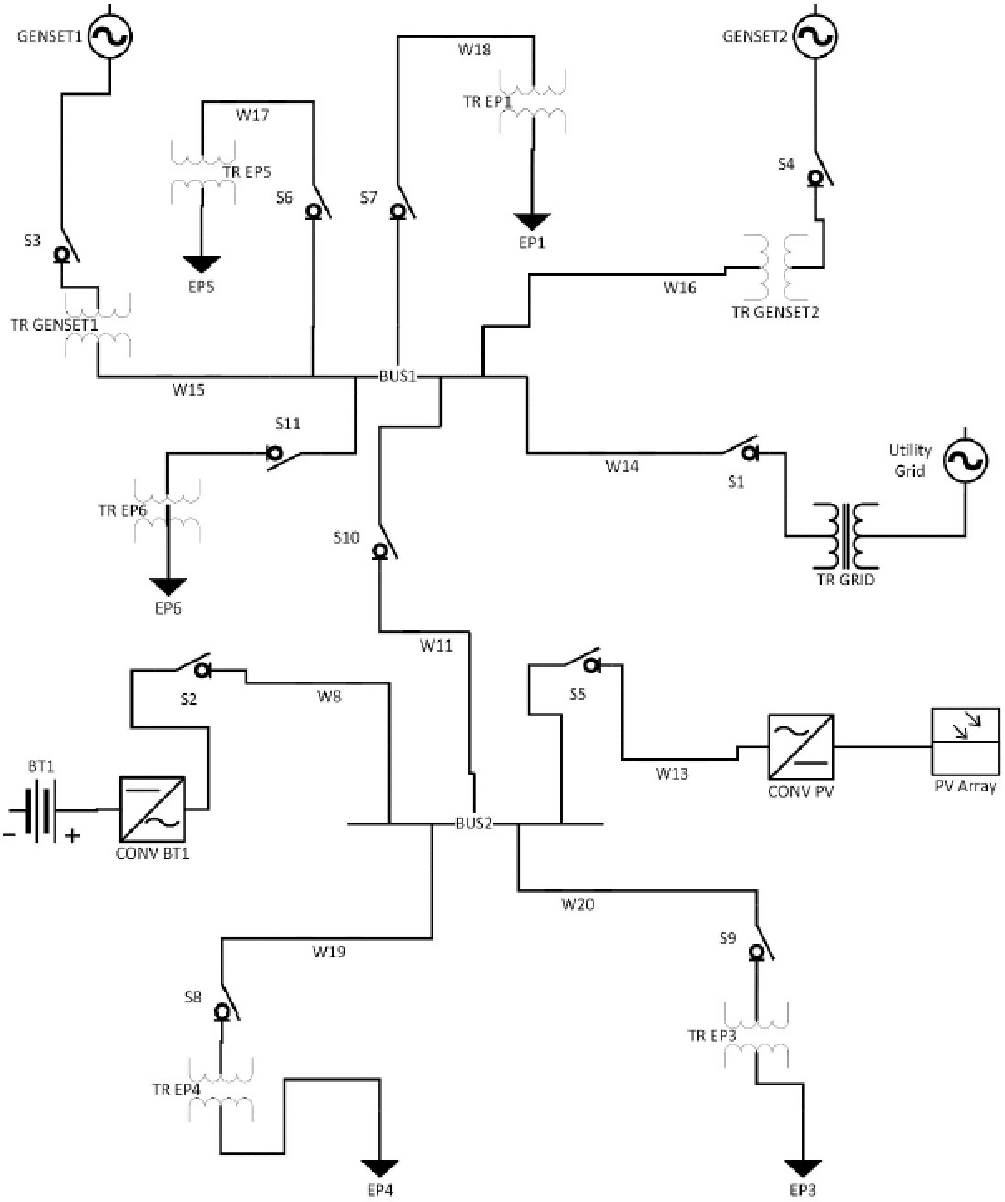


Figure 16. A Microgrid Representative Model. Source: Hildebrand (2020).

B. MODEL GAP ANALYSIS

The analysis of the three models requires a uniform process to determine the gaps that exist in the models when the six climate risks identified in this report are considered. The process for the analysis is categorized into three categories. These categories include the model's approach, input parameters, and assumptions. The gap analysis is performed by examining the impact of each separate climate risk on each category of the model. Table 5 identifies the three categories of the analysis and the questions asked to determine if a gap exists in the category for each climate risk.

Table 5. Categories of Model Analysis

Analysis Category	Considerations Or Questions
Modeling Approach	Does the model identify the six climate risks in the model?
	Does the model address climate risks that occur over a long period of time?
	Does the model incorporate climate risks and exposure to the climate risks over an extended duration of time?
Modeling Assumptions	Do the assumptions made in the model limit the incorporation of the climate risks?
Modeling Input Parameters	How do the climate risks affect the input data?
	Can the model user incorporate short term climate risks (historic weather events, flooding, wildfires, and temperature spikes)?
	Can the model incorporate long term climate risks (increased frequency of exposure to all climate risks, gradual temperature increases and decreases, and drought)?

The gap analysis on the model's approach examines if the approach allows for the incorporation of the climate risks. This includes determining if the model addresses the six climate risks and whether the climate risks are accurately represented in the model. Additionally, the analysis determines whether the model considers the changes in climate over time and if the incorporation of the changes in climate affect the output for models that predict the future state of the microgrid. The analysis does not quantify the impact that the changes in climate might have on the future state of the microgrid.

Performing the analysis on the model input parameters consists of identifying the input parameters that are affected by the climate risks. This includes determining the level of impact the climate risk has on the model input parameter. If a model input parameter can be impacted by either a first or second order affect and is not considered in the model, this is considered a gap in the model. These impacts are documented for each climate risk.

The model analysis examines the impact of each climate risk on the assumptions in the model. Each assumption is analyzed to determine if the climate risk changes the assumption made in the model. Additionally, the analysis determines whether there are assumptions that should be variable inputs and whether the model requires additional assumptions when incorporating the climate risks.

1. Resilience and Cost Modeling of Renewable Energy Microgrids Gap Analysis

Analyzing Dr. Anderson's resilience and cost model began with understanding both the approach and assumptions of the model. The model outputs a resilience and cost trade space for the design of distributed energy resource microgrids. The model utilizes extreme weather events, such as hurricanes and wildfires, to subject the microgrid to a disturbance for the resilience measure. The approach allows for the incorporation of weather events; however, there is one assumption that limits the model from completely addressing the climate risks. Dr. Anderson states that, "the model assumes the disruptive event occurs at a point in time" (Anderson 2020). Extreme weather events, wildfires, and extreme hot or cold temperatures can last periods of days to weeks. The impacts due to floods, extreme weather events, and wildfires can be felt for even longer periods of time. Droughts can last for years to decades. The assumption of the disruptive event occurring at a point in time limits suggests the inability to model the impacts of prolonged exposure to the climate risks.

The analysis into Dr. Anderson's model requires the identification of input and variable parameters to determine whether climate change is addressed (Anderson 2020). The resilience model segments the parameters into input parameters, decision variable parameters, and variable parameters. The parameters of interest for this analysis include the availability, capacity of each energy resource, diesel generator fuel consumption rate, repair times for medium maintenance level, disturbance scenario, probability of damage, disturbance time, demand profile, mean time to repair, and damage to DER. Each of these variables are listed in Table 6. Table 6 identifies the climate risks that impact the parameters and the potential level of impact the climate risks have on the model output.

Table 6. Model Parameters Source: Anderson (2020).

Parameter	**Climate Risk(s)**
Availability factor of a wind turbine (A)	Cold, Weather Extremes, Flooding
Capacity factor of DER (C)	Flooding, Cold, Heat, Wildfires, Weather Extremes
Disturbance for scenario k (S_k)	Drought, Flooding, Cold, Heat, Wildfires, Weather Extremes
Critical infrastructure demand at time t (D_t)	Drought, Flooding, Cold, Heat, Wildfires, Weather Extremes
Time to repair a damaged DER (λ)	Flooding, Cold, Heat, Wildfires, Weather Extremes
Probability of DER being damaged given disturbance ($P(d/S_k)$)	Drought, Flooding, Cold, Heat, Wildfires, Weather Extremes
Diesel Generator's maximum fuel consumption rate (W)	Cold, Heat
Power rating of DER i at time t (P_{ti})	Flooding, Cold, Heat, Wildfires, Weather Extremes
Power generated by microgrid at time t (G_t)	Flooding, Cold, Heat, Wildfires, Weather Extremes
Fuel consumption for diesel generator i in time period t (z_{ti})	Cold, Heat
Mean Time to Repair (MTTR) the damaged DER ($MTTR_i$)	Flooding, Cold, Heat, Wildfires, Weather Extremes

Dr. Anderson defines the availability factor as "the percentage of time that the wind turbine operates, that is it is not inoperable due to maintenance being needed and/or performed" (Anderson 2020). The availability factor is a constant factor in the overall microgrid power rating and is set at a value of 0.98 or 98%. This indicates that the wind turbines are operable 98% of the time. A 98% availability rate also translates to the wind turbine being inoperable due to maintenance for seven days out of a full year. The availability factor for photovoltaic cells is set to 1, or 100%, because photovoltaic systems are assumed to have a high availability rate.

The climate risks associated to Naval Installations identified throughout this report have impacts to the availability of wind turbines and photovoltaic cells. Coastal and riverine floods can cause minor to severe damage to both wind turbines and photovoltaic cells. Minor damage may not result in a loss of the DER but will increase the amount of maintenance required for the system to ensure the system operates at the intended capacity throughout the determined system life cycle. An increase in required maintenance will impact the availability of both wind turbine and photovoltaic systems. The parameter of 98% availability for wind turbines and 100% for photovoltaic cells may not suffice for modeling the resilience of microgrid systems.

Dr. Anderson (2020) utilizes capacity factors to incorporate the factor of actual energy produced into the resilience model. Dr. Anderson defines the capacity of DERs, including renewable energy (RE) resources, as an indicator for "how much power a particular RE generates for a specific location and is the ration of the actual energy produced in a given time period to the maximum possible" (Anderson 2020). Dr. Anderson reports that the total power generation for a wind turbine increases from 8:00 P.M. to 8:00 A.M. The total power generator for photovoltaic panels is 0 kW from 8:00 P.M. to 8:00 A.M. The capacity factor of both wind turbines and photovoltaic panels considers the diurnal variations. To prevent overestimation in energy generation from wind turbines, the capacity factor for wind turbines is reduced by 50%. The capacity factor is doubled for photovoltaic panels to prevent underestimation of the energy produced.

The capacity factors of DERs do not consider the impacts due to the climate risks. Wind turbines and photovoltaic cells are impacted by weather extremes, temperature, wildfires, and flooding. Cloud cover and high winds are associated with weather extremes. During these weather extremes, wind turbines are deactivated to reduce the risk to damage on the system. Additionally, photovoltaic panels do not generate power at the nominal rating due to cloud cover. When weather extremes occur, it can be expected that the capacity factor will not be the same as when the weather conditions are optimal for these systems. Flooding will also result in a lower capacity factor due to the risk mitigation procedures at the Naval installation resulting in the deactivation in wind turbines and other energy sources. Wildfires have a similar effect on photovoltaic panels as weather extremes when considering the smoke cover. The smoke from the wildfire acts similarity to cloud cover, resulting in a lower power output from photovoltaic panels. This is not accounted for in the capacity factor parameter. An increased number of particles in the air due to the dryness of drought can contribute to reduced area as the particles in the air settle on the surface of the array. This may also be a contributor to reduced efficiency in electrical production when less sunlight reaches the cells that convert the solar energy to electricity. Extreme high and low temperatures also impact the capacity factors of DERs. Extreme heat causes a reduction in power output from photovoltaic cells. As the operational temperature rises, the efficiency decreases in a linear fashion (Dubey et al., 2013). Extreme cold temperatures can cause wind turbine components to freeze. The freezing of the wind turbine does not typically result in damage but will affect the expected power output.

Diesel generators are also affected by the climate risks. Diesel generator capacity, defined as the rating of the diesel generator, is determined by including temperature and pressure considerations (Generator Source n.d.). Diesel generator efficiency is also affected by the same factors. Heat is required for efficient combustion of fuel. However, too much heat could cause destruction of gaskets and other components. Extreme cold reduces efficiency. Depending on what components are exposed, materials could become brittle leading to ease of breakage during vibrations or other physical pressures. The efficiency is also affected by the load where a generator can be less efficient with high loads and low loads. A prolonged exposure to high heat or overload would cause degradation of the equipment over time. The loads may come from the use of HVAC and personal space heaters to combat temperature extremes, water pumps activated during and after a flood, and other electrical equipment.

Dr. Anderson uses a critical infrastructure demand profile through his microgrid model. The critical infrastructure demand profile used in Anderson's model does not provide information on the reasoning or assumptions regarding the demand profile (Anderson 2020). If a climate risk puts a strain on the Naval installation, the energy demand profile could be higher at each time step to operate pumps after a flood, HVAC due to prolonged cold or hot temperatures, or additional critical infrastructure needs after a weather extreme. The record low temperatures in Texas in 2021 (Wright 2021) demonstrates that a spike in energy demand to heat homes and buildings can cause power grid failures. If an event like this occurs at a Naval installation, the energy demand will likely rise past the expected energy demand. Extreme weather brings cloud cover which often results in an increase demand to illuminate an area by turning on more lights. Drought and wildfires potentially increase the particle count in the air which eventually results in reduced efficiency in air flow through clogged filters and possibly increased maintenance costs if filters need to be changed sooner. The demand profile must consider the changes in the demand during or after a Naval installation encounters a climate risk.

The time to repair a damaged DER and the MTTR the damaged DER are other input parameters that must consider the regional climate risks. Flooding, wildfires, and extreme cold can result in an increased MTTR. If equipment is damaged during a flood and excess water accumulated around damaged microgrid components, the access to the damaged equipment may be limited, requiring pumps to remove the water, or waiting until the water recedes. The increased time required to gain access to the damaged microgrid component will increase the time to repair the damaged component, resulting in an increased MTTR. Additionally, the prolonged exposure to water will increase the rate of corrosion for microgrid components. The U.S Geological Survey states that "corrosive groundwater, if untreated, can dissolve lead and other metals from pipes and other components" (Belitz et al., 2016). This will primarily impact the operational availability of the microgrid component. Wildfires will also impact the MTTR of microgrid components due to the accessibility to the damaged equipment from either the wildfire or the smoke from the wildfire. Extreme cold temperatures can impact the effectiveness of maintenance crews, increasing the time to repair the damaged microgrid component. These impacts must be considered when considering the input parameters for the MTTR of the microgrid system.

The power output of a diesel generator can be affected by hot and cold temperatures. Hot and cold temperatures reduce the efficiency of diesel generators, resulting in either a reduced power output or an increase in fuel consumption to maintain the required power output. Elsebaay et. al evaluate the effect of ambient temperatures on generator power rating identifying that the generator capability "should be decreased (de-rating the generator power) as a result of the increase in ambient temperature above the maximum (40 °C) to keep insulation temperature within range" (Elsebaay et al., 2017). The model utilizes the diesel generator maximum fuel consumption rate and the fuel consumption at a time interval as parameters to the model. Hot and cold temperatures may increase the maximum fuel consumption rate past the assumed point and increase the consumption rate at each time interval.

The impacts to the capacity factor, availability factor, and MTTR due to the climate risks will impact the overall power generated by the microgrid. Dr. Anderson's model determines the power generated by the microgrid at a time interval by calculating the sum of the power generated by each energy resource. When the climate risks impact the capacity factor, availability factor, and MTTR, the power generated by each energy resource will vary. For example, a hurricane may damage photovoltaic panels and wind turbines, significantly reducing the power generated by both systems. Unless the other energy resources can increase the power generation to meet the demand, the microgrid will operate at a lower power output

2. Mission Impact Model Gap Analysis

An analysis of Chris Peterson's microgrid model was performed to understand to what degree climate risks are incorporated. The model's method of utilizing input parameters limits the ability to accurately represent the impacts of climate risks on the output of the model. A limited period (e.g. 14 days, etc.) is modeled using current or historical data. Inspection of the model indicates that the approach of the model does not allow for the incorporation of necessary climate and weather data to demonstrate the effects of the long-term climate risks on the mission impact.

Table 7. Mission Impact Model Inputs Potentially Affected by Climate
Source: Peterson (2019).

Parameter	**Climate Risk(s)**
Generator size (capacity)	Flooding, Wildfires, Weather Extremes
Generator fuel storage	Flooding, Cold, Heat, Wildfires, Weather Extremes
Generator efficiency	Cold, Heat
Generator refuel	Flooding, Wildfires, Weather Extremes
Generator Probability of refuel	Flooding, Cold, Heat, Wildfires, Weather Extremes
ESS (BT1) storage	Flooding, Cold, Heat, Wildfires, Weather Extremes
ESS Maximum Output	Flooding, Cold, Heat, Wildfires, Weather Extremes
ESS efficiency	Cold, Heat
PV array area	Drought, Flooding, Wildfires, Weather Extremes
PV efficiency	Drought, Flooding, Cold, Heat, Wildfires, Weather Extremes
Hourly facility loads	Drought, Cold, Heat, Wildfires, Weather Extremes
Solar incidence data	Wildfires, Weather Extremes

The climate risks, the ordered effects, and the impacts to the microgrid are not directly included in the model. Changing the value of the inputs to this model requires a change to the source code. Table 7 lists the parameters available for modification within the model’s code that could potentially be affected by one or more of the six climate risks identified in Section III.D.

Peterson's model utilizes inputs that are common to Dr. Anderson's model. These common inputs include the generator size, generator efficiency, PV efficiency, solar incidence data, hourly facility loads, and MTTR. The generator size, efficiency, PV efficiency, and solar incidence data are common inputs with the capacity factor of DERs and power generated by the DER. The specific inputs used in Peterson's model may not be used as a specific input in Dr. Anderson's model but used as factors that inform the inputs in Dr. Anderson's model. The hourly facility loads, and critical infrastructure demand are common between Dr. Anderson's and Peterson's models. This input type is used as a demand profile in both models and are affected by the same climate risks. The MTTR of microgrid components is used in both microgrid models. Both models utilize MTTR to determine the time required to restore a microgrid component to an operational state for the determination of the resilience measure. The climate risks that impact these common input types are identified in Section IV.B.1.

Generator fuel storage could be affected by flooding if the waters enter the tank. If water enters a diesel fuel tank, the water settles to the bottom reducing the amount of diesel fuel that can be added into the tank. The water causes rust which damages the tank and rust can float and clog fuel filters. Flood water may also allow algae to grow and cause similar issues (Ricochet Fuel Distributors 2020). Fuel storage could be affected by flooding if the flooding undermines the foundation of the storage container, whether it is above ground or in the ground. Wildfires and Extreme weather events could also cause damage.

Generator refuel is the time between each refueling of the generator fuel tanks. Generator Probability of refuel is a fixed value of 0.95 probability of success of refueling the fuel tank. Weather events could impact deliveries of fuel for the generators possibly due to delays of delivery vehicles because of challenges in arriving at the storage tank or by damage to pipelines due to trees falling in the wind.

ESS (BT1) Storage can be affected by environmental factors that prevent its transmission of energy, reduce its efficiency, or prevent it from being recharged so it can continue to supply energy upon demand. BT1 is a fixed value of battery storage of 3000 kW*h. While normally set to 20% of the ESS storage capacity in the model, the ESS maximum output is fixed in this version of the model to a maximum output of 300 kW.

When a battery is left unused over time, it will self-discharge. Some of this charge is recoverable by recharging the battery before use. Over time, the capacity of the battery is reduced permanently with heat accelerating the permanent damage (Battery University 2021). Storing a battery below 0 degrees C will also permanently harm the battery (Lejtman 2022). Humidity (often a byproduct of rain) can cause corrosion and leakage and should be minimized (Panasonic n.d.).

The model utilizes equipment failure scenarios to represent damaged equipment. These failure scenarios can represent the impacts of weather extremes, such as hurricanes; however, the failure scenarios lack the ability to represent the degradation over longer durations of time due to longer duration climate risks. The failure scenarios assume that a microgrid component has completely failed resulting in no power output from the component. Longer duration climate risks, such as heat waves that may occur over a couple of weeks and gradual temperature increases that may occur over a few years, could also result in scenarios that result in component degradation rather than complete component failure.

3. Life Cycle Cost of Microgrid Resilience Model Gap Analysis

The gap analysis of the model outlined in Hildebrand's thesis, "Estimating the Life Cycle Cost of Microgrid Resilience," focuses on the model's incorporation of the climate risks in the approach and the impact of the climate risks on the model's input parameters and assumptions. The analysis into the approach examines the methodology of the DOE and the estimation of the LCC for the resilience and cost relationships. The examination into the input parameters and assumptions lists the different inputs and assumptions that can be affected by the climate risks as seen in Table 8 below

Table 8. Life Cycle Cost Model Inputs Potentially Affected by Climate Risks

Parameter	Climate Risk(s)
Fuel Capacity	Flooding, Wildfires, Weather Extremes

Parameter	Climate Risk(s)
Total Generator Capacity	Flooding, Heat, Cold, Wildfires, Weather extremes
Total Generator Efficiency	Flooding, Heat, Cold, Wildfires, Weather extremes
Microgrid Load	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes
PV Array Size	Drought, Flooding, Wildfires, Weather extremes
PV Array Efficiency	Drought, Wildfires, Weather extremes
ESS Capacity	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes
ESS Efficiency	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes
Failure Scenario	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes
O+S Cost	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes
Investment Cost	Drought, Flooding, Heat, Cold, Wildfires, Weather extremes

The model developed by Hildebrand utilizes input types that are common between Dr. Anderson's and Peterson's microgrid models. These common inputs include the fuel capacity, total generator capacity, total generator efficiency, microgrid load, PV array size, PV array efficiency, ESS capacity, and ESS efficiency. Hildebrand utilizes ELMI, the resilience measure developed by Peterson, to measure the resilience of the modeled microgrid. Since this measure is common between the two models, most of the model inputs are similar. Hildebrand expands the use of ELMI by incorporating microgrid costs, such as O&S and investment costs, to determine the LCC of the microgrid. These cost metrics were not used in either Dr. Anderson's or Peterson's models. The method for determining the failure scenarios was also not utilized in the same manner as Dr. Anderson's or Peterson's models. Thus, the inputs of cost metrics and failure scenarios, are analyzed in this section.

The failure scenarios addressed in Hildebrand's thesis lack the inclusion of potential environmental risk factors. The binary system is expressed as pass or fail, so the scenarios fail to include the effects of climate risks on the system components. For example, the current model fails to address what the power generation capability for the model will look like if a wildfire occurs reducing the PV generation capability due to reduced sunlight from smoke. Additionally, the DG generation capability is reduced from the smoke in the air clogging intakes and reducing oxygen levels. By using a binary system, the model fails to account for reductions in working capacity and how those reductions would affect the microgrid while acting in an islanded mode.

The operational and support costs are constant in the model which limit the incorporation of the impacts due to the climate risks on the operational and support costs. Temperature changes causing increased needs for climate control in buildings means increased fuel consumption for DG's. Weather events can cause damage to components of the microgrid requiring repair or replacement. Operational and support costs can vary greatly year to year, so variability should be permitted for this input.

Investment costs are also used as a constant input in this model, as only the costs of the initial purchase and phased replacements are allocated over the life cycle of the specific component. The model fails to consider possible failures requiring replacements at a faster rate. Failures caused by weather events can affect different components in different ways. For example, if consistent flooding causes damage to the PV array requiring replacement after 6 years vice the 10 years that was estimated, investment costs will increase in order to retain the same level of resiliency.

The model considers nine components when evaluating the microgrid's life cycle cost. These include the layout and design of the DERs, layout and design of the ESS, distribution lines, transformers, microgrid controller, AC/DC converters, switches and brakers, average annual DG fuel consumption, and infrastructure required to tie the microgrid into the main utility grid. The method for calculating the LCC assumes a static annual operations and sustainment cost. As the microgrid is increasingly exposed to the climate risks, the sustainment cost will likely increase. This will vary the LCC of the microgrid. The variation in the LCC must be considered in the NPV used to determine the relationships between cost and resilience of the microgrid.

The model utilizes ELMI to measure the resilience of the microgrid. The calculation of ELMI requires the determination of scenarios, the recovery time, and the mission impact for each scenario. Hildebrand identifies nine factors that can affect the measure of ELMI. These include the size of the ESS, layout of distribution cables, on hand fuel storage capacity, distribution for centralized DERs, size of DERs, level of investment in system maintenance, system redundancy, reliability, and maintainability of all microgrid components, and rate and probability of fuel supply. Maintainability of a system is measured in MTTR. As described in Section IV.B.1, the MTTR can vary based on the severity of damage to the microgrid component. The damage will vary based on the severity of the climate risk. The model uses a constant MTTR, therefore, the output of the model may not accurately represent the actual resilience of the microgrid when exposed to the climate risks. Additionally, the rate and probability of fuel supply can be affected by the ordered effects of climate risks. Wildfires, weather extremes, and flooding can limit access to areas of an installation. This can affect the probability of fuel being delivered, which in some cases may bring the probability to almost 0 in some extreme cases. The rate of fuel resupply will also significantly decrease due to limited accessibility and the increased time to reach fuel storage area.

4. Summary of Model Gaps

Table 9 provides a summary of the inputs of the models discussed above to include the climate risks that may affect those inputs. The inputs from the three models are placed into the category parameters listed in Table 9. For example, the capacity factor of DERs utilized in Dr. Anderson’s model and the capacity of the generators utilized in Peterson’s and Hildebrand’s model are common input types that are affected by the same number of climate risks. These input types were combined under the capacity factor of DERs since generators are an aspect of a microgrid utilizing DERs.

Table 9. Summary of Model Inputs Potentially Affected by Climate Risks

Parameter	**Model**			**Climate Risk(s)**					
	Anderson	**Peterson**	**Hildebrand**	**Drought**	**Flooding**	**Cold**	**Heat**	**Wildfires**	**Weather Extremes**
Availability factor of a wind turbine	X				X	X			X
Capacity factor of DER	X	X	X		X	X	X	X	X
Disturbance for scenario	X			X	X	X	X	X	X
Critical demand (load)	X	X	X	X	X	X	X	X	X
Time to repair a damaged DER	X				X	X	X	X	X
Probability of DER being damaged given disturbance	X			X	X	X	X	X	X
Diesel generator's maximum fuel consumption rate	X					X	X		
Power rating of DER i at time t	X				X	X	X	X	X
Power generated by microgrid	X				X	X	X	X	X
Fuel consumption for diesel generator	X					X	X		
Mean Time to Repair (MTTR) the damaged DER	X				X	X	X	X	X
Generator fuel storage		X			X	X	X	X	X
Efficiency of DER	X	X	X		X	X	X	X	X
Generator refuel		X			X			X	X
Generator probability of refuel		X			X	X	X	X	X
ESS (BT1) storage		X			X	X	X	X	X
ESS maximum output		X	X		X	X	X	X	X
PV array area		X	X	X	X			X	X
Solar incidence data		X						X	X
Failure scenario		X	X	X	X	X	X	X	X
O+S cost			X	X	X	X	X	X	X
Investment cost			X	X	X	X	X	X	X

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

This report examined the gaps in microgrid models when considering the climate risks at Naval installations. The gap analysis in the models required a thorough understanding of the climate risks at Naval installations. The climate risks identified included drought, flooding, hot temperatures, cold temperatures, wildfire, and weather extremes. Ordered effects were determined for each climate risk, which then were used to identify the impacts that each climate risk may have on a microgrid. The climate risks, the ordered effects, and the impacts to the microgrid were used to analyze the models to determine if these concerns were addressed.

Table 10 is a non-exhaustive summary of potential effects and impacts attributed to climate risks identified in this report. An analysis of the listed impacts reveals duplication of impacts from multiple climate risks. Multiple climate risks lead to similar impacts on microgrids. Conversely, impacts have contributing factors from multiple climate risks. The consideration of multiple climate risks is necessary to minimize impacts that threaten microgrids.

Table 10. Aggregation of Risks, Effects, and Impacts

	ORDERS OF EFFECT				IMPACT
DROUGHT	Significantly less precipitation	Reduction of Vegetation	Reduced vegetation root system	Increased erosion	Damage to foundations to buildings, etc.
			Increased soil temperature	Less shade and higher environmental temperatures	Increased demand on grid for climate control
		Loss of Environmental Moisture	Increased dust particulants		Clogged Engine and Air Filters
			Cracking soil	Foundation compromise	Increased maintenance and repair costs
		Depleted Water Reserves	Weaker Currents		Reduced flow for hydroelectric energy
FLOODING	Fast-Moving Water and Flash fFoods	Soil erosion	Undermined foundations		Increased maintenance and repair costs
		Fast-flowing debris hazards	Equipment damage		Increased repair costs
					Lack of electrical power
	Soil Saturation	Mudslides	Damage and Blockage of Equipment		Increased repair costs
					Lack of electrical power
		Metal corrosion	Damage to equipment and support structures		Increased repair costs
	Increased humidity	Increased corrosion			Incrased maintenance and repair costs
	Standing Water Hazard	Dewatering efforts (pumps)			Increased Energy Used for De-Watering
		Water intrusion	Limited physical access to equipment		Higher MTTR and MDT
			Limited physical access to energy		Lower availability. Delay in getting energy
			Equipment rust and corrosion	Contaminated fuel, algae growth, and blocked fuel filters	Increased repair costs
					Reduced fuel storage
			Confined space flooding		Electrical Hazard in Equipment Spaces
			Indoor flooding		Increased electricity use for fans
HEAT	Sustained, elevated, moderate temperatures or extreme heat	Exasperation of drought conditions	Decreased Water Quantity		Less water for equipment cooling
		Increase demand for moderating indoor temperatures	Higher demand for electrical power	Higher loads on DGs reduces DG efficiency	Greater resource consumption
					Hightened risk of wildfire
		Damage to heat-sensitive	Equipment control electronics failure	Damage to Equipment	Increased MTTR and repair consts
		Reduced battery storage capacity			Reduced electronic storage of energy capacity
		Overheated diesel generators	Reduced diesel generator efficiency	Prolonged expososure degrades equipment	Reduced energy from diesel generators
		Overheated PV arrays	Reduced PV array efficiency		Reduced energy from PV arrays
COLD	Sustained Cold and Moderate to Severe Freezing Temperatures	Human Discomfort	Increased load due to HVAC usage		Potential overload and lower efficiency
		Reduced Equipment Efficiency	Higher DG Fuel Consumption		Higher Fuel Costs
			Potential WT Damage		WT Repair Costs
		Freezing Liquids	Bursting Pipes	Leaking Fuel	Fire Hazard
				Other Leaking Contaminates	Hazard Material Waste to Cleanup
		Material Brittleness	Mechanical Failure		Increased Repair Cost to due Damage and Personal Protection Equipment Requirements
WILDFIRE	Extreme Heat Exposure				Limited access to structures, increasing MTTR.
	Combustion	Smoke and Airborne Ash	Smoke Cover	Reduction in PV Efficiency	Reduced Efficiency of PV Panels
			Ash Particles	Caking and Layering of Ash	Reduced Efficiency of WT
					Clogged Filters for Engines and Machinery
		Burning Hazard	Hazard to DG Fuel	Potential explosions	Depletion of DG Fuel Source
			Removal of Vegetation	Soil erosion and mudlides	Destruction of property
			Reduced access to eqipment		Increased MTTR
			Reduced access to energy		Lower availability.
			Hazard to Installation Facilities and Buildings		Destruction of Structures and Utilities
EXTREME WEATHER	Precipitation	Rain	Flooding		See Flooding for details
		Snow and freezing rain	Solar incidence blocking	Reduced PV array area and efficiency	Reducion in available power
			Equipment machinery icing	Damage to equipment	Increased maintenance and repair costs
	Wind	High Gust and Sustained Wind Speeds	Downed Power Lines	Conductor is exposed to ground	Loss of power (Open circuit)
			Flying Debris Hazard		Danger to equipment
			Deactivation of Wind Turbines to protect against high winds		Unavailable energy from wind turbines
			Structural damage		Damage to facilities and ancilliary systems
	Cloud Cover	Reduced PV Array Area and Efficiency			Reduced electrical energy available
		Reduced illumination	Increased demand for indoor illumination	Increased load on gnerators	Reduced generator efficiency
	Thunder Storms with Lightning Strikes	Fire			See Wildfires for details
		Electrical Overload	Overload in circuit to equipment		Damage to energy generation equipment
					Damage to all connected and unprotected equipment
		Direct Strikes	Acute phyiscal and heat-related damage		Immediate and violent damage to strike area

The various impacts that were derived from the six climate risks were consolidated and categorized. Table 11 shows the quantity of risks that align with each climate risk. This table indicates flooding and extreme weather events are the most common across the common impacts. This result aligns with the report cited in Section III.B by the UNDRR stating that flooding and storms were leading weather events that were categorized as disasters (United Nations Office for Disaster Risk Reduction 2020).

Table 11. Categories of Impact per Risk

Count of Categories of Impact per Risk	**Drought**	**Flooding**	**Heat**	**Cold**	**Wildfire**	**Extreme Weather**
Increased maintenance and repair costs	2	7	1	3	2	5
Loss of equipment or materials	1	0	1	1	0	1
Increased load / demand	1	2	0	0	3	1
Reduced available energy	1	4	3	0	5	4
Environment impact/ damage from microgrid equipment	0	1	2	1	0	0
Total	5	14	7	5	10	11

The impacts of the six climate risks will vary based on the region of interest. An example of the variation in impacts is the damage due to flooding in a coastal region when compared to flooding in an inland region. This report did not determine the variation of the climate risks in each region. It is important to understand the regional climate risks when incorporating the climate risks into the models. Additionally, the data used in the models must accurately represent the predictive climate trends of the region of interest. Accurate regional climate data and climate trends will result in better informed climate risks impacts on the microgrid in the region of interest.

The analysis of the three models indicated that gaps exist in each model when climate risks are considered. These gaps are categorized into the three categories identified in the model analysis framework which consists of the analysis into the approach, the input parameters, and the assumptions of the model. Each model utilizes inputs that can be informed by climate data; however, the approach of each model does not allow for the incorporation of climate data that changes over time. The models also utilize input parameters that can vary based on the exposure to the climate risks. If these input parameters cannot account for the variations, the output of the model will likely not represent the actual output of the microgrid while under the effects of the climate risks. The models also utilize assumptions that do not allow for the incorporation of prolonged exposure to climate risks, such as the exposure to drought and prolonged increases or decreases in regional temperature.

When considering these climate risks over the lifespan of the microgrid, the models do not consider the impacts of the climate risks on the inputs of the models, therefore the accuracy of the models cannot be verified. The models utilize common inputs for each model. These common inputs include the capacity of the DERs, the efficiency of the DERs, the critical demand on the microgrid, the failure scenarios used in the model, the MTTR or failure rates, the DG fuel consumption, and the diesel fuel storage. Each of these input types have multiple climate risks that will affect the input data used in the model. Figure 17 provides a representation of the relationship between common input types across the three models and the number of climate risks that affect the input type. This relationship is used to make recommendations on the prioritization of efforts in addressing the impact of the climate risks on the input type. For example, critical demand and failure scenarios are input categories used in all three models and are affected by all six climate risks. The capacity and efficiency of DERs are also used in in all three models but are only affected by five categories. Fuel storage is also affected by five climate risks but only used in two models. This informs modelers on the number of climate risks that affect the input types.

Additionally, it informs researchers on topics that address both the greatest number of climate risks and models with common input types.

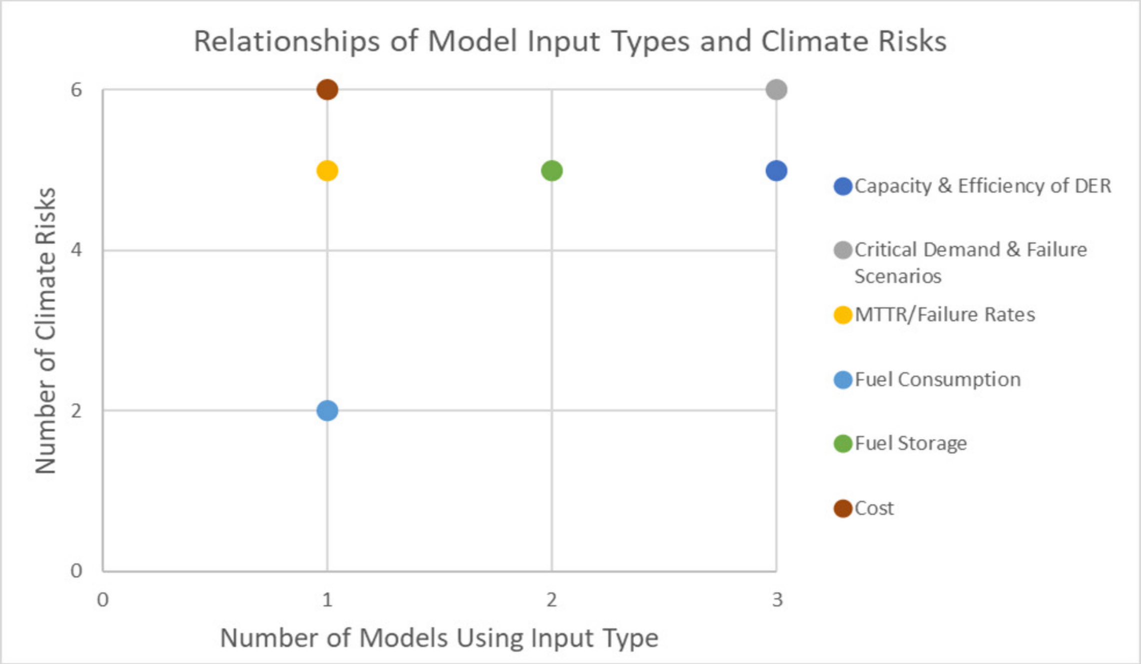


Figure 17. Model Input Type vs. Climate Risks

The analysis of the inputs used in the models indicates that the critical demand and failure scenarios used in all three models are affected by all six climate risks. As discussed in each model analysis, the data used in the failure scenarios is either from historic data or a binary representation of an event occurring. The use of static historic data to inform failure scenarios and the binary representation do not utilize climate change trends to inform the failure scenarios and the impacts to the microgrid. The critical demand also utilizes historic or expected energy demands rather than critical energy demands that are informed by climate trends. Without climate change informed failure scenarios and critical energy demand, the output of the microgrid models may not accurately represent the state of the microgrid when exposed to the six climate risks.

The capacity and efficiency of DERs and the fuel storage capacity of the microgrid are also inputs that are used in multiple models while being affected by five of the six climate risks. The capacity and efficiency of DERs determines the power generated by the microgrid. Exposure to the five identified climate risks will affect the capacity and efficiency, resulting in a lower power output of the microgrid. Quantifying the climate risk impacts to the capacity and efficiency of DERs is necessary to accurately model the microgrid power output. Fuel storage was utilized as an input in two models and is affected by five climate risks. The five climate risks will have different levels of impact on the fuel storage capability of the microgrid. The impact on the fuel storage capability has not been quantified for each climate risk.

The LCC, MTTR, and failure rates are also inputs affected by five or more climate risks but are only used in one model. The LCC of microgrid resilience model is the only model that utilizes cost of the microgrid which includes both investment and O&S costs. The resilience and cost model utilizes MTTR and failure rates to determine the operating status, the time to restore, and the frequency of failures of the DERs. The failure rates of components will impact the LCC of a microgrid. As exposure to the climate risks increase over time, the failure rates of components will likely increase. The relationship between LCC and failure rates would indicate that these input categories could be combined to represent the impact of at least five climate risks on two similar inputs in separate models.

The research performed in this report concludes with three recommendations for the incorporation of the climate risks into microgrid models. The three recommendations require accurate climate change data to incorporate the climate risks into the microgrid models. Changes in climate will increase the microgrid exposure to the six climate risks. The increase in exposure must be accounted for in the models to ensure microgrids are designed to withstand the short-term and long-term effects of the climate risks. These three recommendations include the following:

- Evaluation of climate risks impacts on failure scenario metrics and critical energy demand on the microgrid.
- Evaluation of the relationship between the climate risks, LCC, and failure rates utilized in microgrid models.
- Quantify the climate risks and impacts of the climate risks on microgrids.

The failure scenario and critical energy demand on the microgrid are two input parameters that must be informed by the climate risks and climate trends. The six climate risks will change the failure scenarios and the probability of damage when the microgrid is exposed to climate risks. Additionally, the critical energy demand will vary as the climate changes. These inputs require accurate climate change data and climate change trends to determine the effects by the climate risks. It is recommended that additional research is conducted to inform the failure scenarios and the critical energy demand on the microgrid when the microgrid is exposed to climate risks.

This report recommends that the relationship between the climate risks, LCC, and failure rates must be evaluated to determine the impacts of the climate risks on these input parameters. The models utilize failure data from component specifications. This data is not informed by the climate risks to include the short-term and long-term effects on the microgrid. Increased exposure to the five climate risks will impact the failure rates of components resulting in increased down times, maintenance actions, and component replacement. The increase in maintenance actions and component replacements will increase the investment and O&S cost of the microgrid. The evaluation into the impacts of the climate risks on failure rates will inform the cost metrics used in microgrid models which will assist in the incorporation of the climate risks into several microgrid models.

The decomposition of the climate risks into ordered effects and the impact to the microgrid is necessary when holistically evaluating the impacts of climate risks on microgrids. This report decomposed the six climate risks identified to indicate the different impacts that each climate risk may have on a microgrid. A quantitative analysis into the impacts of the climate risk on microgrids will better inform modelers and end users of the approach and input parameters that will accurately represent the impacts of the climate risks. The quantitative analysis could be performed by analyzing the probability of the event occurring and the severity of the event to determine the risk level for each impact

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Allen-Dumas, Melissa R., Binita KC, and Colin I. Cunliff. 2019. Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods. U.S. Department of Energy Report, Oak Ridge, TN: Oak Ridge National Laboratory.

Anderson, William W. 2020. "Resilience Assessment of Islanded Renewable Energy Microgrids." Dissertation, Monterey, CA: Naval Postgraduate School.

Associated Press. 2018. Rampant Wildfire Closes Military Base. September 06. Accessed September 13, 2022. https://www.navytimes.com/news/your-navy/2018/09/06/rampant-wildfire-closes-military-base/.

Bartlett, Jeff S. 2019. How Hot Weather Affects Your Car Battery and What to Do About It. May 04. Accessed Oct 02, 2022. https://www.consumerreports.org/cars/car-batteries/how-hot-weather-affects-your-car-battery-what-to-do-about-it-a4527456418/.

Battery University. 2021. "How to Store Batteries." October 27. Accessed November 06, 2022. https://batteryuniversity.com/article/bu-702-how-to-store-batteries.

Belitz, Kenneth, Bryant C Jurgens, and Tyler D Johnson. 2016. "Potential corrosivity of untreated groundwater in the United States."

Bolen, Curtis D, Victoria Chu, Andy Q Dang, Paul T Kim, Christian Proctor, and Bridget R Shideler. 2021. "Integrating Power-Flow, Resilience, and Cost Models for Naval Installation Microgrids."

Bowes, Michael D. 2009. Impact of Climate Change on Naval Operations in the Arctic. April 23. Accessed Oct 08, 2022. https://www.cna.org/reports/2009/impact-of-climate-change-on-naval-operations.

CBS 8 Staff. 2021. Wildfire that burned 1,000 acres on Camp Pendleton is in patrol status. June 09. Accessed September 13, 2022. https://www.cbs8.com/article/news/local/wildfire/wildfire-camp-pendleton-mandatory-evacuations-san-diego-fire-military-base/509-6ca331f6-4265-4b77-98f6-f5e944387d3b.

Cohn, Lisa. 2014. "Research-Heavy UC San DIego Counts on Microgrid for Reliability." Microgrid Knowledge. October 23. Accessed October 30, 2022. https://microgridknowledge.com/research-heavy-uc-san-diego-counts-microgrid-reliability/.

Cusick, Daniel. 2021. Not a Drill: Navy Struggles to Complete Adaptation Mission. Eenews. October 12. Accessed September 13, 2022. https://www.eenews.net/articles/not-a-drill-navy-struggles-to-complete-adaptation-mission/.

David, Jensen, Irem Y Tumer, and Tolga Kurtoglu. 2009. "Flow State Logic (FSL) for Analysis of Failure Propogation in Early Design." In International Design Eningeering Technical Conferences and Computers and Information in Engineering Conference Volume 8: 1033–1043.

Department of Defense. 2021. "Department of Defense Climate Adaptation Plan." September 1.

Department of Energy, Office of Electricity. n.d. "Grid Modernization and the Smart Grid." Accessed October 2022, 2022. https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid.

Department of the Navy, Office of the Assistant Secretary of the Navy for Energy, Installations, and Environment. 2022. "Department of the Navy Climate Action 2030." Government Report, Washington, D.C.

Drought.gov. What is drought: drought basics. Accessed September 23, 2022. https://www.drought.gov/what-is-drought/drought-basics.

Dubey, Swapnil, Jatin Narotam Sarvarya, and Bharath Seshadri. 2013. "Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World - A Review." Energy Procedia (SciVerse ScienceDirect) 311–321. Accessed November 06, 2022. https://www.sciencedirect.com/science/article/pii/S1876610213000829.

Elsebaay, Ahmed, Maged A. Abu Adma, and Mahmoud Ramadan. 2017. "Analyzing the Effect of Ambient Temperature and Loads Power Factor on Electric Generator Power Rating."

Environmental Protection Agency (EPA). 2022. Climate Change Indicators: Weather and Climate. August 1. Accessed August 25, 2022. https://www.epa.gov/climate-indicators/weather-climate.

Farley, Robert. 2021. Climate Change Threatens the U.S. Navy's MAin Base in Norfolk, Virginia. March 01. Accessed Oct 08, 2022. https://nationalinterest.org/blog/reboot/climate-change-threatens-us-navy%E2%80%99s-main-base-norfolk-virginia-178817.

Gade, J.T., P.M. Seman, A.O. Pinson, A.K. Jordan, J.R. Arnold, B.A. Thames, P.S. O'Brien, C.A. Hiemstra, P.M. 2020. "Department of Defense Climate Assessment Tool." Washington, D.C.: U.S. Army Corps of Engineers.

Gan, Nectar. 2022. China's worst heat wave on record is crippling power supplies. How it reacts will impact us all. CNN. August 26. Accessed August 28, 2022. https://www.cnn.com/2022/08/26/china/china-sichuan-power-crunch-climate-change-mic-intl-hnk/index.html.

GAO. 2022. Defense Infrastructure: DOD Should Better Manage Risks Posed by Deferred Facility Maintenance. Report to the Subcommittee on Readiness and Management Support Committee on Armed Services, U.S. Senate, Washington: United States Government Accountability Office, 65. https://www.gao.gov/products/gao-22-104481.

Generator Source. n.d. "Factors Affecting Generator Output Rating." Accessed November 06, 2022. https://www.generatorsource.com/Generator_Output_Rating.

Giachetti, Ronald E, Christopher J Peterson, Douglas L Van Bossuyt, and Gary W Parker. "Systems Engineering Issues in Microgrids for Military Installations." *In INCOSE International Symposium,* vol 30, no. 1, pp. 731–746. 2020.

Giachetti, Ronald E., Douglas L. Van Bossuyt, William W. Anderson, and Giovanna Oriti. "Resilience and Cost Trade Space for Microgrids on Islands." *IEEE Systems Journal* 16, no. 3. pp. 3939–3949. 2021

Glenn, Hannah. 2019. Do Solar Panels Work Less Efficiently at Certain Temperatures? Oct 01. Accessed Oct 02, 2022. https://www.solar.com/learn/do-solar-panels-work-less-efficiently-at-certain-temperatures/.

Gudmundsson, Hilmar, Adrian Jenkins, and Bertie Miles. 2022. "What to Know about Antarctica's Conger Ice Shelf Collapse." Scientific American. March 29. Accessed October 10, 2022. https://www.scientificamerican.com/article/what-to-know-about-antarcticas-conger-ice-shelf-collapse/.

Hamm, Keith. 2016. Vandenberg Beats Back Four Separate Fires. September 29. Accessed Oct 08, 2022. https://www.independent.com/2016/09/29/vandenberg-beats-back-four-separate-fires/.

Hefner, Rick. 2020. "Resiliency in Systems Engineering." California Institute of Technology, Center for Technology and Management Education. August 18.

Hildebrand, Joshua P. 2020. Estimating the Life Cycle Cost of Microgrid Resilience. Master's Thesis, Monterey, CA: Naval Postgraduate School.

Lantero, Allison. 2014. "How Microgrids Work."

Lejtman, Ana. 2022. "What Is The Correct Battery Storage Temperature?" ClimateBiz. May 24. Accessed November 06, 2022. https://climatebiz.com/battery-storage-temperature/.

Lodewick, Colin. 2022. Earth's 'Doomsday Glacier' Is Holding On 'By Its Fingernails,' Scientists Say. September 06. Accessed September 07, 2022. https://fortune.com/2022/09/06/doomsday-glacier-thwaite-new-study-sea-level-rise-climate-change-antarctica/.

Lopez, C. Todd. 2021. DOD, Navy Confront Climate Change Challenges in Southern Virginia. July 21. Accessed September 13, 2022. https://www.defense.gov/News/News-Stories/Article/Article/2703096/dod-navy-confront-climate-change-challenges-in-southern-virginia/.

Losey, Stephen. 2020. After massive flood, Offutt looks to build a better base. August 07. Accessed Oct 08, 2022. https://www.airforcetimes.com/news/your-air-force/2020/08/07/after-massive-floods-offutt-looks-to-build-a-better-base/.

Marfin, Catherine, Jesus Jimenez, and Tom Steele. 2021. Hundreds of thousands remain without power as more snow is headed to Dallas-Fort Worth on heels of record cold. February 16. Accessed August 28, 2022. https://www.dallasnews.com/news/weather/2021/02/16/thousands-still-without-power-as-north-texas-reaches-record-low-temperature/.

Merriam-Webster Dictionary. n.d. Accessed November 08, 2022. https://www.merriam-webster.com/dictionary/climate.

Milczarek, Adam, Mariusz Malinowski, and Josep M Guerrero. 2015. Reactive Power Management in Islanded Microgrid - Proportional Power Sharing in Hierarchical Droop Control. IEEE.

Minsky, Dave. 2021. Survivors Relive Deadly 1977 CA Wildfire in New Documentary. June 01. Accessed Oct 08, 2022. Firehouse. https://www.firehouse.com/operations-training/wildland/news/21225004/survivors-relive-deadly-1977-ca-fire-in-new-documentary.

Modly, Thomas B. 2020. Department of the Navy Installation Energy Resilience Strategy. SECNAV Climate Report, Washington, D.C.: Department of the Navy.

Narayanan, Anu, Michael J. Lostumbo, Kristin Van Abel, Michael T. Wilson, Anna Jean Wirth, and Rahim Ali. 2021. The Growing Exposure of Air Force Installations to Natural Disasters. Accessed Oct 08, 2022. https://www.rand.org/pubs/research_briefs/RBA523-1.html.

NASA. n.d. Global Temperatures. Accessed Oct 06, 2022. https://earthobservatory.nasa.gov/world-of-change/global-temperatures.

National Weather Service. n.d. Flood Related Hazards. Accessed September 23, 2022. https://www.weather.gov/safety/flood-hazards#:~:text=Flooding%20typically%20occurs%20when%20prolonged,as%20a%20levee%20or%20dam.

Newport News Government Information. n.d. Flood Protection. Accessed August 28, 2022. https://www.nnva.gov/2298/Flood-Information.

Novak, Lisa M. 2008. Navy helps cleanup efforts after violent storm hits Rota, Spain. October 15. Accessed Oct 08, 2022. https://www.stripes.com/branches/navy-helps-cleanup-efforts-after-violent-storm-hits-rota-spain-1.84102.

Panasonic. n.d. “How to Store Batteries.” Accessed November 06, 2022. https://www.panasonic-batteries.com/en/news/how-store-batteries.

Perry, Tony. 2015. Navy bases do their part to conserve water in California drought. June 27. Accessed September 13, 2022. https://www.latimes.com/local/california/la-me-navy-water-20150628-story.html.

Peterson, Christopher. 2019. Systems Architecture Design and Validation Methods for Microgrid Systems. Naval Postgraduate School.

Peterson, Peterson J, Douglas L Van Bossuyt, Ronald E Giachetti, and Giovanna Oriti. 2021. “Analyzing Mission Impact of Military Installations Microgrid for Resilience.” Edited by Vladimir Bures. Systems (MDPI) 69.

Pinson, A.O., K.D. White, E.E. Ritchie, H.M. Conners, and J.R. Arnold. 2021. DOD Installation Exposure to Climate Change at Home and Abroad. Technical Report, Washington, D.C.: U.S. Army Corps of Engineers.

Rachel Adams-Heard, Javier Blas, Mark Chediak. 2021. A Giant Flaw in Texas Blackouts: It Cut Power to Gas Supplies. February 19. Accessed August 28, 2022. https://www.bloomberg.com/news/articles/2021-02-20/a-giant-flaw-in-texas-blackouts-it-cut-power-to-gas-supplies#xj4y7vzkg.

Reeves, Magen M. 2019. Tyndall AFB continues rebuild effort one year after Hurricane Michael. October 10. Accessed Oct 08, 2022. https://www.af.mil/News/Article-Display/Article/1985948/tyndall-afb-continues-rebuild-effort-one-year-after-hurricane-michael/.

Ricochet Fuel Distributors. 2020. “How to Know if There’s Water in your Diesel Fuel.” February 25. Accessed November 04, 2022. https://www.ricochetfuel.com/blog/how-to-know-if-theres-water-in-your-diesel-fuel/#:~:text=Just%20like%20oil%20and%20water,and%20damaging%20your%20fuel%20filters.

Schneider, Stephen H., and Robert E. Dickinson. 1974. Reviews of Geophysics. August. Accessed Oct 08, 2022. https://doi.org/10.1029/RG012i003p00447.

Ton, Dan T, and Merrill A Smith. 2012. The U.S. Department of Energy’s Microgrid Initiative. Elsevier Inc.

Tostado-V´eliz, Marcos, Paul Ar´evalo, and Francisco Jurado. 2021. “A Comprehensive Electrical-Gas-Hydrogen Microgrid Model for Energy Management Applications.” Energy Conversion and Management.

Tweten, Ross. 2012. Homestead ARB and Hurricane Andrew: A look back, a look forward. August 29. Accessed Oct 08, 2022. https://www.homestead.afrc.af.mil/News/Article-Display/Article/701110/homestead-arb-and-hurricane-andrew-a-look-back-a-look-forward/.

United Nations Office for Disaster Risk Reduction. 2020. Human Cost of Disasters: An Overview of the Last 20 Years 2000–2019. United Nations Climate Report, United Nations.

United Nations. n.d. “Climate Action.” Accessed October 22, 2022. https://www.un.org/en/climatechange/what-is-climate-change.

United States Congress House Committee on Armed Services. 2019. National Defense Authorization Act for Fiscal Year 2020. Report of the Committee on Armed Services, Washington, D.C.: U.S. Government Publishing Office.

United States Environmental Protection Agency. 2022. Glossary of Climate Change Terms. Accessed August 26, 2022. https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html.

VECKTA. 2020. “Microgrids vs DER vs SmartGrids.” September 29. Accessed October 18, 2022. https://www.veckta.com/2020/09/29/microgrid-vs-der-vs-smart-grid/.

Wallace, Joe. 2018. Natural Disasters at Military Bases. October 21. Accessed October 08, 2022. https://veteran.com/natural-disasters-bases/.

Wilcox, Stephen. 2012. National Solar Radiation Database 1991–2010 Update: User’s Manual. Technical Report, U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Golden: National Renewable Energy Laboratory, 9. https://www.nrel.gov/docs/fy12osti/54824.pdf.

Wong, Dennis, and Han Huang. 2022. China’s record heatwave, worst drought in decades. Aug 31. Accessed Oct 07, 2022. SCMP. https://multimedia.scmp.com/infographics/news/china/article/3190803/china-drought/index.html.

Wright, Will. 2021. Burst Pipes and Power Outages in Battered Texas. February 21. NYTimes. Accessed Oct 08, 2022. https://www.nytimes.com/live/2021/02/17/us/winter-storm-weather-live.

YaleEnvironment360. 2020. Extreme Weather Events Have Increased Significantly in the Last 20 Years. October 13. Accessed September 13, 2022. https://e360.yale.edu/digest/extreme-weather-events-have-increased-significantly-in-the-last-20-years.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California