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Military Energy Resilience Models and Climate: Do Our Models Adequately Consider Climate Risks?

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Abstract

Military bases must be operationally available to complete their missions regardless of the operational and physical environmental conditions. A key component of maintaining operational availability is a secure and reliable source of energy, which is resilient in the face of a variety of possible threats both natural and man-made. Towards that goal, the U.S. Department of Defense has supported the development of analytical and simulation-based resilience models to support facility managers in assessing and improving the energy resilience of military bases. This paper examines how well these models consider climate change into their analyses with a focus on near-term and medium-term climate changes. The paper presents a framework describing what it entails for a model to consider climate risks. The evaluation found the resilience models generally do not sufficiently assess risks due to climate change. The paper proposes model characteristics of scenario-based risk assessment to handle the increased uncertainty of climate change, and for models to consider second and higher order effects of climate change.

Index Terms

resilience, risk, systems engineering, military base, climate change, quantitative risk assessment, disaster

I. Introduction

The U.S. Navy recognizes the critical role shore-side military installations play in the combat effectiveness of the fleet. For this reason, the Navy has issued policy guidance on the operational security of these bases. One of these policy documents is energy security for Navy installations, which looks to ensure reliability, efficiency, and resilience of the base [1]. To help inform decision makers on investments that advance energy security, the Navy has invested in developing various analytical, physics-based, and simulation models. Facility managers use these models to evaluate the risks of weather events and other threats to military bases, and to support resource allocation decisions.

The scientific community, based on an abundance of evidence, has widely accepted that the current world climate is changing. Controversy may surround what the effects of climate change will be, the degree to which human activity has contributed to climate change, and whether we should do anything about the ongoing climate change. However none of these controversies are material to the present study. Climate change is inducing more extreme weather events, and as a result posing a risk to military installations because extreme weather can damage equipment, disrupt operations, and cause other negative effects. Multiple examples of these risks are evident around the globe including prolonged drought, heat waves, flooding, and storms. These extreme weather events affect energy infrastructure from heat waves leading to increases in demand for power such as occurred during the 70 day heat wave in China [2] to the severe winter storms bringing down the power grid in Texas [3] among other recent events.

The costs and consequences for failing to adapt to climate change are increasing. There is world-wide concern about climate change with the United Nations estimating the global cost of adaptation [4] and European Union investigating the impacts to Europe [5]. The U.S. government has recognized this and in the 2020 National Defense Authorization Act (NDAA) directed the U.S. Department of Defense (DOD) to prepare for climate risks, develop an extreme weather vulnerability and risk assessment tool, and assess how climate change impacts DOD's ability to accomplish its mission every four years. This requirement motivated this research to evaluate whether climate change is introducing risk to shore-side military bases that has not been considered.

This paper examines climate risks to military bases. Specifically, the purpose of the study is to evaluate how well the extant resilience models in use by the Navy consider climate risks, and to make recommendations on how the resilience models can incorporate potential climate risk. These models have focused on energy security, and may miss the broader resilience concerns of the military bases. Moreover, this research asks the question whether organizations such as the military need to consider

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climate risks? This work contributes to the body of research on energy resilience a framework and guidance for how military bases as well as other facilities can perform risk analysis with respect to climate change.

The paper is organized as follows. Section II describes the background of military base operations, resilience, climate change, and reviews related literature. Section III presents a framework for analyzing resilience models. Section IV evaluates a few models used in the Navy. Section V proposes how the resilience models can incorporate climate change risks. Section VI draws conclusions.

II. Background

The U.S. DOD owns and operates military bases located within the U.S. and around the world. These military bases house soldiers, civilians, military equipment, and other resources. The military bases support military operations, allow for training of soldiers, and provide maintenance of equipment among other functions. Military bases fulfill an important role for the military and must be secure against threats from enemies but also must be resilient against natural disasters and other potential disruptions to their continual operation.

Military bases will often have power generation, water, sewage, and other services on base but only for backup purposes. They otherwise depend primarily upon the surrounding community and local government for power, water, sewage, and other needed services. Interestingly, military bases can also act to increase the resilience of the local community [6] such as when the Southern California Edison power company requests Marine Air Station at Miramar to switch to their own power, the equivalent of powering 3000 homes. Given the interdependency of the military base and the surrounding communities, it is imperative to take a systems view of examining military bases and risk as part of a larger containing system, i.e., the surrounding community.

We have been studying how military bases can be more resilient in the face of both man-made and natural threats to their facilities and operations [7]–[14]. However, we have not considered any effects from climate change. Climate can affect how the DOD maintains readiness of their forces, supports operations from military bases, and it also may change the types of missions they perform; e.g., more humanitarian missions or increasing operations in the Arctic region [15], [16]. This section provides some background on resilience of military bases and on the research of climate change in order to establish the groundwork for understanding climate risks to military bases.

1) Resilience: Resilience describes a system's capability to anticipate, resist, and recover from any disruptions to the system's performance. Resilience is multidimensional because it includes the invulnerability of the system to disruption, the ability of the system to recovery, and the ability of the system to learn and adapt to actual disruptions or forecasted disruptions [7]. The later component of adaptation will be found particularly relevant to climate change because the ability to learn from events and build less vulnerable and more adaptable systems is critical to climate resilience [17].

Figure 1 shows the resilience curve, which helps describe the multiple components of resilience.

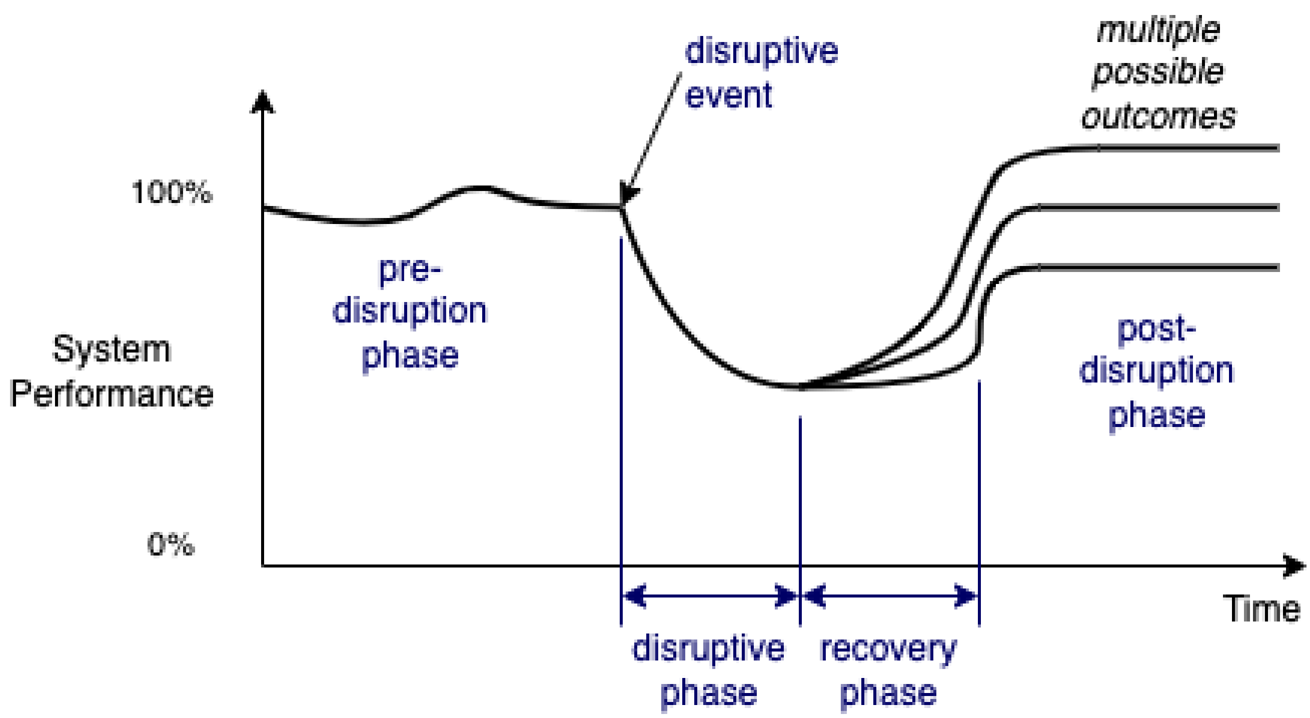

Fig. 1. Notional resilience curve

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The pre-disturbance phase describes before the disruption occurs and allows for planning for disruptions. A military base will design and implement modifications to the systems for avoiding threats, hardening against threats, and faster recovery from threats during the pre-disturbance phase. A facilities manager will also train the personnel by simulating black start operations and other operations. Once a disturbance occurs, how much performance the system loses depends on the hardening against the disturbance. The system then enters a stabilization phase followed by a recovery phase. During these phases the personnel secure the system, switch to backup systems if appropriate, and commence recovery operations by making repairs and take necessary actions to regain desired system performance.

As described above, resilience is due to a system's design to avoid, resist, and recover from disturbances as well as a system's operation. A resilient system design has both physical and functional redundancy, is hardened to make it less vulnerable to threats and their consequences, and has good maintainability to support recoverability after the disturbance. The system operation increases resilience through training personnel to recognize and prepare for impending disturbances, being able to recover the systems, and having spares and other logistical policies that enhance resilience.

2) Climate Change: Weather describes the short-term atmospheric conditions of temperature, rain, humidity, and so forth. Climate refers to the long-term prevailing weather patterns in a particular region, usually measured over a period of time of 30 years or more. When it is said that the climate is changing, this means that the historical weather patterns previously observed are not continuing into the future. For instance, the average temperature in the arctic has been gradually rising and the extent of sea ice in Greenland during the month of December has declined from 1975 til today. Consequently, this is an observation of climate change – a change in the prevailing temperature in the arctic with first-order effects of declining sea ice.

There is extensive evidence the climate is changing faster than it has in previous spans of time. NASA's data shows an increase in global average temperatures with nine of the ten hottest years on record occurring the past decade [18]. Computer models predict the warming trend is likely to continue into the foreseeable future [19]. The climate change data indicates changes in averages but also changes in the distributions surrounding those averages. Many distributions are "fat-tailed" meaning extreme events are becoming more common [20]. Changes also occur in both the severity and timing of extreme weather events such as earlier frosts in some regions (and later frosts in other regions). Climate change, even though it appears to be changing faster, still occurs over long time horizons.

To summarize this section, this article posits that climate change is increasing the uncertainty facing military bases and their operations with respect to weather events. Climate change means historical data is less reliable, the effects depend on the interplay of natural systems, government policies, and technology, and it increases the uncertainty in characterizing the frequency and severity of potential events.

A. Related Work

The study of resilience is multi-faceted because it touches on many disciplinary topics including risk analysis and system architecture; is contextual; and depends on the time horizon considered [21]. Many studies focus on measuring resilience by using the resilience curve; see for example [22]–[24]. The resilience curve assumes a single, discrete event affects a system, from which the system recovers. The general approach is to identify potential hazards to the system and analyze how well the system can resist and recover from the hazards. Most risk-based approaches assume a stationary climate with known probabilities of weather-related risks, and assume the attendant costs and benefits can be measured using expected values. Giachetti et al. [7] exemplify this approach in their analysis of resilience of isolated energy systems on islands.

The high amount of uncertainty surrounding climate change and its effects diminishes the ability of traditional risk management approaches such as expected utility theory or cost-benefit analysis [25], [26]. Model uncertainty is a central component of the current challenges in climate risk measurement. Possible changes can occur not only in the mean (average) but also in the overall distribution or severity of extreme events or changes in the dates of significant events, such as first frost [27], allowing some estimation of risk to ecosystems [28]. Climate risks occur gradually over longer periods of time, which is another reason their effects are highly uncertain. The variability of the weather events emanating from climate change exhibit greater variability and have probability distributions with thick tails [20].

Given the difficulty of measuring climate risk, one way to deal with future uncertainty is to use scenarios [29], [30]. Scenarios allow for dealing with events where assignment of values to uncertainty is not possible, whether to the probability of the event or its severity. Scenarios are also suitable for longer time periods amenable to understanding climate risks.

Linkov et al. [31] claim the high interconnectedness and interdependency between systems as well as the uncertainty associated with climate impacts makes untenable the identification of hazards and their effects on a system. For this reason, climate risk analysis and management demands the integration of multiple disciplines to gather climate data, characterize the effects, understand the interdependence between systems, and develop means to deal with potential climate risks.

A few articles explicitly consider climate related risks such as sea level rise [32] on a rail network in which they consider the socio-technical issues affecting resilience. The US Department of Defense (DOD) developed the Defense Climate Assessment Tool (DCAT) for military bases to determine their exposure to climate induced risks in terms of frequency and severity of weather events [33]. Goldstein et al. [34] use data on 1630 companies of which more than half identified one or more climate risks as highly likely yet most companies have inconsistent approaches to managing the risks. While there is wide recognition and acknowledgement of climate risks, the development of models and methods is under-developed.

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Given the deep uncertainty and complex interactions involved in both the climate risks and adaptation strategies, one approach is the development of mental models to improve decision making on adapting to climate risks. Bessette et al. [35] illustrate the approach with a case study of New Orleans by identifying the causal network of climate changes including flood risk, sea-level rise, coastal erosion and how various adaptions and/or mitigation strategies would affect these risks.

One means to deal with the uncertainty inherent in climate risk is through participatory approaches to assess risk, which form the basis of a bottoms-up risk approach to developing adaptation strategies [36], [37].

The engineering literature on resilience predominantly has its roots in traditional engineering risk analysis [38]. These approaches work well for many types of hazards, but literature focused on climate change has identified multiple issues that upset the risk-based approach when the climate is changing. These issues include the greater uncertainty of events, uncertainty of the severity, interdependence of multiple systems, and gradual change.

III. Climate Risk Framework

This section presents a framework for structuring climate risks, characterizing the risks, identifying their higher order effects, and identifying the consequences on military installations (see Table I). The purpose of the framework is to first establish a baseline to evaluate existing resilience models, and second to determine the requirements for models to incorporate climate change risks so as to better inform decision makers.

The literature review revealed two shortfalls of traditional quantitative risk analysis when applied to climate change. The first challenge is it can be very difficult to rigorously establish the probability of the risk, its consequences, and the severity of the consequences of climate risks with any sort of evidence. The second challenge is the traditional risk analysis approach of gauging the probability of the event and the consequences of the event works well for short-term events such as hurricanes. However, what can be overlooked are gradual changes, compounding over a longer period of time, which have negative effects on the facility. Many of the climate change risks are like this because they unfold over a period of time. Models for climate risks need to consider longer term, gradual changes affecting the facility and its operations.

All models require data. When including climate change, we observe that most military energy resilience models use historical data. However, under climate change the frequency and/or severity of weather events are changing, and the use of historic data might under-estimate risks associated with climate change because essentially the modelers are assuming future weather events will be similar to past weather events. To avoid this outcome, the models can consider using forecasted trends in the data. Additionally, the data should consider if there are any regional differences because the risk analysis of a military base covers a small geographical area.

This research follows Francis and Bakera [24] in emphasizing the importance of the temporal aspects of system resilience. However, those authors only considered time in the recovery of the system. Time is also important in the gradual unfolding of risk events and their consequences characteristic of climate risk. There is a need to model the causal pathways through which climate change affects military bases and their operations. Concomitant with this, there is a need to evaluate how the military base interacts with other systems.

TABLE I
Framework for Military Energy Resilience Model Assessment

Analysis Category	Considerations
Model Data	Does the model use forecasting?
	Does the model consider regional differences?
	Can the model represent all climate risks?
Model Assumptions	Does the model make assumptions limiting the inclusion of climate risks?
Model Structure	What is the type of model?
	Does the model consider higher order effects?
	Does the model allow for gradual temporal events?
	Does the model include the interconnections with other systems?
Model Variables	Does the model have input variables to model climate risks?
	How does the model represent uncertainty?
Model Output	What outputs does the model make?

IV. Evaluation of Energy Resilience Models

The purpose of the military's analytical models is to inform resource allocation decisions for improving the energy security of military installations. We use the list of approved models in the appendix of the soon to be released Unified Facilities Criteria for Military Installation Microgrids. The list includes commercial and government computer models a facilities manager or others can use for analyzing the risks, resilience, costs, and other aspects required for justifying investment decisions in a facilities energy infrastructure. These tools include: Distributed Energy Resources Customer Adoption Model (DER-CAM) [39], HOMER [40], [41], Microgrid Design Toolkit [42], MicrogridUP [43], REopt [44], Xendee [45], and the Naval Postgraduate School Microgrid Analysis tools [46]–[48]. Additionally, we review other relevant models not listed in the Unified Facilities Criteria for Military Installation Microgrids but that are available in the literature.

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Implicit in the energy security models is the use of a microgrid at the military base to provide backup power in case of disconnection from the main utility grid. The microgrids can provide physical redundancy, diversity of power sources, and excess capacity – all of which serve to improve energy resilience. Figure 2 shows a notional microgrid architecture with multiple distributed energy resources, storage, and multiple loads.

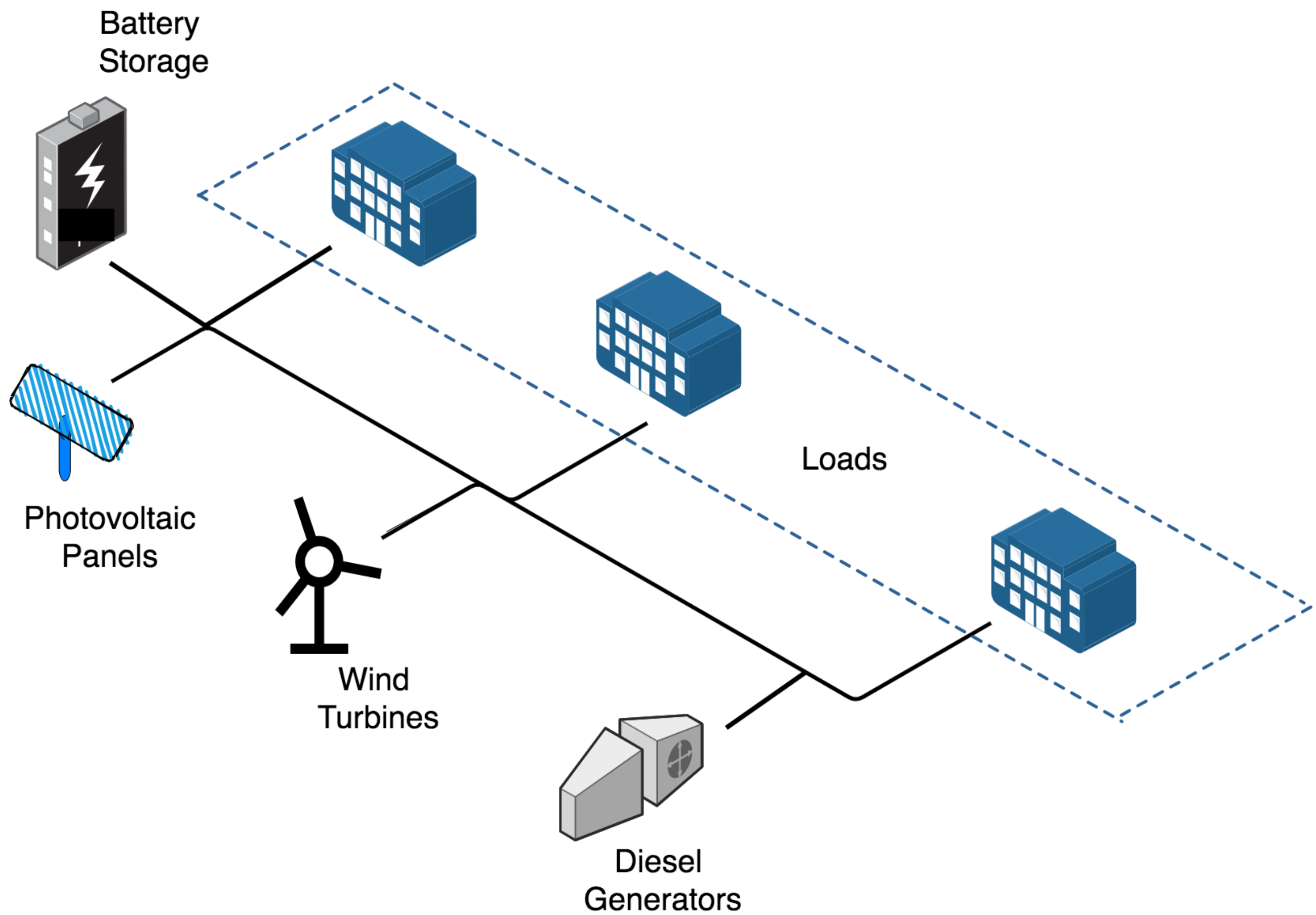

Fig. 2. Notional microgrid

The analytical models for assessing risk assume the historical weather patterns will persist into the future. When tools consider climate change, they include forecasts for the foreseeable trends in weather. For instance, the DCAT tool uses both historical weather data and projections of future weather conditions.

This article now undertakes the evaluation of three models for whether they address climate risks and to understand what it will take for these models to address climate risks.

1) DER-CAM: DER-CAM is a microgrid optimization tool focused on distributed energy resource investment decisions [39]. The software has the ability to conduct analysis to minimize total annual costs or minimize CO_2 emissions. It is a mixed-integer linear program. Data import is available although no explicit climate change variables are present. A user could develop import data that reflects climate change information but it is not a native capability within DER-CAM.

2) Xendee: Xendee is a web-based tool built on and extended from DER-CAM [45]. It retains the mixed-integer linear program and includes optimization and trade space exploration tools. Cost modeling capabilities are present. Nascent resilience modeling is available although it does not yet account for weather-related phenomena. Climate change analysis is limited to CO_2 emissions optimization.

3) Homer: Homer is a microgrid optimization tool that can take input data including load, generation, storage, and others and produces potential microgrid design configurations [40], [41]. Resilience analysis is possible with simulated outages. However, the outages are not tied to climate change events. Sensitivity analysis is possible with Homer.

4) Microgrid Design Toolkit: The Microgrid Design Toolkit produced by Sandia National Labs [42] develops trade-space analyses for potential microgrid deployments. A multi-objective optimization algorithm executes a discrete event Monte Carlo simulation. This allows for performance and reliability to be analyzed based on user input of load, generation, storage, and

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related data. Data can be imported and extensive input variables are available. Resilience analysis can be conducted in some fashion via the microgrid performance and reliability model within the software.

It is not clear if sufficient variables exist to allow the Microgrid Design Toolkit to represent all climate risk aspects. While reliability and resilience can be analyzed, and historical climate data can be used, future climate predictions appear to not be integrated into the software.

5) MicrogridUP: Little is currently available in the literature on MicrogridUP. Development of MicrogridUP was funded in 2022 with a three year time horizon for the project. The software is not yet available for general use. However, the software is expected to provide microgrid modeling capabilities including generation resources, storage, loads, network segmentation and load shedding, resilience analysis, cost analysis, operations and maintenance analysis, and other capabilities. MicrogridUP is expected to have data import capabilities [43].

Based on what public information is available, optimized sizing for generation and storage will be model outputs. Additionally, a resilience analysis report, financial report, and fuel consumption report will be generated from the model. The tool appears to be being developed to support rural electric cooperatives although based on its inclusion in the new Unified Facilities Criteria, it is expected to be applicable to military microgrids.

6) ReOPT: ReOpt is a mixed integer optimization model to find the lowest cost design subject to constraints on load balance, resources, sizing, policy, and CO2 emissions. The model supports multiple DERs of photovoltaics, wind, biomass, landfill generators, and conventional generators and energy storage technologies. ReOpt addresses resilience by determining the most cost effective design to survive a grid outage of a specified duration. The user specifies an outage duration and the critical load size they want to sustain during an outage of a specified duration, then ReOpt determines the minimum cost design for that outage [44].

The model requires the modeler to input data on loss of grid connection which is the only outage type the ReOPT model considers. Other outage types such as damage internal to a microgrid caused by storms is not considered. The reasons for a loss of grid connection such as those related to climate change-driven events are not directly captured but could be cataloged by a user in a companion document. The ReOPT model allows the user to input data and conceivably the data could reflect expected changes due to climate data.

7) Microgrid Resilience and Cost Trade-Off Tool (MRCT): The MRCT supports facility designers in understanding the costs and benefits of excess capacity, physical redundancy, and functional redundancy in the microgrid design [7]. The MRCT model takes user input on the microgrid components, facility demand profile, solar irradiance, and wind speeds. The modeler also must input hazards, their probability of occurrence, and determine the conditional probabilities the hazards cause damage to a microgrid component. The model executes a Monte Carlo simulation and outputs two measures of microgrid resilience and the cost of energy. The tool supports a designer in iteratively developing microgrid designs to strike a balance between resilience and cost. Note that the MRCT is being integrated into the Naval Postgraduate School Microgrid Analysis tools.

On model data, the model requires the modeler to identify risks such as hurricanes or floods, their probability of occurrence, and the conditional probabilities those hazards would cause to various components of the microgrid. The model assumes historical data is available for the modeler to do this. No explicit consideration of climate change is made in the data collection, but there is nothing preventing a user from forecasting future trends in the data. The model is capable of addressing singular events. It is not clear if the model could handle data for persistent weather pattern changes such as droughts.

On model structure, the model only considers the first-order effects of the risk event using the conditional probability that given a risk event occurs, there is a microgrid component damaged. Moreover, the model only considers whether a component is damaged or not damaged. The possibility of degraded component performance such as solar panels producing lower output due to wildfire smoke is not possible. Likewise, the model can not handle gradual temporal events; the MRCT represents only the microgrid components and consequently misses any interdependence with other facility systems or anything external to the military base.

On the model variables, it is not clear whether the MRCT model has sufficient variables to represent all aspects of climate risks. The MRCT model represents uncertainty in the risk events with probabilities in a Monte Carlo simulation. The MRCT model does not represent any uncertainty in the severity of the consequences.

The MRCT model outputs the microgrid's resilience and cost of energy. For each output variable, the MRCT provides a visualization to support trade-off decisions.

8) Microgrid Mission Impact Resilience Model (MMIRM): The MMIRM [9], [49] supports military base energy managers in assessing the relative severity of impact to critical base missions (e.g.: radar early warning systems, port operations, hospitals, water and sewer services, etc.) from power disruption. The Mission Dependency Index (MDI) [50], [51] is used to assess the criticality of each load on a military base although there is some disagreement over the efficacy of MDI [52]. MMIRM can simulate multiple loads and generation sources, and has the ability to conduct Monte Carlo simulations with optional random equipment failure events after the initial disturbance occurs. Further, specific outage scenarios where specific generation resources and loads go on and offline can be simulated.

The model requires the modeler to identify risks such as floods, fires, hurricanes, and similar prior to commencing modeling. This information can be used to develop specific outage scenarios that is then inputted into the model. Historical solar irradiance data is pulled from 10 years of historical data provided by the National Renewable Energy Laboratory. The model is capable of assessing complex multi-event scenarios over a two week period but requires the modeler to develop said scenarios. No explicit consideration of climate change is made in the data collection; however, some researchers have attempted to conduct analyses with the MMIRM on scenarios related to climate [8], [53].

The model can use probability data to simulate random equipment failure after the initial disturbance. However, the model is designed assuming the disturbance happens and is thus scenario-driven. The model only considers if a component works or is failed and cannot account for damaged or degraded components that can still function at partial capacity. The model can account for components being repaired and incremental improvement of the microgrid's condition, and some researchers have pursued such analyses [54].

It is not clear whether MMIRM has sufficient variables to represent all aspects of climate risks. MMIRM cannot handle uncertainty or complex probabilistic distributions but it is scenario-driven and has the capability of performing Monte Carlo simulations of random equipment failures during an event. The MMIRM does account for the severity of consequence for specific loads losing service due to the use of MDI.

9) DCAT: Unlike the other energy resilience models, the DCAT is specifically intended to support facility managers in assessing risks due to climate change and is instead a climate risk assessment tool [33]. The DCAT uses the history of weather related events combined with forecasts of climate change induced events such as floods, sea level rise, and droughts to assess the vulnerability of military bases. Here vulnerability is defined as exposure to a risk, which is based on DCAT's data, and the facility manager determines the severity of the event to their facility.

Referring back to the framework for model assessment in Table I, DCAT fully addresses all of the model data considerations: DCAT uses forecasting based on climate trends, accounts for regional differences, and captures all potential climate risks. The DCAT only deals with the data needs for doing a resilience analysis. Consequently, DCAT is not a resilience tool in the sense of the other tools, but rather could serve as the data input to those tools. Further, DCAT does not provide microgrid analysis support. Instead, the output from DCAT could be fed into another model.

10) U.S. Army's Climate Resilience Handbook (ACRH) Model: The U.S. Army uses the ACRH to provide a rigorous analytical framework for facility managers to understand climate risks and develop plans of action to deal with those risks [55]. The framework is based upon traditional risk analysis. The method assesses the climate risks in terms of exposure and severity, analyzes the cause and effect of the risks, assesses the capacity to deal with the risk, and identifies additional measures the base can take to prepare and be more resilient in the face of the possible climate risks.

The framework does use forecasting and regional data to inform the climate risks. The framework has extensive coverage of the climate risks as well. Unlike the other models, the ACRH is a framework and not a particular type of analytical or simulation model. The benefit of a framework is its applicability to a wide array of bases and its ease of use by facility managers. The drawback is the outcomes of the resilience assessment depends on the knowledge, skills, and abilities of the facility manager using it. The framework has scope for considering higher order effects of climate change through its suggestion of using Ishikawa diagrams. One shortcoming of Ishikawa diagrams is the lack of feedback loops, which is prevalent in climate change scenarios.

The framework does not have variables as such. Its input is the climate risk data, the profile of the base (mission, number of personnel, etc.), and current capacity for dealing with climate change. The framework's output is a series of actions the base can take to avoid, reduce severity, or increase recoverability from climate change. Unlike the other models, the ACRH is able to consider more than the energy system of the base.

V. Resilience Modeling Incorporating Climate Change

Here we describe characteristics of a model that can consider resilience to climate change. This article approaches the problem of assessing vulnerability and severity of climate risks from a systems-based perspective. This entails viewing a military base as a system and examining how the climate risks affect base operations and performance.

1) Climate Risk Exposure and Severity: Understanding climate risks is a first component of incorporating climate risks into an analysis of system resilience. The DCAT [33] lets a facility manager see the threats to a facility according to the base's location, making it a useful tool for understanding the exposure to various extreme weather events. What is missing is a means to determine the effects and severity of those weather events. The literature review identified some of the challenges herein, and a main one is the second and higher order effects emanating from climate change. One means of understanding these is causal modeling done in the next subsection.

2) Interrelationship between Systems: Climate changes affect the entire environment and the socio-technical systems the military base is a part of and interdependent with [56]. The analysis of climate risks must therefore identify, analyze, and evaluate these interdependencies. Figure 3 shows a causal loop diagram for increasing average temperatures in a region (Western U.S.). The causal loop diagram shows variables and the relationships between them as either positive or negative. We put in bold those variables that directly affect the military base's microgrid. The diagram is for the Western U.S., which is predicted to see increasing occurrences and severity of drought. The first order effects are drought conditions and also increased demand for power due to increased usage of air conditioning and other reasons. The utility grid has upper limits on the power that can be generated, so as demand increases the utility grid seeks out ways to decrease demand through conservation as well as reducing power supplied to major industrial users. Drought conditions have a host of effects that eventually lead back to the military base's operations. Drought conditions decrease the vegetation coverage over time, which leads to more airborne dust, and drought conditions increase the probability of wildfires. For example, Vandenberg Space Force Base faces a year-round wildfire risk and as a result hosts a wildland firefighting crew [57]. More dust and smoke from fire negatively impact the generation of energy from solar panels on the base [58], [59]. The drought conditions also affect the demand for water, another critical system to the military base. With time, less water in the reservoirs and groundwater leads to less hydroelectric power generation, which leads to the need for power generation from other sources.

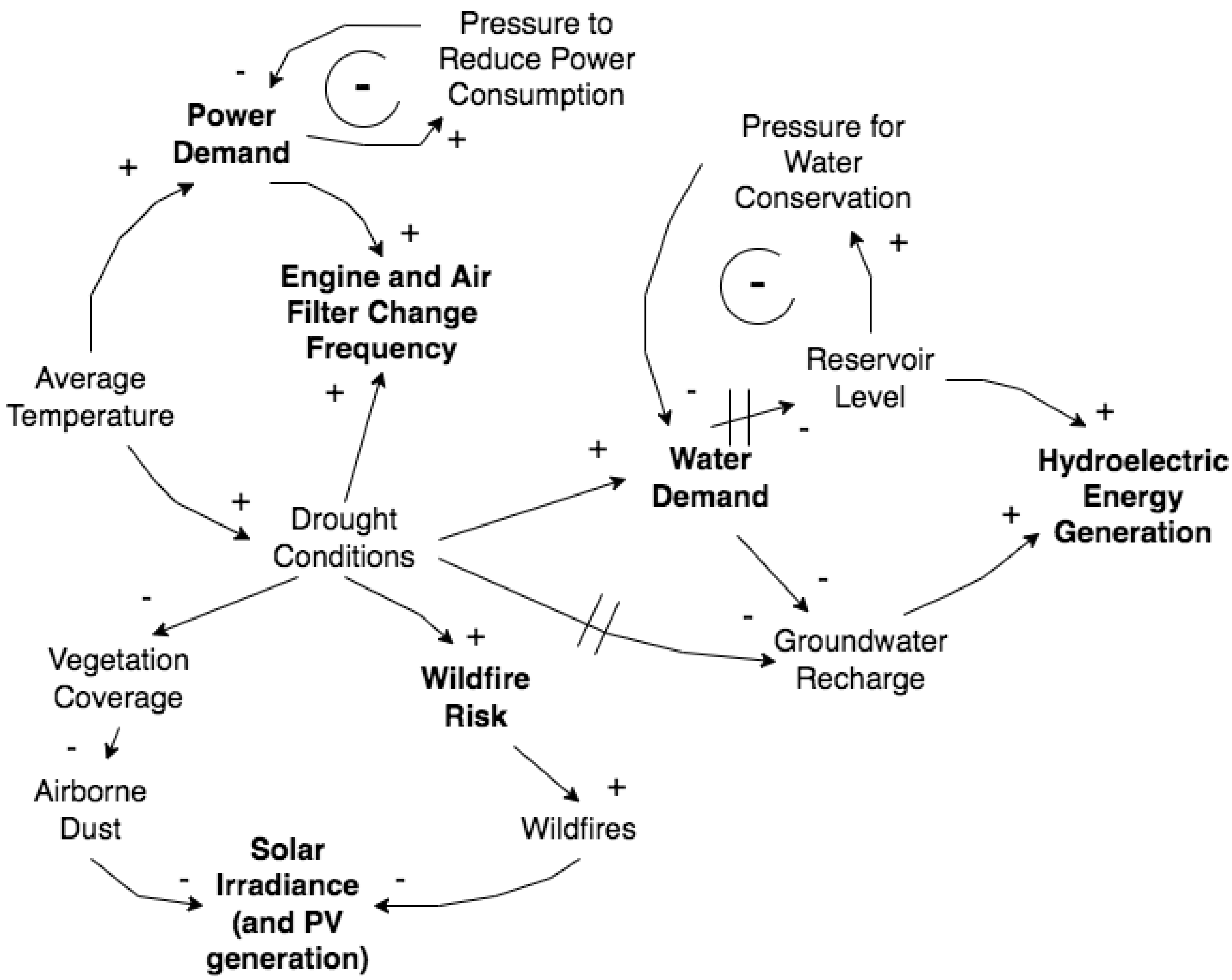

Fig. 3. Causal loop diagram for increasing heat

It is important to consider the second order and even further effects of the risk event and the interdependence between systems. To explain why, the story of an organization in South Florida who's IT department had a plan for continuity of operations during a hurricane that was relayed to the authors is illustrative. Key personnel would leave South Florida once a hurricane warning was declared for another location and reestablish operations there. However, this contingency plan failed during a recent hurricane when the flights for the personnel were cancelled and they were unable to depart. The organization has since revised its plan to have key personnel depart earlier. The story highlights the need to consider interdependencies among systems, in this case flight cancellations in the community's transportation system, in order to develop a risk management plan. While this example is not directly energy resilience related, such an event could have a significant impact on a microgrid operator if the impacted company supplied the SCADA software for a microgrid. Without availability of the IT department, the ability to support deployed SCADA systems may be adversely impacted which could lead to degraded microgrid performance at military bases far away from Florida.

Returning to the increased heat example, additional knock-on effects may and feedback loops may be present. For instance, extreme heat may prevent repair crews from conducting scheduled maintenance on critical equipment. Similarly, wildfires may block access to critical supply routes to bring in consumables such as lubrication oil and air filters for generators. Indeed,

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we experienced blocked supply routes firsthand during the 2020 Creek Fire in California [60] which led to generator failure due to low oil and clogged air filters even though sufficient fuel was available onsite during a six week grid outage and a month-long isolation from resupply. While most energy resilience analyses performed for the military use a 14 day outage as a benchmark, drought conditions can lead to significantly longer grid outages. A later follow-on effect of some wildfires and significant drought conditions can be the development of hydrophobic soil where moisture is not readily absorbed and instead rainwater and snow melt immediately run off the land. This can cause flooding and landslides which can create grid power outages and damage base infrastructure.

An underlying assumption of many military microgrid resilience analyses is that critical functions can be relocated or replicated at an unaffected facility within 14 days. Recent storm activity across the globe and especially in North America indicate that multiple climate change-related events may occur simultaneously in the future which may exacerbate efforts to either support a base during a grid outage or relocate/replicate critical functions to other facilities.

3) Interrelationship with System Environment: The focus of this article has been on the resilience of military bases in the face of climate change and related risks. The military base is part of the surrounding community and cannot be isolated from what occurs therein. The interdependencies between the military base and external socio-technical systems mean any issues in one can spill over into the other. A prolonged emergency such as a blackout or flooding affects the whole community. Even if the military base is prepared, any vulnerabilities in the local community will spill over because most military personnel and their families live off base in the local community. The military base would find itself in the position of having to support the local community [10].

The interrelationship between a military base and its surrounding community can extend to other environmental factors that can either come from the base, the community, or a mixture of both. For instance, Naval Base Ventura County hosts the Port of Hueneme deep-water port. A recent grant is working to provide electric shore power to ships docked at the northern cargo terminal [61]. This project will reduce emissions from ships idling while loading and unloading cargo which in turn will reduce emissions in the surrounding community. However, electrical power is needed to allow ships to shutdown their engines while in port.

Another example of the interrelationship that a military base and a community have with one another is at Camp Pendleton. A significant live fire range exists at Camp Pendleton where Marines train. When wildfires started in the surrounding community encroach on the base, live fire training is shutdown until any fire on the base is extinguished and until the air quality is safe for outdoor activities. Conversely, wildfires do occasionally start on the base and impact the surrounding community with smoke, increased traffic due to firefighting crews and support staff, and the potential for wildfires to leave the base perimeter and impact the community directly [62]. These fires, whether from on-base or off-base ignition sources, can impact electrical power infrastructure and in the most extreme cases can either require lines to be deenergized for safety thus leading to local or regional blackouts, or destroy critical power infrastructure.

4) Cost Analysis: At some point a cost analysis must be done to support investment in avoiding and/or otherwise mitigating against climate change risks. Typical means of increasing system resilience is hardening the system to reduce exposure to risk events, redundancy in the system, diversity (functional redundancy) in the system, and taking measures to improve recovery time. While estimating the cost of such actions are often straightforward, ascribing a value to the benefits of avoiding and/or reducing the severity of the climate risk is more difficult. When limited to the power system, then the benefits can be measured based on costs avoided as well as the economic value of the activity that continues in spite of the interruptions caused by the risk event [7], [63]. There is a clear economic benefit for a supermarket that would otherwise lose all their meat, dairy and produce to spoilage due to a power outage. However, it is not so clear the economic benefit of maintaining a military base's capacity for operations. For this reason, the military has sought other measures such as the previously mentioned MDI. These measures remain questionable [30], and the quantification of benefits remains an open issue. However, the lack of good measures has not prevented taking action against climate change. For instance, the U.S. Navy's shipyard at Norfolk is at risk due to flooding and already has a project in place to protect the facilities against 500-year flood [64].

A. Broader Applicability

While this article has focused on military base energy resilience models from the perspective of climate change, the process of analyzing resilience models to verify they account for climate change is important for all 16 sectors of critical infrastructure. Further, communities improving their resilience to natural disasters, such as rural and mountain communities in the American West facing wildfire threats, must take into account changing climate in their resilience assessments.

Indeed, the MRCT and MMIRM both can be used for resilience assessment of community microgrids. In some high fire danger areas, utility companies are actively establishing microgrids to serve residential and commercial customers to improve reliability due to public safety power shutoffs [65].

VI. Discussion and Future Work

The proposed framework for military energy resilience model assessment for structuring climate risks, characterizing the risks, identifying risk higher order effects, and identifying consequences on military installations can be used to assess existing

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models as well as drive development of future models. For initial analysis, a simple yes/no check of the model data and model assumptions categories is sufficient although as models are further developed and refined to explicitly include climate change, these categories should have more nuance applied to their assessments. Similarly, the other categories can be initially assessed at a high level but should have more rigor included in later assessments.

The models analyzed are not exhaustive because there may be other models available and in use by services other than the Navy. However, the models analyzed are representative. The analysis indicates that most if not all military microgrid models do not explicitly consider climate change and climate risks. We suggest that model developers expand existing models and develop new models that can account for climate risk.

One potential area of future work is to develop a resilience analysis approach that drives improved system performance during an off-nominal event versus a baseline system. While many efforts during the pre-disturbance phase attempt to make a system more robust to an event so that resilience is not needed, there may be benefit to developing systems that can make use of events to improve system performance during the event. For instance, recent winter storms in California challenged the resilience of a microgrid at a small military installation on the central coast due to greatly increased water runoff flows and wind causing trees to uproot, thus knocking out offsite power. Had a micro hydro-turbine been available on the base, the high runoff flows could have been used to generate power and fulfill part of the base's energy needs while disconnected from the grid.

VII. Conclusions

This paper sought to understand whether existing analytical and simulation models for assessing energy resilience take into account climate change. It is important to consider climate change because climate change potentially creates risks that both directly and indirectly affect military bases. If the models do not explicitly represent climate risks, etc. then there it is possible the base does not make the best decisions with respect to resource allocation.

Towards evaluating the resilience models, the paper developed a framework based on a review of the literature. The paper used the framework to evaluate atypical models for energy resilience. The models have the following gaps with respect to their consideration of climate change risks. The data is often historic, which fails to consider trends going into the future. Some progress towards closing this gap is evident in the release of the DCAT model. The models focus on singular events at a fixed point in time or a short duration (e.g., a hurricane) and fail to consider gradual risks characteristic of climate change. The models do not consider second and higher order effects. The models are limited to the energy system of the base and do not consider the interdependencies with other systems such as water, food, etc. nor with systems outside of the military base.

The paper then examined what model characteristics are needed for addressing risks associated with climate change. Climate change confounds the straight-forward application of traditional risk management tools because of the greater uncertainty, interdependence between multiple related systems, and many of the effects are indirect. Using scenarios provides a means for handling the greater uncertainty surrounding the exposure to climate-related risks and their severity. Scenarios also allow a facility manager to customize risk analysis to particular sites because risk is not uniform across all locations. Models also need to to holistically look at risk to all aspects of military base operations because climate change affects multiple aspects of the facility and its operation. Singling out energy security alone under-appreciates the exposure to risk faced by the base. Moreover, because many of these effects are indirect, understanding the interconnections is important. The paper illustrates an approach of identifying the understand the chains of cause and effect using a causal loop diagram.

A systems perspective is important for evaluating climate change risks to military bases. Resilience against climate change requires a combination of system design, policy implementation, system operation, and understanding of natural systems. Models for assessing resilience need to enlarge their perspective to the entire system so that facility managers can determine the best means to limit exposure and avoid the consequences of climate-related risks.

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