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Extreme Weather and Climate Hazard Impacts on Energy and Water Utilities

Implications for Department of the Air Force Installation
Climate Resilience Planning

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Published by the RAND Corporation, Santa Monica, Calif.

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About This Report

In this report, we present an approach for estimating utility system exposure to extreme weather- and climate-related hazards for the purposes of informing where the Department of the Air Force (DAF) might consider prioritizing deep-dive vulnerability assessments. The approach explored herein uses geography to define the unit of study for conducting utility system exposure assessments (i.e., to one region of the United States) and for informing the area over which relevant exposure measures can and should be calculated for a given utility system. Furthermore, the findings and recommendations (1) consider the decisionmaking contexts under which the DAF could use regional perspectives to support installation level-planning and (2) offer insights on how to best leverage existing extreme weather and climate hazard data, information, and tools to help meet planning objectives.

The intended audience for this report is the Office of the Deputy Assistant Secretary of the Air Force for Environment, Safety, and Infrastructure, as well as DAF engineers, logisticians, and installation planners. Utility resilience is a broad area of concern within the joint community as well, and this report might also be of interest to utility managers and community planners.

The research reported here was commissioned by the Deputy Assistant Secretary of the Air Force for Environment, Safety, and Infrastructure and conducted within the Resource Management Program of RAND Project AIR FORCE as part of a fiscal year 2021 project, “Implications of Climate Change for Energy and Water Infrastructure Resilience.”

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This report documents work originally shared with the DAF on August 17, 2022. The draft report, dated August 2022, was reviewed by formal peer reviewers and DAF subject-matter experts.

Acknowledgments

We are deeply grateful to our sponsor, Nancy Balkus, the Deputy Assistant Secretary of the Air Force for Environment, Safety, and Infrastructure, and to Mark Correll, who commissioned the work while in that role in 2021. We also value the guidance and input from our action officer, Douglas Tucker. Ashley Haugo provided valuable assistance to us throughout the project.

We are also appreciative of the time given by numerous individuals when we reached out to conduct informational discussions to develop the research background. Listed alphabetically, these include Lt Yaquarri Adams, Marius Anelauskas, Mark Berger, Maj Joseph Birkhold, Josh Coleman, Maj William Henning, Timothy Hughes, Caitlin Jones, Jonathan Monken, Allan Schurr, Naina Sharma, and Jeff Szatanek.

Finally, we thank several RAND colleagues who were instrumental in enabling this work to succeed: first, our research program leadership, Stephanie Young, Anna Jean Wirth, and Patrick Mills; second, our research quality reviewers, Anu Narayanan, James Powers, and Brad DeBlois; and finally, several colleagues including Christopher Maerzluft and Michael Wilson, among others.

Summary

Issue

A changing climate and extreme weather are increasingly concerning for military installation resilience. A basic first step in improving the resilience of installation infrastructure is understanding potential infrastructure exposure to extreme weather- and climate-related effects. RAND Project AIR FORCE (PAF) was asked to develop an approach for estimating utility system exposure to extreme weather- and climate-related hazards for the purpose of informing where the Department of the Air Force (DAF) might consider prioritizing deep-dive vulnerability assessments. Previous efforts to understand the implications of climate change have focused on installations; in this study, we focused on utility infrastructures that are outside the fence line.

Approach

We used case studies supported by qualitative and quantitative analysis to demonstrate our hazard exposure approach, which characterizes the historical and, where possible, potential future exposure of energy and water utility systems supporting DAF installations. We focused on a select set of extreme weather- and climate-related effects for three regions: the mid-Atlantic, the Southwest, and Alaska. Our analysis considers the local and regional regulatory environment and demonstrates an approach that estimates the relative resilience capacity of utility systems in these regions using a set of indicators.

Key Findings

- Climate hazards are predictably different in various parts of the United States; however, the geographic extent of utility networks—which, in some cases, can fan out across an area almost half the size of the continental United States—means that it is possible for geographically distant hazards from the area of interest (e.g., the installation) to have impact (although, in some cases, a geographically distributed utility supply chain can also be more resilient).
- All energy and water utilities are directly and indirectly exposed to extreme weather and climate-related effects at every point along the system—from source all the way to end user behavior (demand pressure). However, these effects do not impact all utility system components uniformly. The location of assets, the system configuration, and the condition of infrastructure can influence infrastructure sensitivity and potential vulnerability to climate hazards. Additionally, the regulatory environment, state and local policies, and utility investment decisions are important to consider alongside physical attributes in determining potential vulnerabilities in utility systems that support DAF installations.

- The availability and accessibility of data to measure climate variables and their changes in a standardized way across utility systems are limited. But understanding the hazards faced in a region and how well resilience planning is addressing these hazards sets up a logical approach for prioritizing vulnerability assessments based on mission. Thus, an analytic approach that combines quantitative data and qualitative insights is valuable.
- Measuring utility system exposure can be resource-intensive; however, taken in combination, climate anomaly data (or other relevant accessible exposure metrics) and historical utility service reliability can be used as low-cost initial screens to determine the relevance of utility system exposure information to the decision context at hand.

Recommendations

- **Update resilience policy to include a regional screening-level assessment of energy and water utility system potential exposure to climate hazards to determine relevance to priority-setting decision contexts.** From a priority-setting perspective, information about utility exposure might not always be useful because accessible data do not always yield useful differences. However, a few simple steps can be taken to determine the relevance of utility system exposure to the decision context. We outline a few simple steps that can be taken to perform this high-level screening in the next recommendation.
- **Use a qualitative climate hazard taxonomy, accessible climate anomaly data, and utility reliability measures to obtain a first-order estimation of utility system exposure.** Taken together, climate anomalies compared with a historical baseline and historical utility reliability measures can provide a valuable and low-cost initial screen for whether data show variability across the set of installations of interest.
- **Articulate data and tool needs and strengthen partnerships to help access tools that track utility resilience measures.** Existing weather, climate, and policy data require varying degrees of manipulation or review to address questions of utility system potential exposure, which hinders the progress of resilience planning. Before investing in new standalone analyses and tools, the DAF should further pursue engagement with organizations that already gather, process, analyze, visualize, and disseminate utility system resilience-relevant data, many of which will be motivated to work with the DAF to support real-world decisions. These organizations include, among many others, the utilities themselves, the 14th Weather Squadron, and the National Oceanic and Atmospheric Administration (including its affiliated regional integrated sciences and assessments collaborations).
- **Maintain an archive of relevant weather and climate data, tools, and products that support climate hazard exposure assessments.** This archive can support the efficient use of resources when updating or conducting new assessments and can serve as a mechanism to share information across various assessment efforts.

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Introduction

A changing climate and extreme weather are increasingly concerning for military installation resilience. In recent years, extreme weather events have caused billions of dollars in damage to installations in the United States and degraded operational capabilities (U.S. Department of Defense [DoD], Office of the Under Secretary of Defense [Acquisition and Sustainment], 2021; DoD, Office of the Under Secretary for Policy [Strategy, Plans, and Capabilities], 2021). Some notable examples of the effects of extreme weather to installations and the surrounding communities include the following:

- **Winter Storm Uri in February 2021**, in which failures in natural gas infrastructure caused widespread power outages across Texas, left millions without heat and running water, and delayed or stopped military operations for some amount of time (Norton, 2021)
- **severe flooding at Offutt Air Force Base (AFB) in 2019**, in which about one-third of the base was flooded and just under one-half of the structures damaged in the flood were deemed unsalvageable (Losey, 2020)
- **Hurricane Michael in 2018**, which completely wiped out Tyndall AFB, causing many units to operate out of alternative locations for months post-disaster (Reeves, 2019)
- **the Canyon Fire in 2016 on Vandenberg Space Force Base (SFB)**, which caused widespread power outages on the base and delayed the launch of an Atlas V rocket (Kim and Jacobson, 2016; Scully, 2017).

There is strong consensus in the scientific community that extreme weather and climate trends will continue to intensify in the coming decades. Among many impacts, there will be adverse implications for the built environment, including for infrastructure on Department of the Air Force (DAF) installations and the off-installation–supporting infrastructure on which the installations rely, such as commercial utility systems (which include source areas, transmission, distribution, and other infrastructure). DoD has previously acknowledged the national security implications of extreme weather- and climate-related effects as far back as its 2010 *Quadrennial Defense Review*, in which climate change was mentioned specifically in the context of shaping the operating environment and impacts to facilities and military capabilities (DoD, 2010). In 2021, DoD released an updated climate adaptation plan, which built on previous plans, directives, and reports and reemphasized the need for DoD and the military services to seriously consider climate change in planning and to “take bold steps to accelerate adaptation to reduce the adverse impacts of climate change” (DoD, Office of the Under Secretary of Defense [Acquisition and Sustainment], 2021, p. 3).¹ This plan outlined five lines of effort, one of which is focused on achieving resilient installation infrastructure.

¹ For the previous plans, directives, and reports, see, for example, DoD (2014b); DoD (2014a); Department of Defense Directive 4715.21 (2016); DoD (2018); and DoD (2020).

A basic first step in improving the resilience of installation infrastructure (including that which supports utility systems) is understanding the potential exposure of infrastructure to extreme weather- and climate-related effects, particularly those effects that might be exacerbated by climate change. Understanding the nature of exposure (to *what* and *where*) can aid in DAF decisionmaking on where to focus efforts on more-resource-intensive vulnerability assessments, and ultimately, on investments in resilience.

Research Scope

Previous efforts to better understand the threat of extreme weather and climate change for installation resilience have been focused on understanding the threat on installations, or “inside the fence line,” as we describe in the section that follows. However, because the DAF is heavily reliant on commercial utilities and because existing plans and tools do not generally account for the effects of system-level, regional-scale hazards on the utilities outside the fence line, it is important to understand what potential climate risks the DAF is implicitly accepting by relying heavily on these utility systems. To help further this understanding, the DAF asked RAND to develop and apply a systematic approach to identify potential energy- and water-related vulnerabilities for DAF missions stemming from the exposure of utility systems to extreme weather and climate change to help guide setting assessment priorities.

Therefore, the research in this report aims to answer the following questions:

1. How can the DAF use information about potential commercial utility system exposure to extreme weather- and climate-related effects to set priorities for installation-focused deep-dive vulnerability assessments?
2. What attributes of energy and water utility systems influence the systems’ relative sensitivity and potential vulnerability to extreme weather- and climate-related effects?

To address these research questions, we used three regional case studies—the mid-Atlantic, the Southwest, and Alaska—supported by qualitative and quantitative analysis to demonstrate one approach to assessing hazard exposure, which characterizes the historical and, where possible, potential future exposure of energy and water utility systems supporting DAF installations. We also include a description of the regulatory environment and a relative measure of the resilience capacity of utility systems in these regions, using a set of indicators. We focused on readily accessible data and information to enable the development of a scalable approach across the DAF enterprise. Details of our approach to conducting utility-based exposure assessments appear in Chapter 2. The approach is intended to inform setting priorities among installations *within one region* and not across regions or the full DAF enterprise of installations. This is primarily because of the regional nature of how climate hazards present themselves. We discuss this point further in Chapter 2.

We made some simplifying assumptions and scoping decisions to ensure the research design was feasible for a 12-month study. We assumed that the missions conducted across locations for a given case study region are equally sensitive to disruptions in energy and water utility service to the installation. In reality, we know that mission sensitivity to energy and water utility disruptions varies widely across the enterprise and that mission sensitivity should factor into resource allocation

decisions, but this assumption allowed us to focus on only the potential vulnerability factors that inform utility system exposure and not on mission dependence or mission impact.

In addition, we consider only the independent effects of single hazards on utility systems. Although we include multiple hazards in our analysis, we do not account for the interactions of these hazards or the specific effects of combined hazards on energy and water utility infrastructure for two primary reasons. First, the full set of relevant weather- and climate-related hazards are not directly comparable across at least the following dimensions:

- **Time:** Some hazards can be projected or simulated for future conditions (e.g., sea level rise, temperature, precipitation changes); for others, we only have historical records (e.g., tropical storms, drought).
- **Regions:** Not all datasets contain data for all regions of interest, different methods have been used to derive the same metrics (e.g., intensity-duration-frequency curves²), and “normal” weather and climate conditions may influence the baseline level of utility resilience.
- **Features:** Normalization (or scaling) of hazards might give a false signal of a given hazard’s potential to disrupt utilities or to affect resilience (i.e., the number of days annually projected to be below a specific temperature might not be correlated with the intensity of extreme cold events).

Second, the implications for energy and water systems of the interactions between hazards—and the related cascading effects—are not yet well known or supported with data. Thus, we are not able to make general statements (with certainty) about the nature of the impacts to utility systems from exposure to the combined effects of weather- and climate-related phenomena. Although we can glean insights from historical examples, the academic literature is sparse when it comes to the impacts of combined effects of hazards, particularly for quantitative assessment methods that measure performance of infrastructure.

Several Prior Efforts Inform This Work

The DAF has already invested in initiatives and other research and analysis aimed at improving the department’s understanding of the threat of extreme weather and climate change for installation resilience inside the fence line. We provide a brief summary of some of this work here, selected because it specifically informs this research and because we refer to it elsewhere in this report. We begin with recent work completed by RAND Project AIR FORCE (PAF), which includes efforts to characterize installation exposure to natural hazards;³ to develop approaches for assessing, valuing, and prioritizing investments in electric power resilience;⁴ and to prioritize the conduct of electric power resilience assessments.⁵ We start with an overview of the PAF work completed in FY 2019 and FY 2020 because our methodology follows aspects of that research. We then provide additional

² For a discussion of intensity-duration-frequency curves, see Miro et al. (2021).

³ Completed in fiscal year (FY) 2020; see Narayanan, Lostumbo, et al. (2021).

⁴ Completed in FY 2016 and FY 2018; see Narayanan et al. (2017) and Narayanan et al. (2019).

⁵ Completed in FY 2019; see Narayanan, Van Abel, et al. (2021).

information on existing DoD and DAF capabilities that are particularly relevant to the current research, which include the Defense Climate Assessment Tool (DCAT), the 14th Weather Squadron (WS), and the Severe Weather Playbook.

RAND PAF Criteria-Based Approach to Prioritizing Electric Power Resilience Assessments

In FY 2019, PAF researchers developed a criteria-based approach for setting priorities for assessments of electric power resilience investments (herein referred to as the *priority-setting approach*) (Narayanan, Van Abel, et al., 2021), consisting of the following criteria:

- **mission sensitivity**—a function of the mission’s dependency on electric power and how its geographic operational configuration contributes to or mitigates the potential vulnerability to power disruptions
- **location vulnerability**—a function of the reliability of the commercial grid supporting the installations of interest and the resilience measures in place to mitigate the effects of a power disruption
- **location density**—the number of missions supported at a given installation.

The authors document the following four steps to prioritizing missions to receive electric power resilience assessments:

1. Identify and prioritize missions that require forces to be employed in place.
2. Make initial assessments of each mission’s sensitivity and the corresponding location’s vulnerability to electric power disruption.
3. Compare mission sensitivity and location vulnerability across missions and prioritize accordingly.
4. Use location density to prioritize among missions that are otherwise equal on the previous criteria.

The research sponsor asked that we consider this priority-setting approach to inform the work presented in this report.

RAND PAF Enterprise-Wide Look at Department of the Air Force Installation Exposure to Natural Hazards

In FY 2020, PAF researchers developed a screening-level approach to characterize the exposure of DAF installations to flooding, high winds, and wildfires using different types of data, including publicly available hazard data, base boundaries, and geospatial data on airfield and power infrastructure (Narayanan, Lostumbo, et al., 2021).⁶ For the high winds hazard, the authors also explored policy options for investing in hardening measures before a disaster happens versus the

⁶ The wildfire exposure analysis included some consideration of off-base power infrastructure within a small buffer of the base boundary, but the main focus of this work was on areas within the installation boundary.

potential costs of repairing damage and rebuilding infrastructure post-disaster. They also considered how hazard seasonality data might be used to inform identification of alternative operating locations for temporary mission relocation.

Although we do not directly build on this work, we highlight it because some of the insights from it informed how we approached the research presented in this report. Specifically, we drew from insights about the use cases for and limitations of hazard data, different approaches to geospatial analysis, and the concepts underpinning what it means to be exposed to a hazard from a resilience perspective.

Existing DoD or DAF Weather- and Climate-Related Tools and Datasets

A few primary resources are available to the DAF for considering installation exposure to weather and climate hazards, including DCAT, the Air Force Civil Engineering Center (AFCEC) Severe Weather/Climate Hazard Screening and Risk Assessment Playbook, capabilities of and products developed by the 14th WS, and data collected to develop and update installation energy plans (IEPs) and the newly required installation climate resilience plans (ICRPs).⁷ These resources focus primarily on understanding the threat of severe weather and climate change to mission execution from potential damage to or loss of infrastructure inside the installation boundary, but the ICRP requires an installation to identify whether there are community infrastructure or resources that are necessary to maintain mission capabilities (e.g., electricity infrastructure) and whether those infrastructure and resources might be vulnerable to the same climate risks as on base infrastructure.

In the process of developing the IEPs, the Office of Energy Assurance asks for some information about utilities, such as outage risks, to inform the assessment of potential vulnerabilities for the installation, but the information is not formally reported in the IEP. Additionally, for some hazards, the 14th WS threat assessment methodology considers weather and climate data in a buffer area around the installation, as does DCAT. However, the lens from which the selected hazards and assessments of exposure, potential vulnerability, or potential risk are viewed is the perspective of the mission, not the off-installation utilities, which is also the lens we use in this study. We include information about these other resources to provide the reader with a broader sense of the type of information that the DAF can consistently access. (Appendix A discusses these resources in greater detail.)

Organization of This Report

In this report, we (1) describe the process we undertook to develop a utility system hazard exposure estimation approach and (2) demonstrate that approach using three case studies. The approach we outline provides the DAF with one way to incorporate information about the potential vulnerabilities of utilities to extreme weather and climate hazards into existing decisionmaking processes, in which prioritizing vulnerability and resilience assessments is the focus. In Chapter 2, we

⁷ The ICRPs will be a component of the installation development plan and is required per Air Force Instruction 32-1015 (2021). In FY 2022, the DAF was in the process of selecting a few installations to serve as pilots for developing the plans and templates, and thus, no plans were available to inform our project.

discuss the process we used to develop the approach, as well as the important assumptions and definitions implicit in our work.

In Chapters 3 and 4, we tackle the research questions outlined earlier in this chapter in reverse order. In Chapter 3, we describe the preparatory work that is required before conducting a hazard exposure assessment. The results of that preparatory work feed the three case study assessments that we describe in Chapter 4, which includes the results of those assessments and the lessons that we learned from conducting the cases that further refined our approach. In Chapter 5, we discuss the themes identified across the three case studies we examined and our recommendations for how the DAF can use the information gleaned from these case studies, in combination with previously proposed criteria and metrics, to guide priority-setting of more-extensive vulnerability assessments.

The report also contains several appendixes. In Appendix A, we provide additional information about existing DoD and DAF weather and climate-related tools and datasets. In Appendix B, we include various views of a climate hazard taxonomy that show the relationship between a given hazard and the subcomponents of each utility type considered in this work (i.e., electricity, natural gas, drinking water, and wastewater). In Appendix C, we outline our approach to and findings from our codes and standards review, and in Appendix D, we provide detailed information about other potential indicators of utility system resilience capacity. In Appendix E, we discuss the role of installation and community partnerships in resilience measures, and in Appendix F, we include additional details on utility system resilience indicators for the mid-Atlantic case study.

A Utilities-Based Approach to Assessing Installation Exposure to Climate Hazards

In this chapter, we describe the process that we used to develop our approach for estimating utility system exposure to weather- and climate-related hazards. Our exposure assessment approach draws from principles from prior RAND work (described in Chapter 1) and catastrophe modeling theory (described below) and operates according to a set of assumptions (also described below).⁸ We also explain how and why we selected case studies to demonstrate our assessment approach and compare findings on utilities-based exposure across different parts of the United States.

Underlying Principles, Definitions, and Assumptions

Before turning to the assessment approach, we begin with a discussion of the broad underlying principles and important definitions and assumptions that frame our work.

Principles

There is no established playbook for how to conduct an outside-the-fence-line exposure assessment for the purposes of climate resilience planning. Many—if not all—of the resources readily accessible to the DAF for resilience assessments and planning are installation-focused. However, estimating installation exposure to climate-related hazards from a utilities (outside the fence line) perspective necessarily involves taking a much broader geographic perspective on exposure because utility systems—including sources, processing, and transmission and distribution architecture—span a much broader geographic scale than a given installation’s boundaries.⁹ Several consumers of this report will have experienced a power outage or a potable water problem even when the instigating storm, flood, heat wave, drought or other problem was not directly felt at their home or place of work. **Consequently, metrics for utility system exposure should consider data across a broad area, as**

⁸ *Catastrophe models* are used by the insurance industry to estimate insurance and reinsurance needs (among other things) based on anticipated damages resulting from large natural disasters (Zanardo and Salinas, 2022). These simulations have been in use in various forms since the 1960s and thus enjoy a well-established academic literature and community of practice.

⁹ Adding to the complexity, many utilities participate in organized markets in which capacity availability and real-time load balancing is the responsibility of a third party that is not the distribution utility itself.

opposed to at a point in space. This is a fundamentally different way of looking at exposure than estimating a runway’s susceptibility to flooding, for example.

Additionally, **extreme weather and climate hazards are regional in nature and driven by geographically defined phenomena**, such as the location of warm ocean water that triggers storm generation or the presence of low-lying coastal areas. Even heat waves and cold snaps, which by their nature imply a departure from “normal” weather, are governed by defined physical ocean-atmosphere processes and the ability to respond to them, which changes by region (think about the differences in how Alaska would handle a cold snap in comparison with Texas and vice-versa when considering a heat wave). Moreover, the effects of different hazards in different regions are not directly comparable in many cases. Extreme wind from a tropical storm affects electricity transmission infrastructure very differently than does permafrost thaw, even though both can ultimately cause power outages (the extent and duration of which are determined by a multitude of additional factors—such as resilience planning—that can be regionally determined). Potable water contamination resulting from drought-induced toxic dust storms is similarly difficult to compare with contamination caused by high seawater levels and coastal inundation. The utility industry is engaged in valuable debates on how to move from reliability planning to a focus on resilience because of ongoing and anticipated future impacts of climate change on the physical infrastructure and on supply and demand (Levite, 2020; South-Central Partnership for Energy Efficiency as a Resource, 2021).

Given these two key realities of the problem, we explored using geography to define the unit of study for conducting utility exposure assessments—that is, bounding the geographic area under consideration based on a relatively high amount of overlap in broadly similar geographic and climatic features. This approach limited the number of installations examined in each case study but offered an opportunity to consider a common set of hazards across those installations and some similarities in the utility systems themselves, which are structured and connected in ways that are regional in nature.

Additionally, two key principles from catastrophe modeling theory informed our methodological design. These principles include *taking a multidisciplinary approach* by including socioeconomic, financial, and engineering variables alongside natural hazard science (Knös et al., 2022) and *drawing on prior histories or experience* to understand likely impacts and to consider that exposure or risk may change over time (Mitchell-Wallace et al., 2017). Understanding how past disasters and other weather-driven problems have affected utility systems continues to be valuable even though climate change may undermine the utility of planning assumptions used in the past. Despite this challenge, history provides considerable insight into what may or may not damage a utility system and why.¹⁰

Although we did not conduct catastrophe modeling, our exposure assessment approach explicitly focused on identifying the mechanisms of climate hazard exposure of utility system components, from both physical and policy perspectives (the latter of which included socioeconomic and financial considerations), using a series of historical examples, academic literature, and internal subject-matter expertise of geophysical climate systems and civil and environmental engineering.

¹⁰ We acknowledge that future climate change might strain utilities systems in different or unexpected ways if and when novel physical thresholds are encountered. However, the specifics on expectations about what conditions physical infrastructure and supply systems should withstand to maintain continuity of service is beyond the scope of this research. We consider whether codes and standards contain assumptions related to climate change, but we do not assess whether those assumptions are the right ones.

Definitions

In this research we adapted the widely accepted Intergovernmental Panel on Climate Change (IPCC) definitions of hazard, exposure, and sensitivity to the context and scope of our work.¹¹ We define *hazard* as the potential occurrence of a weather- or climate-related physical event or trend that may cause loss, damage, or stress to infrastructure. We define *exposure* as the state of being subject to significant climate variations that could have adverse effects, and we define *sensitivity* as “the nature and degree to which a system [may be affected when] exposed to significant climate variations” (IPCC, 2014). Importantly, this means that in our assessment approach, we took into consideration different types of climate hazards and the need for measures to describe their severity.

Another key term is *utility system*. In the most general sense, this term encompasses the geography of the commodity source (or generation source) and the path it takes to get to the DAF end user.¹² In this report, we are primarily focused on the physical features of source areas and the infrastructures for transport and distribution, although we recognize the importance of personnel, organizations, and software for utility systems.

We use the term *catchment* to denote the collective area inhabited by the components of a utility system. The inspiration for this term is the idea that the flow of water at a given point in a river is driven by a vast network of smaller waterways and sources further upstream. For part of this research, we are focused on the usefulness of such a concept for utilities-based exposure assessments and how the term should practically be defined in infrastructure terms and geographic scope. We will return to this in the context of our case studies.

Utility system impact mechanism means the process or pathway by which a given weather or climate hazard could cause disruption in utility service. We anchor identification of the impact mechanism to the physical effects of a hazard, such as water inundation, wind damage, or temperature-related impacts.

Finally, we recognized early in the research that climate-related hazard impacts are not entirely based on “natural” causes. Rather, decisions made by people factor significantly into what the impacts of an extreme weather or longer-duration climate event will have on a utility. Thus, we incorporated the idea that the regulatory environment and policy can also influence *utility system resilience capacity* – that is, the extent to which the regulatory environment, related policies, and operational and utility investment decisions have the potential to mitigate effects of climate-related hazards.

Assumptions

Three key assumptions are inherent in our work. The first is that **there is more than one “right” way to approximate installation utilities’ exposure to climate hazards**. This assumption emphasizes the point that there are several metrics that one could use to estimate climate hazard exposure. Our focus in this project was on using existing data and tools readily accessible to the DAF. But we

¹¹ Air Force Instruction 90-2011 defines *hazard* as “any real or potential condition that can cause mission degradation, injury, illness, death to personnel, or damage to or loss of equipment or property” (2019, p. 27). We chose to modify the IPCC’s definition because it is specifically focused on weather- and climate-related hazards, and we are not tying hazards to mission degradation in this work.

¹² We did not include the port infrastructure used to transport natural gas from offshore wells in the scope of this project.

recognize this might not be the *only* approach that one could use to assess exposure of utility infrastructure.

Second, we assumed that **the presence of weather or climate anomalies – whether in the recent past or projected future – suggest that climate is moving away from stationary or expected patterns.**¹³ This assumption underpins our reliance (discussed later in this chapter) on recent weather changes in the context of the historical (instrumented) weather record baseline to inform an initial understanding of exposure. Alternatives to using instrumental weather records, which became more widely used in the United States starting just prior to the beginning of the 20th century, would be to look at future climate projections or paleoclimate records that extend back hundreds to thousands of years. Looking forward and looking back provide broader perspective but are also less certain and more resource-intensive. As described later, we initiated physical exposure assessments using the more certain (and less resource-intensive) instrumental record as a means of scoping the analysis to determine where more resources to include projections and paleoclimate records would be the most valuable.

Finally, we assumed that **anomalous climate and weather patterns and effects threaten the reliability and resilience of utilities in ways that can be understood based on the historical past, even if their anticipated magnitude, duration, or frequency is expected to change.** Implied in this assumption is that the instrumental record we discussed previously should include the range of expected types of future events (perhaps not frequency or severity), and thus we do not include consideration of complete surprises in our analysis (e.g., the development of permafrost in Texas or the beginning of a tropical storm season in Alaska).

Developing a Utilities-Based Exposure Assessment

The fundamental challenge of a utilities-based exposure assessment is to track and measure all possible exposure points along the utility system from source to end user that vary in geographic extent depending on location and utility type. We designed our assessment approach with the idea that the process should *aim to reveal differences between installations*, such that a prioritization can ultimately be achieved. This assessment approach is novel in its design for the purpose of utilities-based exposure assessment but draws from prior PAF work and catastrophe modeling theory, as discussed previously. For example, the approach described below relies on understanding how hazards physically damage utility infrastructure, which is a theme of catastrophe modeling. Importantly, we did not directly draw on any particular method from catastrophe modeling because our research purpose is distinct from how insurance and other industries evaluate potential damage and costs resulting from hazards.

Figure 2.1 summarizes the broad steps we took in designing our approach, noting that this approach was both a key need for developing and analyzing our case studies (discussed in the next section) and a beneficiary of the lessons that we discovered when using those case studies as a vehicle

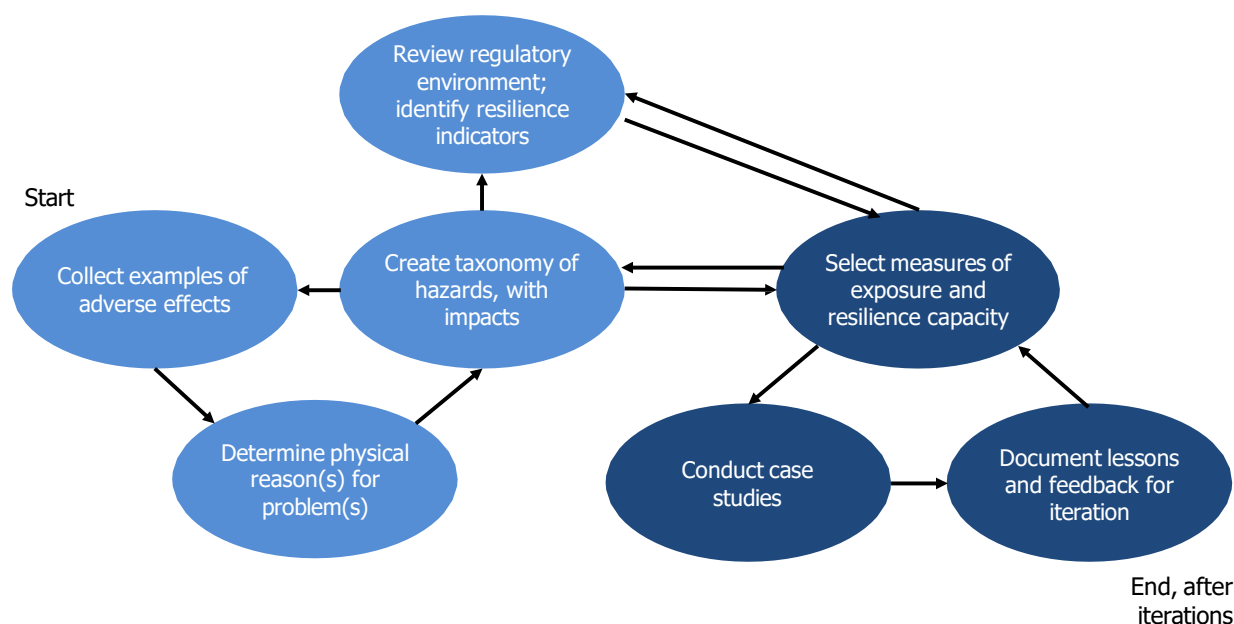
¹³ *Climate anomalies* represent the “departure from a reference value or long-term average” (National Centers for Environmental Information [NCEI], undated-c).

to employ our approach. In other words, we took an iterative approach (as denoted by the feedback arrows between the left and the right side of Figure 2.1), although this report necessarily takes a linear perspective in describing it. The approach depicted in the figure can be described in two parts:

- On the left side of the figure, in light blue, are the preparatory steps that must be taken to initiate an assessment. These steps do not have to be repeated each time that a new assessment is conducted, but they will need to be updated over time as needed. The process started with collecting examples of adverse effects of extreme weather and climate hazards on utility systems, which is needed to determine the physical reason for the problem (e.g., physical damage to the infrastructure, impact availability of source). These examples informed the development of a hazard taxonomy, including the component-level impacts to the utility infrastructure. Next, we used the impact mechanisms to focus on where to look for information about potential required mitigations in the codes and standards. In addition to reviewing codes and standards, we also developed a set of potential indicators of utility system capacity to mitigate the effects of climate hazards. In Chapter 3 and Appendix B, we discuss this part of the process in more detail.
- The right side of the figure, in dark blue, focuses on identifying exposure measures and resilience capacity indicators with the aid of case studies. Using the taxonomy, we selected a few hazards of most concern for each of our regional case studies and then identified some measures of physical exposure and resilience capacity indicators for each case study. We necessarily had to take an iterative approach because there are many ways to measure exposure for any one hazard (we discuss this in more detail later). Finally, we considered our case study to be complete when we identified measures that revealed variability in either (or both) physical exposure or resilience capacity. In Chapter 4, we present our case studies and results from the steps depicted in the right-hand side of Figure 2.1.

In the following sections, we describe the key steps in further detail.

Figure 2.1. Steps Taken to Craft Utilities-Based Exposure Assessment



Preparatory Steps

Creating a Hazard Taxonomy with Impacts

To begin, we collected examples of adverse climate or weather effects affecting a utility system, which we identified through a literature scan and various reports from the Environmental Protection Agency (EPA), the National Institute of Standards and Technology (NIST), and the Department of Energy (DOE). After documenting the various physical impacts that led to disruption of utility services, we developed a taxonomy of climate-related hazards with associated utility component-specific impacts accounting for types of impact, such as physical damage to infrastructure, potential changes in source availability, and demand pressures (see summary in Table 2.1). Details by utility type are included in Appendix B.

We then categorized the hazards into three bins according to the duration of the hazard: short-term event (e.g., hurricane, El Niño event); long-lasting event (e.g., multiyear drought, enduring insect infestation); and persistent, long-term trend (e.g., permanent sea level rise, changes in average temperature). This categorization was necessary because even if the mechanism causing the adverse impact is the same across these three types of hazards, it would be measured very differently. Consider, for example, high temperature, which can be measured as a heat wave (short-term event), an unusually warm summer or winter season (long-lasting event), or an average annual temperature increase (long-term trend).

Although the effect on any given day might feel the same (hot), the respective impacts on utilities can be somewhat different. Short-term hazards can create unanticipated demand pressure and sudden disruptions to the utility system. Longer-lasting events tend to have bigger impacts on supply and cause strain on transmission and distribution infrastructure. For example, widespread vegetation could

die off, downing transmission lines or increasing susceptibility to future wildfire or permafrost melting, which—combined with the right soil type—could result in land instability and infrastructure cracking. The biggest effects of relatively steady trends, such as annual temperature and sea level rise, could occur through second-order mechanisms, such as the frequency and intensity of heavy rain events (e.g., an El Niño event) or in making the impacts of tropical storm–induced coastal flooding more dangerous.

We iterated several times on the hazards taxonomy to create a qualitative tool that covered phenomena of interest without becoming repetitive. Several hazards were subsets of others or had related effects that could together form an impact pathway. Although we did not extensively look at the combined effects of hazards, we did consider this as we built the taxonomy. We demonstrate an example of a combined effect of rising temperatures on both permafrost melt and wildfires in the Alaska case study. Wildfires can exacerbate melting permafrost and can down electricity transmission infrastructure.

Table 2.1. Summary of Climate Hazard Taxonomy

Hazard	Natural			Other/Compound Effects
	Electricity	Gas	Water	
Short-term event				
Coastal flooding	X	X	X	Erosion, landslide, saltwater intrusion
Extreme cold	X	X	X	Demand pressure (natural gas)
Extreme heat	X		X	Demand pressure (electrical, drinking water), loss of ice or snowpack, permafrost melt, rapid ice or snow melt, vegetation die-off, wildfire
Hail	X			
Heavy ice or snow	X			Rapid ice or snow melt
Heavy rain	X	X	X	Inland flooding, erosion, landslide, loss of ice or snowpack, rapid ice or snow melt
Hurricane or tropical storm	X	X	X	Heavy rain, inland or coastal flooding, erosion, landslide, storm surge, wind
Inland flooding	X	X	X	Erosion, landslide
Landslide	X	X	X	
Lightning	X			
Rapid ice or snow melt	X	X	X	Inland flooding, erosion, landslide
Storm surge	X	X	X	Coastal flooding, erosion, landslide
Thunderstorm	X	X	X	Heavy rain, inland flooding, hail, lightning, wind, tornado
Tornado	X		X	Wind
Wildfire	X	X	X	Dust; erosion; landslide; toxicity, pathogens, and algae
Wind	X		X	Dust, wildfire
Winter storm	X	X	X	Extreme cold, heavy ice or snow, wind

Hazard	Natural			Other/Compound Effects
	Electricity	Gas	Water	
Long-lasting event				
Demand pressure	X	X	X	
Drought	X		X	Dust, insect infestation, loss of ice or snowpack, vegetation die-off, wildfire
Dust	X		X	
Insect infestation	X			Vegetation die-off
Toxicity, pathogens, and algae			X	
Vegetation die-off	X		X	Dust, erosion, landslide, wildfire
Persistent, long-term trend				
Erosion			X	Dust; toxicity, pathogens, and algae
Loss of ice or snowpack	X		X	Insect infestation, vegetation die-off, wildfire
Permafrost melt	X	X	X	Erosion, landslide, wildfire
Saltwater intrusion			X	
Sea level rise	X	X	X	Coastal flooding, erosion, landslide, saltwater intrusion, storm surge

Identifying Potential Utility System Resilience Capacity Indicators

Following the development of the hazard taxonomy, we used the utility impact mechanisms to identify a sample of specific regulations, codes, standards, and guidance documents that would be relevant. This sample included codes, standards, and specifications at a federal, state, county, and (if applicable) local level. Additionally, we expanded our search to identify other resources and documents relevant to climate change and natural hazard resilience, including best management practices, guidelines, and climate action plans. We then reviewed these documents to identify references to climate change or natural hazard resilience.

Early in the process, we were able to identify that the information in these documents alone did not easily facilitate a relative prioritization among installations. Thus, we turned to academic and gray literature to assemble a list of potential other indicators to provide richness to the assessment of a utility's resilience capacity. Summaries of our regulatory review and resilience indicators appear in Chapter 3, and details are presented in Appendix B.

Case Study Selection

Together with the sponsor, we selected three disparate geographical regions for our case studies—the mid-Atlantic, the Southwest, and Alaska—each of which features some commonality in geography and climate and encompassed multiple installations (outlined in Table 2.2). In our approach, we treated each region as a unique location with its own set of vulnerabilities that are not necessarily any more or less important or impactful than those of any other region.

These three case studies were deemed optimal because they covered the three major categories of climate hazard types (heat, water, and wind) and were selected specifically to examine the known climate hazard problems that are likely to grow over time, such as tropical storms, drought, and permafrost melt. Additionally, these case studies maximize physical distance so that no aspect of the respective utility systems would be shared by more than one case study. Without overlap of the case study regions, these analyses could provide truly independent looks at the problem.

Table 2.2. Overview of Case Studies

Region	Installations	Climate Hazards and Infrastructure Type	Physical Exposure Metrics	Indicators of Utility Resilience Capacity
Mid-Atlantic	• JB McGuire-Dix-Lakehurst • Dover AFB • JB Andrews • JB Anacostia-Bolling • JB Langley-Eustis	• Tropical storms and electrical systems	• Precipitation anomaly and annualized strong wind frequency	• SAIDI/CAIDI MED
Southwest	• Peterson SFB • Luke AFB • Edwards AFB	• Drought and water systems	• Temperature anomalies • Palmer Drought Severity Index anomalies	• Drinking water hazard mitigation projects • Drought plan
Alaska	• JB Elmendorf-Richardson • Eielson AFB • New, theoretical forward-operating locations at Utqiagvik (Barrow)	• Permafrost melt, wildfires, and energy systems	• Ground subsidence • Loss of bearing capacity • Wildfire	• SAIDI/SAIFI and LAUF gas as a percentage of total consumption

NOTE: CAIDI = customer average interruption duration index; JB = Joint Base; LAUF = loss and unaccounted for; MED = major event day; SAIDI = system average interruption duration index; SAIFI = system average interruption frequency index.

Steps for Estimating Exposure

Exposure measures were then used to probe our primary research question: How can the DAF use information about potential commercial utility system exposure to extreme weather and climate-related effects in setting priorities for installation-focused deep-dive vulnerability assessments? In brief, we began with a physical exposure assessment that leveraged accessible metrics. That is, we created an initial assessment using broadly available data on recent climate anomalies, basic utility infrastructure, and installation locations. This required us to first identify our catchment(s) of interest, which, as defined previously, is *the collective area inhabited by the components of a utility system*.

Defining a Catchment

In practice, there are several issues with defining catchments and employing this concept. Different utilities have different catchment extents and shapes. Different aspects of a single utility system (e.g., source and transmission) might have separate catchment locations of varying area and could be worth differentiating because hazards can asymmetrically impact the various components of a utility system, as we will discuss in Chapter 3.

Furthermore, we had to use proxies to define our catchments. There is no widely employed defined set of catchments advertised by U.S. utilities. Thus, we had to come up with several alternative options for approximating what the catchment could be. These included the following examples:

- major U.S. river basins (water)
- local watersheds (water)
- Petroleum Administration for Defense Districts (natural gas)
- natural gas provider regions
- North American Electric Reliability Corporation (NERC)–defined reliability coordinators or independent system operators (electricity)
- local electricity distribution areas (electricity)
- electric utility service area (electricity)
- climate divisions¹⁴
- state boundaries
- regions of the United States that tend to experience similar impacts from global ocean-atmosphere drivers such that their mean historical climatologies are closely aligned in terms of patterns (e.g., mid-Atlantic, Southwest, Alaska).¹⁵

We considered several factors when choosing among these options. On the one hand, making a catchment too broad (e.g., the entire Eastern Interconnection for electricity) makes the electricity utility system for any given DAF installation seem subject to a huge number of hazards that do not matter for local service. Langley AFB in Virginia will not be affected by tornadoes or thunderstorms near Wright-Patterson AFB in Ohio except (perhaps) under unfathomably extreme conditions and several other contributing factors that would lead to failure across the Eastern Interconnection.

On the other hand, making a catchment too small (e.g., local water pipelines only) could miss important outside-the-fence-line hazards. For example, several DAF installations in the western United States are somewhat connected to the same water source coming from the Colorado River. In this instance, the local snowpack near Hill AFB can remotely impact water supply concerns near Los Angeles AFB and Luke AFB.

We also had to consider functionally what made the most sense as a proxy for catchment. Should natural gas source areas be included if these do not typically appear affected by weather and climate

¹⁴ A *climate division* is a unit in which the statistical similarities between weather and climate are very high and not just in the general sense that they are within a U.S. region. For example, the weather in one part of coastal northern California is normally similar to that in any other part of coastal northern California.

¹⁵ The mid-Atlantic experiences relatively mild winters, hot and humid summers, and a hurricane season. Alaska is subject to sub-Arctic and Arctic temperatures and other weather patterns. The Southwest experiences hot and dry temperatures and has monsoon storms in the summer.

hazards? How does stormwater management factor into local or regional water resources? Are areas scoped for electricity planning (e.g., demand management) as important as the actual structure of the local grid itself?

In the end, we concluded that defining catchments is necessary for the analysis and is very specific to the case study area, type of utility, and even the nature of the hazards in question. In other words, the determination of which of the catchment proxy examples shown in the list above (or others) was made in the context of each region and case study. Some catchment types are only used in specific states. For example, Alaska uses energy regions within the state for planning.

Selecting Exposure Measures

We focused on recent anomalies (2001–2021 average) compared with a historical baseline (1895–2000) from the National Oceanic and Atmospheric Administration (NOAA) (NOAA, undated). There are many other sources of instrumental, remotely sensed, and other recent data, such as that which is available in the large holdings of the National Aeronautics and Space Administration (NASA) (NASA, undated). These historical datasets are readily available, are generally reliable, and have fewer assumptions and caveats than do future projections or paleoclimate data. Furthermore, anomalies could be early indicators of a longer-term change in a direction that utilities might not have optimally planned for (e.g., whether utilities are prepared to deal with conditions in which the current maximum is the new normal). Anomalies also do a better job of representing climate variability over larger geographic areas (such as those for utility systems that we considered in this study) than do absolute measures of climate variables. Thus, climate anomalies provide a way to perform more meaningful comparisons across locations in the context of this study.

When climate anomalies were not available, we looked to other historical exposure measures or, where appropriate, future climate projections to supplement the analysis, with the goal of identifying data and measures that emphasize installation differences. Lastly, we identified cases in which additional complex data analysis could be used in the future to refine the approach and provide more-precise estimates of potential exposure.

Considering Utility System Resilience Capacity

Following the physical exposure estimation, we considered potential indicators of utility system resilience capacity. Whereas physical variables had the potential to increase or intensify installation exposure to the negative impacts of climate change, we defined utility system resilience capacity such that these variables could be counted for positive mitigation of climate impacts. We also describe these variables in more detail in Chapter 3. For now, we simply note that we considered both (1) the specifics of selected codes and standards and (2) less-direct measures of utility capacity to mitigate potential effects of weather- and climate-related hazards that could cause disruptions in utility service other than day-to-day reliability issues.

Exposure Characterization

Through conducting the case studies and documenting the lessons learned, we sought to link our findings on catchment area, regional physical exposure, and state or local policy and planning issues to

exposure at a given DAF installation. We ultimately discovered that directly comparing numbers for exposure between installations was, not surprisingly, highly sensitive to how catchments were defined and which metrics were used. The results of the physical exposure and utility system resilience capacity estimation and relative priority of installations make up the heart of the analysis because they demonstrate a way to estimate exposure and to use these data to inform prioritization of deep-dive vulnerability assessments based on utility system exposure to extreme weather and climate hazards.

Limitations to Estimation Approach

Determining Appropriate Catchments

The problem of determining appropriate catchments and then finding data to examine exposure within the catchments remains one of the most difficult issues to contend with in analyzing utility-based exposure to weather and climate hazards. Available and readily accessible data typically do not match the catchment area precisely (or even remotely closely, in some cases). There are no data to approximate physical exposure specifically for utility catchments. We experimented with defining catchments according to area delineations for which data were available. The most successful example of this was in looking at drought data calculated across different river basins that track water supply reasonably well when regional or local water is primarily sourced from a particular river system. Another possibility worth exploring further is overlaying climate divisions and their associated data with utility catchments. Climate divisions are small areas of the United States that can be considered homogenous based on historical climate data. Measuring hazards by looking across the climate divisions that intersect with a utility catchment can be promising when using historical climate data is acceptable as a first step. Although there are defined climate areas, these areas do not always match up with the boundaries of regional data availability. A good example comes from looking at the difference between NOAA's defined U.S. climatic regions (NCEI, undated-e) and those regions for which NOAA supports Regional Integrated Sciences and Assessments Programs (Climate Program Office, undated).

It is difficult to make this a repeatable step in any analysis, and scaling up to an enterprise-level look at exposure would be very time consuming because it would require determining utility catchments for each DAF installation, which will vary considerably in size and shape. In other words, there is no rule of thumb that can be employed to characterize a utility catchment.

Data Availability and Accessibility

A critical issue we observed is that many times, an ideal metric for a hazard is not available or accessible. Various forms of climate data can require a substantial amount of processing and analysis and cannot be quickly manipulated for new purposes. One example (of many) is wind speed, which is measured at different heights. If one dataset for existing or projected conditions reflects wind speed at

50 meters, but more-accurate information for impacts to the electric grid would be at five to ten meters, then additional analysis must be done to get the data into the right format.¹⁶

Data-related issues also came up when reviewing the regulatory environment and identifying potential utility system resilience indicators. It takes considerable effort to examine regional, state, and local plans and programs to identify and track data related to resilience planning. There is no U.S.-wide picture that provides visibility into how each local utility is handling resilience planning. But having a resilience document or mention of climate hazards in policy does not equate to having the capacity to do something about a concern or measure progress. Furthermore, the bar against which such plans and policies should be measured varies depending on the region and its hazards. Arizona utilities that serve such installations as Luke AFB would not be expected to cover impacts from melting permafrost, for example. Thus, we turned to proxy indicators and had to contend with the assumptions behind these indicators. Is poor reliability a forward indicator of poor resilience? Do regulatory problems suggest poor management and capacity for resilience, or do they instead suggest that positive change is underway? Although these indicators do not provide a perfect, precise picture of a utility's resilience capacity, they nonetheless can provide insight into how a given utility is considering natural hazard and climate change risks and into what steps the utility is taking to safeguard against future climate-related impacts.

¹⁶ It is possible to estimate wind speeds at different heights using a logarithmic wind profile, but this provides a rough estimate only.

Energy and Water Utility System Sensitivities

In the previous chapter, we described the process that we used to develop our approach for estimating utility system exposure to weather- and climate-related hazards. We now turn to how we used information about climate hazards and utility system sensitivities to further define our case studies.

We noted previously that the fundamental challenge of a utilities-based exposure assessment is to track and measure all possible exposure points along the utility system from source to end user that vary in geographic extent and type of impact depending on location and utility type. Furthermore, exposure in and of itself might not be an issue of concern for a utility system if the infrastructure is not sensitive to the hazard or if the utility has implemented measures to mitigate against the effects of climate hazards to which the infrastructure might be exposed. Thus, in this chapter, we address the second research question: *What attributes of energy and water utility systems influence the systems' relative sensitivity and potential vulnerability to extreme weather- and climate-related effects?*

To do so, we characterized energy and water utility system sensitivities to climate hazards by looking at the mechanisms by which utilities have been affected by climate hazards using historical examples. We considered the impacts of hazards independently of one another and thus did not seek to rank hazards in terms of the likelihood to disrupt infrastructure or of the severity of the impact. However, we note when these types of assessments exist in the literature.

An early insight from this work is the importance, alongside physical exposure, of the extent to which utilities are directed or encouraged to implement policies that mitigate against climate and weather-driven reliability and resilience problems. Our review of historical cases of weather and climate-related utility disruptions suggested, not surprisingly, that various policies have the potential to directly impact a utility's capacity to alleviate effects from exposure to extreme weather and climate hazards. Utilities can be more or less sensitive to the effects of extreme weather and climate hazards depending on the regional or local regulatory environment and the extent to which the utilities have elected to partner with stakeholders to plan long term and adopt resilience measures. We elaborate further on this finding later in this chapter.

Utility System Impact Mechanisms

Climate-related hazards do not affect all utility system components uniformly. The direct impacts of some hazards affect only one to two components: For instance, drought and persistent changes in precipitation affect water supply. Short-term, event-based hazards—such as tropical cyclones, thunderstorms, tornadoes, winter storms, and wildfire—have the potential to directly affect all

components of the system, albeit in different ways. In the sections that follow, we summarize the relevant hazards, describing how they affect components of the system for each utility type. We write in generalities but note that utility system configuration varies widely across the United States.

Energy Systems

Many of the sensitivities of energy system infrastructure to climate hazards are already known because we have plenty of historical examples in which components of natural gas and electric systems have been affected by these hazards. We discussed some notable examples of extreme weather impacts in Chapter 1. Here, we dive deeper into the specific exposure points in the system. Table 3.1 summarizes the key regional climate hazards relevant to energy systems. We discuss each energy system separately and show a generic schematic of the components for each utility type (see Figures 3.1 and 3.2) and denote (in red) which hazards have the potential to cause disruptions in service. This information is also detailed in various views of the taxonomy presented in Appendix B.

Table 3.1. Summary of Regional Climate Hazards Relevant to Energy Systems

Climate Hazard	Energy System Component	Region Most Affected ^a
Extreme heat	Electricity demand pressure, reduced capacity of electricity infrastructure	All regions
Extreme cold	Gas production and transmission	Midwest and Plains regions, Alaska
Heavy precipitation and flooding, other than from tropical storms	All gas and electricity infrastructure	Northern regions, Southeast
Drought	Hydropower generation	Western and southern regions
Wildfire	Electricity transmission and distribution	Western region, Alaska
Sea level rise	All gas and electricity infrastructure	Nearly all coastal regions
Storm surge	Gas transmission and storage, all electricity infrastructure	Nearly all coastal regions
Hurricanes	Gas production, all gas and electricity infrastructure	Gulf and Atlantic regions, Hawaii, Puerto Rico
Permafrost thaw	Gas production, all gas and electricity infrastructure	Alaska
Reduced snowpack	Hydropower generation	Western regions

SOURCES: Features information from DOE, 2015, Figure ES-1, p. i; FEMA, 2021b.

^a Regions correspond to the geographic regions used in the Third National Climate Assessment (Melillo, Richmond, and Yohe, 2014).

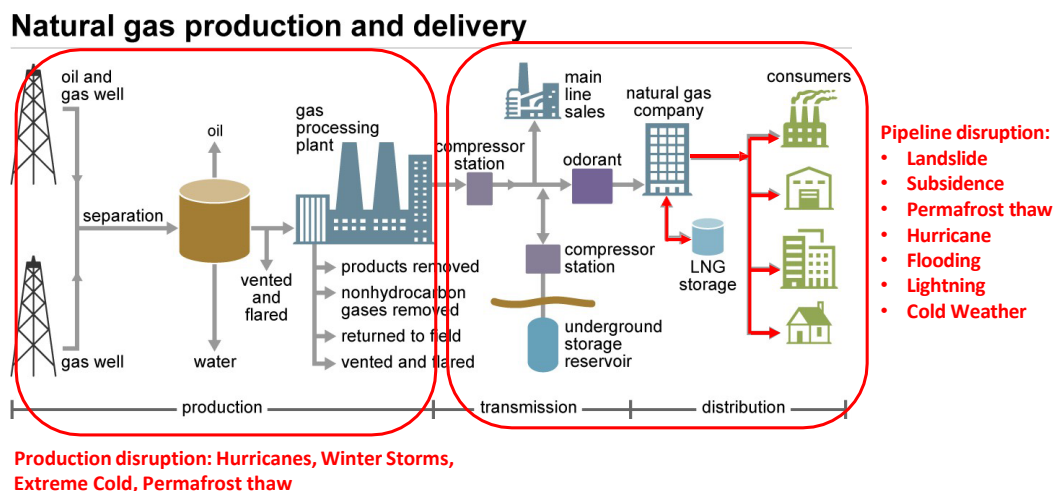
Natural Gas

Natural gas in the United States is produced from wells and coal beds and goes through extensive cleaning and processing before being transported to end users. Once cleaned and processed, the natural gas is transmitted to the pipeline system (a highly interconnected system across the country), placed in storage (e.g., salt caverns or depleted oil or gas fields) or compressed for surface- or ship-based transportation. Natural gas companies distribute the commodity directly to consumers, industry, municipal entities, and electric generation facilities. Figure 3.1 shows the generic processes and infrastructure assets that support natural gas production, transmission, and distribution and denotes in red the hazards we identified as being relevant to each of the components.

Production and distribution infrastructure are the system components most at risk to climate-related hazards. Many transmission pipelines run underground and are therefore less susceptible to direct weather effects, although they can be affected by second-order effects, such as flooding, subsidence, or permafrost melt. Generally, hurricanes, winter storms, and extreme cold events can affect production infrastructure, and landslides, subsidence, permafrost loss, hurricanes, flooding, lightening and extreme cold weather can affect pipelines (Cruz and Kraussman, 2013; DOE, 2015; Girgin and Kraussman, 2014).

Extreme weather and climate-related phenomena can have varying impacts on natural gas infrastructure depending on geographic location and system configuration. Factors that can influence the nature of the impact include the number and location of sources that the system draws from, the dependence of a particular region on gas-based electricity generation (demand pressure), and storage conditions (NERC, 2017). Different regions of the United States have different infrastructure, are subject to different regulatory environments, and have different demand signals that affect regional sensitivity to production and transmission disruptions. Furthermore, natural gas infrastructure is subject to strict siting constraints (permitting and topographical) for pipelines, more so than for electricity infrastructure (NERC, 2017).

Figure 3.1. Climate Hazards That Have the Potential to Disrupt Natural Gas Service



SOURCE: Adapted from U.S. Energy Information Administration (EIA), 2022b.

Potential Disruptions to Production

DOE has assessed that the climate-related hazards with the most potential to cause disruptions to natural gas production assets include intense hurricanes (most concerning for offshore oil and gas facilities); extreme cold temperatures (because of the potential to freeze wellheads); and permafrost thaw in Alaska, which can cause differential settling that undermines the foundations of structures, including drilling pads, production installations, and supporting structures (DOE, 2015). The EIA performed a comparative analysis of the loss in production from an extreme cold event in 2011 against that of four intense hurricanes from the preceding six years and found that the 2011 disruption “rivalled losses from major summer storms” (EIA, 2011).¹⁷ However, the infrastructure damage from a hurricane takes longer to repair, whereas production equipment may return to function with rising temperatures. In recent years, natural gas production has largely transitioned onshore: In 2004, offshore production accounted for about 20 percent; in 2020, offshore production accounted for only about 2 percent of total U.S. production (EIA, 2023b; Natural Gas Council, 2017). This shift reduces the vulnerability of production infrastructure to certain climate hazards—such as hurricanes—that historically have caused problems.

Potential Disruptions to Transmission and Distribution Pipelines

Girgin and Kraussman (2014) reviewed 45 years (1968–2012) of incident data from the U.S. Department of Transportation Pipeline and Hazardous Safety Administration (PHMSA), looking specifically for disruptions to pipelines caused by natural events.¹⁸ They found the following weather- and climate-related hazards to be causes of incidents, listed in descending order by percentage contribution to overall natural hazard induced incidents: landslide, flooding, lightning, frost, subsidence, tropical cyclone, cold weather, heavy rainfall, and storms. Permafrost thaw did not show up as a cause in their review, but we note that permafrost loss in Alaska can impact transmission infrastructure, such as the Trans-Alaska Pipeline System and fuel storage tanks, among other types of infrastructure (DOE, 2015).

Electricity

The electricity grid in the United States is complex. Power is generated at thousands of power plants across the country from various sources (e.g., hydrocarbon, renewables) and moves through the grid (a system of interconnected local grids that together are made up of millions of miles of transmission and distribution lines, substations, and transformers) to end users. Adding to this complexity are that different types of utilities have different organizational configurations and that retail markets differ regionally.¹⁹ Figure 3.2 shows the generic processes and infrastructure assets that support electricity generation, transmission, and distribution. Drought and extreme heat can impact

¹⁷ EIA noted that, historically, hurricanes have disrupted more production than winter freezes but that recent “freeze-offs in the Southwest rivalled hurricane proportions, at least for a few days” (EIA, 2011).

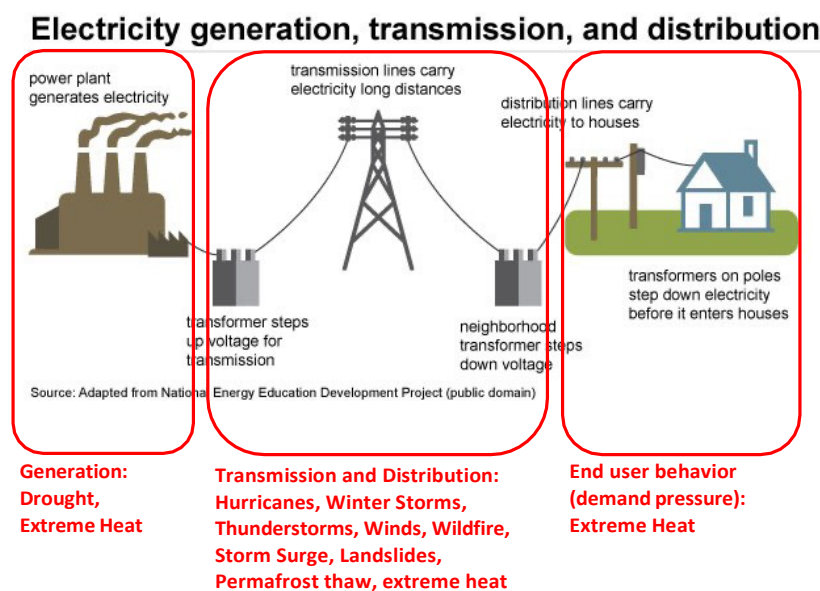
¹⁸ Their review included natural hazards that we do not consider in this study because they are not weather- or climate-related.

¹⁹ Some utilities sell only the electricity that they generate with their own power plant assets, while others buy from other utilities in a wholesale market, some only generate electricity, and others do a combination. The types of utilities include municipal electric utilities, cooperatives owned by members, private for-profit investor-owned utilities, and power marketers. A few federally owned authorities, such as the Tennessee Valley Authority, participate in wholesale and retail markets as well.

power generation assets; hurricanes, winter storms, thunderstorms, winds, and wildfire can impact transmission lines, substations, and transformers; and extreme heat can impact distribution lines (DOE, 2015).

Historical disruption data from 2003 to 2017 indicate that thunderstorms (47 percent), hurricanes (31.5 percent), and winter storms (19.5 percent) were responsible for 98 percent of weather-related electric disruptions (Shield et al., 2021).²⁰ DOE has assessed that increasing temperatures, heavy rainfall events, wildfire, hurricanes, and storm surge are likely to be the most impactful to the grid in the future. From a resilience perspective, hurricanes have been the most problematic because they have been associated with the highest restoration costs and longest restoration times (Shield et al., 2021). However, as the frequency and severity of other types of hazards increase, it is possible that there will be less recovery time in between events. As a result, events that would otherwise cause little to no issues for resilience could become a much bigger problem for the electric grid.

Figure 3.2. Climate-Related Hazards That Have the Potential to Disrupt Electricity Service



SOURCE: Adapted from EIA, 2022a.

Potential Disruptions to Generation

The 2022 *Summer Reliability Assessment* from NERC highlights two climate hazards that are expected to affect the ability of the electrical grid to meet expected demand (NERC, 2022). Summer temperature and drought forecasts were noted as affecting the grid in several ways. Low snowpack

²⁰ The study documents “the occurrence and variability of major weather-related electrical power disruptions,” showing that “weather is responsible for 50% of all events” for the date range included in the study (Shield et al., 2017). Outage data were collected from the DOE Office of Electricity Delivery and Energy Reliability Form OE-417 annual summaries for all 50 U.S. states and matched to NCEI storm data. The OE-417 has to be filed when certain conditions have been met related to the size and extent of the outage (Office of Electricity, 2021).

levels in the West are expected to affect hydropower generation. Heat can increase the outage rate for thermal generation, which corresponds to increases in peak demand. Drought in the Missouri River Basin is impacting the use of water for cooling at electrical generation facilities. NERC also considers the reliance on natural gas for electricity generation to be a potential climate-related risk.²¹

Potential Disruptions to Transmission and Distribution

Wildfire risk potential was identified as a risk to electrical grid operations. The existing wildfire risk and the expected drought continuation is projected to result in elevated wildfire risk across the western United States by late summer. Distribution lines and transmission lines are shut off in high-fire risk areas to prevent wildfire ignitions; the interconnected transmission system can be affected because of the threat of wildfire. Wind effects associated with thunderstorms, hurricanes, and winter storms can also impact overhead transmission lines.

High heat and drought expectations in the West will impact electricity distribution on several fronts. Extreme heat reduces wire carrying capacity and can cause wires to sag and arc and make contact with vegetation, igniting wildfires. Drought and the spread of large-scale insect infestations pose hazards to distribution infrastructure from the direct impact of fallen trees and from increased wildfire risk. Wildfires can cause local distribution grids to shut down as a safety measure. In other regions, impacts from increased precipitation and hurricane intensity include flooding, landslides, and collisions with wind-uprooted trees. Increasing rates of permafrost melt in Alaska threaten to damage or topple poles and lines (DOE, 2015). Although we have grouped distribution and transmission lines together, it is important to note that distribution-level damages are often repaired more quickly than transmission damages because of location, equipment, and supply chain factors.

Water Systems

Water infrastructure broadly includes drinking water, wastewater, and stormwater. In this section, we show a general schematic of the water systems that most people interact with and rely on daily: drinking water and wastewater. Sensitivities of drinking water infrastructure to high-intensity climate events are known from historical examples, such as surface water contamination following wildfires in Colorado (Fountain, 2021). Additionally, drinking water and wastewater infrastructure depend heavily on electricity to operate. We did not analyze the dependency of water on electricity, but any major disruptions to electricity have the potential to affect water infrastructure as well, as seen in Texas during the 2021 winter storm (Norton, 2021). Table 3.2 summarizes the key regional climate hazards relevant to energy systems. Climate impacts to wastewater and stormwater systems are included in the taxonomy presented in Appendix B.

²¹ Generation availability as a function of variables, such as operating reserves, demand response, and capacity performance, is an important leading indicator for susceptibility to climate-driven outages.

Table 3.2. Summary of Regional Climate Hazards Relevant to Water Systems

Climate Hazard	Water System Component	Region Most Affected^a
Extreme heat	Demand pressure, source (water quality)	All regions
Extreme cold	Source, pipeline infrastructure	Midwest, Plains region, Alaska
Heavy precipitation and flooding other than from tropical storms	All water infrastructure	Northern region, Southeast
Drought	Source	Western and Southern regions
Wildfire	Source	Western region, Alaska
Sea level rise leading to saltwater intrusion	Source	Nearly all coastal regions
Storm surge	All water infrastructure	Nearly all coastal regions
Hurricanes	All water infrastructure	Gulf and Atlantic regions, Hawaii, Puerto Rico
Permafrost thaw	Source	Alaska
Reduced snowpack	Source	Western region
Erosion and dust	Source, processing/pumping	Contiguous United States, Puerto Rico ^b

SOURCES: Uses information on regional hazards from DOE, 2015; Melillo, Richmond, and Yohe, 2014; and FEMA National Risk Index.

^a Regions correspond to the geographic regions used in Melillo, Richmond, and Yohe, 2014.

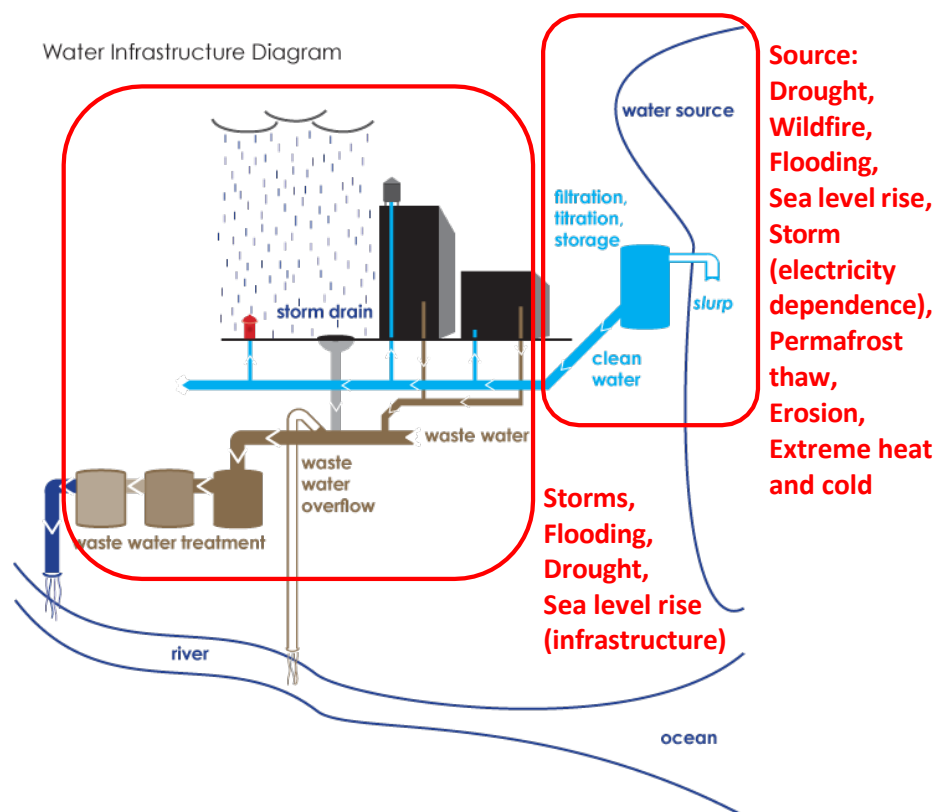
^b Determined by regions threatened by increasing drought and aridification in Duniway et al., 2019.

Drinking Water Systems

Approximately 90 percent of people in the United States get their drinking water from public water systems (EPA, 2023a). Drinking water is delivered to consumers through a network of pipes or other constructed conveyances. Sources of drinking water include surface water (e.g., lake or reservoir), groundwater (e.g., an aquifer), or recycled water. Most public water systems are supplied from surface or groundwater sources, both kinds of which are fed or recharged by rainfall or snowmelt and could be hundreds of miles away from the end user. With surface water sources, there is an intake structure that conveys the water to a treatment (NIST, 2016). With groundwater, aquifers are tapped using a well system that is powered by electrical pumps (NIST, 2016).

Figure 3.3 shows the generic processes and infrastructure assets that support drinking water treatment, storage, and distribution and wastewater collection, treatment, and outflow. Generally, drought, storms, flooding, sea level rise, wildfire, erosion, and turbidity and debris are the primary climate-related hazards of concern for water utilities (EPA, 2023h; Pamidimukkala et al., 2021).

Figure 3.3. Climate-Related Hazards That Have the Potential to Disrupt Drinking Water and Wastewater Service



SOURCE: Adapted from Norén, 2011, CC BY-NC-SA 3.0 DEED.

Water Source

The two main mechanisms through which water sources can be affected are reduction in water availability and contamination. The types of extreme weather conditions identified in the literature that have the potential to affect water source include floods, droughts, wildfires, and erosion (Pamidimukkala, 2021). During floods, groundwater wells can be inundated, which can lead to contamination and a need to flush the system (NIST, 2016). Stormwater runoff can also lead to increased concentration in water supplies (EPA, 2023j). Contamination can also occur because of wildfires that destabilize ground cover and lead to landslides, which, combined with precipitation, can cause the release of contaminants into the water supply. A consequence of fires in Colorado in 2012 was an increased concentration of contaminants and, subsequently, treatment by-products (Rhoades, Entwistle, and Butler, 2011; Writer et al., 2014). Drought, on the other hand, can have a more direct impact on the availability of source water (EPA, 2023j). Finally, rising sea levels can cause saltwater intrusion of coastal surface and groundwater (EPA, 2023j).

Water Treatment

Extreme weather and climate hazards impact water treatment in the sense that demand for treatment can intensify or change when water is contaminated. This most typically occurs as the result of flooding or other incursion of salty or contaminated water into drinking water sources (NIST, 2016).

Water Storage and Distribution

Often, surface water impoundments function as water supply sources and provide recreational and flood control benefits. Dam failure can be an indirect hazard after a heavy rainfall or flood event. Extreme precipitation and flooding can overtop and potentially break a dam. These types of failures are rare; however, they can still present risks to communities and downstream infrastructure systems (NIST, 2016). Although less common, water towers that are used to store water and pressurize water for distribution can be damaged or destroyed during hurricanes, tornadoes, and other strong wind events.

Large-diameter transmission pipelines move water to and from treatment plants and to storage facilities before branching out into smaller distribution pipelines. Usually, water transmission pipelines are buried, which reduces the pipelines' vulnerability to some hazards, such as strong wind events. However, floods, long-term rains, and wildfire that can cause landslides can also damage water transmission lines (NIST, 2016). Unlike electricity lines, a loss in service and corresponding loss in pressure can lead to pipe collapses that prevent restoration of the water flow and require significant repair.

Wastewater Systems

There are several major issues when it comes to extreme weather and climate hazards and wastewater systems. For this project, we do not focus as much on wastewater issues, but we do briefly describe the impact pathways here for completeness. The first type of impact is the possibility of inundation and flooding during severe storms, when stormwater is not appropriately captured or directed toward a river or ocean. Specifically, problems of untreated sewage being released is a common occurrence during major flood events when inflow and infiltration can overwhelm wastewater collection systems or when there are combined sewer overflows (NIST, 2016). The second type of impact is also related to extreme precipitation: when sewage systems back up and can cause sewage to flood low-lying areas of infrastructure. Like water pipelines, wastewater distribution pipelines can also be damaged by floods, long-term rains, and wildfire that can cause landslides, which can also damage the sewer lines.

Attributes That Influence Utility Sensitivity to Climate Hazards

Drawing from our work in developing the hazard taxonomy and documenting impact mechanisms, we identified the following three physical attributes of utility systems that can influence sensitivity and potential vulnerability to climate hazards:

- **Location of assets** encompasses both where assets are *relative to the surface* (e.g., above-ground versus below-ground electrical lines, on a hill or in a valley, distance from the surface) and where assets are *geographically* (e.g., coastal, inland).
- **System configuration** describes the nature and degree of interconnected infrastructure but not specifically the design standards to which the assets were built.
- **Asset condition** most directly ties to the sensitivity and potential vulnerability of utility system infrastructure. Asset condition is a function of age, design, operation and maintenance strategies, and previous exposure to physical perturbations.

From a screening-level priority-setting perspective, we recommend focusing effort on identifying the location of assets and obtaining a first-order approximation of system configuration. The condition of utility system infrastructure is very important in determining the vulnerability and risk but is much more difficult to obtain information about. Therefore, we do not recommend spending effort on collecting information about the condition of infrastructure in this first step. However, should this information be readily accessible, the DAF could certainly use it to inform decisions on where to conduct deeper dive vulnerability assessments.

Some information about the location of assets is relatively easy to obtain once the system has been mapped, which is not as easily accomplished. Mapping the system requires gathering information about utility company–specific infrastructure, which is not always publicly available. Publicly available geospatial datasets can be downloaded from the Homeland Infrastructure Foundational-Level Data (HIFLD) website (HIFLD, undated). For energy systems, these datasets include retail electric service company territories, independent system operator territories, power plants, electric substations, natural gas compressor stations, natural gas processing plants, pumping stations, hydrocarbon gas liquid pipelines, oil and natural gas wells, and natural gas storage facilities. These datasets sometimes include the owner or operator of the asset, whether the asset is in service or out of service, and physical attributes, such as above-ground versus below-ground powerlines or the voltage capacity of the line. However, this information is not consistently available for all utility systems. The datasets also do not indicate how the assets or systems are interconnected, which is a function of more than just the physical location: It also depends on the agreements made between the utility operators in a given market.

Water infrastructure is a little more difficult to ascertain information about, but HIFLD does have aquifer locations, a national hydrography dataset, watershed boundary lines, the National Flood Hazard Layer, reservoirs, hydrological unit boundaries, and dam lines. Whereas with the energy system files, one can begin to get a picture of interconnections between infrastructure within a given service territory, the water-related datasets do not support the same analysis.

Utility System Resilience Capacity

Having described *how* utilities can be affected by climate hazards, we now turn to our analysis of how to measure the extent to which the regulatory environment, related policies, and utility investment decisions have the potential to mitigate effects of climate-related hazards. We first used the utility impact mechanisms described in the previous sections to identify a sample of specific regulations, codes, standards, and guidance documents that would be relevant. This sample included codes, standards, and specifications at a federal, state, county, and (if applicable) local level. Next, we expanded our search to identify other resources and documents relevant to climate change and natural hazard resilience, including best management practices, guidelines, and climate action plans. We then reviewed these documents to identify references to climate change or natural hazard resilience. We present the summary of this review below and additional detail in Appendix C.

Early in the process, we were able to identify that the information in these documents alone did not easily facilitate a relative prioritization among installations. Thus, we turned to other indicators to provide richness to the assessment of a utility's resilience capacity. We also summarize these indicators below and present detailed information in Appendix D.

Summary of Regulations, Codes, Standards, and Guidance Document Review

Regulations at the federal level relevant to climate change resilience tend to be general in nature and focus on requirements for emergency planning, risk assessments, and reliability. For example, the 2018 America's Water Infrastructure Act requires community water systems of a specific size to perform a risk assessment to identify vulnerabilities from potential climate hazard exposure (EPA, 2019). For natural gas systems, federal regulations focus on pipeline and fuel transportation safety and security and consider extreme weather a safety hazard. Electrical system regulations focus on reliability measures and on developing plans to ensure that reliability standards can be met (Pub. L. 109-58, 2005).

There is consensus in the industry that a prescriptive approach to climate resilience is not appropriate in all cases given the regional variability in climate hazards and how important the local context is for designing and planning for resilience. States can (and do) establish additional regulations, some of which mandate the adoption of specific industry or region codes and standards. Codes specify *what* to do, and standards specify *how* to do it. For example, the National Electric Safety Code (NESC) says that extreme wind should be considered in the design of transmission and distribution poles and specifies a wind-loading standard that should be used. However, different versions of the NESC have been adopted across the country, and identifying what is different in these versions requires a detailed technical review. Further complicating this review is that not all codes and standards are mandatory. Voluntary standards, such as best management practices, often include specific technical and planning information for innovative and strategic approaches to plan and prepare for impacts from climate change exposure. These are arguably more useful in some cases for assessing a utility's resilience capacity, but it is not always easy to determine if a utility is following relevant voluntary standards unless the utility has made explicit their practices in a published plan or

on their website. Table 3.3 includes a sample of different types of code requirements for energy and water systems. A detailed review can be found in Appendix C.

We also found examples of federal guidance documents that focus on more-technical engineering design criteria—for instance, the Rural Utility Service Bulletin 1724E-200 includes recommended load factors and strength factors for calculating extreme wind load and ice loads for high voltage transmission lines (Rural Utilities Service, U.S. Department of Agriculture, 2015)—or on specific infrastructure hardening (e.g., strength requirements for pipeline or utility poles).

Although we found evidence of regional variability of climate change considerations in codes and standards, identifying and comparing these differences requires a detailed technical review—something we conclude is not ideal for supporting high-level screening for the purposes of setting priorities as a primary proxy. However, understanding the regulatory environment generally (e.g., a state or region adopts the latest codes as mandatory or requires vulnerability assessments) in combination with other factors could be useful for informing priority-setting. For example, utilities can be incentivized to incorporate resilience measures into their operation, maintenance, and planning efforts. The state of Connecticut established a grant program in 2012 to provide funding for municipalities to install microgrids for critical facilities, including water and wastewater treatment plants (Connecticut Department of Energy and Environmental Protection, 2020). In the next section, we discuss a set of indicators that we identified as potentially relevant to utility system resilience capacity.

Table 3.3. Sample of Codes Related to Resilience for Energy and Water Utility Systems

System	Case Study	Sample Text	Reference
Energy (electricity)	- Installation: Andrews AFB	<i>D. SAIDI and SAIFI Standards. (6) A utility's annual SAIDI result shall be equal to or less than its annual SAIDI reliability standard established in §D(1) of this regulation.</i>	Maryland Code of Regulations, Title 20, Subtitle 50, Chapter 20.50.12, Section 20.50.12.02
	- Case Study Region: Mid-Atlantic		
	- State: Maryland	<i>(7) A utility's annual SAIFI result shall be equal to or less than its annual SAIFI reliability standard established in §D(1) of this regulation.</i>	
	- County: Prince George's County		
Energy (natural gas)	- Installation: Elmendorf AFB	<i>Line pressure regulators shall comply with all of the following:</i>	Alaska Plumbing Code 2018, Chapter 12, Section 1208.8.4
	- Case Study Region: Arctic	<i>(4) At locations where regulators might be submerged during floods, a special antiflood-type breather vent fitting shall be installed, or the vent line shall be extended above the height of the expected flood waters.</i>	
	- State: Alaska		
	- County: Anchorage Municipality		
Water	- Installation: JB McGuire	<i>Water purveyors serving more than 3,000 residents, and other purveyors when requested by the Department shall develop and submit to the Department: (1) Emergency response plans by February 16, 1986, for water purveyors serving more than 50,000 residents or by March 19, 1991 for water purveyors serving more than 3,000 residents but not more than 50,000 residents. (i) The plans shall include, but not be limited to: (1) Organization structure including names of emergency response team members and telephone numbers; (2) Emergency notification and communication procedures; (3) Interconnections and backup supplies to be utilized; (4) Interim water restrictions, conservation measures and alternate sources of water; (5) Coordination procedures for emergency response with other agencies; (6) Resources inventory; (7) Vulnerability assessment; and (8) Any other information the Department deems necessary to respond to unforeseen water emergencies and long-term relatively predictable water emergencies.</i>	New Jersey Administrative Code, Title 7, Chapter 19, Subchapter 11, Section 7:19-11.2
	- Case Study Region: Mid-Atlantic		
	- State: New Jersey		
	- County: Burlington County		

Summary of Other Potential Indicators of Utility Resilience

Although we found that there is regional variability in how codes and standards consider extreme weather and climate hazards, the assessment of these regulations requires a detailed and technical review to identify these differences. Furthermore, there is a lack of accepted metrics to assess an energy or water utility's ability to prepare or respond to extreme weather or climate hazards (Kallay,

Napoleon, Havumaki, et al., 2021). Thus, we examined how other factors beyond the regulatory environment might play a role in helping utilities prepare for potential impacts from climate change. Here, we provide an overview of these indicators that could potentially be considered when assessing regional variations in a utility's climate change or extreme weather resilience initiatives. Our approach to selecting the indicators involved (1) conducting a literature review to identify factors that affect a utility's ability to invest, incorporate, or implement climate change resilience measures and (2) selecting indicators for which we could collect information through publicly available data to use for screening at a high level.²² The final set of potential indicators can be grouped into the following categories:

- **State or local resilience planning efforts:** The existence of (or lack of) approved plans or planning efforts that explicitly consider climate change and natural hazard risk may signal whether these hazards are a priority in planning efforts and whether there are initiatives or investments planned or underway to improve resilience.²³
- **Regulatory and financial mechanisms:** These mechanisms can enable or inhibit improvements to systemwide resilience by establishing standards (for energy efficiency or requirements for energy storage, for example), granting agencies or entities the authority to control or govern conduct in climate change resilience planning, or making available financial resources for the purpose of improving system resilience.
- **Community partnerships:** Installations that have a history of developing and participating in partnerships that are focused on resilience outside the fence line signal that improving broader system resilience is important and a priority for the installation.
- **Basic overview of the utility:** Some business characteristics of a utility, such as the number of customers and the size of the service territory, can provide insight into how utilities of different sizes might fare against a hazard of the same severity. For example, the American Society of Civil Engineers (ASCE) reported that smaller water utilities can have twice as many pipe failures because such utilities have more miles of pipeline per customer and smaller revenue streams than larger water utilities (ASCE, 2020).
- **Financial strength and investment capability:** Similar to the regulatory and financial mechanism category, a utility's credit rating, for example, can enable or inhibit the utility from accessing available financial resources to invest in system resilience.
- **Utility regulatory compliance:** Good or poor compliance with regulations indicates whether a utility is meeting minimum standards, rules, and requirements and thus could signal potential mismanagement or the ability or desire to prioritize resilience investments.

²² Additional variables of interest for which we could not collect information (because it is not publicly available) but that could potentially be useful in supporting this analysis include several regional grid operation variables, such as the relative availability of transmission interchange, asset redundancy, generation reserves, capacity performance, and fuel diversity.

²³ Our focus was on resilience planning efforts, but it is also possible that the processes and assessments that lead to the development of these plans could be sources of information, such as the state-level Threat and Hazard Identification and Risk Assessments and any hazard-specific annexes that might be added to state-level emergency operations plans. In our review of public documents, the information did not include any more information on potential exposure or climate risks than is available in other climate- and resilience-related state-level planning documents.

- **Utility service reliability:** Although not a direct indicator of resilience, service reliability metrics can provide insight into which systems might already be operating at reduced capacity under normal conditions and thus might be further stressed by a climate hazard.
- **Utility management of climate change:** Governance and accountability practices that include clear definitions of roles and responsibility as they pertain to climate resilience signal how a given utility might prioritize climate-related resilience initiatives.

Table 3.4 includes an overview of the indicators we considered for each category listed above. We provide further detail on the indicators and their potential tie to climate change resilience in Appendix D.

Table 3.4. Potential Indicators of Utility System Resilience Capacity

Category	Indicator
State or local resilience planning efforts	• Is there a state or local hazard mitigation plan? • Is there a state or local energy plan? • Is there a state or local water plan? • Does the base or community annual water quality report mention climate change, resilience, or infrastructure investments?
Regulatory and financial mechanisms	• Programs to support utility investments in resilience • Statewide renewable portfolio standard • Energy storage financial incentives • Energy storage targets • Energy efficiency standards • Net metering
Community partnerships	• Does the installation have a Readiness and Environmental Protection Integration (REPI) project? • Has the installation and community ever conducted a Compatible Use/Joint Land Use Study? • Has the installation and community ever received a Defense Community Infrastructure Pilot (DCIP) program, Military Installation Resilience Review (MIRR), or other Office of the Secretary of Defense (OSD) partnership grant? • Has the installation had an Air Force Community Partnership (AFCP) workshop in the past?
Basic overview of utility	• Number of customers served • Size of service territory • Type of utility (e.g., public or private, municipally owned or cooperative) • Urban versus rural • Infrastructure asset size
Financial strength and investment capability	• Long-term issuer credit rating • Short-term issuer credit rating • Investment capability based on corporate structure
Utility regulatory compliance	• Does the utility have any civil penalties within the past ten years? • Does the utility have any violations with federal or state regulators?
Utility service reliability	• SAIFI • SAIDI • MED declarations • Renewable energy generation portfolio • Number of report gas distribution incidents that have caused breakdown • LAUF gas as percentage of total consumption • Bare steel main miles (by state) • Cast iron main miles (by state) • Congestion revenue rights/financial transmission rights (CRRs/FTRs)
Utility management of climate change	• Utility Climate Change Governance Score • Does the utility have a climate change plan or other plans relevant to climate change (e.g., drought plan, energy resilience)? • Has the utility or local community completed hazard mitigation projects through the Federal Emergency Management Agency's (FEMA's) Hazard Mitigation Grant Program (HMGP)?

Category	Indicator
	• CDP 2021 Climate Score • CDP 2021 Water Security Score

In our analysis, we found that some indicators are better suited for community-level assessments, such as those listed in the *state or local resilience planning efforts* or *community partnerships* categories. Other indicators might only be available for certain types of utilities. For instance, historical electric grid reliability data (e.g., SAIFI and SAIDI) is available through the EIA for most electric utilities in the United States; however, we were unable to find an analogous data source on service reliability for water utilities. In developing this list, we did not seek to determine and assign a relative value for each indicator's contribution or tie it to resilience. Ultimately, these indicators should be used collectively to enable a relative ranking for the set of utilities of interest. For any given assessment, it might not be necessary to collect information on each one of these potential indicators to perform such a ranking. Generally, the better a utility does in embodying these potential indicators, the higher its resilience capacity is likely to be.

Key Findings About Climate Hazard Impact Mechanisms and Utility System Resilience Capacity

Drawing from our assessment of utility system impact mechanisms and identification of potential indicators of utility system resilience capacity, we identified several key findings, as follows:

- All energy and water utilities are directly and indirectly exposed to extreme weather and climate-related effects at every point along the system, from source all the way to end user behavior (demand pressure). However, these effects do not impact all utility system components uniformly. The direct impacts of some hazards affect only one to two components; for example, drought and persistent changes in precipitation impact water supply. Short-term, event-based hazards—such as tropical cyclones, thunderstorms, tornadoes, winter storms, and wildfire—have the potential to directly affect all components of the system, albeit in different ways.
- Climate hazards are predictably different in various parts of the United States; however, the geographic extent of utility networks, which, in some cases, can fan out across an area almost half the size of the continental United States, means that it is possible for geographically distant hazards from the area of interest (e.g., the installation) to have impact. (Although, in some cases, a geographically distributed utility supply chain can also be more resilient.)
- The three fundamental weather or climate drivers of hazards are heat, precipitation, and wind; impacts of utilities are realized through short-term events (e.g., storms), long-term events (e.g., droughts), and persistent trends (e.g., sea level rise).
- Utility systems are exposed to multiple hazards, which often compound effects simultaneously (e.g., sea level rise + tropical storm = coastal flooding; heat + wildfire = permafrost melt) or consecutively (e.g., low winter snowfall followed by summer heat wave = drought; forest insect infestation followed by wildfire = land slope instability).

- The three primary effects of exposure are (1) depletion or contamination of source(s), (2) damage to transmission and distribution infrastructure, and (3) increase in demand pressure.
- The regulatory environment, policies, and utility investment decisions are important to consider alongside physical exposure as indicators of a given utility's ability to mitigate against climate- and weather-driven reliability and resilience problems. Utilities can be more or less sensitive to physical problems depending on the regional or local regulatory environment and the extent to which they have elected to partner with stakeholders to plan long term and adopt resilience measures.

Utilities System Exposure Assessment

In the previous two chapters, we discussed our process for developing a utilities-based exposure assessment (Chapter 2) and how we defined the focus of each regional case study using information about how climate is changing regionally and utility sensitivities to climate hazards (Chapter 3). In this chapter, we use our case studies to answer our primary research question: **How can the DAF use information about potential commercial utility system exposure to extreme weather and climate-related effects in setting priorities for installation-focused deep-dive vulnerability assessments?**

We noted in Chapter 2 the challenges with defining the catchment for a given utility system over which the exposure assessment should be conducted—something that is necessary irrespective of the geographic scope of the study. Even harder is finding a generalizable approach across a given utility type; harder yet is defining one across utility types. As we demonstrate with our case studies, catchments might be better defined by the hazard of interest rather than the utility type. Additionally, metrics should only be considered for the utility components that are potentially sensitive to that effect; for example, if flooding does not have the potential to cause damage to a utility component (and thus the potential to cause a disruption in service), there is no need to include that metric in the assessment. This distinction is important for determining the geographic unit over which to calculate the exposure metric value.

Furthermore, because utility systems vary considerably in their geographic extent and some hazards, such as a storm, can be local in scale, we would ideally examine trends in storm tracks to define a relevant utility catchment area such that we do not skew the assessment by averaging over too broad a geographic area or attributing potential effects to a given system component that in reality is not in the path of the hazard (even if it is potentially sensitive to the effects of the hazard).

All of this is important to consider for getting a more precise understanding of potential vulnerability. But because we are informing the step prior to doing a vulnerability assessment, we traded some precision for readily accessible weather and climate data across the United States and that which is available by predefined, widely used geographic units, such as climate divisions, hydrological units, counties, utility service territories, and state boundaries. Using accessible data allows us to follow a repeatable approach that minimizes the required level of effort and specialized data-wrangling skills.

We used our case studies to work through these challenges, devise a utilities-based approach to exposure assessments, and understand possible implications for DAF decisionmaking. For each case study, we introduce why it was selected before providing an overview of the geography, common natural hazards, utility-system specifics, and DAF installations and their specific missions. Then, we demonstrate the physical exposure analysis, followed by a summary of potential utility-system resilience capacity indicators. Finally, we discuss the findings of each case study with reference to the

primary research question and, in particular, focus on what new insights may or may not be revealed that would assist the DAF with prioritizing installations for further examination.

Case Study: Tropical Storms in the Mid-Atlantic

Our first case study focused on electric utility system exposure to tropical storms in the mid-Atlantic region, which includes coastal states from Virginia in the south to New York in the north. This region is highly prone to coastal flooding when the sea is high and/or precipitation is intense because of its low-lying geography and sandy coastlines, which can be relatively easily eroded and overtopped. It is also relatively flat in places, especially at the coasts, leaving little natural protection against strong winds. Hurricane Sandy in 2012 is an example of the disastrous type of storm that could increase in frequency in this region as the climate continues to change.

We chose the mid-Atlantic region as one case in which to trace why electric utilities are impacted by tropical storms and their associated strong winds, intense precipitation, and high seas. As we describe in more detail in this section, we used this information to select metrics and conduct an assessment that was intended to highlight potential differences in installation exposure to hazard-related disruption in electric utility service. Although we could have also looked at the Gulf States, we decided to focus on a region with somewhat lower susceptibility to tropical storms, with the idea that differences in exposure might be more apparent. In addition, we had access to colleagues at RAND who led the Mid-Atlantic Regional Integrated Sciences and Assessments program at the time of this writing and were thus available to provide detailed information on weather and climate in this region (see, for example, Romita Grocholski et al., 2022).

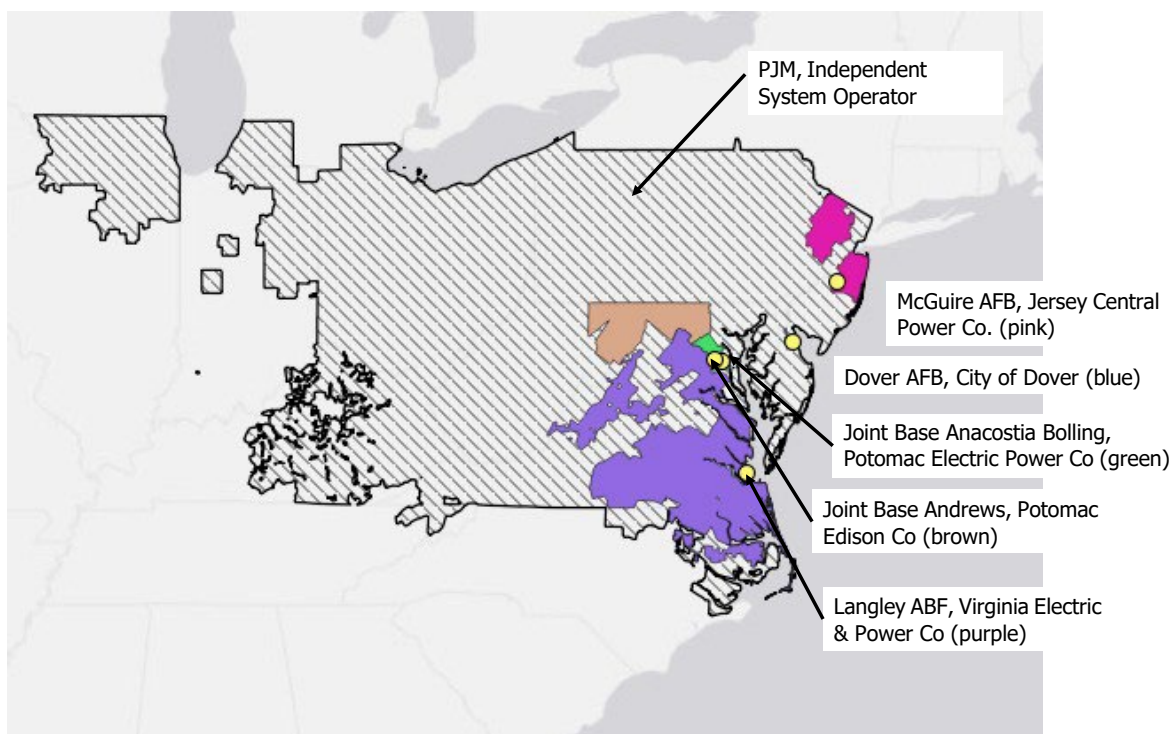
Overview

The geography of the mid-Atlantic region consists of a flat coastal plain in the east rising to the foothills of the eastern Appalachian mountain range, a ridge-and-valley mountainous topography, and the Appalachian Plateau on the western boundary, with rolling hills and serpentine waterways (Polsky et al., 2000). As discussed in Chapter 3, climatic factors that affect electric utility systems in the mid-Atlantic region include trends of increasing extreme heat days, increasing heavy rainfall (and resultant flooding), and increasing sea levels and storm surge (and associated coastal erosion). Additionally, strong winds (including tornadoes), winter storms, thunderstorms, and hurricanes are extreme weather events that affect all levels of utility infrastructure.

Electricity generation in the mid-Atlantic is supplied by coal (thermoelectric), natural gas (combined cycle) and nuclear power plants (Brown, 2013). The transmission-level grid is operated by the regional independent system operator PJM Interconnection. Distribution electrical providers vary locally. For example, JB Andrews and JB Anacostia-Bolling, colocated in the Potomac River Watershed, are serviced by Potomac Edison (approximately 400,000 customers) and Potomac Electric Power Company (approximately 890,000 customers), respectively. JB McGuire-Dix-Lakehurst electricity is provided by Jersey Central Power and Light, a large utility serving over 1 million customers. In contrast, Dover AFB is served by the City of Dover Electric Department, which has close to 25,000 customers. JB Langley-Eustis is served by a subsidiary of Dominion Energy.

With 7 million customers, Dominion Energy is the largest electricity operator among those serving the mid-Atlantic installations. Figure 4.1 shows the spatial relationship between the installations (yellow dots), the electric utility providers service territories (various colors denoted next to the installation name), and PJM's transmission-level service territory.

Figure 4.1. Electric Utility Service Territory and Independent System Operator Region



SOURCE: Features information from HIFLD, undated.

McGuire AFB (New Jersey) houses the 305th Air Mobility Wing, which conducts strategic airlift and air refueling missions with KC-10 and C-17 aircraft and operates strategic aerial ports for cargo delivery to combatant commanders. The 305th Operations Group “perform[s] aerial refueling and airlift in support of tactical, strategic, reconnaissance, transport, and bombardment forces in high-threat and chemical warfare environments” (JB McGuire-Dix-Lakehurst, 2021). The 621st Contingency Response Wing extends Air Mobility Command’s reach by specialized rapid deployment of personnel and equipment.

Dover AFB (Delaware) is home to the 426th Airlift Wing and the 512th Airlift Wing, active and reserve flying squadrons, as well as Air Force Mortuary Affairs Operations and the Campus for the Families of the Fallen, which are “designed to provide families with an area of privacy, comfort and support while they . . . witness dignified transfer of their loved one” (Air Force Mortuary Affairs Operations, undated). The Armed Forces Medical Examiner System at Dover AFB supports DoD and other federal agencies with forensic services.

JB Andrews (Maryland) houses the 316th Wing, whose mission includes capital airspace security and contingency immediate response rotary-wing aircraft.

Bolling AFB's (Washington, D.C.) 11th Wing prepares "all subordinate group and squadron functions to support host-unit requirements for the wing and its approximately 70 mission partners" (JB Anacostia-Bolling, undated).

Langley AFB (Virginia) houses Air Combat Command headquarters. The 1st Fighter Wing delivers one-third of the Air Force's combat F-22 Raptors, supporting combatant command short notice taskings. The 363rd Intelligence, Surveillance, and Reconnaissance (ISR) Wing conducts operations across "air, space, and cyber operations; full spectrum targeting; special operations ISR; and ISR testing, tactics development and advanced training" (Sixteenth Air Force [Air Forces Cyber], undated). The 192nd Wing flies and maintains F-22 Raptors and supports the intelligence mission.

Physical Exposure Analysis

As stated previously, we focused on the potential impacts of tropical storms and their associated strong winds, intense precipitation, and high seas on electric utilities in this region. Because tropical storm activity is seasonal (National Hurricane Center and Central Pacific Hurricane Center, undated), we looked at data only for the Atlantic season, which runs from June 1 to November 30. Tropical storms are discrete, short-term weather events with a defined geographic area of impact. Thus, ideal exposure metrics should measure short-term, direct effects, such as changes in extreme precipitation days, one-day max precipitation, coastal inundation from storm surge, and wind speeds at ten meters per second. However, these weather and climate anomalies are not calculated over the geographic units deemed most relevant to our research (see Chapter 3 and discussed above) as part of the normal set of products produced for public consumption by such organizations as NOAA. As discussed briefly in Chapter 3, in some cases, ideal metrics could be calculated, but it requires a substantial amount of processing and analysis of climate data and cannot be quickly manipulated for new purposes.

Rather than go down that road in this study, we wanted to test if other readily accessible metrics might be useful for informing prioritization efforts despite them being less directly linked to the specific hazard chosen for this case study. Therefore, we compared precipitation anomalies (2001–2021 average) with a historical baseline (1895–2000²⁴) and the annualized frequency of strong wind events (calculated from historical data from 1986 to 2017²⁵), looking for where these measures show variability across the region. Figure 4.2 shows the precipitation anomaly by climate division. Darker green colors indicate a higher anomaly; lighter green colors indicate a lower anomaly. Figure 4.3 shows the same map from Figure 4.2 but includes the utility service territory as an overlay. Figure 4.4 shows the annualized frequency of strong wind events by county. As shown in Figure 4.2, it is hard to discern much variability in the precipitation anomaly exposure measures for the climate divisions within which the installations lie. Even when looking at neighboring climate divisions within the utility service territory (Figure 4.3), it does not appear there is much variability. Looking across PJM Interconnection's territory, we see some variability, but given that all the utilities share (to some extent) transmission-level infrastructure, it gets even harder to track where exposure might differ

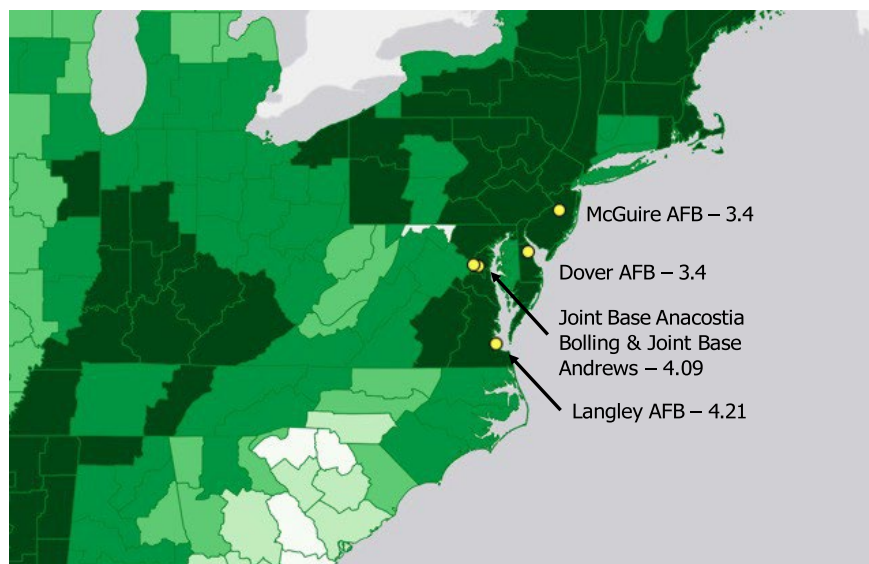
²⁴ Data were downloaded from NOAA, undated.

²⁵ Data obtained from the National Risk Index (FEMA, undated). This measure includes winds greater than 58 miles per hour.

looking across this level of a catchment. One could dive deeper and assess the system configuration, noting specific connection points, but this would require gathering additional data from the utilities about interconnection agreements: an activity that seems more appropriate for a deeper dive vulnerability assessment rather than a first-order, screening-level assessment.

The strong wind events annualized frequency by county exposure metric shows a little more discernable variability immediately outside the installation boundaries, but the same issue of trying to aggregate across the unit of study (county) complicates getting to one exposure value for the utility systems supporting these installations. Figure 4.4 shows that McGuire AFB, JB Anacostia-Bolling, and JB Andrews are in counties that have the highest annualized frequency of strong wind events (darkest blue, 5.36–7.87), Dover is in the second highest category (3.72–5.35), and Langley is in the lowest category (pale yellow, 0.00–0.99).

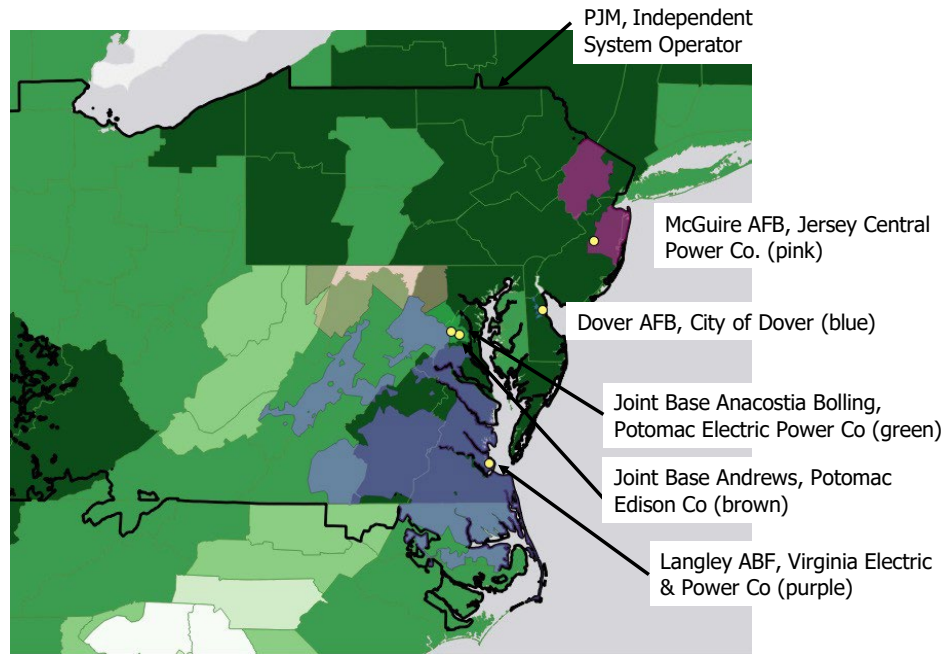
Figure 4.2. Precipitation Anomaly (2001–2021 average) Compared with Baseline (1895–2000)



SOURCE: Features information from HIFLD, undated; and NOAA, undated.

NOTE: The varying shades of green represent a categorized measure for the precipitation anomaly averaged over climate divisions. Dark green indicates higher anomalies; lighter greens indicate lower anomalies.

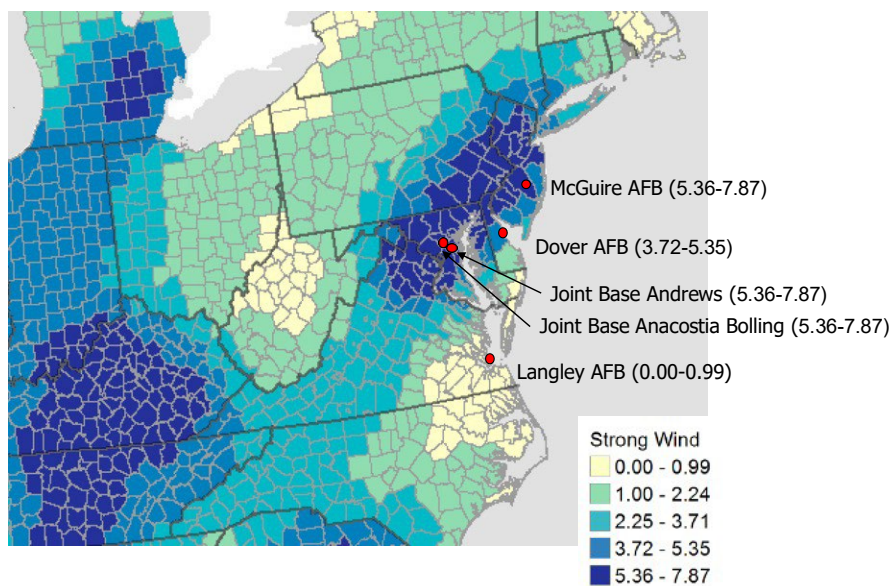
Figure 4.3. Electric Service Territory and Independent System Operator Region Overlay on Precipitation Anomaly



SOURCE: Features information from HIFLD, undated; and NOAA, undated.

NOTE: The varying shades of green represent a categorized measure for the precipitation anomaly averaged over climate divisions. Dark green indicates higher anomalies, lighter greens indicate lower anomalies.

Figure 4.4. Annualized Frequency of Strong Wind Events (1986–2017)



SOURCE: Base map is from the National Risk Index (FEMA, undated).

Indicators of Utility System Resilience Capacity

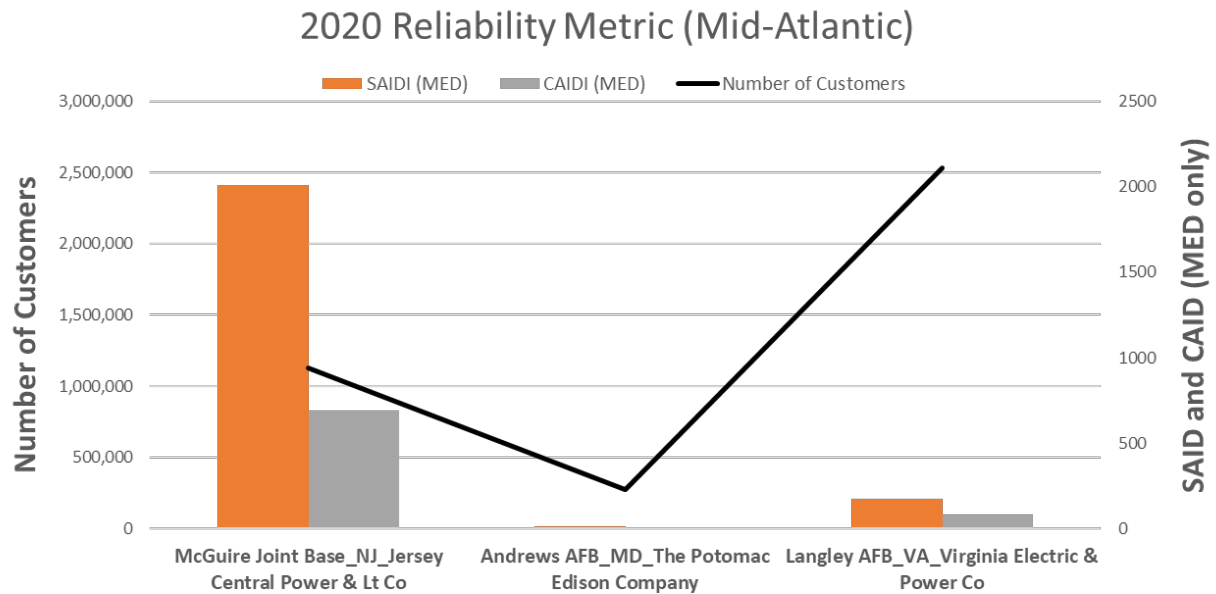
Having explored two measures of physical exposure, we now turn to indicators of utility system resilience capacity to see what we can learn about each utility's relative level of resilience capacity. We start with the well-known grid reliability metrics SAIDI and CAIDI, which both capture interruption and recovery, but we focus on data reported by utilities on MEDs because this captures longer duration outages than common reliability issues.²⁶ Figure 4.5 shows the results of this analysis for McGuire, Andrews, and Langley. There were no MED data available for Dover or Anacostia-Bolling. Our analysis shows that, in 2020, McGuire experienced more MEDs than did Andrews or Langley. This measure on its own is not particularly useful because there are a lot of factors that could explain the difference in performance: This alone does not indicate that McGuire is less resilient. But coupling this measure with a look at the number of large-scale extreme weather events or climate hazards could help place these values in context. Table 4.1 shows, by state, the number of extreme weather events experienced in 2020.²⁷ We can see that Virginia was hit with the most hazards (six severe storms and two tropical cyclones) but, according to the MED data, Langley did not experience as many long-duration outages as McGuire, which is situated in New Jersey, which experienced the fewest extreme weather events (three severe storms and one tropical cyclone). These data suggest that, all else equal, the DAF might want to prioritize a deeper dive assessment at McGuire over Langley or Andrews based on the electric utility's reliability performance.

We also collected information for the other potential indicators of utility system resilience capacity described in Chapter 3 and Appendix D. For electricity systems, we see some differences revealed across these indicators that, taken in combination with the information presented above, could help inform where to focus deeper dive assessments. For example, the utility that supports Langley operates seven power plants, whereas the utility that supports Andrews operates no power plants and only maintains transmission and distribution lines. Dover and Andrews are supported by municipally owned utilities, whereas McGuire, Anacostia-Bolling, and Langley are supported by investor-owned utilities. This means that the mechanisms for investing in resilience are different. (Investor-owned utilities are subject to state regulatory boards and must submit rate cases, whereas municipally owned utilities do not have to follow the same rules.) The details for each potential indicator can be found in Appendix F.

²⁶ MED is defined by the Institute of Electrical and Electronics Engineers' (IEEE's) standard 1366 as "a day in which the daily SAIDI [or CAIDI] exceeds a threshold value T_{MED} " (IEEE, 2022). This threshold value is based on the utility's past five years of SAIDI or CAIDI (whichever is being calculated).

²⁷ Data were taken from NOAA's disaster database (NCEI, undated-a).

Figure 4.5. Analysis of SAIDI and CAIDI Major Event Day Data



SOURCE: Authors' analysis of data from EIA, 2023a.

Table 4.1. Summary of Extreme Weather Events in 2020

Year	State	Drought	Flooding	Freeze	Severe Storm	Tropical Cyclone	Wildfire	Winter Storm
2020	MD	0	0	0	4	1	0	0
2020	NJ	0	0	0	3	1	0	0
2020	VA	0	0	0	6	2	0	0

SOURCE: Features information from NCEI, undated-b.

Findings

We explored two physical exposure metrics for the mid-Atlantic region: average precipitation anomaly and annualized high-wind event frequency. The precipitation anomaly did not appear to be very useful for prioritizing, because to get real variation across the utility systems, we had to look across PJM Interconnector's service territory, and that makes determining one exposure value for a utility system even harder. Furthermore, it is unclear how much of an impact small changes in average precipitation have on utilities: Does one more inch of rain on average in one region over another really mean anything for potential utility service disruptions? Annualized high-wind-event frequency proved more useful in this respect because the impact mechanism of wind on transmission and distribution lines is clearer and more direct. Additionally, we saw some variable in values, with McGuire,

Anacostia-Bolling, and Andrews located in counties in the highest category, Dover in the second-highest category, and Langley in the lowest category.

Taking this information and looking at MED data, we again see McGuire at the top of the list and Langley at the bottom. However, because there are no MED data for Anacostia-Bolling and Dover, we are unable to compare across all the installations. Considering a few more potential indicators, it appears that the surrounding community for McGuire and Jersey Central Power are relatively active in planning for climate change. We found that Jersey Central Power has a climate change-specific plan (all utilities for these installations do, except for Dover), and the community is the only one out of the five that has completed hazard mitigation projects through FEMA's HMGP. Still, Jersey Central Power's reliability ranking is the lowest in this region. This would suggest that, if the DAF were concerned *only* about prioritizing based on potential for electric utility service disruption, McGuire appears to be the first place that the department should look.

Case Study: Drought in the Southwest

Water has been a key issue for the Southwest for decades. The region's largest river, the powerful Colorado, is a lifeline for the Lower Basin states: California, Nevada, Arizona, and New Mexico. These net water consumers have often found themselves at odds with Upper Basin states, such as Colorado and Utah, whose rivers and streams feed the water supply. Not only is this region arid generally, but it has also suffered from massive droughts to the point where it is no longer clear whether intensively dry, hot conditions are a climatological anomaly or simply the new normal.

Drought in the Southwest is projected to get worse over time with climate change. The combination of very dry conditions, changes in the relative amount of precipitation that falls as snow (convenient for natural water capture and storage), and intense heat creates severe problems for the potable water supply. Furthermore, the heat and dryness also increase demand for water across the board: for household use, agriculture, and hydropower (for cooling). In this sense, drought is a double-edged sword, increasing demand while simultaneously decreasing supply and storage. In the following sections, we demonstrate our assessment of DAF installations' relative exposure to physical and policy conditions associated with drought and its impacts on potable water.

Overview

The Southwest encompasses a large region with diverse climates, from California's coastal Mediterranean climate with dry summers and wet winters to variations in precipitation and winter temperatures in the Sonoran, Chihuahuan, Mojave, and Colorado deserts (National Park Service, 2017). Temperatures have increased across the Southwest in the past century, resulting in reductions in seasonal snowpack (a slow-release form of natural water storage) and earlier spring melts. Three-quarters of land in the Southwest is forest or shrubland, ecologically adapted to wildfire yet increasingly experiencing wildfires that burn hotter and over larger areas, exacerbated by drought (Gonzalez et al., 2018). Wildfires can destroy or lead to the shutdown of electrical transmission and distribution systems, thereby disabling water treatment facilities and pumps, which cannot operate without electricity.

Additionally, there are numerous pathways for post-wildfire hazards to degrade surface water quality (such as dust, erosion, landslide, and toxic contaminants). *Aridification*, a permanent change to drier conditions, has the potential to cause widespread levels of dust and erosion, posing additional threats to drinking water quality in surface waters. Precipitation, although expected to decrease overall, is also expected to occur in more-extreme rainfall events, such as atmospheric rivers (Warner, Mass, and Salathé, 2015). Although flooding poses risks to water infrastructure in the Southwest, we focus our case study on the threats associated with drought. High rainfall events in spring can cause snowpack that would otherwise melt slowly to release all at once; the high-flow event during a heavy downpour is then followed by decreased water supply later in the season, exacerbating drought conditions.

The Colorado River Basin encompasses upper and lower basins, with climatic shifts in both basin regions threatening the water supply of seven basin states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming). Increased demand for irrigation waters and increasing population pressures, including increased user demand for water associated with hot and dry conditions, makes water scarcity in the Southwest a matter of serious concern (Bureau of Reclamation, 2016). However, depending on one's location and utility configuration, water sourced from the Upper Basin may provide most of one's potable water or may provide none of it. (For example, Peterson SFB sources water entirely from the Upper Basin in Colorado; Vandenberg SFB is serviced by water sourced exclusively from California watersheds.) Thus, in addition to the climatic conditions of the upper and lower basins, local precipitation, temperature, snowpack levels, and follow-on effects of drought and wildfire play a role in the quality and quantity of water sourced from aqueducts, reservoirs, and transport canals across the Southwest.

The utility that provides drinking water at Vandenberg SFB is American Water. Water is purchased from Central Coast Water Authority, which, in turn, treats and delivers water from the California Aqueduct's Coastal Branch (surface waters from the Sierra Nevada mountains). Additionally, American Water operates four onsite wells (local groundwater) (American Water, 2022). The water utility configuration at Luke AFB includes multiple sources and operators, including Valley Utilities, Liberty Utilities, and EPCOR-Agua Fria (Luke AFB, 2021). Water sources include groundwater wells from the West Salt River Valley sub-basin and surface water from Lake Pleasant. Lake Pleasant is fed naturally by the intermittent Agua Fria River and supplemented by the Central Arizona Project canal, which provides water from the Colorado River (Central Arizona Project, 2022). Peterson SFB is entirely reliant on water sourced from up to 200 miles away by Colorado Springs Utilities. Mountain stream water is collected, transported by pipeline, and held in reservoirs along the continental divide in Colorado. Several local reservoirs hold the imported water closer to Colorado Springs, and water supplies are supplemented by local surface water collection and by purchased water from the Fryingpan-Arkansas Project (source near Aspen, Colorado, transported by pipeline and the Arkansas River) (Colorado Springs Utilities, 2022).

Vandenberg SFB is home to Space Operations Command West, which is the headquarters and staff location of U.S. Space Command's Combined Force Space Component Command and the Combined Space Operations Center. Space Launch Delta 30 manages DoD missile testing and West Coast satellite launch. Space Training and Readiness Command's Space Delta 1 at Vandenberg SFB provides basic and specialized warfighter training for U.S. Space Force forces. The 576th Flight Test

Squadron conducts ground and flight tests and identifies missile system requirements and improvements, gathering and providing data to the Joint Staff, U.S. Strategic Command, Air Staff, and Air Force Global Strike Command.

Luke AFB houses the 56th Fighter Wing, including the 56th Operations Group (fighter-training mission) and 56th Maintenance Group (providing maintenance for 77 F-16 and 86 F-35 Joint Strike Fighter aircraft and training to more than 3,000 maintenance technicians each year). The 56th Mission Support Group consists of more than 1,800 members accountable for a broad variety of missions, including communications, infrastructure, cyber defense, and logistics. The 944th Fighter Wing at Luke is a reserve command unit.

Peterson SFB is the headquarters of Space Base Delta 1 (under the direction of Space Operations Command) with over 100 mission partners globally, including the 302nd Airlift Wing (reserve). Also at Peterson are Space Delta 2 (combat-ready Space Domain Awareness operations) and Space Delta 3 (trains and deploys combat-ready space electronic warfare forces). Space Delta 7 at Peterson is responsible for the U.S. Space Force operational ISR mission. U.S. Northern Command is headquartered at Peterson and organizes and executes homeland defense and humanitarian and disaster recovery missions. The North American Aerospace Defense Command (NORAD), headquartered at Peterson, is responsible for aerospace warning, aerospace control, and maritime warning for North America.

Analysis of Physical Exposure and Utility System Resilience Indicators

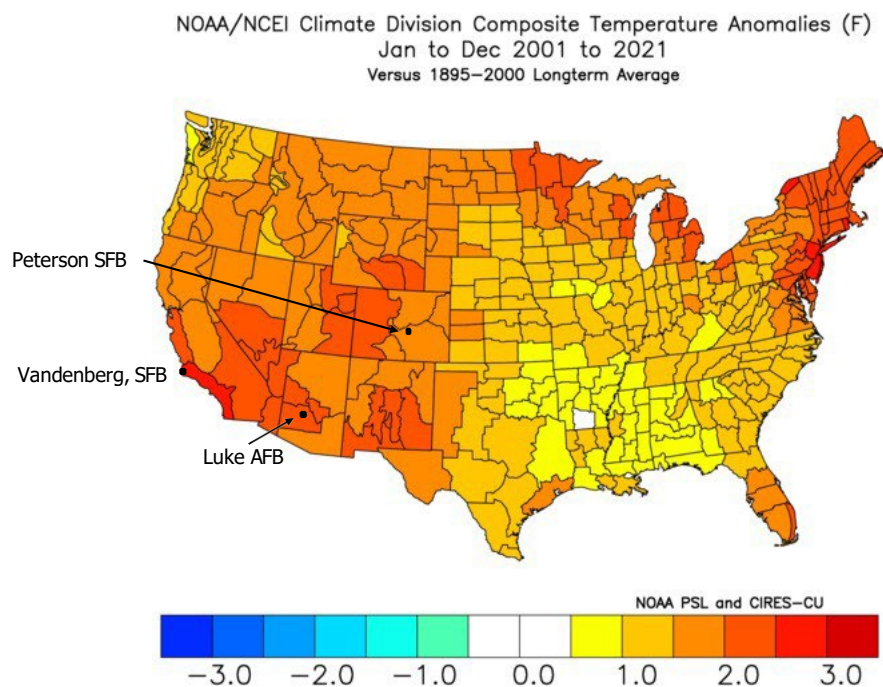
On balance, Luke AFB might be the most exposed of the three bases for a few reasons. First, its climate anomaly scores for temperature and Palmer Drought Severity Index are relatively intense (see Figures 4.6 and 4.7). Although Vandenberg SFB also shares similar scores, it is on the edge of two climate divisions, one of which (to the north) appears to be on a less adverse trajectory. Second, Luke AFB is in a Lower Basin state (Arizona) with few options to turn to besides the river other than improved stormwater capture. (Although there is not much precipitation, Arizona does experience, for example, a summer monsoon that deposits a minimal amount of difficult-to-capture rainfall.)

In contrast, both Peterson SFB and Vandenberg SFB are geographically closer to mountains that serve as natural water towers. Examining recent and projected future April 1 snow water equivalent is a key metric for better understanding the health of the natural water generation and storage system and whether policy action might be needed to seek alternative water storage systems (e.g., for more precipitation falling as rain instead of snow).

We next looked at a few potential indicators of utility system resilience. Unlike for energy systems, there are no readily accessible metrics for water service reliability. One potential reliability measure would be to look at the number of days that a particular location was subject to water use restrictions. We were not able to find a comprehensive database that included this historical information, although some state water boards post current water use restrictions on their websites. In the absence of reliability metrics, we looked at whether the utilities have drought mitigation plans (which they all do) and whether they have completed any hazard mitigation projects through FEMA's HMGP (Luke and Vandenberg have, Peterson has not). Policy observations or metrics are needed to understand the extent to which local water sources are being developed (storage, in particular) and whether local,

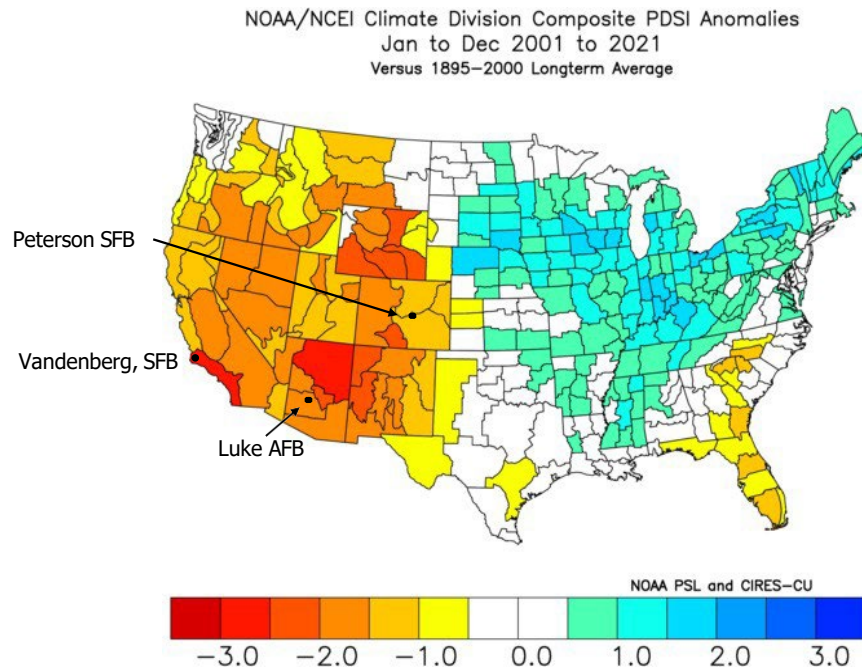
state, and federal water rights specify who can use locally captured water. Other useful metrics include projected future demand pressure as a function of both anticipated population growth and actions to extend supply (e.g., use of recycled water for non-potable needs). Installation growth plans could be affected if demand pressure on water supplies grows.

Figure 4.6. Temperature Anomalies Across the United States (January to December, 2001–2021) Compared with a Baseline (1895–2000)



SOURCE: Adapted from NOAA, undated.

**Figure 4.7. Palmer Drought Severity Index Anomalies (January to December, 2001–2021)
Compared with a Baseline (1895–2000)**



SOURCE: Adapted from NOAA, undated.

Findings

As an illustration of our approach, this is a case in which looking at climate anomalies provides most of the perspective needed on physical exposure. The only metric that would likely be worth the additional investment of resources, as well as the acceptance of some additional uncertainty, is the April 1 snow water equivalent (or similar) because this metric addresses the problem of what form the precipitation takes and the implications for water storage. It is possible that more information on extreme precipitation could be useful; however, rainfall in all three areas is reasonably low, so efforts to invest in stormwater capture are likely to have minimal impact except for Vandenberg AFB.

One way to easily understand the effect of potential future drought on resources coming from the Colorado River would be to track, for example, historical and current water levels at Lake Mead, a key reservoir for the river and a good proxy measure for the supply available to several states. However, this metric does not enable any differentiation between installations in this area.

Whereas the physical exposure analysis was reasonably straightforward, the policy examination for this case study was quite complex. Water resources in the Southwest are very interconnected, which is not something easily captured by considering DCAT data alone. Understanding the complexity of the policy landscape in the Southwest requires extensive knowledge ahead of the analysis regarding water law and policy and how different regions of the southwestern United States manage their respective water sources, which might also include other rivers, groundwater, stormwater, and desalination plants. In other words, a nested set of laws and policies really seem to

govern how exposed and vulnerable DAF installations are to water shortages for this region, less so the physical metrics.

Case Study: Permafrost Thawing in Alaska

Thawing of permafrost, caused by the rapidly warming Arctic climate, is exposing the region to hazards that have not been experienced for thousands of years in some cases, long before there were utilities to consider. As we articulate below in greater detail, Alaska's (often) fragile local energy infrastructure is painfully exposed to land and vegetation instability related to permafrost melting, wildfires, and pests. These heat-induced hazards have begun damaging and (in some cases) destroying electricity and natural gas transmission and distribution infrastructure.

Unlike our other two case studies, we introduce a theoretical decision context to conduct a richer analysis given that the DAF has two installations (Eielson and Elmendorf), both below the Arctic Circle. We posit that, to further implement the goals of its Arctic strategy, the DAF could consider options to expand its permanent infrastructure in the far north of Alaska, where the impacts of permafrost thaw are more likely to be felt in the future but where problems associated with falling trees are less intense (at least for now). We conduct an exposure assessment comparing Eielson and Elmendorf with Utqiagvik, a hub of far northern human activity that does not host DAF (or any other U.S. federal government) infrastructure.

Overview

Alaska's large landmass has over 6,000 miles of coastline, with seas in the north, west, and south. Ocean waters and seasonal sea ice exert a moderating climatic influence on coastal regions. The interior of Alaska experiences a continental climate with more extreme seasonal and daily temperature ranges. The Arctic region, in northern Alaska, is separated from the rest of the state by the Brooks Mountain Range; mean annual temperatures in the Arctic are well below freezing. Nonetheless, mean seasonal and average temperatures are increasing more rapidly in the Arctic relative to the rest of Alaska (Alaska Climate Research Center, undated). The observed climate change effects that are most relevant to utility infrastructure are coastal erosion, earlier spring snowmelt, permafrost melt, insect outbreaks (leading to boreal forest die-off), lightning, and wildfire. Wildfires, ignited by human activity and increasingly frequent lightning storms, are exasperated by ground collapse and fallen trees because of permafrost melt, high temperatures drying out vegetation, and insect infestations. Tundra and peatlands, as well, are vulnerable to wildfire, and research has shown that permafrost melt increases after fire, creating sinkholes called *thermokarst* (Chen et al., 2021).

Eielson AFB has a coal-fired heat and electric plant.²⁸ The base is further supplied with electricity from Golden Valley Electric Association, enough to keep some functions of the base operating through a shutdown of the onsite power plant. However, Eielson has no backup for central heat (Ellis, 2021).

²⁸ In September 2022, the DAF released a request for proposal for a nuclear reactor as part of the Micro-Reactor Pilot Program, which is the DAF's response to the requirement in the FY 2019 National Defense Authorization Act to have an operational micro-reactor by 2027 (Pub. L. 115-232, 2018).

The utility provider for JB Elmendorf-Richardson is Doyon Utilities, an Alaska full-service utility provider that also provides to Fort Wainwright and Fort Greely. JB Elmendorf-Richardson has an extensive on-base natural gas distribution system. Doyon and Anchorage Solid Waste Services Department partner in a local landfill-to-energy project, providing off-peak power on the Fort Richardson side of the base and 25 percent of JB Elmendorf-Richardson's total electrical demand. Additional electricity is delivered to JB Elmendorf-Richardson by Chugach Electric, a large utility that has more than 90,000 customers in the Anchorage area.

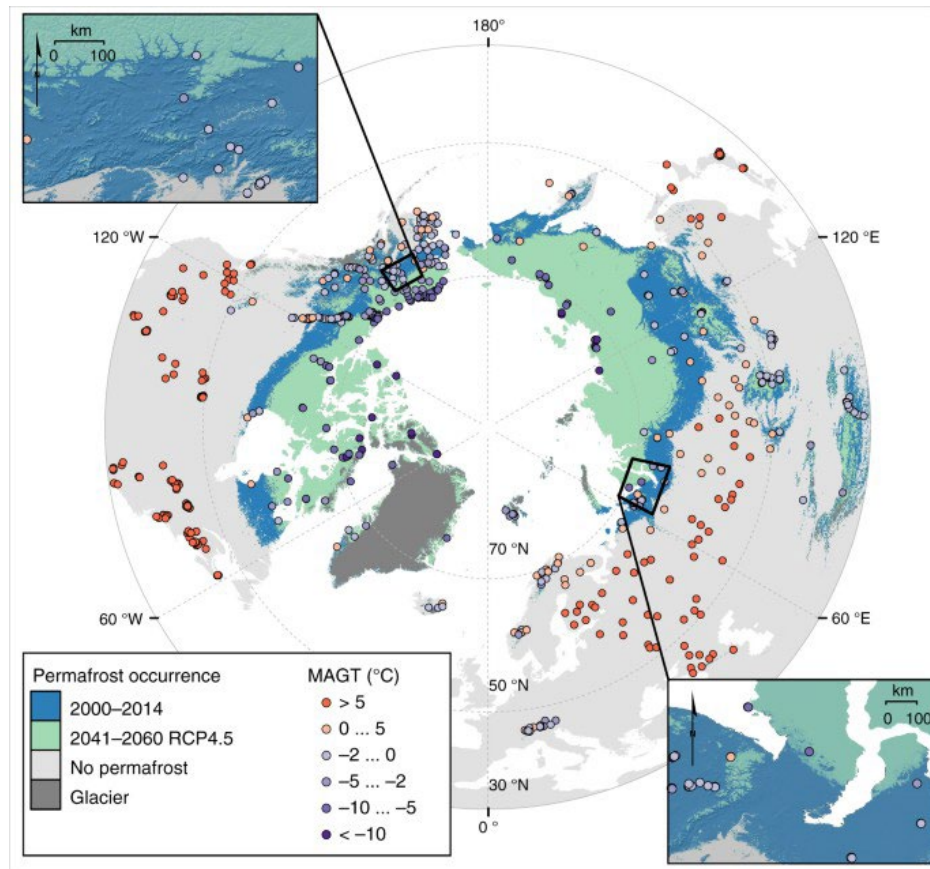
The host unit at Eielson AFB is the 354th Fighter Wing, whose mission is to provide training and combat-ready aircraft and forces for U.S. Indo-Pacific Command. The 168th Wing (Air National Guard) conduct air refueling, missile warning, and space surveillance operations. Other units at Eielson include detachment 460, whose mission is to monitor earth seismic activity, and the Arctic Survival School (run by Detachment 1, 66th Training Squadron).

The Elmendorf AFB host unit is the 673d Air Base Wing, whose mission enables "America's premier strategic power projection platform" (JB Elmendorf-Richardson, undated). Elmendorf houses the Alaskan NORAD Region headquarters, whose mission is aerospace warning, aerospace control, and maritime warning within the state of Alaska and surrounding waters. Alaskan Command, headquartered at Elmendorf, is responsible for Alaska force readiness and worldwide contingency force deployment directed by U.S. Northern Command. The 11th Air Force defends Alaska, Hawaii, Guam, and other strategic locations by providing combat-ready forces for the Commander, Pacific Air Forces; additionally, the 11th Air Force supports federal and state civil missions. The 3rd Wing provides global mobility, staging, and throughput for U.S. Pacific Command and around the world. The 176th Wing at Elmendorf conducts rescue operations, combat support, strategic airlift, and homeland defense and civil missions. The 477th Fighter Group trains and maintains a Reserve F-22A Raptor unit. Other tenants at Elmendorf include ISR, civil engineering, special investigations, and air mobility missions.

Analysis of Physical Exposure and Indicators of Utility System Resilience

The only relevant climatological anomaly data for this case study are temperature data. Summertime temperatures are rising quickly, but these data do not provide sufficiently detailed information on the hazards we are concerned with. This is a good example of a case in which taking the extra time and effort to incorporate additional data is necessary. Here, we used two metrics not available as climatological anomalies: (1) degree of exposure to permafrost-induced soil instability (function of melting and soil type) and (2) presence or absence of tree species susceptible to pests and wildfires. For the first type of measure, much work has been done in the academic community (see Figure 4.8, which shows permafrost occurrence in the Arctic) but is not necessarily available as data that are easily accessible within a tool or as a layer to incorporate into a geographic information system.

Figure 4.8. Permafrost Occurrence in the Arctic



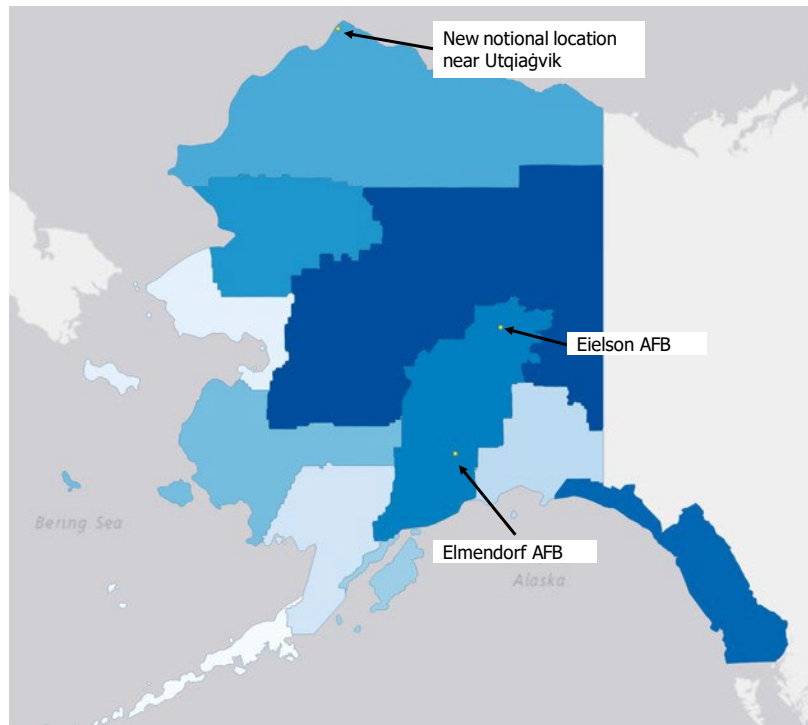
SOURCE: Reproduced from Hjort et al., 2018, CC BY 4.0 DEED.

NOTE: MAGT = mean annual ground temperature.

Between the two existing DAF installations, Eielson appears more physically exposed because it is located within a permafrost zone and is also surrounded by boreal forest that is vulnerable to forest fires, which can further stimulate permafrost melt and other effects that can destabilize the ground (e.g., slopes can become unstable after fires because tree roots and trunks hold soil and rocks in place).

This case study highlights one instance in which two installations could be considered in the same catchment—if we define that catchment as the electricity planning region in this case (see Figure 4.9)—but the installations themselves do not have the same level of exposure. This observation does not invalidate the idea of using catchments. Rather, assessments should identify catchments that enable potential differences between installations to be highlighted.

Figure 4.9. Alaska Energy Planning Regions



Furthermore, it is useful to note that plans within a defined region or catchment that includes more than one DAF installation could serve some of those installations better than others. This is useful information that can be identified only by examining both physical exposure and policy data. In this case, we used the SAIFI and SAIDI data to suggest that additional information might be needed to assess whether the planning region has taken the necessary resilience measures to account for the Fairbanks area's heightened exposure to permafrost melt and wildfires.

Utqiagvik is not subject to wildfires, but the extent of permafrost there and the extreme (relative) warming make it very exposed to permafrost melt. A full exposure assessment of this non-DAF location would also require some knowledge of the local electricity infrastructure (limited and fragile).

Findings

From the perspective of developing a high-level screening approach, this case study demonstrated three lessons:

- Physical exposure data is different for Alaska than it is within the continental United States (CONUS), making it hard to compare Alaskan installations with those in CONUS or elsewhere. This is not surprising because the Alaskan climate is unique, and the underlying data and models needed to produce the requisite information for decisionmakers can often be different from those used at lower latitudes. Thus, this demonstrates why a regional approach could make sense.

- The policy measures were very important in this case study because they helped to further differentiate the two DAF installations. The SAIFI and SAIDI data, despite focusing on reliability, offered a useful window into resilience in this case because the lower scores for the Eielson area suggested that there is a need to investigate whether plans take permafrost melt sufficiently into account. The lower reliance on renewables in the Fairbanks region, likely driven by distance from gusty onshore winds, is also suggestive of resilience issues.
- Future exposure and vulnerability assessments should take infrastructure into account. The Alaska case study and the mid-Atlantic case study highlight how much the implications of climate hazards are scaled based on the extent of infrastructure that is in harm's way. In this case, using projected economic losses from permafrost melt as a check on the physical exposure analysis was not a good measure because Utqiagvik appeared less affected than Fairbanks (but only because it has so much less infrastructure).

Recommendations

For this study, we were asked to develop an approach for prioritizing where to do deeper-dive vulnerability assessments based on potential extreme weather- and climate-related hazard vulnerabilities in energy and water infrastructure outside the fence line. In Chapter 2, we described the process that we used to develop the hazard exposure assessment approach. In Chapter 3, we described the preparatory work that is required before conducting a hazard exposure assessment. The results of that preparatory work fed into the three case study assessments that we described in Chapter 4, which included the results of those assessments and the lessons that we learned from conducting the case studies that further refined our approach.

Throughout this report, we have highlighted the various challenges that we encountered with developing an approach to characterize utility system exposure, estimate potential utility system resilience capacity, and then use this information to inform priority-setting to support deep-dive vulnerability assessments for mission assurance. These questions have not previously been tackled in a comprehensive or systematic way, and what work has been done has not been from the perspective of informing priority-setting within DoD or any of the services. Therefore, this work was exploratory in nature and revealed many areas in which additional research is needed. However, we were able to identify (1) steps that can be taken to inform priority-setting and (2) how to screen for the relevance of utility system exposure to priority-setting decision contexts.

In this concluding chapter, we provide recommendations that, taken together, can screen for the relevance of utility system exposure to priority-setting decision contexts and, where deemed relevant, can support implementing an approach for characterizing utility system potential exposure to climate hazards and potential utility system resilience capacity.

Recommendations

In this section, we present four recommendations regarding the implementation of exposure assessments that consider the utility systems on which DAF installations rely. We focused these recommendations toward our research sponsor, although the recommendations have implications for other DAF offices and organizations.

Update Resilience Policy to Include a Regional Screening-Level Assessment of Energy and Water Utility System Exposure to Climate Hazards to Determine Relevance to Priority-Setting Decision Contexts

Developing and demonstrating our approach for characterizing utility system exposure and potential resilience capacity revealed that this is by no means a straightforward process. We designed our estimation approach with the idea that the process should aim to reveal differences between installations such that a prioritization can ultimately be achieved. We found that readily accessible information does not always reveal useful differences among the set of installations for which a prioritization is desired and that measuring utility system exposure can be resource-intensive. Thus, we recommend that the DAF first conduct a screening-level assessment to determine whether improving utility system exposure estimations is useful to the decision context at hand. This assessment will help ensure that the department does not unnecessarily spend time and effort to collect information that, in the end, might not be useful for setting priorities. We outline a few simple steps that can be taken to perform this high-level screening in the following recommendation.

Furthermore, throughout this report, we have articulated that looking at hazards and utility systems within a defined region is needed to depict and contextualize exposure. Acknowledging that both climate hazards and utilities occur or operate at a subnational scale helps to avoid bias in how exposure is defined. Understanding that an installation may be exposed via utility infrastructure relatively far away prevents taking an overly localized view of the problem for any given installation. Thus, we recommend that screening-level assessments and any further characterization of exposure start first within an appropriate regional scale.

Use a Qualitative Climate Hazard Taxonomy, Accessible Climate Anomaly Data, and Utility Reliability Measures to Obtain a First-Order Estimation of Utility System Exposure

Generally, our case study findings suggest that an approach that starts with leveraging present climate anomalies compared with a historical baseline can provide a valuable and low-cost initial screen that could either enable a sufficient physical exposure comparison between installations or identify cases in which it makes sense to devote additional time and resources to looking at projected, paleoclimate, or otherwise further-analyzed data. From a utility-system resilience capacity perspective, our case studies revealed that combining standard historical reliability data with qualitative knowledge about regional and local policy and resilience planning similarly provided a valuable initial look that either led to an ability to compare installation exposure or drove needs for a deeper dive into other, less accessible data.

Articulate Data and Tool Needs and Strengthen Partnerships to Help Access Tools That Track Utility Resilience Measures

The DAF will need to consider climate data accessibility in determining physical exposure metrics and the area over which the physical exposure value is calculated, and it will need to use a combination

of potential utility system resilience capacity indicators to guide priority-setting. This research was scoped to utility systems, but prior PAF and other work referenced herein also recognized the need for further understanding and developing tactics and tools to plan and prepare for the impacts of severe weather- and climate-related hazards on installations. Our research suggests that, although physical weather and climate exposure data can be readily obtained, a substantial portion of the data requires at least a nuanced understanding of what the data mean and some light manipulation to examine questions of utility system exposure more directly.

Utility system resilience capacity data and tools are typically more difficult to access and generally are not “ready-made” to address questions of how utility vulnerability to extreme weather- and climate-related hazards affects installation and mission assurance. The insights from our look at codes, standards, and other resilience-relevant policies suggests that there is variability in regional and local utility efforts and capacity to plan for long-term resilience issues associated with extreme weather and climate hazards. The DAF should seek greater awareness at the enterprise level about utilities that support DAF installations, including an explicit and consistent understanding of how installation managers are or are not already coordinating or even collaborating on initiatives. Gathering this type of information will require guidance to collect the data and communicate the expectations for how installations are working with utilities on resilience problems.

Furthermore, our hazards taxonomy and analysis of potential utility system impact pathways demonstrates the variety and complexity of potential resilience issues and how grounded they are in regional to local geography, weather, and climate. We do not think it would be sufficient to deliberate on extreme weather and climate hazards on a national policymaker level and then expect effective approaches to trickle down. Thus, communication at the local installation and utility level is very important and should be an expectation communicated in guidance.

The primary motivation for articulating data and tool needs is to inform the best use of limited time and budget to deepen existing partnerships and create new ones to help meet identified needs. The DAF should be pursuing engagement with organizations that already gather, process, analyze, visualize, and disseminate climate and utility system resilience–relevant data. These include, among many others, utilities themselves, the 14th WS, and NOAA (including its affiliated regional integrated sciences and assessments collaborations). In cases in which organizations and consortia have the right expertise, capacity, data access, and computing, it might be as straightforward for the DAF as making a request to tailor future analyses in a particular direction. Sharing the information will be more seamless for some organizations (e.g., the U.S. government) than others (e.g., utilities). We are recommending that the DAF seek ways of more fully using existing resources through the development of deeper and additional collaborations. Many potential partners will be motivated to work with the DAF because being able to provide evidence that their products and tools support real-world decisions often leads to greater credibility and funding for these organizations.

Given its expansive geographic distribution of installations across the United States, the DAF could help improve utility system resilience broadly by playing a role in normalizing the expectation that utilities and major users work together on resilience problems. In this way, a modest investment of policy guidance, time, and possibly personnel resources could pay off significantly for the DAF. The DAF would be situated to have good awareness of utility system exposure and vulnerabilities and

could help shore up inconsistencies in attention to utility system resilience problems across the United States.

One mechanism that could be useful in identifying and articulating needs is Weapons and Tactics (WEPTAC)–style conferences and workshops (internally, perhaps with some invited external participants, including utilities managers) to address the need for more community-of-interest problem solving in this area.

Holding such workshops requires resources. The DAF can consider working within the framework of existing WEPTACs. The DAF can also hold biannual virtual events within the installations and logistics community. A final option would be to host a series of small workshops within individual organizations or at individual installations on independent schedules and set up a system for gathering inputs from these small events ahead of a short, community-wide meeting to discuss findings and outstanding issues. This is a good opportunity to engage installation energy personnel in the process to improve visibility into on-base infrastructure and operational needs.

Maintain an Archive of Relevant Weather and Climate Data, Tools, and Products That Support Climate Hazard Exposure Assessments

Maintaining a central archive of relevant weather and climate data, tools, and products, in addition to the assessments themselves, at an organizational level higher than an installation will help ensure more-efficient use of resources when updating or conducting new climate hazard exposure assessments. Given that there is frequent turnover in installation staff and among DAF senior leaders, capturing that institutional knowledge in a central location can help mitigate the potential risk of losing time on reinventing the process.

Additionally, an archive of this nature could serve as means for installation planners, base civil engineers, or other personnel who are involved in these efforts to glean insights more easily about the approaches taken, assumptions made, metrics selected, and challenges and solutions encountered in other assessments. As our research has shown, there are many variables to consider when conducting a utility system exposure assessment. Information-sharing across silos will be important in ensuring that assessments are using the most up-to-date, relevant resources and that consistent practices are employed across the enterprise.

This archive could be maintained by an organization in the civil engineering reporting chain. We believe that AFCEC is well positioned to maintain such an archive because it already has Severe Weather Playbook assessments for installations, along with other information related to resilience planning efforts. Collecting other data or tools that are developed in support of climate hazard exposure assessments nicely complements these efforts.

Existing DoD or DAF Weather- and Climate-Related Tools and Datasets

In this appendix, we expand on the introduction in Chapter 1 to existing DoD and DAF weather- and climate-related tools and datasets.

Defense Climate Assessment Tool

DCAT is a web-based, screening tool that is intended to provide a consistent way to assess the relative level of exposure to eight extreme weather and climate-related hazards at installations: historic extreme weather events, drought, coastal flooding, riverine flooding, heat, energy demand, wildfire, and land degradation (DoD, 2021). The tool produces two types of scores using the weighted ordered weighted average methodology: (1) one for each hazard category and (2) a total weighted score that combines all the indicators (Bewley et al., 2021).

The metrics are generally developed to identify hazards that will have an impact on planning processes for installation siting or improvements (Bewley et al., 2021). An analysis of DCAT found that the best use of the screening assessment is to either consider the change in the level of exposure at one installation between different time points or to consider how the exposure to one hazard differs between installations (Bewley et al., 2021). The developed indexes in DCAT are based on current and thorough national data and simulations from the Fourth National Climate Assessment (Wuebbles et al., 2017). Therefore, the indexes have some of the same limitations of other metrics in other tools: Specifically, historical data might be inconsistent.

Future simulations are dependent on assumptions and selected climate scenarios. DCAT contains relative scores for select hazards and some facility or installation-level maps for within-the-fence assessments. Continuous, mappable data for hazards are not contained in DCAT. The hazards are normalized and weighted according to user inputs that indicate relative importance. Data for CONUS, Alaska, and the “rest of the world” (ROW) are collected differently. DCAT used existing data collected by different entities; CONUS uses the most-comprehensive datasets. Indicators for each region (CONUS, Alaska, ROW) are calculated with types of data on different scales using different methods (Bewley et al., 2021, p. iv). Scores for installations should not be compared across these geographic regions.

Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook

The AFCEC has developed a screening framework for assessing risks to infrastructure for a minimum list of severe weather and climate hazards at installations (desertification, volcanic, seismic, tsunami, subsidence/sinkholes, sea level change, precipitation changes, annual average temperature increase, extreme cold and extreme heat).²⁹ This framework is documented in the *Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook*, which includes methods to determine the level of exposure to a given hazard, suggested datasets and tools to determine potential exposure, and suggested ways to use the outputs of the assessment in existing planning and decisionmaking processes (AFCEC, 2020).

14th Weather Squadron Products and Capabilities

The 14th WS collects, maintains, and analyzes weather data in support of military and intelligence operations and planning for any branch of DoD (14th Weather Squadron, 2022). The squadron houses DoD's only meteorological archive, which dates to 1901 and contains hourly surface and upper air data from 4,000 sites globally. The 14th WS provides weather products that cover expected normal conditions and a historical look at hazards for a given location. Weather information that supports forecasting needs for the execution of operation comes from the Operational Weather Squadrons outside the 14th WS. For example, determination of the expected window of appropriate flight conditions for a specific sortie or operation would come from the Operational Weather Squadrons.

The 14th WS has a core climatology mission that centers around helping the DAF, DoD, the intelligence community, and the North Atlantic Treaty Organization understand what the weather was on a specific date at a specific location. The weather determination may be used to support contract litigation or characterize plane flight disruptions or military behavior (e.g., delayed take-off or landing, movement of equipment).

The 14th WS has developed a threat assessment for every DAF installation over the past 30 years. These threat assessments describe the relative impact to the site by hail, light winds, tornadoes, extreme heat, and extreme cold. The threat assessments are based on historical weather analysis and are not projections: They are intended to provide the wing or installation commander baseline expectations for the weather in that location.

Installation Energy Plan and Installation Climate Resilience Plan

An installation energy plan (IEP) is a component plan of the broader installation development plan (IDP), which is the DAF's mechanism to address environmental planning, sustainable design and development, sustainable range planning, real property master planning, and military installation resilience issues (U.S. Code, Title 10, Section 2864). IEPs cover long-range plans for energy resilience

²⁹ Although seismic events and volcanic activity are natural hazards, they are not caused by weather.

to support mission assurance and are meant to serve as a roadmap to enable an installation to meet strategic energy goals. Despite the name, these plans are also meant to cover strategic water planning as it relates to use on the installation. The plans establish a baseline of resource consumption using information about current and planned energy and water use; the condition of key infrastructure; completed, ongoing, and planned energy projects; and critical mission energy requirements. A gap analysis is then conducted comparing the baseline with the installation's vision and goals. Options are identified to fill any gaps, along with implementation plans for selected options.

Similarly, an ICRP is a component plan of the broader IDP. The ICRP is supposed to identify and discuss severe weather and other climate-related or changing environmental factors that could have implications for mission assurance. As with the IEP, a baseline understanding of existing and potential risks should be documented, along with completed, ongoing, or planned infrastructure projects that might mitigate these risks. The plans are also supposed to identify community resources and plans and agreements with the public or private entities that enable mission continuity or that impact the installation's resilience.

Climate Hazard Taxonomy, Utility System Impact Mechanisms, and Physical Exposure Data Sources

This appendix includes additional detail on how we developed our climate hazard taxonomy and the utility system impact mechanisms that we identified through our review of historical case examples, academic literature, and various reports. The information in this appendix supplements the summary of our climate hazard taxonomy from Chapter 2 and the summary of impact mechanisms from Chapter 3.

Developing a Climate Hazard Taxonomy

Our starting point was examples of adverse climate or weather effects impacting a utility system identified through a literature scan and various EPA, DOE, and NIST reports. After documenting the various physical impacts that led to disruption of the utility service, we developed a taxonomy of weather- and climate-related hazards with associated utility component-specific impacts accounting for different types of effects, such as physical damage to infrastructure, potential changes in source availability, and demand pressures. Utility infrastructure is a complex and interdependent system. To firmly establish the nature of first-order climate impacts, our aim was to characterize direct hazard-impact pairings. Other infrastructure effects (such as transportation network disruptions) or cascading hazards across utilities (such as disruptions in electrical supply leading to inoperable water infrastructure) were occasionally noted in the taxonomy.

We then categorized the hazards into three bins according to the duration of the hazard: (1) persistent, long-term trend (e.g., permanent sea level rise, changes in average temperature), (2) long-lasting event (e.g., multiyear drought, enduring insect infestation), and (3) short-term event (e.g., hurricane, El Niño event). This categorization was necessary because even if the mechanism that caused the adverse impact is the same across these three bins, it would be measured very differently. Consider, for example, high temperature. This can be measured as an average annual temperature increase (long-term trend), an unusually warm summer or winter season (long-lasting event), or a heat wave (short-term event). Although the effect on any given day might feel the same (hot), the respective impacts on utilities can be somewhat different. Short-term hazards can create unanticipated demand pressure and sudden disruptions to the utility system. Longer-term trends tend to have a bigger impact on supply and on transmission and distribution infrastructure (e.g., widespread vegetation die-off downing transmission lines or increasing susceptibility to future wildfire and permafrost melting and, if combined with the right soil type, resulting in land instability and infrastructure cracking).

Relatively steady trends, such as annual temperature and sea level rise, could have their biggest impacts through second-order mechanisms, such as the frequency and intensity of heavy rain events (e.g., an El Niño event) or in making the impacts of tropical storm–induced coastal flooding more dangerous. Table B.1 provides a summary view of the taxonomy.

Table B.1. Summary View of the Taxonomy

Hazard Type	Hazard	Natural Drinking				
		Electricity	Gas	Water	Wastewater	Stormwater
Short-term event	Coastal flooding	X	X	X	X	X
Short-term event	Extreme cold	X	X	X	X	X
Short-term event	Extreme heat	X		X	X	X
Short-term event	Hail	X				
Short-term event	Heavy ice or snow	X				
Short-term event	Heavy rain	X	X	X	X	X
Short-term event	Hurricane or tropical storm	X	X	X	X	X
Short-term event	Inland flooding	X	X	X	X	X
Short-term event	Landslide	X	X	X	X	X
Short-term event	Lightning	X				
Short-term event	Rapid ice or snow melt	X	X	X	X	X
Short-term event	Storm surge	X	X	X	X	X
Short-term event	Thunderstorm	X	X	X	X	X
Short-term event	Tornado	X		X		
Short-term event	Wildfire	X	X	X		
Short-term event	Wind	X		X		
Short-term event	Winter storm	X	X	X	X	X
Long-lasting event	Demand pressure	X	X	X		
Long-lasting event	Drought	X		X		
Long-lasting event	Dust	X		X		
Long-lasting event	Insect infestation	X				
Long-lasting event	Toxicity, pathogens, and algae			X		

Hazard Type	Hazard	Electricity	Natural Drinking			
			Gas	Water	Wastewater	Stormwater
Long-lasting event	Vegetation die-off	X		X		
Persistent, long-term trend	Erosion			X		
Persistent, long-term trend	Loss of ice or snowpack	X		X		
Persistent, long-term trend	Permafrost melt	X	X	X	X	X
Persistent, long-term trend	Saltwater intrusion			X		
Persistent, long-term trend	Sea level rise	X	X	X	X	X

For the second split in the taxonomy, we focused on the fundamental mechanism of climate change impact—temperature, moisture, and wind—for each of the categories of long-term trend, long-lasting event, and short-term hazard. Drawing from FEMA, EPA, and NIST reports and the team’s subject-matter expertise, we broke out each utility system into its subcomponents so that we could review (on a finer scale than a whole utility system) each hazard-utility component pairing (e.g., long-lasting events and potable water source, long-term trends and electricity distribution) to identify specific climate or extreme weather hazards, such as drought and sea level rise, that have the clear ability to impact that utility component. Utility infrastructure can broadly be categorized as having to do with generation and processing, storage, and conveyance and delivery. However, variations in the configuration between electricity, natural gas, and water infrastructures led us to create four infrastructure bins for subcomponents of drinking water and electricity and three bins each for natural gas, stormwater, and wastewater. These bins reflect physical, functional, and operational differences (i.e., electrical transmission versus distribution infrastructure) and reflect documented differences in risk exposure. The subcomponent mappings of natural gas, electricity, drinking water, stormwater, and wastewater infrastructure and hazards are shown in Tables B.2 through B.6.

At this point, the taxonomy had three layers: duration, mechanism, and hazard. We then created two outputs to serve our analysis, each taking a different format. First, we continued from the hazard layer to create a new layer that summarized measurement. We explored examples of *ideal metrics*, which were identified using what the closest conceivable measures might be to capture the way in which the given hazard impacts utility supply chains. We also explored examples of *accessible metrics*: that is, those that are easily and freely found and manipulated at scale from online sources. We did not include DCAT metrics or any data from products directly associated with installation-level plans as examples of ideal or accessible metrics. Although these data sources are accessible and perhaps, in some cases, even ideal, we wanted to position our research to test our research question about the value added of taking additional steps to look outside the fence line for possible sources of exposure. The *accessible metrics* we documented ultimately fed our physical exposure analyses in the case studies.

Second, we separately pivoted the taxonomy so that the point of departure was each of the utilities, followed by the most-relevant components of their supply chains, and ending with the hazards most applicable to each utility component. Relevant hazards vary considerably by region and depend on the characteristics of utility systems. We attempted to be as inclusive as possible and did not look to specifically designate in which state(s) each hazard would be relevant because this can change over time and can be derived as a starting point from different vetted sources, such as the national climate assessments and DOE risk profiles for the energy sector (Office of Electricity, undated). It was our assumption that a planner looking at utilities in Florida would be able to catch that permafrost is not an issue to focus on and that, similarly, a planner in Alaska would not look to include tropical storms. We used this taxonomy to guide aspects of our policy metrics development and application of these in the case studies.

We separated short-term coastal flooding from storm surge because, in the literature, *storm surge* always refers to wave impact. *Coastal flooding* here is broader than wave impact and can include saltwater intrusion in storm drains during high tide, for example. From the perspective of impacts to utility infrastructure, this distinction matters for water infrastructure.

Thunderstorm and tornado are often grouped together in the literature (NOAA, 2023), but we separated them because thunderstorms in the West and Southwest are often not accompanied by tornadoes and because the metrics are separate.

We did not include temperature trends as a persistent, long-term trend because we are capturing the effects of this trend with a demand pressure hazard.

Table B.2. Potential Impacts to Natural Gas Infrastructure

	Hazard Impact on Natural Gas Utility Infrastructure			
Hazard	Production and Processing	Transmission and Distribution	Storage	Source(s)
Short-term event				
Coastal flooding	Facilities and equipment submersion	Corrosion and damage to pipeline infrastructure	Damage to storage infrastructure	DOE, 2015
Extreme cold	- Frozen water in wellheads - Repair access prevented by icy roads - Mechanical failures - Increased demand for heating via demand pressure	- Flow of gas blocked by frozen water in pipelines and equipment - Service area shut off because of falling pressure in system		DOE, 2015; Federal Energy Regulatory Commission (FERC) and NERC, 2011
Extreme heat ^a				
Hail				
Heavy ice or snow				
Heavy rain	Facilities and equipment submersion via inland flooding	Corrosion and damage to pipeline infrastructure via inland flooding and landslide	Damage to storage infrastructure via inland flooding and landslide	DOE, 2015
Hurricane or tropical storm	- Impacts across all utility infrastructure with effects from heavy rain, coastal flooding, inland flooding, erosion, landslide, storm surge, and wind - Impacts amplified by sea level rise			DOE, 2015; NIST 2016
Inland flooding	Facilities and equipment submersion	Corrosion and damage to pipeline infrastructure	Damage to storage infrastructure	DOE, 2015
Landslide		Damage to pipeline infrastructure		NIST, 2016; DOE, 2015
Lightning				

Hazard Impact on Natural Gas Utility Infrastructure				
Hazard	Production and Processing	Transmission and Distribution	Storage	Source(s)
Rapid ice or snow melt	Facilities and equipment submersion via inland flooding	Corrosion and damage to pipeline infrastructure via inland flooding	Damage to storage infrastructure via inland flooding	DOE, 2015; Welty and Zeng, 2021
Storm surge		- Wave impact damage to pipeline infrastructure - Corrosion and damage to pipelines via coastal flooding - Damage to ports and transport	Wave impact damage to storage infrastructure, including transport and ports	DOE, 2015; NIST 2016
Thunderstorm	- Impacts across all utility infrastructure with effects from hail, heavy rain, inland flooding, erosion, landslide, lightning, and wind - Can be accompanied by tornado			DOE, 2015; NIST 2016
Tornado				
Wildfire	Damage to above-ground facilities, compressor stations, and metering stations	Damage to pipeline infrastructure due to follow-on effect of heavy rain after wildfire amplifies landslide		Moftakhari and AghaKouchak, 2019
Wind				
Winter storm	Impacts across all utility infrastructure with effects from extreme cold, heavy ice or snow, and wind			DOE, 2015
Long-lasting event				
Demand pressure	Resource strain due to increased demand for heating			
Drought				
Dust				
Insect infestation				
Toxicity, pathogens, and algae				
Vegetation die-off				

Hazard Impact on Natural Gas Utility Infrastructure				
Hazard	Production and Processing	Transmission and Distribution	Storage	Source(s)
Persistent, long-term trend				
Erosion				
Loss of ice or snowpack				
Permafrost melt	Damage to facilities due to ground subsistence and reduced ground-bearing capacity	Damage to pipelines due to ground subsistence	Damage to storage tanks and connections due to ground subsistence and reduced ground-bearing capacity	DOE, 2015
Saltwater intrusion				
Sea level rise	Impacts across all utility infrastructure with amplified hurricane or tropical storm impacts, including coastal flooding, erosion, landslide, and storm surge			

^a Extreme heat can additionally hinder rail and transportation networks.

Table B.3. Potential Impacts to Electricity Infrastructure

Hazard	Hazard Impact on Electrical Utility Infrastructure				Source(s)
	Generation and Storage	Substations	Transmission	Distribution	
Short-term event					
Coastal flooding	Facilities and equipment submersion	Facilities and equipment submersion	Damage and corrosion of buried lines	- Damage and corrosion of buried transformers - Saltwater damage to communication and control equipment	Allen-Dumas, KC, and Cunliff, 2019; DOE, 2015
Extreme cold				Freezing of wires and disruption of communications and control equipment	NIST, 2016
Extreme heat	- Less efficient thermoelectric generation - Increased demand for cooling via demand pressure	Equipment failure due to operating temperatures exceeding design thresholds	- Reduced carrying capacity of HV lines - Sagging lines caused by thermal expansion, risking contact with vegetation	- Transformer failure due to persistent heat - Reduced carrying capacity of MV lines - Sagging lines caused by thermal expansion, risking contact with vegetation	Allen-Dumas, KC, and Cunliff, 2019; DOE, 2015, p. 4-1
Hail ^a	Reduced energy output due to damage to wind turbines and photovoltaic panels				Letson et al., 2020; Muehleisen et al., 2018
Heavy ice or snow			Physical overloading of wires due to ice and snow accumulation	Physical overloading of wires due to ice and snow accumulation	Allen-Dumas, KC, and Cunliff, 2019

Hazard Impact on Electrical Utility Infrastructure					
Hazard	Generation and Storage	Substations	Transmission	Distribution	Source(s)
Heavy rain	Facilities and equipment submersion via inland flooding	Facilities and equipment submersion via inland flooding	Damage and corrosion of buried transmission lines via inland flooding and landslide	Via inland flooding and landslide: - toppled poles and lines - damage to buried infrastructure	Allen-Dumas, KC, and Cunliff, 2019; NIST, 2016; Welty and Zeng, 2021
Hurricane or tropical storm	- Impacts across all utility infrastructure with effects from heavy rain, coastal flooding, inland flooding, erosion, landslide, storm surge, and wind - Impacts amplified by sea level rise				DOE, 2015; NIST 2016
Inland flooding	Facilities and equipment submersion	Facilities and equipment submersion	Damage and corrosion of buried transmission lines	- Damage to distribution poles - Submersion of underground transformers	Allen-Dumas, KC, and Cunliff, 2019; NIST, 2016
Landslide ^b			Damage to buried transmission lines	- Toppled poles and lines - Damage to buried infrastructure	NIST, 2016
Lightning			Damage to HV lines	- Damage to MV/LV lines, poles, and transformers - Further damage caused by resulting explosion or flames via wildfire	NIST, 2016
Rapid ice or snow melt	Facilities and equipment submersion via inland flooding	Facilities and equipment submersion via inland flooding	Damage and corrosion of buried transmission lines via inland flooding	- Damage to distribution poles via inland flooding - Submersion of underground transformers	Allen-Dumas, KC, and Cunliff, 2019; NIST, 2016; Welty and Zeng, 2021

Hazard Impact on Electrical Utility Infrastructure					
Hazard	Generation and Storage	Substations	Transmission	Distribution	Source(s)
Storm surge	- Wave impact damage to facilities and equipment - Saltwater damage to electronics - Submersion via coastal flooding	- Wave impact damage to facilities and equipment - Saltwater damage to electronics - Submersion via coastal flooding	- Wave impact damage to transmission infrastructure - Saltwater damage to electronics - Damage and corrosion of buried lines via coastal flooding	- Wave impact damage to poles and wires - Saltwater damage to communication and control equipment - Damage and corrosion of buried transformers via coastal flooding	DOE, 2015; Allen-Dumas, KC, and Cunliff, 2019
Thunderstorm	- Impacts across all utility infrastructure with effects from hail, heavy rain, inland flooding, erosion, landslide, lightning, and wind - Can be accompanied by tornado				DOE, 2015; NIST 2016
Tornado	Damage to wind turbines when wind exceeds design thresholds		- Damage to transmission towers and poles - Toppled trees falling on lines	- Damage to poles - Toppled trees falling on lines	DOE, 2015; Allen-Dumas, KC, and Cunliff, 2019
Wildfire			- Transmission line insulation damage from wildfire smoke - Physical damage to towers, poles, and lines - Outage caused by extreme heat	- Physical damage to distribution lines and poles - Shutting off of service to protect infrastructure	California Public Utilities Commission, 2018; Allen-Dumas, KC, and Cunliff, 2019
Wind	Damage to wind turbines when wind exceeds design thresholds		- Damage to transmission towers and poles - Toppled trees falling on lines	- Damage to poles - Toppled trees falling on lines	DOE, 2015; Allen-Dumas, KC, and Cunliff, 2019
Winter storm	Impacts across all utility infrastructure with effects from extreme cold, heavy ice or snow, and wind				

Hazard Impact on Electrical Utility Infrastructure					
Hazard	Generation and Storage	Substations	Transmission	Distribution	Source(s)
Long-lasting event					
Demand pressure	Brownouts (reduced voltage) or blackouts caused by increased demand for cooling				DOE, 2015
Drought	Reduced output of thermoelectric power plants.				DOE, 2015
Dust	Reduced photovoltaic output		Flashover in HV lines can be caused by accumulated dust	- Clogging of communication and control equipment - Flashover in MV lines when rain turns accumulated dust to mud	NIST, 2016; Juaidi et al., 2022; Malik, Al-Arainy, and Qureshi, 1997; Jiang et al., 2020; Liggins, 2021
Insect infestation			HV lines damaged by downed trees and branches via vegetation die-off	MV/LV lines damaged by downed trees and branches via vegetation die off	
Toxicity, pathogens, and algae					
Vegetation die-off			Dead trees and branches falling on HV lines	Dead trees and branches falling on MV/LV lines	NIST, 2016
Persistent, long-term trend					
Erosion					
Loss of ice or snowpack	Reduced hydropower output during peak summer usage				DOE, 2015

Hazard Impact on Electrical Utility Infrastructure					
Hazard	Generation and Storage	Substations	Transmission	Distribution	Source(s)
Permafrost melt	Damage to facilities due to ground subsistence and reduced ground-bearing capacity	Damage to facilities due to ground subsistence and reduced ground-bearing capacity	- Structural damage to towers due to ground subsistence and reduced ground-bearing capacity - Damage to buried transmission lines	Structural damage to poles due to ground subsistence and reduced ground-bearing capacity	DoD, Office of the Under Secretary of Defense (Acquisition and Sustainment) 2021; Nelson et al., 2003
Saltwater intrusion					
Sea level rise	Impacts across all utility infrastructure with amplified hurricane or tropical storm impacts, including coastal flooding, erosion, landslide, and storm surge				Hummel, Berry, and Stacey, 2018

NOTE: HV = high voltage; LV = low voltage; MV = medium voltage.

^a Interdependency: Hail can additionally hinder transportation networks, blocking repair access to damaged infrastructure.

^b Interdependency: Landslide can additionally hinder transportation networks, blocking repair access to damaged infrastructure.

Table B.4. Potential Impacts to Drinking Water Infrastructure

	Hazard Impact on Drinking Water Utility Infrastructure				
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Short term event					
Coastal flooding	- Wellhead submersion - Saltwater intrusion in groundwater wells and aquifers	- Facilities and equipment submersion - Damage to pumps	Damage to pipelines, canals, and culverts	Damage to pipes and storage tanks	Mahmoodzadeh and Karamouz, 2017; NIST, 2016
Extreme cold	Frozen reservoirs and surface waters		Damage to pipes due to cold water intake, temperature differentials, and/or ground freezing	Damage to pipes due to cold water intake, temperature differentials, and/or ground freezing	Hedgpeth, 2022; Hovey, 2022; Stone, 2020; WaterISAC, 2021
Extreme heat	- Increased demand for potable water via demand pressure - Increased toxicity, pathogens, and algae				Georgakakos et al., 2014
Hail					
Heavy ice or snow					

Hazard Impact on Drinking Water Utility Infrastructure					
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Heavy rain	Via inland flooding, erosion, and landslide: • Damage to dams and pumps caused by debris in floodwaters • Increased sediments and contaminants in surface waters • Wellhead submersion • Introduction of contaminants into water supply	Via inland flooding, erosion, and landslide: • Facilities and equipment submersion • Damage to pumps • Clogged filters	Via inland flooding, erosion, and landslide: • Damage to pipelines, canals, and culverts	Via inland flooding, erosion, and landslide: • Damage to pipes, storage tanks	NIST, 2016
Hurricane or tropical storm	• Impacts across all utility infrastructure with effects from heavy rain, coastal flooding, inland flooding, erosion, landslide, storm surge, and wind • Impacts amplified by sea level rise				DOE, 2015
Inland flooding	• Damage to dams and pumps caused by debris in floodwaters • Increased sediments and contaminants in surface waters • Wellhead submersion • Introduction of contaminants into water supply	• Facilities and equipment submersion • Damage to pumps	• Damage to pipelines, canals, and culverts	• Damage to pipes and storage tanks	NIST, 2016
Landslide	• Contaminants in surface water • Risk of landslide increases via wildfire	• Clogged filters and pumps caused by suspended solids	• Damage to pipelines, canals, and culverts		Chow, Karanfil, and Dahlgren, 2021; NIST, 2016
Lightning					

Hazard Impact on Drinking Water Utility Infrastructure					
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Rapid ice or snow melt	Via inland flooding: • Damage to dams and pumps caused by debris in floodwaters • Increased sediments and contaminants in surface waters • Wellhead submersion • Introduction of contaminants into water supply	Via inland flooding: • Facilities and equipment submersion • Damage to pumps	Via inland flooding: • Damage to pipelines, canals, and culverts	Via inland flooding: • Damage to pipes and storage tanks	NIST, 2016; Welty and Zeng, 2021
Storm surge	• Wellhead submersion • Saltwater intrusion in groundwater wells and aquifers	• Facilities and equipment submersion • Damage to pumps	• Damage to pipelines, canals, and culverts.	• Damaged or collapsed water storage infrastructure (such as elevated tanks) caused by wave impact	NIST, 2016
Thunderstorm	• Impacts across all utility Infrastructure with effects from hail, heavy rain, inland flooding, erosion, landslide, lightning, and wind • Can be accompanied by tornado				
Tornado			• Uplifted or damaged buried pipes caused by uprooted trees	• Uplifted or damaged buried pipes caused by uprooted trees • Damaged or collapsed water storage infrastructure, such as elevated tanks	NIST, 2016

Hazard Impact on Drinking Water Utility Infrastructure					
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Wildfire ^a	Contaminants and increased nutrients in surface waters (via post-wildfire dust, erosion, and landslide), leading to toxicity, pathogens, and algae				Wagner, Jähn, and Schepanski, 2018; NIST, 2016; California Department of Water Resources, 2021
Wind			Uplifted or damaged buried pipes when toppled trees fall	- Uplifted or damaged buried pipes when toppled trees fall - Damaged or collapsed water storage infrastructure, such as elevated tanks	NIST, 2016
Winter storm	Impacts across all utility infrastructure with effects from extreme cold, heavy ice or snow, and wind.				
Long-lasting event					
Demand pressure	Resources strained by increased demand for water				
Drought	- Depleted or reduced aquifers, reservoirs, and surface waters - Increased demand for water for landscaping via demand pressure				EPA, 2023d; American Water Works Association, 2021
Dust	Contaminants and increased nutrients in surface waters, leading to toxicity, pathogens, and algae	Clogged filters caused by suspended solids in water			Chow, Karanfil, and Dahlgren, 2021

Hazard Impact on Drinking Water Utility Infrastructure					
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Insect infestation					
Toxicity, pathogens, and algae	- Increased contaminants and nutrient levels via dust, erosion, landslide, and coastal or inland flooding - Algae blooms exacerbated by changing precipitation patterns and extreme heat - Emergence of new pathogens due to increased average temperatures - Toxicity introduced after wildfire				EPA, 2023i; EPA, 2023g; NIST, 2016
Vegetation die-off	Increased toxicity, pathogens, and algae in surface waters because of increased dust and erosion from loss of vegetation				EPA, 2023h; EPA, 2023g; NIST, 2016
Persistent, long-term trend					
Erosion	- Contaminants introduced into surface water - Increased risk due to effects of heavy rain after wildfire, leading to toxicity, pathogens, and algae	Clogged filters and pumps caused by suspended solids			Chow, Karanfil, and Dahlgren, 2021; EPA, 2023e; NIST, 2016

Hazard Impact on Drinking Water Utility Infrastructure					
Hazard	Water Source	Processing and Pumping	Conveyance	Distribution and Local Storage	Source(s)
Loss of ice or snowpack	- Loss of natural water storage - Reduced surface water and groundwater supply in dry season				IPCC, 2013
Permafrost melt	Surface water contamination via erosion of thawed soils				Wauthy et al., 2018
Saltwater intrusion	Saltwater intrusion in coastal wells and groundwater aquifers				EPA, 2023b
Sea level rise	Impacts across all utility infrastructure with amplified hurricane or tropical storm impacts, including coastal flooding, erosion, landslide, and storm surge				

^a Interdependency: Wildfire disrupts all levels of electricity infrastructure, rendering drinking water facilities inoperable.

Table B.5. Potential Impacts to Stormwater Infrastructure

	Hazard Impact on Stormwater Utility Infrastructure			
Hazard	Conveyance	Pumping	Storage	Source(s)
Short-term event				
Coastal flooding	Damage to drains, canals and culverts	Pump submersion	Damage to natural systems' stormwater absorptive capacity	EPA, 2023c
Extreme cold	Damage to drains, canals, and culverts caused by freezing			Sabatino, 2021
Extreme heat				
Hail				
Heavy ice or snow				
Heavy rain	Overwhelmed drainage systems			EPA, 2023f
Hurricane or tropical storm	- Impacts across all utility infrastructure with effects from heavy rain, coastal flooding, inland flooding, erosion, landslide, storm surge, and wind - Impacts amplified by sea level rise			
Inland flooding	Damage to drains, canals and culverts	Pump submersion	Damage to natural systems' stormwater absorptive capacity	EPA, 2023c
Landslide	Damage or blocked drains, canals, and culverts			NIST, 2016
Lightning				
Rapid ice or snow melt	Overwhelmed drainage systems			EPA, 2023f; Welty and Zeng, 2021
Storm surge	Overwhelmed drainage systems, especially during simultaneous heavy rain	Pump submersion		NIST, 2016

Hazard	Hazard Impact on Stormwater Utility Infrastructure			Source(s)
	Conveyance	Pumping	Storage	
Thunderstorm	- Impacts across all utility infrastructure with effects from hail, heavy rain, inland flooding, erosion, landslide, lightning, and wind - May be accompanied by tornado			
Tornado				
Wildfire				
Wind				
Winter storm	Impacts across all utility infrastructure with effects from extreme cold, heavy ice or snow, and wind			
Long-lasting event				
Demand pressure				
Drought				
Dust				
Insect infestation				
Toxicity, pathogens, and algae				
Vegetation die-off				
Persistent, long-term trend				
Erosion				
Loss of ice or snowpack				
Permafrost melt		Structural damage to drains, canals and culverts		Hjort et al., 2018; Brubaker et al., 2012
Saltwater intrusion				
Sea level rise	Impacts across all utility infrastructure with amplified hurricane or tropical storm impacts, including coastal flooding, erosion, landslide, and storm surge			

Table B.6. Potential Impacts to Wastewater Infrastructure

	Hazard Impact on Wastewater Utility Infrastructure			
Hazard	Conveyance	Processing	Discharge	Source(s)
Short-term event				
Coastal flooding	- Overwhelmed or damaged sewer pipes and tanks - Inundated pump stations	Facilities and equipment submersion	- Damage to drains, canals, and culverts - Discharge of untreated wastewater into environment	Hummel, Berry, and Stacey, 2018; McKenzie, Habel, and Dulai, 2021; NIST, 2016
Extreme cold		- Waste breakdown prevented by slow metabolic rates - Freezing of processes, such as lagoon systems.		Decterov and Holmquist, 2018; WaterISAC, 2021
Extreme heat			Treated effluent temperature too high to safely release	EPA, 2023f
Hail				
Heavy ice or snow				
Heavy rain	- Overwhelmed sewer pipes and tanks - Damage to sewer pipes via inland flooding - Flooded pump stations	- Overwhelmed treatment plants - Facilities and equipment submersion via inland flooding	Damage to drains, canals, and culverts via inland flooding	NIST, 2016; Willmsen and Mapes, 2017
Hurricane or tropical storm	- Impacts across all utility infrastructure with effects from heavy rain, coastal flooding, inland flooding, erosion, landslide, storm surge, and wind - Impacts amplified by sea level rise			
Inland flooding	- Damage to sewer pipes - Flooded pump stations	Facilities and equipment submersion	Damage to drains, canals, and culverts	NIST, 2016

Hazard Impact on Wastewater Utility Infrastructure				
Hazard	Conveyance	Processing	Discharge	Source(s)
Landslide	Damage to sewer pipes		Damage or blocked drains, canals, and culverts	NIST, 2016
Lightning				
Rapid ice or snow melt	- Overwhelmed sewer pipes and tanks - Damage to sewer pipes via inland flooding - Flooded pump stations	Facilities and equipment submersion via inland flooding	Damage to drains, canals, and culverts via inland flooding	NIST, 2016; Welty and Zeng, 2021
Storm surge	- Damage to sewer pipes - Flooded pump stations	- Facilities and equipment submersion - Wave impact damage	- Damage to drains, canals, and culverts - Untreated wastewater discharged into environment - Backflow	Hummel, Berry, and Stacey, 2018; McKenzie, Habel, and Dulai, 2021; NIST, 2016; EPA, 2023f
Thunderstorm	Impacts across all utility infrastructure with effects from hail, heavy rain, inland flooding, erosion, landslide, lightning, and wind; may be accompanied by tornado			
Tornado				
Wildfire				
Wind				
Winter storm	Impacts across all utility infrastructure with effects from extreme cold, heavy ice or snow, and wind			
Long-lasting event				
Demand pressure				
Drought				
Dust				
Insect infestation				

Hazard	Hazard Impact on Wastewater Utility Infrastructure			Source(s)
	Conveyance	Processing	Discharge	
Toxicity, pathogens, and algae				
Vegetation die-off				
Persistent, long-term trend				
Erosion				
Loss of ice or snowpack				
Permafrost melt	Damage to sewer pipes and infrastructure from ground subsistence and erosion	Damage to facilities and processes, such as lagoon systems		Brubaker et al., 2012
Saltwater intrusion				
Sea level rise	Impacts across all utility infrastructure with amplified hurricane or tropical storm impacts, including coastal flooding, erosion, landslide, and storm surge.			

Potential Impacts to Utility Systems from Exposure to Extreme Weather and Climate-Related Hazards

In the following sections, we outline (1) the potential impacts to energy and water utilities, (2) some strategies to improve resilience of the infrastructure or system, and (3) which climate hazards could cause the impacts. The tables in the following sections informed the component-level impacts listed in the taxonomy tables in the previous section.

Electricity

Tables B.7 through B.10 include a list of the high-level potential impacts to and strategies for improving resilience of electric utility infrastructure. The tables are organized by electric infrastructure components.

Table B.7. Potential Impacts to and Resilience Strategies for Distribution Systems

Impact	Strategies to Improve Resilience	Hazard(s)
Reduction in capacity and useful life of distribution lines	• Protect distribution lines through insulation or fuses that trip • Add redundancy in lines to reduce load on system	Extreme heat; extreme cold; wildfire
Overloading weight capacity or sagging of distribution lines	• Protect distribution lines through insulation or fuses that trip	Extreme heat; extreme cold; heavy ice or snow; wildfire
Damage to distribution lines and distribution towers and poles	• Manage vegetation surrounding distribution systems and equipment • Insulate and/or waterproof distribution lines • Install fire-resistant coating • Retrofit existing aboveground distribution lines to underground or install new underground distribution lines	Wildfire; wind; coastal flooding; hurricane or tropical storm; inland flooding; storm surge; tornado; winter storm; sea level rise

SOURCE: Authors' analysis of data from Allen-Dumas, KC, and Cunliff, 2019; U.S. Government Accountability Office, 2021; Schweikert and Deinert, 2021.

Table B.8. Potential Impacts to and Resilience Strategies for Transformers and Transmission Systems

Impact	Strategies to Improve Resilience	Hazard(s)
Reduction in capacity and useful life of transmission lines	• Protect transmission lines through insulation or fuses that trip • Add redundancy in lines to reduce load on system • Implement cooling systems for transformers	Extreme heat; wildfire
Overloading weight capacity or sagging of transmission lines	• Protect transmission lines through insulation or fuses that trip	Extreme heat; extreme cold; heavy ice or snow; wildfire
Damage to transmission lines and transmission towers and poles	• Manage vegetation surrounding transmission systems and equipment • Insulate and/or waterproof transmission lines • Install fire-resistant coating • Retrofit existing aboveground transmission lines to underground or install new underground transmission lines	Wildfire; wind; coastal flooding; hurricane or tropical storm; inland flooding; lightning; storm surge; tornado; winter storm; sea level rise

SOURCE: Authors' analysis of data from Allen-Dumas, KC, and Cunliff, 2019; California Public Utilities Commission, 2008; U.S. Government Accountability Office, 2021; Schweikert and Deinert, 2021; Burillo, 2019.

Table B.9. Potential Impacts to and Resilience Strategies for Substations

Impact	Strategies to Improve Resilience	Hazard(s)
Reduction in substation capacity	• Install fuses, create redundant circuits, and upgrade cooling systems	Extreme heat; extreme cold; wildfire
Physical damage to substation	• Relocate substations outside hazard areas	Coastal flooding; wildfire; wind; inland flooding; tornado; sea level rise
Equipment failure or erosion of hardware	• Install fuses, create redundant circuits, and upgrade cooling systems • Relocate substations outside hazard areas	Extreme heat; wildfire; coastal flooding; hurricane or tropical storm; inland flooding; storm surge; erosion; saltwater intrusion

SOURCE: Authors' analysis of data from Allen-Dumas, KC, and Cunliff, 2019; Burillo, 2019; Sathaye et al., 2012.

Table B.10. Potential Impacts to and Resilience Strategies for Electric Generation

Impact	Strategies to Improve Resilience	Hazard(s)
Generation system strain or curtailment because of demand pressure	• Improve energy efficiency and resource allocation for extreme demand events	Extreme heat; extreme cold; demand pressure
Physical damage to facilities used for electric power generation	• Relocate power generation facilities outside hazard areas • Retrofit or upgrade power generation facilities to withstand hazard conditions (e.g., flood-resistant construction)	Extreme heat; wildfire; coastal flooding; hurricane or tropical storm; inland flooding; storm surge; saltwater intrusion
Generation system strain or curtailment because of insufficient water to generate electricity or to cool equipment	• Use alternate cooling systems for electricity generation	Drought; saltwater intrusion

SOURCE: Authors' analysis of data from Allen-Dumas, KC, and Cunliff, 2019; Burillo, 2019.

Energy (Natural Gas)

Tables B.11 through B.13 include a list of the high-level potential impacts to and strategies for improving resilience of natural gas utility systems. The tables are organized by natural gas infrastructure components.

Table B.11. Potential Impacts to and Resilience Strategies for Natural Gas Production

Impact	Strategies to Improve Resilience	Hazard(s)
System capacity and/or storage reserves may be strained because of demand pressure	• Use demand-side management and energy efficiency programs to reduce severity of increases in demand. • Expand system capacity to meet increases in demand	Extreme heat; extreme cold; drought; wildfires; hurricanes or tropical storm; demand pressure; winter storm
Production limited because of changing soil conditions	• Alter structures and foundations for equipment (e.g., drilling pads) appropriate for changing environmental conditions • Add insulation to protect soil conditions (e.g., construct gravel pads or use thermal piles)	Extreme heat; extreme cold; heavy rain; inland flooding; rapid ice or snow melt; storm surge; erosion; loss of ice or snowpack; permafrost melt; sea level rise
Natural gas wellheads can freeze due to hydrates from freezing temperatures	• Construct insulated facilities to protect equipment, such as meters, valves, and tanks	Extreme cold; heavy ice or snow; winter storm
Contaminated water can lead to damage to the chemical processing and storage facilities	• Increase monitoring of water quality and chemical processing	Coastal flooding; hurricanes or tropical storms; inland flooding; sea level rise; insect infestation; toxicity, pathogens, and algae; erosion

SOURCE: Authors' analysis of data from DOE, 2015; American Gas Foundation, 2021; American Gas Association, 2014.

Table B.12. Potential Impacts to and Resilience Strategies for Natural Gas Storage and Transportation

Impact	Strategies to Improve Resilience	Hazard(s)
Damage and disruption to storage infrastructure, including ports, refineries, and pumping stations	• Increase maintenance of support structures serving fuel storage • Anchor or increase strength of storage tanks • Upgrade drainage system to account for increased runoff • Construct insulated facilities to protect equipment, such as meters, valves, and tanks • Winterize equipment and pipeline used for storage • Install wind girders on fuel storage tanks	Coastal flooding; extreme cold; heavy ice or snow; heavy rain; hurricane or tropical storm; inland flooding; landslide; rapid ice or snow melt; storm surge; tornado; wildfire; winter storm; erosion; loss of ice or snowpack; permafrost melt; sea level rise
Damage and disruption to transportation systems (e.g., highways and railroads)	• Protect or modify transportation infrastructure (e.g., elevate or relocate railroads outside flood hazard area) • Add redundancies or reroute transportation routes/systems • Perform maintenance of transportation and shipping access (e.g., dredging)	Coastal flooding; extreme cold; heavy ice or snow; heavy rain; hurricanes or tropical storm; inland flooding; landslide; rapid ice or snow melt; storm surge; tornado; wildfire; winter storm; erosion; loss of ice or snowpack; permafrost melt; sea level rise

SOURCE: Authors' analysis of data from DOE, 2015; American Gas Foundation, 2021; American Gas Association, 2014.

Table B.13. Potential Impacts to and Resilience Strategies for Natural Gas Distribution

Impact	Strategies to Improve Resilience	Hazard(s)
Damage or erosion to pipeline and pipeline equipment for distribution	• Use resilient pipeline material (i.e., material less likely to leak or rupture, such as coated steel in lieu of cast iron) • Elevate, reroute, or protect pipeline infrastructure to avoid or reduce hazard risk • Upgrade thermosyphons to limit damage from changing permafrost conditions • Inject antifreeze into transportation and distribution pipelines • Winterize compressors and pipelines	Coastal flooding; extreme cold; heavy ice or snow; heavy rain; hurricane or tropical storm; inland flooding; landslide; rapid ice or snow melt; storm surge; tornado; wildfire; winter storm; erosion; loss of ice or snowpack; permafrost melt; sea level rise
Damage to facilities and infrastructure used for fuel distribution	• Protect facilities to avoid or reduce hazard risk (e.g., elevate structures) • Install emergency backup energy supply for critical operations, such as pumping stations and refueling centers	Coastal flooding; extreme heat; extreme cold; heavy ice or snow; heavy rain; hurricane or tropical storm; inland flooding; landslide; rapid ice or snow melt; storm surge; tornado; wildfire; winter storm; erosion; loss of ice or snowpack; permafrost melt; sea level rise

SOURCE: Authors' analysis of data from DOE, 2015; American Gas Foundation, 2021; American Gas Association, 2014.

Water

Tables B.14 through B.17 include a high-level overview of the potential impacts to and strategies for improving resilience of water utility systems. The tables are organized by water utility infrastructure component.

Table B.14. Potential Impacts to and Resilience Strategies for Water Acquisition and Distribution

Impact	Strategies to Improve Resilience	Hazard(s)
Damage or deterioration of water collection and intake infrastructure (e.g., wells, pumps)	• Monitor and inspect existing infrastructure for structural integrity • Upgrade intake infrastructure to meet future climate conditions • Improve water collection and intake efficiency	Coastal flooding; extreme heat; extreme cold; heavy rain; hurricane or tropical storm; inland flooding; storm surge; tornado; winter storm; erosion; loss of ice or snowpack; permafrost melt; saltwater intrusion; sea level rise; wildfire
Reduced water quality and potential contamination from a hazard shock (e.g., flash flood event) or stressor (e.g., sea level rise)	• Implement policies and procedures for post-hazard event inspection and repairs • Retrofit intake infrastructure to protect from water contamination (e.g., accommodate different water levels)	Coastal flooding; extreme heat; hurricane or tropical storm; wildfire; dust; insect infestation; toxicity, pathogens, and algae; erosion; loss of ice or snowpack; saltwater intrusion; sea level rise
Damage of pipeline infrastructure or equipment used for distribution	• Protect pipeline infrastructure or equipment using strategies (such as flood barriers) or relocate/reroute piping outside hazard area • Perform vegetation management and/or create a defensible space around pipeline infrastructure and equipment	Coastal flooding; extreme heat; extreme cold; heavy rain; hurricane or tropical storm; inland flooding; storm surge; wind; tornado; wildfire; winter storm; erosion; permafrost melt; sea level rise; saltwater intrusion
Deterioration of pipeline infrastructure causing water mains to break or distribution pipeline to leak	• Increase monitoring and inspection efforts of existing infrastructure	Coastal flooding; extreme heat; extreme cold; heavy rain; hurricane or tropical storm; inland flooding; storm surge; wind; tornado; wildfire; winter storm; erosion; permafrost melt; sea level rise; saltwater intrusion
Physical damage to constructed conveyances (e.g., canals and culverts)	• Protect canals and culverts using strategies (such as flood barriers) or relocate/reroute canals and culverts outside hazard area	Coastal flooding; extreme heat; extreme cold; heavy rain; hurricane or tropical storm; inland flooding; storm surge; wind; tornado; wildfire; winter storm; erosion; permafrost melt; sea level rise; saltwater intrusion

Impact	Strategies to Improve Resilience	Hazard(s)
Constructed conveyances (e.g., canals and culverts) exceed capacity	• Manage watershed and ecosystems to regulate runoff and streamflow • Implement nature-based features (e.g., green roofs or wetlands) to manage excess capacity • Develop coastal restoration efforts	Coastal flooding; heavy rain; hurricane or tropical storm; rapid ice or snow melt; storm surge; sea level rise; erosion

SOURCE: Authors' analysis of data from EPA, 2023j; EPA, 2023h; American Water Works Association, 2021; FEMA, 2021a; Riggins, 2022.

Table B.15. Potential Impacts to and Resilience Strategies for Water Treatment Facilities

Impact	Strategies to Improve Resilience	Hazard(s)
Damage to or deterioration of water treatment facilities and/or equipment	• Protect facilities and/or equipment with hazard mitigation strategies (e.g., build flood barriers) • Retrofit facilities to avoid damages or disruption (e.g., install watertight doors or elevate building)	Coastal flooding; hurricane or tropical storm; landslide; storm surge; tornado; wildfire; wind; erosion; sea level rise; permafrost melt
Inability for wastewater treatment systems to function because of changes in environmental conditions (e.g., increase in surface water temperature)	• Conduct stress testing on wastewater treatment biological systems to assess tolerances to different environmental conditions • Increase monitoring and inspection of existing infrastructure	Coastal flooding; extreme cold; extreme heat; inland flooding; storm surge; wildfire; winter storm; dust; insect infestation; toxicity, pathogens, and algae; vegetation die-off; erosion; saltwater intrusion; sea level rise
Water levels fall below intake levels for water treatment as a result of streamflow declines	• Increase monitoring of streamflow conditions and implement capital improvement projects to meet design thresholds based on future climate conditions	Extreme heat; drought
Inability to operate/function because of loss of power	• Improve energy efficiency and optimization of facility operations to reduce vulnerability to power disruptions • Incorporate backup power generation and/or implement alternate energy approaches (e.g., microgrids)	Extreme heat; extreme cold; coastal flooding; hurricane or tropical storm; inland flooding; storm surge; tornado; wildfire; wind; winter storm; demand pressure

SOURCE: Authors' analysis of data from EPA, 2023j; EPA, 2023h; American Water Works Association, 2021; FEMA, 2021a; Riggins, 2022.

Table B.16. Potential Impacts to and Resilience Strategies for Water Supply and Storage

Impact	Strategies to Improve Resilience	Hazard(s)
Water scarcity issues because of overuse of infrastructure (e.g., aquifers being depleted)	• Diversify options for water supply (e.g., use surface water and groundwater) • Diversify options for water storage • Implement systems to recycle water and practice conjunctive use (i.e., use both surface and groundwater intra- and inter-annually) • Use water demand measures to reduce and control water demand • Improve water use efficiency	Extreme heat; wildfire; drought; loss of ice or snowpack; demand pressure
Water scarcity issues because of potential damage to water source infrastructure (e.g., dams)	• Diversify options for water supply (e.g., use surface water and groundwater) • Increase monitoring and inspection of existing water infrastructure • Retrofit existing water source infrastructure to prepare for future climate conditions	Coastal flooding; extreme cold; extreme heat; heavy rain; hurricane or tropical storm; inland flooding; landslide; storm surge; tornado; wildfire; wind; winter storm; drought; erosion; saltwater intrusion; sea level rise
Changes to water reservoir quality and/or possible water contamination	• Conduct stress testing on water supply to assess tolerances to different environmental conditions • Implement barriers and/or aquifer recharge to prevent saltwater intrusion	Extreme heat; extreme cold; coastal flooding; hurricane or tropical storm; heavy rain; storm surge; wildfire; dust; insect infestation; toxicity, pathogens, and algae; vegetation die-off; permafrost melt; saltwater intrusion; sea level rise

SOURCE: Authors' analysis of data from EPA, 2023j; EPA, 2023h; American Water Works Association, 2021; FEMA, 2021a; Riggins, 2022.

Table B.17. Potential Impacts to and Resilience Strategies for Water Stormwater Management

Impact	Strategies to Improve Resilience	Hazard(s)
Damage to or deterioration of stormwater pipeline infrastructure and/or equipment	• Implement protective measures for stormwater infrastructure (e.g., construct flood barriers) • Relocate/reroute pipeline infrastructure outside hazard area • Monitor and inspect existing stormwater infrastructure for structural integrity	Coastal flooding; extreme cold; extreme heat; hurricane or tropical storm; inland flooding; landslide; tornado; wildfire; wind; winter storm; erosion; permafrost melt; sea level rise
Insufficient capacity of drainage system to manage stormwater	• Manage and regulate runoff and streamflow • Implement nature-based drainage features (e.g., wetlands or bioretention areas) to manage excess capacity	Coastal flooding; heavy rain; hurricane or tropical storm; inland flooding; rapid ice or snow melt; storm surge; loss of ice or snowpack; sea level rise

SOURCE: Authors' analysis of data from EPA, 2023j; EPA, 2023h; American Water Works Association, 2021; FEMA, 2021a.

Characteristics of Climate Hazard Data

In the following sections, we describe the basic information sources and what might be most useful to consider in the context of utilities disruption. We consider the rate at which the data are updated and how representative they might be of future conditions.

Tropical Storms and Hurricanes

Hurricanes are responsible for many utility disruption events, and the frequency and intensity of hurricanes and tropical storms is likely to increase because of increasing sea surface temperature (Wuebbles et al., 2017). However, the tracks and locations of future hurricanes cannot be predicted with any meaningful resolution (Marsooli et al., 2019). The areas in which hurricanes have had an impact in the past is an indication that hurricanes are at least possible in those areas.

The annualized hurricane frequency value from FEMA's National Risk Index (NRI) is combined with exposure data (asset value) to calculate the hurricane historic loss ratio. The annualized frequency is based on a count of the number of recorded hurricanes that were reported within each U.S. county. That count follows mapping of the tracks of individual hurricanes; hurricane tracks are recorded by NOAA (Office for Coastal Management, 2023a). The number of hurricane events in a county is an indication of how many recorded hurricanes were around the relevant electrical substations and proximal delivery infrastructure.

Cold Weather, Winter Weather, and Winter Storms

Some recent research forecasts that melting sea ice and warming surface temperatures will cause more extreme cold events in the United States (Cohen et al., 2021). Other modeling efforts indicate that the increasing global temperatures will result in fewer, less extreme cold weather events. Some studies indicate that the pattern of sea ice loss drives the disruption of the polar vortex and cannot be predicted (Lindsey, 2021). Although there is no consensus about changes in extreme cold events in either location or intensity, there is a historical record for extreme cold events through the National Weather Service (NWS).

The FEMA NRI aggregates warnings of extreme cold issued by the NWS to reflect the risk from extreme cold at the county level. The aggregated NWS warnings counted in days reflect the number of Cold Wave event-days from 2005 to 2017 (FEMA, 2021b, “Cold Wave,” p. 8-1). This count indicates the relative amount of time that the utility area around an installation was impacted by extreme cold. In some instances, the most relevant county to be affected might be the location of a natural gas–fueled electricity generation facility serving an installation.

The 2014 U.S. National Climate Assessment states that “[w]inter storms have increased in frequency and intensity since the 1950s, and their tracks have shifted northward” (Walsh et al., 2014). Another appropriate metric is the tracking and count of climate events that cost at least \$1 billion in recovery (Smith, 2022); the storm types that are counted include winter storms. Counts of each storm type with large enough impact is displayed by state. The compilation of impactful winter storms from 1980 to 2018 includes measurable impacts from Texas across the eastern United States; the highest levels of counts are in New York and Pennsylvania (Climate.gov, 2019).

The FEMA NRI aggregates winter storm events, including snow, sleet, or freezing rain as the main form of precipitation. The aggregated NWS warnings for winter weather counted in days reflect the days impacted over 12 years (FEMA, 2021b, “Winter Weather,” p. 23-1). This count indicates the relative amount of time that the utility area around an installation was impacted by winter storms.

Heat Wave and Extreme Heat

The timing, locations, and intensity of heat waves is difficult to project into the future. A 2015 study of heat waves in U.S. cities from 1961 to 2010 using historical daily temperature data found statistical trends in the intensity and duration of heat waves (Habeeb, Vargo, and Stone, 2015). The study found that all the assessed cities have had significant increases in frequency, duration, timing, and intensity of heat waves. The analysis found that all four metrics of heat waves are increasing faster than the national average in Austin, Birmingham, New Orleans, Pittsburgh, and Raleigh.

The FEMA NRI aggregates heat warnings issued by the NWS at the county level. The aggregated NWS warnings counted in days reflect the heat wave event–days from 2005 to 2017 (FEMA, 2021b, “Heat Waves,” p. 12-1). This count indicates the relative amount of time that the utility area around an installation was impacted by heat.

The tracking and count of climate events that cost at least \$1 billion in recovery (Smith, 2022) include the combination of drought and heat waves and are displayed by state. The compilation of high-impact heat-related events from 1980 to 2018 includes observable frequencies across the United States. The highest levels of counts are in Texas, Oklahoma, and Kansas (Climate.gov, 2019).

Tornadoes

Tornadoes are categorized according to the Enhanced F-scale (EF), ranging from EF0 (tornadoes with wind speeds of at least 65 miles per hour) to EF5 (tornadoes with winds speeds of 200 miles per hour or more) (NWS, undated). Because local NWS forecast offices must investigate and verify reports of tornadoes, which can take several months, preliminary counts reported by the NWS Storm Prediction Center (SPC) might not match confirmed counts months later. According to NCEI, “[h]istorically, for every 100 preliminary tornado reports, at least 65 tornadoes are confirmed” (NCEI, undated-d). Thus, caution should be exercised when using tornado counts from the NWS SPC Monthly Climate Reports because the data might not reflect confirmed counts across the United States. Tornado data from 1986 to 2019 is compiled by FEMA NRI (FEMA, 2021b, “Tornado,” p. 19-1). The track of the tornado is buffered to an 80-km radius to make a polygon and scaled to overlay the counts onto counties. The number of storms identified in each county is counted for the assessed time.

Flooding

One way that the potential severity of flooding in an area can be indicated is to consider the proportion of the area that lies in the flood plain. FEMA NRI calculates the developed area in the 100-year (1 percent) flood plain in km² using the FEMA National Flood Hazard Layer (NFHL) and the intersection of Census block polygons (FEMA, 2021b, “Riverine Flooding,” p. 17-1). This area is likely to be a reasonable indication of the amount of utility infrastructure to be flooded under severe flood conditions. The NFHL maps are based on historical flood conditions, and there is some modeling that indicates that the maps do not reflect changes in flooding patterns expected under climate change.

Wing et al. (2022) projected changes to flood risk from climate change for the continental United States. Elevated flood risk is based on an estimation of the change in local flood intensities and frequencies. The biggest change in flood hazard was found to be in areas on the East Coast that are hit by hurricanes. Riverine flooding is highly uncertain to model, but some trends are seen for short-duration rainfall and for sea level rise. Although these data are not consistently available for all U.S. states, they might be useful in considering the potential change in flooding from two systems that are equally at risk from historical flooding.

Landslides

The FEMA NRI captures the number of landslide events from the Cooperative Open Online Landslide Repository, a project of NASA’s Precipitation Measurement Missions from 2010 to 2019. Each recorded landslide event was associated with one county. The number of all recorded events per county is an indication of area exposure (FEMA, 2021b, “Landslide,” p. 15-1).

Climate change is generally expected to increase extreme precipitation events; therefore, it might be associated with more-frequent and larger landslides. However, the amount and location of precipitation events cannot be reliably projected. Landslides are also influenced by other climate hazards, specifically wildfires, increasing sea level rise, and permafrost loss (Coe, 2017).

Wildfire

The U.S. Forest Service's Fire Modeling Institute produces a map of Wildfire Hazard Potential (Dillon, undated). The "wildland fire potential (WFP) [is] a raster geospatial product that can help to inform evaluations of wildfire risk or prioritization of fuels management needs across very large spatial scales (millions of acres)" (Dillion, Menakis, and Fay, 2015). The wildland fire potential indicates current wildfire risk and is updated approximately every five years. The wildland fire potential is not predictive and does not account for recent fire, human activity, or other potential sources of ignition. It also does not include any information on current or forecasted weather or fuel moisture conditions.

Drought

Drought can only be projected one season out. However, historical drought conditions can be aggregated using many types of data, including observations from local experts across the country. The U.S. Drought Monitor captures historic changes but not predictions of future conditions (National Integrated Drought Information System, undated). Historic occurrence of drought (event days) between 2000 and 2017 are aggregated at the county level in FEMA's NRI (FEMA, 2021b, "Drought," p. 9-1).

Sea Level Rise

NOAA's Office for Coastal Management's Sea Level Rise (SLR) Viewer (Office for Coastal Management, 2023b) allows a way to visualize whether a specific level of SLR would impact a site of interest. For example, an SLR of 3 ft could be assessed to see whether the area around an installation that contains utility infrastructure would be affected. This forward-looking metric is an indication of which installation-serving utilities are likely to be impacted by SLR. Alaska is not a part of the mapping tool.

Wind

The FEMA NRI characterizes instances of strong wind as exceeding 58 miles per hour that is often associated with thunderstorms (FEMA, 2021b, "Strong Wind," p. 18-1). The NWS SPC has records of strong wind conditions from 1986 to 2017. The starting and ending point of the wind events were surrounded by an 80 km buffer to create an event polygon. The number of strong wind event polygons that intersect a specific area provide a count. The event count that is scaled is reported at the county level.

The strong winds recorded by the NWS SPC are often associated with a storm. However, there is some indication that climate change is reducing strong winds at the global scale. Data plotted over the past 50 years show trends of declining land-surface wind speeds over North America (Zhao, Luo, and Jiang, 2011). Therefore, the future trend of this hazard may be declining.

Permafrost Loss in Alaska

In 2015, the U.S. Geological Survey modeled the loss of permafrost in Alaska (Pastick et al., 2015). Three IPCC scenarios over two different time horizons were used to project the loss of permafrost in Alaska. The authors noted that “the complex interactions and feedbacks affecting the resilience and vulnerability of permafrost to climate change (Jorgenson et al., 2010) lead to substantial uncertainty in estimating future permafrost distributions” (Pastick et al., 2015). Regional maps estimate the amount of permafrost that underlies each region of Alaska, as well as the expected percentage loss of that permafrost. The near surface permafrost is at the highest risk for loss, so the probability of near-surface permafrost is a good reflection of the location-specific risk of permafrost loss.

Review of Codes, Standards, and Specifications for Energy and Water Utility Systems

In this appendix, we detail our approach to reviewing regulation, codes, standards and guidance documents for energy and water utility systems and present our detailed findings for the case study regions. This information supplements the summary we provided in Chapter 3.

The Role of Codes and Standards in Climate Resilience

Codes and standards play a significant role in extreme weather and climate resilience for infrastructure design. Codes and standards were originally developed with the intent of improving life safety in buildings but have evolved to include other aspects of the built environment. For energy and water infrastructure, this includes ensuring the reliability of supply by meeting demand through sufficient supply and through reliable operations and physical infrastructure. Historically, the driver for updating regulations (and related codes and standards) to account for climate and extreme weather resilience has been a major natural disaster event. For instance, in 2013, the New Jersey Department of Environmental Planning updated its Flood Hazard Area Control Act rule to incorporate updated flood mapping and acceptable flood protection levels after Hurricane Sandy impacted parts of New Jersey in October 2012 (Loder, 2022). Most recently, the electric power outages resulting from 2021 Winter Storm Uri in Texas led to recommendations by FERC and NERC to revise cold-weather reliability standards for electric generating units (FERC, NERC, and Regional Entities, 2021).

By regulating the design, construction, and operation of infrastructure and equipment, codes and standards aim to reduce vulnerabilities from natural hazards (e.g., floods, extreme wind, wildfires), as well as man-made hazards (e.g., cyberattacks) (International Code Council, 2021). Within the context of energy and water utility systems, regulations, codes, and standards can address or mitigate the effects of extreme weather and climate hazards through the following ways:

- **Emergency preparedness actions and risk assessments:** Most regulations and related codes and standards address climate and extreme weather resilience by requiring utilities to develop climate change risk assessments and/or emergency response plans. The California Public Utilities Commission, for instance, issued an order in 2018 that requires energy utilities to file vulnerability assessments to identify climate risks and options for mitigating those risks (California Public Utilities Commission, 2018).

- **Infrastructure hardening requirements:** Some codes and standards focus on the design and construction of infrastructure and equipment to withstand and survive potential impacts from hazards. For example, the National Electrical Safety Code includes extreme wind loading standards for the design of transmission or distribution poles.
- **Reliability or quality performance standards:** Other regulations, codes, and standards address climate resilience by requiring utilities to meet a minimum level of reliability or quality of a particular service. For instance, federal regulations through the EPA, such as the Water Quality Guidance for the Great Lakes System, include minimum acceptable contaminant levels for utilities that source water from the Great Lakes region.

Many entities, including ones at the federal, state, and, in some cases, local level, are involved in the development, adoption, and enforcement of codes and standards for energy and water utilities through the establishment of regulations. Federal agencies, such as FERC and NERC, regulate the transmission of electricity, natural gas, and oil and develop reliability and other performance standards for electric and natural gas utilities. Other federal agencies include the U.S. Department of Transportation Pipeline and Hazardous Material Safety Administration (PHMSA), which establishes regulations for the transportation of energy and hazardous material transport, and the EPA, which establishes drinking water requirements for states and public water systems. Additionally, state legislatures and public utility commissions are involved in the development of rules and regulations for energy and water utilities.

With various stakeholders involved with different governing processes, regional variations in codes and standards for electric and water utilities exist. The state of Maryland, for instance, enacted a bill in 2021 that requires the Maryland Public Service Commission to consider climate change in the regulation of energy and water utilities (Maryland General Assembly, 2021). Other states, however, have faced challenges with passing regulations related to climate change resilience and utilities. The state of Vermont, for instance, proposed the “Clean Heat Standard,” which would require reductions in greenhouse gas emissions for entities involved in the sale of heating fuel; however, the bill was vetoed in 2022 and did not get implemented (Vermont General Assembly, 2022). Additionally, states may adopt different versions of the same code. For example, some states, such as Oregon and Florida, have adopted the 2017 version of the NESC (Oregon Administrative Rules, Rule 860-024-0010; Florida Administrative Code, Rule 25-6.0345); others, such as Kansas, appear to still be using the 1997 version as their standard (Kansas Administrative Code, Section 82-12-2).³⁰ It is important to note that older versions of a code might not be less resilient to climate hazards; however, there is literature that suggests that there are benefits in climate change resilience for buildings that adopt the latest set of codes and standards (Porter et al., 2019).

Some studies have attempted to quantify the impacts from climate change on outdated codes and standards. For example, Lopez-Cantu and Samaras (2018) assessed how the design of stormwater infrastructure using Department of Transportation guidelines might use precipitation data that are outdated and might not account for future changing climate conditions.

³⁰ IEEE released the most recent version of the code (NESC 2023) during the course of our research.

Method of Reviewing Regulations, Codes and Standards

In our review of codes and standards, we looked specifically for *how* climate change or natural hazard resilience is considered, the *geographic scale* at which there is variability in the regulatory and policy environment, and whether that variability can be used to *inform priority-setting* for deep-dive installation-focused vulnerability assessments.

First, we conducted a literature review to identify the known vulnerabilities of energy and water utility systems to climate hazards. Second, we used these vulnerabilities to identify a sample of specific regulations, codes, and standards that would be relevant at federal, state, county, and (if applicable) local levels. Additionally, we expanded our search to identify other resources and documents relevant to climate change and natural hazard resilience for energy and water utilities, including best management practices, guidelines, and climate action plans. Third, we reviewed the documents to identify references to climate change or natural hazard resilience. Our review process included key word searches (e.g., climate, resilience, hazard, emergency, reliability, infrastructure protection) in the document.

The list of identified codes, standards, specifications, and other references that we reviewed are included in a detailed spreadsheet that is available on request. For each reference, we collected relevant attributes, including the reference type (e.g., code, standard, best management practice), the last year updated, the implementation level, the author or regulating agency, a description of the reference, the resilience contributions (e.g., infrastructure hardening, emergency planning, reliability), and sample excerpts from the reference. Note that this is not a comprehensive list of all regulations, codes, standards, and best management practices related to climate change and extreme weather resilience for the given utility system. Instead, the list represents a sample of relevant references pertaining to climate change or natural hazard resilience for a given region.

Energy (Electric Power)

- Federal standards, such as those developed by NERC, consider climate change resilience through requirements of emergency response and preparedness from natural hazard events. More recently, NERC is in the process of developing standards to incorporate climate change and extreme weather events into reliability standards; however, this development is nascent (FERC, NERC, and Regional Entities, 2021).
- Some federal codes, such as the NESC and Rural Utilities Services bulletins, specify infrastructure-hardening requirements (e.g., strength requirements for distribution poles) or operational and maintenance requirements (e.g., vegetation management to mitigate risk of disruption from wildfires). Although states may adopt different versions of the NESC, we did not identify major differences pertaining to infrastructure hardening requirements between the most recent updates from 2017 to 2022.
- Local or statewide regulations can account for climate change resilience through reliability performance requirements. For instance, New Jersey Administrative Code, Title 14, Section 14:5-8.2 sets reliability performance levels based on SAIFI and CAIDI. The

minimum performance requirements for SAIFI, CAIDI, and other reliability metrics vary regionally.

Energy (Natural Gas)

- Codes and standards pertaining to natural gas transmission and distribution systems typically focus on safety requirements and are developed through consensus-based organizations, such as the American Society of Mechanical Engineers or American Petroleum Institute.
- Federal regulations, such as ones developed by the Department of Transportation, consider extreme weather events as safety hazards for pipeline and fuel transportation. For example, in 2019, the PHMSA amended pipeline safety regulations to improve and extend pipeline safety risk assessment and management related to extreme weather events.
- Some federal regulations specific to extreme weather events are early in development. For instance, FERC and NERC are considering the development of electric reliability standards that include winterization and cold weather preparedness of natural gas infrastructure (O'Driscoll, 2021).

Water

- Natural hazard or climate change resilience for water utility systems is typically implemented through voluntary standards or best management practices, incentives for utility implementation actions, or requirements of risk and vulnerability assessments. Federal regulations, such as those enforced by the EPA, focus on resilience planning and risk assessments to customize approaches for different local risks and needs for water utilities.
- State and local climate action plans sometimes identify vulnerabilities and resilience strategies for water utility systems. In some instances, climate action plans include requirements that utilities must follow. For example, the 2019 Anchorage Climate Action Plan includes an action to “enforce municipal stormwater treatment and green infrastructure requirements” (Hahn et al., 2019).
- Federal, state, and local agencies focus on providing education, assistance, and resources to support utilities in implementing climate change resilience measures. For example, the Creating Resilient Water Utilities initiative, the Adaptation Resource Center, and the Climate Resilience Evaluation and Awareness Tool are examples of resources developed by the EPA to assist water utilities in identifying potential risk and adaptation options for climate change resilience. However, it is difficult to determine whether a water utility has taken advantage of such tools. Additionally, vulnerability assessments developed through these tools and resources by water utilities are not publicly available.

Other Potential Indicators of Utility Resilience

This appendix supplements the summary of utility system resilience indicators in Chapter 3.

State or Local Resilience Planning Efforts

Climate change resilience plans for energy, water, and other services is an important tool that enables states and other local governments to assess threats, identify or develop policies to mitigate climate change risk, and prioritize investments to improve climate change resilience efforts. Developing an understanding of the threats at a detailed resolution (i.e., at the local community or utility level) helps in resilience investment decisionmaking (Cramer et al., 2021). Additionally, long-term and comprehensive planning can help in effective strategy development, identification of strengths and weaknesses, and opportunities for efficiency (FEMA, 2013). Climate change planning efforts can vary at the state or local level. For instance, 85 percent of the country's population resides in communities in which a local hazard mitigation plan exists. However, only 14 states have enhanced state mitigation plans as of October 27, 2023 (FEMA, 2023b).³¹ Some of the local hazard mitigation plans now include regional plans for multiple jurisdictions (e.g., the Pikes Peak *Multi-Hazard Mitigation Plan Update 2020* in the Colorado Springs area [Pikes Peak Regional Office of Emergency Management, 2021]) because of the importance of regional planning and collaboration in hazard mitigation activities and planning. Table D.1 lists the indicators that we included as part of our assessment of state or local resilience planning efforts.

³¹ States with enhanced hazard mitigation plans are eligible for additional funding through FEMA's HMGP.

Table D.1. State or Local Resilience Planning Efforts Assessment Criteria

Indicator	Description	Contribution to Resilience
Is there a state or local hazard mitigation plan?	Hazard mitigation plans, at either the state or local level, are a tool that communities can use to identify natural hazard risks and strategies or intents to mitigate those risks. Additionally, state or local hazard mitigation plans are required to receive nonemergency funding assistance through FEMA. State hazard mitigation plans are required to be submitted to FEMA every five years for approval.	• An approved and updated hazard mitigation plan indicates that the state or local community is including climate change and natural hazard risks in their planning efforts. • Approved hazard mitigation plans indicate communities that are eligible for FEMA hazard mitigation funding.
Is there a state or local energy plan?	Energy plans can be used to develop targeted goals to meet energy resource demands and energy infrastructure needs in a cost-effective manner. Energy plans also identify challenges, including impacts from climate change and natural hazards, as well as strategies, programs, and resources available to overcome those challenges.	• A lack of an energy plan or an outdated energy plan indicates that climate change or natural hazard resilience investments might not be prioritized in planning efforts.
Is there a state or local water plan?	State or local water plans help regional and local water planners determine priorities for funding, assess risks to water supply and distribution systems, and forecast for socioeconomic changes (McLaughlin, Schwab, and Tucker, 2021). As of this writing, 29 out of 50 states in the United States have developed formal water plans that indicate regional variability in state water planning efforts (Werner and Svedin, 2017). Additionally, some states with formal water plans might not have updated them for over a decade.	• A lack of a water plan or an outdated water plan indicates that climate change or natural hazard resilience investments might not be prioritized in planning efforts.
Does the base or community Annual Water Quality report mention climate change, resilience, or infrastructure investments? ^a	The EPA requires community water systems to provide an annual water quality report to its customers. The annual water quality report includes information on where water is sourced, the list of contaminants and contaminant levels that are detected in the water supply, and the potential negative health consequences (EPA, 2018).	• The identification or mention of climate change impacts in water quality reports is a potential indicator in assessing how the water utility is considering climate change risk and communicating that risk to customers.

^a Metric specific to water utilities.

Regulatory and Financial Mechanisms

Regulatory and financial mechanisms are approaches that can enable or inhibit improvements for systemwide resilience from climate change impacts (Kallay, Napoleon, Hall, et al., 2021). Regulatory mechanisms, such as standards for energy efficiency or requirements for energy storage, allow agencies or entities to control or govern conduct in climate change resilience planning (Maddocks, 2011). Lack of regulatory mechanisms implies that utilities' investments in climate change resilience will be voluntary and not enforceable. Additionally, energy and water utilities rely on infrastructure that is aging, deteriorating, and at risk of climate change impacts. One of the challenges that utilities face in making infrastructure investments is the availability of financial resources (e.g., loans or grants) and mechanisms (e.g., incentives) (Hukka and Katko, 2015). Table D.2 lists the indicators that we included as part of our assessment of regulatory and financial mechanisms.

Table D.2. Regulatory and Financial Mechanisms Assessment Criteria

Indicator	Description	Contribution to Resilience
Programs to support utility investments in resilience	State or local programs for resilience investments include grants or loans.	Financial incentives or funding resources, such as grants, provide utilities and communities with mechanisms for investing in climate resilience efforts.
Statewide renewable portfolio standard ^a	Renewable portfolio standards include requirements for utilities to sell a specific percentage of electricity from renewable sources.	Integrating renewables through energy storage and advanced energy management, such as load shifting, improves resiliency because it aligns demand with supply.
Energy storage financial incentives ^a	Energy storage financial incentives support communities in investing in energy storage systems.	Energy storage financial incentives can increase adoption of energy storage technologies. Scaled electricity storage allows for improved resource availability.
Energy storage targets ^a	Energy storage targets indicate a state's goals and objectives for energy storage.	Like incentives, targets are another regulatory mechanism to increase storage adoption.
Energy efficiency standards ^a	Energy efficiency standards indicate a state's objectives in reducing energy usage versus expanding generation.	Energy efficiency allows for reduced usage but also provides protection at coinciding energy and weather crises (e.g., heat waves and insulation).
Net metering ^a	If an entity generates electricity greater than its use, net metering determines how the entity is compensated.	Net metering compensates consumers with generating capacity to provide electricity to the grid. Having net metering creates a more resilient grid because other producers are incentivized to generate electricity for the broader system.

^a Metric specific to electric utilities.

Community Partnerships

Military installation and community partnerships can and have been playing an important role in helping DAF bases reduce the impact of extreme weather and climate change on their military missions. An *installation and community partnership* is when a military base works together with one or more community partner(s) for mutual benefit, and each partner invests in that relationship based on mutual trust by sharing resources, information, expertise, responsibilities, risks, and benefits (Lachman, Resetar, and Camm, 2016). Community partners can include private companies, local and state agencies, other parts of DoD, other government agencies, nongovernmental organizations (NGOs), universities, and other organizations and individuals. Across the United States, thousands of mutually beneficial and diverse installation and community partnerships exist in a wide variety of functional areas, including fire, emergency medical services, and other emergency services; safety and security; water management and resilience; energy management and resilience; environmental management; transportation; social services; recreation; children; medical and health issues; and testing, training, and other military missions (Lachman, Resetar, and Camm, 2016). An installation that has been developing and participating in such partnerships, especially with local governments, shows a capacity and history of collaborating outside the fence line, which in itself can be a useful indicator that the community could help the utility invest more in resilience to support the base. If a utility is already involved in a partnership, it can indicate that the utility is focusing on resilience investments. Table D.3 lists the indicators that we included as part of our assessment of community partnerships.

Table D.3. Community Partnerships Assessment Criteria

Indicator	Description	Contribution to Resilience
Does the installation have any REPI projects?	Programs, such as REPI, are tools used to indicate whether installations have community partnerships.	Can help improve the overall installation, community, and regional resilience to extreme weather and climate change impacts (e.g., drought, wildfires, and flooding) and can help with water supply.
Has the installation and community ever conducted a Compatible Use/Joint Land Use Study?	A Compatible Use/Joint Land Use Study is a regional community and installation plan helping to ensure that civilian growth and development (e.g., location of community roads, housing developments, and power lines) are compatible with installation testing, training, and other operations.	Can help improve regional resilience investments (e.g., stormwater management).
Has the installation and community ever received a DCIP program, MIRR, or other OSD partnership grant?	These are grants to help communities assess and develop community infrastructure projects to support a military installation, which can include projects focused on water and energy utility resilience.	DCIP helps communities implement investments in energy or water infrastructure projects that support an installation. Using the results of a vulnerability assessment, MIRR produces a list of community resilience investment projects (including utility ones) that support the military installation.
Has the installation had an Air Force Community Partnership (AFCP) workshop in the past?	AFCP workshops provide a framework for Air Force installations and communities to collaborate in solving problems that both the installation and the community face.	Participation in AFCP workshops demonstrates that the installation may be working together with energy or water utilities to implement climate change resilience strategies.

Basic Overview of Utility Assessment

Energy and water utilities vary in terms of characteristics, such as number of customers served, corporate structure, and scale or age of infrastructure. These characteristics may provide an indication of the potential risk to climate change impacts and the ability to invest or implement resilience measures. For example, aging water infrastructure increases the risk of pipe breaks and leaks, and smaller water utilities, when compared with larger water utilities, can have twice as many pipe failures as a result of more miles of pipeline per customer and a smaller revenue stream (ASCE, 2021). Additionally, utilities with little or no experience in applying for resilience funding might require additional guidance to take advantage of climate change resilience tools and resources (Monks and Vajjhala, 2022). Table D.4 lists the indicators that we included as part of our assessment of the basic overview of each utility.

Table D.4. Basic Corporate Overview of Utility Assessment Criteria

Indicator	Description	Contribution to Resilience
Number of customers served	The number of customers to whom the utility provides service	The number of customers for a given utility provides an indication of the scale of revenue. For instance, a utility with a smaller customer base may have a lower revenue stream as compared with a utility with a larger customer base. Revenue is a resource for asset management, including infrastructure resilience.
Size of service territory	The size in square miles of the utility service territory	The size of the service territory indicates potential exposure to a given hazard and indicates potential risk of management capacity concerns for a utility. A utility that has a wide service territory that spans multiple states may have more regulatory and physical exposure challenges as compared with a utility with a more regional focus.
Type of utility (e.g., public or private, municipally owned or cooperative)	The corporate structure of the utility, such as whether it is investor-owned or part of a municipality	Funding priorities, mechanisms, and sources can vary by utility corporate structure. For instance, municipal electric utilities are owned by local governments and may benefit from municipal bonds, which fund large capital projects, including resilience initiatives.
Urban versus rural	Whether the utility provides service primarily in an urban or a rural area, as defined by the U.S. Census Bureau: Urban areas have “at least 2,000 housing units or have a population of at least 5,000” (U.S. Census Bureau, 2023)	Utilities primarily located or providing service to rural areas may lack experience, exposure, or awareness of climate change resilience tools and resources available for utilities.
Infrastructure asset size	The number of assets that the utility has (such as power plants, equipment, and pumps) and the miles of pipeline	The asset inventory of a utility indicates the scale of a utility’s asset management needs. For instance, a utility that is small, but has a high number of miles of pipe per customer, may have less funding for infrastructure improvements and repairs.

Financial Strength and Investment Capability

Investments in resilience require significant financial resources over short and long time horizons. A utility might have competing priorities that require financial resources, and a utility’s ability to borrow funding for infrastructure repair, retrofit, or improvements is considerable. Credit rating agencies provide informed opinions on a company’s relative creditworthiness. This rating is a consistent set of assessments across utilities, corporate structures, and regions, making it a useful tool

for tracking across installations and utilities (S&P Global Ratings, undated). Table D.5 lists the indicators that we included as part of our assessment of a utility’s financial strength and investment capability.

Table D.5. Financial Strength and Investment Capability Assessment Criteria

Indicator	Description	Contribution to Resilience
Long-term issuer credit rating	The long-term issuer credit rating is an independent assessment of an organization’s financial strength and ability to honor unsecured debt based on a time horizon of greater than one year.	Capital-intensive resilience projects require large investments. Investment grade (IG) entities are thus more likely to successfully finance these projects than are non-IG entities.
Short-term issuer credit rating	The short-term issuer credit rating is an independent assessment of an organization’s financial strength and ability to honor unsecured debt based on a time horizon of less than one year.	The onset of a resilience crisis typically stresses an entity’s short-term liquidity. By having access to short-term liquidity, these entities exhibit their abilities to withstand the crisis and have resources to bring their systems back to an operating baseline.
Investment capability based on corporate structure	Investment capability was assessed based on the utility’s corporate structure using the following criteria: • high investment capability: IG entity with an ability to access capital markets • medium investment capability: large customer base with IG rating, but unable to access equity markets • low investment capability: small customer base, sub-IG rating, unable to access equity markets.	Given the potential need for large capital investments, entities’ corporate structures were also considered. Smaller firms or municipalities with poor credit ratings are uniquely susceptible to resilience crises because they do not have limited access to capital markets to fund their recovery.

Utility Regulatory Compliance

Compliance with regulations provides an indication of whether the utility is following minimum standards, rules, and requirements. Utilities with regulatory compliance issues indicate potential mismanagement and the inability to prioritize resilience initiatives. Table D.6 lists the indicators that we included as part of our assessment of the utility’s regulatory compliance.

Table D.6. Utility Regulatory Compliance Assessment Criteria

Indicator	Description	Contribution to Resilience
Does the utility have any civil penalties within the past ten years?	Utilities face civil penalties from either state or federal entities for violating codes, standards, or other regulations.	Utilities that face civil penalties indicate potential mismanagement and inability to prioritize or invest in resilience measures.
Does the utility have any violations with federal or state regulators in the past ten years?	Violations with federal or state entities indicate that utilities are not in compliance with regulations or other requirements.	Utilities with violations of federal or state regulations indicate potential mismanagement and the inability to invest in resilience measures.

Utility Service Reliability

Resilience and reliability are interconnected and related but vary conceptually. Whereas *resilience* can be considered as the ability to prepare, respond, recover, and adapt to threats or hazards, *reliability* focuses on reducing interruptions to services. Reliability metrics, however, can be used to consistently compare a utility's ability to provide services without disruptions. Table D.7 lists the indicators that included as part of our assessment of utility service reliability.

Table D.7. Utility Service Reliability Assessment Criteria

Indicator	Description	Contribution to Resilience
SAIFI ^a	SAIFI is a metric used to measure the service interruption of electric utilities through the EIA. SAIFI is measured by taking the average number of occurrences that a customer experiences a power interruption in a one-year period for a given utility.	- Three types of SAIFI/SAIDI are reported to EIA typically: (1) with MED, (2) without MED, and (3) with MED minus loss of supply. - SAIFI/SAIDI with MED captures past service interruptions for a utility, including tail events. A high number indicates a vulnerable system, as well as longer time to recover the system.
SAIDI ^a	SAIDI is a metric used to measure the service interruption of electric utilities through the EIA. SAIDI is measured by taking the average duration (in minutes) that a customer experiences a power interruption in a one-year period for a given utility.	Utility-to-utility comparison requires pairing with extreme weather event data and number of customers; a simple comparison might be misleading because of, for example, the size of the utility, exposure level, or climate hazard types.
MED declarations ^a	MEDs are defined by IEEE standard 1366 as “a day in which the daily SAIDI [or CAIDI] exceeds a threshold value T_{MED} ” (IEEE, 2022). This threshold value is based on the utility’s past five years of SAIDI or CAIDI, whichever is being calculated.	This metric captures longer-duration outages than common reliability issues and, coupled with disaster data, can provide insight into how well a utility system performed in the past when faced with hazards.
Renewable energy generation portfolio ^a	This indicator represents the percentage of electric power generated through renewable energy sources.	Integrating renewable energy generation energy storage and advanced energy management, such as load shifting, improves resiliency because it aligns demand with supply.
Number of reported gas distribution incidents that have caused breakdown ^b	Natural gas pipeline operators are required to report pipeline incidents or accidents (e.g., man-made accidents, natural hazards, cyberattacks).	Utilities with a high number of distribution incidents indicate, for example, vulnerable infrastructure, lack of coordination with other functions (e.g., construction).
LAUF gas as a percentage of total consumption ^b	LAUF is the difference between the total gas purchased versus the amount delivered to customers. It includes all components of loss, such as leakage, venting, theft, and gas used by the distribution company itself, adjusted by meter errors, billing cycle issues, and other operational factors.	High positive or negative LAUF values indicate lower efficiency of a state’s gas system and provides insight on ineffective management of the state’s respective systems (ICF International, 2014).

Indicator	Description	Contribution to Resilience
Bare steel main miles (by state) ^b Cast iron main miles (by state) ^b	Bare steel and cast-iron pipelines are among the oldest energy pipelines constructed in the United States (U.S. Department of Transportation, 2023), and national efforts to replace those aging and high-risk pipelines have been in place. PHMSA provides an annual inventory of high-risk pipeline infrastructure by state.	• Absent a special regulatory or legislative mandate, replacement and upgrades of the pipelines are challenging because no clear means of cost-recovery exists for utilities (Thanos and Zitelman, 2020) (similar to resilient enhancing investment). • States with higher miles of bare steel and cast-iron pipelines indicate risky and aged infrastructure, as well as having no proactive policy in place (e.g., regulatory or legislative actions) to replace those infrastructure.
Auction clearing prices for CRRs/FTRs ^a	The purposes of the FTRs/CRRs are to offer economic signals for charging (or compensating) transmission usage (or investment) and to facilitate the implementation of an economically efficient transmission congestion management	• The price provides a forward-looking market view of possible transmission constraints across different areas. • A high positive auction clearing price for a path to an installation indicates that the market is expecting a high congestion and is willing to pay risk premium for that path.

^a Metric specific to electric utilities.

^b Metric specific to natural gas utilities.

Utility Management of Climate Change

The management of a utility, which includes such factors as governance, accountability, and leadership, is a considerable aspect that can contribute to effective climate change preparedness and resilience. Governance and accountability practices include the clear definition of roles and responsibilities as they relate to resilience, considering resilience in the utility's overall corporate strategy, and incorporating climate change resilience into decisionmaking (Zamuda et al., 2019). Additionally, effective leadership contributes to engagement with local communities and other stakeholders involved in climate change resilience initiatives, as well as the prioritization of resilience planning. Table D.8 lists the indicators that we included as part of our assessment of the utility management of climate change.

Table D.8. Utility Management of Climate Change Assessment Criteria

Indicator	Description	Contribution to Resilience
Utility climate change governance score	- The utility climate change governance score is based on assessing a utility's 10-K report filed with the U.S. Securities and Exchange Commission or environmental, social, governance (ESG) reports on the following criteria: high: clear and robust description of roles and responsibilities; includes description of processes to identify climate-related issues and reports the frequency of such issues; describes monitoring implementation and performance medium: informative but not tied to climate-related issues or resilience low: includes a few sentences on climate change or sustainability none: does not disclose any information around governance or climate/sustainability N/A: does not report 10-K or ESG.	- Utility's organization governance around climate-related risks and opportunities (Task Force on Climate-Related Financial Disclosures, 2017) - Evaluation of the role of the board and management in overseeing climate-related issues, as well as assessing and managing those issues
Does the utility have a climate change plan or other plans relevant to climate change (e.g., drought plan, energy resilience, vulnerability assessment)?	Some utilities may develop their own climate change plans or other plans that are relevant to climate change, such as a stormwater management plan or drought plan. Climate change plans or other plans typically outline risks from climate change, strategies to mitigate those risks, and progress that the utility has made to achieve those goals.	- This can be a "gold standard" in terms of resilience because exposure to climate hazards vary geographically, and individual utility systems may have unique infrastructure vulnerabilities to climate hazards. - As of now, performing a deep-dive assessment on the vulnerability of a utility's operation and establishing adaptation plans from climate hazards is in an advanced state.
Has the utility or local community completed hazard mitigation projects through FEMA's HMGP?	FEMA's HMGP provides communities (state or local) with financial assistance to rebuild infrastructure to mitigate long-term natural hazard risks to people and property.	A utility or local community that has completed or has ongoing hazard mitigation projects demonstrates an investment in resilient infrastructure.
CDP 2021 Climate Score	CDP is a nonprofit organization that manages a global disclosure system for environmental impact for different	CDP provides sector-specific scoring measures from D to A based on the level of detail and

Indicator	Description	Contribution to Resilience
CDP 2021 Water Security Score	entities, including companies, cities, and states. The CDP 2021 Climate Score assesses an entity's awareness and management toward climate change–related issues. The CDP 2021 Water Security Score assesses an entity's awareness and management toward water issues and water stewardship.	comprehensiveness of the content, as well as the company's awareness of climate change issues, management methods, and progress toward action taken on climate change. • CDP provides sector-specific scoring measures from D to A based on the level of detail and comprehensiveness in a response, as well as the company's awareness of water issues, management methods, and progress toward water stewardship.

The Role of Installation and Community Partnerships in Resilience Measures

Military installation and community partnerships can and have been playing an important role in helping utilities invest in resilience measures that can reduce the impact of extreme weather and climate change on DAF missions. These partnerships can provide both the installation and the utility with resilience benefits. These benefits can look different depending on the type of utility, the geography (including types of hazards being contended with) and architecture of the infrastructure, and the form of the partnership. Some examples of mutual benefits achieved through partnerships include increasing redundancy in supply, developing alternative joint supply sources (e.g., large-scale renewable energy projects and reusing wastewater), ensuring alternative pathways for transmitting and distributing a utility, realizing cost savings, and taking advantage of opportunities to update infrastructure when opportunities arise (e.g., the building of a road necessitating the unearthing of pipelines, which can then be updated in this target of opportunity), enabling both to increase redundancy in water supply.

Partnerships can take on many forms, from the sharing of ideas or plans (e.g., sitting on a board together), to pooling resources to shore up supply or utility logistics on which the community and base are mutually dependent, to a local utility building infrastructure on the installation.

Partnerships can be viewed on a continuum from a loose partnership with less commitment—which is more like a collaboration—to a more in-depth partnership involving a high level of mutual interdependence and more shared resources and risks. Most installation and community partnerships fall somewhere in between these two extremes. A collaboration is mostly based on joint cooperation without as much investment in the relationship: less information-sharing, less commitment to specific tasks, almost no to no sharing of risks, less sharing of resources, and less long-term commitments but some basic agreement on joint goals and on voluntary actions to achieve those goals. A common partnership of this type is partnering to conduct a joint activity or event, such as an installation and community marathon run or a joint Earth Day event (Lachman, Resetar, and Camm, 2016).

More specifically, some of these military installation and community partnerships help directly with overall installation resilience to severe weather events and the impacts of climate, while others help with utility facilities and infrastructure resilience. We elaborate on both types of resilience partnerships. Some partnerships can help improve the overall installation's, community's, and regional's resilience to severe weather and natural hazards events (e.g., wildfires and flooding), which can help off-base and on-base utility resilience. For example, Goodfellow AFB, Texas, has a wildland

fire mitigation partnership with Texas A&M Forest Service for this partner to conduct prescribed burn to help reduce the fuel load and the potential risk and impact of wildfires.

Many REPI partnership projects also can help with overall installation resilience. In fact, an installation having REPI projects can be a good indicator of broader regional collaboration to support installation resilience. Started in 2003, the REPI Program is an OSD program that helps protect installations from different types of encroachment pressures (e.g., urban and suburban development near an installation runway) (for more information on the REPI Program, see REPI, 2022). Originally, REPI supported cost-sharing partnerships authorized by Congress (U.S. Code, Title 10, Section 2684a) between the military services, private conservation groups, and state and local governments to protect military test and training capabilities and conserve land by providing partial funding. Through these partnerships, the installation partners acquire conservation and restrictive easements or other interests in land from willing sellers to preserve compatible land uses and sustain wildlife habitats near installations and ranges at which the military operates, tests, and trains. These partnerships can be very diverse and often involve multiple community partners and can help protect watersheds and water supply, help with ecosystem and wildfire management, and help with erosion and stormwater runoff issues. REPI partnerships include these traditional land-based projects, Sentinel Landscapes Partnerships, and challenge grant projects. In 2013, REPI partnered with the U.S. Department of Agriculture (USDA) and the Department of the Interior to establish the Sentinel Landscapes Partnership, another REPI initiative that helps installations strategically partner with regional stakeholders over a broader landscape-scale to help prevent encroachment on military installation missions and other operations, to help preserve farms and other working lands, and to conserve habitat and natural resources. The Sentinel Landscapes partnerships also focus on addressing climate change issues and long-term installation and community resilience. In fact, the FY 2019 National Defense Authorization Act (Pub. L. 115-232, 2018) expanded the 2684a authority for REPI to include agreements that improve military installation resilience (for more information, see DoD, undated). REPI now focuses more directly on installation resilience issues.

We illustrate how these different types of REPI projects can help with installation resilience related to water conservation and wildfire risk reduction with one installation: Fort Huachuca, Arizona. Through multiple traditional REPI projects and with more than a dozen partners, Fort Huachuca has purchased easements to protect groundwater supplies within the San Pedro Riparian National Conservation Area, helping protect the future of the San Pedro and Babocomari rivers in this drought-prone part of the United States (Sentinel Landscapes Partnership, undated). Fort Huachuca has also partnered with other federal agencies, state agencies, and NGOs in the regional Fort Huachuca Sentinel Landscape. This partnership is helping to protect regional water quantity and quality, long-term agricultural viability, native habitat restoration, and military mission by using conservation easements and other tools to help protect open space, habitat, and agricultural lands and to prevent overuse of the groundwater (Sentinel Landscapes Partnership, undated; USDA, DoD, and U.S. Department of the Interior, 2016). Lastly, through a 2020 REPI Challenge grant, Fort Huachuca funded an interagency agreement with the U.S. Forest Service to support wildfire mitigation strategies to decrease wildfire risk in the nearby Coronado National Forest, where the Army conducts testing activities (REPI, 2021).

Examples of Resilience-Focused Energy and Water Partnerships

Military installation and community partnerships can focus directly on energy and water resilience issues both on and off base. We illustrate with diverse examples related to power generation, water supply, a wastewater treatment facility, and a redundant water supply line. Tinker AFB and Oklahoma Gas and Electric partnered to install on-site power generation at the base to provide the base with energy security and resilience, especially because of concerns regarding tornadoes in the region. This partnership enables Tinker AFB to isolate itself from the power grid during an emergency. Oklahoma Gas and Electric installed an 80-megawatt peaking generating station in 1988, and it owns, operates, and maintains the plant (see Box 3.4 in Lachman, Resetar, and Camm, 2016, p. 31). A water supply partnership example occurs at JB San Antonio; this base partnered with San Antonio Water Systems and other local government entities to provide a reliable, redundant source of water supply to the base (see San Antonio Water System, 2015; Texas Public Radio, 2015). One example of a wastewater infrastructure partnership is Florida's Okaloosa County using 225 acres on Eglin AFB to build and operate a 10-million-gallon-per-day wastewater system that treats both installation and community effluent. Eglin AFB has provided a 30-year lease to Okaloosa County for the property, with payments to the base of \$325,000 per year for the construction of the Arbennie Pritchett Water Reclamation Facility. This facility mostly treats community wastewater (Lachman, Resetar, and Camm, 2016, p. 29; Lachman et al., 2019). Fort Leonard Wood partnered with the City of Saint Robert to install a redundant water supply line that enhances installation and community water security. The state and city helped to fund this project. To ensure ongoing water supply, the installation and the city are installing an emergency connector water line between the two systems. Through this line, the city will be able to supply the 3 million gallons per day that Fort Leonard Wood would need to use in an emergency (for more information on this partnership, see Lachman et al., 2020).

The U.S. Army Garrison (USAG) Hawaii partnership for power generation at Schofield Barracks (U.S. Army), Hawaii, is increasing the resilience of energy power generation for both the community and military. USAG Hawaii partnered with the Hawaiian Electric Company (HECO) to construct a 50-megawatt power plant on Schofield Barracks on central Oahu. The plant runs on a mixture of biofuel and conventional diesel fuel, feeding directly into the electric grid and serving all customers in Oahu (Sheftick, 2018). This partnership provides cost savings and enhanced resilience for the Army, HECO, and the community (such as an estimated net present value savings of \$4.3 million to customers over the 30-year life of the project) (Hawaii Public Utilities Commission, 2015). The Schofield Generating Station has black-start capabilities and is located inland and above the tsunami zone, increasing the overall resilience and reliability of the grid (Hawaiian Electric, 2021; U.S. Army, 2024).

In another example, Moody AFB experiences installation resilience benefits from a water intergovernmental support agreement (IGSA) partnership.³² Moody AFB has an IGSA with Lowndes County, Georgia, for the county to operate and maintain the base's water and wastewater

³² An IGSA is a military installation partnership with a state or local government for the installation to receive, provide, or share an installation-support service when that public partner is already providing the service for itself because of U.S. Code, Title 10, Section 2679.

plants and infrastructure (Beavers, 2021). This arrangement includes a one-time installation of a valved interconnection between the city and base water supply systems to provide redundant service during an emergency (for more information, see Robinson, 2016). The base has enhanced water security by gaining service redundancy to enhance antiterrorism and force protection measures via the interconnect.³³ Lowndes County also experiences multiple benefits from this partnership: The deal provides increased revenue and capacity for the county, and the county saves money by not having to build another treatment plant. The county also has enhanced water security by gaining service redundancy and enhanced antiterrorism and force protection.

Water partnerships can also help with drought and water quality issues. There is a partnership for potable water quality at Altus AFB, Oklahoma, with the city of Altus. Altus AFB is participating on the city's Water Task Force Working Group because of drought and water quality concerns regarding the water provided to the base from the city. Water from the city exceeded the EPA and state limits of 80 parts-per-billion for trihalomethanes. Members of this collaborative water working group include the Altus Chamber of Commerce, the city council, city staff, Altus AFB, and area companies. The group's purpose is to plan, coordinate, and execute a plan to improve water quality and quantity for all residents. Because of this partnership, the city of Altus implemented projects (e.g., it rehabilitated two and drilled two additional groundwater wells and reconfigured the reverse osmosis treatment facility) that added 1 million gallons per day of supply and improved water quality (Davis, 2015).

These installation and community partnerships are with both public and private utilities and can be facilitated or partially funded by state and local governments (e.g., the Fort Leonard Wood redundant water supply line partnership discussed earlier) or by leasing out installation land. For instance, at Nellis AFB in Nevada, the U.S. Air Force has an enhanced-use lease agreement with the city of North Las Vegas, in which the city provided \$25 million to build a base fitness center and \$10.8 million for base-reclaimed water infrastructure in exchange for building a water treatment facility on base land.³⁴ The in-kind consideration of reclaimed water and water supply infrastructure worth an estimated \$10.8 million improved aging infrastructure, irrigation for the golf course using reclaimed water, and the use of reverse osmosis quality water to wash aircraft (City of North Las Vegas, 2008). It also reduced the cost of wastewater treatment for the base.

Such water infrastructure enhances water security and resilience by reducing the risk of aged infrastructure failing and saving scarce potable water resources so that they can be used for installation readiness rather than for irrigating a golf course.³⁵ For the city, this partnership provides access to additional water supply (i.e., reclaimed water).

Similarly, military installation leasing partnerships can play an important role in helping installations to implement adaptation activities that help on and off base utilities with resilience and

³³ The base also saves about \$200,000 per year, a 38-percent savings when compared with previous contracts (Beavers, 2021; Robinson, 2016).

³⁴ An *enhanced-use lease agreement* is a large-scale leasing deal focused on developing excess property on the installation in collaboration with the community. A lease is legally considered a real estate deal, not a partnership. However, a large-scale leasing arrangement often can act like and is called a partnership because of the close-working trusted relationship that often develops between the installation and the partner over the long term and with frequent and ongoing communications, mutual problem-solving, and other factors that characterize a partnership. For more information, see Lachman et al., 2019.

³⁵ For more information on this enhanced-use lease agreement and the lessons learned from it, see Lachman et al., 2019, pp. 97–99.

other energy objectives. For instance, Luke AFB and Arizona Public Service partnered to install a 10-megawatt solar array on the base with a 30-year lease. This partnership helps the Air Force increase the base's energy flexibility and diversity, helps the state of Arizona and Arizona Public Service meet renewable energy goals, and helps reduce greenhouse gas (carbon dioxide) and other emissions (for more information on this partnership, see Lachman et al., 2019).

Energy and water partnerships also help increase a base's resilience by providing funding for base resilience investments, such as an enhanced use lease deal at JB McGuire-Dix-Lakehurst. JB McGuire-Dix-Lakehurst has a multiparty 40-year partnership for a 16.5-megawatt solar array on the base. The Air Force gets \$250,000 per year in revenue for 40 years from leasing the land that it invests in energy resilience (for more information, see Lachman et al., 2019, pp. 95–96).

Installation and utility partnerships have also helped off-base utilities avoid brownouts. For instance, Edwards AFB partnered with Southern California Edison in a demand-response program in which, during high-demand periods at this California desert location, air conditioning was automatically shut off for 15 minutes in certain buildings every one to two hours to help reduce load and avoid potential brownouts. Edwards AFB received some major energy bill cost reductions by participating in this demand response program (Lachman et al., 2011).

These partnerships can also focus on nontraditional alternative water sources, such as a partnership at Fort Bliss for the Kay Bailey Hutchison Desalination Plant, which is located on Fort Bliss but is owned and operated by El Paso Water Utilities (EPWU). The \$91 million plant was funded by different federal sources and EPWU and has a total capacity of 27.5 million gallons per day of potable water. The facility treats brackish groundwater and helps protect water quality in the associated aquifer (an underground, porous rock formation that stores water) and provides additional potable water to EPWU customers. Fort Bliss gains both cost savings and water quality benefits from this partnership. By helping to protect water quality in the aquifer, this facility helps prevent brackish water from contaminating Fort Bliss' potable well sources. EPWU gives Fort Bliss multiple credits on its monthly water bill in exchange for using its land and the easement for the water pipelines and plant on the post.

Sources of Funding

There are also many sources of funding to help fund off-base utility resilience investments that support military installations and to fund broader installation and community resilience efforts (e.g., regional activities to minimize risks of drought and wildfire risk reduction projects) that can benefit off-base utilities. The list of sources includes federal, state, and local governments, as well as some foundations and other nongovernmental sources. OSD provides many grants that help support military installation resilience in collaboration with community organizations that focus on issues in the regions surrounding an installation. As explained previously, these include REPI projects: the more traditional projects, Sentinel Landscapes partnerships, and REPI Challenge projects. In fact, in the past two years, these projects are focusing more on installation resilience issues.

Given the importance of this OSD assistance program for supporting off-base utilities' resilience, we briefly explain the Office of Local Defense Community Cooperation (OLDCC) next. OLDCC (formerly the Office of Economic Adjustment) provides technical and financial assistance to states and

communities to support the readiness and resilience of military installations and defense communities. It has several programs that help with military installation and community partnerships that can help with the resilience of off-base utilities (for more information on OLDCC, see OLDCC, undated-c). OLDCC's Installation Resilience program provides technical and financial assistance to states and local governments to analyze and implement activities to facilitate, protect, and enhance military installation sustainability. The program encompasses the previous Compatible Use/Joint Land Use Study program, as well as the recently authorized installation resilience authority (for more information, see OLDCC, undated-b). A Compatible Use Study is a strategic plan to help ensure that regional civilian growth and development are compatible with installation testing, training, and other operations. It is developed through a collaborative planning partnership between the military installation and its surrounding local governments, with grant funding provided by OLDCC. OLDCC also runs the DCIP program. DCIP provides grants to state and local governments to address deficiencies in community infrastructure that supports military installations to help improve military value, installation resilience, and military family quality of life. For example, in 2021, DCIP awarded a grant for over \$9.8 million to the city of Minot, North Dakota, to help with a regional flood protection project along the Mouse River, with a total cost of over \$23.6 million that benefits the community and Minot Air Force Base, North Dakota. Flooding has been a concern for the base because in 2011, a flood inundated and damaged roadways that Air Force staff use to access the base's missile sites. The project also received \$8.9 million from the state and \$4.8 million from a city sales tax (for more information, see Schramm, 2021; and OLDCC, undated-a).

In the past few years, OLDCC also has funded some MIRR projects. An MIRR project specifically focuses on identifying the risks, hazards, and vulnerabilities of major concern related to the ability of a military installation to perform its missions and that could be mitigated through resilience investments and other solutions in the community. MIRR helps identify community resilience investment projects based on assessing longer-term climate change projections. For example, Northern Virginia has a regional MIRR project (for more information, see Northern Virginia Regional Commission, undated). The military installations involved are Fort Belvoir, JB Myer-Henderson Hall, and Marine Corps Base Quantico. The installations, the counties (e.g., Fairfax and Arlington counties), Virginia Department of Transportation, Northern Virginia Regional Commission, and off-installation utility providers (e.g., Washington Gas, American Water, and Dominion Energy) are collaborating in these processes to identify resilience investments that could be made in the communities based on a vulnerability and risk assessment for each installation using climate change scenario projections. In summary, OSD's OLDCC provides grants to help communities increase resilience in support of military installations, including DCIP, Compatible Use/Joint Land Use Study, and MIRR grants.

FEMA also provides funding to help increase community resilience to natural hazards (e.g., Building Resilient Infrastructure and Communities [BRIC] and hazard mitigation assistance grants) that can potentially help military installations and utilities that support them. The BRIC program provides grant funding to states, local communities, tribes, and territories to undertake hazard mitigation projects, reducing the risks they face from disasters and natural hazards. BRIC requires community partnership funding for projects for which it provides funding. BRIC projects can include projects to build more-resilient utilities (e.g., projects to increase water quality and supply because of

drought, install an electrical powerline hardening to address extreme summer heat, enhance groundwater storage to help with drought management, and build stormwater infrastructure or improve sewer systems because of flooding risks). Total FEMA funding for all BRIC projects for FY 2021 is \$1 billion (for more information, see FEMA, 2023a).

There are also some other federal sources, such as the National Coastal Resilience Fund and the America the Beautiful Challenge. Official state grant programs (e.g., Texas Defense Economic Adjustment Assistance Grant Program [Office of the Texas Governor, undated]) that assist military installations and communities can also be used to assist in resilience infrastructure projects. In some cases, other state and local financial assistance can also be used for some resilience investments (e.g., the Fort Leonard Wood water supply line project discussed earlier).

Details of Potential Indicators of Utility System Resilience Capacity for the Mid-Atlantic Case Study

This appendix contains details for the values of each of the potential indicators of utility system resilience capacity for the mid-Atlantic case study. Table F.1 shows the answers to broader questions of whether there are state and local resilience planning efforts, the existence of regulatory and financial mechanisms, and community partnerships. Table F.2 shows assessed values for the remaining utility-specific indicators for the region.

Table F.1. State and Local Planning, Regulatory and Financial Mechanisms, and Community Partnerships

Indicator Criteria	McGuire	Dover	Andrews	Bolling	Langley
State and local planning resilience efforts					
Is there a state or local hazard mitigation plan?	Yes (county level)	Yes (county level)	Yes (county level)	Yes	Yes (state level)
Is there a state or local energy plan?	Yes	Yes	Yes	Yes	Yes
Is there a state or local water plan?	Yes	No	Yes	No	Yes
Does the base or community Annual Water Quality report mention climate change, resilience, or infrastructure investments?	No	Unknown	Unknown	Unknown	Unknown
Regulatory and financial mechanisms					
Programs to support utility investments in resilience	Yes	Yes	Yes	No	Yes
Statewide renewable portfolio standard	50% by 2030; 100% by 2050	25% by 2026	25% by 2026	100% by 2032	100% by 2045/2050
Energy storage financial incentives	State grant, rebate, or performance- based incentive program	None	None	State tax credit	None
Energy storage targets	2,000 megawatts by 2030	None	None	None	3,100 megawatts by 2035
Energy efficiency standards	Standard	Goal	Goal	Standard	Standard
Net metering	Less than retail rate	At retail rate; credits do not expire	At retail rate; credits do not expire	Less than retail rate	Less than retail rate

Indicator Criteria	McGuire	Dover	Andrews	Bolling	Langley
Community partnerships					
Does the installation have a REPI project or has it been involved with the REPI program?	Yes	No	Yes	No	Yes
Has the installation and community ever conducted a Compatible Use/ Joint Land Use Study?	Yes	No	Yes	No	Yes
Has the installation and community ever received a DCIP, MIRR, or other OSD partnership grant?	No	No	No	No	Yes
Has the installation had an AFCP workshop in the past?	Unclear	Yes	Yes	No	Yes

Table F.2. Utility-Specific Indicators

Indicator Criteria	McGuire	Dover	Andrews	Bolling	Langley
Basic overview of utility					
Number of customers served	1,100,000	25,000	257,000	10,000,000	7,000,000
Size of service territory	3,200 square miles	75 square miles	65,000 square miles	70 square miles	30,000 square miles
Type of utility (e.g., public or private; municipally owned or cooperative)	Investor owned	Municipally owned	Municipally owned	Investor owned	Investor owned
Urban versus rural	Urban	Urban	Urban	Urban	Urban
Infrastructure asset size	• One power plant • 24,000 miles of lines	• One power plant • 15 substations • 45.92 miles of overhead transmission lines • 0.12 miles of underground transmission lines • 132.49 miles of overhead distribution lines • 300.10 miles of underground distribution lines	• 24,000 miles of transmission lines	• One power plant • 22 transmission substations • 39 sub-transmission substations • 116 distribution substations • 14,266 miles of overhead lines • 10,718 miles of underground cable • 2,945 miles of underground conduit	• Seven power plants • 6,700 miles of transmission lines • 58,510 miles of distribution lines

Indicator Criteria	McGuire	Dover	Andrews	Bolling	Langley
Financial strength and investment capability					
Long-term issuer credit rating	• S&P: BBB • Moody's: A3	• S&P: N/A • Moody's: Aa2	• S&P: BBB • Moody's: Baa2	• S&P: A– • Moody's: Baa2	• S&P: BBB+ • Moody's: A2
Short-term issuer credit rating	No rating	No rating	No rating	• S&P: No rating • Moody's: P-2	• S&P: A-2 • Moody's: P-1
Investment capability based on corporate structure	High	High	High	High	High
Utility regulatory compliance					
Does the utility have any civil penalties within the past ten years?	No	Unknown	Unknown	Unknown	Unknown
Does the utility have any violations with federal or state regulators in the past ten years?	No	Unknown	Unknown	Unknown	Unknown
Utility service reliability					
SAIFI	1.99	Unavailable	1.12	0.66	1.53
SAIDI	899.51	Unavailable	214.59	94.32	242.09
Renewable energy generation portfolio	5.4%	Unknown	5.4%	6.5%	5.0%
Utility management of climate change					
Utility climate change governance score	High	N/A	N/A	N/A	N/A
Does the utility have a climate change plan or other plans relevant to climate change (e.g., drought plan, energy resilience)?	Yes	No	Yes	Yes	Yes

Indicator Criteria	McGuire	Dover	Andrews	Bolling	Langley
Has the utility or local community completed hazard mitigation projects through the FEMA's HMGP?	Yes (county)	No	No	No	No
CDP 2021 Climate Score	B-	N/A	B-	A-	A-
CDP 2021 Water Security Score	B-	N/A	B-	B	A-

Abbreviations

AFB	Air Force base
AFCEC	Air Force Civil Engineering Center
AFCP	Air Force Community Partnership
ASCE	American Society of Civil Engineers
CAIDI	Customer Average Interruption Duration Index
CONUS	continental United States
CRR	congestion revenue right
DAF	Department of the Air Force
DCAT	Defense Climate Assessment Tool
DCIP	Defense Community Infrastructure Pilot
DoD	U.S. Department of Defense
DOE	Department of Energy
EIA	U.S. Energy Information Administration
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FTR	financial transmission right
FY	fiscal year
HIFLD	Homeland Infrastructure Foundational-Level Data
HMGP	Hazard Mitigation Grant Program
ICRP	installation climate resilience plan
IDP	installation development plan
IEEE	Institute of Electrical and Electronics Engineers
IEP	installation energy plan
IGSA	intergovernmental support agreement

IPCC	Intergovernmental Panel on Climate Change
ISR	intelligence, surveillance, and reconnaissance
JB	Joint Base
LAUF	lost and unaccounted for
MED	major event day
MIRR	Military Installation Resilience Review
NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NERC	North American Electric Reliability Corporation
NESC	National Electric Safety Code
NGO	nongovernmental organization
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NRI	National Risk Index
NWS	National Weather Service
OLDCC	Office of Local Defense Community Cooperation
OSD	Office of the Secretary of Defense
PAF	Project AIR FORCE
PHMSA	Pipeline and Hazardous Safety Administration
REPI	Readiness and Environmental Protection Integration
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SFB	Space Force base
SPC	Storm Prediction Center
USDA	U.S. Department of Agriculture
WS	Weather Squadron

References

- 14th Weather Squadron, “Mission Brief,” briefing slides provided to the authors, June 2022.
- AFCEC—*See* Air Force Civil Engineer Center.
- AFCP—*See* Air Force Community Partnership.
- Air Force Civil Engineer Center, *Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook*, April 24, 2020.
- Air Force Instruction 32-1015, *Integrated Installation Planning*, Department of the Air Force, incorporating change 1, corrective action, January 4, 2021.
- Air Force Instruction 90-2001, *Mission Sustainment*, Department of the Air Force, July 31, 2019.
- Air Force Mortuary Affairs Operations, “Families of the Fallen,” webpage, undated. As of December 7, 2024: <https://www.mortuary.af.mil/About-Us/Families-of-the-Fallen>
- Alaska Climate Research Center, “Climate Change in Alaska,” webpage, undated. As of July 22, 2022: <https://akclimate.org/climate-change-in-alaska>
- Alaska Plumbing Code 2018, Chapter 12, Fuel Gas Piping; Section 12.08.8.4, Venting of Line Pressure Regulators.
- Allen-Dumas, Melissa R., Binita KC, and Colin I. Cunliff, *Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods*, Oak Ridge National Laboratory, August 16, 2019.
- American Gas Association, *Natural Gas Resiliency*, April 29, 2014.
- American Gas Foundation, *Building a Resilient Energy Future: How the Gas System Contributes to US Energy System Resilience*, January 2021.
- American Society of Civil Engineers, *2021 Infrastructure Report Card: Drinking Water*, 2021.
- American Water, Vandenberg Space Force Base, *2022 Annual Water Quality Report*, 2022.
- American Water Works Association, *Climate Action Plans—Adaptive Management Strategies for Utilities*, Manual of Water Supply Practices, M71, 2021.
- ASCE—*See* American Society of Civil Engineers.
- Beavers, Briana, “Moody AFB First to Renew 10-Year IGSA,” Moody Air Force Base, July 12, 2021.
- Bewley, Jennifer L., Jacob B. Bartel, Shelley M. Cazares, and Sara C. Runkel, *Final Assessment of the Extreme Weather and Climate Change Vulnerability and Risk Assessment Tool*, Institute for Defense Analyses, D-21598, March 2021.
- Brown, M. Tyson, “Electricity in the Mid-Atlantic Region Is Predominantly Fueled by Coal and Nuclear Sources,” webpage, U.S. Energy Information Administration, November 18, 2013. As of July 15, 2022: <https://www.eia.gov/todayinenergy/detail.php?id=13831>

- Brubaker, Michael, Prithviraj Chavan, James Berner, Mike Black, and John Warren, *Climate Change in Selawik, Alaska: Strategies for Community Health*, Alaska Native Tribal Health Consortium, May 2012.
- Bureau of Reclamation, *SECURE Water Act Section 9503(c)—Reclamation Climate Change and Water 2016*, U.S. Department of the Interior, March 2016.
- Burillo, Daniel, “Effects of Climate Change in Electric Power Infrastructures,” in Kenneth Eloghene Okedu, ed., *Power System Stability*, IntechOpen, 2019.
- California Department of Water Resources, “Wildfire and Impacts to Water,” November 1, 2021.
- California Public Utilities Commission, *Attachment 1A: Effect of Wildfires on Transmission Line Reliability*, January 2008.
- California Public Utilities Commission, “Order Instituting Rulemaking to Consider Strategies and Guidance for Climate Change Adaptation,” R.18-04-019, May 7, 2018.
- Central Arizona Project, “Lake Pleasant,” webpage, updated February 2022. As of July 21, 2022: <https://www.cap-az.com/water/cap-system/water-operations/lake-pleasant>
- Chen, Yaping, Mark J. Lara, Benjamin M. Jones, Gerald V. Frost, and Feng Sheng Hu, “Thermokarst Acceleration in Arctic Tundra Driven by Climate Change and Fire Disturbance,” *One Earth*, Vol. 4, No. 12, December 17, 2021.
- Chow, A. T. S., T. Karanfil, and R. A. Dahlgren, “Wildfires Are Threatening Municipal Water Supplies,” *Eos*, August 12, 2021.
- City of North Las Vegas, *Final Environmental Assessment for Enhanced Use Lease of U.S. Air Force Lands to the City of North Las Vegas for Construction and Operation of a Water Reclamation Facility, Nellis Air Force Base, Nevada*, 2008.
- Climate Program Office, “Climate Adaptation Partnerships Program,” webpage, National Oceanic and Atmospheric Administration, undated. As of December 3, 2023: <https://cpo.noaa.gov/divisions-programs/climate-and-societal-interactions/cap-risa>
- Climate.gov, “Billion-Dollar Weather and Climate Disasters Frequency Mapping: 1980–2018,” webpage, February 5, 2019. As of August 16, 2022: <https://www.climate.gov/media/10191>
- Coe, Jeffrey A., “Landslide Hazards and Climate Change: A Perspective from the United States,” in Ken Ho, Suzanne Lacasse, and Luciano Picarelli, eds., *Slope Safety Preparedness for Impact of Climate Change*, CRC Press, 2017.
- Cohen, Judah, Laurie Agel, Mathew Barlow, Chaim I. Garfinkel, and Ian White, “Linking Arctic Variability and Change with Extreme Winter Weather in the United States,” *Science*, Vol. 373, No. 6559, September 1, 2021.
- Colorado Springs Utilities, *2022 Drinking Water Quality Report*, 2022.
- Connecticut Department of Energy and Environmental Protection, “Microgrid Grant and Loan Program,” webpage, updated January 2020. As of July 27, 2022: <https://portal.ct.gov/DEEP/Energy/Microgrid-Grant-and-Loan/Microgrid-Grant-and-Loan-Program>

Cramer, Sam, Campbell Delahoyde, Kelsey Jones, Kristen Verclas, Dan Lauf, and Matt Rogotzke, *State Governance, Planning, and Financing to Enhance Energy Resilience*, National Association of State Energy Officials and National Governors Association, December 2021.

Cruz, Ana Maria, and Elisabeth Krausmann, “Vulnerability of the Oil and Gas Sector to Climate Change and Extreme Weather Events,” *Climatic Change*, Vol. 121, No. 1, November 2013.

DAF—*See* Department of the Air Force.

Davis, Dillon, “City of Altus Plans for Water Quality Improvements,” Altus Air Force Base, February 11, 2015.

Dectero, Tonya, and Julie Holmquist, “Overcoming Winter Wastewater Challenges via Bioaugmentation,” *Treatment Plant Operator*, February 12, 2018.

Department of Defense Directive 4715.21, *Climate Change Adaptation and Resilience*, U.S. Department of Defense, January 14, 2016.

Dillon, Greg, “Wildfire Hazard Potential,” webpage, Missoula Fire Sciences Laboratory, undated. As of August 16, 2022:
<https://www.firelab.org/project/wildfire-hazard-potential>

Dillon, Greg, James Menakis, and Frank Fay, “Wildland Fire Potential: A Tool for Assessing Wildfire Risk and Fuels Management Needs,” in Robert E., Keane, Matt Jolly, Russell Parsons, and Karin Riley, eds., *Proceedings of the Large Wildland Fires Conference: May 19–23, 2014*, 2015.

DoD—*See* U.S. Department of Defense. DOE—
See U.S. Department of Energy.

Duniway, Michael C., Alix A. Pfennigwerth, Stephen E. Fick, Travis W. Nauman, Jayne Belnap, and Nichole N. Barger, “Wind Erosion and Dust from US Drylands: A Review of Causes, Consequences, and Solutions in a Changing World,” *Ecosphere*, Vol. 10, No. 3, March 2019.

EIA—*See* U.S. Energy Information Administration.

Ellis, Tim, “Eielson Air Force Base May Have a Small Nuclear Power Plant by 2027,” KTOO, November 5, 2021.

EPA—*See* U.S. Environmental Protection Agency.

Federal Emergency Management Agency, “The National Risk Index,” webpage, undated. As of August 16, 2022:
<https://hazards.fema.gov/nri>

Federal Emergency Management Agency, *Local Mitigation Planning Handbook*, March 2013.

Federal Emergency Management Agency, “Building Community Resilience with Nature-Based Solutions: A Guide for Local Communities,” June 2021a.

Federal Emergency Management Agency, *National Risk Index: Technical Documentation*, November 2021b.

Federal Emergency Management Agency, “Building Resilient Infrastructure and Communities FY 2021 Subapplication and Selection Status,” webpage, updated May 19, 2023a. As of December 14, 2023:
<https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities/after-apply/fy-2021-subapplication-status>

- Federal Emergency Management Agency, “Hazard Mitigation Plan Status,” webpage, updated November 21, 2023b. As of December 14, 2023:
<https://www.fema.gov/emergency-managers/risk-management/hazard-mitigation-planning/status>
- Federal Energy Regulatory Commission and North American Electric Reliability Corporation, *Report on Outages and Curtailments During the Southwest Cold Weather Event on February 1–5, 2011: Causes and Recommendations*, August 2011.
- Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities, *The February 2021 Cold Weather Outages in Texas and the South Central United States*, November 2021.
- FEMA—*See* Federal Emergency Management Agency. FERC—*See* Federal Energy Regulatory Commission.
- Florida Administrative Code, Division 25, Public Service Commission; Chapter 25-6, Electric Service by Electric Public Utilities; Rule 25-6.0345, Safety Standards for Construction of New Transmission and Distribution Facilities.
- Fountain, Henry, “Wildfires Threaten Urban Water Supplies, Long After the Flames Are Out,” *New York Times*, August 6, 2021.
- Georgakakos, Aris, Paul Fleming, Michael Dettinger, Christa Peters-Lidard, Terese Richmond, Ken Reckhow, Kathleen White, and David Yates, “Water Resources,” in Jerry M. Melillo, Terese (T. C.) Richmond, and Gary W. Yohe, eds., *Climate Change Impact in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program, 2014.
- Girgin, Serkan, and Elisabeth Krausmann, *Analysis of Pipeline Accidents Induced by Natural Hazards: Final Report*, European Commission, Joint Research Centre, JRC 88410, 2014.
- Gonzalez, Patrick, Greg M. Garfin, David D. Breshears, Keely M. Brooks, Heidi E. Brown, Emile H. Elias, Amrith Gunasekara, Nancy Huntly, Julie K. Maldonado, Nathan J. Mantua, Helene G. Margolis, Skyli McAfee, Beth Rose Middleton, and Bradley H. Udall, “Southwest,” in D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, eds., *Fourth National Climate Assessment*, Vol. II: *Impacts, Risks, and Adaptation in the United States*, U.S. Global Change Research Program, 2018.
- Habeeb, Dana, Jason Vargo, and Brian Stone, Jr., “Rising Heat Wave Trends in Large US Cities,” *Natural Hazards*, Vol. 76, No. 3, April 2015.
- Hahn, Michah, Shaina Kilcoyne, Catherine Kemp, Chelsea Ward-Waller, Alexandra Long, Shannon Donovan, Brian Bettschneider, and Libby Roderick, *Anchorage Climate Action Plan*, 2019.
- Hawaiian Electric, “Hawaiian Electric Microgrid Powers Three Central O‘ahu Army Installations During Test of Energy Resilience,” press release, June 7, 2021.
- Hawaii Public Utilities Commission, “Before the Public Utilities Commission of the State of Hawaii, Docket Number 2014-0113,” September 29, 2015.
- Hedgpeth, Dana, “More Water Main Breaks Likely in D.C. Region as Temperatures Remain Low,” *Washington Post*, February 1, 2022.
- HIFLD—*See* Homeland Infrastructure Foundational-Level Data.

- Hjort, Jan, Olli Karjalainen, Juha Aalto, Sebastian Westermann, Vladimir E. Romanovsky, Frederick E. Nelson, Bernd Etzelmüller, and Miska Luoto, “Degrading Permafrost Puts Arctic Infrastructure at Risk by Mid-Century,” *Nature Communications*, Vol. 9, December 11, 2018.
- Homeland Infrastructure Foundational-Level Data, “HIFLD Open Data,” webpage, undated. As of January 17, 2024:
<https://hifld-geoplatform.opendata.arcgis.com>
- Hovey, Davis, “Unalakleet Endures Water Shortage After Nasty Freeze-Up,” Alaska Public Media, January 10, 2022.
- Hukka, Jarmo J., and Tapio S. Katko, “Resilient Asset Management and Governance for Deteriorating Water Services Infrastructure,” *Procedia Economics and Finance*, Vol. 21, 2015.
- Hummel, Michelle A., Matthew S. Berry, and Mark T. Stacey, “Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts,” *Earth's Future*, Vol. 6, No. 4, April 2018.
- ICF International, *Lost and Unaccounted for Gas*, December 23, 2014.
- IEEE—See Institute of Electrical and Electronics Engineers.
- Institute of Electrical and Electronics Engineers Standards Association, *IEEE Guide for Electric Power Distribution Reliability Indices*, IEEE 1366-2022, November 22, 2022.
- Intergovernmental Panel on Climate Change, “Summary for Policymakers,” in Thomas. F. Stocker, Dahe Qin, Gian-Kasper Plattner, Melinda M. B. Tignor, Simon K. Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M. Midgley, eds., *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2013.
- Intergovernmental Panel on Climate Change, *AR5 Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, 2014.
- International Code Council, *Delivering Climate Responsive Resilient Building Codes and Standards: Findings from the Global Resiliency Dialogue Survey of Building Code Stakeholders in Canada, Australia, New Zealand, and the United States*, Global Resiliency Dialogue, November 2021.
- IPCC—See Intergovernmental Panel on Climate Change. JB—
 See Joint Base.
- Jiang, Miao, Jingrun Guo, Yunpeng Jiang, Lee Li, and Ming Lu, “Dust Contamination on Surface of Transmission Line Insulators in Air-Polluted Regions in China: Statistical Characteristics, Adhesion Mechanism, and Environmental Impact Factors,” *Environmental Science and Pollution Research*, Vol. 27, No. 19, July 2020.
- Joint Base Anacostia-Bolling, “About JBAB,” webpage, undated. As of January 17, 2024:
<https://www.jbab.jb.mil/About-JBAB>
- Joint Base Elmendorf-Richardson, “Air Force Units,” webpage, undated. As of December 4, 2023:
<https://www.jber.jb.mil/Info/Air-Force-Units>
- Joint Base McGuire-Dix-Lakehurst, “305th Operations Group,” fact sheet, November 15, 2021.

- Jorgenson, M. Torre, Vladimir Romanovsky, Jennifer Harden, Yuri Shur, Jonathan O'Donnell, Edward A. G. Schuur, Mikhail Kanevskiy, and Sergei Marchenko, "Resilience and Vulnerability of Permafrost to Climate Change," *Canadian Journal of Forest Research*, Vol. 40, No. 7, July 2010.
- Juaidi, Adel, Hatem Haj Muhammad, Ramez Abdallah, Rula Abdalhaq, Aiman Albatayneh, and Faris Kawa, "Experimental Validation of Dust Impact On-Grid Connected PV System Performance in Palestine: An Energy Nexus Perspective," *Energy Nexus*, Vol. 6, June 16, 2022.
- Kallay, Jennifer, Alice Napoleon, Jamie Hall, Ben Havumaki, Asa Hopkins, Melissa Whited, Tim Woolf, Jen Stevenson, Robert Broderick, Robert Jeffers, and Brooke Marshall Garcia, *Regulatory Mechanisms to Enable Investments in Electric Utility Resilience, Designing Resilient Communities: A Consequence-Based Approach for Grid Investment Report Series*, Sandia National Laboratories, SAND2021-6781, June 2021.
- Kallay, Jennifer, Alice Napoleon, Ben Havumaki, Jamie Hall, Caitlin Odom, Asa Hopkins, Melissa Whited, Tim Woolf, Max Chang, Robert Broderick, Robert Jeffers, and Brooke Marshall Garcia, *Performance Metrics to Evaluate Utility Resilience Investments—Designing Resilient Communities: A Consequence-Based Approach for Grid Investment Report Series*, Sandia National Laboratories, SAND2021-5919, May 2021.
- Kansas Administrative Code, Agency 82, Kansas Corporation Commission; Article 12, Wire-Stringing Rules; Section 82-12-2, Adoption by Reference of the National Electrical Safety Code, or NESC, 1997 Edition.
- Kim, Gina, and Willis Jacobson, "Canyon Fire Scorches over 12,000 Acres, 45-Percent Contained," *Lompoc Record*, September 22, 2016.
- Knös, Daniel, Konstantinos Karagiorgos, Jan Haas, Barbara Blumenthal, Lars Nyberg, and Sven Halldin, "Cloudburst-Disaster Modelling: A New Open-Source Catastrophe Model," *International Journal of Disaster Risk Reduction*, Vol. 67, January 2022.
- Lachman, Beth E., Kimberly Curry Hall, Aimee E. Curtright, and Kimberly Colloton, *Making the Connection: Beneficial Collaboration Between Army Installations and Energy Utility Companies*, RAND Corporation, MG-1126-A, 2011. As of July 23, 2022:
<https://www.rand.org/pubs/monographs/MG1126.html>
- Lachman, Beth E., Jaime L. Hastings, Mary Kate Adgie, Bradley M. Knopp, and Steven Deane-Shinbrot, *Improving Army Installation Facility and Land Use Deals and Partnerships*, RAND Corporation, RR-2696-A, 2019. As of December 7, 2023:
https://www.rand.org/pubs/research_reports/RR2696.html
- Lachman, Beth E., Ellen M. Pint, Aimee E. Curtright, and Cole Sutura, *Alternatives for Reducing Army Installation Utility Bills While Enhancing Installation Readiness*, RAND Corporation, RR-2773-1-A, 2020. As of December 7, 2023:
https://www.rand.org/pubs/research_reports/RR2773-1.html
- Lachman, Beth E., Susan A. Resetar, and Frank Camm, *Military Installation Public-to-Public Partnerships: Lessons from Past and Current Experiences*, RAND Corporation, RR-1419-A/AF/NAVY/OSD, 2016. As of July 13, 2022:
https://www.rand.org/pubs/research_reports/RR1419.html
- Letson, Frederick, Thomas J. Shepherd, Rebecca J. Barthelmie, and Sara C. Pryor, "WRF Modeling of Deep Convection and Hail for Wind Power Applications," *Journal of Applied Meteorology and Climatology*, Vol. 59, No. 10, October 2020.
- Levite, Brian, "The Moving Targets of Reliability and Resilience," *EE Online*, Vol. 23, No. 4, January 2021.

- Liggins, Greg, “PG&E Blames Dust and Rain Combo for Power Outage,” KTVU FOX 2, September 24, 2021.
- Lindsey, Rebecca, “Understanding the Arctic Polar Vortex,” National Oceanic and Atmospheric Administration, March 5, 2021.
- Loder, Stephanie, “Groups Counter NJ ‘Emergency’ Flood Construction Rules,” *Engineering News-Record*, June 8, 2022.
- Lopez-Cantu, Tania, and Constantine Samaras, “Temporal and Spatial Evaluation of Stormwater Engineering Standards Reveals Risks and Priorities Across the United States,” *Environmental Research Letters*, Vol. 13, No. 7, July 2018.
- Losey, Stephen, “After Massive Flood, Offutt Looks to Build a Better Base,” *Air Force Times*, August 7, 2020.
- Luke AFB—See Luke Air Force Base.
- Luke Air Force Base, *2020 Annual Water Quality Report (Consumer Confidence Report)*, 2021.
- Maddocks, *The Role of Regulation in Facilitating or Constraining Adaptation to Climate Change for Australian Infrastructure: Report for the Department of Climate Change and Energy Efficiency*, Department of Climate Change and Energy Efficiency, Australian Government, 2011.
- Mahmoodzadeh, Davood, and Mohammad Karamouz, “Influence of Coastal Flooding on Seawater Intrusion in Coastal Aquifers,” *World Environmental and Water Resources Congress 2017*, American Society of Civil Engineers, May 18, 2017.
- Malik, N. H., A. A. Al-Arainy, and M. L. Qureshi, “Impact of Sand/Dust Pollution on the Engineering Design Criteria of High Voltage Air Insulated Networks,” *Journal of King Saud University—Engineering Sciences*, Vol. 9, No. 1, 1997.
- Marsooli, Reza, Ning Lin, Kerry Emanuel, and Kairui Feng, “Climate Change Exacerbates Hurricane Flood Hazards Along US Atlantic and Gulf Coasts in Spatially Varying Patterns,” *Nature Communications*, Vol. 10, August 22, 2019.
- Maryland Code of Regulations, Title 20, Public Service Commission; Subtitle 50, Service Supplied by Electric Companies; Chapter 20.50.12, Service Quality and Reliability Standards, Section 20.50.12.02, System-Wide Reliability Standards.
- Maryland General Assembly, Utility Regulation—Consideration of Climate and Labor, House Bill 298, May 30, 2021.
- McKenzie, Tristan, Shellie Habel, and Henrietta Dulai, “Sea-Level Rise Drives Wastewater Leakage to Coastal Waters and Storm Drains,” *Limnology and Oceanography Letters*, Vol. 6, No. 3, June 2021.
- McLaughlin, Aislinn, Caroline Schwab, and Katherine Tucker, *State Water Plan Review*, Interstate Council on Water Policy, May 2021.
- Melillo, Jerry M., Terese (T. C.) Richmond, and Gary W. Yohe, eds., *Climate Change Impacts in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program, 2014.

- Miro, Michelle E., Arthur T. DeGaetano, Tania López-Cantú, Constantine Samaras, Marissa Webber, and Krista Romita Grocholski, *Developing Future Projected Intensity-Duration-Frequency (IDF) Curves: A Technical Report on Data, Methods, and IDF Curves for the Chesapeake Bay Watershed and Virginia*, RAND Corporation, TL-A1365-1, 2021. As of November 28, 2023:
<https://www.rand.org/pubs/tools/TLA1365-1.html>
- Mitchell-Wallace, Kirsten, Matthew Jones, John Hillier, and Matthew Foote, *Natural Catastrophe Risk Management and Modelling: A Practitioner's Guide*, Wiley Blackwell, 2017.
- Moftakhari, Hamed, and Amir AghaKouchak, “Increasing Exposure of Energy Infrastructure to Compound Hazards: Cascading Wildfires and Extreme Rainfall,” *Environmental Research Letters*, Vol. 14, No. 10, October 2019.
- Monks, Ellory, and Shalini Vajjhala, “Transformative Infrastructure Funding Is Here. The Application Process for Getting It Still Needs Work,” Brookings Institution, July 18, 2022.
- Muehleisen, Wolfgang, Gabriele C. Eder, Yuliya Voronko, Markus Spielberger, Horst Sonnleitner, Karl Knoebl, Rita Ebner, Gusztav Ujvari, and Christina Hirschl, “Outdoor Detection and Visualization of Hailstorm Damages of Photovoltaic Plants,” *Renewable Energy*, Vol. 118, April 2018.
- Narayanan, Anu, Debra Knopman, Kristin Van Abel, Benjamin M. Miller, Nicholas Burger, Martha V. Merrill, Alexander D. Rothenberg, Luke Muggy, and Patrick Mills, *Valuing Air Force Electric Power Resilience: A Framework for Mission-Level Investment Prioritization*, RAND Corporation, RR-2771-AF, 2019. As of July 13, 2022:
https://www.rand.org/pubs/research_reports/RR2771.html
- Narayanan, Anu, Debra Knopman, James D. Powers, Bryan Boling, Benjamin M. Miller, Patrick Mills, Kristin Van Abel, Katherine Anania, Blake Cignarella, and Connor P. Jackson, *Air Force Installation Energy Assurance: An Assessment Framework*, RAND Corporation, RR-2066-AF, 2017. As of July 13, 2022:
https://www.rand.org/pubs/research_reports/RR2066.html
- Narayanan, Anu, Kristin Van Abel, Debra Knopman, Drake Warren, and Michael T. Wilson, *Setting Priorities for Electric Power Resilience Assessments to Support Cross-Mission Investment Decisionmaking*, RAND Corporation, 2021, Not available to the general public.
- Narayanan, Anu, Michael J. Lostumbo, Kristin Van Abel, Michael T. Wilson, Anna Jean Wirth, and Rahim Ali, *Grounded: An Enterprise-Wide Look at Department of the Air Force Installation Exposure to Natural Hazards: Implications for Infrastructure Investment Decisionmaking and Continuity of Operations Planning*, RAND Corporation, RR-A523-1, 2021. As of July 23, 2022:
https://www.rand.org/pubs/research_reports/RR-A523-1.html
- NASA—See National Aeronautics and Space Administration.
- National Aeronautics and Space Administration, “Find Data,” webpage, undated. As of August 18, 2022:
<https://www.earthdata.nasa.gov/learn/find-data>
- National Centers for Environmental Information, “Billion-Dollar Weather and Climate Disasters,” webpage, National Oceanic and Atmospheric Administration, undated-a. As of December 7, 2023:
<https://www.ncei.noaa.gov/access/billions>
- National Centers for Environmental Information, “Disaster Cost and Frequency,” webpage, National Oceanic and Atmospheric Administration, undated-b. As of December 7, 2023:
<https://www.ncei.noaa.gov/access/billions/mapping>

National Centers for Environmental Information, “Global Surface Temperature Anomalies: Background Information—FAQ,” webpage, National Oceanic and Atmospheric Administration, undated-c. As of July 15, 2022:
<https://www.ncei.noaa.gov/access/monitoring/global-temperature-anomalies>

National Centers for Environmental Information, “Tornado Count,” webpage, National Oceanic and Atmospheric Administration, undated-d. As of January 18, 2024:
<https://www.ncei.noaa.gov/access/monitoring/dyk/tornadocount>

National Centers for Environmental Information, “U.S. Climate Regions,” webpage, National Oceanic and Atmospheric Administration, undated-e. As of August 16, 2022:
<https://www.ncei.noaa.gov/access/monitoring/reference-maps/us-climate-regions>

National Hurricane Center and Central Pacific Hurricane Center, “Tropical Cyclone Climatology,” webpage, undated. As of July 25, 2022:
<https://www.nhc.noaa.gov/climo>

National Institute of Standards and Technology, *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, Vol. II, NIST Special Publication 1190, May 2016.

National Integrated Drought Information System, “Historical Data and Conditions,” webpage, undated. As of August 17, 2022:
<https://www.drought.gov/historical-information>

National Oceanic and Atmospheric Administration, “NOAA/NCEI U.S. Climate Division Data: Plotting and Analysis,” webpage, undated. As of August 18, 2022:
<https://psl.noaa.gov/data/usclimdivs>

National Oceanic and Atmospheric Administration, “Thunderstorm Hazards—Tornadoes,” webpage, updated June 22, 2023. As of December 8, 2023:
<https://www.noaa.gov/jetstream/thunderstorms/thunderstorm-hazards-tornadoes>

National Park Service, “Climate Change in the Southwest—Introduction and Current Climate,” webpage, updated August 14, 2017. As of July 20, 2022:
<https://www.nps.gov/articles/climate-change-in-the-southwest-introduction.htm>

National Weather Service, “Severe Weather Awareness—Tornado Classification and Safety,” National Oceanic and Atmospheric Administration, webpage, undated. As of January 18, 2024:
https://www.weather.gov/mkx/taw-tornado_classification_safety

Natural Gas Council, *Natural Gas Systems: Reliable & Resilient*, July 2017.

NCEI—*See* National Centers for Environmental Information.

Nelson, Frederick E., Lawson W. Brigham, Kenneth M. Hinkel, Walter Parker, Vladimir E. Romanovsky, Nikolay I. Shiklomanov, Orson Smith, Walter Tucker, and Ted Vinson, *Climate Change, Permafrost, and Impacts on Civil Infrastructure*, U.S. Arctic Research Commission, December 2003.

NERC—*See* North American Electric Reliability Corporation.

New Jersey Administrative Code, Title 7, Environmental Protection; Chapter 19, Water Supply Allocation Permits; Subchapter 11, General Powers of the Department; Section 7:19-11.2, Water Purveyor Emergency Response Plans and Teams.

New Jersey Administrative Code, Title 14, Public Utilities; Chapter 5, Electric Service; Subchapter 8, Electric Distribution Service Reliability and Quality Standards; Section 14:5-8.2, Reliability Performance Levels.

NIST—*See* National Institute of Standards and Technology. NOAA—

See National Oceanic and Atmospheric Administration.

Norén, Laura, “Water Infrastructure Delivery Diagram,” *Graphic Sociology* blog, February 22, 2011. As of December 6, 2023:

<https://thesocietypages.org/graphicsociology/2011/02/22/water-infrastructure-delivery-diagram>

North American Electric Reliability Corporation, *2022 Summer Reliability Assessment*, May 2022.

North American Electric Reliability Corporation, *Special Reliability Assessment: Potential Bulk Power System Impacts Due to Severe Disruptions on the Natural Gas System*, November 2017.

Northern Virginia Regional Commission, “Military Installation Resilience Review,” webpage, undated. As of August 17, 2022:

<https://www.novaregion.org/1571/Military-Installation-Resilience-Review>

Norton, Kara, “Why Texas Was Not Prepared for Winter Storm Uri,” PBS, March 25, 2021.

NWS—*See* National Weather Service.

O’Driscoll, Mary, “FERC, NERC Staff Review 2021 Winter Freeze, Recommend Standards Improvements,” press release, September 23, 2021.

Office of Electricity, “Archived State and Regional Risk Profiles,” U.S. Department of Energy, webpage, undated. As of August 18, 2022:

<https://www.energy.gov/oe/archived-state-and-regional-risk-profiles>

Office of Electricity, *DOE-417: Electric Emergency Incident and Disturbance Report*, form instructions, U.S. Department of Energy, May 31, 2021.

Office of Local Defense Community Cooperation, “Defense Community Infrastructure Program,” webpage, U.S. Department of Defense, undated-a. As of May 20, 2021:

<https://oldcc.gov/defense-community-infrastructure-program-dcip>

Office of Local Defense Community Cooperation, “Installation Resilience,” webpage, U.S. Department of Defense, undated-b. As of December 20, 2023:

<https://oldcc.gov/our-programs/installation-resilience>

Office of Local Defense Community Cooperation, “Our Mission and History,” webpage, U.S. Department of Defense, undated-c. As of May 20, 2021:

<https://oldcc.gov/mission-and-history>

Office of the Texas Governor, “Grant Program—Defense Economic Adjustment Assistance Grant (DEAAG),” webpage, undated. As of July 27, 2022:

<https://gov.texas.gov/organization/military/grants>

Office for Coastal Management, “Historical Hurricane Tracks,” webpage, National Oceanic and Atmospheric Administration, updated October 31, 2023a. As of December 5, 2023:

<https://coast.noaa.gov/hurricanes>

Office for Coastal Management, “Sea Level Rise Viewer,” webpage, National Oceanic and Atmospheric Administration, updated December 5, 2023b. As of December 14, 2023:
<https://coast.noaa.gov/digitalcoast/tools/slr.html>

OLDCC—*See* Office of Local Defense Community Cooperation.

Oregon Administrative Rules, Chapter 860, Public Utility Commission; Division 24, Safety Standards; Rule 860-024-0010, Construction, Operation, and Maintenance of Electrical Supply and Communication Lines.

Pamidimukkala, Apurva, Sharareh Kermanshachi, Nikhitha Adepu, and Elnaz Safapour, “Resilience in Water Infrastructures: A Review of Challenges and Adoption Strategies,” *Sustainability*, Vol. 13, No. 23, December 2021.

Pastick, Neal J., M. Torre Jorgenson, Bruce K. Wylie, Shawn J. Nield, Kristofer D. Johnson, and Andrew O. Finley, “Distribution of Near-Surface Permafrost in Alaska: Estimates of Present and Future Conditions,” *Remote Sensing of Environment*, Vol. 168, October 2015.

Pikes Peak Regional Office of Emergency Management, *Multi-Hazard Mitigation Plan Update 2020*, January 5, 2021.

Polsky, Colin, Jason Allard, Nate Currit, Robert Crane, and Brent Yarnal, “The Mid-Atlantic Region and Its Climate: Past, Present, and Future,” *Climate Research*, Vol. 14, No. 3, May 2000.

Porter, Keith, Charles Scawthorn, Charles Huyck, Nicole Dash, Joost Santos, Kevin Mickey, Tarek Rashed, Adam Reeder, Michael Eguchi, Ron Eguchi, Sannidhye Ghosh, Zhenghui Hu, Moad Isteita, and Althea Cohen-Porter, *Natural Hazard Mitigation Saves: 2019 Report*, Multihazard Mitigation Council, National Institute of Building Sciences, December 2019.

Public Law 109-58, Energy Policy Act of 2005, August 8, 2005.

Public Law 115-232, John S. McCain National Defense Authorization Act for Fiscal Year 2019, August 13, 2018.

Readiness and Environmental Protection Integration Program, *Building Resilience to Climate Change Through Off-Base Natural Infrastructure Solutions*, U.S. Department of Defense, September 2021.

Readiness and Environmental Protection Integration Program, *The Department of Defense’s Readiness and Environmental Protection Integration (REPI) Program: A Guide for State, Local, and Private Partners*, Office of the Assistant Secretary of Defense (Sustainment), March 2022.

Reeves, Magen M., “Tyndall AFB Continues Rebuild Effort One Year After Hurricane Michael,” 325th Fighter Wing Public Affairs, U.S. Air Force, October 10, 2019.

REPI—*See* Readiness and Environmental Protection Integration Program.

Rhoades, Charles C., Deborah Entwistle, and Dana Butler, “The Influence of Wildfire Extent and Severity on Streamwater Chemistry, Sediment and Temperature Following the Hayman Fire, Colorado,” *International Journal of Wildland Fire*, Vol. 20, No. 3, May 2011.

Riggins, Lyn, “Residents Should Prepare for More Water Main Breaks as Potomac River Temperature Hits New Seasonal Low,” press release, Washington Suburban Sanitary Commission, February 1, 2022.

Robinson, Janiqua P., “Moody Finalizes DoD Initiative,” Moody Air Force Base, October 5, 2016.

Romita Grocholski, Krista, Michelle E. Miro, Lena Easton-Calabria, Jessica Spaccio, Samantha Borisoff, and Arthur T. DeGaetano, *Mid-Atlantic Regional Climate Impacts Summary and Outlook: Winter 2021–2022*, RAND Corporation, TL-A386-8, 2022. As of June 23, 2022:
<https://www.rand.org/pubs/tools/TLA386-8.html>

Rural Utilities Service, U.S. Department of Agriculture, “Design Manual for High Voltage Transmission Lines,” Bulletin 1724E-200, RD-GD-2015-78, December 2015.

S&P Global Ratings, “A Credit Rating Is an Informed Opinion,” webpage, undated. As of July 27, 2022:
<https://www.spglobal.com/ratings/en/about/intro-to-credit-ratings>

Sabatino, Kara, “Infrastructure Failures in the Face of Freezing Temperatures,” *AQUALIS* blog, February 23, 2021.

San Antonio Water System, “Texas Grants \$5 Million for San Antonio Military Water Fix,” December 11, 2015.

Sathaye, Jayant, Larry Dale, Peter Larsen, Gary Fitts, Kevin Koy, Sarah Lewis, and Andre Lucena, “Estimating Risk to California Energy Infrastructure from Projected Climate Change,” Lawrence Berkeley National Laboratory, February 2012.

Schramm, Jill, “Defense Grant to Help with Flood Wall Project,” *Minot Daily News*, September 27, 2021.

Schweikert, Amy E., and Mark R. Deinert, “Vulnerability and Resilience of Power Systems Infrastructure to Natural Hazards and Climate Change,” *WIREs Climate Change*, Vol. 12, No. 5, September–October 2021.

Scully, Janene, “Vandenberg AFB Commander Details Infrastructure Damage from Canyon Fire,” *Noozhawk*, March 10, 2017.

Sentinel Landscapes Partnership, “Fort Huachuca Sentinel Landscape,” webpage, undated. As of December 19, 2023:
<https://sentinellandscapes.org/landscapes/fort-huachuca>

Sheftick, Gary, “Sustainable Energy Projects Help Army Garner Award,” Army News Service, December 26, 2018.

Shield, Stephen A., Steven M. Quiring, Jordan V. Pino, and Ken Buckstaff, “Major Impacts of Weather Events on the Electrical Power Delivery System in the United States,” *Energy*, Vol. 218, March 1, 2021.

Sixteenth Air Force (Air Forces Cyber), “363D ISR Wing,” webpage, undated. As of December 7, 2023:
<https://www.16af.af.mil/Units/363ISRW>

Smith, Adam B., “2021 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context,” *Beyond the Data* blog, January 24, 2022.

South-Central Partnership for Energy Efficiency as a Resource, “Virtual Panel: Resilience, Reliability, Utilities & Policy,” video, September 9, 2021. As of July 25, 2022:
https://www.youtube.com/watch?v=GPcT4XjsG_s

Stone, Eric, “Saxman’s Main Water Source Freezes, Officials Urge Conservation,” Alaska Public Media, January 17, 2020.

Task Force on Climate-Related Financial Disclosures, *Recommendations of the Task Force on Climate-Related Financial Disclosures*, June 2017.

Texas Public Radio, “SAWS to Provide Water to Joint Base San Antonio,” September 15, 2015.

Thanos, Andreas, and Kiera Zitelman, *Natural Gas Distribution Infrastructure Replacement and Modernization: A Review of State Programs*, National Association of Regulatory Utility Commissioners, January 2020.

U.S. Army, “Schofield Generating Station: A Pillar of Stability for Oahu's Power Grid,” January 11, 2024.

U.S. Census Bureau, “Urban and Rural,” webpage, updated September 26, 2023. As of January 18, 2024: <https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural.html>

U.S. Code, Title 10, Section 2679, Installation-Support Services: Intergovernmental Support Agreements.

U.S. Code, Title 10, Section 2684A, Agreements to Limit Encroachments and Other Constraints on Military Training, Testing, and Operations.

U.S. Code, Title 10, Section 2864, Master Plans for Major Military Installations.

USDA—*See* U.S. Department of Agriculture.

U.S. Department of Agriculture, U.S. Department of Defense, and U.S. Department of the Interior, *Sentinel Landscapes: 2016 Report*, December 12, 2016.

U.S. Department of Defense, “The REPI Primer Series: A Guide to the Military’s Leading Climate Change and Conservation Program,” webpage, undated. As of December 20, 2023: <https://repiprimer.org>

U.S. Department of Defense, *Quadrennial Defense Review Report*, February 2010.

U.S. Department of Defense, *Quadrennial Defense Review 2014*, March 2014a.

U.S. Department of Defense, *2014 Climate Change Adaptation Roadmap*, June 2014b.

U.S. Department of Defense, *Department of Defense Climate-Related Risk to DoD Infrastructure Initial Vulnerability Assessment Survey (SLVAS) Report*, January 2018.

U.S. Department of Defense, *Installation Master Planning*, Unified Facilities Criteria 2-100-01, September 30, 2020.

U.S. Department of Defense, *DoD Climate Assessment Tool*, Washington, D.C., April 2021.

U.S. Department of Defense, Office of the Under Secretary of Defense (Acquisition and Sustainment), *Department of Defense Draft Climate Adaptation Plan*, report submitted to National Climate Task Force and Federal Chief Sustainability Officer, September 1, 2021.

U.S. Department of Defense, Office of the Under Secretary for Policy (Strategy, Plans, and Capabilities), *Department of Defense Climate Risk Analysis*, report submitted to National Security Council, 2021.

U.S. Department of Energy, *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions*, October 2015.

U.S. Department of Transportation, “Pipeline Replacement Background,” webpage, updated March 22, 2023. As of December 6, 2023: <https://www.phmsa.dot.gov/data-and-statistics/pipeline-replacement/pipeline-replacement-background>

U.S. Energy Information Administration, “Winter Supply Disruptions from Well Freeze-Offs Can Rival Effects of Summer Storms,” webpage, October 6, 2011. As of July 21, 2022: <https://www.eia.gov/todayinenergy/detail.php?id=3390>

- U.S. Energy Information Administration, “Electricity Explained: How Electricity Is Delivered to Consumers,” webpage, August 11, 2022a. As of December 6, 2023:
<https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php>
- U.S. Energy Information Administration, “Natural Gas Explained,” webpage, updated December 27, 2022b. As of December 6, 2023:
<https://www.eia.gov/energyexplained/natural-gas>
- U.S. Energy Information Administration, “Annual Electric Power Industry Report, Form EIA-861 Detailed Data Files,” webpage, October 5, 2023a. As of January 17, 2024:
<https://www.eia.gov/electricity/data/eia861>
- U.S. Energy Information Administration, “Natural Gas Explained: Where Our Natural Gas Comes From,” webpage, updated November 15, 2023b. As of December 6, 2023:
<https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php>
- U.S. Environmental Protection Agency, *Understanding Your Water Quality Report*, 2018.
- U.S. Environmental Protection Agency, “New Risk Assessment and Emergency Response Plan Requirements for Community Water Systems,” *Federal Register*, Vol. 84, No. 59, March 27, 2019.
- U.S. Environmental Protection Agency, “Basic Information About Your Drinking Water,” webpage, updated January 9, 2023a. As of December 20, 2023:
<https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-your-drinking-water>
- U.S. Environmental Protection Agency, “Climate Adaptation and Saltwater Intrusion,” webpage, updated June 14, 2023b. As of December 20, 2023:
<https://www.epa.gov/arc-x/climate-adaptation-and-saltwater-intrusion>
- U.S. Environmental Protection Agency, “Manage Flood Risk,” webpage, updated June 15, 2023c. As of December 20, 2023:
<https://www.epa.gov/green-infrastructure/manage-flood-risk>
- U.S. Environmental Protection Agency, “Climate Adaptation and Drought,” webpage, updated June 21, 2023d. As of December 20, 2023:
<https://www.epa.gov/arc-x/climate-adaptation-and-drought>
- U.S. Environmental Protection Agency, “Climate Adaptation and Water Quality,” webpage, updated June 21, 2023e. As of December 20, 2023:
<https://www.epa.gov/arc-x/climate-adaptation-and-water-quality>
- U.S. Environmental Protection Agency, “Climate Impacts on Water Utilities,” webpage, updated July 31, 2023f. As of December 20, 2023:
<https://www.epa.gov/arc-x/climate-impacts-water-utilities>
- U.S. Environmental Protection Agency, “Water Quality Topics: Pathogens,” webpage, updated August 29, 2023g. As of December 20, 2023:
<https://www.epa.gov/wqclr/water-quality-topics-pathogens>
- U.S. Environmental Protection Agency, “Climate Change Adaptation Resource Center (ARC-X),” webpage, updated October 30, 2023h. As of December 20, 2023:
<https://www.epa.gov/arc-x>

- U.S. Environmental Protection Agency, “Climate Change and Harmful Algal Blooms,” webpage, updated November 24, 2023i. As of December 20, 2023:
<https://www.epa.gov/nutrientpollution/climate-change-and-harmful-algal-blooms>
- U.S. Environmental Protection Agency, “Adaptation Actions for Water Utilities,” webpage, updated December 19, 2023j. As of December 20, 2023:
<https://www.epa.gov/arc-x/adaptation-actions-water-utilities>
- U.S. Government Accountability Office, *Electricity Grid Resilience: Climate Change Is Expected to Have Far-Reaching Effects and DOE and FERC Should Take Actions*, GAO-21-346, March 2021.
- Vermont General Assembly, An Act Relating to the Clean Heat Standard, House Bill H.715 (Vetoed), May 6, 2022.
- Wagner, Robert, Michael Jähn, and Kerstin Schepanski, “Wildfires as a Source of Airborne Mineral Dust—Revisiting a Conceptual Model Using Large-Eddy Simulation (LES),” *Atmospheric Chemistry and Physics*, Vol. 18, No. 16, August 20, 2018.
- Walsh, John, Donald Wuebbles, Katharine Hayhoe, James Kossin, Kenneth Kunkel, Graeme Stephens, Peter Thorne, Russell Vose, Michael Wehner, Josh Willis, David Anderson, Scott Doney, Richard Feely, Paula Hennon, Viatcheslav Kharin, Thomas Knutson, Felix Landerer, Tim Lenton, John Kennedy, and Richard Somerville, “Our Changing Climate,” in Jerry M. Melillo, Terese (T. C.) Richmond, and Gary W. Yohe, eds., *Climate Change Impact in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program, 2014.
- Warner, Michael D., Clifford F. Mass, and Eric P. Salathé, Jr., “Changes in Winter Atmospheric Rivers Along the North American West Coast in CMIP5 Climate Models,” *Journal of Hydrometeorology*, Vol. 16, No. 1, February 2015.
- WaterISAC, “Winter Storms and Extreme Cold Impacting Critical Infrastructure, Including Water and Power Services,” March 2, 2021.
- Wauthy, Maxime, Milla Rautio, Kirsten S. Christoffersen, Laura Forsström, Isabelle Laurion, Heather L. Mariash, Sari Peura, and Warwick F. Vincent, “Increasing Dominance of Terrigenous Organic Matter in Circumpolar Freshwaters Due to Permafrost Thaw,” *Limnology and Oceanography Letters*, Vol. 3, No. 3, June 2018.
- Welty, Josh, and Xubin Zeng, “Characteristics and Causes of Extreme Snowmelt over the Conterminous United States,” *Bulletin of the American Meteorological Society*, Vol. 102, No. 8, August 2021.
- Werner, Kevin, and Lina Svedin, “States, Water, and Climate: Who’s Planning for Change?” *Climate Risk Management*, Vol. 16, 2017.
- Willmsen, Christine, and Lynda V. Mapes, “A Disaster Years in the Making,” *Seattle Times*, April 28, 2017.
- Wing, Oliver E. J., William Lehman, Paul D. Bates, Christopher C. Sampson, Niall Quinn, Andrew M. Smith, Jeffrey C. Neal, Jeremy R. Porter, and Carolyn Kousky, “Inequitable Patterns of US Flood Risk in the Anthropocene,” *Nature Climate Change*, Vol. 12, No. 2, February 2022.
- Writer, Jeffrey H., Amanda Hohner, Jill Oropeza, Amanda Schmidt, Kaelin M. Cawley, and Fernando L. Rosario-Ortiz, “Water Treatment Implications After the High Park Wildfire, Colorado,” *Journal AWWA*, Vol. 106, No. 4, April 2014.

- Wuebbles, Donald J., David W. Fahey, Kathy A. Hibbard, David J. Dokken, Brooke C. Stewart, and Thomas K. Maycock, eds., *Fourth National Climate Assessment: Vol. I, Climate Science Special Report*, U.S. Global Change Research Program, 2017.
- Zamuda, Craig D., Thomas Wall, Leah Guzowski, Joshua Bergerson, Janet Ford, Lawrence Paul Lewis, Robert Fredric Jeffers, and Sean DeRosa, “Resilience Management Practices for Electric Utilities and Extreme Weather,” *Electricity Journal*, Vol. 32, No. 9, November 2019.
- Zanardo, Stefano, and Jose Luis Salinas, “An Introduction to Flood Modeling for Catastrophe Risk Management,” *WIREs Water*, Vol. 9, No. 1, January–February 2022.
- Zhao, Zongci, Yong Luo, and Ying Jiang, “Is Global Strong Wind Declining?” *Advances in Climate Change Research*, Vol. 2, No. 4, December 2011.

Extreme Weather and Climate Hazard Impacts on Energy and Water Utilities

Implications for Department of the Air Force Installation Climate Resilience Planning

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ISSUE

A changing climate and extreme weather are increasingly concerning for military installation resilience. A basic first step in improving the resilience of installation infrastructure is understanding potential infrastructure exposure to extreme weather- and climate-related effects. RAND Project AIR FORCE (PAF) was asked to develop an approach for estimating utility system exposure to extreme weather- and climate-related hazards for the purpose of informing where the Department of the Air Force (DAF) might consider prioritizing deep-dive vulnerability assessments. Previous efforts to understand the implications of climate change have focused on installations; in this study, we focused on utility infrastructures that are outside the fence line.



APPROACH

We used case studies supported by qualitative and quantitative analysis to demonstrate our hazard exposure approach, which characterizes the historical and, where possible, potential future exposure of energy and water utility systems supporting DAF installations. We focused on a select set of extreme weather- and climate-related effects for three regions: the mid-Atlantic, the Southwest, and Alaska. Our analysis considers the local and regional regulatory environment and demonstrates an approach that estimates the relative resilience capacity of utility systems in these regions using a set of indicators.



KEY FINDINGS

- Climate hazards are predictably different in various parts of the United States; however, the geographic extent of utility networks—which, in some cases, can fan out across an area almost half the size of the continental United States—means that it is possible for geographically distant hazards from the area of interest (e.g., the installation) to have impact (although, in some cases, a geographically distributed utility supply chain can also be more resilient).

- All energy and water utilities are directly and indirectly exposed to extreme weather and climate-related effects at every point along the system—from source all the way to end user behavior (demand pressure). However, these effects do not impact all utility system components uniformly. The location of assets, the system configuration, and the condition of infrastructure can influence infrastructure sensitivity and potential vulnerability to climate hazards. Additionally, the regulatory environment, state and local policies, and utility investment decisions are important to consider alongside physical attributes in determining potential vulnerabilities in utility systems that support DAF installations.
- The availability and accessibility of data to measure climate variables and their changes in a standardized way across utility systems are limited. But understanding the hazards faced in a region and how well resilience planning is addressing these hazards sets up a logical approach for prioritizing vulnerability assessments based on mission. Thus, an analytic approach that combines quantitative data and qualitative insights is valuable.
- Measuring utility system exposure can be resource-intensive; however, taken in combination, climate anomaly data (or other relevant accessible exposure metrics) and historical utility service reliability can be used as low-cost initial screens to determine the relevance of utility system exposure information to the decision context at hand.



RECOMMENDATIONS

- **Update resilience policy to include a regional screening-level assessment of energy and water utility system potential exposure to climate hazards to determine relevance to priority-setting decision contexts.** From a priority-setting perspective, information about utility exposure might not always be useful because accessible data do not always yield useful differences. However, a few simple steps can be taken to determine the relevance of utility system exposure to the decision context. We outline a few simple steps that can be taken to perform this high-level screening in the next recommendation.
- **Use a qualitative climate hazard taxonomy, accessible climate anomaly data, and utility reliability measures to obtain a first-order estimation of utility system exposure.** Taken together, climate anomalies compared with a historical baseline and historical utility reliability measures can provide a valuable and low-cost initial screen for whether data show variability across the set of installations of interest.
- **Articulate data and tool needs and strengthen partnerships to help access tools that track utility resilience measures.** Existing weather, climate, and policy data require varying degrees of manipulation or review to address questions of utility system potential exposure, which hinders the progress of resilience planning. Before investing in new standalone analyses and tools, the DAF should further pursue engagement with organizations that already gather, process, analyze, visualize, and disseminate utility system resilience-relevant data, many of which will be motivated to work with the DAF to support real-world decisions. These organizations include, among many others, the utilities themselves, the 14th Weather Squadron, and the National Oceanic and Atmospheric Administration (including its affiliated regional integrated sciences and assessments collaborations).
- **Maintain an archive of relevant weather and climate data, tools, and products that support climate hazard exposure assessments.** This archive can support the efficient use of resources when updating or conducting new assessments and can serve as a mechanism to share information across various assessment efforts.



PROJECT AIR FORCE

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