

Incorporating Climate Change into Risk-Informed Resilience Planning

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ABSTRACT

In response to the development of portfolio-wide climate action plans by United States (U.S.) federal agencies, federal sites are working to incorporate the impacts of climate change into their resilience assessments. However, this can be challenging given the uncertainty inherent in climate change modeling. Incorporating these factors into a resilience plan requires an understanding of what the different climate scenarios mean, as well as how to estimate potential impacts of climate change on hazard occurrence on a regional, or even local, scale. We discuss approaches to incorporating this data into risk-informed resilience assessment processes, such as those implemented in the Department of Energy's (DOE) Federal Energy Management Program's Technical Resilience Navigator (TRN) and the DOE Sustainability Performance Division's Vulnerability Assessment and Resilience Plan (VARP) Risk Assessment Tool. We also describe the climate scenarios and the availability of hazard data for site resilience planning, based on modeling included in the International Panel on Climate Change (IPCC), the National Climate Assessment (NCA), and state-level reports. We present examples from the TRN risk assessment and the VARP Risk Assessment Tool to illustrate how sensitivity analysis can be used to incorporate climate change projections into the resilience planning process.

Introduction

Executive Order (E.O.) 14008¹ was signed by President Joseph R. Biden on January 27, 2021, requiring federal agencies to develop an adaptation and resilience plan to address their most significant climate risks and vulnerabilities (86 Federal Register 7619 2021). These plans included common themes across agencies, including enhancing the climate literacy of staff, incorporating climate change into procurement and decision-making processes, and the need to develop "climate-ready" federal facilities and assets that are protected from the impacts of climate change. In their climate adaptation plans, many agencies noted that their sites would be conducting climate vulnerability and climate risk assessments at facilities across the portfolio (Office of the Federal Chief Sustainability Officer 2021). Ensuring a site is "climate ready" requires an assessment of the hazards that are likely to cause disruptions at the site and how hazards might change in the future due to climate change.

It is becoming increasingly essential for those working on federal facilities, including energy managers and sustainability managers, to understand how to incorporate climate change data and scenarios into their risk and resilience assessments to enable continuous support of the critical missions supported by federal sites. Methods for producing downscaled model projections have improved in recent years (Avery et al. 2018). However, there is an appreciable need for consistent guidance on how to use and incorporate climate data to enable sites to

¹ <https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad>

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effectively develop climate resilience plans based on the best available information. This paper lays out a risk-informed process for incorporating climate change data into resilience planning that considers the unique needs and requirements of federal sites. By addressing this gap, federal sites will be able to address the requirements set out by Executive Order 14008 more efficiently and cost-effectively.

Risk-Informed Resilience Planning

Resilience planning for federal sites is targeted towards identifying areas where the site is exposed to negative impacts from an initiating event (e.g., natural hazard) and determining whether solutions can be implemented to increase resilience to those events. A key requirement for informed decision-making as part of this planning process is a robust, replicable framework with which to capture potential areas for improvement. Additionally, the planning process must include an assessment of the expected impact of potential solutions on site resilience. While resilience planning generally focuses on conceptual descriptions of strategies for improving resilience (e.g., resourcefulness, redundancy, robustness, recovery), risk analysis provides a well-established and robust technique that can help a resilience planning process to achieve these goals. A formal risk analysis results in a series of risk scenarios which highlight key risk drivers at the site. By identifying the drivers of risk, resilience planners can focus effort on creating solutions in areas likely to have the biggest impact.

Conducting a Formal Risk Analysis

A standard risk analysis starts with identifying an initiating event, such as a natural hazard, a technological hazard (e.g., equipment failure), or a malicious attack. This focuses the analysis on answering the question “What could go wrong?” to begin developing a risk scenario. In this paper, the focus is on natural hazards, particularly those that are likely to be impacted by climate change. The hazards relevant for a particular site are likely to be highly location-specific, as the characteristics of natural hazards are often strongly dependent on local geography. Once the relevant hazards have been identified, a traditional risk approach requires the characterization of 1) the expected impact or consequence to the site if the hazard were to occur, and 2) the likelihood that the consequence will be realized. This likelihood value includes the likelihood that the hazard itself will take place as well as the probability that, if that hazard were to occur, the consequence will be realized (i.e., vulnerability of the system to the hazard.) This can be expressed using the risk equation, $R = H * V * C * W$, where R is the risk, H is the hazard likelihood, V is the system vulnerability, C is the consequence if the hazard takes place and any mitigation measures fail, and W is a weighting factor accounting for the relative importance of assets to the site². While risk analysis techniques can vary in terms of how qualitative (e.g., a risk matrix analysis) or quantitative (e.g., a probabilistic risk assessment) they are, a well-structured risk analysis must account for both the likelihood and consequence elements of a risk scenario as described here.

² For a more detailed description of risk analysis, see Unwin et al. 2020.
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Characterizing Hazards for Risk Analysis

In a risk assessment, hazards can be characterized by identifying the potential impact from the worst-case version of that hazard (e.g., a category 5 hurricane) as well as any less severe, but potentially more frequent versions of the hazard that are still likely to cause significant damage to the site (e.g., a tropical storm). If the impacts of these types of events are significantly different, they can be analyzed separately. Otherwise, the hazard can be analyzed as one event type. Once the hazards that will be included in the risk analysis and their expected consequences are identified, the likelihood that the hazard will occur must be determined. Because the true probability of occurrence for natural hazards generally requires complex and geographically granular analysis (e.g., earthquake ground motion maps produced by the United States Geological Survey [Petersen et al. 2021]), the likelihood of hazard occurrence is often approximated using the observed hazard frequency. Hazard frequencies can be obtained at a relatively granular geographic scale, such as the county level from sources like the Federal Emergency Management Agency's National Risk Index (NRI) tool (FEMA 2022).

Impact of Climate Change on Hazards

This approach to characterizing hazard probability based on observed frequencies is generally the most reliable way to obtain location-specific hazard information. However, the strategy assumes that past behavior is indicative of future behavior. This is a particularly significant problem in the case of hazards likely to be impacted by climate change. In these cases, historical hazard frequencies are unlikely to be representative of future behavior. Rather, it is critical to consider how climate change may impact the hazard. A challenge, particularly for energy managers or facilities managers who may not be well-versed in the climate change literature, is interpreting climate change projections and determining how to incorporate these data into a risk assessment. This can arise from the fact that climate change projections are generally framed as changes (i.e., increases or decreases in frequency or severity) largely due to model or inter-model uncertainty with respect to specific projections. As a result, some resilience assessments have defined hazards as an increase or decrease in the hazard frequency or severity. For example, rather than defining a hazard as “coastal flooding,” the hazard would be defined as “increased coastal flooding.” This approach captures the projected directional change in the hazard but does not capture the anticipated likelihood (current or future) of the hazard actually occurring or the anticipated severity of the hazard at a particular site. A motivating factor for taking this approach may be that federal sites are striving to ensure a focus on climate change impacts rather than focusing exclusively on historical data. However, this approach can lead to an inconsistent or even lack of quantification of likelihood and impact across hazard types.

The challenge of incorporating climate change data into a risk assessment can be addressed by leveraging the fact that climate projections are presented as *changes to a historical average*, with a baseline period generally specified as part of the reported projection. Therefore, to ascertain the actual projected hazard behavior, it is critical to first characterize the historical behavior of that hazard and then overlay the climate projection. Taking the coastal flooding example, a risk assessment focused on climate change must begin by characterizing the historical “coastal flooding” hazard and then overlaying the projected change in coastal flooding frequency and severity/extent due to climate change relative to that historical baseline.

Even when this type of methodical approach is implemented, another significant challenge lies in the quality of climate projections for extreme events. There are few hazards where quantitative data is available from climate projections that can be used to precisely modify the historical frequency and severity estimates in a risk model. The cases where this is possible are for hazards where the initiating event is directly tied to changes in temperature (e.g., heat waves) or precipitation. For these event types, quantitative regional or local projections are sometimes available (e.g., Rosenzweig et al. 2011). However, in the case of many extreme events (e.g., hurricanes, winter storms, tornadoes, intense precipitation events), these types of specific projections are not possible or contain large uncertainty. This is largely due to technical limitations of climate models (Seneviratne et al. 2012). Below, we discuss climate models and the type of data that they can produce to inform hazard assessments for risk analysis.

Climate Change Scenarios

Climate projections are based on Global Climate Models (GCMs) which simulate changes in the Earth's climate (Hayhoe et al. 2018). These models provide geographic grid-based projections of temperature, precipitation, and other climate variables. Climate modelers also rely heavily on climate scenarios to describe possible future outcomes of climate change impacts on systems, facilities, and communities. Today, Representative Concentration Pathways (RCPs) are the chief scenarios used in climate change assessments (Pachauri 2014). RCPs describe different climate futures that are considered plausible depending on the volume of greenhouse gases emitted in the years to come. For example, the International Panel on Climate Change (IPCC) used four pathways—RCP 8.5, RCP 6.0, RCP 4.5 and RCP 2.6—to produce the IPCC fifth assessment report in 2014 (Pachauri 2014). The numbers associated with an RCP denote the radiative forcing values in 2100 (e.g., 8.5, 6.0, 4.5 and 2.6 W/m², respectively). RCP 8.5 denotes a future with continued high emissions growth, while the other RCPs represent mitigation pathways with varying stringency. Note that the most recent IPCC report uses similar climate scenarios called shared socioeconomic pathways (Masson-Delmotte 2021). The National Climate Assessment (NCA), a federally mandated climate change report released every four years, focused on RCP 8.5 as a high-end climate scenario and RCP 4.5 as a low-end climate scenario for its fourth NCA in 2018, using RCP 2.6 only when instructive, for example in analyses of mitigation opportunities (USGCRP 2015). The NCA used a high-end and low-end climate scenario to facilitate communication of assessment findings and to capture a range of uncertainties and plausible futures, which is key for risk assessment.

Climate Change Projections

The resolution of GCMs has increased considerably over time. However, even the latest experimental high-resolution simulations are unable to project fine-scale processes occurring at regional to local scales associated with some hazards with a high degree of certainty (Aalbers et al. 2018; Maraun et al. 2010). As a result, a range of methods, typically referred to as “downscaling” are used to correct systematic biases in global projections and generate climate projections at a finer geographic scale. Two primary methods are used to arrive at higher resolution climate model projections: dynamical downscaling and statistical downscaling. Regional planners rely on downscaling methods to generate higher-resolution information required for climate change impact assessments.

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Even with downscaling techniques, climate models can be limited in the types of hazards for which projections can be made. To model the complex physics of the climate system on a global or regional scale, climate models are required to mathematically simplify the physical processes involved. Generally, the scale of these models is larger than the relevant physical and temporal scale of many extreme events. This includes being unable to account for local geographic and topographic factors that can be critical for the development of certain types of extreme hazard events. Because of these factors, climate projections are generally limited to qualitative, directional estimates of changes in the frequency or severity of extreme events. For example, the NCA projects that hurricanes in the Atlantic are likely to become more intense (medium confidence) and the most intense hurricanes are likely to become more frequent (low confidence) (Wuebbles 2017). To use this information in a risk assessment, one must answer the questions “more severe than what?” and “more frequent than what?” Assessing the risk impact associated with climate change requires data with more granular spatial resolution and localized projections than are available in GCMs to make informed resilience planning decisions at the site level. In some cases, even regional assessments based on downscaling are unable to capture key local variability resulting from geographic features and weather patterns.

Availability of High-Resolution Climate Change Projections in the United States

The inconsistent availability of granular climate change projections for extreme events across the United States (U.S.) is a significant challenge for the incorporation of climate change data into federal site risk assessments. A review of state-level climate change assessments across the U.S. states and the District of Columbia revealed diverse methods for incorporating more localized climate change projections. This analysis used the Georgetown Climate Center’s State Adaptation Progress Tracker to identify assessments and reports that provide state-level climate change projections and assessments across the U.S. (Georgetown Climate Center 2022). A key observation is that the majority of states have not sponsored these more granular analyses. For the states that have conducted state-level assessments, the methods used are discussed below. Note that the findings are not comprehensive as some of the state-level reports lacked in-depth details regarding their assessment methodology. Nevertheless, the survey of state-level climate change assessments provides a basic understanding of the availability of more granular climate change projections and the set of current practices for performing high-resolution assessments.

Modeling Strategies for State-Level Climate Change Assessments

The review of all 50 states and the District of Columbia revealed that at least 14 states have performed state-level projections using downscaling beyond that provided in the NCA. These states primarily used statistical downscaling to provide localized projections better suited to inform state and sub-state resilience assessments (e.g., risk assessments at federal sites). The model resolution of these assessments ranged from 6–12 kilometers (km) in the reports where the grid scale was identified. For example, California’s fourth climate assessment (Bedsworth et al. 2018) used a statistical downscaling method, similar to the latest NCA, to provide projections of temperature, precipitation, sea level rise and other variables of interest at a grid scale of 6 km. Modeling efforts were generally more robust with localized projections in states where the research was completed by climate expert groups and dedicated climate research centers. For example, researchers from the Northeast Climate Science Center developed downscaled county-level projections of sea level rise, temperature, and precipitation for the Massachusetts Climate

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Change Assessment (Massachusetts Climate Change Assessment 2018). Similarly, the University of Washington Climate Impacts Group provided projections of sea level rise for 171 distinct locations along the Washington coastline (McGuire Elsner 2009).

Though the states that have conducted detailed climate change assessments have broad similarities, the specific approaches differed between states. Most of the climate change projections were based on simulations from recent climate models from the fifth IPCC assessment report. Climate projection models in the reports were sometimes shown for different climate scenarios or RCPs, but not always. Many of the state assessments used the four IPCC RCPs, with a focus on RCP 4.5 and 8.5, consistent with the latest NCA. The availability of such information on climate change impacts based on multiple climate scenarios can be critical to federal sites' ability to be responsive to agency requests to incorporate multiple climate scenarios into their resilience assessments (86 Federal Register 7619 2021).

Types of Hazard Data Provided in State-Level Assessments

While some state analyses discussed anticipated changes in extreme events at the state or sub-state level (e.g., Indiana [Widhalm et al. 2018]; New York [Rosenzweig et al. 2011]), most analyses focused on changes in mean temperature and precipitation. Many coastal states also included specific discussion of sea level rise projections for coastal areas and how they differ from the global mean sea level rise projections, for example North Carolina (Kunkel et al. 2020). These variations are largely due to local subsidence or rebound patterns that may differ from the global average. Among the states that included downscaled information related to extremes, examples of common projections reported included number of days with daily maximum temperature above 95°F and changes in energy demand for cooling and heating as measured by cooling degree days and heating degree days.

States that discussed potential climate change impacts on specific hazards (e.g., hurricanes, wildfires, ice storms) were largely qualitative. There are both technical and societal reasons for this. One explanation is related to the inherent uncertainty associated with high impact low frequency events, as discussed above. This uncertainty results from the fact that these events occur infrequently and are often produced by small-scale physical processes that are below the resolution of climate models (both temporally and spatially). This also relates to the type of downscaling selected. For example, dynamical downscaling using high-resolution regional-scale climate models can provide simulations of impacts that are not adequately captured by statistical downscaling, such as interarrival time of storms, extreme wind, extreme humidity, precipitation from summer convective storms and lake-effect snow (Hamlet et al. 2020)³. The downside of dynamical downscaling is that it has much larger computational requirements. These requirements limit this type of downscaling to using a single large-scale global forcing scenario, meaning that it does not evaluate the range of uncertainty that statistical downscaling can accommodate more easily. Yet, perhaps the most important explanation for the difference between assessments that include downscaled projections on extremes and those that do not may relate to a lack of resources available to perform regional climate assessments. Many states may not have climate experts readily available to perform their own downscaled projections, and to do so can be costly. Thus, state and local planners rely heavily on sources,

³ By applying bias corrections based on observed probability distributions, however, statistical downscaling can be appropriate for evaluating projections of extreme temperature and precipitation at fine scales.

such as the NCA which may not provide interpretation of the climate data at the required resolution for site-level planning.

High-Resolution Projections for Specific Hazards

Recognizing the lack of resources and expertise for performing regional climate change assessments at the sub-regional level, the U.S. Global Change Research Program (USGCRP) which produces the NCA, and individual federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA), have developed more user-friendly tools to help inform sub-regional resilience planning in recent years. These resources include NOAA's "State Climate Summaries" which contain extended historical climate records and future climate model projections of climate conditions for states for the 21st century⁴ and the USGCRP-developed Climate Explorer, a highly interactive webtool which provides climate projections for key climate variables derived from GCMs for counties and county-equivalents for all 50 states and U.S. territories⁵. Some of these tools can be used to derive information on extremes. For example, in the Climate Explorer, users can download information related to extreme heat (days with maximum temperature above 95°F). The U.S. Forest Service's Wildfire Risk to Communities webtool⁶ uses long-term simulations of large wildfire behavior along with other data such as historical weather patterns to convey information on wildfire risk for use by municipal, county and state elected officials.

Overall, the availability of high-resolution climate change projections for use in site-level resilience planning is inconsistent. Sites with access to higher-resolution state analyses may apply those to their resilience plans. Other sites may rely on available hazard-specific tools, such as those described above, and regional projections such as those in the NCA.

Incorporating Climate Scenarios into Risk Assessments

Regardless of whether a site has access to high-resolution climate projection information, incorporating climate projections into a risk assessment should follow the same basic process. Below are two examples from DOE of risk-informed resilience planning tools which use historical hazard characterization to baseline the hazard behavior and then overlay climate change projection information on top of that baseline: the Technical Resilience Navigator (TRN) and the Vulnerability Assessment and Resilience Plan (VARP).

The Technical Resilience Navigator

The TRN is a risk-informed resilience planning tool designed to help energy, water, and facilities managers through the energy and water resilience planning process. The TRN characterizes hazards based on annual frequency and, due to a focus on federal energy and water resilience, characterizes consequence in terms of hours of mission outage time due to an energy or water outage. Due to the technical constraints of hazard analysis described above, the first focus of resilience assessments within the TRN is based on historical data of severe events. The TRN provides an informational resource for identifying historical hazard events for a given site, derived from the NRI tool, using zip code or county inputs. The NRI provides annual frequencies

4 The State Climate Summaries can be found at <https://statesummaries.ncics.org>

5 The Climate Explorer webtool can be found at <https://crt-climate-explorer.nemac.org/>

6 The Wildfire Risk to Communities webtool can be found at <https://wildfirerisk.org>

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for 18 natural hazards, including coastal flooding, cold waves, and tornados. Because of the TRN's focus on site-resilience, the TRN Identify Potential Hazards tool modifies the NRI dataset to display the likely annual frequency of a hazard at a site-level rather than the annual frequency of a hazard at a county-level. For example, using the county-level output from the NRI data for a tornado hazard provides an overestimation for the frequency with which tornados might reasonably be expected to hit a site given a tornado's limited physical area of impact relative to the size of the county. In this case, tornado frequency at a site is refined by multiplying by the average area of impact for tornados (0.65 miles² [Schaefer, Kelly, and Abbey 1985]) and dividing by the area of the county (Thom 1963).

These site-level estimates for annual frequency can be used as a starting point for determining the frequencies used in the TRN analysis. Because the TRN takes a screening approach rather than requiring users to do in-depth hazard assessments to determine specific probabilistic inputs, the hazard frequencies are incorporated into the TRN risk assessment using order-of-magnitude and half-order-of-magnitude annual frequency categories (Table 1). Based on the hazard frequency data obtained from the Identify Potential Hazards resource, the TRN uses geometric mean breakpoints to assign a frequency category to the hazard of interest.

Table 1. Order-of-magnitude and half-order-of-magnitude hazard frequency categories

Hazard likelihood category	Annual frequency (number of events/year)
Almost certain (3 times/ year)	3
Likely (once a year)	1
Anticipated (1 in 10 years)	0.1
Unlikely (1 in 100 years)	0.01
Extremely unlikely (1 in 1,000 years)	0.001

For each identified hazard and anticipated annual frequency, TRN users are directed to assign an outage duration category (1 hour, 1 day, 1 week, 1 month, 6 months) that would be expected in the event the hazard is realized. This can be estimated from historic observations of the impact the hazard has had on energy or water supply in the region.

As discussed above, sites that are interested in considering the potential impacts of climate change in their TRN risk assessment can build upon these historical estimates of hazard frequency and consequence. In the TRN, this can be accomplished through a sensitivity analysis approach where a new sensitivity case can be built for each relevant parameter being interrogated. For a climate change analysis, this may involve creating sensitivity cases representing different climate scenarios (e.g., different RCPs) or creating sensitivity cases representing different specific changes in particular subsets of hazards based on qualitative climate projections.

To demonstrate this, consider an example site presented by Unwin et al. (2020)⁷. This example includes two facilities with electric and water loads. The only natural hazard included in the original example was earthquakes; here, hurricanes and ice storms are added to the analysis to incorporate natural hazards likely to be impacted by climate change. For the example, we

⁷ Example site is based on the example presented in Unwin et al. 2020.
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consider hazard frequencies for a hurricane and ice storm based on a search in the TRN Identify Potential Hazards tool. This search results in an annual frequency for hurricanes of 0.1 (which translates to a rating of “Anticipated (1 in 10 years)” in the TRN). Based on past observations at the fictional site, hurricanes are expected to cause a one-day electric outage for the site. However, the water supply is more robust and only about one in every ten hurricanes is expected to cause a water outage. These outages are anticipated to last for a whole week. Therefore, the water outage frequency and outage duration for hurricanes is estimated to be “Unlikely (1 in 100 years)” and 1 week, respectively. The estimated historical annual frequency for ice storms of 0.7 (which translates to a rating of “Likely (once a year)” in the TRN). Based on past observations of ice storms in the region, it is anticipated that an ice storm will cause a one-day electric outage but not cause a water outage.

Table 2. Hazard inputs and outputs for three sensitivity cases of a TRN risk model

		Sensitivity cases		
		Historical	Increased severity (hurricane)	Increased frequency (hurricane and ice storm)
Natural hazard inputs				
Hurricane, electricity	Outage duration	1 day	1 week	1 day
	Frequency	Anticipated (1 in 10 years)	Anticipated (1 in 10 years)	Likely (once a year)
Hurricane, water	Outage duration	1 week	1 month	1 week
	Frequency	Unlikely (1 in 100 years)	Unlikely (1 in 100 years)	Anticipated (1 in 10 years)
Ice storm, electricity	Outage duration	1 day	1 day	1 day
	Frequency	Likely (once a year)	Likely (once a year)	Almost certain (3 times/year)
Ice storm, water	Outage duration	N/A	N/A	N/A
	Frequency	N/A	N/A	N/A
Earthquake, electricity	Outage duration	1 week	1 week	1 week
	Frequency	Unlikely (1 in 100 years)	Unlikely (1 in 100 years)	Unlikely (1 in 100 years)
Earthquake, water	Outage duration	1 week	1 week	1 week
	Frequency	Unlikely (1 in 100 years)	Unlikely (1 in 100 years)	Unlikely (1 in 100 years)
Risk outputs				
Total unweighted risk (hours/year)		25.0	72.4	81.3
Total weighted risk		196.2	534.2	683.3

The “historical” case uses severity (outage duration) and frequency data based on historical observations. The other two cases modify either the severity or frequency of climate hazards based on climate change projections. Values in light grey font indicate inputs that were not modified for the sensitivity case relative to the historical case.

To account for climate change impacts, national or regional level analyses such as those found in the NCA, or state and sub-state level analyses available for some states can be used. Based on such resources, climate change is anticipated to lead to an increase in intensity of Atlantic hurricanes and lead to an increase in frequency for both ice storms and the most intense hurricanes. To investigate these potential changes, sensitivity cases are created to consider 1) an increase in hurricane severity and 2) an increase in the frequency of both hurricanes and ice storms. Note that in the first sensitivity case, changes in severity are modeled by adjusting the

consequence term for the hazard (i.e., outage duration). A summary of the historical inputs and the adjusted inputs for the sensitivity cases can be found in Table 2.

From this sensitivity analysis, the user can gain an understanding of the range of risk exposure depending on the assumptions made about future hazard occurrence. These results show that the risk estimated based on historical hazard data is likely a lower-bound on the actual risk that the site should anticipate (Figure 1). By considering the two climate change sensitivity cases, it can be seen that the anticipated increase in hurricane severity could lead to a >180 percent increase in the unweighted risk (a probability-modulated representation of annual mission outage duration). A climate change scenario where the frequencies of both hurricanes and ice storms increase relative to the historical average could lead to a >225 percent increase in unweighted risk. Similar patterns are seen for weighted risk, a risk representation that incorporates the relative importance of critical functions for the site's ability to fulfil its missions.

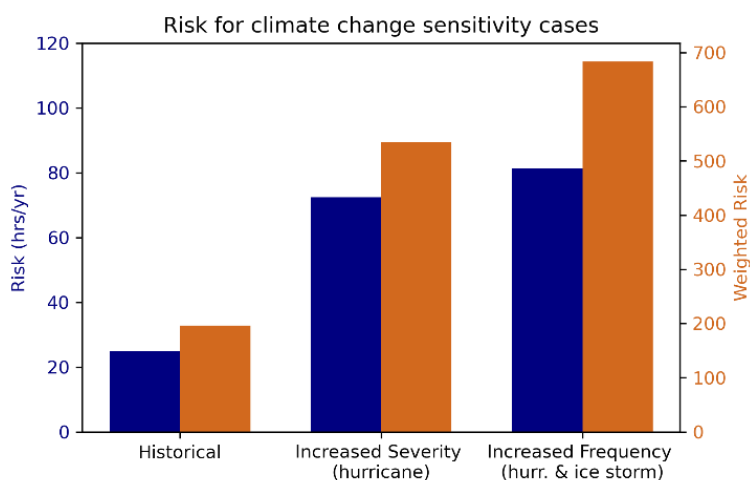


Figure 1. Risk calculated using the TRN risk assessment methodology for an example site (Unwin et al., 2020) for three scenarios: 1) based on historical hazard data, 2) incorporating an increase in hurricane severity, and 3) incorporating an increase in hurricane and ice storm severity.

This approach to sensitivity analysis provides a rough sense of the potential impacts of climate change based on the directionality of change. However, given that in most cases, precise hazard projections are unavailable, this is a reasonable starting point until more precise climate projections are available.

The Vulnerability Assessment and Resilience Plan Risk Assessment Tool

As outlined in the 2021 DOE Climate Adaptation and Resilience Plan (the Department of Energy's (DOE) response to E.O. 14008), DOE sites are required to conduct climate vulnerability assessments and develop resilience plans by September 2022. Specifically, DOE sites are charged to protect DOE assets from climate change impacts via vulnerability assessment and actions that ensure resilient operations (DOE 2021). To meet this need, DOE sites are required to develop a VARP, based on a guidance document which builds upon existing DOE risk assessment processes (DOE 2022).

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The VARP guidance document includes the spreadsheet based VARP Risk Assessment Tool (hereafter referred to as the VARP tool). This tool enables DOE users to assess forward-looking risk to site assets and infrastructure when considering the effects of climate change. Despite its relative simplicity and ease of use, it adheres to traditional risk assessment best practices, with appropriate quantification of the risk components of hazard likelihood, vulnerability, impact (or consequence), and an asset criticality score (or weight). Though, like the TRN, the VARP tool follows a risk-informed approach, the VARP tool has a broader scope, addressing all infrastructure-types relevant to DOE sites completing the assessment, whereas the TRN incorporates a more detailed analysis of energy and water systems. While this tool may be used to analyze the risk associated with any type of hazard, its primary focus is on hazards that may be affected by climate change.

As discussed earlier in this paper, it is not sufficient to merely estimate the direction of the effect of climate change on a hazard (e.g., increased frequency or severity). To make the analysis actionable, it is important to first understand the current, or baseline, characteristics of the hazard. To address this issue, the VARP tool’s hazard analysis incorporates both current expected annual frequencies of hazards, as well as any effects on hazard frequency anticipated to result from climate change. The tool bins the hazard frequencies into order-of-magnitude or half-order-of-magnitude categories, mirroring the approach used in the TRN (Table 1).

To demonstrate the tool’s hazard analysis approach, consider an example VARP tool analysis. This analysis focuses on assessing the risk associated with three critical assets: two onsite waste disposal facilities and a bus depot. This example considers three hazards: coastal flooding, earthquake, and winter weather. For each of these hazards, a user must specify the “Current Annual Frequency at the Site.” Sources such as the NRI, the TRN’s Identify Potential Hazard tool, or other data relevant to the specific site may be used. In this example we assume that coastal flooding is currently expected, on average, to occur 1.5 times per year, earthquakes (sufficient to damage infrastructure) 0.009 times per year, and winter weather 2.3 times per year. Table 3 reports the user-assigned baseline hazard frequencies and their associated hazard likelihood categories.

Table 3. Baseline historical hazard frequencies and categories for VARP tool example analysis

Regional Hazards Impacting DOE Site (user input)	Current Annual Frequency at the Site (user input, average # of events/yr)	Current Hazard Likelihood Category
Coastal Flooding	1.5	Likely
Earthquake	0.009	Unlikely
Winter Weather	2.3	Almost Certain

In order to assess how climate change may affect these hazards, users are asked to describe how each hazard’s frequency is expected to change over time, by choosing one of three options for a “Projected Effect of Climate Change”: “Increase,” “No Change,” or “Decrease.” This directional information may be obtained from the NCA and, as available, more granular local data. The tool then assigns a “Projected Hazard Likelihood with Climate Change” category, and an associated frequency (as shown in Table 1). Projected Hazard Likelihood with Climate

Change is determined by using two prior data elements: Current Hazard Likelihood, and Projected Effect of Climate Change.

If climate change is anticipated to increase the hazard frequency, the Projected Hazard Likelihood is shifted to the category with the next highest frequency, relative to that set for the Current Hazard Likelihood. Similarly, if climate change is anticipated to decrease the hazard frequency, the Projected Hazard Likelihood is shifted to the category with the next lowest frequency, relative to that set for the Current Hazard Likelihood. The Projected Hazard Likelihood is left unchanged from the Current Hazard Likelihood if: 1) climate change is not expected to affect the hazard frequency, or 2) a shift isn't possible due to the Current Hazard Likelihood already being set to the highest or lowest category.

Table 4 reports the anticipated frequencies and likelihood categories considering climate change impacts on each of the three hazards. Coastal flooding is shifted from the “Likely” to the “Almost Certain” hazard likelihood category, due to the projection of climate change increasing the annual frequency of that hazard. Winter weather shifts downward, from the “Almost Certain” to the “Likely” category, given an anticipated decrease in annual frequency. The earthquake hazard remains unaffected by climate change.

Table 4. Example of hazard frequencies and likelihood categories considering climate change projections

Regional Hazards Impacting DOE Site	Current Hazard Likelihood Category	Projected Effect of Climate Change (user input)	Projected Annual Frequency at the Site with Climate Change (events/year)	Projected Hazard Likelihood with Climate Change
Coastal Flooding	Likely	Increase	3	Almost Certain
Earthquake	Unlikely	No Change	0.01	Unlikely
Winter Weather	Almost Certain	Decrease	1	Likely

Once the climate change projections have been applied to the baseline hazard likelihood category, the “Projected Annual Frequency at the Site with Climate Change” is used in the tool’s risk calculations. The projected hazard frequency is multiplied by user-specified values of impact (corresponding to the consequence term in the risk equation), vulnerability, and asset criticality to derive risk for each asset and hazard combination. To compress the resulting values into a smaller, more easily understandable range, a logarithmic transformation is applied to the calculated risk values, resulting in VARP risk scores that range from roughly 0 to 10. Figure 2 provides an example of the VARP Risk Assessment Tool’s final output risk matrix. In this example, the risk matrix calls attention to two onsite waste disposal facilities facing high risk, considering climate change, due to coastal flooding. This output can help to focus the development of resilience solutions (and associated funding) on the assets and hazard types of most concern to the site.

VARP Risk Score and Color Key					
High	>= 7				
Medium	3.5 - < 7				
Low	< 3.5				
None	Zero Calculated Risk				

Critical Asset and Infrastructure Systems	Asset and Infrastructure System Type	Asset or Infrastructure Name/Identifier	Hazards		
			Coastal Flooding	Earthquake	Winter Weather
	Onsite Waste Disposal Facility	Waste disposal 1	9.0	6.0	7.0
	Onsite Waste Disposal Facility	Waste disposal 2	7.5	5.0	6.0
	Transportation and Fleet Infrastructure	Bus depot	5.8	1.5	6.5

Figure 2. Example output from the VARP Risk Assessment Tool

It is important to note that the VARP approach, like the TRN, does not use high-precision estimates of hazard frequencies when considering climate change. Shifting by order-of-magnitude categories provides a rough estimate of such hazard frequencies, capturing the directionality of climate change impacts. But, for some extreme events, it likely does provide results at about the level of resolution possible with current data and climate models. In cases where more precise projections of hazard frequency are available (e.g., heat waves for sites in New York state), these can be incorporated by simply entering the projected frequency as the current frequency and entering “No Change” for the “Projected Effect of Climate Change” input.

Another key item to note is that the estimates of hazard likelihood reflecting climate change do not capture continued changes in hazard frequencies over time, as the effects of climate change continue to evolve. Rather, for simplicity, any shifts in hazard frequency are assumed to be stationary, modeled as a step function with logarithmic steps. A more precise risk assessment that accounts for the evolution of hazard frequency and severity over time would require co-varying all components of risk (hazard frequency, vulnerability, and consequence) over time and calculating risk as a time-dependent function. This is beyond the scope of both the TRN and the VARP, which are simplified risk assessments designed for easy use by facility focused staff. Additionally, it is beyond the resolution of data available for most extreme events that would be considered in the risk assessment. That said, users do have the ability to perform sensitivity analysis by altering their estimates of baseline hazard frequencies to evaluate how much their calculated risk is impacted by uncertainty and variability in hazard frequency estimates.

Conclusions

Climate change is a significant challenge facing communities and organizations globally. To meet this challenge, recent administration and agency-level policies require U.S. federal sites to conduct resilience assessments to identify how to best prepare for the future, including potential climate change scenarios where hazards may become more frequent and/or severe. These types of assessments are best served by implementing a robust risk assessment approach where a site’s hazard exposure and the consequences associated with that hazard are taken into account in a meaningful calculation. However, incorporating the impacts of climate change into

such an assessment can be challenging. Climate change impacts are regionally, and sometimes locally, specific and available data for anticipated changes in extreme events generally indicates only the directionality of the change rather than providing a quantitative projection. Therefore, a traditional risk screening methodology can consider climate change impacts by first determining the historical frequency with which a hazard impacts the site. Then, expected climate change impacts can be overlaid on this historical baseline to incorporate changes in hazard frequency or severity resulting from climate change. This approach is demonstrated in the TRN and in the VARP tool, as discussed in this paper. By accounting for climate change impacts in this way, resilience assessments can generate meaningful results where risk is evaluated based on the consequences to a site associated with a range of modeled hazards, and the likelihood that those consequences will be realized. This method also provides a consistent approach that builds on already existing tools for addressing energy and water resilience. By providing a consistent approach that leverages existing federal tools, federal sites will be better equipped to meet their resilience goals in a more efficient and cost-effective manner.

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