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Methodology for Valuing Resilience to Severe Events for Department of Energy Sites

July 2018

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U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Richland, Washington 99352

Abstract

This study outlines an approach that operators of U.S. Department of Energy sites can use to value resilience. Qualitative screening and assessments often effectively identify vulnerabilities and measures that would enhance resilience. However, the implementation of these measures may be limited by a lack of a quantifiable cost-benefit analysis that compares action to inaction. The method presented here is intended to help overcome this barrier by detailing how DOE sites can quantify the costs and benefits of site resilience measures, and to compare that to the value of inaction. The approach mirrors common vulnerability assessment and resilience planning methods following five key steps (e.g., establish the baseline, assess vulnerability and risk, develop the resilience action plan), and provides detailed guidance on methods for quantification within each step. The five-step methodology was implemented in a case study of the U.S. Department of Energy's Hanford Site, which demonstrated the value of two resilience measures aimed at helping the site to avoid lost work hours due to expected increases in the number of high heat days.

Summary

Determining and implementing measures that improve resilience at U.S. Department of Energy (DOE) sites will help ensure the necessary conditions are in place to enable DOE to fulfill its mission without long-term detriment to physical assets, human capital, or productivity. Operators of DOE sites are becoming adept at using vulnerability screening and assessment methods to identify vulnerabilities and measures to enhance resilience, leveraging established guidance from DOE and other agencies. However, the difficulty of quantifying uncertainty, benefits, and costs associated with different measures that reduce these vulnerabilities can be a barrier to taking action. This study outlines a methodology that operators of DOE sites can use to value resilience. This methodology aims to complement, not replace such assessments, by enabling a more robust, quantitative analysis of alternatives when warranted. It is intended to help overcome barriers to action by establishing a replicable method that DOE sites can use to value the costs and benefits of site resilience measures, and to compare that to the value of inaction.

Resilience in this paper is defined as the ability to prepare for and to withstand an extreme event with little or no damage, or to recover more quickly from an extreme event. Since each site faces different hazards, levels of exposure, and vulnerabilities, the methodology was developed to be adaptable to each site. The valuation methodology can apply to a variety of hazards and threats, however this study focuses on extreme weather events and a limited set of other exposures that create operational vulnerability.

The valuation methodology consists broadly of a five-step approach for estimating the costs and benefits of discrete, additive resilience measures and compares alternatives. The five steps are:

1) Establish a baseline condition of the site's infrastructure and assets,
2) Assess vulnerability and risk to those assets,
3) Develop a resilience plan that includes alternative measures that mitigate the harm (hereafter, "alternatives"),
4) Undertake cost-benefit analysis, and
5) Develop a decision portfolio for investment in alternatives.

The methodology identifies potential hazards to the site by assessing its vulnerabilities; it identifies the impacts and their probability of occurrence to on-site systems, determines the degree of the site's resilience, places a monetary value on the infrastructure systems, and determines the impact over the selected time horizons. The process is then repeated for any identified mitigation alternatives provided by subject matter experts associated with the system evaluated. Finally, a cost-benefit analysis enables comparison of the alternatives to the baseline to inform and prioritize decision-making for investment in the vetted resilience measures.

Undertaking a site resilience valuation requires a multi-disciplinary team of subject matter experts (SMEs). Climate and earth scientists and experts in probability calculations for natural and man-made hazards are needed to evaluate even the most probable of events. Other SMEs include planners of various disciplines, engineers, economists, and other scientists.

Specialists evaluating site resilience valuation must begin by determining the following:

- Probability of a hazard's occurrence,
- Impact[1] associated with the hazard for the baseline and alternatives, and
- Monetary value of impacts to the infrastructure[2] from the hazard.

Figure S.1 depicts this methodological approach.

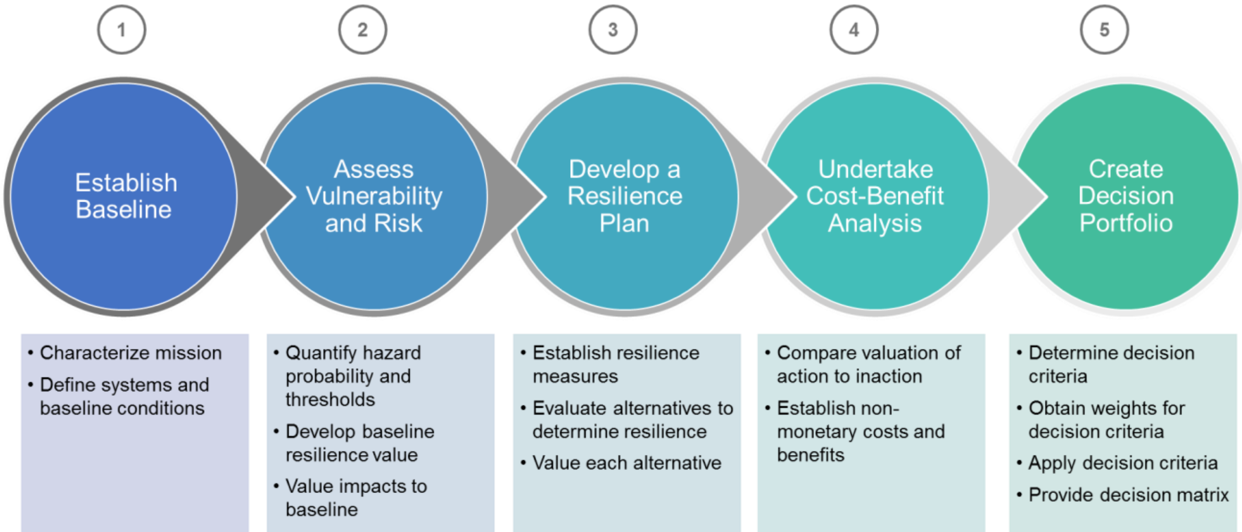

Figure S.1. Resilience Valuation Approach

This five-step approach was tested at the Hanford Site to develop a case study. At that site, a previous vulnerability screening study had identified the rise of average annual temperatures as a primary stressor that could impact worker productivity and operating costs. This study aimed to value the specific impacts of longer periods of sustained high temperatures on site operations, by examining changes in outside worker productivity and building HVAC system operations. While the impact of high temperatures on HVAC system operating costs weren't identified as a priority concern of the Hanford Site in the initial vulnerability screening, HVAC systems have been identified as a major vulnerability at other sites and are included here for illustration.

The baseline approach (business-as-usual) and alternative measures were evaluated at two different temperature forecasts: Representative Concentration Pathways[3] (RCPs) 4.5 and 8.5, represented as RCP4.5 and RCP8.5 in Table S.1 and Table S.2. The results of the heat stress analysis on outdoor worker safety and productivity, and therefore operations costs (Table S.1), indicate that both night shift work and ice vests reduce the costs of the baseline over the remaining projected operating period for Hanford (2018–2090). The results are indicative because expert opinion on the percentages of work that could be attributed to each category of work (light, moderate, heavy, and very heavy), formed the basis. The costs for ice vests only include the value at risk for work and do not include the costs of the vests, because data

[1] The impact is based on a fragility curve or damage function which enumerates the how the specific infrastructure is damaged by a specific hazard.
[2] Infrastructure is defined as all-encompassing including systems, processes, individual assets, and people.
[3] Representative Concentration Pathways are scenarios created by the Intergovernmental Panel on Climate Change (IPCC) describing future atmospheric greenhouse gas concentration levels.

on the number of vests required could not be obtained. However, a cost-effectiveness analysis was performed for the vests, and they were shown to be cost effective.

Table S.1. Comparison of Net Present Cost of the Baseline and Alternatives for Lost Work

Forecast	Component	Net Present Cost ($MM; r = 3%)	Net Present Cost ($MM; r = 7%)
RCP4.5 (stabilization scenario)	Baseline	365	229
	Night shift work	45	30
	Ice vests	23	15
RCP8.5 (growth scenario)	Baseline	355	217
	Night shift work	42	25
	Ice vests	19	12

This study's estimated net present cost/value of the baseline and alternative measures discounts the life-cycle costs using a discount rate. However, the difference in discount rates did not change the overall result, as the savings at the 7% discount rate ranged near $200 million; for a 3% discount rate, the savings were slightly greater than $300 million. The savings could be higher, but most of the outdoor work at Hanford will be completed before 2060, when the effects of higher temperatures are projected to become more pronounced. Any delay due to a lack of funding could significantly impact these values.

The analysis of the HVAC systems found that the systems' cooling and heating loads were more balanced as a result of increasing temperatures. As a result, although the cooling load did increase, the decreased heating load offset the increases (see Table S.2). Overall change in energy costs netted to an estimated reduction of $1.3 million to $1.5 million at a 7% discount rate based on the increased temperature forecast for RCP4.5 and RCP8.5, respectively. At a 3% discount rate, the net reduction in cost was $2.9 million to $3.4 million for respective temperature forecasts. The cooling costs did increase as expected. Because the initial Hanford Site vulnerability assessment did not identify building energy systems/use as a priority, no mitigation alternatives were analyzed.

Table S.2. HVAC Cooling Results

Net Present Value	HVAC Energy Cost ($MM)			Cooling-Only Energy Cost ($)		
	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
2018–2090 @ 7%	19.6	18.4	18.2	3.0	3.4	3.5
Change in energy cost		(1.3)	(1.5)		0.4	0.5
2018–2090 @ 3%	37.7	34.8	34.3	5.7	6.6	6.8
Change in energy cost		(2.9)	(3.4)		0.9	1.1

The Hanford Site resilience valuation case study is for illustrative purposes. Different assumptions about site conditions and hazards would lead to different results. The method in this study provides guidance on using the results of initial vulnerability screenings or assessments to evaluate and prioritize different resilience alternatives.

Acknowledgments

The research team thanks our colleagues for helping obtain the data required: at the U.S. Department of Energy's Richland Operations Office, Tom Fern, Stephen Korenkiewicz, and Tobin Mott; at the Mission Support Alliance, Lana Strickling, Michelle Rehberg, Christian Seavoy, and Ken Moser. We would also like to thank Josh Silverman and Eric Bradley from the U.S. Department of Energy Office of the Associate Under Secretary for Environment, Health, Safety, and Security, and Steve Bruno and Christina Rambo from the Sustainability Performance Office for their valuable comments on our draft documents. We also wish to thank Nickolas McHenry, U.S. Army Corp of Engineers, and Kevin Harrington, Project Time and Cost.

Acronyms and Abbreviations

BCR	benefit-cost ratio
BLS	Bureau of Labor Statistics
DOD	Department of Defense
DOE	U.S. Department of Energy
DX	direct expansion (a type of cooling equipment)
EPA	Environment Protection Agency
FEDS	Facility Energy Decision System model
FEMA	Federal Emergency Management Agency
GWh	gigawatt hour
HVAC	heating ventilation, and air conditioning
KW	kilowatt
KWh	kilowatt-hour
MSA	Mission Support Alliance
NAVFAC	Naval Facilities
NOAA	National Oceanic and Atmospheric Administration
O&M	operations and maintenance
OMB	Office of Management and Budget
ORP	(U.S. Department of Energy) Office of River Protection
OSHA	Occupational Safety and Health Administration
PNNL	Pacific Northwest National Laboratory
Prob	probability
RCP 4.5	Representative Concentration Pathway 4.5 watts per square meter
RCP 8.5	Representative Concentration Pathway 8.5 watts per square meter
RL	(U.S. Department of Energy) Richland Operations Office
SME	subject matter expert
TMY	typical meteorological year
WBGT	wet bulb globe temperature

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1.0 Introduction

Determining and improving the resilience of the U.S. Department of Energy's (DOE) sites to impacts from natural hazards will help ensure that the Department can continue to carry out its mission with reduced likelihood of operational disruption or casualty. This methodology establishes the economic basis for valuing enhanced resilience of DOE sites to natural hazards, such as extreme weather events and earthquakes, although it can be used to monetize other hazards and threats that create operational vulnerability. The approach develops a replicable methodology that DOE sites can use to quantitatively assess costs and benefits of site resilience measures.

Resilience in this paper is defined as the ability to prepare for and to withstand an extreme event, with little or no damage, or to recover more quickly from an extreme event. The valuation methodology uses a 5-step approach for estimating the costs and benefits of added resilience and compares alternatives: (1) establish baseline, (2) assess vulnerability and risk, (3) develop a resilience plan, (4) undertake cost-benefit analysis, and (5) create decision portfolio. This paper details processes within each of these steps for conducting a more quantitative analysis, such as establishing the probability of exposure to hazards, valuing infrastructure systems, and valuing resilience-enhancing alternatives.

2.0 Background

Like many Federal agencies, the DOE is faced with the challenge of strengthening its resilience to a growing number of hazards. These can include natural hazards (e.g., extreme weather events), man-made hazards (e.g., physical attacks on infrastructure), hazards associated with aging infrastructure, and others. The need to make sites more operationally-resilient to a variety of hazards has become evident.[1] Making sites more resilient means making them capable of withstanding potentially more frequent and severe hazards and enabling them to quickly return to normal operations. Resilience measures can include adding backup power as well as hardening the electrical, fire protection, building automation, and mass notification systems. Thus, the facility remains operational, partially operational, or reopens more quickly in times of disaster and provides distributed systems and redundancy of systems.[2] Resilient sites may cost more initially, but they can provide increased value in terms of improved operational and electrical efficiency, reduced down-time and risk to operations, improved productivity, reduction of injury or loss of life, and greater mission assurance.

The following methodology synthesizes several approaches to valuing resilience found in the literature. The approach taken by the Naval Facilities, or NAVFAC[3] (2017), uses four stages to value mitigation alternatives to sea level rise and inundation of a naval site. Each stage contains four to five steps to accomplish the process of valuing the resilience of adaptation. Bond et al. (2017)[4] provides a six-step method of valuing resilience, which is very similar to the NAVFAC approach. They use expert judgement to determine the impact of events on the baseline and the alternatives. Judson et al. (2016)[5] uses a more sophisticated method of valuing resilience by using a mean-time-to-failure approach that directly examines the resilience of the baseline and alternatives or provides a system efficiency. The approach used in this methodology assumes that a vulnerability screening has already been completed.

[1] Ramirez, B. Feb 2016. "Finance and the Cost-Benefit Analysis of Climate-Resilient Projects." In PA Times, accessed October 7, 2016 at http://patimes.org/finance-cost-benefit-analysis-climate-resilient-projects/

[2] Siemens. "Disaster Preparedness: Advanced Building Strategies Make Buildings More Resilient." Accessed October 6, 2016 at http://www.facilitiesnet.com/buildingautomation/native/Building-Automation-Systems-Can-Play-a-New-Role--31579

[3] NAVFAC – Naval Facilities Engineering Command. 2017. Climate Change: Installation Adaptation and Resilience. Prepared by Leidos, Inc. and Louis Berger, Inc. Washington, DC.

[4] Bond, CA, A Strong, N Burger, S Weilant. 2017. Guide to the Resilience Dividend Valuation Model. RAND Corporation, prepared for the The Rockefeller Foundation.

[5] Judson, N, AL Pina, EV Dydek. S>B. Van Broekhoven, Group 73, AS Castillo. 2016. Application of a Resilience Framework to Military Installations: A Methodology for Energy Resilience Business Case Decisions. Technical Report 1216. Lexington Massachusetts.

3.0 Resilience Valuation Methodology

Undertaking a site resilience valuation[1] requires a multi-disciplinary team of subject matter experts (SMEs). Scientists and experts in probability calculations for natural and man-made hazards are needed to develop the most probable events. Other SMEs may include planners, engineers, economists, and other scientists. As the data analysis and supporting predictive tools become more prevalent, this need for subject matter expertise may diminish, but it is important to recognize that this is an active but still developing field.

The resilience valuation methodology compares the costs and benefits of a baseline scenario with alternatives that improve resilience using the five-step approach. As part of this process, costs and benefits are quantified by establishing the probability of a hazard occurring, determining the impact based on a fragility curve[2] associated with the hazard for the baseline and alternatives, and monetizing (as applicable) impacts to the infrastructure from the hazard. The fragility curve provides the damage associated with a specific hazard such as an earthquake and its impact on a particular type of building. For example, the magnitude of the earthquake combined with the building code for which the structure was built will provide a probability for the amount of damage caused to the facility.

Applying Step 2 in the graphic below for each mitigation alternative provides the estimated value of the impact from measures to improve the site resilience. The combination of the alternatives and baseline results provides a portfolio of measures containing values of monetary and non-monetary benefits and costs along with decision criteria including weights for the decision criteria. Figure 3.1 depicts this approach.

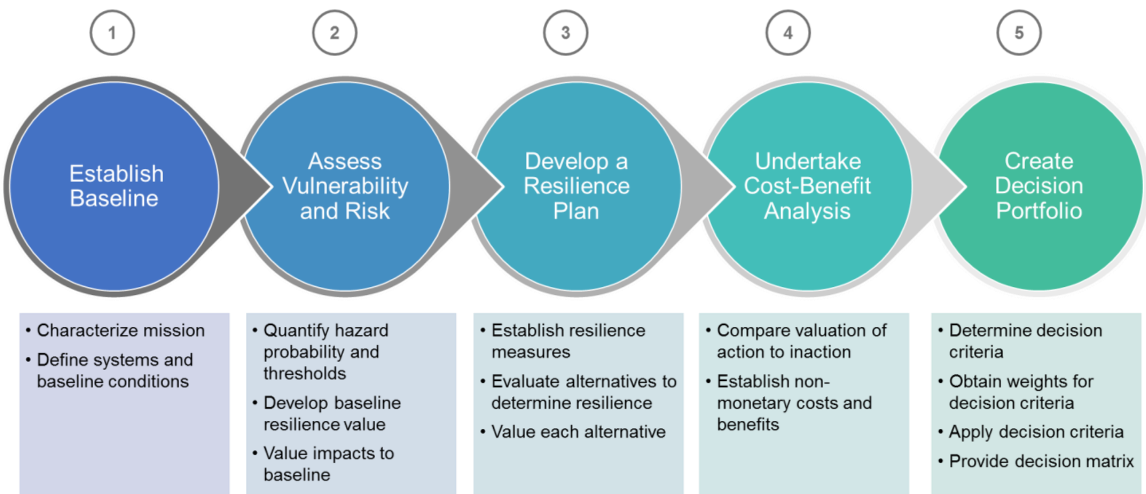


Figure 3.1. Resilience Valuation Approach

This five-step resilience valuation approach has a number of sub-steps described below:

- Establish Baseline
  - *Characterize mission*

[1] Valuation is defined as determining a monetary value for a site's ability to remain operational in the face of increasing hazards.
[2] Fragility curves indicate the damage to infrastructure from the impact of a hazard such temperature, fire, flooding, wind, etc.

Characterize the mission (e.g., primary production, research, environmental remediation, weapons production and maintenance) to determine critical systems and potential valuation methods.

– *Define systems and baseline conditions*

  Determine a baseline that identifies the current conditions for the DOE site to be analyzed, including its infrastructure systems (e.g. facilities, utilities), as well as natural and human "systems" that could be exposed to hazards and would need to be quantified.

- Assess Vulnerability and Risk
  - *Quantify hazard probability and thresholds*

    For relevant hazards, determine the probability of occurrence at the specified DOE site. In addition, establish any thresholds for exceedance that may provide an indicator of vulnerability and impact.

  - *Establish baseline resilience value*

    Using a vulnerability screening or assessment, assess resilience value or damage to baseline based on fragility curve. This is the probability of damage.

  - *Value impacts to baseline*

    For the potential site vulnerabilities identified, value the impacts of a hazard on the baseline. Determine the life-cycle costs over time based on probability of occurrence, vulnerability and resilience value of the baseline using outlined valuation approaches or other methods.

- Develop a Resilience Plan
  - *Establish resilience measures*

    Develop alternative measures to improve resilience and mitigate impacts of hazards and delineate how the improvements increase resilience. This is primarily a qualitative assessment.

  - *Evaluate alternatives to determine resilience*

    Determine feasible alternatives by preliminarily eliminating alternatives that are technologically underdeveloped, do not meet budget parameters or are not cost effective. This is a high level feasibility analysis. Provide a resilience value for each remaining alternative.

  - *Value each alternative*

    Using methodology in Step 2, determine the life-cycle costs based on probability of occurrence, vulnerability and resilience value for each remaining alternative. Value implementation costs for each alternative and value any benefits. Determine the net present cost of each alternative.

- Undertake Cost-Benefit Analysis
  - *Compare valuation of action to inaction*

    Using net present cost/value analysis, compare alternative actions with the baseline.

  - *Establish non-monetary costs and benefits*

    Define non-monetary costs and benefits for the baseline and alternatives for use in the decision portfolio.

- Create Decision Portfolio
  - *Determine decision criteria*

Obtain information on criteria important to decision-makers.

– *Obtain weights for decision criteria*

  Work with the decision-maker to develop weights that reflect the importance of each criteria to the ultimate decision on which alternative is best.

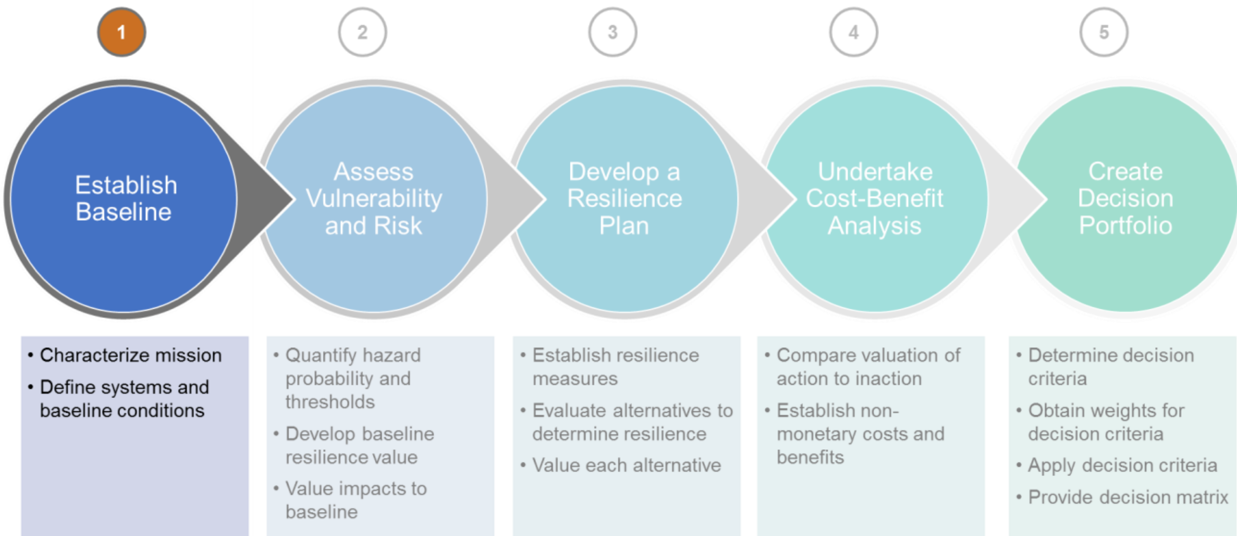
– *Apply decision criteria*

  Apply the weights and decision criteria to the alternatives to develop a decision matrix.

– *Provide decision matrix*

  Provide portfolio of options to the decision-maker so that a decision can be made.

3.1 Step 1: Establish the Baseline



Step 1 characterizes the mission and establishes the cost baseline for the systems at risk throughout the analysis period. The inputs required to develop the site's baseline costs include an inventory of the affected systems such as facilities, human capital, and adjoining infrastructure including roads, electricity, water, and waste connections, and annual operation and maintenance (O&M) costs for the affected missions. An important part of the baseline is the timeframe over which resilience will be valued. Mission life and/or asset life determines the time period for which costs are obtained and/or developed. Mission life is the period over which the project will be completed. If the mission life or asset life is 100 years, then costs would be assessed over the 100 time period. Table 3.1 provides the inputs required to complete Step 1 and potential sources of that information. The outputs from this process are estimated costs over the lifetime of the mission or asset.

Table 3.1. Inputs, Outputs and Data Sources for Step 1, Establish the Baseline

	Core Systems to Effectively Deliver Missions(s)								
	Facilities	Human Capital	Energy	Water	Transportation	Supply Chains	Communications Systems	Ecosystems	Health Services
Inputs									
Mission Length	Years	Years	Years	Years	Years	Years	Years	Years	Years
Value required	Number and types of facilities and square footage	Number of workers	MMBTUs by energy sources, Number and type of connections by energy type	Gallon capacity, miles of pipe, storage	Miles by type	Number and types	Miles of cable, number of landlines and wireless phones, communication systems		Number of beds, staff, ambulances, emergency rooms
Lifetimes	Facility life		Expected lifetime by type of equipment						
Replacement Period	Years of remaining life		Years of remaining life	Years of remaining life	Years of remaining life		Years of remaining life		Years of remaining life
Current Value	$/square foot	Annual cost	Annual cost	Annual cost	Annual cost	Impact to mission	$/system		$/square foot
Replacement value	$/square foot		Cost	Cost	Cost		$/system	Replacement cost	$/year on services
Operations and Maintenance Costs	$/year (exclude workers below)	Average salary/year	$/year, $/MWh, $	$/year	$/year		$/year	Maintenance cost	$/year
Outputs									
Estimate Baseline Costs	Cost t0	Cost t0	Cost t0	Cost t0	Cost t0	Cost t0	Cost t0	Cost t0	Cost t0
	Cost t1	Cost t1	Cost t1	Cost t1	Cost t1	Cost t1	Cost t1	Cost t1	Cost t1
	Cost ….	Cost ….	Cost ….	Cost ….	Cost ….	Cost ….	Cost ….	Cost ….	Cost ….
	Cost tn	Cost tn	Cost tn	Cost tn	Cost tn	Cost tn	Cost tn	Cost tn	Cost tn
Data Sources									
Site*	Project budgets	Human Resources	Project budgets	Project budgets	Project budgets	Project budgets	Project budgets	Project budgets	Project budgets
Other	RS Means**	RSMeans	RSMeans	RSMeans	RSMeans	RSMeans	RSMeans	RSMeans	RSMeans
	Army Corp of Engineers estimates		Utility companies	Utility companies	Department of Transportation	Manufacturing databases	Utility companies	Utility companies	Local hospitals

* Be sure to avoid double counting between systems

**RSMeans is a tool to estimate costs.

3.1.1 Characterize the mission

The exact missions supported by each site need to be understood by the evaluation team to determine how hazards may impact the ability of DOE to carry out those missions. Understanding the mission will help in the identification of the critical infrastructure and services required to complete the mission that needs to be valued. DOE has four primary missions: energy transformation, science and innovation, nuclear safety and security including nuclear waste cleanup, and management and operational excellence. These missions are carried out by a wide range of facilities across the country that include national laboratories, nuclear production facilities, power marketing administrations, environmental remediation projects, and more. Each facility's mission will directly impact the value of disruption to its operations by a hazard. For example, sites with research missions will have different critical infrastructure requirements than nuclear material maintenance sites or primarily waste remediation sites. Different missions may influence decision criteria as well as what is considered a critical asset that needs to be valued.

The site vulnerability screening or assessment describes the mission and the systems most likely to have a high probability of a hazard that results in a high consequence. Generally, only the systems that have high risk and consequence will be assessed. An example from the Hanford Site vulnerability assessment is provided below in Figure 3.2. As shown in the figure, only Ecosystem Recovery and Worker Safety and Health systems were identified as high vulnerability systems (red), from exposures to wildfire and high temperatures respectively. The red categories are the systems and hazards that will be evaluated and for which further information will be obtained or developed as required. The combined hazards and exposures in yellow and green were not thought to have significant impact on the site's ability to complete the mission based on the qualitative evaluation. Other hazards that could be evaluated include earthquakes, man-made events, accidents, and malicious intent.

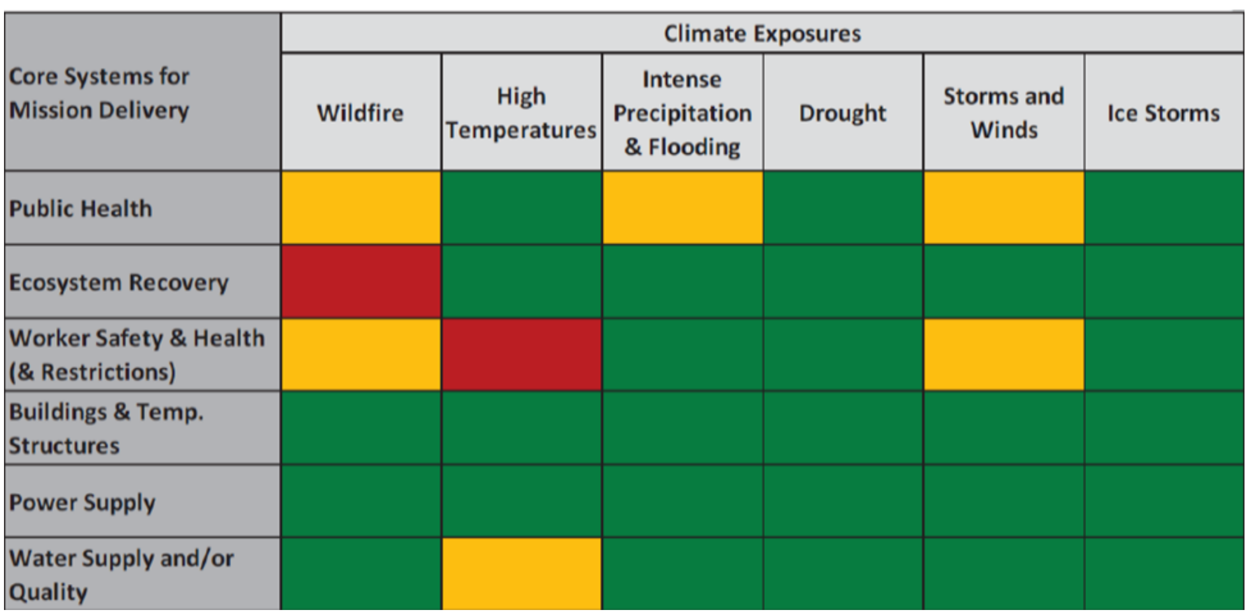


Figure 3.2. Characterization of Hanford Site Risks to Mission Delivery

3.1.2 Define systems and baseline conditions

The systems with high risk of impact to exposures (based on in the initial screening) need to be defined, and the costs associated with the baseline need to be developed. Initial asset values for hazard-effected buildings and equipment can be obtained from project costs or can be developed using RSMeans[11] or $/square foot if the value is unknown. Information on the lifetimes of assets and equipment coupled with their remaining life indicates when replacement costs need to be implemented in the baseline. The asset lifetime dictates how many times the asset will be replaced over the mission life. Replacement costs may be less than initial costs because of reduced installation costs. Current value for annual costs refers to baseline costs for labor, energy, water, or any other significant recurring cost. Operations and maintenance costs refers to those costs for replacement parts or upkeep of assets and equipment. Care should be taken to not double count labor costs in the human capital and operations and maintenance categories. An additional consideration is the overall timeframe for the analysis. Asset lifetime provides a minimum timeframe. Site personnel can provide an appropriate timeframe for the baseline they wish to be analyzed. More information on the exact items to be valued can be found in Appendix A.

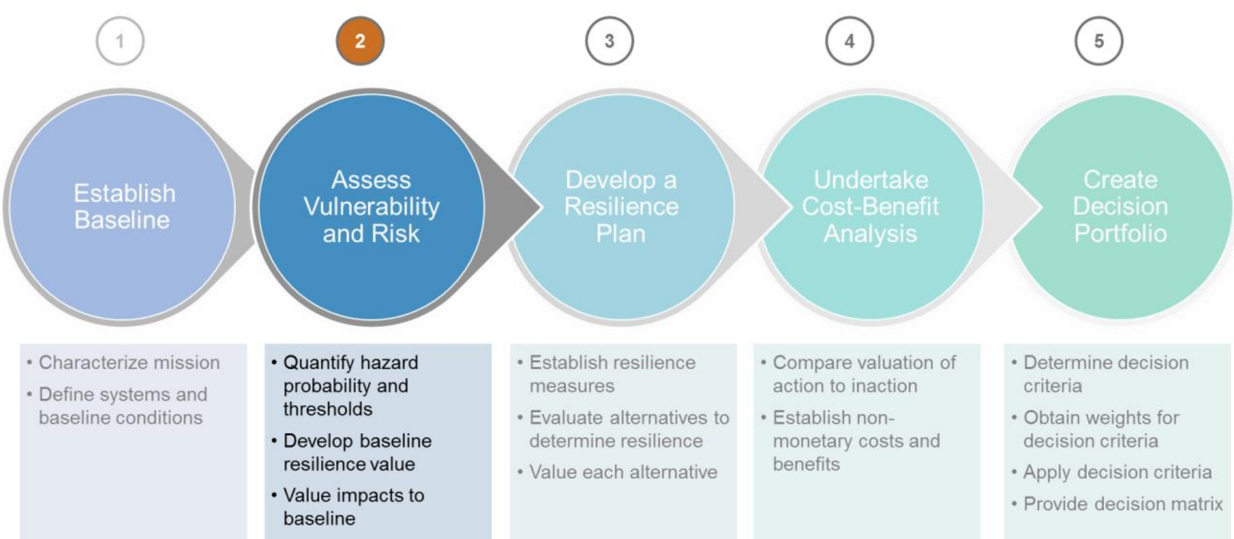
The resulting output from the baseline are the costs by system by year, for example, the labor and capital requirements by project affected by high temperatures on the Hanford Site. The costs can be obtained from the project budgets. To the extent that the project budgets do not provide enough information on affected systems, RSMeans or other cost estimating tools can be used. Project budgets usually include near-term costs plus costs until completion. The out-year costs that are not explicitly stated can be determined by interpolation to complete the cost string. The resulting baseline will include costs for the baseline for each year for each system:

$$[c_{0ij}+c_{1j}+c_{2j}+...+c_{nj}]$$

where

c_0 = t year costs
1...cn = out-year costs by year
n = mission length or asset life
i = the i^{th} cost typej refers the j^{th} system such as facilities, human capital

3.2 Step 2: Assess Vulnerability and Risk



[11] RSMeans is a tool to estimate costs.

Step 2 quantifies hazard probabilities, develops a resilience value or damage to the baseline, and establishes the value at risk by valuing the impacts of the hazards. Vulnerability assessments are assumed to have been completed by a site using the vulnerability assessment guidance released in 2015.[12] General vulnerabilities can be found from vulnerability screenings.[13] Vulnerability screenings and assessments provide key knowledge which is instrumental in this step. Lastly, the resilience of the site's current baseline conditions is established and a quantitative value is placed on that baseline using the timeframe of the analysis, probabilities of occurrence, the damage caused by the hazard, and the value of facilities to obtain a value at risk.

This can be summarized as follows. The risk exposed to infrastructure by a hazard needs to be captured quantitatively so that the value of resilience measures can be assessed in a methodical manner. The methodology includes finding the probability of a hazard, the impact of the hazard on the infrastructure and resilience measures in place, and the value of infrastructure impacted. The valuation requires the following set of information:

- Probability of a hazard
- The vulnerability of specific systems based on site assessment
- The fragility curves for the infrastructure impacted and
- Quantified and monetized (as applicable) impacts to facility from the hazard

The fragility of infrastructure is defined by, and calculated based on its preparedness to anticipate, mitigate, respond to, and recover from a hazard. The fragility curve indicates the amount of damage or impact that the hazard will have on a specified type of infrastructure. The multiplication of the amount of damage and the value of that damage will be the cost of repair or replacement of the infrastructure. Figure 3.3 illustrates this approach to valuing the damage to infrastructure based on a fragility curve. The resultant calculation will yield the expected impact to the infrastructure based on the probability distribution of a hazard. However, the actual realized value (due to a hazard) may be different because of the existing or alternative resilience measures at the facility.

[12] Practical Strategies for Climate Change Vulnerability Assessments. SPO. December 2015. https://powerpedia.energy.gov/w/images/6/6b/Practical_Strategies_for_Climate_Change_Vulnerability_Assessments_12.8.15.pdf

[13] Climate Change Vulnerability Screenings. SPO. January 2017. https://powerpedia.energy.gov/w/images/e/e6/DOE_Vulnerability_Screening_Guidance.pdf

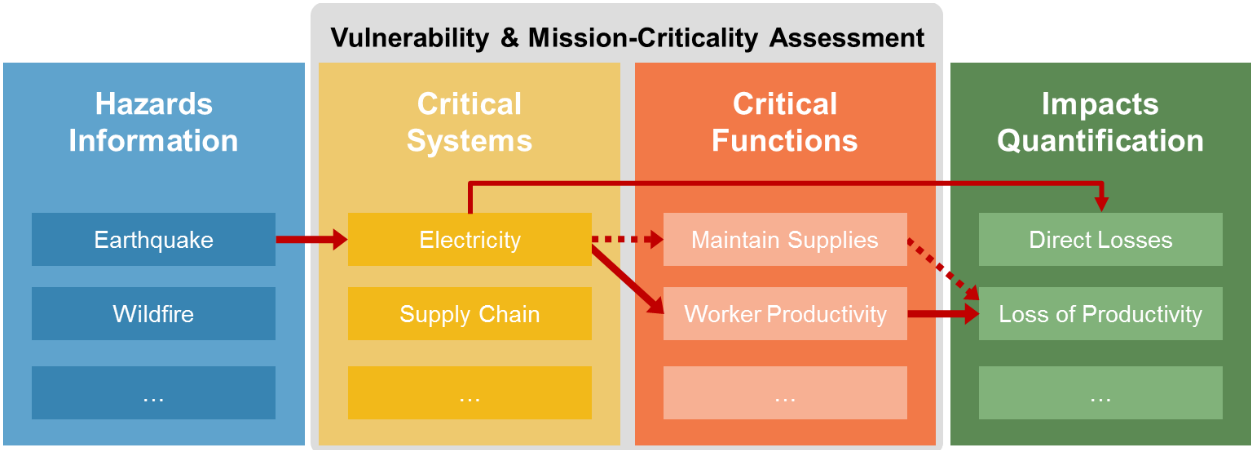


Figure 3.3. Mapping Impacts to Critical Infrastructure and Functions to Determine Resilience. Impacts quantification includes direct and indirect impacts and interactions.

The inputs and outputs of this step are shown in Table 3.2. The inputs to this step include the costs developed in Step 1, the hazard and probability over time, the fragility curve and associated damage function, and any identified benefits. The outputs of this step are the net present costs/benefits of the baseline.

Table 3.2. Inputs and Outputs for Step 2. Assess Vulnerability and Risk

	System Baseline Resilience Value
Inputs	
	Costs developed for baseline
	Hazards probabilities
	Fragility curve and associated damage function
	Itemized benefits (if any) by year
Outputs	
	Cost t0 × HP0 × Fragility Curve Score$_0$
Estimate Discounted Lifecycle Resilience Costs/Benefits	((Cost t_1 × HP_1 × Fragility Curve Score$_1$) / (1+d)^^{1}) + ((B_{11} + … + B_{1n})/(1+d)^^{1}))
	((Cost t... × HP... × Fragility Curve Score...) / (1+d)^...) + ((B11 + … + B1...)/(1+d)^...))
	((Cost tn × HP_n × Fragility Curve Score$_n$) / (1+d)^^{n}) + ((B_{1n} + … + B_{nn})/(1+d)^^{n}))
Data Sources	
Site*	Budget personnel, human resources, technical personnel
Other	Hazard forecasts
	Fragility curve literature or developed with input from SMEs

3.2.1 Quantify hazard probability and thresholds

After the baseline cost is established, the next stage is to understand the hazards that might affect the site and to quantify the probabilities of occurrence or exceedance of a relevant threshold. Focus on the hazards of greatest concern based on the vulnerability screening or assessment because probability determination often requires subject matter expertise and effort.

DOE assets are at risk from natural hazards such as earthquakes, wildfires, and floods, as well as man-made hazards and threats, such as technological accidents and terrorist attacks. These hazards or threats pose a risk to life and property and can compromise mission fulfillment; understanding these risks so that they can be appropriately mitigated or otherwise addressed is of clear importance to DOE and to the Nation. The hazards and threats described are considered to be those most likely faced by DOE and are not a comprehensive list (see Table 3.3).

Table 3.3. Examples of Hazards and Threats

Severe Weather	Natural Hazards	Other
Hurricanes	Sea Level Rise	Terrorist Attacks
Ice Storms	Wildfire	Failure to Perform
Lightning	Desertification	Infrastructure Maintenance
High Temperatures	Erosion & Sedimentation	Accidents
Heat Waves	Ground Stability	Armed Assault
Severe Cold	Landslides	Cyber Security Attack
Drought	Invasive Species Earthquake	

Understanding and quantifying the hazards requires translating them into observable hazard information for weather indicators, and finding the probabilities and magnitudes for various natural and man-made hazards. Preferably the data will include data series with enough observations that a baseline can be established from which change is measured. Here we discuss each of the indicators and the most easily accessible data source. Each individual data source will contain information about its own quality assurance/quality control process and the reliability of the data in particular circumstances. As such, we refrain from making conclusions about data quality here, as the issues that are likely to emerge will be site- and situation-specific. The process to develop the probability involves several steps.

A first step in quantifying the hazard is identifying which environmental variables match the stressor. In the Hanford Site example, temperature, precipitation, and snow cover are key variables required to assess the hazards. If there are other derivative variables that have important exceedance thresholds, which would indicate system impacts, those should be identified as well. For example, Hanford Site wet bulb globe temperature (WBGT), which is a measure of heat stress in direct sunlight, affects the ability of workers to perform duties outdoors. At different WBGT thresholds, different work/rest regimens apply.

Next, collect data for those variables at the site being analyzed, of the correct temporal resolution. This typically means acquiring data on current conditions and forecasted changes to those variables during the mission or asset lifetime. Potential data sources for different hazards are described in 4.2.5.4Appendix B. In some cases, forecasts for future conditions are not available and must be calculated. For example, calculating WBGT requires information about temperature, relative humidity, wind speed, cloud cover, and sun angle. In some cases, daily WBGT may be measured directly and is available for analysis. In many cases, longer-term records of daily data will only be available for the constituent variables, i.e., temperature, relative humidity, wind speed, and cloud cover. (Sun angle can be calculated as a function of latitude and day of year.) Because the environmental hazard of heat stress is calculated on an individual day basis, it is important to obtain data for those variables at a daily or finer frequency. Sub-daily data is useful for understanding how many hours per day workers may be affected; this can be approximated by obtaining daily maximum and minimum temperature, which is likely more readily available than sub-daily data. It is important that the data cover a sufficiently long time period to calculate statistics. An even longer period will enable assessments of stationarity, i.e., whether the distributions are changing over time, and how well those shifts can be characterized to quantify future probabilities of occurrence.

Lastly, calculate probability distributions of the variables of interest. This is often done by creating histograms and fitting those histograms to generalized extreme value distributions. (See 4.2.5.4Appendix B for more information on determining probabilities for hazards.) (Other distributions may also be applicable, but extreme events have largely been shown to be well characterized by generalized extreme value distributions.) This information is needed to complete the next sub-steps, "Develop baseline resilience value" and "Value impacts to baseline," which estimates the damage function of the stressor on the baseline system based on the probability of the hazard and intensity, and places a value on the damage. The information is also needed for Step 3, which values the resilience impact of mitigation alternatives. Figure 3.4 provides an example of a probability for floods.

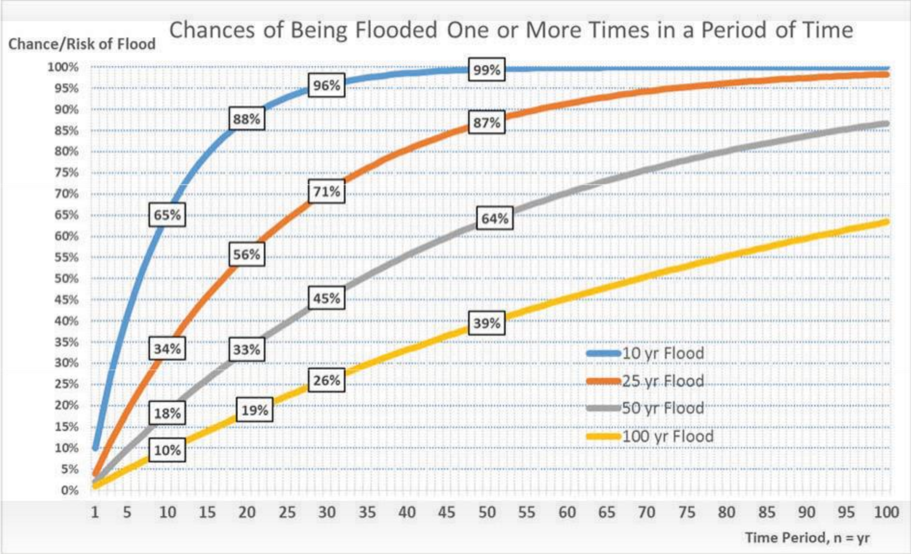


Figure 3.4. Probability of Floods of Varying Return Periods (or severities; colored lines) Occurring within a Given Period of Time. Determining the return periods and how those return periods might change is a key outcome of environmental risk assessments, such as the ones described in this document. Figure 3.4 is reprinted from Figure III.4 of the Naval Facilities Engineering Command's volume on installation adaptation and resilience.[14]

Summarizing this stage, the required minimum input for each environmental hazard is data corresponding to variables that characterize the hazard on the appropriate temporal frequency. The output of this stage will be probability distributions of occurrence at different levels for those variables.

3.2.2 Develop baseline resilience value

Using results from the vulnerability screening or assessment, develop a current resilience value for the site based on robustness of current measures implemented to manage the risks. This considers the potential loss impact if a specific type of hazard (e.g., high temperatures, flooding) were to occur as well as the facility's vulnerability to such a hazard based on security measures in place. The scale of loss is likely to differ between facilities and is dependent upon the activities and objectives of each location. The loss impacts are analyzed at different scales from a hazard that inflicts minimal impact to one that is catastrophic. The preventative measures in place (such as infrastructure resilience measures) help to guide

[14] NAVFAC (2017), Climate Change Installation Adaptation and Resilience: Planning Handbook, 193 pp.

the probability of such events occurring. The combination of the loss impact and level of vulnerability are then combined to evaluate the level of inherent risk the facility faces for each type of scenario.

Using a vulnerability assessment of the site infrastructure, evaluate the impact of hazards and stressors on facilities and the resultant costs due to damage, lost time, and any environmental damage. Each site's impact from hazards will likely be different. In some cases, hazards may have little or no impact. For example, sites not located in an earthquake subduction zone are not likely to have an earthquake hazard and facilities not located on the ocean or bays are not likely impacted by sea level rise or inundation hazards. Even a site in an earthquake prone area may not have much damage from an earthquake depending on the magnitude and the facilities' construction.

This methodology requires an in-depth knowledge of the *event tree* or how an event impacts the infrastructure. A hazard impacts critical systems, which leads to disruptions in performance of critical functions, leading to impacts from direct loss of work, life and/or property. The impact assessment also considers external economic losses, such as those occurring from the loss of productivity (see Table 3.4).

When a stressor exceeds a threshold, fragility curves can be used to assess damage or the impact to a system, such as labor or facilities. Fragility curves are specific to the hazard and the system being impacted. Thus, the fragility curve needs to be determined and adapted to the site's conditions. The fragility curve will indicate the vulnerability of the system to exceeding the hazard threshold where damage occurs. Greater impact will likely occur as the threshold is further exceeded.

Fragility curves have been developed for a number of hazards including sea level rise, seismic activity, flooding, hurricanes, human health, heat effects on human productivity, agricultural productivity, household energy demand, and fire. The impacts from the hazards have been developed for a number of different types of infrastructure.[15,16] The fragility indicates the amount of damage to an infrastructure based upon statistical evidence.

Select the appropriate fragility curve(s) based on the stressor and the system components being impacted by the stressor. For example, the heat stress in the Hanford system impacts work productivity based on levels of temperature exceedance. Figure 3.5 provides an example of the fragility curves for WBGT exceedance at each level. The original data is sourced from the Occupational Safety and Health Administration (OSHA). Note that the work regime is instituted only if the WBGT exceeds the listed temperature.

[15] National Institute of Building Sciences. Dec 2017 "Natural Hazard Mitigation Saves: 2017 Interim Report. Washington, DC.

[16] Roson, R, M. Sartori. June 2016. "Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database." World Bank Group. Policy Research Working Paper 7728. Accessed January 31, 2018 at http://documents.worldbank.org/curated/en/175901467994702565/pdf/WPS7728.pdf

Table 3.4. Examples of Impacts and Interactions with Other Systems

Critical Systems	Impacts	Interactions
Energy		
Energy Resources	• Lack of energy delivery • Higher energy cost	• Reduced productivity • Lost work time • Lost experimental data
Electricity	• Outage • Sensitive equipment damage • Power quality	• Lost work time • Reduced production • Lost experimental data
Facilities	• Destruction • Damage	• Lost work time • Lost experimental data
Communication		
Telecommunications	• Loss of service	• Less effective work • Lost work time
Information Services	• Loss of service	• Less effective work • Lost work time
Human Capital	• Lost time	• Lost life • Reduced research •
Water Resources	• Insufficient cooling power • Damage to equipment	• Lost work time • Heat stroke
Transportation	• Damaged transportation modes	• Increased accidents • Lost life • Lost work time
Mission-critical Services and Supply Chains	• Facility destruction • Supply disruption	• Output reduction • Lost work time • Reduced productivity
Healthcare and Public Health	• Radioactive waste spillage	• Lost life • Radioactive illnesses • Increased regulatory oversight (mission curtailment)

MSA Screening Criteria for Heat Stress Exposure (WBGT values)

	Acclimatized				Unacclimatized			
Work Demands	Light	Moderate	Heavy	Very Heavy	Light	Moderate	Heavy	Very Heavy
100%	85.1°F	81.5°F	78.8°F		81.5°F	77.0°F	72.5°F	
75% Work; 25% Rest	86.9°F	83.3°F	81.5°F		84.2°F	79.7°F	76.1°F	
50% Work; 50% Rest	88.7°F	85.1°F	83.3°F	81.5°F	86.0°F	82.4°F	79.7°F	77.0°F
25% Work; 75% Rest	90.5°F	87.8°F	86.0°F	85.1°F	87.8°F	84.2°F	82.4°F	79.7°F

Clothing Type	WBGT Additions
Work Clothes (long sleeve shirt and Pants)	0° F
Cloth (woven material) overalls	6°F
Double-cloth overalls	9°F
SMS polypropylene coveralls	1°F
Polyolefin coveralls	2°F

Figure 3.5. Fragility Curve for Worker Productivity at the Hanford Site[17]

In the figure, the threshold where work is not impacted depends on the level of exertion. The temperature threshold for productivity declines as the workload increases. Additionally, the temperature thresholds are lower during the acclimatization period. Thus, the acclimatization period length needs to be accounted for in the estimation of impact as well as that amount of work that falls into each of the four categories. The example indicates that the forecasts for WBGT need to include length period during the day when the thresholds are exceeded. Some mitigation strategies include working during the night. Without knowing whether the WBGT thresholds are exceeded during the night, the resulting damages could be understated. In addition, the type of clothing lowers the WBGT.

The output of this step is the damage function by year. The damage function in conjunction with the hazard probability indicates how badly a facility, equipment, other structure or workforce is damaged, and the amount of repairs required to resume function. Additionally, it may indicate how each of the associated systems are affected. Make sure to investigate interactions between the systems based on the damage function. In the example above, the fragility curve will indicate how many more hours are required in order to obtain the same amount work.

3.2.3 Value impacts to baseline

Using the probabilities of hazard and the fragility curve information obtained in the two previous sub-steps, value the impacts of a hazard on the baseline using outlined valuation approaches or other methods. See 4.2.5.4Appendix C for more information on valuing the components of the baseline. Some of the impacts include destruction of or damage to facilities, lost work time, and potentially loss of or reduced life span. There may be economic benefits as well as costs due to the impacts from severe events. Table 3.5 provides examples of impacts to be valued.

[17] SW Davis. Oct 2016. Hanford Climate Vulnerability Assessment and Resilience Action Plan. Mission Support Alliance. HNF-60309-VA

Table 3.5. Example Impacts to be Valued

Critical Systems	Valuation Approach
Energy	
Energy Resources	• Willingness to pay • Cost of storage • Economic impact
Electricity	• Value of lost load • Replacement or repair damaged equipment • Economic impact
Facilities	• Replacement • Repair costs • Changed O&M • Economic Impact
Communication	
Telecommunications	• Willingness to pay • Economic impact
Information Services	• Willingness to pay • Economic impact
Human Capital	• Willingness to pay • Value of human life • Economic impact
Water Resources	• Increased equipment repair or replacement • Willingness to pay • Economic impact
Transportation	• Willingness to pay • Increased cost of network infrastructure • Cost of repair or replacement • Economic impact
Mission-critical Services and Supply Chains	• Value of deterrence • Willingness to pay • Economic impact
Healthcare and Public Health	• Cost of increased health care • Reduced lifespan • Increased cleanup costs • Increased liability for health care

3.2.3.1 Value the Costs and Benefits of the Baseline

The costs of the impacts of the baseline needs to be estimated for each system analyzed. The approach should include individuals who can ensure that the valuations are defensible. They include budget planners, cost professionals, engineers, and the purchasing office who will probably have access to procurement invoices.

Some of the impacts include destruction of or damage to facilities, lost work time, and potential loss of assets or reduced life span of assets and human resources. There may be economic benefits as well as costs due to the impacts of hazards. Several Federal agencies have different tools to estimate costs and value impacts such as the Department of Defense (DOD), Bureau of Labor Statistics (BLS), Environment Protection Agency (EPA) and the Federal Emergency Management Agency (FEMA). For example FEMA has tools to assist in valuing the impact of floods, hurricanes, earthquakes etc.[18] There are private sector tools as well.

3.2.3.2 Determine Timing of Costs and Lifecycle Costs

Life cycle costs need to be developed to determine the timing of impacts and to complete the valuation of impacts. Lifecycle costs represent the total costs of a project including: planning, design, construction, operations and maintenance, replacement, and decommissioning. Lifecycle costs can be estimated by applying the timing of impacts to values of cost estimated in the valuation approaches above. Working with technical experts and the probabilities determined from analysis of the hazards in Step 2, apply the timing of impacts across the timeframe developed with site assessment personnel. The timing of baseline-preventative maintenance and operations costs need to be included in "spreading" costs and impacts. As such, the costs of the baseline should be spread over time as the discounting of costs will impact net present cost/value calculations in a later step. Lastly, apply the value at risk equation to determine the value of the impact after resilience is determined:

$$\text{Expected Value at Risk }(X) = \sum_{i,t>0} \text{Expected Value at Risk }(X_i) = \sum_{i,j,t} \text{Prob}(\text{H}_{ijt}) \times \text{Prob}(\text{F}_{ijt}) \times \text{Prob}(\text{V}_{ijt})$$

where

X_i = infrastructure i
H_j = hazard j
F_{ij} = fragility impact of hazard j on infrastructure X_i
V = value of impact on X_i
t = year in the framework ($t \geq 0$)

Probability ranges and expected values should be determined to the extent possible. Refer to the information provided by points of contact (POCs) that provided the hazard probabilities and the resilience measures. Expert judgement may be required using triangular distributions of the risk (also known as lowest probability, expected probability, and highest probability of occurrence) if quantifiable risk probabilities do not exist. The experts required to undertake the risk quantification include POCs from the vulnerability assessment, as well as other SMEs.

3.2.3.3 Calculate Net Present Cost/Value of Baseline

The net present cost/value of the baseline discounts the life-cycle costs using a discount rate. The resulting value can then be used to compare costs and benefits of alternatives on a time-of-occurrence basis. Near-term impacts are valued more highly than costs that occur in the future. Note there are two approaches to calculating the net present cost/value. The first approach calculates the net present cost of the baseline. This can only be used if the baseline has no benefits. The alternative approach values the reduction in damages and improvements in O&M costs as benefits over the baseline. If there are benefits associated with the baseline, net present value is the most appropriate approach.

[18] FEMA-Federal Emergency Management Agency. 2011. FEMA Benefit-Cost Analysis: Re-engineering, Develop of Standard Economic Values. Version 6.0. Accessed September 25, 2017 at https://www.hudexchange.info/course-content/ndrc-nofa-benefit-cost-analysis-data-resources-and-expert-tips-webinar/FEMA-BCAR-Resource.pdf

Net present cost

$$\text{Expected Value}(X) = \sum_{it} \text{Prob}(\text{Hazard}_{it}) \times \text{Prob}(\text{Fragility Impact}_{it}) \times \text{Prob}(\text{Value of Impact}_{it})/(1+r)^{\wedge t})$$

where

Expected Value	=	the cost or value of resilience in the baseline
i	=	i^{th} hazard
t	=	year t in the framework from 0 to t years
r	=	the discount rate

Net present value

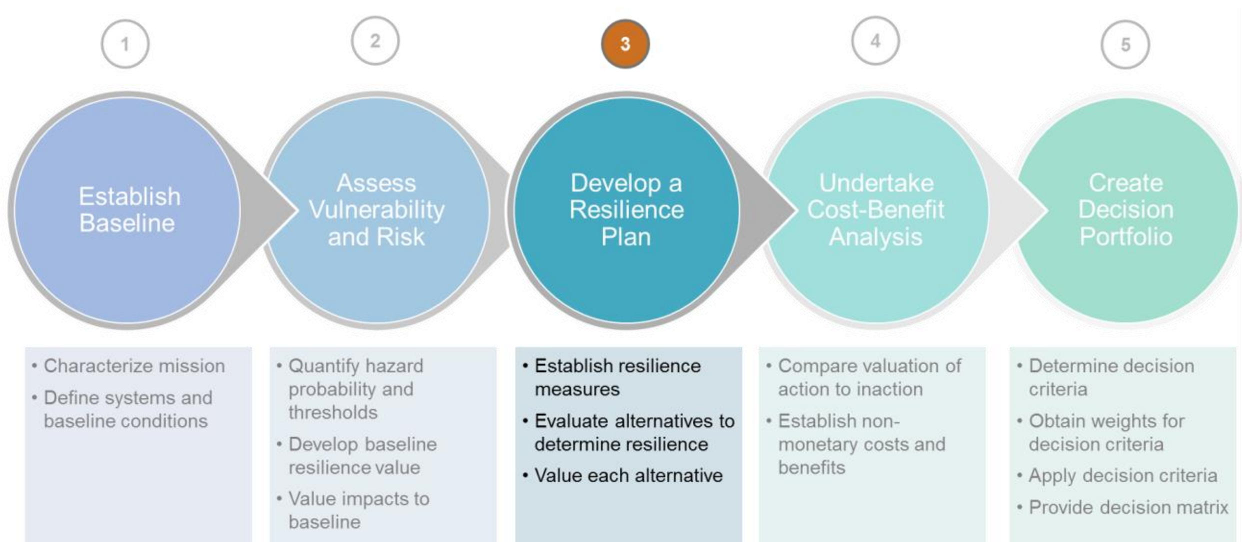
$$\text{Expected Value}(X) = \sum_{it} (-\text{Prob}(\text{Hazard}_{it}) \times \text{Prob}(\text{Fragility Impact}_{it}) \times \text{Prob}(\text{Value of Impact}_{it} + \text{Prob}(\text{Benefits}_{t}))/(1+r)^{\wedge t}$$

where

Expected Value	=	the cost or value of resilience in the baseline
i	=	i^{th} hazard
t	=	year t in the framework from 0 to t years
r	=	the discount rate

Appropriate real discount rates for the analyses are 7%, the market rate of return, according to the Office of Management and Budget (OMB) circular A94.[19] Other discount rates can be included to indicate the sensitivity of the baseline to different discount rates. The internal rate of return of the baseline is one alternative. Another rate of return could be the real discount rate of 3%.

3.3 Step 3: Develop a Resilience Plan



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[19] White House. 1992. Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Accessed September 23, 2017 at https://www.whitehouse.gov/omb/circulars_a094

In this step, resilience measures that mitigate the impacts of severe events will be identified, each alternative will be evaluated using the methodology in Step 2 to determine the improved resilience as compared with the baseline, and a value will be established. Thus the inputs to this step are the mitigation alternatives that improve the resilience of the baseline, their costs, hazard probability and the fragility or damage assessment improvement and any itemized benefits of the mitigation alternative. The outputs are the lifecycle costs and the net present cost or value (Table 3.6).

Table 3.6. Inputs and Outputs of Step 3

	Alternative X
Inputs	
	Costs developed for Alternative X based on approach in Step 1
	Hazard Probability developed in Step 2.1
	Damage curve from Step 2.2
	Itemized benefits by year for Alternative X
Outputs	
Estimate Discounted Lifecycle Resilience Costs/Benefits	Cost t_0 × HP_0 × Damage Curve $Score_0$
	((Cost t_1 × HP_1 × Damage Curve $Score_1$) / (1+d)^^{1}) + ((B_{11} + … + B_{1n})/(1+d)$^{\wedge 1}$))
	((Cost $t_{\ldots}$ × $HP_{\ldots}$ × Damage Curve $Score_{\ldots}$) / (1+d)^$^{\cdots}$) + ((B_{11} + … + $B_{1\ldots}$)/(1+d)$^{\wedge\cdots}$))
	((Cost t_n × HP_n × Damage Curve $Score_n$) / (1+d)^^{n}) + ((B_{1n} + … + B_{nn})/(1+d)$^{\wedge n}$))
Data Sources	
Site	Budget personnel, human resources, technical personnel
Other	Hazard forecasts
	Damage curve literature

3.3.1 Establish resilience measures

The vulnerability assessment should have identified the critical systems and priorities of the site. Alternative resilience measures should be identified based on the vulnerability assessment results. The resilience alternatives need to be technologically and politically feasible. Alternatives that are not feasible should not be included in further analysis. Only measures that improve resilience of the critical systems need to be analyzed.

Resilience measures reduce or mitigate the impact of a hazard to critical systems. Resilience measures include adding extra fuel storage if fuel is a critical supply in a system. Adding storage would improve resilience during a period of system disruption by adding days of operation due to a break in shipments. Similarly, providing backup power or energy storage for critical systems improves resilience of the electrical system in the face of outages. See Table 3.7 for examples of resilience measures.

Table 3.7. Example Resilience Measures[20,21]

Critical Systems	Resilience Measures	
Energy		
Energy Resources	• Energy conservation measures (e.g. increased insulation, high efficiency windows)	• Storage
Electricity	• Surge protectors • Regular maintenance of electrical systems	• On-site renewable energy • Microgrids • Backup power • Additional feeders
Facilities	• Harden facilities (earthquake-resistant infrastructure, fire-proofing, security, etc.)	• Clarification of responsibilities of infrastructure partners
Communication		
Telecommunications	• Improved distribution infrastructure and equipment	• Clarification of responsibilities of telecommunication partners
Information Services	• Offline backups • Restoration and recovery support	• Data security measures • Cybersecurity training
Human Capital	• Telework enabled workforce • Enhanced safety procedures • Information sharing and coordination of procedures with necessary partners • Establish protocols for threat and incident reporting	• Business continuity planning and training • An environment that supports security and monitoring practices
Water Resources	• Water conservation measures • Backup water storage • Maintenance of infrastructure network	• Strengthen partnership with resource suppliers
Transportation	• Improved network infrastructure • Maximizing efficient usage of resources • Redundant and/or substitute systems	• Regular maintenance
Mission-critical Services and Supply Chains	• Harden facilities • Establish multiple alternative supply agreements	• Clarification of responsibilities of supply chain partners and/or suppliers
Healthcare and Public Health	• Improved protection of waste sites • Prioritization of actions during emergencies • Biomedical hazard detection equipment and training	• Planning and training to respond to events and mitigate damage • Backup generation • Additional fuel/water storage

Measures to improve facility resilience include the following: hardening the facility to extreme weather events or earthquakes by bringing facilities up to current building codes to resist potentially higher than currently expected hazards, and providing preventative maintenance rather than deferring the maintenance

[20] NIAC, 2009, Critical Infrastructure Resilience, Final Report and Recommendations, U.S. Department of Homeland Security, Washington, D.C., available at http://www.dhs.gov/xlibrary/assets/niac/niac_critical_infrastructure_resilience.pdf

[21] U.S. Department of Homeland Security. National Infrastructure Protection Plan: Partnering to enhance protection and resilience. Washington, D.C.: U.S. Department of Homeland Security, 2009. https://emilms.fema.gov/IS821/assets/NIPP_Plan.pdf

and clarification of responsibilities if more than one group is responsible for facility maintenance and operations. Other potential hardening could include placing backup power and pump facilities at higher floors rather than in basements, if flooding is a potential hazard. Measures could include upgrading equipment and going beyond standard corrective maintenance. Additional measures could include moving facilities to higher ground either at replacement or in the present, depending on resilience improvements. For Heat Stress and Worker Safety at the Hanford Site, the most important resilience alternative is to switch to night shifts when WBGTs rise to the point that work is affected. The addition of a heat exchanger could improve cooling capacities to provide relief for longer period of higher temperatures. See 4.2.5.4Appendix D on methods to evaluate mitigation strategies.

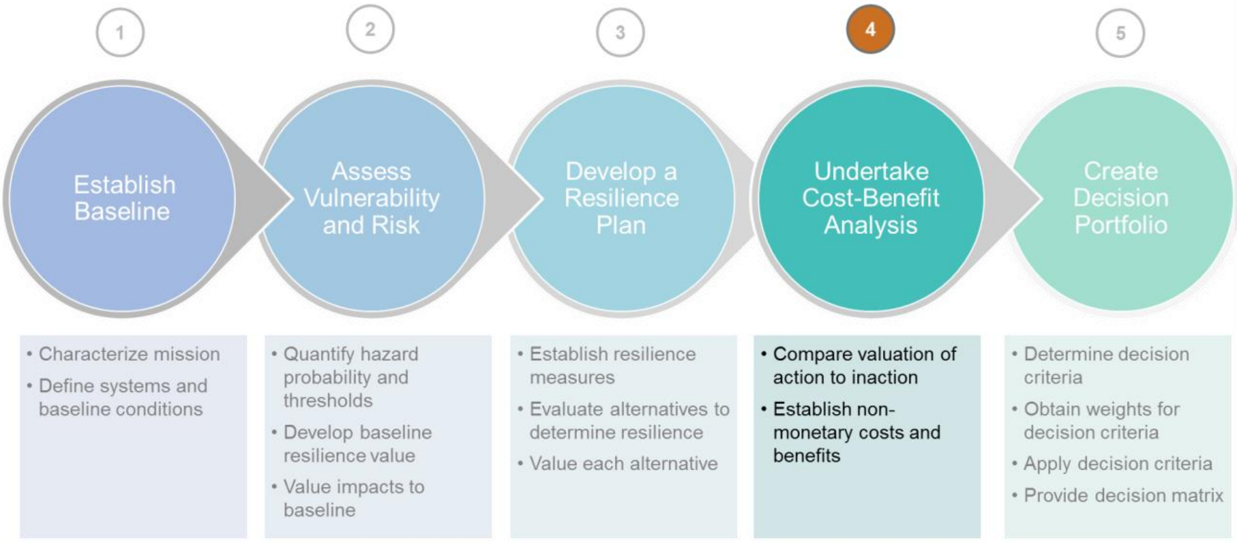
3.3.2 Evaluate alternatives to determine resilience

Once mitigation alternatives have been decided upon, Step 2 should be used to evaluate the impact of the alternative in terms of its damage reduction. The literature can be used to find the impact reductions. If data do not exist related to the reduced impact of the severe event, SMEs may need to be consulted and efforts may be needed to develop the data. They may be able to provide rules of thumb or point to the literature. For example, the subject matter expert indicated that most manufacturers provide guides on how much the capacity of an HVAC system decreases or increases in temperature. As a rule of thumb, the SME indicated that for every 10°F increase, the capacity drops 6%. Thus to maintain the same capacity, it would need to be increased 6% for every 10º increase in temperature. Each site will have a different outcome for a resilience measure, so care should be taken when applying results from one DOE site to another site. Appendix D provides some risk strategies for approaching uncertainty and risk.

3.3.3 Value each alternative

The proposed alternatives which improve the resilience of a site should be valued using the methodology in Step 2 above. The hazards' probabilities remain the same, but a new value for the damage based on the reduced impact determined in Step 3, should be calculated based on the alternative proposed. Once the value at risk has been estimated, the costs, life-cycle costs and net present cost/value for each alternative need to be calculated.

3.4 Step 4: Undertake Cost-Benefit Analysis



The cost-benefit analysis is completed by valuing the impacts on systems in real terms (no inflation included), applying the probabilities of occurrence by year, and using resilience measures to determine the overall costs/benefits per period of time. All the pertinent costs of the baseline and alternatives should be included to determine the life cycle costs. The net present costs/value can then be determined. If net present cost was used, the lowest net present cost is the optimal approach. The highest net present value provides the optimal alternative if costs and benefits are used. A sensitivity analysis can show the extent to which alternatives may change ranking depending on probability ranges and/or the discount rate. If rankings remain the same, then the probability ranges and/or timing of alternatives is not a factor in the later decision-making.

The inputs (Table 3.8) to the cost-benefits analysis include the net present value/costs of the baseline and each mitigation alternative evaluated. The outputs of Step 4 are the ranking of the alternatives based on their metrics and the non-monetary costs and benefits established for each alternative.

Table 3.8. Inputs and Outputs of Step 4

	Alternative X
Inputs	
	Net present cost or value for baseline and alternatives
Outputs	
Benefit/Cost Information	Ranked benefit/cost by metrics
	Non-Monetary benefits and cost
Data Sources	
Site	Budget personnel, human resources, technical personnel
	Subject matter experts

3.4.1 Compare valuation of action to inaction

Once the alternatives have been valued in net present cost/value terms, several metrics can be used to evaluate the baseline and the alternatives. If based on costs, net present cost would be the main metric. The lowest overall cost would be optimal. For net present value approaches, the benefit/cost ratio provides a metric that evaluates whether benefits were greater than the costs that were needed to obtain the benefits. A benefit/cost ratio of less than one is not financially feasible as it does not return benefits greater than its costs. Table 3.9 portrays why different metrics can be useful for evaluating alternatives. The underlined cells indicate the best value for each category.

The baseline or current plans/measures option provides the lowest cost option and highest benefit cost ratio (BCR). The highest benefit is provided by alternative 3, but it is also the highest cost with a negative net present value. The highest net present value is alternative 1, while the best BCR is the baseline. Alternative 2 provides the second highest benefits but only has a BCR of 1.17. Thus, the decision-maker in this example needs criteria to choose between the alternatives which will be discussed in Step 5.

Table 3.9. Example Comparison of Metrics for Alternatives Evaluation

Alternative	Cost	Benefit	NPV	Benefit/Cost

Baseline	100	200	100	2.00
Alt. #1	1000	1700	700	1.7
Alt. #2	3000	3500	500	1.17
Alt. #3	5000	4000	−1000	0.80

3.4.2 Establish non-monetary cost and benefits

Non-monetary or intangible benefits may provide a part of the answer to which of the above alternatives is the best option. Non-monetary costs and benefits are hard to value financially but need to be included in the overall decision-making process. Examples include stakeholder and regulator relations, aesthetics, quality of work environment, historic preservation, security, safety, and sustainability. Intangibles need to be included in the overall evaluation of resilience alternatives. To evaluate the impact of the intangibles associated with an alternative, each intangible needs to be discussed with enough depth that decision-makers can properly factor the component into their decisions. The approach should include the commonalities between the alternatives and those that are unique to a particular area.[22] Some potential non-monetary costs and benefits are shown in Table 3.10. Some effort needs to be spent with those who developed the vulnerability assessment to determine what non-monetary benefits could potentially discriminate between alternatives and whether the differences between the benefits in the alternatives can be differentiated in a decision framework.

Table 3.10. Non-Monetary Benefits/Costs Examples

Critical Systems	Non-Monetary Benefits/Costs
Energy	
Energy Resources	Improved environmental quality
Electricity	Improved aesthetics with underground wiring
Facilities	Improved quality of life Improved worker retention
Communication	
Telecommunications	Enhanced user experience
Information Services	Wider variety of resources
Human Capital	
Mission	Reduced stress from hazard
Mission Support	
Water Resources	Enhanced recreational experience
Transportation	Improved worker experience
Mission-critical Services	
Supply Chains	Improved competition
Healthcare and Public Health	Improved quality of life

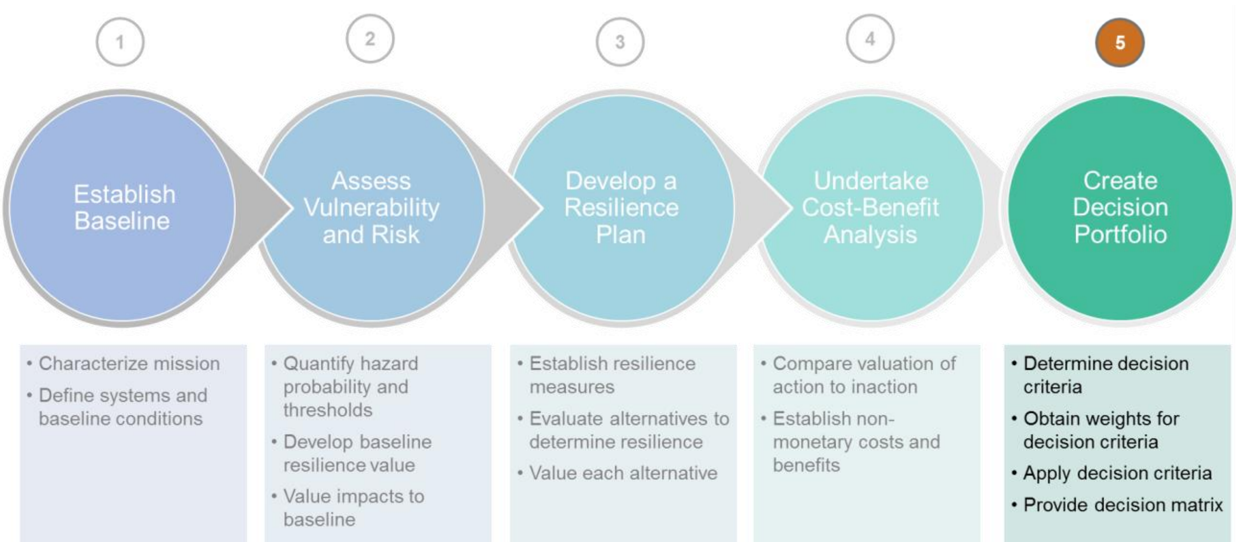
[22] National Institute of Building Sciences. 2016. Consider Non-Monetary Benefits such as Aesthetics, Historic Preservation, Resilience, and Sustainability. Accessed September 16, 2016 at https://www.wbdg.org/design-objectives/cost-effective/consider-non-monetary-benefits

The importance of non-monetary benefits needs to be stressed. They could in certain cases be more important than the monetary benefits and costs. For example, reductions in worker stress can lead to improved performance over time, which in government operations is useful. Measuring the reduced stress on performance may occur only by estimating the increased work output. Allocating the amount of improved work output to reduced stress would require separating out the stress component from the other potential sources of increased productivity such as improved information services or improved computing services. As another example, placing electric lines underground to avoid the effects of high winds can provide improved aesthetics of a DOE site. The improved aesthetics are important to worker productivity as it could improve worker retention and potentially help to reduce workplace stress.

However, care needs to be taken because what could be a mitigation strategy for one site may actually increase the probability of damage at another site. For example, if flooding were the hazard, placing electric lines underground could exacerbate the problem. Thus mitigation measures should be run through the vulnerability assessment to assure that the impact is mitigated.

Non-monetary costs rather than benefits could include reduced aesthetics as putting in a structure to improve earthquake resistance or high wind resistance could potentially reduce vistas, or even facility appearance. Thus, aesthetics could be either improved or reduced by the implementation of an alternative.

3.5 Step 5: Create Decision Portfolio



Once the baseline and the resilient alternatives have been valued and ranked in net present value/cost terms, decision criteria need to be applied. There are four steps to the process: determine decision criteria, obtain weights for decision criteria, apply decision criteria, and provide the decision matrix to the decision-maker. The inputs (Table 3.11) for this step include the net present cost/value information for the baseline and alternatives along with each of their non-monetary costs and benefits, the decision criteria to be applied to the baseline and alternatives and the decision-makers weights. The output from the step is the decision matrix.

Table 3.11. Inputs and Outputs for Step 5

	Alternative X
Inputs	
	Ranked net present cost/benefits for baseline and alternatives
	Decision criteria
	Criteria weights
Outputs	
	Decision matrix
Data Sources	
	Decision- makers
	Subject matter experts

3.5.1 Determine decision criteria

Applying decision criteria requires the team to develop a set of criteria which are of importance to decision-makers. Among these are the strategies used to develop the alternatives, which are discussed in greater detail in 4.2.5.4Appendix D. In summary, uncertainty strategies included approaches that provide "no regrets," flexibility, margin of safety, or change time horizons. Uncertainty strategies allow decisions to be made when probabilities cannot be assigned. No regrets yields benefits whether or not forecasts are met. Flexibility implies the decision could be reversed without loss. Margin of safety reduces vulnerability by increasing the scope of an alternative. Changed time horizons implies that if outcomes are highly uncertain then a shorter time frame should be included.

Risk approaches included assume, share, avoid, and control. Assuming risk is a strategy which may be useful if hazards are expected to only have minor impacts. When the risk is moderate, the best strategy may be to transferred or shared among stakeholders. Controlling risk strategies are used when the magnitude is large such modifying infrastructure. Avoiding risk is the preferred strategy if the damage from a hazard is likely to be catastrophic. The decision-maker may have other criteria for decisions such as that it must fit within a certain budget constraint. The key is to approach and elicit the criteria from the decision-maker. In addition, the items listed below need to be established to help the decision-maker.

- Evaluate the characteristics of the baseline and resilience alternatives analyzed
    1. Net present value of baselines and alternative
    2. Physical characteristics
    3. Non-monetary benefits/costs
    4. Data gaps that could impact alternatives
    5. Impact of assumptions
    6. Size of annual budget required for alternative implementation
- Use sensitivity analysis to determine potential for overlap of outcomes

3.5.2 Obtain weights for decision criteria

Once the decision criteria are known, decision-makers will need to provide weights for each of the criteria. In Table 3.12, three criteria are provided: net present value, budget and aesthetics. For example, the weights could be as follows: budgets are usually the most important and receive a 50% weight and the remaining criteria could be 25% each, as aesthetics may be as important as the net present value.

3.5.3 Apply the decision criteria.

Finally, the decision-maker's criteria for ranking the alternatives needs to be applied. Lastly, the attributes are portrayed in a matrix.[23] Table 3.12 provides an example of a decision matrix with a limited number of characteristics.

Table 3.12. Resilience Decision Matrix

	Net Present Value	Budget	Aesthetics
Do nothing	$−2 million	$ 0	Very good
Harden facilities	$1 million	$ 3 million	Good
Replace building	$42 million	$ 27 million	Excellent

3.5.4 Provide decision matrix

Note that the differences provide the decision-maker with some significantly different results and hard choices. Doing nothing costs $2 million but the aesthetics are very good. Hardening the facilities provides a savings of $1 million above costs and is better than doing nothing, but the aesthetics of the facilities decreases. The option with the highest net present value requires the largest expenditure but also dramatically improves the aesthetics. Applying the decision-makers weights will allow them to see which alternative is the best option. Decision-makers may want to change their weights after seeing the results. An example of resilience scoring criteria for the Strategic Petroleum Reserve is shown in Table 3.12Table 3.13.

[23] Norris, GA, HE Marshall. 1995. Multi-attribute Decision Analysis Method for Evaluating Buildings and Building Systems. NIST – National Institute of Standards and Technology. NISTIR 5663.

Table 3.13. Resilience Scoring Criteria Example (Source: Strategic Petroleum Reserve. 2017. Climate Change Risk and Resilience Assessment. SPR Publication No. 0291)

Assessment Criterion	Score Description		
	Good	Fair	Poor
Effectiveness	Would completely or nearly eliminate the sensitivity's risk	Would significantly reduce part or all of the sensitivity's risk	Would not significantly reduce the sensitivity's risk
Feasibility	Could be implemented technically and organizationally	Some reservations about the ability to implement the action technically and organizationally, or only a part of the action could be implemented	Could not be implemented technically or organizationally
Cost	Would have relatively low monetary cost to implement; generally, desk-style projects, often with no or few infrastructure components.	Would have relatively moderate monetary costs; could include a modest infrastructure component	Would have relatively high monetary costs; could include significant infrastructure components

4.0 Hanford Site Case Study

The Hanford Site was used as a case study to test the methodology for resilience valuation. A mostly qualitative vulnerability assessment for the Hanford Site had been undertaken and two systems were found to be at high risk from severe events: outdoor workers, whose productivity could be affected by work restrictions imposed to manage heat stress, and the site ecosystem from wildfire impacts.

Mission Support Alliance (MSA) was contacted to understand the stressors, the impacts on the site from the two severe events, and to determine where the data to support the analysis could be found. As temperatures increase, outdoor workers face increased stress on body functions, which can lead to heat exhaustion and/or heat stroke. To manage this risk to workers, MSA follows OSHA guidelines to employ different combinations of work and rest based on how strenuous the work is. To undertake the study, we developed a baseline for outdoor work, forecast the probability of increased WBGTs and estimated the impacts on workers. We then determined alternatives to improve worker resilience.

Discussions with MSA indicated that everything possible was being done to prevent wildfires and thus, they did not believe there were any additional resilience strategies to reduce the incidence of wildfires. Some of the strategies included controlled burns, fireguards, and removing vegetation that was need infrastructure such as building and electric power lines. HVAC systems were suggested as an alternative as most DOE sites would face stress on energy use of HVAC systems as temperatures rise.

The case study will be discussed following the methodological approach developed. The forecast budget for the site is shown in Figure 4.1. The forecast budget contains the costs for outdoor work and the HVAC systems. Both infrastructure systems analyses use the budget baseline which totals $107 billion (current $).

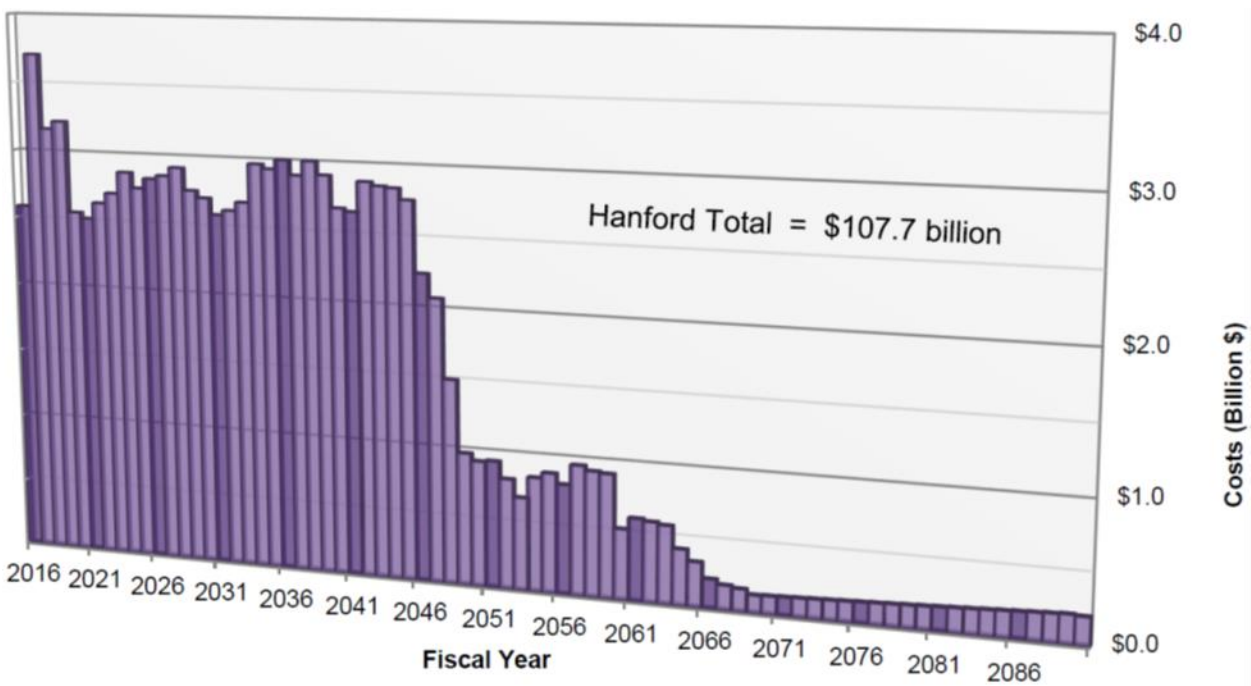


Figure 4.1. Hanford Site Remaining Estimated Cleanup Costs by Fiscal Year (includes both RL and ORP).[1]

4.1 Valuing Resilience of Heat Stress on Workers

4.1.1 Step 1. Establish the Baseline for Heat Stress

As temperatures increase, outdoor workers face increased stress on body functions, which can lead to heat exhaustion and/or heat stroke. To prevent the health impacts, OSHA has developed standards to avoid these impacts. The approach calls for combinations of work and rest based on how strenuous the work is. To undertake the study we developed a baseline for outdoor work, forecast the probability of increased WBGTs and estimated the impacts on workers. We then determined alternatives to improve worker resilience.

4.1.1.1 Characterize the Mission

The Hanford Site's mission is to clean up the radioactive waste created during the making of plutonium for nuclear weapons. The cleanup requires the Decommissioning and Demolition (D&D) of facilities and containment of waste sites. Completing the mission requires some amount of outdoor manual work, although a substantial amount of the work is completed using automated equipment.

4.1.1.2 Define Systems and Baseline Conditions

The requested data to perform the work included the amount of outdoor work forecasted for major mission support in hours and the average burdened salary. Personnel from the budget baseline group at Hanford provided a basis from which to calculate the cost baseline for outdoor work. The group of SMEs developed the percentages of work by category but are still experts' opinion as to the percentage of the baseline considered to be work, outdoor work, and work by exertion category (see Table 4.1). There are 14 major program baselines. The overall budget data was provided in the 2016 budget baseline.[2]

According to the SMEs, most of the D&D work would be performed by workers inside air conditioned equipment. The remaining work would be individuals standing in the sun evaluating the degree to which contaminants were reaching beyond a specified distance from the target area. They consider these jobs as light work as they would require little exertion to perform the work. The heavy work would include potentially re-roofing activities for facilities that were not going to D&D. They believed that work beyond the light work would be evenly split between the medium, heavy and very heavy work. Therefore outdoor labor was expected to be only about 12% of the budget baseline.

[1] DOE 2015. 2016 Hanford Lifecycle Scope, Schedule and Cost Report, DOE/RL-2015-10, Accessed online at: www.hanford.gov/files.cfm/2016_LCR_Fact_Sheet_Final.pdf as of 1/2/2018.
[2] DOE 2015. 2016 Hanford Lifecycle Scope, Schedule and Cost Report, DOE/RL-2015-10, Accessed online at: www.hanford.gov/files.cfm/2016_LCR_Fact_Sheet_Final.pdf as of 1/2/2018.

Table 4.1. Estimating Outdoor Work

Work	Percentage
Percent labor	80%
Discrete labor	30%
Outdoor work	50% of 30%
Light work	90% - 95%
Medium, heavy, and very heavy	Remaining split equally

Additionally, based on the information in Figure 4.1, most D&D work is completed around 2060. At that time, the site moves to long-term stewardship which is based on their belief that the site will be monitored remotely. Outdoor work is estimated at $8 billion in constant 2017 dollars.

4.1.2 Step 2: Assess Vulnerability and Risk for Heat Stress

4.1.2.1 Quantify Hazard Probability and Thresholds

Heat stress directly impacts Hanford workers' abilities to work outside. Heat stress is quantified using the WBGT, which takes into account high temperatures, but also other environmental conditions (e.g., humidity) that outdoor workers might experience.

Hanford has safety procedures in place to protect worker health in environments where heat stress may occur. Based on the WBGT, type of work, and whether the worker is acclimated to heat, safety professionals may choose to institute a work/rest regimen. As will be discussed in subsequent sections, work/rest regimens result in real costs to projects. For example, one month of 50% work and 50% rest can result in 80 hours lost per worker, amounting to a 4% cost or time overrun for that year. If temperature increases continue, conditions may be less conducive to working outdoors, requiring adaptive measures to ensure that the Hanford mission is met.

WBGT measurements and estimates are used to quantify the impact of heat stress on mission, how those impacts might change in the future, and whether there are simple mitigation measures that can be undertaken to alleviate these impacts.

Methods

The WBGT analysis focuses on two sets of data. The first is meteorological data collected at the Hanford Site. The second involves simulations using an Earth System Model, evaluated over two different time periods. The historical time period (1979–2005) involves forcing the model with historical values of large-scale forcers, such as methane and aerosols (e.g., sulfate, black carbon, and dust). The two future scenarios (2006–2100) correspond to RCP4.5 and RCP8.5, which are two Representative Concentration Pathways.[3] RCP4.5 is a "middle of the road" scenario involving some emissions reductions over the 21st century, but with moderate continued warming. The RCP8.5 scenario is akin to a "no policy" scenario with little to no emissions reduction and continuing warming throughout the 21st century.

[3] van Vuuren, D. P. et al. (2011), The Representative Concentration Pathways: An Overview, Climatic Change, 109, doi:10.1007/s10584-011-0148-z.

The WBGT temperature is calculated based on the formula provided by Liljegren et al. (2008)[4] and requires the following inputs: air temperature near the surface, relative humidity near the surface, total solar irradiance incident at the surface, pressure, wind speed, and solar angle.

The Hanford meteorological data was obtained from the National Centers for Environmental Information[5] at hourly frequency. This high frequency reflects the fact that safety professionals evaluating heat stress at the Hanford Site would monitor weather conditions throughout the day and could institute a work/rest regimen at any time. This data was available for all necessary inputs except incident solar irradiance. That data was obtained from the National Solar Radiation Database[6], represented by the sum of direct normal irradiance and diffuse horizontal irradiance. Missing data was filled in via shape-preserving piecewise cubic interpolation, resulting in continuous hourly estimates of WBGT for the period 2006-2012. The results of this are shown Figure 4.2.

The modeling data was obtained from simulations using CanESM2[7], which provides global gridded values with 2.875° horizontal resolution. The data used for analysis is the grid box containing the Hanford Site (x=86 out of 128, y=46 out of 64), which covers an approximately 300 × 300 km^2 area of Eastern Washington.

The data was obtained with daily frequency, which is insufficient for this purpose. We therefore, performed an interpolation procedure to recover the diurnal cycle of WBGT. Based on analysis of the measured meteorological data at the Hanford Site, minimum daily temperature and WBGT in the summer occur at approximately 5 AM, maximum at approximately 12 PM, and the average daily temperature at 9 AM and 9 PM. Based on these four points, for which we have model output every day, we again used shape-preserving piecewise cubic interpolation to reconstruct an hourly dataset. The results are shown in Figure 4.3. As verification that this process does not introduce undue errors, Figure 4.4 shows a scatter plot between WBGT derived from Hanford meteorological data (as described above) and WBGT calculated by interpolating between the four points available every day (5 AM, 9 AM, 12 PM, and 9 PM). If the two methods resulted in exactly the same information, all of the blue dots in Figure 4.4 would lie exactly on the red line, which would have a slope of 1, a y-intercept of 0, and an R^2 of 1. Clearly these criteria are not met perfectly, but on average, these conditions are met well enough that we have confidence in the ability of the interpolation method to represent typical daily and seasonal variations in WBGT.

[4] Liljegren, J. C., R. A. Carhart, P. Lawday, S. Tschopp, and R. Sharp (2008), Modeling the wet bulb globe temperature using standard meteorological measurements, Journal of Occupational and Environmental Hygiene, 5, 645-655, doi:10.1080/15459620802310770.

[5] NCEI (2017), Hanford, WA, Local Climatological Data, National Centers for Environmental Information, National Oceanographic and Atmospheric Administration, available online at https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:94187/detail, last accessed 6 January 2018.

[6] NREL (2017), National Solar Radiation Database, National Renewable Energy Laboratory, available online at http://rredc.nrel.gov/solar/old_data/nsrdb/, last accessed 6 January 2018.

[7] Arora, V. K., et al. (2011), Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases, Geophysical Research Letters, 38, doi:10.1029/2010GL046270.

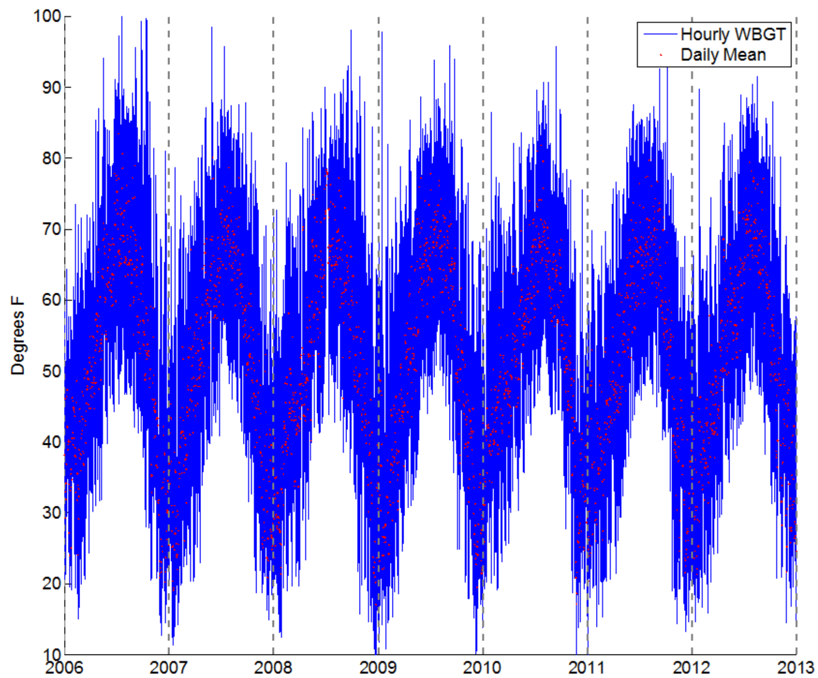


Figure 4.2. Hourly (blue lines) and Daily Mean (red dots) WBGT (°F) Calculated from Meteorological Data Collected at the Hanford Site

The calculated WBGT can then be used to calculate approximate work/rest regimens based on each type of work. Figure 3.3Figure 3.5 in Step 2 provides thresholds for each type of work and whether a worker is acclimated to the heat; if a threshold is exceeded, then a work/rest regimen is instituted. We note that MSA (2017)[8] provides an updated WBGT screening criteria table, which we have not used in our analysis. While results are expected to be comparable, some differences are likely to emerge should the analysis be repeated with this updated information. Moreover, MSA (2017) states that the table is meant to be used as a screening guideline to determine whether a heat stress condition exists, whereas in the analysis presented here, we have assumed that the table provides firm guidance as to when heat stress may occur.

[8] MSA (2017), Heat Stress Control, Mission Support Alliance, PRC-PRO-SH-121, available online at http://chprc.hanford.gov/files.cfm/PRC-PRO-SH-121_rev_2-0.pdf, , last accessed 6 January 2018.

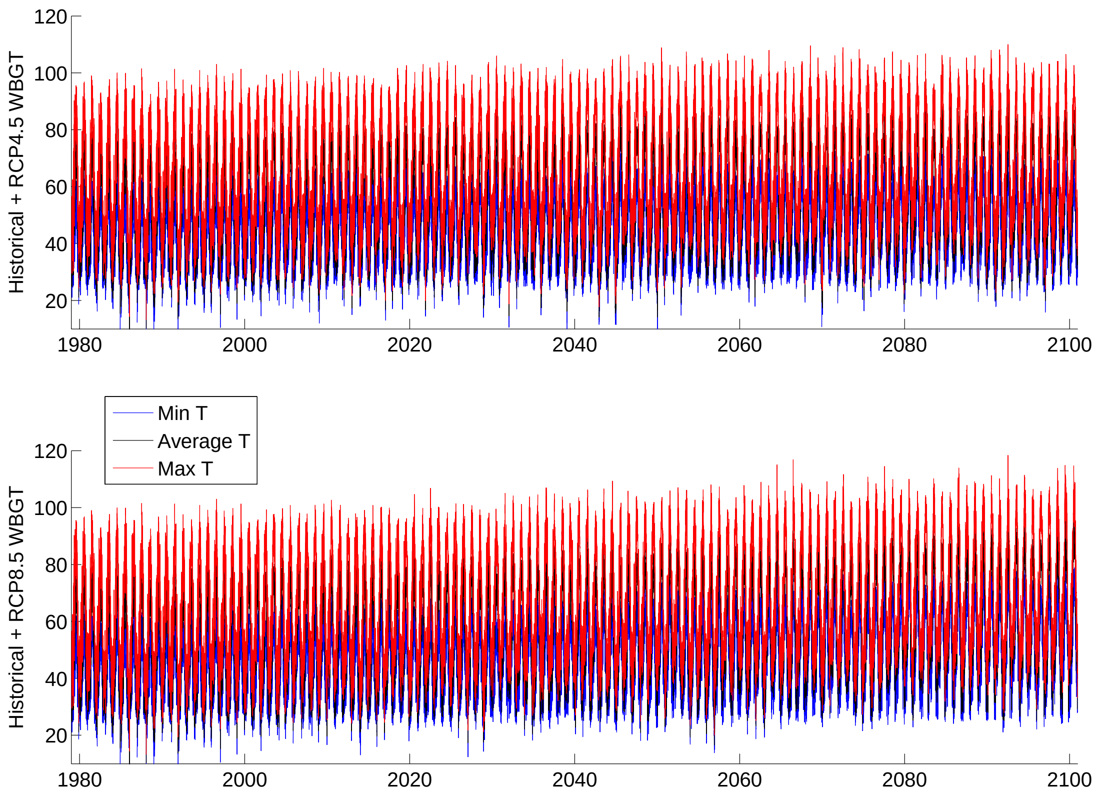


Figure 4.3. WBGT (°F) Calculated from Simulated Daily Data for the Historical, RCP4.5, and RCP8.5 Simulations

The control procedure is applied on an hourly basis (i.e., heat stress is reassessed every hour). Then the number of workable hours in a shift is calculated. For example, if one hour is deemed to be within the range of a 25% work/75% rest regimen, that hour-long period is deemed to have 0.25 workable hours. Calculations are conducted assuming four 10-hour shifts per week on Mondays, Tuesdays, Wednesdays, and Thursdays. "Normal" shifts are assumed to be 6 AM to 4 PM, and night shifts are assumed to be 8 PM to 6 AM. Some calculations are performed using the assumption of a variable shift, which uses the 10-hour consecutive period in any day that has the highest number of workable hours, under the (incorrect) assumption that shift start times can vary on a day-to-day basis.

Per the Heat Stress Control Procedure, very heavy work begins at a maximum work load of 50% work/50% rest, so there is a maximum of five workable hours in a shift. All other types of work have a maximum of ten workable hours in a shift.

For calculations of the effectiveness of switching to a different shift schedule in a given year, the difference in percent of workable hours is multiplied by 2000, the nominal number of available hours in any given year.

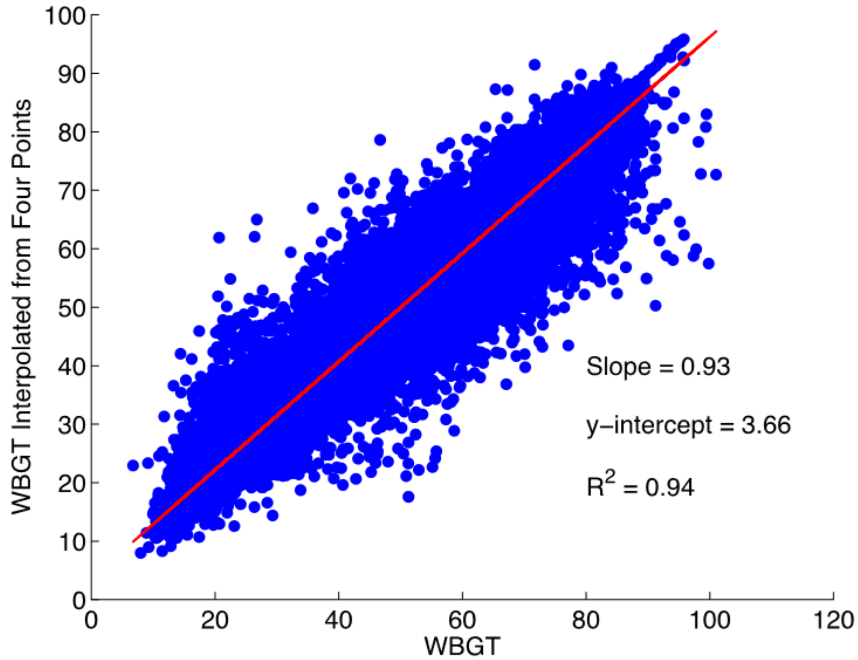


Figure 4.4. Correlation between WBGT calculated from hourly observed meteorological data (x-axis) and a reconstructed hourly time series of WBGT based on interpolation between minimum, maximum, and average daily values (y-axis; see Section 2).

Results for meteorological data

Figure 4.2 shows that over the period 2006-2012, WBGT varies between approximately 10°F and 100°F. Figure 4.5 shows that over this period, over 98.7% of all available hours can be worked during regular day shifts for all types of work. Figure 4.7 and Figure 4.7 show the percentages of workable hours by shifting to night shifts and variable shifts, respectively, and Figure 4.8 and Figure 4.9 show the total increase in workable hours for night shifts and variable shifts, respectively, over that seven-year period. The colors in the figures reflect the percentage of workable hours shown on the right side of each figure. The results show a slight increase in workable hours by switching to night shifts, not exceeding one hour per year. By switching to variable shifts, the gain increases to approximately 20 hours per year in some cases. Although these calculations were performed for the entire time period, in general, WBGT is only high enough in the summer to invoke a work/rest regimen.

These calculations indicate that over the period 2006-2012, all types of work could be conducted for their entire shifts, indicating little benefit to implementing adaptive measures, such as switching the start time of shifts. However, these calculations were performed using meteorological data and without consulting a safety professional or the actual work logs, so the number of worked shifts or times that a work/rest regimen was implemented might differ from the calculations presented here.

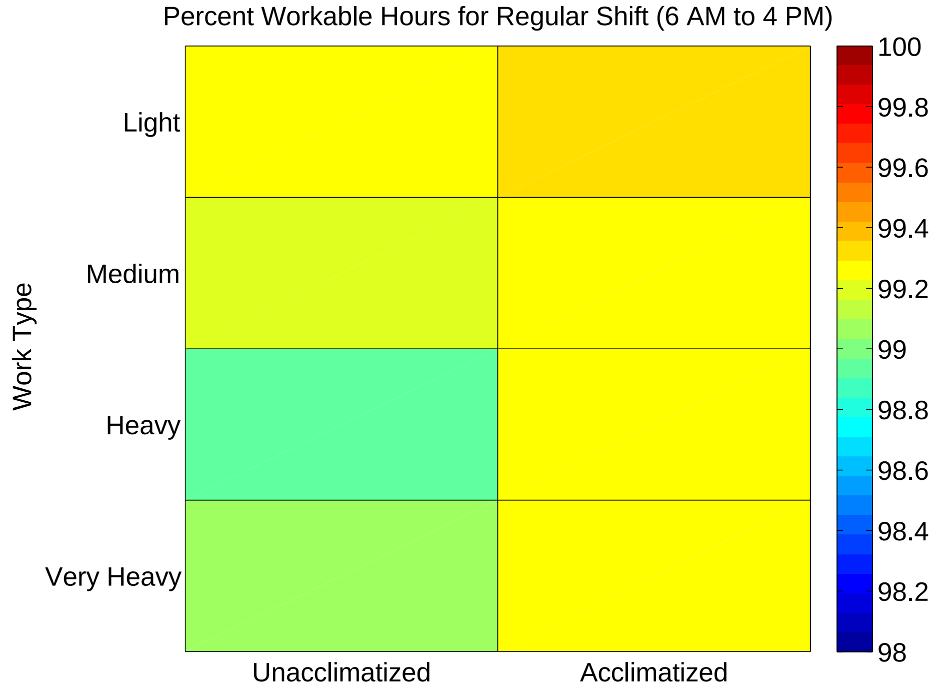


Figure 4.5. Percent of Workable Hours for a Regular Shift (as calculated from observed meteorological data over the period 2006–2012)

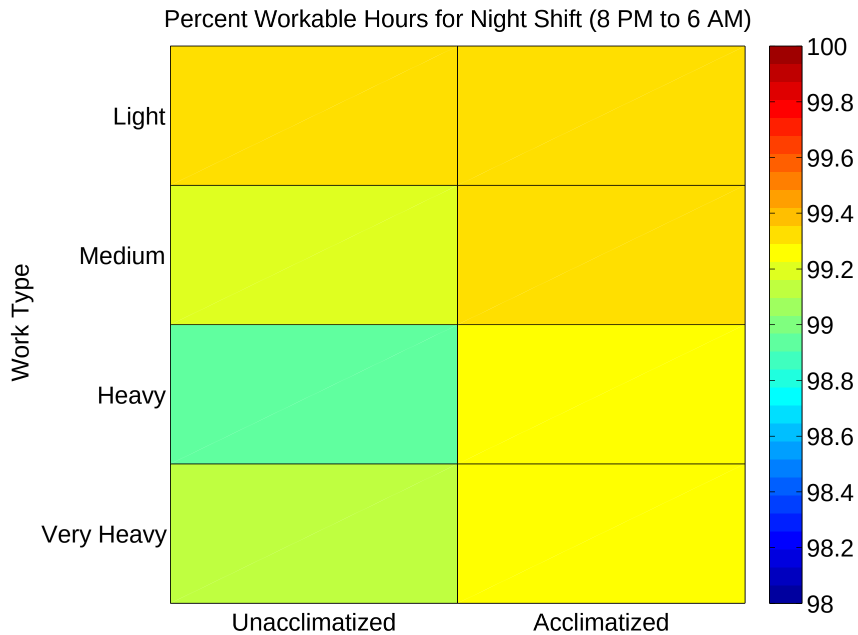


Figure 4.6. As in Figure 4.5, but for Night Shifts during 2006–2012

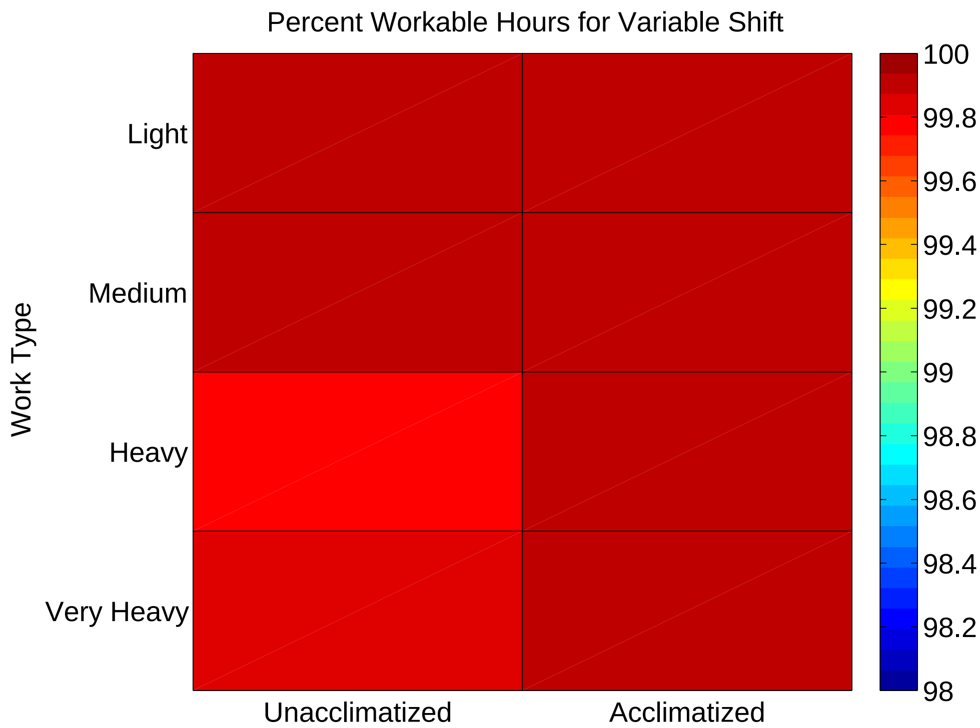


Figure 4.7. As in Figure 4.5, but for Variable Shifts

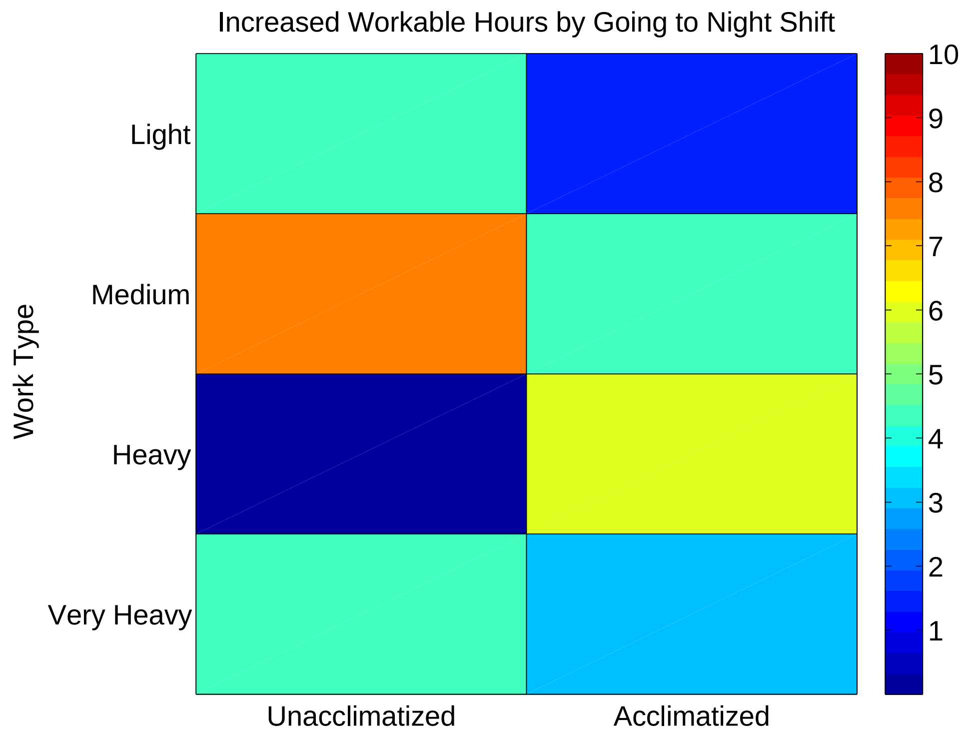


Figure 4.8. Increased Workable Hours by Going from Regular Shifts (Figure 4.5) to Night Shifts (Figure 4.6), Assuming a Maximum of 2000 Working Hours Available per Year

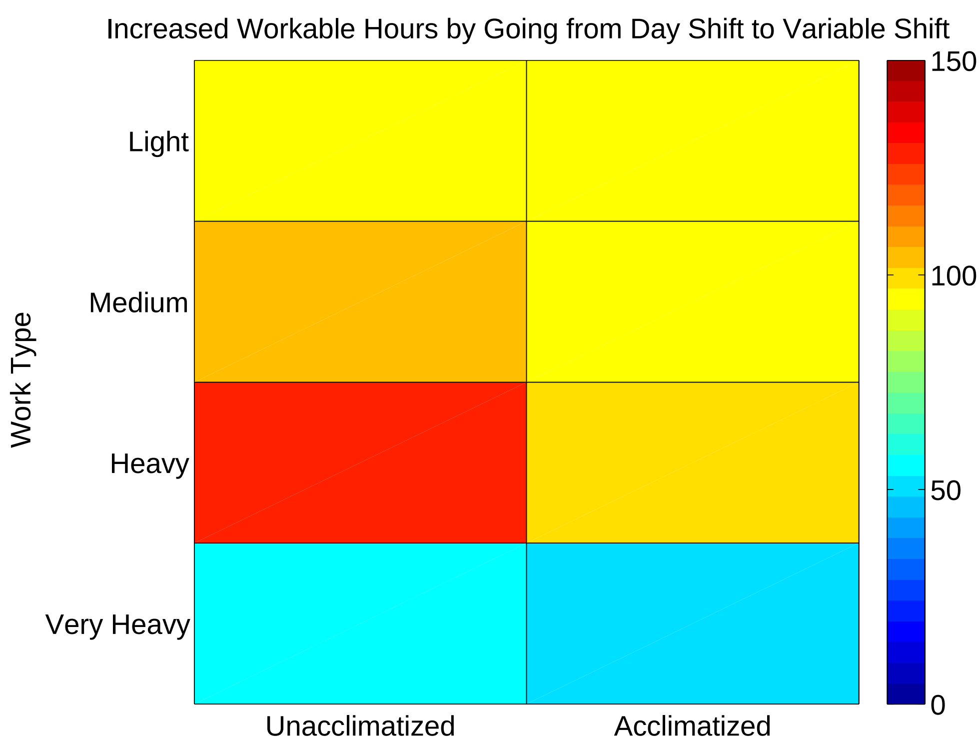


Figure 4.9. Increased Workable Hours by Going from Regular Shifts (Figure 4.5) to Variable Shifts (Figure 4.7), Assuming a Maximum of 2000 Hours Working Available per Year

4.1.2.2 Develop Baseline Resilience Value

Figure 4.10 shows histograms of WBGT over different time periods for the model simulations in the model grid box containing Hanford. Results are consistent with expectations: both RCPs have more heat extremes and fewer cold extremes than in the historical period, with RCP8.5 having more heat extremes than RCP4.5. Heat extreme counts increase as time progresses, and cold WBGT values decrease in frequency of occurrence.

Figure 4.11 shows the percent of workable hours in a given year for the model simulations. Results in the historical period indicate far fewer workable hours than the analysis using observed meteorological data. There are several potential reasons for this discrepancy. The Earth System Model is forced with large-scale forcers, but not observed meteorology. Moreover, the model output used to represent the Hanford Site is a large grid box covering a sizable portion of Eastern Washington, meaning that it ignores any sub-grid scale variability or microclimates that may impact Hanford differently from the grid-box average conditions. As such, it would not be expected that the simulation would reproduce any real-world data. It is included to provide a baseline for comparison for the two future scenarios.

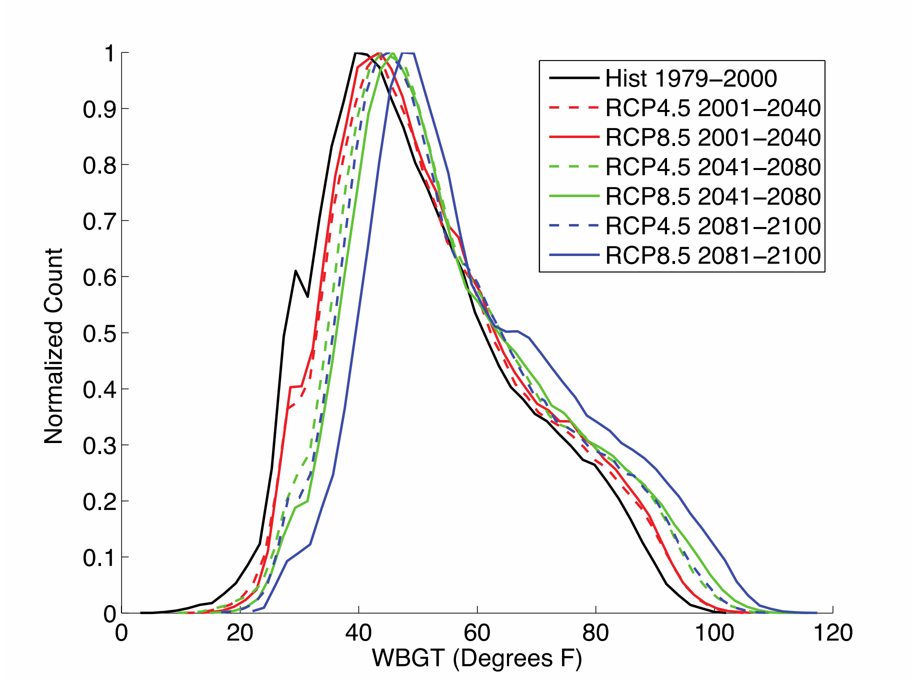


Figure 4.10. Histogram of WBGT (°F) for Different Simulations and Different Time Periods. All histograms are normalized to a maximum of 1.

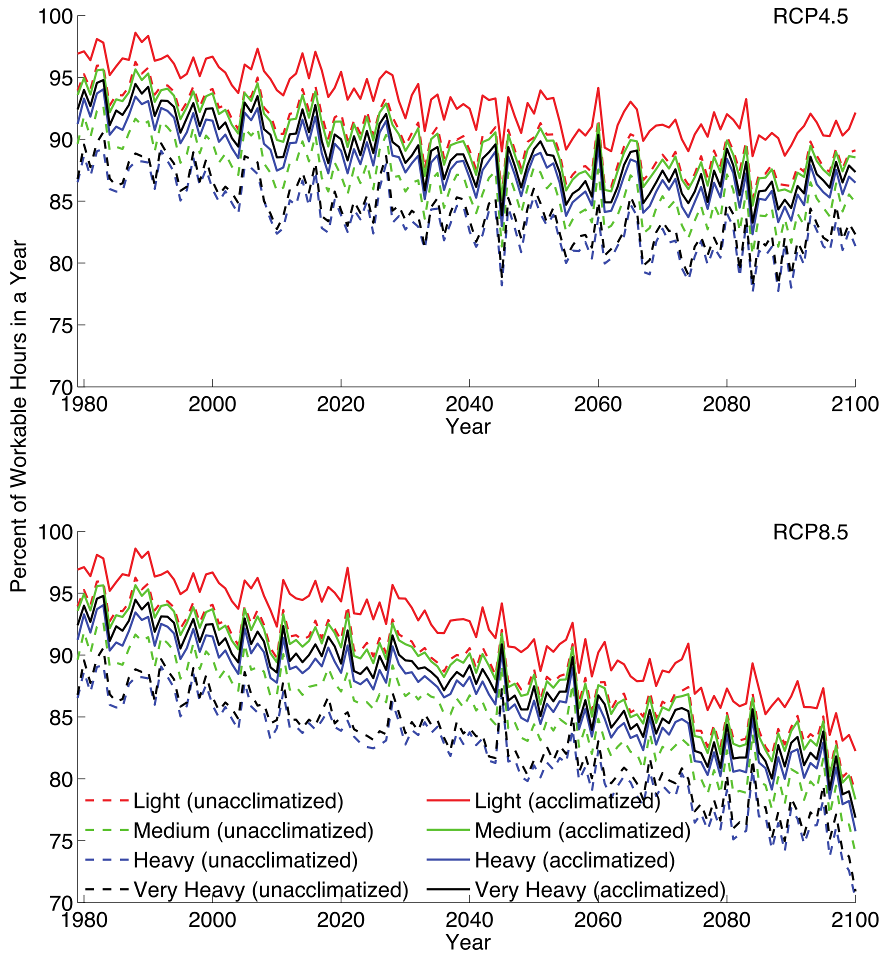


Figure 4.11. Percent of Workable Hours in a Given Year for Regular/Day Shifts, as Calculated from the Simulations. Top panel shows the combined historical and RCP4.5 simulations, and bottom panel shows the combined historical and RCP8.5 simulations.

Consistent with the steady increase in WBGT values in Figure 4.3, the percent of workable hours declines throughout all simulations, with a steeper decline in the RCP8.5 simulation. The RCP4.5 simulation appears to stabilize by the end of the 21st century, whereas the percentage of workable hours continues to decline in the RCP8.5 simulation.

4.1.2.3 Value Impacts to Baseline

The amount of work at risk, given the probability of working outside in light, medium, heavy and very heavy conditions, was calculated using the data behind Figure 4.11, the percent of workable hours in the baseline assuming that work is undertaken during day shifts. The calculations were undertaken for the RCP4.5 and RCP8.5 forecasts. The dollar value of work at risk is calculated by:

$$\text{Expected Value at Risk}(VAR_{ij}) = (1\text{-Prob}(w_{i1})) \times \text{Prob}(W_1) + \ldots + (1\text{-Prob}(w_{in}) \times \text{Prob}(W_n))$$

where

VAR_{ij} = the dollar value of work at risk by period
w_i = the percent of workable hours by exertion category by year j
W_j = the dollar value of labor being performed by year j

The net present costs of the at risk value baseline is based on the following with r being the discount rate:

$$\text{NPC}_{\text{(Labor Costs)}} = \sum_{j=1}^{n} \frac{VAR_j}{(1+r)^j}$$

The amount of work at risk in the baseline is $229 million and $217 million for the RCP4.5 and RCP8.5 forecasts with a discount rate of 7%. For a 3% discount rate, the value at risk is more than a $100 million more (see Table 4.2). Note that the net present costs are counterintuitive, with the forecast for higher temperatures with RCP8.5 being associated with the lesser value at risk. The percent of workable hours is greater for RCP8.5 in the early periods, but decreases significantly in the period after 2060. With Hanford's budget declining significantly after 2060 and with discounting, the higher impact RCP 8.5 forecast does not affect the value at risk as much as it would if costs continued on until 2100.

Table 4.2. Value of Work at Risk in Hanford Site Baseline (working regular dayshifts only) ($ million)

Forecast	Net Present Cost (r = 3%)	Net Present Cost (r = 7%)
RCP4.5	$365	$229
RCP8.5	$355	$217

4.1.3 Step 3: Develop a Resilience Plan for Heat Stress

4.1.3.1 Establish Resilience Measures

Two mitigating alternatives were provided by Mission Support Alliance (MSA) to improve resilience and worker safety: night shifts and ice vests. Night shifts and ice vests are already being used when necessary to increase work activity during periods when heat stress would be an issue. Night shifts allow more work to be undertaken because of the lack of the direct sunlight variable in the WBGT calculation, and lower temperatures during the night.

The other alternative, ice vests, are currently used, when workers desire to use them. Ice vests provide cooling to body temperature. They need to be frozen before they provide cooling. However, workers are not forced to use the vests. With vests, the amount of time available for additional work is dependent on heart rate. When the heart exceeds the threshold (180 – age), then rest is provided until the heart rate has declined to 120 beats per minute.

4.1.3.2 Evaluate Alternatives to Determine Resilience

Night shift work

Figure 4.12 shows a similar set of values to Figure 4.11 of the baseline, except that the values are for night shifts. The difference is that the declines are far less precipitous over the 21st century. The decline in workable hours on night shifts appears to accelerate in the latter half of the 21st century, particularly for the RCP8.5 simulation. This is consistent with known effects of global warming, particularly that nights warm faster than daytime temperatures.[9] Because nights are far cooler than days, it takes a few decades before the effects of this known feature are significant enough to impact work schedules.

[9] Stenchikov, G. L. and A. Robock (1995), Diurnal asymmetry of climatic response to increased CO_2 and aerosols: Forcings and feedbacks, *Journal of Geophysical Research*, *100*, 26211-26227, doi:10.1029/95JD02166.

Figure 4.13 shows the improvement in number of workable hours by switching to a night shift. Improvements are comparable in both simulations, with greater improvements later in the simulations as temperatures are hotter. By the end of the 21st century, improvements reach approximately 300 hours, or 15% of the total number of workable hours in a given year.

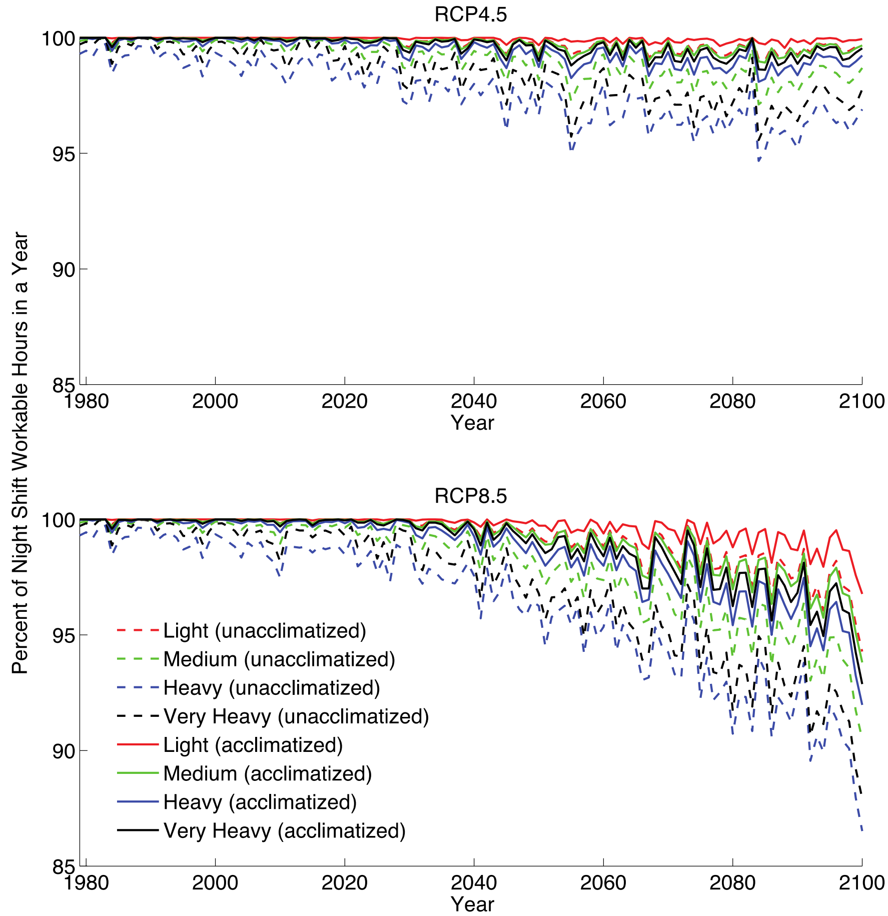


Figure 4.12. Percent of Workable Hours in a Given Year for Night Shifts, as Calculated from the Simulations.

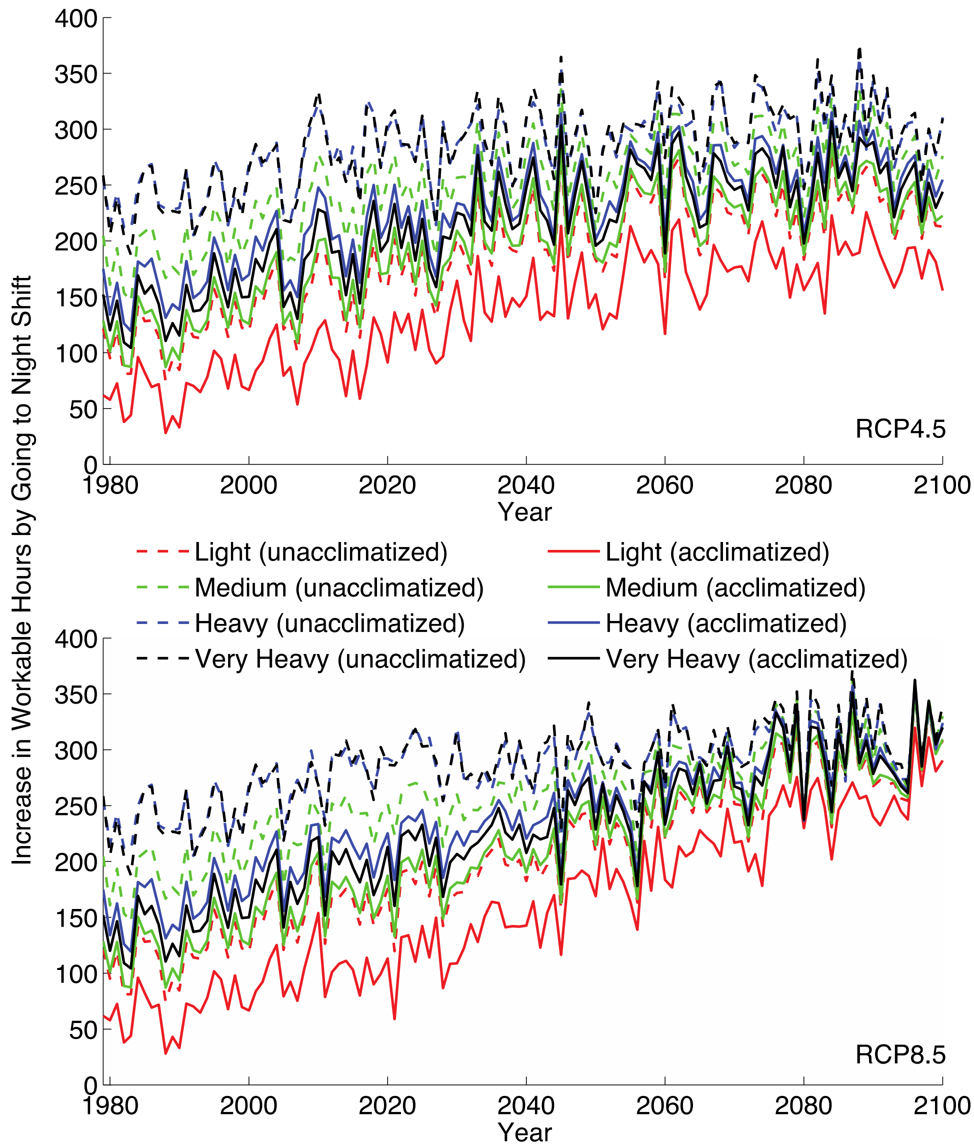


Figure 4.13. Difference Between Figure 4.11 and Figure 4.12, Assuming a Maximum of 2000 Hours Working Available per Year

Ice vests alternative

The evaluation of ice vests is limited in scope because of a few missing data requirements. Information was required for the amount of work that would be available at different WBGT temperatures. Data on increased worktime for ice vests only extended to WBGT of 95° F and work time for temperatures at 100° F are needed. Currently, the SME indicated that the vests add about 15 minutes of work. For this analysis, 15 minutes of extra time per hour were assumed.

A further limitation is that the number of workers affected could not be obtained. The number of workers are needed to determine how many vests are required and the freezer capacity required to calculate the added costs of the alternative. For this analysis we only included the increased work time availability and made an estimate of the equipment capital and operating costs on a per vest basis, to determine if the vests are cost effective.

4.1.3.3 Value Each Alternative for Heat Stress

Night shifts alternative

Two calculations are required to capture the cost of night shift work: a 10% penalty for working nights according to the budget SMEs and the amount of work lost due to heat stress. Night shift work is expected to impose a 10% cost penalty as compared to daytime work. The penalty was approximated by multiplying the ratio of work completed percentage for nighttime work divided by work percentage completed in daytime work times lost daytime work × 10% penalty.

The penalty equation:

$$\text{Penalty} = N\%/D\% \times DW \times 10\%$$

where

N%	=	the Percentage of night shift work completed
D%	=	the percentage of daytime work
DW	=	value of daytime work lost

The expected value of lost work uses the same equation as in calculation for lost work for day shift work.

$$\text{Expected Value at Risk}(VAR_{ij}) = (1\text{-Prob}(w_{i1})) \times \text{Prob}(W_1)+\ldots.+ (1\text{-Prob}(w_{in}) \times \text{Prob}(W_n))$$

where

VAR_{ij}	=	the dollar value of work at risk by period
w_i	=	the percent of workable hours by exertion category by year j
W_j	=	the dollar value of labor being performed by year j

The net present costs of the at risk value baseline is based on the following with r being the discount rate:

$$NPC_{(\text{Labor Costs})} = \sum_{j=1}^{n} \frac{VAR_j}{(1+r)^j}$$

The value at risk for night shift work is $30 million for RCP4.5 at a 7% discount rate while RCP8.5 costs about $25 million (see Table 4.3). Again, the result is counterintuitive as one would expect the higher greenhouse gas forcing function to increase the value at risk. The issue is that the main amount of work falls in the first half of the century while RCP8.5 becomes a larger penalty in the second half. In addition, the impact of discounting reduces the out-year costs. The 10% penalty is a significant component of the value at risk comprising $28 and $23 million of the totals for RCP4.5 and RCP8.5, respectively. As expected discounting at 3% increases the penalty associated with heat stress on workers but it does not change the ordering of the forecast value at risk.

Table 4.3. Value at Risk with Night Shift Work ($ million)

Forecast	Component	Net Present Cost (r = 3%)	Net Present Cost (r = 7%)
RCP4.5	Night shift penalty	$43	$28
	Lost work	$3	$1
	Total	**$45**	**$30**
RCP8.5	Night shift penalty	$38	$23
	Lost work	$4	$2
	Total	**$42**	**$25**

Ice Vests Alternative

Ice vests were assumed to completely cover lost work time for the light and moderate categories. Because the heavy category assumes a 50/50 work rest regime, only half of the lost time could be recovered using ice vests. The very heavy category required a 75/25 work rest regimen thus only 1/3 was saved indicating that 2/3 of the work in the very heavy category remained. The value at risk, $12 to $15 million (7% discount rate) is shown in Table 4.4.

Table 4.4. Value at Risk with Ice Vests ($ million)

Forecast	Component	Net Present Cost (r = 3%)	Net Present Cost (r = 7%)
RCP4.5	Lost work	$23	$15
RCP8.5	Lost work	$19	$12

The added costs of the vest depend on the type of vest purchased. Cooling vest costs range from $31 to $199.[10] Assuming that a vest is used according to the number of hours by category of work and the vest only lasts one year, the cost per vest ranges from $0.40/hour to $4/hour per year. Additional costs include the freezer and cost of electricity. Assuming the cost of an 11.2 cubic foot freezer at $1199[11], the annualized cost of freezing the vests is approximately $4 a vest at a 7% discount rate and $3.50 at a 3% discount rate, providing a total cost of $4.40 to $8.00 depending the amount work. This includes, annualized capital, energy and O&M costs. Assuming the prevailing wage rates including fringe benefits of $42/hour to $45/hour, the vests appear to pay for themselves at every category level with 15 minutes per hour worth $10-$11/hour.

4.1.4 Step 4: Undertake Cost-Benefit Analysis for Heat Stress

The baseline is compared with the two alternatives, night shift work and ice vests for work during WBGT days. Data to determine the number of workers, which is required to do a complete analysis of how many

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[10] Walmart. 2018. "Cooling Vests." Accessed January 23, 2018 at https://www.walmart.com/c/kp/cooling-vests

[11] Webrestaurant Store. 2018. "Freezers." Accessed January 23, 2018 at https://www.webstaurantstore.com/search/freezer.html?gclid=EAIaIQobChMItdWB5-ju2AIVBVt-Ch0ltg5NEAAYAiAAEgJBq_D_BwE

ice vests are required, could not be provided by the Hanford budget office. Thus, the complete impact of ice packs on worker time could not be estimated.

4.1.4.1 Compare Valuation of Action to Inaction for Heat Stress on Workers

Table 4.5 provides the net present cost of the value at risk for the baseline compared with the night shift and ice vest alternatives. The night shift alternative significantly improves the amount of lost work at 3% and 7% discount rates under both forecast scenarios. Both alternatives provide significant improvement over the baseline work, decreasing the lost work by approximately $200 million over the Hanford Site lifetime. However, due to the lack of information on total ice vest costs, differences in total values at risk between the two alternatives cannot be determined.

Table 4.5. Comparison of value at risk for the baseline and alternatives ($ million)

Forecast	Component	Net Present Cost (r = 3%)	Net Present Cost (r = 7%)
RCP4.5	Baseline	$365	$229
	Night shift work	$45	$30
	Ice vests	$23	$15
RCP8.5	Baseline	$355	$217
	Night shift work	$42	$25
	Ice vests	$19	$12

4.1.4.2 Establish Non-monetary Costs and Benefits

There are non-monetary costs associated with the night shift work. The quality of night work does not necessarily match the quality of work where better lighting is available. For example, a part of the job in D&D is to determine where the debris is landing. In night work, with less visibility than during day shift work, the ability to assure the size of the debris field is reduced. In addition, night work causes more stress to individuals than daytime work.

The non-monetary costs of the ice vests is that they uncomfortable and workers do not like them. Workers are not currently required to wear them. A contract requirement would be necessary.

4.1.5 Step 5: Create Decision Portfolio for Heat Stress

4.1.5.1 Determine Decision Criteria

The decision-makers in the context of Hanford work are the contractors. Without access to the contractors' management, the decision criteria were set up based on information about the baseline and alternatives as discussed when setting up the alternatives. Clearly net present cost is important to the Hanford Site. Completing site cleanup at the lowest cost possible is a significant priority. Noted during conversations about the vests and night work was the dislike for ice vests and the added stress of working night shifts, so worker morale was included as a decision criteria. Lastly worker safety is an important criteria for DOE and OSHA, thus, the last decision criteria includes worker safety.

4.1.5.2 Obtain Weights for Decision Criteria

The decision-makers in the context of Hanford work are the contractors and thus weights could not be determined for purposes of this case study as DOE didn't permit interaction with the contractors.

4.1.5.3 Apply Decision Criteria

The decision criteria were applied to the available data (see Table 4.6). The decisions would appear to be between whether to use ice vests or do shift work. Currently both options are being used by contractors at the Hanford Site. The level of reduced costs are significant. One point made during the meetings was that another $100 million today in added budget would reduce out-year costs significantly because there is annual $300 million in "Min-Safe" costs to keep buildings safe until D&D is complete. The opposite is also true in that delays significantly increase the costs of the site.

Table 4.6. Resilience Decision Matrix for Heat Stress Alternatives

Forecast	Component	Net Present Cost (r = 3%) ($MM)	Net Present Cost (r = 7%) ($MM)	Worker Morale	Worker Safety
RCP4.5	Baseline	$365	$229	Highest	Highest
	Night shift work	$45	$30	Lowest	Medium
	Ice vests	$23	$15	Medium	Lowest
RCP8.5	Baseline	$355	$217	Highest	Highest
	Night shift work	$42	$25	Lowest	Medium
	Ice vests	$19	$12	Medium	Lowest

4.1.5.4 Provide Decision Matrix

The decision matrix provides tradeoffs between worker morale and worker safety as provided in Table 4.6. The values for worker morale are based on conjecture and to provide a set of tradeoffs. Discussions with workers would be able to verify whether the order of impact on worker morale and safety is correct..

4.2 Temperature Stress Impact on HVAC Systems

4.2.1 Step 1: Establish the Baseline for HVAC systems

Resilience is also a question for the facilities of the Hanford Site. The Site is expected to continue its mission to remediate the legacy waste of the nation's nuclear weapons research and production activities that began there in the 1940's. Remediation activities are expected to continue until about 2060, after which, long-term monitoring and maintenance of the site will proceed.[12] Figure 4.1 illustrates recent estimates of remaining cleanup costs over time.

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[12] DOE 2015. 2016 Hanford Lifecycle Scope, Schedule and Cost Report, DOE/RL-2015-10, Accessed online at: www.hanford.gov/files.cfm/2016_LCR_Fact_Sheet_Final.pdf as of 1/2/2018.

Continuing remediation operations at the Site imply that the Site will continue to employ a substantial workforce to carry out the planned actions. The current building stock will continue to house these employees, related support services, utilities, etc. Therefore, another aspect of resilience deals with the risk posed by increasing ambient temperatures on the continued operation of the current and future building stock in place to carry out the mission of the Site.

Warming temperatures would be expected to affect the currently installed base of heating, air conditioning, and ventilation (HVAC) equipment. In theory, rising higher average temperatures would cause the cooling demand to increase and the air conditioning modes of existing equipment would run for more hours in a year than currently. Similarly, with higher average heating season temperatures, the heating modes of the equipment would be expected to run for less hours in a typical year. Compared to baseline conditions, if the temperature effects and the duration of increased cooling requirements on the operation of the equipment lead to premature failure, increased maintenance costs, or periods of reduced comfort for the workforce utilizing the floor space, then a resilience impact would be expected.

4.2.2 Step 2: Assess Vulnerability and Risk for HVAC systems

The Hanford Site is located in the low-elevation, arid, intermountain region of Eastern Washington State, within International Energy Conservation Code climate zone 5. Energy use is winter dominated, meaning that peak electrical system demand occurs in the winter, and more energy is used for heating than for cooling. Currently projected temperature change will shift this balance over time by reducing heating season energy use and increasing energy use for cooling. Figure 4.14 and Figure 4.15 illustrate the progressing change in number of Cooling Degree Days (CDD) and Heating Degree Days (HDD) under two widely accepted projections RCP 4.5 and RCP 8.5.

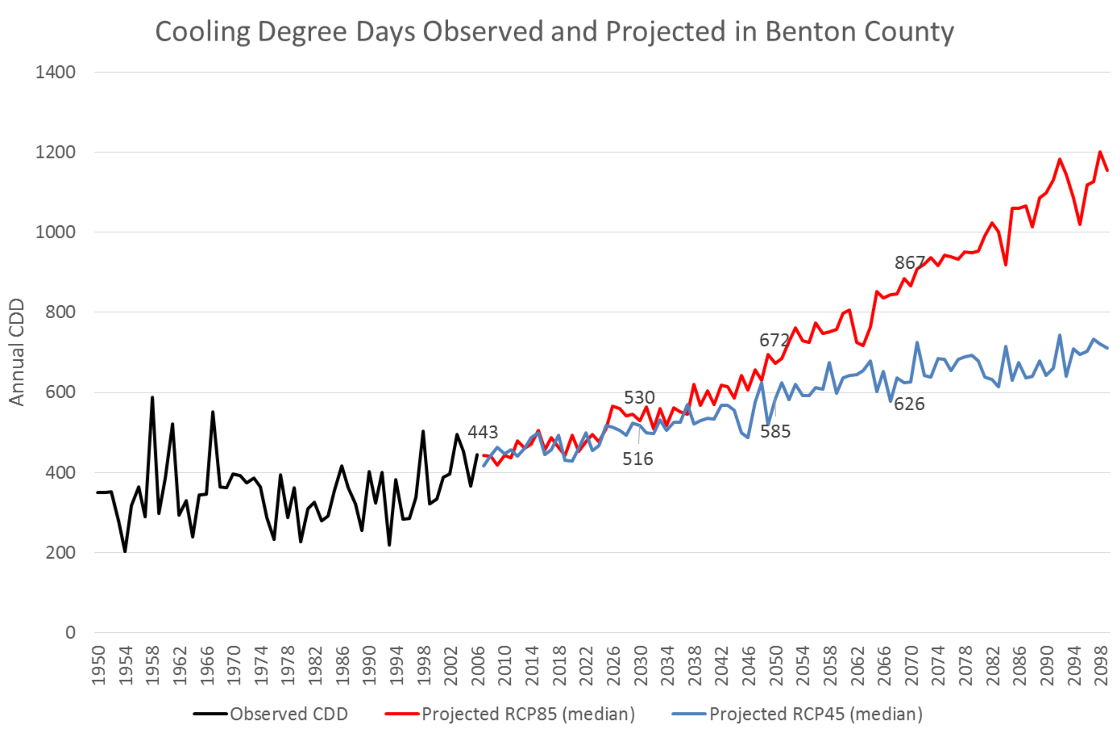

Figure 4.14. Number of Cooling Degree Days in Benton County (Source: NOAA Climate Explorer http://climateexplorer.habitatseven.work/)

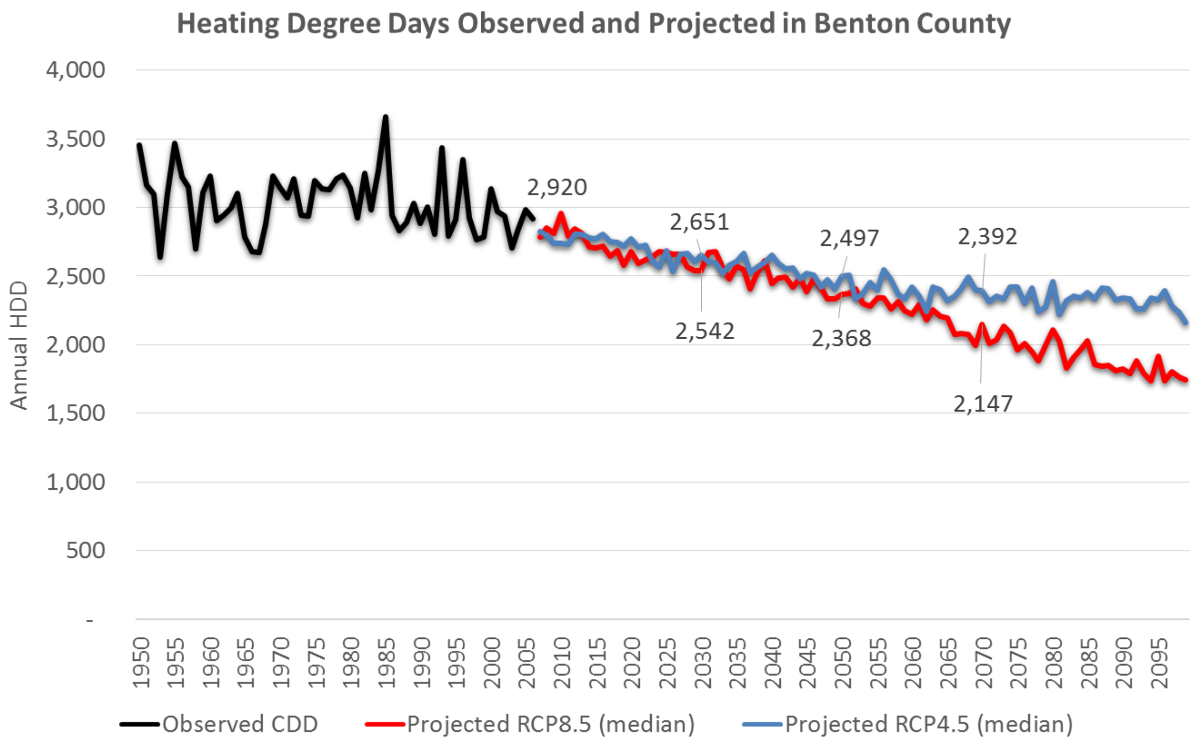

Figure 4.15. Number of Heating Degree Days in Benton County (Source: NOAA Climate Explorer http://climateexplorer.habitatseven.work/)

To estimate the effects of this trend on HVAC systems of the Hanford Site, the research team utilized the Facility Energy Decision System (FEDS) model in reduced form to model the current Site building stock energy usage and equipment operating regimes.[13] PNNL obtained current accounting of the existing building stock on the Site with the cooperation of MSA.

To parameterize the FEDS model, MSA's building stock data covering hundreds of buildings on the Hanford Site were analyzed and categorized into representative building types to serve as proxies for large blocks of the reported floor space. This feature of FEDS is useful and often used when time and expense will not permit detailed energy modeling of each individual building at a site. Table 4.7 lists the breakdown of the Site building stock as modeled by FEDS.

Table 4.7. Hanford Site 2018 Baseline Building Stock as Modeled Using FEDS

FEDS Building Set	Number of Buildings	Floor Space (ft^2)	Average Floor Space (ft^2)	Average Vintage
Office - 1	10	302,352	30,235	1949
Office - 2	15	298,638	19,909	1982
Office - 3	8	158,665	19,833	1994

[13] PNNL 2014. Facility Energy Decision System Release 7.0 User's Guide, PNNL-SA-107079, accessed online at: https://www.pnnl.gov/FEDS/, as of 1/17/2018. FEDS is PNNL-developed, open-access, software designed for flexible and robust modeling of building energy use.

FEDS Building Set	Number of Buildings	Floor Space (ft^2)	Average Floor Space (ft^2)	Average Vintage
Office - 4	8	83,053	10,382	2006
Labs	5	121,308	24,262	1961
Service/Support	11	86,203	7,837	1976
Plant	65	536,873	8,260	1976
Shop	46	290,551	6,316	1988
Warehouse/Storage	55	320,788	5,833	1983
Office Trailers - 1	39	61,764	1,584	1980
Office Trailers - 2	79	98,318	1,245	1992
Office Trailers - 3	228	278,443	1,221	2008
Office Trailers - Large	20	220,141	11,007	1992
TOTAL SITE	589	2,857,097	4,851	

For each FEDS building set, the extensive FEDS library of typical building and equipment features is queried to model the proxy building with the most likely characteristics, given the specified size, type, vintage, and purpose. The FEDS library of characteristics has been compiled from U.S. DOE building survey data (e.g., Commercial Building Energy Consumption Survey data) plus decades of experience from numerous on-site energy audits of many Federal and other installations covering many thousands of buildings. FEDS utilizes typical meteorological year (TMY) weather data[14] for the specified geography in combination with building characteristics to simulate hourly performance and energy use and derive HVAC equipment operation regimes.[15]

Baseline energy use and operational data for the installed HVAC equipment were modeled using FEDS and the resulting baseline conditions are reported in Table 4.8.

[14] Ibid.

[15] TMY is defined as year of hourly observations that contain real weather sequences for a particular location that represent long-term climatic conditions.

Table 4.8. Hanford Site Estimated 2018 Baseline Building Energy Use Using FEDS

FEDS Building Set	Total Annual Energy Use (kWh)	Total Annual Energy Cost ($)	Peak Demand (kW)	Heating (kWh)	Cooling (kWh)	Ventilation (kWh)
Office - 1	6,915,213	276,609	2,321	2,367,694	769,204	1,102,804
Office - 2	5,361,066	214,443	1,923	1,386,282	507,034	838,190
Office - 3	3,075,247	123,010	1,118	717,835	423,004	537,628
Office - 4	1,701,683	68,067	601	524,020	161,705	283,565
Labs	2,748,658	109,946	902	854,884	313,841	492,340
Service/Support	2,682,699	107,308	813	522,597	237,293	623,544
Plant	11,120,408	444,816	4,661	2,695,034	45,076	456,567
Shop	4,930,706	97,228	2,291	1,372,138	121,420	311,559
Warehouse/ Storage	4,784,978	191,399	3,262	3,273,559	49,633	303,965
Office Trailers - 1	1,611,851	64,474	1,118	769,584	209,042	91,561
Office Trailers - 2	2,127,220	85,089	1,311	830,874	316,591	117,075
Office Trailers - 3	5,527,627	221,105	3,373	2,108,340	687,037	289,512
Office Trailers - Large	3,394,941	135,798	1,659	902,674	431,030	137,579
TOTAL SITE	55,982,296	2,239,292	24,445	18,325,512	4,271,909	5,585,891

Table 4.8 confirms the winter dominance suggested earlier. Currently, heating energy use is over four times greater than cooling energy use, as a result of higher heating loads and duration combined with lower efficiency of most HVAC equipment in heating mode rather than cooling. Under current projections, this imbalance between heating and cooling would be expected to shift more into balance at the Hanford Site. FEDS simulation was used to determine the resulting impact on the operating regimes of the HVAC equipment. For baseline conditions, Table 4.9 provides the estimated operating regimes for a representation of the Hanford building stock that covers most of the on-site workforce.

Table 4.9. FEDS-derived Representative HVAC Equipment 2018 Baseline Operating Regimes

FEDS Building Set	Heating Capacity (tons)	Cooling Capacity (tons)	Modeled Run Hours - Heat	Modeled Run Hours - Cool	Modeled Run Hours - Total	Avg. Cycle Hours - Heat	Avg. Cycle Hours - Cool
Office - 4	5.9	7.1	1,754	1,864	3,618	0.238	0.304
Office Trailers - Large	23.45	27.2	1,347	845	2,192	0.149	0.165

Projected changes in these metrics are expected to illustrate the magnitude of any resilience impact that may be expected in the future. For example, increased overall runtime or mode-specific run time may affect the equipment performance. Also, more frequent cycling of the equipment may affect the performance and lead to earlier failure and need for replacement.

4.2.2.1 Quantify Hazard Probability and Thresholds

The risk being modeled is whether projected temperature changes would result in added stress on the HVAC equipment such that its lifetime may be shortened or that more frequent maintenance and repair would be required, and how it would affect energy costs. PNNL modeled two cases to identify any potential resilience impacts. These cases, illustrated above in Figure 4.14 and Figure 4.15, reflect the application of RCP 4.5 and RCP 8.5 as alternative scenarios. The RCP 4.5 case assumes that more action will be taken to reduce temperatures over time than the RCP 8.5 case, and thus more moderate average warming.

4.2.2.2 Develop Baseline Resilience Value

The FEDS model was exercised to estimate the temperature effects on the Hanford Site building stock HVAC systems. The TMY data for the Hanford Site were adjusted to reflect the RCP 4.5 and RCP 8.5 case alternatives as projected to impact Benton County, Washington, where the Site is located. The existing building stock was simulated under current conditions, assuming these conditions would persist into the future, to reflect the baseline. For the two alternatives, snapshots were modeled for 2025, 2050, and 2075 under RCP 4.5 and RCP 8.5 to reflect the trend in temperature effects on HVAC systems. Linear interpolation was used to span between the analysis years and to extrapolate to 2090. Table 4.10 reports the FEDS simulation results for the baseline and alternatives, based on the current building stock persisting in place over the analysis period.

Table 4.10. 2018–2090 Aggregate HVAC Energy Consumption in Hanford Site Building Stock

Case	Total HVAC Energy Use, GWh	Heating (GWh)	Ventilation (GWh)	Cooling (GWh)
Baseline	1,106.90	719.73	219.39	167.78
RCP 4.5	1,019.64	607.96	216.58	195.10
RCP 8.5	1,004.44	586.00	216.39	202.06
Change in energy usage				
RCP 4.5	(87.26)	(111.77)	(2.81)	27.32
RCP 8.5	(102.46)	(133.73)	(3.00)	34.28
Percentage Change in energy usage				
RCP 4.5	(7.9%)	(15.5%)	(1.3%)	16.3%
RCP 8.5	(9.3%)	(18.6%)	(1.4%)	20.4%

However, paying more or less for energy used for HVAC services depending on changing temperatures is only a part of the resiliency question. The other part of the question is whether temperature-induced load changes would result in earlier replacement or additional maintenance and repair costs being incurred. Impacts on the resiliency of the HVAC equipment to alternative cases is a function of the operating parameters of the machines themselves, not simply the energy they use. In theory, the more operating hours HVAC equipment logs, the more wear and tear occurs. And perhaps more importantly, the short cycling of equipment (exhibited by increased on and off cycles) is known to lead to earlier equipment failure rates.

Table **4.11** illustrates the runtime and cycling impacts resulting from FEDS modeling of a select subset of the modeled Hanford Site building stock.

Table 4.11. Hanford Site Average Cooling System Operation under Alternative Temperature Scenarios

FEDS Building Set	Year	Temperature Case	Run Hours - Heat	Run Hours - Cool	Run Hours - Total	Avg. Cycle Minutes - Heat	Avg. Cycle Minutes - Cool
Office-4	2018	Baseline	1,754	1,864	3,618	14.3	18.2
	2025	RCP 4.5	1,616	2,007	3,623	14.1	17.9
	2050	RCP 4.5	1,533	2,110	3,643	14.0	17.9
	2075	RCP 4.5	1,469	2,175	3,644	14.0	17.8
	2090	RCP 4.5	1,431	2,214	3,645	14.0	17.7
	2025	RCP 8.5	1,600	2,022	3,622	14.0	17.4
	2050	RCP 8.5	1,483	2,170	3,653	14.0	17.8
	2075	RCP 8.5	1,342	2,342	3,684	13.9	17.6
	2090	RCP 8.5	1,257	2,445	3,703	13.8	17.5
Office Trailers - Large	2018	Baseline	1,347	845	2,192	8.9	9.8
	2025	RCP 4.5	1,261	904	2,165	8.7	9.7
	2050	RCP 4.5	1,191	947	2,138	8.6	9.7
	2075	RCP 4.5	1,148	978	2,126	8.6	9.6
	2090	RCP 4.5	1,122	997	2,119	8.5	9.6
	2025	RCP 8.5	1,247	912	2,159	8.7	9.7
	2050	RCP 8.5	1,155	975	2,130	9.9	9.6
	2075	RCP 8.5	1,141	1,007	2,148	8.3	9.6
	2090	RCP 8.5	1,133	1,026	2,159	7.4	9.5

Figure 4.16 illustrates these metrics graphically. These results suggest there would be only a limited resiliency issue for HVAC equipment installed on the Hanford Site due to temperature changes. A majority of cooling equipment in the Hanford building stock utilizes direct expansion (DX) technologies, as opposed to chillers. On average, this equipment is likely oversized for current loads, as a result of standard practice, and confirmed based on limited reported evidence for select buildings. PNNL understands that current operating practice includes running equipment until failure and generally beyond what might be considered normal expected lifetimes. This combination of design and operations serves to mitigate resilience issues. Short-cycling is an established contributor to DX equipment failure although there is insufficient data to provide accurate correlation or estimate expected impacts. Short cycling is being reduced during the peak cooling months and the length of the cooling season is also increasing, creating a need to cool earlier in the year as well as later. In these shoulder periods, when cooling may not have been needed before, short cycling of equipment increases. Thus the net impact is that the cooling systems run more of the year, for longer times during the peak summer periods, but also shorter times during other parts of the year. It is difficult to estimate the net impact but expert opinion of the modeled results is that this would not result in an appreciable change in equipment lives.

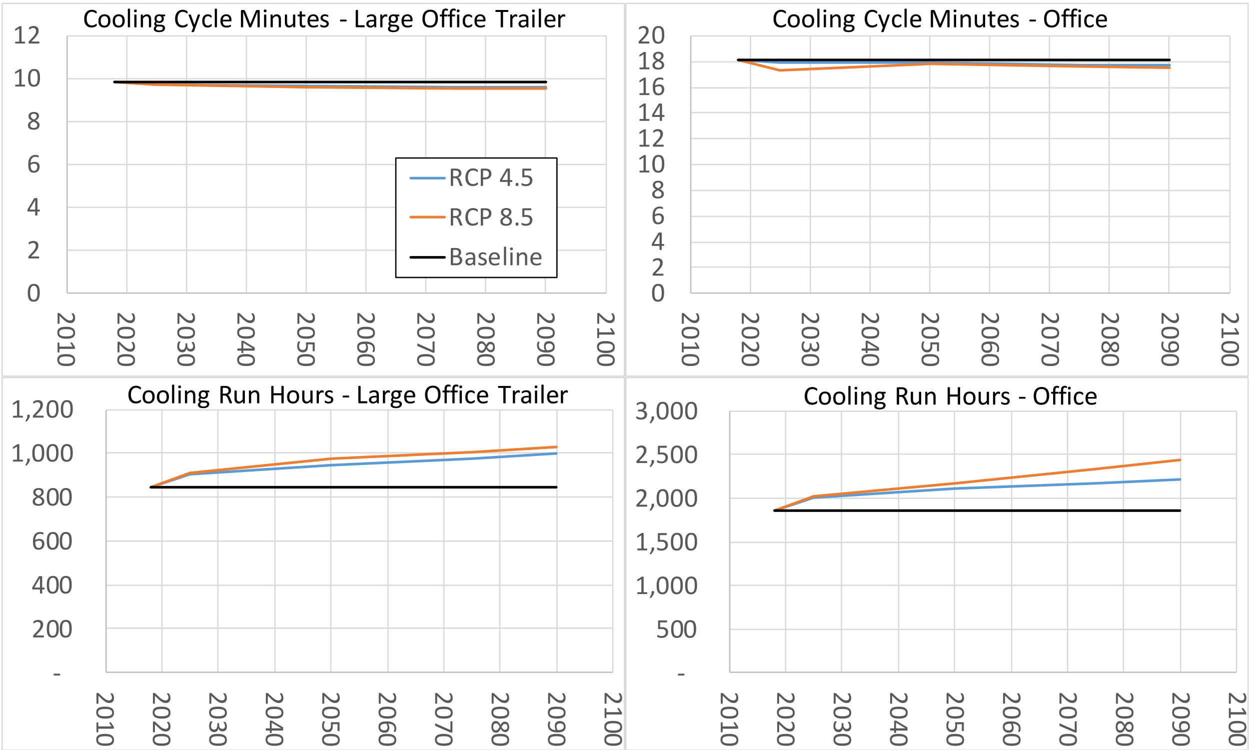

Figure 4.16. Hanford Site Average Cooling System Operation Under Alternative Scenarios

FEDS simulation results also indicate that peak cooling loads will increase by 9% by 2050, rising to 34% by 2075, and thus, equipment will eventually have a more difficult time meeting peak loads. However, for the following reasons, capacity increases for most equipment can likely be scheduled over time under typical replacement intervals, or at worst under slightly decreased replacement intervals. The projected scale and time period of increase (10-15% increase over 50 years) is not particularly worrisome, though reaching an increase of 30% or more becomes noticeable. Also, the analysis is based on the reasonable assumption that most cooling equipment is likely oversized. Under these conditions, some equipment will not fare as well and will likely fail or provide unsatisfactory service and need to be replaced earlier, but this will likely be a smaller fraction. There will most likely be some equipment that will be pushed to earlier replacement due to increased peak summer cooling loads including systems that are not currently oversized or those that may already be degrading. However, it is not possible to accurately estimate the expected trade-off of these factors. On net, there is likely to be an overall benefit resulting from a narrowing of the load-to-capacity gap. On the heating side (except for heat pumps) there is less of an impact of this type and the biggest benefit is the fewer number of hours and resulting reduction in energy use needed in what will continue to be a heating dominated scenario.

The projected energy cost savings are likely to help offset potential equipment upgrade or replacement impacts. It is expected that there will be some equipment replacement needs driven by these factors as noted above. Depending on what the building stock actually will be in out-years, the net energy cost savings should help offset the required equipment replacement or upgrade costs, perhaps to a significant degree.

The other critical factor to consider is that, given the mission of the Hanford Site, the building stock is forecast to be reduced substantially after 2050. For modeling purposes, the decommissioning of remaining floor space on the Site was assumed to proceed aggressively between 2050 and 2060, resulting in only a minimal stock (5% of current floor space) remaining on the site after 2060. Thus, the impacts discussed above would be occurring on a substantially reduced building stock – further minimizing the resiliency impact of continued temperature change. Given that the temperature impacts modeled would not begin to impact HVAC equipment operation until 2050 or later, and given the severely declining building stock on the Site, PNNL does not anticipate that the building stock would be actively retrofitted with higher capacity cooling equipment. It is anticipated that current practice of replacing failed systems with like models would continue and that building managers would not find alternatives to be cost effective.

4.2.2.3 Value Impacts to Baseline

The baseline against which the two cases were modeled is that currently observed conditions persist indefinitely. Current operating parameters of the HVAC systems on the Hanford Site would continue and the characteristics of HVAC equipment would not change. The size of the building stock is assumed to follow the current long-term plans, given the mission of the Site, and would decline significantly after 2050 to an assumed level of approximately 5% of current levels by 2060.

Based on FEDS modeling results, we see that about 1,107 GWh of energy would be used to provide HVAC service to the Site building stock between now and 2090 under baseline conditions. Depending on the case modeled, about 8% to over 9% of that energy would be saved due to temperature change impacts without any mitigation. About 112–134 GWh of heating energy would be saved, but would be slightly offset by about 27–34 GWh of additional cooling energy consumption. Table 4.12 summarizes the cost implications of the modeled consumption. Given the very long time horizon of the analysis, the dollar values of the energy consumed were discounted using two alternative discount rates, 7% and 3% respectively. Results are presented for total HVAC energy costs and for cooling energy only.

Table 4.12. 2018–2090 Net Present Value of Hanford Site HVAC Energy Costs

Net Present Value	**HVAC Energy Cost ($MM)**			**Cooling-Only Energy Cost ($)**		
	Baseline	**RCP4.5**	**RCP8.5**	**Baseline**	**RCP4.5**	**RCP8.5**
2018-2090 @ 7%	19.6	18.4	18.2	3.0	3.4	3.5
Change in energy cost		(1.3)	(1.5)		0.4	0.5
2018-2090 @ 3%	37.7	34.8	34.3	5.7	6.6	6.8
Change in energy cost		(2.9)	(3.4)		0.9	1.1

In aggregate, HVAC energy costs are less over the 2018–2090 period in both of the cases, compared to the baseline. The present value of costs resulting from heating and ventilation energy more than offset the additional costs losses of additional cooling energy needs over the same period. These results are discussed in more detail in the following sections.

4.2.3 Step 3: Develop a Resilience Plan for HVAC systems

In theory, HVAC system resilience could be provided by upgrading or replacing HVAC systems for operation under expected temperature conditions. For cases likely to affect the Hanford Site, this would entail planning equipment upgrades that would be engineered for higher cooling capacities expected with warming temperatures during the cooling season. Generally, warming temperatures have been estimated to result in lower heating system demand and higher cooling system demand. Retrofit installations would need to account for this over time, rather than simply replacing current systems with identical capacity units.

In reality, as shown by the FEDS modeling results, for the location of the Hanford Site, the temperature impacts are not overall expected to be severe enough to cause building managers to deviate from established practice of replacing systems on failure. There may be exceptions where current equipment capacities may be insufficient to meet needs. However, with the expectation that the building stock will be declining substantially, motivation to retrofit HVAC systems before performance issues arise is expected to be low.

4.2.3.1 Establish Resilience Measures

Potential alternatives to address HVAC system resilience to temperature impacts can include several measures. Measure-by-measure evaluation of energy efficiency options may identify single measures or packages of measures that could reduce cooling system loads and offset cooling energy consumption increases or reduce cooling system loads due to increasing temperatures. HVAC system upgrades also may be an option. The life-cycle costs of these measures are one component of the cost of HVAC resiliency.

4.2.3.2 Evaluate Alternatives to Determine Resilience

Energy efficiency measures that reduce cooling loads or offset cooling load increases due temperature increases should be considered and evaluated for cost-effectiveness. These might include improved insulation, building shell improvements to reduce infiltration, window retrofits, operational HVAC controls, etc. The viability of these measures depends on the expected life of the measure compared to the life of the HVAC equipment and the life and occupancy of the building itself.

While energy-efficiency measures can delay the need to replace HVAC equipment, the equipment itself eventually will require replacement due to age. At that point, it may be economic to replace the equipment with models featuring improved cooling capacity, rather than direct replacement with the same model. Presumably replacement models with higher cooling capacities would cost more than replacement with like models.

4.2.3.3 Value Each Alternative for HVAC Systems

The impact analysis presented in the previous section illustrated the potential impacts on the HVAC systems of the Hanford Site building stock. These impacts were found to be minimal, especially in the context of a significantly reduced building stock at the time when noticeable impacts on systems would be emerging due to increasing temperatures.

Because the estimated impacts would be minor, a formal alternatives analysis is not justified for the Hanford Site. One could be undertaken in which the life-cycle costs and benefits of a range of mitigating measures could be compared. However, given the simulation results indicating minimal impacts to HVAC system resiliency from warming temperatures, it is likely that none of the identified measures would be found to be cost effective for purposes of resiliency enhancement. As noted above, under the cases examined, a net reduction in life-cycle energy costs was estimated. Technically, this would constitute an economic benefit, as the avoided expense for energy could be redirected to other actions, or possibly to address other resiliency issues.

4.2.4 Step 4: Undertake Cost-Benefit Analysis for HVAC systems

For the Hanford Site case, analysis following the full approach outlined in Section 3.3 was not justified, as discussed above. Instead, the life-cycle HVAC energy costs under baseline conditions and two cases were analyzed and reported in Table 4.12, above, for the 2018-2090 period. Based the equation in Section 3.3.3, net present cost of energy costs is calculated as follows:

$$\text{NPC}_{\text{(Energy Costs)}} = \sum_{i=1}^{n} \frac{Cost_i}{(1+r)^i},$$

Where *r* is the selected discount rate, *n* is the number of years for which the NPV is being estimated, and *i* is the ith year in the stream of costs. Because the time horizon extends beyond 30 years, two discount rates were chosen to highlight the sensitivity of the estimates to the opportunity cost of capital. As suggested in Section 3.3.3, a rate of 7% is used to reflect the weighted average cost of capital faced by private firms. To reflect the opportunity cost of capital for investments extending decades in time, a rate more approaching the US Treasury Bill rate should be used. In this case 3% was used.

4.2.4.1 Compare Valuation of Action to Inaction for HVAC Systems

The discussion here is based on results reported in Table 4.12, above. Under the baseline, the net present value of the 2018-2090 stream of HVAC energy costs ranges between $19.7 and $37.7 million, depending on the discount rate chosen. Under the case RCP 4.5, a net savings of $1.3-$2.9 million was estimated, without undertaking any mitigative actions. For the RCP 8.5 case, these HVAC energy cost savings rise to $1.5-$3.5 million. These savings occur despite the additional life-cycle energy costs associated with increased cooling energy use, which range from $0.4-0.9 million under the RCP 4.5 case to $0.5-$1.1 million in the RCP 8.5 case.

4.2.4.2 Establish Non-monetary Costs and Benefits

The principal non-monetary benefit at stake is the thermal comfort of building occupants. Thermal comfort also translates to worker productivity, which may be monetizable, but is treated as qualitative in this study. Impacts on HVAC (especially cooling) systems can reduce (cost) thermal comfort of building occupants if the equipment is unable to meet increased loads effectively. In some cases, performance of sensitive electronic equipment could be affected by variability in thermal conditions, which may result under increased cooling loads.

No mitigative measures have been quantitatively analyzed for the Hanford case. However, it would be expected that any measures that could be considered would ensure that occupant thermal comfort would remain unchanged or not degraded, as opposed to enhanced.

4.2.5 Step 5: Create Decision Portfolio for HVAC systems

Hanford Site decision-makers would need to be compelled by robust analysis to consider mitigative action. The FEDS modeling approach is an industry standard approach for examining fleets of buildings associated with specific sites. Here, it has been used to identify the potential impacts of two scenarios in which notable increases in daily temperatures are forecast for the Hanford Site location in the Pacific Northwest. FEDS has estimated the energy consumption, related costs, and machine operation metrics of the HVAC systems for the building sets representing the entire Site building stock. The analysis did not find temperature-induced heat stress to have more than a minor impact, given the timing of the projected impacts and the timing of expected building stock decommissioning activities.

For other sites, FEDS modeling results would be expected to be somewhat different – especially for sites where energy use is cooling-dominated or peak energy use occurs in the summer. In those cases, mitigative action may prove to be economic and a more formal decision-making process would be warranted. Especially where energy prices may be higher, alternative fuel options beyond electricity may be available, and the cost of implementing projects are lower.

4.2.5.1 Determine Decision Criteria

In the Hanford HVAC case, decision-makers need to evaluate the FEDS analysis and determine whether projected impacts are cause for concern and potential action. Based on PNNL's understanding of current practice and the present planning assumptions affecting the Hanford Site, the FEDS modeling results do not motivate a significant concern with respect to HVAC systems on the Site.

4.2.5.2 Obtain Weights for Decision Criteria

There are no resiliency decisions before decision-makers regarding HVAC system resiliency at the Hanford Site. The FEDS analysis indicates that the concern for temperature-induced HVAC system stress is minimal for this site. No mitigative alternatives are warranted, given the foregoing analysis.

4.2.5.3 Apply Decision Criteria

There are no resiliency decisions before decision-makers regarding HVAC system resiliency at the Hanford Site. The FEDS analysis indicates that the concern for temperature-induced HVAC system stress is minimal for this site. No mitigative alternatives are warranted, given the foregoing analysis.

4.2.5.4 Provide Decision Matrix

There are no resiliency decisions before decision-makers regarding HVAC system resiliency at the Hanford Site. The FEDS analysis indicates that the concern for temperature-induced HVAC system stress is minimal for this site. No mitigative alternatives are warranted, given the foregoing analysis.

Appendix A

Additional Information on Data Required to Build the Cost Baseline

Appendix A

Additional Information on Data Required to Build the Cost Baseline

The site baseline includes an inventory of its systems such as facilities, human capital, and adjoining infrastructure including roads, electricity, water, and waste connections, etc. An important part of the baseline is the timeframe over which resilience will be valued. The timeframe will depend on the mission and hazards being evaluated. Usually the asset life or mission life will determine the timeframe. Vulnerabilities that affect facilities with 100-year lifetimes would be assessed over 100 years. Timeframes of less than 20 to 30 years are unrealistic to assess in terms of sustainability. Remaining life is an important requirement as well. For example, if a critical system only has 15 years remaining in its life, 15 years would be the appropriate lifetime.

The information required to establish a cost baseline includes the actual facilities, replacement value, the number and types of employees, and the value of any other infrastructure required for the site to carry out its mission. Collect information on the following:

A.1 Facilities

- Data needed: Facility replacement value, year facility was built, expected life of the facility, square footage per facility, value per square foot, financial owner, labor business volume ($), number of occupied offices, mission dependency level, number, cost and types of assets within facility, relative location of asset within the facility (ex. basement vs. top floor), designation as to which type of asset would impact mission operation costs if lost, operations and maintenance costs
- Possible sources: Business office, facility management, asset management, accounting office

A.2 Human Capital

- Data needed: Total number of employees at site, total number of employees within each facility, breakdowns by facility environment type (e.g. data center, dry lab, wet lab, office, storage) especially if it is important. Also, list any categories that might be relevant to your methodology such as indoor vs. outdoor workers, essential personnel, and personnel that can telework. For example, outdoor workers may be more vulnerable to certain risks like high heat days.
- Possible sources: HR, facility management office

A.3 Energy

- Data needed: Number and size of electric lines to site, natural gas connections, backup power, and amount of power used by subsystem, primary fuel requirements, powerline replacement value, alternative energy systems
- Possible sources: Local utility, facilities and operations

A.4 Water

- Data needed: size/age of water system, pipeline replacement value, water process/treatment facility replacement value, wastewater treatment replacement value, storage tank replacement value, sewer system replacement value, storm water systems
- Possible sources: American Water Works Association[1], projects and engineering office, facility management office, local water utility

A.5 Transportation

- Data needed: Road replacement value, oil/gas pipeline replacement value
- Possible sources: State department of transportation

A.6 Healthcare

- Data needed: Site health services, local hospital capacity in case of site accidents, health department offices; radiological material and medical waste transportation, storage, and disposal; availability of ambulance/Medivac service
- Possible sources: Local hospitals, the site health office, emergency medical facilities and assets, historical health and safety violations/incidents

A.7 Communication Systems

- Data needed: Replacement value of transmission system, cable system, radio tower, satellite system, warning systems, capacity and redundancy of internet services, cell phone system reliability
- Possible sources: IT Department, communication services department, facility management office, local supplier of communication infrastructure/maintenance

A.8 Mission Specific Services and Supply Chains

- Data needed: Structures, systems, and components, potentially including tank waste storage, nuclear material storage, transportation equipment, processing equipment, and monitoring equipment; strategic supplies and their suppliers
- Possible sources: Facility management office, external partners (if applicable), procurement

In addition, operations and maintenance information is required to provide a baseline operating cost in addition to salaries and wages. Also, information on environmental conditions and waste sites need to be included. Any asset or property with tangible value needs to be included in the initial site assessment. This data can be obtained from the facilities organization of each DOE site.

Evaluations of a site that includes waste management or environmental conditions should include all information available that can assist in the accurate modeling of the facility. This information can include the following: geological/geotechnical appraisals, input/output levels, processing costs, topographical

[1] American Water Works Association. ca 2011. Buried No Longer: Confronting America's Water Infrastructure Challenge. Access September 22 at http://www.awwa.org/Portals/0/files/legreg/documents/BuriedNoLonger.pdf

surveys, rehabilitation/restoration requirements and obligations, waste transfer process and levels, and/or others.[2]

The above only describes the critical infrastructure identified in current DOE vulnerability assessments. The Department of Homeland Security identifies 16 different categories of critical infrastructure.[3]

[2] RICS. 2016. Valuation of Mineral-bearing Land and Waste Management Sites. April, 2016. Accessible at: http://www.rics.org/Global/Valuation_of_mineral_bearing_land_and_waste_management_sites_2nd_edition_PGguidance_2016.pdf

[3] Department of Homeland Security. 2017. Critical Infrastructure Sectors. Accessed September 22, 2017 at https://www.dhs.gov/critical-infrastructure-sectors

Appendix B

Establishing the Probability of a Hazard

Appendix B

Establishing the Probability of a Hazard

Determining probability of occurrence for any of hazards/exposures to DOE sites is a difficult prospect, and one that is an active general area of research. At the most basic level, one must define the threat, which is an easier prospect in some cases than in others. For example, a hurricane impacting a particular site is a clearly demarcated event. Elevated temperatures (on average or as a heat wave) is more nebulous or arbitrary, but one can define thresholds that are attached to some site-relevant metrics (e.g., number of days above 100°F, relevant to outdoor workers). Droughts may have an arbitrary definition (how does one quantify "not enough water"?) and have no clear beginning or end. Next, one must quantify probabilities for the time period of interest. Under the assumption that the past is a good predictor of future statistics (stationarity), one can use historical data to extrapolate to future frequency of occurrence and intensity.

Stationarity (a description of when past conditions are considered to be good representations of future conditions) is widely understood to be an invalid assumption, but it may be approximately valid for particular relevant variables at specific sites. For situations in which stationarity is not valid, one then requires a quantitative understanding of the underlying physical processes that are likely to change probabilities of occurrence or intensity of the event. This is particularly difficult in that many of the threats to sites deal with extreme events, which are at the tails of probability distributions, where change is more difficult to quantify and where there are fewer sample points. Vulnerability screenings for a range of sites are likely to be both straightforward and important, in which all sites prioritize the hazards (identified in Step 2a) that they are most likely to experience and how disruptive those hazards are likely to be. Once the most relevant threats for a site are identified, the sorts of site- and situation-specific analyses discussed previously can then proceed, likely involving a large team that includes scientists that understand the sustainability problems, site managers, and other relevant stakeholders.

B.1 Natural Hazards

B.1.1 Hurricanes and Storm Surge

Hurricanes are immensely destructive forces, producing damaging winds and severe flooding; they are the sources of some of the most severe and costly natural disasters to occur in the United States.[1] Storm surge from sea level rise is the greatest source of damage to coastal cities.[2] Although somewhat inland, the Savannah River National Laboratory lies on a path that coincides with one of the most frequent locations for hurricane landfalls in the continental United States.[3]

Historical records of hurricanes in the satellite era (since 1966) are excellent, as hurricanes are easily observed and measured due to their size and wind speed. Prior to the satellite era, hurricane observations were ones of opportunity, meaning that hurricanes near population centers were more likely to be

[1] Cavallo, E. A. and I. Noy (2011), The economics of natural disasters: A survey, *IDB Working Paper No. 35*, 49 pp., available online at https://papers.ssrn.com/sol3/papers.cfm?abstract id=1817217, last accessed on 26 August 2017.
[2] Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke (2012). Physically based assessment of hurricane surge threat under climate change, *Nature Climate Change*, *2*, 462-467
[3] Vickery, P. J., P. F. Skerlj, and L. A. Twisdale (2000), Simulation of Hurricane Risk in the U.S. Using Empirical Track Model, *Journal of Structural Engineering*, *126*, doi:10.1061/(ASCE)0733-9445(2000)126:10(1222)

observed.[4,5] This introduces an observation bias into historical records of hurricane frequency and intensity. Statistics of hurricanes can be obtained from the North Atlantic Hurricane Database (HURDAT).[6] A National assessment[7] states with medium confidence that hurricanes are expected to reduce in frequency but become more intense as the planet continues to warm; this is currently an active area of research.

B.1.2 Winter Storms

Winter storms cause major disruptions to facilities, making roadways unsafe and sometimes bringing down power lines. As has been seen in recent years, winter storms in the Washington, D.C. area have caused closures of Federal government activities, which has a direct impact on all DOE activities. Winter storm severity can be quantified from many of the same sources as described previously: temperature, precipitation (not only amount, but also whether it falls as a liquid or a solid), wind speed, and atmospheric pressure. Studies of winter storms have been built for select locations.[8] Current understanding indicates that winter storm severity in the U.S. may increase due to a combination of factors, including Arctic sea ice loss, an increase in the atmospheric holding capacity of water, and a weaker, wavier jet stream.[9]

B.1.3 Floods

Flooding can inundate facilities (e.g., data centers) and necessitate shutdown. While these events are somewhat complicated by terrain, infrastructure, vegetation, and water storage, they are by and large driven by commonly measured meteorological variables. In the case of Los Alamos National Laboratory (LANL), unmitigated flooding has the potential to breach storage of low-level radioactive waste, washing it into nearby waterways. From a meteorological standpoint, floods can be measured simply by a historical analysis of the amount of rainfall received and the intensity of rainfall events. For example, a large amount of rain received in a short amount of time cannot be sufficiently absorbed into the ground, creating flooding. If an area is not accustomed to rain and receives a large amount of it, even if that rain is spread out over a long time, this can cause floods. The individual characteristics will be site-specific and may require manual labeling of historical data to obtain an accurate picture of the rainfall characteristics that could cause flooding.

Flooding also has land surface and infrastructure components. Areas at the base of water catchments or on river banks are more likely to experience flooding than areas at higher elevation. In urban areas, drainage capacity and proper surveying can be a main driving source for flooding and flood mitigation. The USGS

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[4] Landsea, C. W., et al. (2004), The Atlantic Hurricane Database Re-analysis Project: Documentation for 1851-1910 Alterations and Additions to the HURDAT Database, in *Hurricanes and Typhoons: Past, Present and Future*, R. J. Murname and K.-B. Liu, eds., Columbia University Press, New York, NY, p 177-221

[5] Vecchi, G. A. and T. R. Knutson (2011), Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878?1965) Using Ship Track Density, *Journal of Climate*, *24*, 1736-1746, doi:10.1175/2010JCLI3810.1

[6] Landsea, C. W., and J. L. Franklin (2013), Atlantic hurricane database uncertainty and presentation of a new database format, *Mon. Wea. Rev.*, *141*, 3576-3592.

[7] USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

[8] Hirsch, M.E., A.T. DeGaetano, and S.J. Colucci (2001), An East Coast Winter Storm Climatology, *J. Climate, 14,* 882-899, doi:10.1175/1520- 0442(2001)014<0882:AECWSC>2.0.CO;2.

[9] Cohen, J, JA Screen, JC Furtado, M Barlow, D Whittleson, D. Coumou, J Francis K Dethloff D Entekhabi, J Overland and J Jones. Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience 7, 627-637 (2014)* doi:10.1038/ngeo22334. http://www.nature.com/ngeo/journal/v7/n9/full/ngeo2234.html

has compiled a database of historical and current flooding,[10] but on a site-specific basis, all of these factors need to be taken into account to quantify risk. Moreover, new construction or retrofitting to mitigate risks from other extreme events may impact flood resilience. Asset location is another factor; for example, data centers may be moved to a higher floor to mitigate flooding risks.

B.1.4 Droughts

Drought can also impact facilities in that there may be insufficient water to cool power plants, computing facilities, or laboratories. There are several metrics of drought that one can calculate. A simple, yet often effective metric is the Keetch-Byram Drought Index (KBDI), which was developed for quantifying the risk of forest fires.[11] This metric only requires historical records of daily maximum temperature, daily rainfall, and the average amount of yearly rainfall at a site, which is often available through Global Historical Climatology Network (GHCN) data.[12,13] More complicated metrics, such as the Palmer Drought Severity Index, are available for large areas of the United States.[14] This more complicated index requires additional variables, such as soil moisture, evapotranspiration, and groundwater recharge rates.[15] Some of these quantities can be estimated through calculations of radiative flux, but the calibration can contain somewhat arbitrary factors, limiting the use of the Palmer Index to well-characterized sites.[16]

We note that drought is not a purely climatological designation, and may require additional input from social and political data sources. As a simple example, droughts can be declared by political officials (e.g., governors) if water resources are insufficient to keep up with demand for any reason, possibly independent of the amount of rainfall received in an area.

B.1.5 High Temperatures and Heat Waves

Higher average temperatures can tax power and water resources (e.g., cooling buildings or computing facilities), placing further strain on facilities that are already facing limited resources. In addition, as average temperatures continue to increase, there is an increased probability of heat waves, which are deadly events that have been associated with large impacts, such as cascading power failures.[17,18] Many DOE sites (such as LANL; see example below) are already experiencing both elevated average temperatures and increased frequency and severity of heat waves, and they will continue to do so as the

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[10] USGS. "USGS Flood Information." Last updated December 16, 2016. Accessed October 3, 2017 at https://water.usgs.gov/floods

[11] Keetch, J. J. and G. M. Byram (1968), A drought index for forest fire control, U.S. Department of Agriculture – Forest Service.

[12] Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston (2012a), An overview of the Global Historical Climatology Network-Daily Database, *Journal of Atmospheric and Oceanic Technology*, *29*, 897-910, doi:10.1175/JTECH-D-11-00103.1

[13] Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E.Gleason, and T.G. Houston (2012b), Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.22, NOAA National Climatic Data Center, http://doi.org/10.7289/V5D21VHZ [11 August 2017].

[14] Dai, A., et al. (2004), A Global Dataset of Palmer Drought Severity Index for 1870?2002: Relationship with Soil Moisture and Effects of Surface Warming, *Journal of Hydrometeorology*, *5*, 1117-1130

[15] Palmer, W. (1965), Meteorological Drought, Research paper No. 45, U.S. Department of Commerce Weather Bureau, 58 pp., available online by the NOAA National Climatic Data Center at [http://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf.-](http://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf)

[16] Alley, W. (1984), The Palmer Drought Severity Index: Limitations and Assumptions, *Journal of Climate and Applied Meteorology*, *23*, 1100-1109

[17] Anderson, G. B. and M. L. Bell (2011), Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities, Environmental Health Perspectives, 119, 210-218, doi:10.1289/ehp.1002313.

[18] G Luber and M McGeehin. Climate Change and Extreme Heat Events. American Journal of Preventive Medicine, Vol. 34:5, Nov 2009, pp.429-435.

change progresses. In general, these sorts of impacts are among the most straightforward to calculate, as they depend only upon readily-available temperature data.[19,20] There are well defined metrics of heat waves that we discuss in more detail in the subsequent section. We caution that the impacts of elevated temperatures or heat waves are not as straightforward to calculate, as they depend upon adaptive capacity (e.g., air conditioning) and whether there are complicating factors (e.g., if the heat wave is accompanied by drought).

B.1.6 Wildfire

Rising temperatures are increasing wildfire risk in parts of the U.S. Wildfires are immensely destructive events that impact facilities and missions on a variety of scales. Facilities can burn or become inaccessible. They can reduce air quality for site personnel. In addition, any waste storage that interacts with wildfires can become aerosolized, spreading contamination. Nearly all DOE facilities have the potential to be affected by fire.

Predictive fire modeling is an active area of research of broad interest to numerous stakeholders. Synthesizing these data into a product with predictive capability for wildfires is considerably less straightforward than evaluating observations of any individual indicators. There have been several attempts to build statistical models with explanatory capability, each of which has been met with some amount of success yet some deficiencies.[21,22,23] More comprehensive tools, including ones that can capture the underlying drivers of fire risk, are an active subject of research and are still forthcoming. In the interim, facilities managers are left in the position to use available tools, which may give general indications of fire risk but are likely to be deficient in key areas and will only work for specific sites.

B.1.7 Aridity and Desertification

More arid regions are more prone to heat waves, droughts, and wildfires. They are also less suitable for agriculture. As an example, LANL and PNNL are located in semi-arid regions; further desertification could place additional strain on available water resources (e.g., the Columbia River), leading to issues such as water rights disputes, which could impact the site's mission. The aridity of an area can be described by the Aridity Index, which is the ratio of annual precipitation to evapotranspiration.[24] Different aridity classifications (humid, sub-humid, semi-arid, arid, and hyper-arid) can be defined in terms of this index, and desertification can be described in terms of reductions in that index for a given land area. Calculating the Aridity Index requires measurements of pressure, evaporation, temperature, wind speed, radiative flux, and relative humidity at each site.[25] All of these variables are commonly measured at meteorological stations and are available through the National Centers for Environmental

[19] Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston (2012a), An overview of the Global Historical Climatology Network-Daily Database, *Journal of Atmospheric and Oceanic Technology*, *29*, 897-910, doi:10.1175/JTECH-D-11-00103.1

[20] Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E.Gleason, and T.G. Houston (2012b), Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.22, NOAA National Climatic Data Center, http://doi.org/10.7289/V5D21VHZ [11 August 2017].

[21] Alley, W. (1984), The Palmer Drought Severity Index: Limitations and Assumptions, Journal of Climate and Applied Meteorology, 23, 1100-1109.

[22] Anderson, G. B. and M. L. Bell (2011), Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities, Environmental Health Perspec- tives, 119, 210-218, doi:10.1289/ehp.1002313.

[23] Cavallo, E. A. and I. Noy (2011), The economics of natural disasters: A survey, IDB Working Paper No. 35, 49 pp., available online at https://papers.ssrn.com/sol3/papers.cfm?abstract id=1817217, last accessed on 26 August 2017.

[24] Middleton, N. J., and D. S. G. Thomas (1992), UNEP: World Atlas of Desertification, Edward Arnold, Sevenoaks.

[25] Fu, Q. and S. Feng (2014), Responses of terrestrial aridity to global warming, *Journal of Geophysical Research*, *119*, doi:10.1002/2014JD021608

Information (https://www.ncdc.noaa.gov). We note that the network of observation stations for this data has somewhat smaller coverage than GHCN, so one may need to be more selective with choice of sites. Aridity is more commonly a threat multiplier than a direct hazard itself, due to its tendency to exacerbate vulnerabilities.

B.1.8 Erosion and Landslides

Landslides can cause major disruptions to daily operations, blocking roads or reducing the stability of structures near hillsides. This can cause severe mission impacts at DOE sites; for example, as was discussed previously, landslides at LANL brought on by flooding and reduced vegetation cover have the potential to wash low-level radioactive waste into nearby waterways. There has been community interest in building a database of landslides to categorize frequency and the circumstances under which they occur, [26] but no such database presently exists. For site-specific investigations, visible satellite imagery would be useful for cataloging landslides.

B.1.9 Sea Level Rise and Inundation

Sea level rise can cause inundation and flooding, impacting facilities and making freshwater brackish and unsuitable for a variety of purposes. In addition, it can exacerbate the severity of storm surge from hurricanes. An example of a DOE site that is vulnerable to sea level rise is Brookhaven National Laboratory, located on Long Island, NY at an elevation of 24 meters above sea level. Sea level rise is well measured throughout the world to a relatively high degree of precision and has an excellent long-term record.[27,28] Although the exact magnitude of sea level rise is difficult to predict, as it depends on numerous complex factors, the probability that it will continue is virtually certain.[29] While this probability provides little information for planners and facilities managers (one plans differently for 1 cm of sea level rise vs 3 m of sea level rise), site managers may benefit from analysis of different scenarios of sea level rise; NOAA has provided useful planning tools for this purpose.[30]

B.1.10 Invasive Species

Invasive species can come in a number of forms, including plants, insects, and aquatic organisms. Evidence suggests that as temperature change progresses, the problem of invasive species is likely to worsen, as are the consequences of those invasions.[31] Although invasive species are unlikely to directly impact facilities, they have the potential to impact the environmental conservation and stewardship of the lands on which those facilities operate. For example, the Oak Ridge National Environmental Research

[26] Kirschbaum, D. B., R. Adler, Y. Hong, S. Hill, and A. Lerner-Lam (2010), A global landslide catalog for hazard applications: method, results, and limitations, *Natural Hazards*, *52*, 561-575, doi:10.1007/s11069-009-9401-4

[27] Church, J. A. and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophysical Research Letters*, *33*, L01602, doi:10.1029/2005GL024826.

[28] Gornitz, V., S. Lebedeff, and J. Hansen (1982), Global sea level trend in the past century, *Science*, *215*, 1611-1614, doi:10.1126/science.215.4540.1611.

[29] Mengel, M., A. Leverman, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann (2016), Future sea level rise constrained by observations and long-term commitment, *Proceedings of the National Academy of Science*, *116*, 2597?2602, doi: 10.1073/pnas.1500515113.

[30] NOAA – National Oceanic and Atmospheric Administration. Sea Level Rise Viewer. Accessed October 3, 2017 at https://coast.noaa.gov/slr/

[31] Kerns, B. and Q. Guo (2012), Climate change and invasive plants in forests and rangelands, US Forest Service, available on-line at https://www.fs.usda.gov/ccrc/topics/climate-change-and-invasive- plants-forests-and-rangelands, last accessed 26 August 2017

Park has 42 "aggressive" invasive species that are threatening endangered or rare native species and have the potential to become "management problems," requiring additional resources to combat.[32]

Because of the wide variety of habitats, native and invasive species, and potential effects, there is no database of indicators that can quantify the severity of invasive species. Any such efforts would necessarily be site-specific. These efforts could be undertaken to some degree through analysis of visible satellite imagery, such as that available through Landsat.

B.1.11 Ground Stability/Sinkholes

One of the major instances of ground instability is sinkholes. Due to changes in the hydrological cycle, sinkhole hazards are projected to increase in the future.[33] Sinkholes can open under facilities, roads, or storage sites, affecting structural integrity. Sinkholes are a regular occurrence in the vicinity of Paducah, KY,[34] where the site of the former Paducah Gaseous Diffusion Plant is located. An environmental assessment produced in 1994 prior to construction of a new waste storage facility at the site did not include assessments of sinkholes,[35] potentially opening the site to risk of groundwater contamination if a sinkhole were to open below or near the storage facility.

Because sinkholes are localized events that depend upon geology and local long-term meteorology, there is no known database of sinkhole occurrence. The exact circumstances under which sinkholes open are also uncertain enough to preclude anticipatory modeling. They can be observed and monitored with any platform that captures visible imagery.

We note that sinkholes are not the only sources of ground instability; soil liquefaction and seismic events may also present serious issues to infrastructure. However, these issues are currently incorporated into planning guidelines for all DOE facilities,[36] and there are no known links between those issues and any environmental changes, so we do not consider these risks here.

B.1.12 Earthquakes

Earthquakes primarily occur as a result of movement of the earth's tectonic plates. The movement of the plates can cause significant damage to facilities, transportation, and electrical infrastructure potentially causing outages or power quality problems for a facility. They can also pose a risk to human life. Geoscientists can identify regions at high risk of earthquakes. Most earthquakes are harmless. However, when significant shifts occur, shaking can cause significant devastation including destruction of facilities, electrical, and water systems as well as transportation systems. Examples of facilities at risk include regional offices of Pacific Northwest National Laboratory with buildings in Portland, Oregon and Seattle, Washington. Additionally, Lawrence Livermore and Lawrence Berkeley Laboratories in the Bay Area of California. The Federal Emergency Management Administration (FEMA) provides hazard maps for

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[32] Drake, S. J., J. F. Weltzin, and P. D. Parr (2003), Assessment of non-native invasive plant species on the United States Department of Energy Oak Ridge Natural Environmental Research Park, *Castanea*, *68*, 15-30

[33]] Linares, R., C. Roqu´e, F. Gutie´errez, M. Zarroca, D. Carbonel, J. Bach, and I. Fabregat (2017), The impacts of drought and climate change on sinkhole occurrence: A case study from the evaporite Karst of the Flu- via Valley, NE Spain, *Science of the Total Environment*, *579*, 345-358, doi:10.1016/j.scitotenv.2016.11.091

[34] Sanchez, A. (2016), Crews work to repair sinkhole in downtown Paducah, available online at http://wwww.wpsdlocal6.com/2016/08/30/crews-work-to-repair-sinkhole-in-downtown-paducah, last accessed 26 August 2017

[35] DOE (1994), Environmental assessment for the construction and operation of waste storage facilities at the Paducah Gaseous Diffusion Plant Paducah, Kentucky, 149 pp

[36] DOE (2012), Natural phenomena hazards analysis and design criteria for DOE facilities, DOE-STD-1020-2012, 90 pp.

earthquakes.[37] The maps indicate the level of earthquake hazard. Probability and magnitude will determine the potential impact on systems. As an example, the San Francisco Bay Regional Model can provide information for that region on the probabilities and magnitudes of earthquakes.[38]

B.2 Man-made Hazards and Threats

While this guidance focused on establishing probabilities for natural hazards, the valuation methodology could be used to enable assessment of man-made hazards and threats as well. Man-made hazards and threats include a range of technological accidents or failures as well as intentional actions/threats from adversaries. Examples of technological accidents and failures include utility disruptions from a failure to properly protect electrical infrastructure, and radiological or hazardous materials release due to inadequate management or containment practices. Examples of human-caused intentional actions or threats include active shooter incidents, explosives attacks, and cyber-attacks against infrastructure or data. Establishing quantitative probabilities for such incidents may be challenging, however general guidance is provided below..

B.2.1 Accidents

Accidents occur with a level of probability based on prior events. Some examples can include:

- An auto accident knocking out the electrical system;
- An accidental release of toxic materials from incorrect activation of a valve; or
- Someone accidentally touching live electrical system, causing a fault.

The prior events associated with a site or facility can provide a basis for determining the probability of such events occurring and the types of impacts on facilities. To evaluate the impact of potential events occurring, a history of the impacts on site infrastructure can be derived from historical site records.

B.2.2 Failure to Maintain Infrastructure

Failure to maintain infrastructure may lead to more accidents, increased operating costs and less resilience to hazards.

- Improperly maintained buildings may impact human health and mission assurance.
- Poor transportation infrastructure can lead to increased maintenance costs for site vehicles and may create potential for accidents.
- Improperly maintained facilities increase inefficiencies and operating costs.
- Discussions with site facilities and operations staff can provide probabilities about how long infrastructure maintenance can be delayed before impacts on human health and site operations will occur.

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[37] FEMA. 2017. Earthquake Hazard Maps. Accessed September 6, 2017 at https://www.fema.gov/earthquake-hazard-maps
[38] USGS. Earthquake Probabilities in the San Francisco Bay Region: 2002-2031. Accessed September 16, 2017 at Figure 3: Histograms of daily maximum temperature for the warm (top) and cold (bottom) seasons at LANL for each of the four time periods, as well as best fit distributions based on an assumed shape of a generalized extreme value distribution.

B.2.3 Terrorist Attacks

Terrorist attacks occur without a known probability, thus they can only be evaluated using uncertainty analysis. Furthermore, likelihood of an attempted terrorist attack is dependent on a multitude of factors. In order to better assess the risk of an attack occurring at a specific site, the Department of Homeland Security has outlined a risk management process for Federal facilities.[39] The process involves a threat assessment of the facility in which supporting information is used such as:

- The type of activity/assets located at the facility
- Methods of attack that would be most likely to be successful given the characteristics of the facility
- Potential history of aggressors targeting the facility
- Types of security measures in place to prevent attacks
- Target attractiveness due to symbolic importance

The above provide a set of hazards that could be applied to DOE sites. The next stage will be to explore site-specific hazards and their data sources to quantify both historical risk to sites as well as how those risks are likely to change in the future. Through this process of calculating probabilities of mission-affecting hazards, as well as calculating the costs of addressing those exposures versus not addressing them, one can provide decision support for how to best deal with changing risks to DOE assets. Terror attacks are a risk that sites can evaluate, but they are not included in current vulnerability/screening guidance.

B.3 Illustrative Example: Heat Wave Risk at LANL

The above descriptions of potential threats to DOE sites are useful from a broad perspective. However, these descriptions do not include all of the necessary detail about how risk at a site is quantified, a process that is much more difficult and labor intensive. As an illustrative example, here we walk through the assessment of specific probabilities of heat waves at Los Alamos National Laboratory (LANL) and how those probabilities might change in the future.

In this example, we proceed in a series of stages. Firstly, we define quantifiable metrics of heat waves. Second, we identify a data source that can be used to quantify changes in those metrics. Finally, one must analyze historical changes in those metrics to ascertain whether there are visible shifts. As we will demonstrate below, for several metrics of interest, there was no observable change in heat wave frequency or severity. For several other probability-based metrics, there were observable changes indicating more intense or frequent extreme heat events.

Here we decide to evaluate four metrics of interest and six probability thresholds based on the available data:

- TNn: annual minimum daily minimum temperature
- TXn: annual minimum daily maximum temperature
- TNx: annual maximum daily minimum temperature
- TXx: annual maximum daily maximum temperature

[39] DHS. 2013. The Risk Management Process for Federal Facilities: An Interagency Security Committee Standard. August, 2013. Accessible at: https://www.dhs.gov/sites/default/files/publications/ISC_Risk-Management-Process_Aug_2013.pdf

- TX10 and TX90: Daily maximum temperature at the 10th and 90th percentiles
- TN10 and TN90: Daily minimum temperature at the 10th and 90th percentiles

We have obtained daily minimum and maximum temperature data at Los Alamos since the 1910s from the GHCN version 3.22.[40,41] Since we decided our metrics based on available GCHN data, calculating the metrics TNn, TXn, TNx, TXx is relatively straightforward; results are displayed in Figure B.1 Changes in these metrics over the historical record are statistically insignificant, indicating that while these metrics may be useful in some circumstances, they are not sensitive indicators of change at LANL.

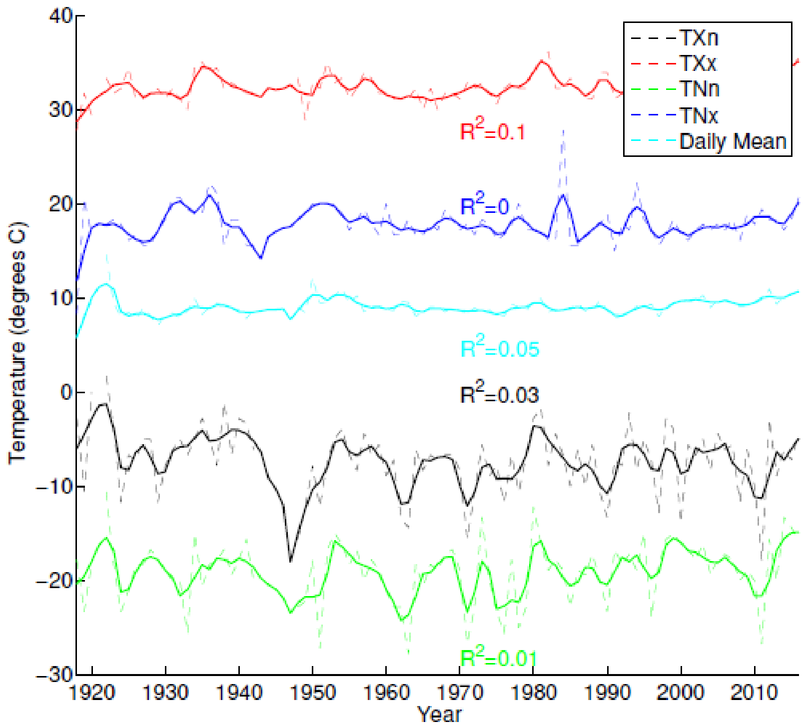

Figure B.1. Plots of Four of the Extreme Indices (black, red, green, and blue), as well as the annual average temperature (daily mean; cyan) over the entire time series of data available at LANL. Dashed lines are annual values, and thick solid lines are the same with five year smoothing applied. R^2 values are for best-fit ordinary least squares regression lines.

To observe changes in TX90, TX10, TN90, and TN10 while maintaining useful statistics, we group the data into four 20-year long periods: 1915-1934, 1947-1966, 1967-1986, and 1994-2013. These periods were chosen because they were relatively volcanically quiescent periods representing early and later portions of the 20th and 21st centuries, and they avoid World War II, which was known to cause a global climatic perturbation due to sulfate aerosol pollution. Calculating these metrics requires fitting a distribution to histograms of the daily minimum and maximum temperature data. The raw distribution is generally bimodal, showing two distinct extremes annually, which is consistent with the local climatology of semi-arid regions: hot summers, somewhat cold winters, and mild springs and autumns. As such, we

[40] Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston (2012a), An overview of the Global Historical Climatology Network-Daily Database, *Journal of Atmospheric and Oceanic Technology*, *29*, 897-910, doi:10.1175/JTECH-D-11-00103.1
[41] Menne, M.J., I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R.S. Vose, B.E.Gleason, and T.G. Houston (2012b), Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.22, NOAA National Climatic Data Center, http://doi.org/10.7289/V5D21VHZ [11 August 2017].

split the distributions into the periods April-September (warm) and October-March (cold). Standard procedure when calculating extremes is to fit the data to a Generalized Extreme Value Distribution.[42,43] The quantile function for the cumulative probability distribution (for a nondegenerate distribution shape parameter) then becomes:

$$Q(p, \mu, \sigma, \xi) = \mu + \frac{\sigma}{p}\left[\left[ln\left(\frac{1}{p}\right)^{-\xi} - 1\right]\right] \quad (1)$$

In this equation, variables are designated as follows: probability $p \in (0, 1)$, shape parameter ξ, scale parameter $\sigma > 0$, and location parameter μ. As an example, to calculate TX90, one can perform this process for maximum daily temperature and set $p = 0.90$. This will return a quantile value below which 90% of the daily maximum temperatures fall.

Figure B.2 shows histograms and best-fit generalized extreme value distributions for temperature at Los Alamos for the four time periods. Table B.1 and Table B.2 show the 10th and 90th percentile event magnitude minimum and maximum temperatures for the warm and cold seasons, respectively. The final takeaway from this is that the fitted distributions for daily maximum temperature generally show a rightward shift in extreme hot events and extreme cold events, consistent with current projections showing an expected increase in the frequency of heat waves.[44] Tables A.2 and A.3 are consistent with this shift: TX90 steadily increases with time in the warm season, as does TN10 in the cold season.

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[42] IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea,
K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp

[43] Kharin, V. V. and F. W. Zwiers (2005), Estimating extremes in transient climate change simulations, *Journal of Climate, 18*, 1156-1173, doi:10.1175/JCLI3320.1

[44] IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

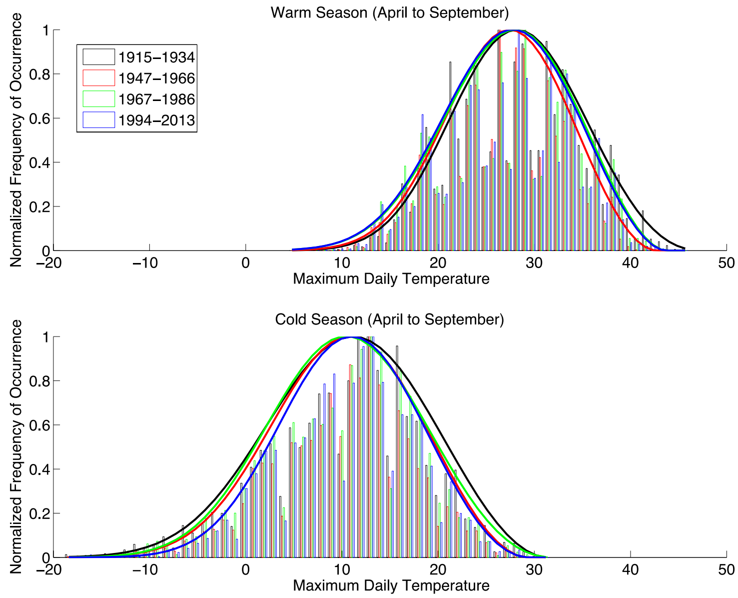

Figure B.2. Histograms of daily maximum temperature for the warm (top) and cold (bottom) seasons at LANL for each of the four time periods, as well as best-fit distributions based on an assumed shape of a generalized extreme value distribution.

Table B.1. 10th (p10) and 90th (p90) percentiles of maximum and minimum daily temperature at LANL in the warm season (April through September) for the four 20-year periods considered here.

Indicator	Years	p10	p90
Maximum daily temperature	1915–1934	19.70	36.63
Maximum daily temperature	1947–1966	18.95	34.63
Maximum daily temperature	1967–1986	18.56	35.53
Maximum daily temperature	1994–2013	18.43	35.37
Minimum daily temperature	1915–1934	3.46	17.45
Minimum daily temperature	1947–1966	4.42	17.26
Minimum daily temperature	1967–1986	4.14	17.81
Minimum daily temperature	1994–2013	5.88	18.74

Table B.2. Same as Table B.2 but for the cold season (October through March).

Indicator	Years	p10	p90
Maximum daily temperature	1915–1934	−0.23	20.68
Maximum daily temperature	1947–1966	0.48	19.49
Maximum daily temperature	1967–1986	0.28	20.08
Maximum daily temperature	1994–2013	1.56	19.48
Minimum daily temperature	1915–1934	−9.18	8.53
Minimum daily temperature	1947–1966	−7.73	8.78
Minimum daily temperature	1967–1986	−7.54	7.68
Minimum daily temperature	1994–2013	−5.45	8.19

Appendix C

Tools to Develop Cost Estimates

Appendix C

Tools to Develop Cost Estimates

The costs of the impacts without resilience need to be estimated for each system analyzed. Approaches to establishing most of the costs that will be encountered are noted below. The approach should include individuals who can ensure that the valuations are defensible. They include budget planners, cost professionals, engineers, and the purchasing office who will probably have access to procurement invoices.

Some of the impacts include destruction of or damage to facilities, lost work time, and potentially loss of assets or reduced life span. There may be economic benefits as well as costs due to the impacts of hazards. Several Federal agencies have different tools to estimate costs and valuing impacts such as the Department of Defense (DOD), Bureau of Labor Statistics (BLS), Environment Protection Agency (EPA) and FEMA. For example, FEMA has a couple of tools to assist in valuing the impact of floods, hurricanes, earthquakes, etc.[1] There are private sector tools as well, such as RSMeans.

C.1 Facilities

RSMeans[2], a widely accepted cost data book, should be used to estimate the construction or repair of facilities. RSMeans includes city cost indexes, productivity rates, crew composition, and contractor's overhead and profit rates. RSMeans also has the capability of producing full lifecycle cost estimates. There are other tools available if RSMeans cannot produce the estimate required. The tools include Parametric Cost Engineering System (PACES) and Micro-Computer Aided Cost Estimating System (MCACES). These are a part of the Tri-Service Automated Cost Energy System (TRACES).[3] The tools are in the process of being converted to online services.

C.2 Replacement or Repair of Damaged Equipment

The equipment that is critical and at risk should be identified and costs of replacement should be estimated. Value of the equipment may need to be updated based on the date of purchase. Remaining life of equipment should be used in estimating the damage. Some equipment may be replaced at regular time periods, thus the expected life of the equipment needs to be included. If RSMeans does not include the items desired, manufacturers, distributors, or retailers can be contacted for quotes. Deferred maintenance can also lead to resilience issues and needs to be accounted for in the resilience issue.

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[1] FEMA-Federal Emergency Management Agency. 2011. FEMA Benefit-Cost Analysis: Re-engineering, Develop of Standard Economic Values. Version 6.0. Accessed September 25, 2017 at https://www.hudexchange.info/course-content/ndrc-nofa-benefit-cost-analysis-data-resources-and-expert-tips-webinar/FEMA-BCAR-Resource.pdf

[2] RSMeans. 2017 "RSMeans Data". Accessed September 25, 2017 at https://www.rsmeans.com/

[3] US Army Corp of Engineers. Tri-Service Automated Cost Engineering System (TRACES). Accessed September 25, 2017 at http://www.hnc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/482084/tri-services-automated-cost-engineering-system/

C.3 Lost Hours

There are two components to valuing human capital, the lost time at work and the value of a human life. The value of lost time at work would include the time to prepare for a disaster, evacuating, cleaning up and repair of damage, and other disaster-related time away from work. Employee compensation averaged $35.28 per hour in June of 2017 according to the Bureau of Labor Statistics (BLS 2017).[4] The $35.28 hourly rate could be used as a value for lost time at work. Use site-specific values if possible.

C.4 Value of Lost Load

The value of lost load for government operations should be estimated as the amount of wages paid to workers for which electricity loss did not allow work to continue. The value of lost load accounts for the lost hours of work associated with the loss of mission capability such as lost super-computer time. See lost hours above for the approach. These may need to be adjusted based on the average wages of the DOE site being evaluated. Wage rates for the site may be obtained from human resources. In addition, the cost of repairing or replacing the equipment would be derived. This varies based on the type and location of damaged equipment. A cost of electricity lost should be included as a reduction in cost. The value is simply the price(s) per kilowatt-hour for the given location multiplied by the number of affected customers.

C.5 Human Life

There are multiple sources to consult when valuing a human life including multiple government agencies. Each source has a slightly different definition or inputs to the value. One widely accepted value from the EPA provides a value of statistical life (VSL) which is the value people are willing to pay for a small reduction in the risk of dying, equal to $7.4 million in 2006 dollars.[5] OMB's Circular A-4 estimates VSL between $1 million to $10 million per statistical life.[6] The value will be dependent on the types of individual lost and their expected remaining lifetime and the value of their services.

C.6 Transportation Costs

The cost of building a mile of road depends of several variables such as number of lanes, location, terrain, surface type, number of bridges, etc. For example, an undivided two-lane road in a rural area typically costs between $2 and $3 million dollars per mile while the same road in an urban environment costs between $3 and $5 million. A four lane highway in a rural or suburban area is about $4 to $6 million per mile while the same road in an urban area is $8 to $10 million per mile.[7]

FEMA's well documented Benefit-Cost Analysis Re-engineering (BCAR) Development of Standard Economic Values[8] derives a methodology to estimate the value of delays due to road and bridge closures.

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[4] BLS – Bureau of Labor Statistics. 2017. "Employer Costs for Employee Compensation." https://www.bls.gov/news.release/pdf/ecec.pdf

[5] EPA-Environmental Protection Agency. 2017. "Mortality Risk Valuation." Undated webpage. Accessed September 25, 2017 at https://www.epa.gov/environmental-economics/mortality-risk-valuation#whatisvsl

[6] The Whitehouse. 2003. "Circular A-4: Regulatory Analysis." September 17, 2003. Accessed September 25, 2017 at https://obamawhitehouse.archives.gov/omb/circulars_a004_a-4/

[7] ARTBA-American Road and Transportation Builders Association. 2017. "Frequently Asked Questions." Accessed September 25, 2017 at http://www.artba.org/about/faq/#9

[8] FEMA-Federal Emergency Management Agency. 2011. FEMA Benefit-Cost Analysis: Re-engineering, Develop of Standard Economic Values. Version 6.0. Accessed September 25, 2017 at https://www.hudexchange.info/course-content/ndrc-nofa-benefit-cost-analysis-data-resources-and-expert-tips-webinar/FEMA-BCAR-Resource.pdf

It uses Department of Transportation data for average vehicle occupancy of 1.67 and percentages of vehicle type on the road (personal passenger – 82% and commercial – 18%). These inputs are combined with the wage rate derived above for value of time. For personal time 50% of the wage rate is used. The following equation determines the value of time per vehicle per hour:

$$\text{Time value per vehicle hour} = ((\%\text{personal\_passenger} \times (\text{wage\_rate} \times 0.5)) + (\%\text{commercial} \times \text{wage\_rate})) \times \text{persons\_per\_vehicle}$$

$$= [(0.82 \times (\$35.28 \times 0.5)) + (0.18 \times \$35.28)] \times 1.67 = \$34.77$$

Thus, a value of $34.77 per hour can be used for lost time due to damaged roads and bridges.

C.7 Hospital Services

FEMA's BCAR Development of Standard Economic Values has a methodology to derive a value of lost hospital services. It includes the cost of the extra distance to get to the secondary hospital, the cost of additional waiting time at the hospital from increases in patient load, and the potential cost in lives due to the extra time required to get to the hospital. Since some of the inputs are dependent on location it is not possible to give a single value but the BCAR report has a detailed explanation and example process to follow.

C.8 Water and Wastewater Services

The BCAR report also assigns values to both wastewater and water supply services. They use 'importance factors' along with GDP data to derive a value for the economic activity of loss of wastewater and water supply. Wastewater loss was valued at $44.43 per capita per day and water supply losses were valued at $42.83 per capita per day. The America Water and Wastewater Association has a tool called 'Buried No Longer' that estimates the cost of repairing and replacing pipes.[9]

C.9 Operations and Maintenance Costs (O&M)

Operations costs and maintenance costs can be obtained from the facilities and operations organization at a site. Difficulties in estimating the reduction in O&M can occur as more resilient facilities may lead to more energy efficient equipment. That in turn, may reduce electricity or fuel costs as an example. The efficiency of existing equipment may be compared with the efficiency of more resilient equipment. As RSMeans can calculate full lifecycle cost, the tool may be able to help estimate O&M costs.

C.10 Cleanup Costs

Cleanup costs may be estimated using RSMeans. However, if the RSMeans does not have these values. Estimates may be derived from previous cleanup efforts at DOE sites. In addition, Goldstein and Ritterling provide a guidebook on estimating cleanup costs.[10]

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[9] American Water Works Association. 2017. "Buried No Longer." Accessed September 25, 2017 at https://www.awwa.org/resources-tools/buried-no-longer.aspx

[10] Goldstein, M, J. Ritterling. 2001. A Practical Guide to Estimating Cleanup Costs. US Environmental Protection Agency. Accessed at http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1027&context =usepapapers

C.11 External Economic Impacts

Economic impacts occur to the surrounding economy when either expenditures increase or decrease at a DOE site. Thus economic impacts can be either costs or benefits. The loss of work hours if employees are no longer paid due to a hazard, can result in an economic impact to the local community and region. Similarly increased construction and expenditures in an area to make a site more resilient would provide a positive economic impact for the community and region. IMPLAN is one tool that can calculate the economic impact.[11] IMPLAN uses datasets based on economic activity, county by county, to determine the impact of reduced or added expenditures to the economy.

C.12 Benefits

One potential benefit that could occur due to the alternatives addressed is improvement to the environment. The NAVFAC manual[12] lists several sources of information for valuing environmental benefits. They include:

- Earth Ecosystems Ecosystem Valuation Toolkit
- FEMA. 2012. Final Sustainability Benefit Benefits Methodology Report
- Alcoma, J, and EM Bennett, 2003. Millennium Ecosystem Assessment
- National Research Council. 2005. Valuing Ecosystems Services: Towards Better Environmental Decision Making, Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems, Water Science and Technology Board Division on Earth and Life Studies. Washington, DC. The National Academies Press

[11] IMPLAN. 2016. IMPLAN Online. Accessed September 25, 2017 at http://implan.com/products/
[12] NAVFAC (2017), Climate Change Installation Adaptation and Resilience: Planning Handbook, 193 pp.

Appendix D

Strategies for Approaching Risk and Uncertainty

Appendix D

Strategies for Approaching Risk and Uncertainty

In deciding which mitigation strategies to apply, the planner should develop approaches that fall in line with decision-makers strategies and their approach to risk.[1] Strategies include solutions that provide *no regrets*, flexibility, margin of safety, or changed time horizons (see Table D.3). Usually a *no regrets* strategy provides for modifications of structures that reduce damage but do not include expensive modifications. In a “no regrets” environment, whether hazards occur or not, the decision-maker has no regrets because there were overall benefits to the change.

Table D.3. Strategies to Address Uncertainty

Strategy	Characteristics	Examples
No Regrets	• Yields benefits whether or not forecasts are met • Addresses ongoing issues that could get works	• Stopping leaks in pipes • Limiting development in flood prone areas
Flexibility	• No modification are necessary • Minimize cost • Could be reversed without loss	• Insurance provides flexibility that can be adjusted by year • Conservative urban planning
Margin of Safety	• Reduce vulnerability by providing for negative, zero or small cost • Design conservatively for construction and include margins for safety	• Building for the future by adding capacity to drainage systems • Conservatively design future construction to with maximum storm conditions
Changed Time Horizons	• Reduce time periods for investment • Choose shorter time periods rather than long-term periods • Avoid long-term commitments by planning for the short term when uncertainty is great	• Use shorter lived species in forestry operations • Use temporary rather than permanent structures • Choose lower cost investments, if areas are vulnerable in the future

Adapted from NAVFAC (2017)[1].

Strategies looking for *flexibility* are those where the modification to the baseline allow for further modification if conditions change. Such conditions include the higher probability-higher damage side of original estimates. In the flexible strategy, additional modifications could be added at a later date to reduce the damage. For example, levees can be added if sea-rise is greater than expected at a facility like the Strategic Petroleum Reserve are at risk.

Another strategy to understand is the decision-maker’s tolerance for *margin of safety*. Making changes to structures that allow for larger than current expected requirements could be overall less expensive than

[1] NAVFAC (2017), Climate Change Installation Adaptation and Resilience: Planning Handbook, 193 pp.

having to rebuild later to meet the same requirement. For example, sizing the heating/cooling capacity of a building for future expected extremes may be cheaper today than having to rebuild systems at a later date.

Yet another strategy may be to plan structures under a *different time horizon* (e.g. reduced lifetime). Such an approach reduces current costs and reduces the uncertainty associated with what a building must be built for today to withstand storms in 2045. It also allows cost-effective use of lands that may become vulnerable in the future, but that will not be in the near term.

The decision-maker's approach to risk needs to be understood as well. Approaches to risk management include assume, share, avoid, and control (see Table D.4). The following are based on the magnitude of the assumed damage probability.

Table D.4. Risk Strategies

Risk Strategy	Description	Examples
Assume	Assuming risk occurs when the impact is expected to be minor	Sandbagging when the risk is minor
Transfer	When impacts are moderate the risk may be shared or transferred	The costs of mitigation strategies may be shared among local stakeholders such as the community mutual fire firefighting agreements on wildfire
Control	Control is the approach if the impact magnitude is large	Once the magnitude of a hazard is large, controlling the risk is the appropriate approach
Avoid	Avoiding risk is the best strategy if the impact is expected to be catastrophic	If the impact could be catastrophic, the appropriate approach is to avoid the risk or undertake actions to minimize its impact

Assuming risk may be useful if hazards are expected to only have minor impacts on the baseline. In other words, temporary fixes may be adequate to solve problems over the study timeframe. For example, if winds are only expected to cause minor damage such as only breaking windows, then adding shutters that can easily be closed may be the appropriate choice if the decision-maker may be willing to assume the risk.

For risks that are of moderate impacts, decision-makers may *transfer* the risk to others who either are willing to assume or share it. This approach allows the costs and benefits to be shared and improve the overall cost-effectiveness of the alternative. Examples might include cases where a local community also has a vulnerability and building a levee to protect both the DOE facility and the local community makes the project cost effective for both.

The decision-maker may also want to *control* risk in cases where the probability of damage is significant. In this case controlling the damage to the site may be the most appropriate strategy. Modifications to existing structures may be required to mitigate the impacts of increased damage from hazards.

If the probability of damage to a site will be catastrophic, the decision-maker’s approach may be to *avoid* the risk. Avoidance of the hazard requires adaptation that minimizes the impact on the site. Moving a site to higher ground if inundation is likely would be an example of avoiding the risk.

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