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Resilient Energy Systems Strategic Initiative

Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis

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ABSTRACT

Sandia National Laboratories' (Sandia) Resilient Energy Systems (RES) Strategic Initiative is establishing a strategic vision for U.S. energy systems' resilience through threat-informed research and development, enabling energy and interdependent infrastructure systems to successfully adapt in an environment of accelerating change. A key challenge in promoting energy systems resilience lies in developing rigorous resilience analysis methodologies to quantify system performance. Resilience analysis methodologies should enable evaluation of the consequences of various disruptions and the relative effectiveness of potential mitigations. To address this challenge, RES synthesized the common components of Sandia's resilience frameworks into an integrated methodology for energy and infrastructure resilience analysis. This report documents, demonstrates, and extends this methodology.

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Many people's expertise went into making this report and integrated methodology a success. Years of effort have been spent on the underlying resilience frameworks highlighted in this report that have contributed to Sandia's work in the resilience domain. A special thanks to the points of contact for these frameworks, including Robert Broderick (ESDM), Eric Vugrin (IRAM), Lon Dawson (ICPIA), and Eva Uribe (CD&R SI).

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EXECUTIVE SUMMARY

In light of growing threats to the nation's energy and infrastructure systems, the U.S. government has prioritized resilience. Presidential Policy Directive-21 (PPD-21) defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" and notes that resilience "includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." [1]

Sandia National Laboratories' (Sandia) Resilient Energy Systems (RES) Strategic Initiative is establishing a strategic vision for U.S. energy systems' resilience through threat-informed research and development, enabling energy and interdependent infrastructure systems to successfully adapt in an environment of accelerating change. A key challenge in promoting energy systems resilience lies in developing rigorous resilience analysis methodologies to quantify system performance. Resilience analysis methodologies should enable evaluation of consequences of various disruptions and the relative effectiveness of potential mitigations.

Over the last two decades, Sandia has developed multiple frameworks to analyze resilience and applied these frameworks to inform designs, investments, and decisions in various energy and interdependent systems. These frameworks—such as the Infrastructure Resilience Analysis Methodology (IRAM), Resilience Analysis Process (RAP), Energy Surety Design Methodology (ESDM), Integrated Cyber Physical Impact Analysis (ICPIA), and Designing Resilient Communities (DRC) Framework—and their applications demonstrate both the breadth and depth of Sandia's resilience analysis expertise. While each of these frameworks delivers a unique value for a particular resilience concern or application context, they rely on a common set of analytical principles. Synthesizing the common components of Sandia's existing frameworks provides an integrated methodology for resilience analysis consisting of the following 5 key steps:

1. Scope and Goals: defining the system, threats, and resilience goals, considering multiple stakeholder perspectives
2. Metrics: defining consequence categories and selecting performance- and consequence-based resilience metrics for individual infrastructures and multi-infrastructure analysis
3. Baseline Analysis: modeling threats/disruptions and component/system impacts; estimating consequences; and calculating metrics (without mitigations)
4. Mitigations: specify alternative resilience mitigations, evaluating/prioritizing resilience mitigations by estimating consequences and calculating metrics with mitigations, and implementing selected resilience mitigations
5. Improvement Analysis: evaluating the real-world effectiveness of resilience mitigations and restarting the cycle as needed

This report documents, demonstrates, and extends Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis. This integrated methodology highlights the unique contributions of Sandia's approach to resilience analysis. First, the method is explicitly threat-informed, drawing on Sandia's extensive expertise in both intentional and natural hazards. Second, it is consequence-focused, considering a range of technical, social, economic, and national security impacts. Third, it is performance-based, using modeling and simulation to evaluate system level impacts of disruptions and potential mitigations. Decisions about model selection and validation are left to the individual to determine based on the needs of the project. Finally, the methodology is attentive to infrastructure dependencies and interdependencies, leveraging Sandia's experience across critical infrastructure sectors.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CC	Civilian Cyber
CCB	Community Center Building
CDRSI	Cyber Deterrence and Resilience Strategic Initiative
DRC	Designing Resilient Communities Framework
ESDM	Energy Surety Design Methodology
ICE	Interruption Cost Estimate
ICPIA	Integrated Cyber Physical Impact Analysis
IRAM	Infrastructure Resilience Analysis Methodology
MDT	Microgrid Design Toolkit
PPD-21	Presidential Policy Directive-21
PV	Photovoltaics
RAP	Resilience Analysis Process
ReNCAT	Resilient Node Cluster Analysis Tool
RES	Resilient Energy Systems
ROI	Return on Investment
SI	Systemic Impact
SLA	Service Level Agreement
TRE	Total Recovery Effort
TSP	Targeted System-Performance
UPRM	University of Puerto Rico-Mayaguez
WDS	Water Distribution System
WNTR	Water Network Tool for Resilience

1. INTRODUCTION

In light of growing threats to our nation's energy and infrastructure systems, the U.S. government has prioritized resilience. Presidential Policy Directive-21 (PPD-21) defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" and notes that resilience "includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." [1]

Sandia National Laboratories' (Sandia) Resilient Energy Systems (RES) Strategic Initiative is establishing a strategic vision for U.S. energy systems' resilience through threat-informed research and development, enabling energy and interdependent infrastructure systems to successfully adapt in an environment of accelerating change. A key challenge in promoting energy systems resilience lies in developing rigorous resilience analysis methodologies to quantify system performance. Resilience analysis methodologies should enable us to evaluate the consequences of various disruptions and the relative effectiveness of potential mitigations. To address this challenge, RES has synthesized the common components of Sandia's resilience frameworks into an integrated methodology for energy and infrastructure resilience analysis.

This report documents, demonstrates, and extends Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis. Section 2 describes the various frameworks Sandia has developed to analyze resilience and applied to inform designs, investments, and decisions in energy and interdependent systems. Drawing on these frameworks, Section 3 proposes an integrated methodology for energy and infrastructure resilience analysis. Section 4 explores how Sandia's work on resilience analysis informs, and is informed by, Sandia's work on cyber deterrence. Several applications of this integrated framework are documented in Section 5 along with key lessons learned. Section 6 concludes and discusses next steps.

2. SANDIA RESILIENCE ANALYSIS FRAMEWORKS

Over the last two decades, Sandia has developed multiple frameworks to analyze resilience and applied these frameworks to inform designs, investments, and decisions in various energy and interdependent systems. Depicted in chronological order below, these frameworks demonstrate both the breadth and depth of Sandia's resilience analysis expertise.

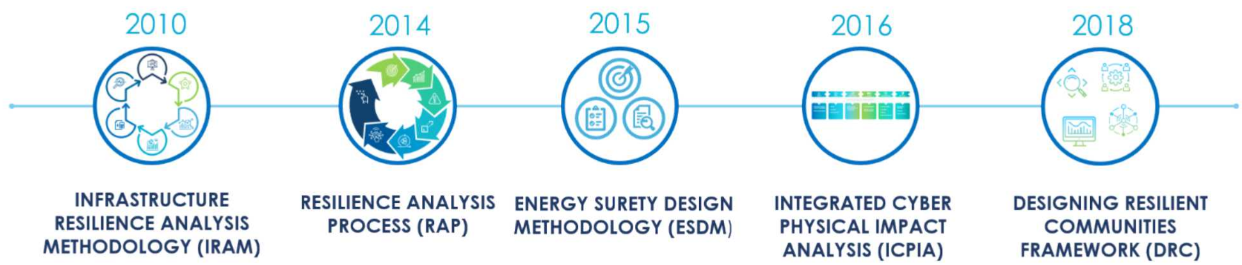

Figure 1: Selected Sandia Resilience Analysis Frameworks

2.1. Infrastructure Resilience Analysis Methodology (IRAM)

The Infrastructure Resilience Analysis Methodology (IRAM) focuses on recovery costs for critical infrastructures, including analysis of both system performance (i.e., systemic impact [SI]) and economic efficiency (i.e., total recovery effort [TRE]). Within this framework, resilience is "determined in part by SI, which represents the deviation from the targeted system-performance (TSP) levels, and TRE, which is a function of the duration of recovery and the recovery effort. The duration of recovery is the length of time for the system-performance level to recover permanently to the TSP level, and the recovery effort is defined as the costs and efforts required to change the structure of the system to recover to the TSP level" [2, pp. 108-109].

SI and TRE are operationalized in a formal resilience analysis process consisting of 6 steps [2, pp. 124-127]:

1. *Define System(s):* "In the first step, the analyst must define the infrastructure system under consideration. Multiple systems can be considered if the analyst wants to compare resilience across multiple systems…"
2. *Define Scenario(s):* "The analyst specifies the disruption scenario that affects the infrastructure system under analysis. Multiple scenarios can be considered if the analyst wants to compare resilience across different events…"
3. *Define Metrics:* "…Step 3 requires identification of metrics that measure these processes. Metrics must be identified for system performance, targeted system performance, and recovery efforts. In theory, any number of metrics can be found, but in practice, a single metric for system performance and corresponding targeted system performance and multiple metrics for recovery effort are usual…"
4. *Obtain Data:* "The fourth step is the collection of system performance and recovery data for the [recovery dependent resilience] calculations. Data can be obtained from:

a. Modeling and simulation. If a numerical model exists that can be used to simulate disruption and recovery of the system, analysts can use the model to generate the necessary data.
b. Historical data. Disruption and recovery data from previous events may be recorded and stored. Analysts can use these data to assess the resilience of the system to that previous event or to extrapolate system performance and recovery estimates for a similar event.
c. Expert judgment. If modeling or historical data are not available, analysts can apply expert judgment to estimate the *SI* and *TRE* quantities. The flexibility to use any of these data sources for quantitative analysis is a strength of the assessment methodology. However, the results of the analysis are only as good as the data used. Hence, if expert judgment is the data source, data should be provided by an individual who is knowledgeable and qualified to provide those estimates."

5. *Calculate Resilience Costs:* "The fifth step calculates resilience costs…Resilience costs are measures of relative resilience to a disruption; a system/scenario with a higher resilience cost has lower resilience than a system/scenario with a lower resilience cost."
6. *Perform Structural Assessment:* "The final step identifies resilience-enhancement features that affect the resilience of a system and lead to the quantitative results. Identification of these features provides guidance on how a system can be improved to become more resilient. This step may also identify behaviors of a system that were not considered previously (especially identification of recovery efforts) in the resilience analysis and may lead back to previous steps."

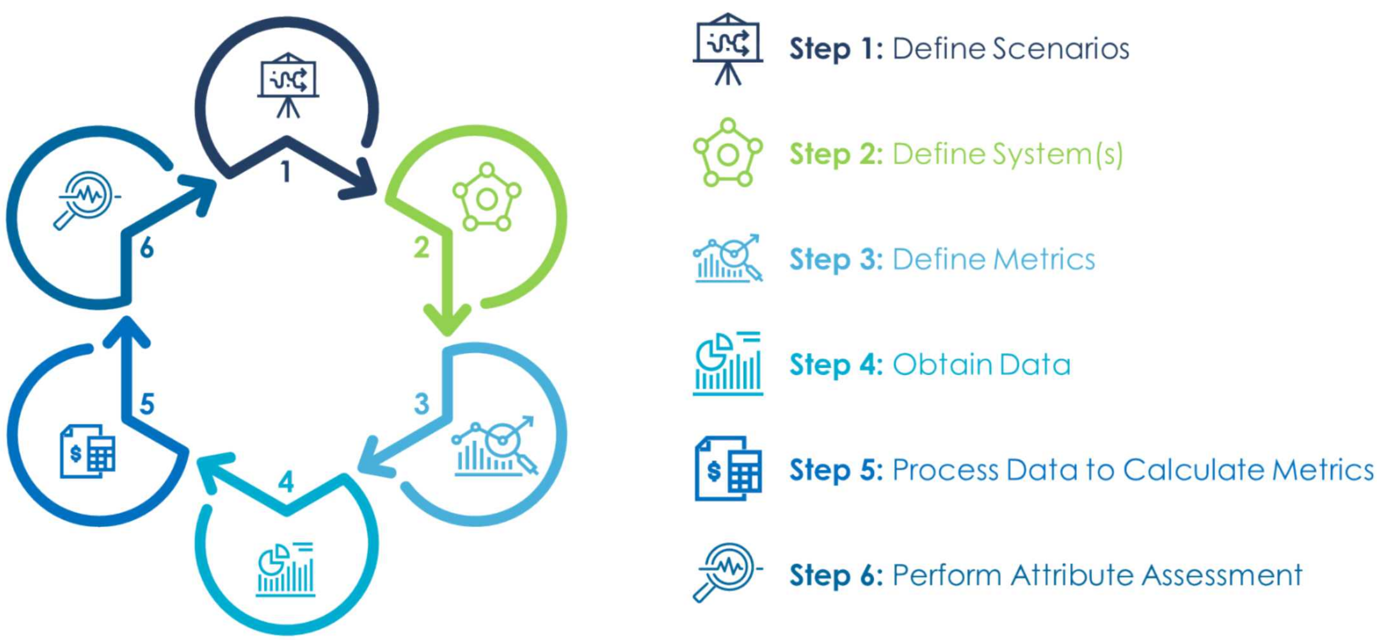

Figure 2: Infrastructure Resilience Analysis Methodology[1]

2.2. Resilience Analysis Process (RAP)

The Resilience Analysis Process (RAP) is a consequence-based framework developed for the Quadrennial Energy Review. "The RAP is designed to support decision makers' high-level goals

[1] Figure reproduced from [2].

with a defensible, risk-based decision. The first six steps of the RAP give decision makers and stakeholders a method for assessing a system's baseline performance. When all seven steps are followed, the focus of the RAP expands identifying improvements that increase resilience. These improvements could be identified by analyzing or by optimizing the characteristics of these proposals to identify the best improvement strategies" [3, pp. 13-14].

The seven steps of RAP are as follows [3, pp. 13-14]:

1. *Define Resilience Goals*: "Before determining the scope of the system relevant for analyzing and selecting appropriate metrics, it is essential to define high-level resilience goals. The goal set during this first RAP step lays the foundation for all following steps."
2. *Define System and Resilience Metrics*: "The system under consideration and the resilience metric definitions determine the analysis' scope. This could include identifying a larger system's geographic boundaries, relevant time periods, and/or relevant components. "
3. *Characterize Threats:* "Threat characterization is critical to understanding how capable the system must be to absorb and adapt to different types of attacks or natural events. When evaluating resilience against multiple hazards, information about (1) the likelihood of each possible threat scenario and (2) the capabilities or strength of the threat are extremely important. In risk analysis, threat and consequence are used to understand which vulnerabilities are most important to address to reduce the consequences associated with the threat."
4. *Determine Level of Disruption:* "Once an understanding of the relevant threats has been solidified, the attributes of each threat are used to determine the amount of damage to the system (infrastructure, equipment, etc.) that is likely to result from that set of threats. This is the RAP step where expectations about structural damage or other system impacts that could affect performance are defined."
5. *Define and Apply System Models:* "The damage states outlined in Step 4 can then be used as input to system models—tying damage to system output levels. For example, anticipated physical damage (or a range of damage outcomes incorporating uncertainty) to an electric grid from an earthquake can be used as input to a system model that ties those outages due to damage to load not served within the system over time. Multiple system models may be required to capture all of the relevant aspects of the complete system. Furthermore, dependencies may exist between models."
6. *Calculate Consequence:* "When evaluating resilience, direct impacts to system output as a result of damage are only part of the story. Most energy systems provide energy [for] some larger social purpose (e.g., transportation, health care, manufacturing, economic gain). During this step, outputs from system models are converted to the resilience metrics that were defined during Step 2. When uncertainty is included in the RAP, probability distributions will characterize the resilience-metric values."
7. *Evaluate Resilience Improvements:* "Unless the RAP is being undertaken purely for assessment purposes, it is likely that some decision or decisions must be made about how to modify operational decisions or plan investments to improve resilience. After completing a baseline RAP through the preceding steps, it is

possible and desirable to populate the metrics for a system configuration that is in some way different from the baseline in order to compare which configuration would provide better resilience. This could be a physical change (e.g., adding a redundant power line); a policy change (e.g., allowing the use of stored gas reserves during a disruption); or a procedural change (e.g., turning on or off equipment in advance of a storm)."

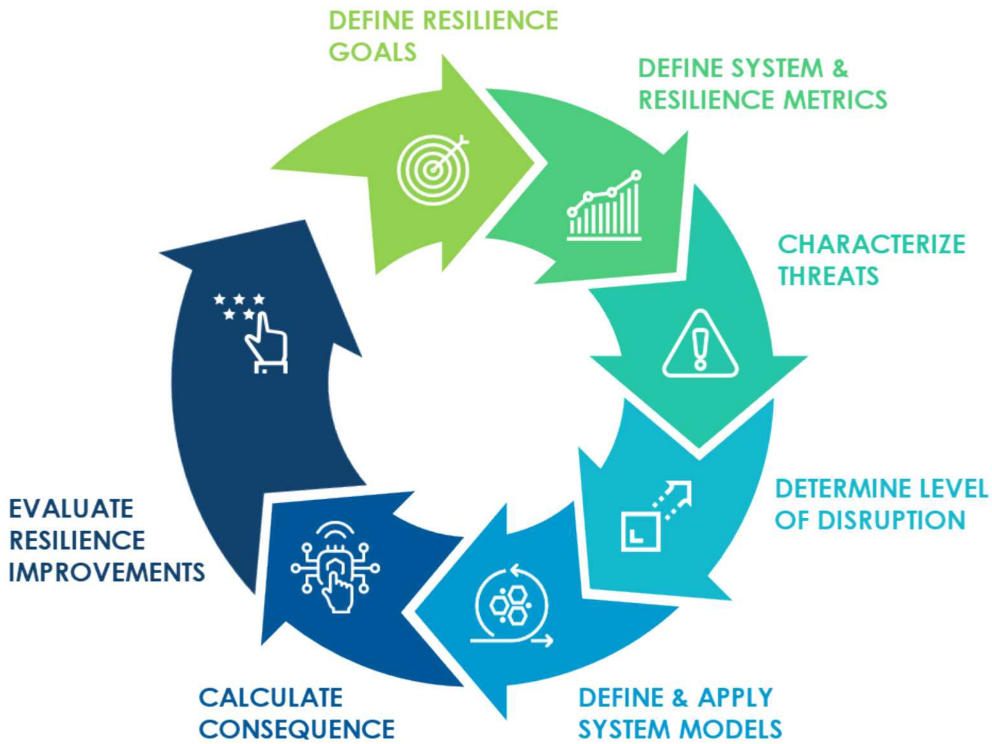

Figure 3: Resilience Analysis Process[2]

2.3. Energy Surety Design Methodology (ESDM)

The Energy Surety Design Methodology (ESDM) is a detailed design methodology for electric grid planning that accounts for resilience as well as other energy surety goals (e.g., safety, security). ESDM "enables users to identify and evaluate alternative design options and generate design recommendations. Examples of possible energy surety improvements include building additional transmission and distribution systems to provide energy supply redundancy, hardening transmission and distribution systems to make them more resistant to storms or attacks, adding additional onsite energy generation and storage systems to protect critical buildings or services and critical mission functions, or the use of microgrids" [4, p. 12].

[2] Figure reproduced from [3].

The ESDM is an iterative design process consisting of steps to reach a final conceptual design, which itself represents the beginning of an iterative implementation process [4, pp. 12-13]:

1. *Characterize Surety Goals*: "The ESDM process begins with establishing surety goals. Reliability, resilience, security, safety, cost, and environmental impact should all be carefully considered. There may be performance goals in all or a subset of these areas. In some cases, there may be a desire to improve a few key areas without decreasing performance in others.
2. *Define Constraints:* "During or closely following the establishment of the surety goals, project constraints should be defined. These constraints may include geographic boundaries, project schedule, budget, and relevant policies and regulations. Since these types of constraints are important to understand the feasibility of surety goals, it is expected that there may be some iteration between defining the constraints and the characterization of surety goals."
3. *Describe Existing System:* "The next step is to describe the existing and planned system components, since understanding of these components is critical to identifying which new design solutions are appropriate. This step includes definition of several system elements: loads, transmission and distribution topology, generation, storage, controls, and dependencies (e.g., grid connect and disconnect responsibilities)."
4. *Develop Initial Conceptual Design:* "The methodology offers an option to stop at an initial conceptual design, which would typically identify one or more viable designs to meet surety goals."
5. *Develop Final Conceptual Design:* "Moving to the final conceptual design phase involves narrowing the design options to select a single design based on an evaluation of performance against energy surety goals. Establishing the final conceptual design also involves deeper investigation into design implementation and validation."

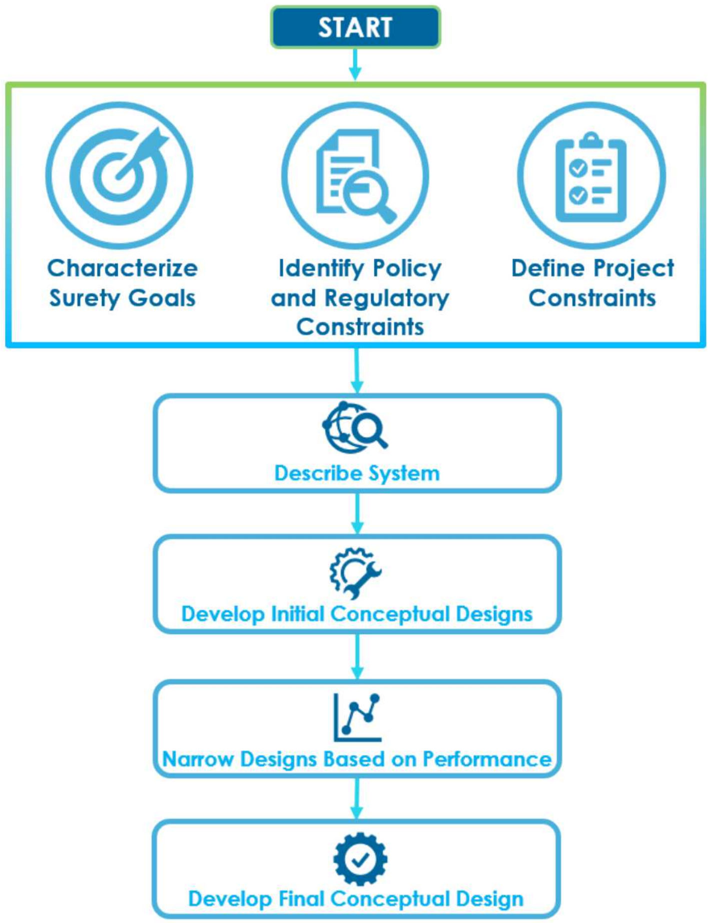

Figure 4: Energy Surety Design Methodology[3]

2.4. Integrated Cyber Physical Impact Analysis (ICPIA)

The Integrated Cyber Physical Impact Analysis (ICPIA) is a full spectrum modeling framework that focuses on resilience to cyber-physical attacks. ICPIA consists of modeling and analysis of six dimensions: threats (e.g., adversary capabilities), events (e.g., attack), components (i.e., physical effect of event on component), systems (i.e., effects of event propagation on cyber and physical systems), consequences (e.g., casualties), and recovery (e.g., reconstruction). The framework also assesses mitigations and feedback throughout the identification, protection, detection, and response phases [5].

ICPIA utilizes various modeling and simulation capabilities such as: threat modeling; adversary-based vulnerability assessment; enterprise network and control system emulation, simulation, and

[3] Figure reproduced from [4].

analysis (Emulytics™); physical modeling and simulation (device to system scale; across domains); and interrelated critical infrastructure impacts. ICPIA can be used to bolster resilience in a variety of application contexts, such as by supporting threat analysis, providing a test bed for systems integration, designing secure architectures, acting as a training tool, and supporting integrated risk management [5].

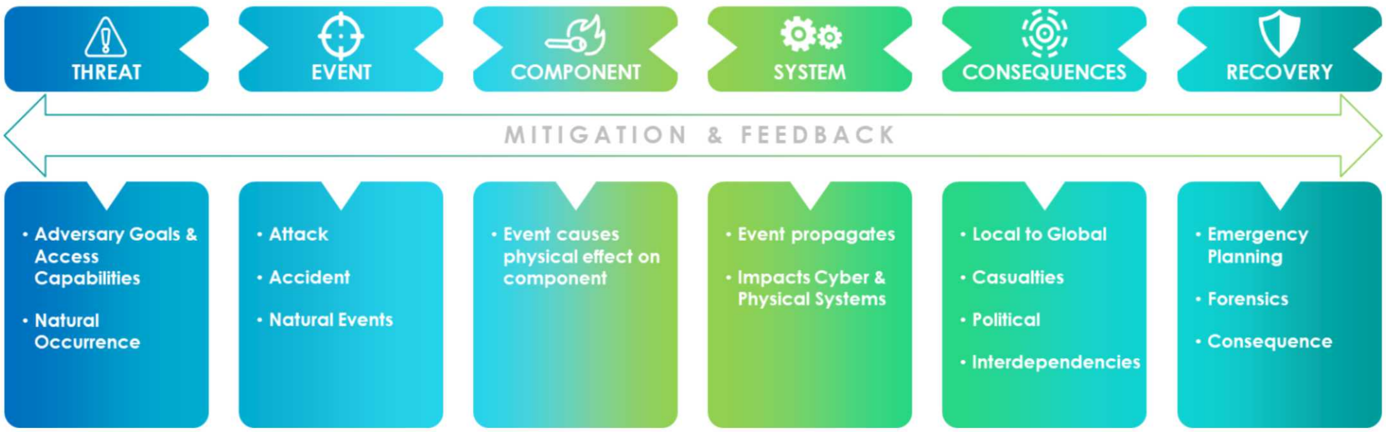

Figure 5: Integrated Cyber Physical Impact Assessment[4]

2.5. Designing Resilient Communities (DRC) Framework

The Designing Resilient Communities (DRC) Framework enables cities and utilities to align their investment planning for a more resilient electrical grid. The framework is implemented iteratively to account for feedback loops both within and across implementation processes (e.g., addressing technological issues in one planning horizon, which may shape and be shaped by addressing market or regulatory issues in another planning horizon) [6].

The four steps of the DRC Framework are as follows [6, pp. 13-17]

1. *Resilience Drivers Determination.* "The first step consists of determining resilience drivers via multi-stakeholder input on the definition of the system, threats, goals, and metrics. A system scope can be defined by geographic/jurisdictional boundaries, sectors/infrastructures, and/or temporal scale. In addition to defining the system, this sub-step should identify the specific planning process for the system (e.g., city sustainability plan, utility integrated resource plan) and the role of resilience therein…For a given system, the threats to resilience (e.g., natural, intentional/accidental, structural) should be specified or a threat-agnostic approach selected. Sandia advocates for focusing on acute threats that create high consequence disruptions, with chronic threats incorporated as constraints and/or drivers. For the sub-step defining resilience goals, the goals should be as detailed as possible and attentive to the system's ability to prepare, withstand, respond, and/or recover. Moreover, other goals relevant to a given planning

[4] Figure reproduced from [5].

process should be defined and prioritized in this sub-step…The final sub-step is identifying consequence categories (e.g., economic, social, national security, and critical service/performance) and associated metrics (e.g., recovery costs, access to community lifeline services, mission assurance, and critical load not served). Sandia advocates for selecting consequence-focused performance metrics, both for individual infrastructures and multi-infrastructure analysis. Ongoing work at DOE national laboratories supports the identification of resilience metrics…"

2. *Baseline Resilience Analysis:* "The second step consists of the baseline resilience analysis. This step begins with assessing the baseline impacts, which entails using historical data and/or simulation to probabilistically forecast disruptions from identified threats and resulting component, infrastructure, and multi-infrastructure impacts over the planning horizon. Having modeled the component, infrastructure, and multi-infrastructure impacts of potential disruptions, the baseline resilience metrics can be calculated. These baseline metrics capture system performance with the disruptions but without any potential mitigations. As noted above, Sandia advocates for consequence-focused performance metrics…"
3. *Resilience Alternatives Specification:* "The third step involves identifying potential alternative investments to enhance resilience. The process begins with a screening of relevant technology, policy, and market conditions. Sandia assumes that for initial implementations of the framework, this step will begin with screening of alternative technologies to meet the goals (e.g., resilience, sustainability, reliability) of the planning process identified in Step 1. However, this step should also consider system constraints, such as regulatory frameworks and utility business models, and the potential evolution of constraints…Having completed this screening, the next step is to specify resilience mitigations. Sandia expects the initial implementation will focus on technology investment portfolios, which consist of potential planning, operational, and policy actions that enhance the system's ability to prepare, withstand, respond, and/or recover…"
4. *Resilience Alternatives Evaluation:* "The final step involves evaluating the resilience alternatives specified in Step 3. Improvements in resilience metrics are evaluated by calculating consequence-focused performance metrics (repeating Step 2) with mitigations (identified in Step 3) …Recognizing that there might be multiple stakeholders and multiple metrics, final selection may involve negotiating weights for various resilience metrics with relevant stakeholders and prioritizing investment portfolios through multi-metric optimization…"

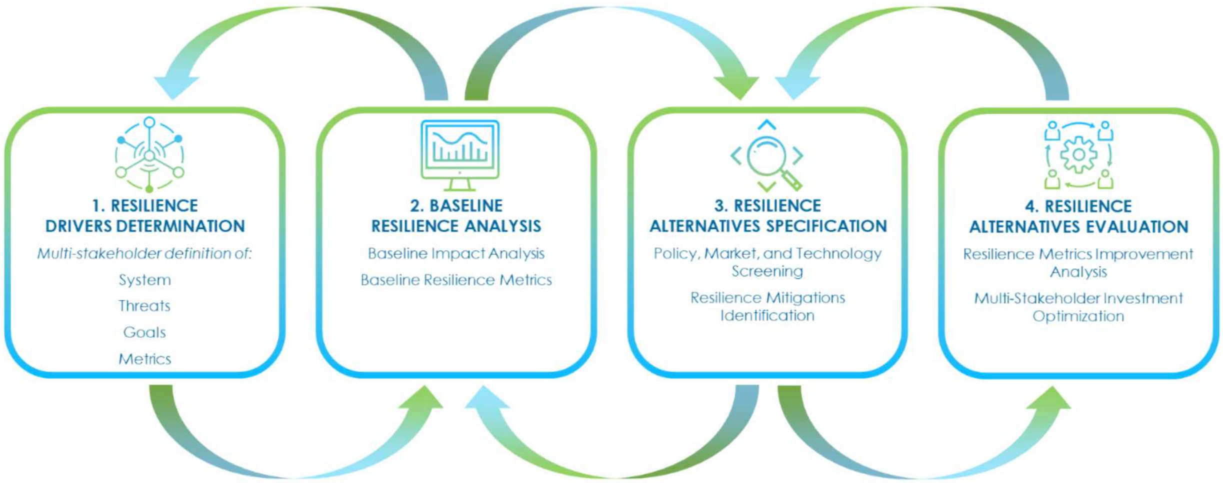

Figure 6: Designing Resilient Communities Framework[5]

[5] Figure reproduced from [6].

3. INTEGRATED METHODOLOGY

3.1. Overview

While each of these frameworks delivers a unique value for a particular resilience concern or application context, they rely on a common set of analytical principles. Synthesizing the common components of Sandia's existing frameworks provides an integrated methodology for resilience analysis consisting of the following 5 key steps as depicted in Figure 7:

1. Scope and Goals: defining the system, threats, and resilience goals, considering multiple stakeholder perspectives

2. Metrics: defining consequence categories and selecting performance- and consequence-based resilience metrics for individual infrastructures and multi-infrastructure analysis

3. Baseline Analysis: modeling threats/disruptions and component/system impacts; estimating consequences; and calculating metrics (without mitigations)

4. Mitigations: specify alternative resilience mitigations, evaluating/prioritizing resilience mitigations by estimating consequences and calculating metrics with mitigations, and implementing selected resilience mitigations

5. Improvement Analysis: evaluating the real-world effectiveness of resilience mitigations and restarting the cycle as needed

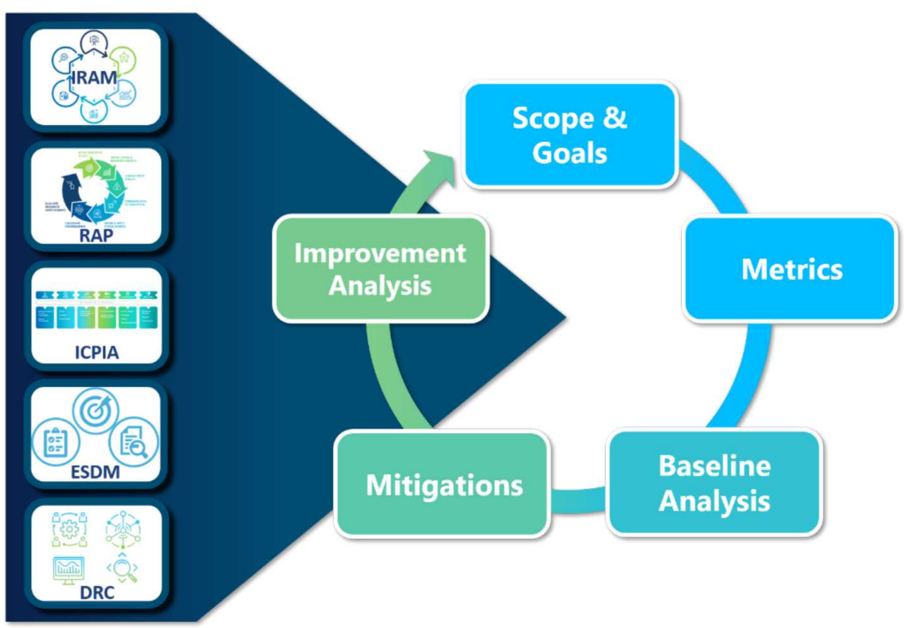

Figure 7: Sandia's Integrated Methodology Energy and Infrastructure Resilience Analysis

3.2. Steps

3.2.1. Scope and Goals

The analysis begins with defining the system scope and the resilience goals. The system scope consists of both spatial (e.g., geographic/jurisdictional boundaries or sectors/infrastructures) and temporal dimension and specifying the threats to which the system is vulnerable. For many infrastructures, GIS-based tools may be helpful in defining system boundaries as well as identifying priorities within a given system; tools such as FASTMap—a "mapping application that browses national infrastructure and emergency resources data and can be configured to display results from independent models generating geospatial and/or temporal output" [7, p. 1]—can support this step. The system scope will determine which stakeholders and impacts are included in the analysis. It may be useful to think about the temporal aspect of resilience with respect to the timeline of a given extreme event (see [3]) and the aspect of resilience enumerated in PPD-21 [1]: prepare, adapt, withstand, and recover.

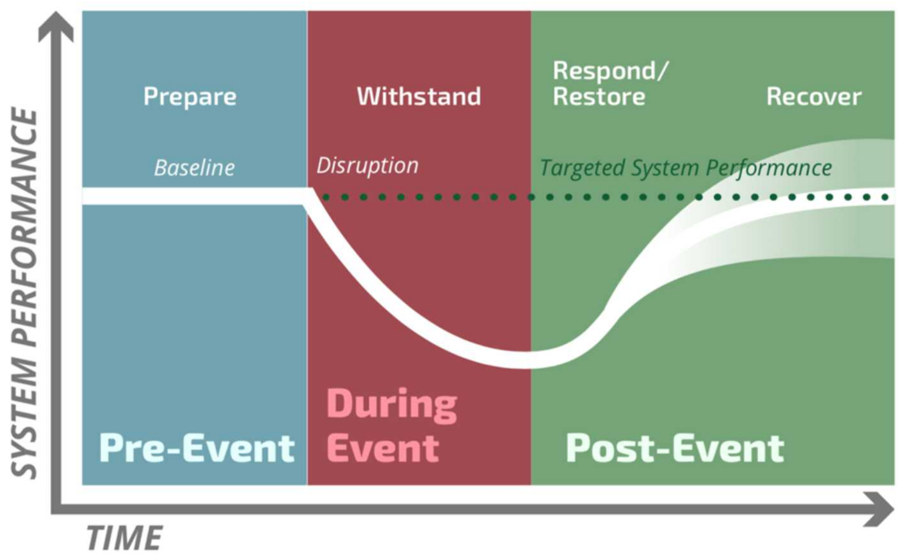

Figure 8: Stages of the Resilience Timeline[6]

Defining the system also provides a foundation for identifying potential threats to resilience, which may be a function of sector or geography. Table 1 provides a summary of threats by type, including natural, man-made, and structural. While it is possible to complete resilience analysis from a threat-agnostic perspective (e.g., if disruptions are deterministic and consistent across many threats), consistent with the definition of resilience in PPD-21, Sandia advocates for a threat-informed approach, that is particularly attentive to threats that may create high impact disruptions. While higher frequency, lower impact threats may not be the central drivers of the analysis, they can be incorporated as variables.

[6] Figure from forthcoming NAERM metrics report.

Table 1: Threats to Energy and Infrastructure Resilience

Natural	Man-Made	Structural
• Hurricane • GMD • Earthquake • Landslide • Tsunami • Tornado • Extreme Temperature • Flooding • Wildfire • Drought	• Cyberattack • EMP Attack • Kinetic/Physical Attack • Human Error • Blackouts/Brownouts	• Economic/Market Shocks • Regulatory/Policy Changes • Aging Infrastructure • System Complexity

Having identified the system and key threats to its resilience, resilience goals should then be specified. Goals may focus on one or more of the aspects of resilience identified in PPD-21: prepare, adapt, withstand, and recover. This goal definition process should involve the broad set of potentially affected stakeholders (e.g., infrastructure owners and operators; local, state, and national policymakers; and interest groups such as consumer, citizen, trade, or professional groups) and should be attentive to how the processes in which resilience is embedded shape goals (e.g., does resilience need to be balanced against other goals, such as affordability?). Stakeholder elicitation methods may support the identification of resilience threats and goals. As discussed in [6, 4], examples of relevant methodologies are: analytic hierarchy process (e.g., PARADE), Delphi technique, multi-attribute utility theory, nominal group technique, risk assessment matrix (e.g., Risk Informed Management of Enterprise Security [8]), notice and comment processes (e.g., IdeaScale [9], a commercial software program that supports several U.S. federal agencies' e-rulemaking and stakeholder engagement processes).

3.2.2. Metrics

Resilience metrics measure system performance and the consequences associated with degradation of system performance. While more attribute-based metrics may serve as useful criteria in resilience analysis, performance-based metrics are necessary for comparing the baseline and improved system. System performance metrics will vary based on the system's role (e.g., delivering electricity to customers) and relevant units (e.g., MWh). Multiple metrics may be necessary to represent the performance of different infrastructure systems. Table 2 presents examples of performance metrics for different infrastructure systems (proposed in a summary of IRAM [10]).

Table 2: Performance Metrics for Critical Infrastructure Systems[7]

Critical Infrastructure System	System Performance Metrics

[7] Table reproduced with minor edits from [10, p. 98].

Critical Infrastructure System	System Performance Metrics
Agriculture and Food	• Rates of and population exposure to food contamination • Average consumer price of food
Chemical	• Shipments to critical chemical-based commodities (e.g., pharmaceuticals)
Emergency Services	• Lives saved • Average response time
Energy: Petroleum, Oil, and Lubricants	• Barrels of refined petroleum product transported to a given region • Price of domestic refined products
Information Technology	• Number and efficacies of cyber attacks
Public Health and Healthcare: vaccines	• Rates of morbidity and mortality • Cost per vaccine given
Transportation Systems: Highway	• Average speed and cost of shipments • Number of disrupted shipments
Communications: Telecommunications	• Number of dropped telephone calls

Translating performance to consequence enables a more holistic accounting of the impacts of resilience, often in units that can be incorporated into decision-making processes (e.g., cost benefit analysis). Consequence focused metrics can measure the performance of a prioritized subset of the system—e.g., community lifeline services—or the economic (e.g., recovery costs), societal (e.g., lives lost), or national security (e.g., mission assurance) impacts. Selection of consequence metrics will vary based on resilience goals for a given system and its stakeholders (e.g., protecting vulnerable populations, maintaining centers of production).

In addition, consequence focused metrics may facilitate multi-infrastructure analysis. For example, the IRAM's "systemic impact" metrics [2, p. 110] include a range of economic (e.g., lost revenue, business interruption costs, decrease gross domestic/regional product) and social (e.g., deaths, number of injured or sick people, population without service) consequences that may be relevant within and across infrastructure systems.

Finally, given that resilience analysis is inherently probabilistic (e.g., stemming from probability and consequence of a given threat and the vulnerability of a given system), it may be necessary to represent uncertainty in resilience metrics by presenting expected values, minimums/maximums, quantiles, or (conditional) values at risk [11].

3.2.3. Baseline Analysis

The baseline analysis begins with modeling threats as disruptions for a given system. Based on the disruptions, the component and system performance can then be analyzed. For both the threat and performance modeling, modeling and simulation, historical data, and subject matter expertise can be used. The selection of tools for baseline analysis will depend on the specific system(s) under consideration, but some tools may be applicable to multiple systems. For example, tools such as FEMA Hazus can support the translation of threats into potential disruptions across a variety of infrastructures [12]. Modeling component and system performance may leverage more system-specific tools and data. For example, resilience analysis for water infrastructure may utilize GIS fragility modeling tools (e.g., WNTR [13]) while resilience analysis for electric power infrastructure leverage production cost models (e.g., PRESCIENT [14]) and a variety of data sources (e.g., EAGLE-I data [15]).

From there, the metrics of system performance as a result of the disruption(s) can be calculated. Figure 9 provides a probability distribution for a unitless consequence metric within a notional baseline system; depending on the stakeholders' goals, the improvement analysis may focus on shifting the mean and/or reducing the extreme values.

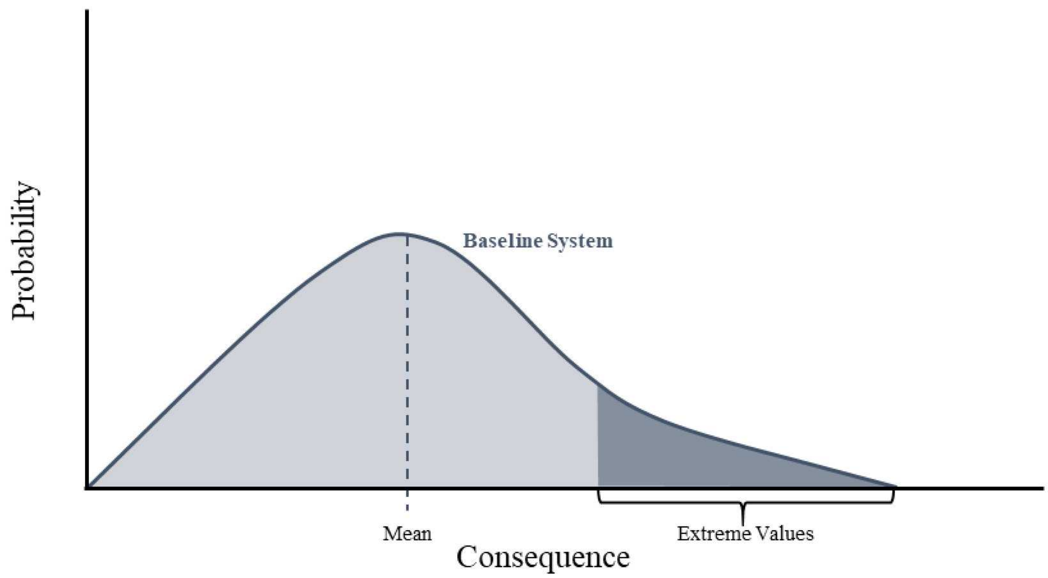

Figure 9: Representation of Baseline System Performance[8]

Stakeholders may choose to translate performance-based metrics into various measures of consequence, as discussed in Section 3.2.2. The selection of tools and data for this step will vary based on the system under consideration and the specific consequences under consideration. For example, the economic consequences of infrastructure disruptions can be calculated using survey-, market-, or modeling-based tools, each requiring a different set of data and computational approaches. Tools may be mature for certain applications but may require new data and refined methodologies for application to resilience; for example the Interruption Cost Estimate (ICE)

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[8] Figure adapted from [4].

Calculator [16] is used to calculate customer damage functions for electric power outages, but is designed to evaluate short duration electric power outages and thus would require additional functionality to capture the economic consequences of long duration and widespread power outages [6].

3.2.4. Mitigations

After analyzing the baseline system, the portfolio of potential mitigations can be assessed. This process begins with specifying alternative resilience mitigations, which are planning (e.g. investment), operational, and/or policy actions that enhance a system's ability to prepare, withstand, respond, and/or recover. When identifying mitigations, project and system (e.g., technology, policy, market) constraints should also be considered.

Having selected potential mitigations, the prioritization can begin. In this step, the component and system performance, and resulting consequences, are analyzed with the disruption and the selection mitigations. By comparing metrics across mitigations, the optimal portfolio can be selected. The selected mitigations can then be implemented. Figure 10 provides a probability distribution for a unitless consequence metric within a notional baseline and improved system, depicting how a selected mitigation is predicted to affect both the mean and extreme values.

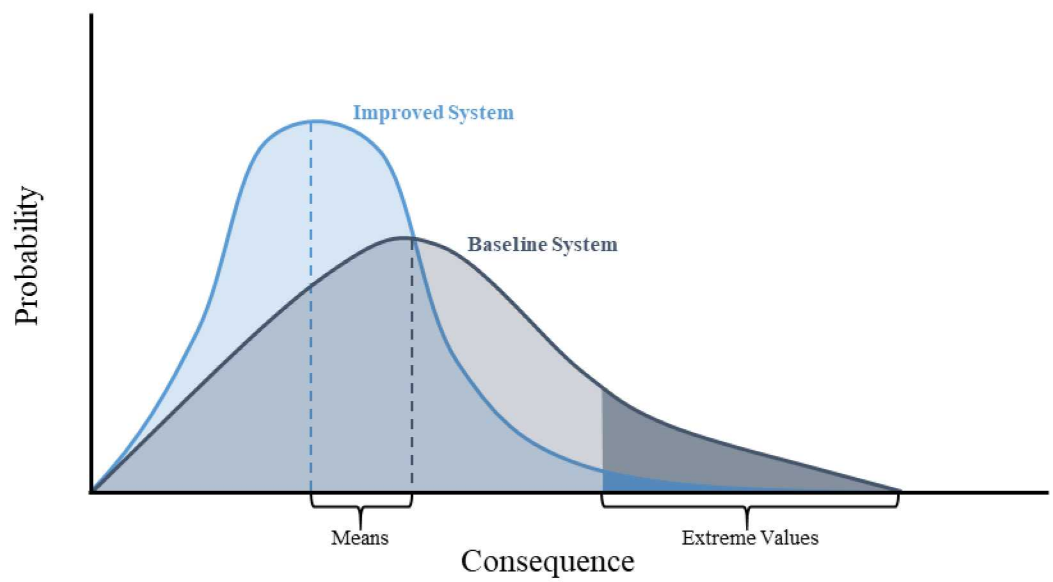

Figure 10: Representation of Improved System Performance[9]

Identification and evaluation of potential mitigations will vary both by infrastructures and resilience goals. For example, the DRC framework identifies a variety of tools that might be relevant to the identification and evaluation of mitigations for the electric grid [6]: An initial step involves screening various technologies, which can be supported by capacity expansion modeling tools such as the Resilient Node Cluster Analysis Tool (ReNCAT), which was used to inform microgrid siting in

[9] Figure adapted from [4].

Puerto Rico [17]. The report also identifies high-level initial design tools (e.g., Microgrid Design Toolkit [18]) which can be coupled with tools to down-select resilience mitigations at various levels: component (e.g., Xyce [19]), distribution system (e.g., CYME [20]), and transmission system (e.g., PowerWorld [21]) [6].

3.2.5. Improvement Analysis

Having implemented the mitigations, the real-world effectiveness can be observed. Ongoing monitoring can both ensure that mitigations are effective and enable refinement of methodologies for resilience analysis. If resilience mitigations prove to be ineffective—either because real-world performance deviates from predicted performance or because the threat space evolves—the resilience analysis process can be restarted and is designed to be iterative.

4. FROM RESILIENCE TO DETERRENCE

4.1. Cyber Deterrence Framework

The Cyber Deterrence and Resilience Strategic Initiative (CDRSI) is developing a Cyber Deterrence Framework, depicted in Figure 11, "to analyze various deterrence options in a standardized way, in order to understand when (and why) deterrence will fail and when (and why) it may be more likely to succeed" [22, p. 22]. Deterrence is defined broadly as "the creation of conditions that dissuade antagonists from taking unwanted actions because they believe that they will incur unacceptably high costs and/or receive insufficient benefits from taking that action" [22, p. 22].

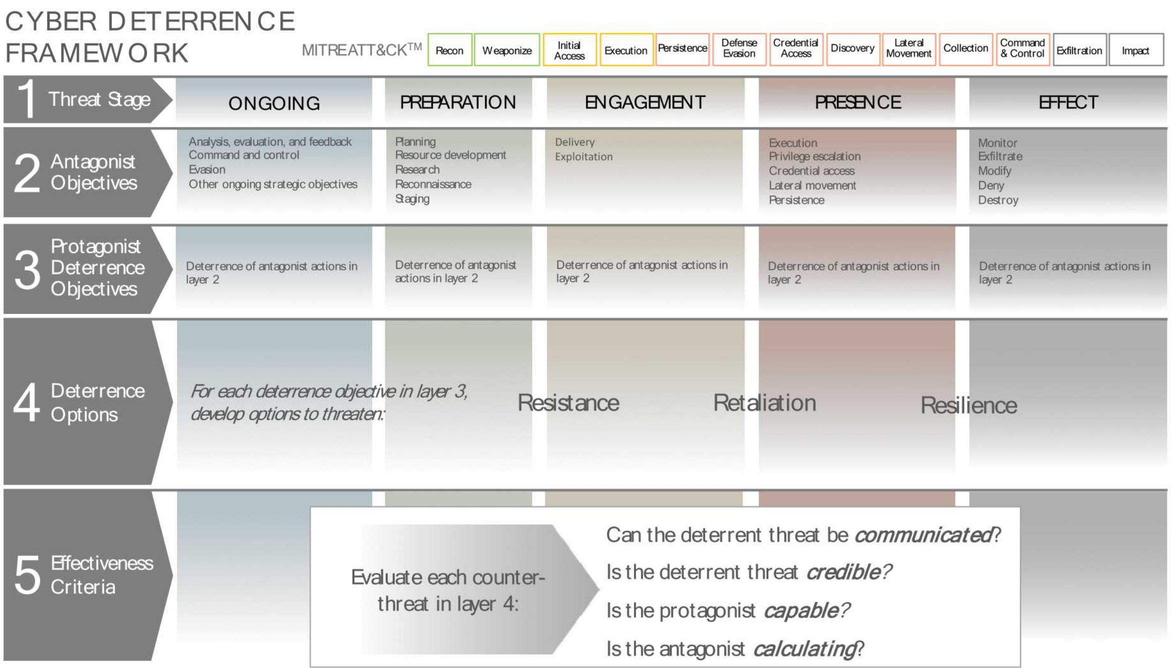

Figure 11: Overview of the Cyber Deterrence Framework[10]

4.2. Resilience and Deterrence: Shared Goal and Distinctive Approaches

The concepts of resilience and deterrence as defined in the RES and CDR Strategic Initiatives, respectively, share a common goal—reducing negative consequences for a given system—but encompass distinctive approaches and assumptions. Key dimensions for the resilience and deterrence as defined in the RES and CDR Strategic Initiatives, respectively, are depicted in Table 3 and discussed below.

Table 3: Key Dimensions of Resilience and Deterrence

	Approach	Threats	Timeframe	Mechanisms	Requirements

[10] Figure from [22, p. 23].

	Approach	Threats	Timeframe	Mechanisms	Requirements
Resilience	Reduce probability of consequences given a threat	Natural, Manmade (Intentional & Accidental), Structural	Pre-event, During-event, Response, Recovery	Prepare, Adapt, Withstand, Recover	Quantifiable, Consequence-based, Threat-informed
Deterrence	Reduce probability of a threat given an adversary	Manmade (Intentional)	Ongoing, Preparation, Engagement, Presence, Impact	Resistance, Retaliation, Resilience	Communicated, Credible, Capable, Calculated

While resilience and deterrence share the overall goal of reducing negative consequences for a given system, the approaches to achieve this goal are unique: deterrence mitigates consequence by preventing a threat to a given system whereas resilience mitigates consequence by reducing the impacts of a threat on system performance.

A key difference resulting from these approaches relates to threats. Deterrence only applies to threats that are caused by an adversary who is "calculating," thus, deterrence focuses only on manmade intentional threats (and in the context of the CDRSI, only cyber manmade intentional threats). In contrast, resilience focuses on a wider range of natural, manmade (intentional and accidental), and structural threats, with an emphasis on those threats that have the potential to create high consequence disruptions to a given system. Thus, the scope of threats for deterrence is a subset of the scope of threats for resilience.

One can understand deterrence and resilience as operating at different ends of the extreme event timeline: deterrence seeks to prevent the event whereas resilience seeks to prepare, withstand, adapt, and recover given the event. Moreover, the deterrence timeline may be more protracted than the resilience timeline, and deterrence goals across threat stages may or may not align with resilience mitigations. For example, the goal of resilience is often to speed up recovery, while the goal of deterrence may be to slow down or prevent an event from unfolding.

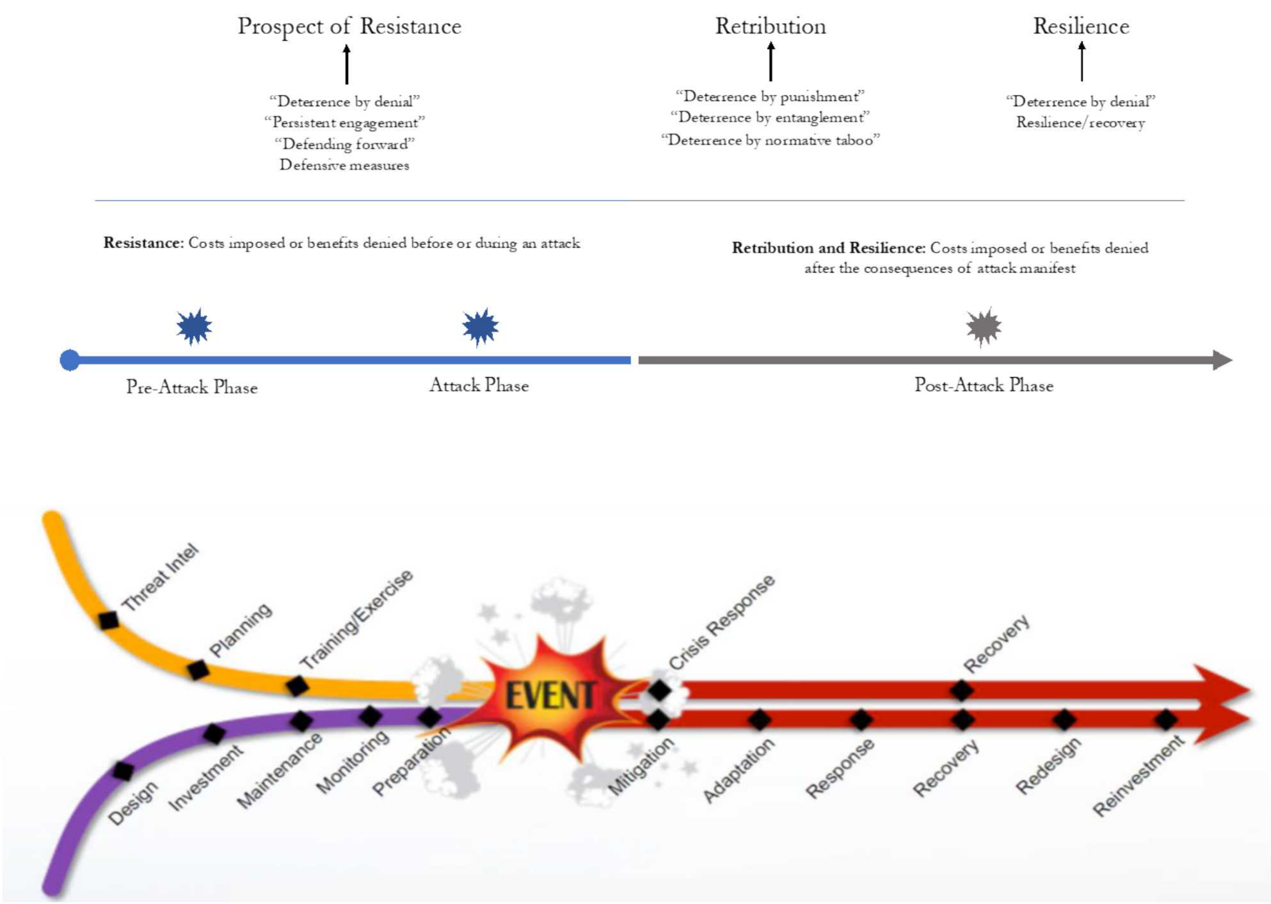

Figure 12: Comparison of Timelines and Mitigations/Mechanisms for Deterrence (top)[11] and Resilience (bottom) [12]

Although the timelines may not align, there is some commonality in mechanisms of mitigation as depicted in Figure 12. For example, in the CDRSI deterrence framework, resilience operates in the "effect" stage of the timeline (i.e., "costs imposed or benefits denied after the consequences of attack manifest" [22, p. 25]). However, the CDRSI deterrence framework also contemplates how resilience may play a role in preventing threats. Observable (i.e., "communicated and credible") system resilience may bolster deterrence by reducing the adversary's perceived probability of success ("…creating conditions to dissuade an actor from taking an action because they perceive that they will be worse off taking the action than refraining from action" [22, p. 25]). The CDRSI framework notes that this can be a function of both demonstrating a system's ability to recover—potentially to a superior level of system performance than before the event—and demonstrating the willingness and ability to operate with degradation of assets (e.g., via grid manual override operations).

[11] Figure from [22, p. 25], depicting "A breakdown of various deterrence mechanisms by time of cost imposition or denial of benefits relative to the attack phase."

[12] Figure from [3, p. 22], depicting "critical infrastructure planning and operations timelines…top-most vector represents operator knowledge and actions…bottom-most vector represents various aspects of system design and operation."

In the resilience context, resilience as deterrence could be understood to be part of the "preparation" stage but may also be understood as a preventative measure. Prevention (of threats) is not explicitly part of the PPD-21 definition but within the RES framework preventative measures are perhaps best represented as mitigations. Thus, within the RES framework, deterrence might be characterized as a mitigation, in the sense that investing in deterrence can reduce consequences via prevention.

Another key difference related to mechanisms is that resistance is treated separately than resilience in the CDRSI deterrence framework, whereas for the RES resilience framework the ability to resist is understood to be part of resilience. The CDRSI framework treats these concepts separately but notes that many actions may operate through both mechanisms (e.g., network segmentation), noting that "[w]hile there may be some overlap between these two categories, we choose to distinguish them in order to facilitate analysts in thinking as broadly as possible about the contribution to deterrence by both defensive tools that raise antagonists' costs during their attack, and by resilience tools that decrease the impact and facilitate recovery once an attack has occurred" [22, p. 30].

Thus, resilience and deterrence, as conceptualized by RES and CDRSI, have shared "ends" but unique "means," suggesting opportunities for further collaboration and learning across the RES and CDR Strategic Initiatives.

5. APPLICATION EXAMPLES

5.1. Integration Example 1: SNL CA Site Integration

An evaluation of energy resilience was conducted at Sandia's California site to assess acute risks to Sandia CA's current missions and facilitate a long-term transition to a low-carbon footprint. The work built upon a previous electric power resilience study. In this site integration use case, the team looked at additional infrastructure sectors including water and communications, as well as at the potential for incorporating renewables, storage, and other measures that could improve resilience.

The SNL CA site integration project utilized a holistic, threat-informed resilience analysis process to create an analysis that can be used by CA site planners to inform future infrastructure and investments. Additionally, the analysis demonstrates the value of resilience and the return on investment (ROI) of making resilience investments over time.

5.1.1. Scope and Goals

The system was defined as Sandia's California site, with a focus on electric power, communications (voice and data), and water infrastructure. These sectors were chosen for their ability to increase mission resilience to known threats. Building prioritization was based on discussions with SMEs based on the missions and functions they provided. Based on a preliminary analysis that identified key locations at the site, two buildings were selected for the analysis and are referred to in this report as Building A and Building B.

Threats were defined and categorized by the infrastructure sector they would impact. Threats of concern, and their corresponding level of disruption, are summarized in Table 4. Note that threats are applied by infrastructure sector.

Table 4. California Site Threats and Disruptions by Infrastructure Sector

Infrastructure Sector	Threats	Disruptions
Electric Power	Multiple threats	Outages up to 30 days
Communications (voice and data)	Flooding, power outage, fiber cut, earthquakes, forest fires	Long-term service interruption
Water	Earthquake	Pipeline damage

The overarching resilience goal for the SNL CA site integration project was to maintain the ability to execute key SNL missions while under long-duration utility outages imposed by these specific threats. While the threats themselves cannot be eliminated, the proposed resilience improvements aim to mitigate the impact of the threats so the system will function at a higher level than in the baseline case. The team outlined three key areas of analysis to further this goal. The first was to evaluate the energy sector and the relative resilience benefits of natural gas generation, photovoltaics

(PV), and battery storage for critical buildings defined or delineated by multiple tiers of criticality. The second was to evaluate the water sector and how best to maintain water pressure for critical water use, firefighting, and pipe stability; ensure water quality for drinking water and lab facilities; and reduce the extent of outages by identifying critical pipes and isolation valves. The third was to evaluate the communications sector and the vulnerabilities of the on-site and off-site communications infrastructure and look at potential investments that would minimize disruptions.

5.1.2. Metrics

Resilience metrics and consequences were also defined by infrastructure sector and are listed in Table 5. Metrics are quantitative measures whereas consequences are consequences to the overall mission and include a mix of qualitative and quantitative measures. Both metrics and consequences are important to evaluate the resilience impact of mitigation strategies. Note that there are also interdependencies between the sectors, making it important to ensure all three stay online during prolonged outages.

Table 5. California Site Metrics by Infrastructure Sector

Infrastructure Sector	Metrics	Consequences
Electric Power	• Energy availability (% of load served) • PV penetration (PV capacity/peak load) • Fuel savings versus diesel generation • Required fuel storage • Cost	• Impaired ability to perform missions • Impact to other infrastructure sectors that rely on electric power
Communications (voice and data)	• Mobile/landline loss of service • Call congestion • Restoration time • Peak blocking	• Loss of ability to monitor and control other systems • Loss of customer support and potential loss of life • Potential impact on emergency response support and 911
Water	• Water service availability • Water pressure deficiencies • Population and services impacted by service outages or pressure deficiencies • Repair time and cost	• Impact to daily operations including lab processes, cooling towers, irrigation, fire protection, and drinking water • Damage to infrastructure • Environmental, financial, and social impacts

5.1.3. Baseline Analysis

The baseline electric power model was built using Sandia's Microgrid Design Toolkit (MDT), which evaluates the potential benefits of various investment and mitigation options during extended outages by evaluating the most optimal options based on defined performance and cost metrics. The analysis focused on two buildings (referred to here as Building A and Building B), which were good candidates for natural gas generation, PV, and battery storage. For the baseline analysis, performance metrics and cost metrics were evaluated using an MDT model with both buildings as shown in the table below. Both buildings use diesel generators and diesel storage tanks, and do not have PV installed. The results of the baseline analysis are shown in Table 6. Note that the amount of diesel fuel used, and the fuel storage required, are both large. Additionally, neither building currently utilizes renewable generation.

Table 6. California Site Electrical Baseline Analysis

Case	Energy Availability	Renewable Penetration/Renewable Energy Use (%)	Diesel Fuel Used (gallons)	Required Fuel Storage (gallons)	Generation Costs ($K)
Building A Baseline	99.3404%	N/A	23,023	7650	$536
Building B Baseline	99.999530%	N/A	1,214	1275	$203

The baseline communications model was built using Sandia's VoiceNet tool. For Buildings A and B, both voice and data networks were analyzed. The team also looked at offsite infrastructure services. The map in Figure 13 was generated by VoiceNet and shows the geographic area supported by the main Livermore switch. The line indicates the tandem switch used in Oakland. The orange circle is the rough area of wireline voice impact in case of a loss of the central office in Livermore.

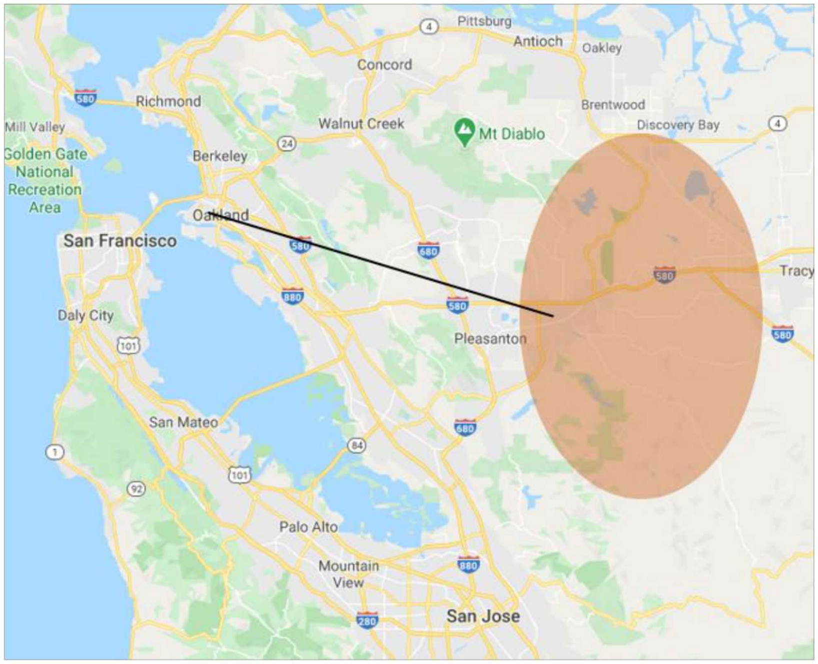

Figure 13. Geographic Area Supported by Main Livermore Switch

The team also looked at the impact of a tandem failure in the Oakland area. The area of greatest impact is shown in red in the map in Figure 14.

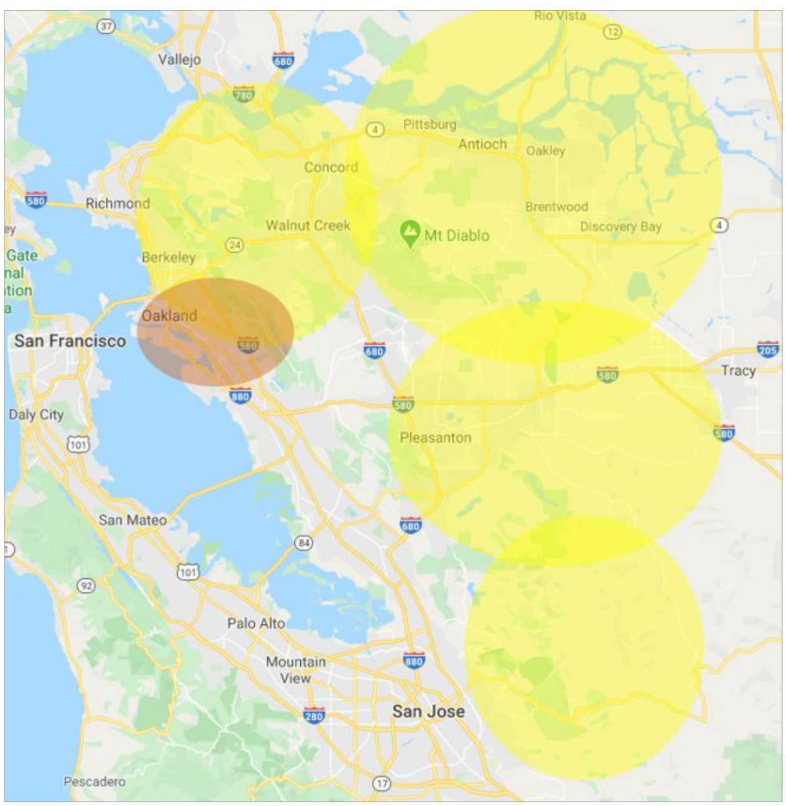

Figure 14. Impact Area of Primary Tandem Failure in Oakland Area

The baseline water distribution system (WDS) model was developed using Sandia's Water Network Tool for Resilience (WNTR). The model included pipe diameter, material, and junction elevation. Estimates were used for the demand profiles and tank/pump/valve operations, but future updates could provide real demand profiles and operations. Using this model enabled the team to conduct a topographic, pipe criticality, valve isolation, and hazard analysis.

Three earthquake scenarios were analyzed using the baseline WDS model. The data for the scenarios was sourced from USGS and included earthquakes of varying magnitudes, including the M6.8 Hayward Fault scenario, the M7.0 Hayward Fault scenario, and the M7.2 Hayward and Rodgers Creek Fault scenario. The model used peak ground acceleration and applied fragility curves defined using lognormal distributions and based on American Lifelines Alliance (ALA) reports to determine minor and major damage to the system.

For the analysis, the team was particularly concerned with how many pipes were expected to be damaged, and how long water pressure stayed below average. As shown in Table 7, a significant number of pipes experienced minor damage with the M6.8 and M7.0 scenarios and pipes experienced high rates of both minor and major damage with the M7.2 scenario.

Table 7. Water Pipe Damage from Earthquakes

Scenario	Peak Ground Acceleration (g)	# of Pipes with Minor Damage (small leak)	# of Pipes with Major Damage (large leak)
M6.8 Hayward Fault	0.34	119	3
M7.0 Hayward Fault	0.65	183	37
M7.2 Hayward and Rodgers Creek Fault	1.24	107	162

The M7.0 and M7.2 scenarios both experienced prolonged low-pressure conditions as seen in Figure 15. The reference line of 20 psi refers to the minimum residual pressure needed for fire hydrants.

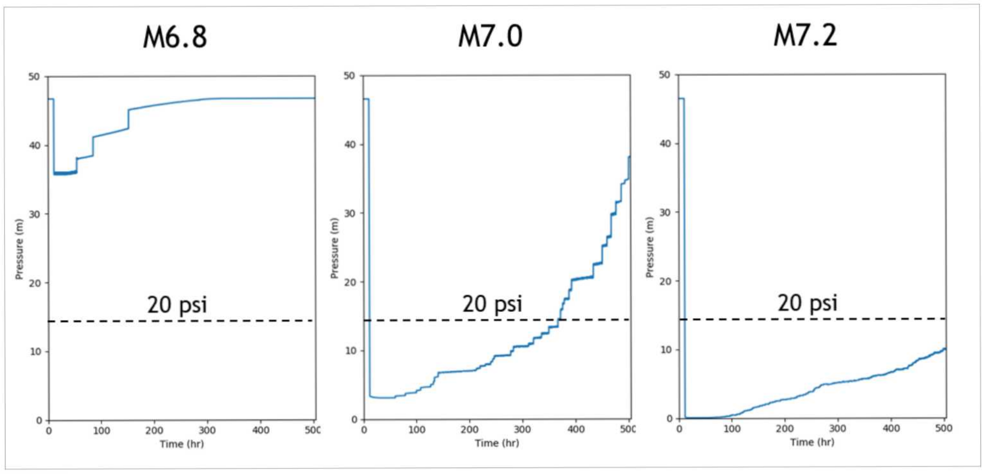

Figure 15. Water Pressure After Earthquakes

5.1.4. Mitigations

Several mitigation alternatives were considered within each infrastructure sector. Since this was a demonstration of capability and not a comprehensive analysis, these recommendations are intended to be representative of final results. Additional data and considerations that were beyond the scope of the effort could impact recommendations.

For the electrical system, the team used MDT to explore switching from diesel generators to natural gas generators, as well as to explore adding PV. Optimizations were run for each of the two buildings being analyzed to look at adding just natural gas generators, and for natural gas generators combined with PV systems. The results of the optimization runs are shown in Table 8, along with the baseline results for comparison.

Table 8. California Site Electrical Mitigation Options

Case	Energy Availability	Renewable Penetration/ Renewable Energy Use (%)	Diesel Fuel Used (gallons)	Required Fuel Storage (gallons)	Battery Storage	Generation Costs ($K)
Building A Baseline	99.3404%	N/A	23,023	7650	30 kW	$536
Building A Optimization	99.9992%	N/A	N/A	N/A	200 kW	$858
Building A Optimization with 400 kW PV	99.9995%	19.4/22.6	N/A	N/A	100 kW	$1,147
Building B Baseline	99.8886%	N/A	1,214	1275	20 kW	$203
Building B Optimization	99.9995%	32.2/46.4	N/A	N/A	0	$125
Building B Optimization with 50 kW PV	99.9997%	31.7, 45.8	N/A	N/A	0	$125

The output of the optimization runs can be represented on a pareto chart, where each non-dominated solution is shown to compare cost and performance. None of the solutions are "better" than any other solution in all dimensions, so the stakeholders would need to decide which metrics to prioritize to make a final decision based on their evaluation of the best set of performance cost tradeoffs in the space of pareto optimal solutions determined by MDT. The performance vs. cost pareto for this analysis is shown in Figure 16.

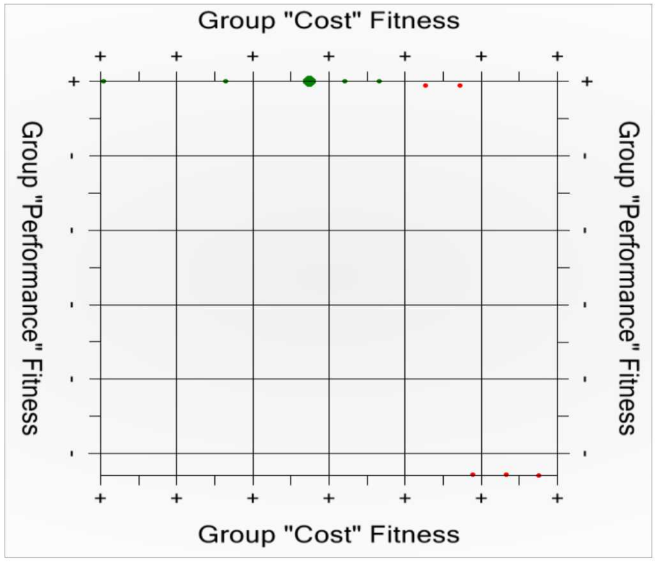

Figure 16. Performance vs. Cost Pareto for Analysis of Electrical Mitigation Options

From the analysis, the team was able to determine that, in its baseline configuration, Building A would require 23k gallons of fuel and Building B would require 1.2k gallons to withstand a 30-day outage. The least cost alternative to increase energy availability would be to change to 800 kW of natural gas generation with 200 kW of battery storage for Building A, and 100 kW of natural gas generation with 50 kW of PV for Building B. For both buildings, adding PV would lead to significant diesel fuel savings over a 30-day outage and additional spinning reserve capacity but would incur higher capital costs which could be offset by the energy output of the PV.

For communications, the team looked at both on-site and off-site mitigation options. On-site options included the ability to route over either fiber, a new data center, establishing business continuity plans for outage events, and investing in 5G connectivity. Off-site options included changing service level agreements (SLAs), improving service provider response times, increasing carrier diversity, and partnering with carriers to develop new fiber paths.

To mitigate the consequences of an outage, the analysis led the team to conclude that the Sandia CA site needs to engineer redundant solutions using multiple circuits and multiple vendors when possible. Diverse routes need to be specified up front and secured against future rerouting. Lastly, geographic diversity within individual carriers could be improved and the site could also benefit from carrier diversity.

Potential mitigations for the WDS are addressed in a recent analysis by Schaaf and Wheeler [23] and include plans to address reliability, redundancy, and deficiency issues. They include:

- Replacing aging sections of the system
- Ensuring all building have fire hydrants within 300 ft
- Adding additional isolation values to reduce outage size during maintenance or failures
- Tapping the supply line from LLNL to add redundancy

Metered data at each building and for irrigation would be needed to include accurate demand profiles. Additionally, more information would be needed about locations for critical water use, and response plans and post-event water needs.

5.1.5. Improvement Analysis

The Sandia CA site integration example presented a baseline analysis and various mitigation options for electric power, communications (voice and data), and water infrastructure. Based on the results of the baseline analysis and the calculated impact of the mitigations on the resilience metrics identified earlier in the process, the next step would be for stakeholders to decide which mitigation options to implement. This would require the prioritization of infrastructure sectors and metrics. Ideally, the infrastructure sectors should be considered in tandem and stakeholders should allocate the first round of funds to the mitigation options that will have the biggest impact on both individual systems and their independencies with the other infrastructure sectors. Once mitigation options are implemented, performance data can be collected to reevaluate the resilience metrics, and the models can be rerun to determine the magnitude of improvement over the baseline system configuration.

5.2. Integration Example 2: Puerto Rico Analysis

In 2017, Hurricane Maria exposed many infrastructure vulnerabilities in Puerto Rico and exacerbated socio-economic problems. The extensive destruction of the transmission and distribution infrastructure yielded the longest blackout in U.S. history, and showed that the centralized, electric infrastructure was not resilient or sustainable [24], [25]. Another impact to infrastructure from hurricane Maria was an island-wide loss of communications. Some communities did not receive power from the grid for a year. A profound transformation is needed to make the electric infrastructure resilient to hurricanes, and to the earthquakes that have affected Puerto Rico since December 2019. The earthquakes produced island-wide blackouts and put out of commission one of the largest power plants on the main island, leaving the electric grid vulnerable to multiple blackouts that afflicted Puerto Ricans during 2020.

A key challenge is how to transform the electric infrastructure when the government-owned utility is bankrupt, there is mistrust among key energy stakeholders and there is a perceived lack of transparency and accountability [25]. Community-based and community-led initiatives have broad support in Puerto Rico and had been pursued as part of the electric grid's transformation even before hurricane Maria (especially distributed generation alternatives). Close-knit communities can address some of the obstacles mentioned above, by providing continuity, participation, and a sense of ownership to community members [25].

This use case applies the integrated methodology framework to perform a threat-informed resilience analysis that would expand and improve the electric energy analysis previously completed for an economically challenged community in Puerto Rico. The resilience analysis could also guide future distributed solar energy investments and serve as an example for similar communities.

5.2.1. Scope and Goals

The area of interest is a community in Southern Puerto Rico. There are 3,000 residents and about 800 houses. There is another community to the West, a state road to the South, and underdeveloped land to the East and North. There is one small grocery store and a community center/general use building within the community. There are no other public or infrastructure services. The community has a solar community initiative to support local, socio-productive development, while serving as a model to reduce fossil fuels for power production. Residents prefer the community managing the initiative or having a partner as a sub-lead. There is also strong support for projects that include building local capacity and following sustainability principles [26]. After hurricane María the community added a goal to increase energy resilience to be able to produce electric power during and after emergencies to supply critical needs.

The board for the community consists of elected community members who provide leadership, coordination of activities, and in most instances, formal connection to external collaborators including the mayor's office. This community has faced diverse environmental and social challenges for decades, for example degraded air quality due to nearby industrial activity [26], [27], [28]. This shared history of struggles has strengthened the social fabric of this community, enabling them to establish the following community principles:

- Strategies must seek self-sufficiency, community-based, sustainable, and socio-productive development
- Proposals must come from the community
- Citizen participation must be direct, non-partisan and secular
- There must be consensus to reach decisions among community residents
- Government entities can participate as facilitators of the community's processes and proposals

In 2014, the community decided to install a photovoltaic (PV) system in their general-use/community center building (CCB) which is a critical service facility for the community. This building is used throughout the year as a meeting place, for community activities, for weekday activities for children during the summer, and as source of income from rentals. The CCB also became a community kitchen and donation distribution point after hurricane María.

Figure 19. Top view of the community center building (large blue rectangle), surrounding houses and streets. Source: Z. Méndez, H. Vega. Final Report for INEL 5195 Design Projects in EE, Advisor: Efraín O'Neill, ECE Department, UPRM, May 2017.

The community's experience with PV included a handful of community members with PV systems (mostly from third-party leasing) and a community member knowledgeable about the assembly of PV panels and systems. That initial knowledge was expanded to solar communities and microgrids with help from faculty and students from the University of Puerto Rico-Mayaguez (UPRM). In consultation with UPRM, the community board expanded their original goal to a community-wide solar initiative [26], [29]. Goal definition involved community members (main stakeholders) through:

- Meetings with the community board and open meeting with community members (2014-2019) [26], [29]
- UPRM energy seminars for the community (2015 and 2016) [26]
- Participation in UPRM's Solar Colloquia – Ponce (April 2017) [28]
- Focus group for the NSF RAPID project (April 2018, Award #1810800) [30]

As a result, the community's solar vision, rooted in their self-sufficiency, community-based, and sustainability principles, is meant not only to provide their CCB with PV, but also to collectively transform the whole community into a solar community. The initiative is based on rooftop PV systems acquired and managed collectively, with benefits and responsibilities shared among community members. Based on the community's resilience goal, the integrated resilience framework was applied, leveraging data and results from previous electric energy analyses published by UPRM researchers. The focus is on electric power infrastructure, but communications infrastructure is also included in the first two steps where data or information were available. Table 9 shows the two infrastructure sectors mentioned the most in stakeholder engagement activities, the associated threats, and the typical duration of disruptions after major events.

Table 9. Puerto Rico Community Threats and Disruptions by Infrastructure Sector

Infrastructure Sector	Threats	Disruptions
Electric Power	Hurricanes (strong winds, flooding, landslides), fragility of power infrastructure, earthquakes	Days to months-long outages, loss of central generation
Communications (for future analysis)	Power outages, hurricanes, road conditions that limit fuel supply for back-up generators	Long-term service interruptions

5.2.2. Metrics

Appropriate quantitative metrics for electric power were identified using comments and results from the stakeholder engagement activities described earlier. Since the community is focused on PV systems and sustainability, the table below includes metrics for percentage of load served, PV penetration, and emissions. Under blue-sky conditions, the goal is to have 100% of the load served. An April 2018 community focus group and an increased interest in resilience led the community to establish the following priorities: available electric power for bedridden persons, for life-support devices, and for the elderly (first priority); and community's ability to self-serve basic needs (community kitchen, refrigeration for medicines, minimal lighting, washing machine, ventilation) [30]. Thus, under black-sky circumstances, critical needs such as the community kitchen, refrigeration for medicines, minimal lighting, and ventilation will be addressed at the CCB with priority to services for the elderly and those with special needs. Critical needs would also be provided by houses that have community-owned PV systems. Metrics are summarized in Table 10.

Table 10. Puerto Rico Community Metrics by Infrastructure Sector

Infrastructure Sector	Metrics	Consequences
Electric Power	• Energy availability (% of load served) • PV penetration • Cost • GHG Emissions (estimated average 1.25 lbs CO2e per kWH for 2018) • Available power for bedridden persons, life-support devices, and elderly • Available power for community to self-serve basic needs	• Environmental, financial, and social impacts • Impact to key infrastructures for communications and water treatment • Impaired ability to provide lifeline/critical services to the community • Potential loss of life
Communications (for future analysis)	• Mobile/landline outages • Restoration time • Call congestion • Energy availability for cell phones, radios, computers	• Potential loss of life

The expectation is that the resilience metrics should show power is available at a minimum level to the most vulnerable community members. After the most vulnerable citizens are served, the critical needs for the rest of the community members will also be addressed as stored energy allows, with priority to refrigerating medicine. The high-level goal with rooftop PV systems is to have uninterrupted power supply for the critical needs listed above, throughout the duration of the outage. The gap between existing conditions and the future state is difficult to determine, since data regarding the number of community members with backup generators is not available. Furthermore, there is no data regarding how many people left the community to get critical services.

5.2.3. Baseline Analysis

The baseline analysis centers on what happened after hurricane Maria and utilizes historical data, comments from community members, and the personal experience of the researchers. The main infrastructure damages after hurricane Maria (relevant to this use case) were [30]:

- Power lines (transmission and distribution) and communication lines destroyed. Many reports of downed power and communications lines unknowingly cut by citizens helping to clear out roads (this delayed restoration).
- Power and communications lost. Approximately 5% of clients (~200,000 people) did not have power for a year. The community in this use case did not have power for three months.
- Roads destroyed, damaged, or blocked from flooding and landslides. This delayed restoration of power and communications, especially in regions outside the San Juan

metropolitan area and in rural/remote areas.

The main consequences from infrastructure damages included [30]:

- Limited access to water
- Scarcity of food
- The most vulnerable population suffered the most (elderly, people immobilized in bed, people in rural areas)
- Communities had to fend for themselves, especially those outside the San Juan metro area
- Since state and local governments did not help, many communities reacted and began providing services themselves (e.g., community meals)
- Dependence on diesel emergency generators for electricity at homes

Emergency back-up generators proved to not be a long-term solution for events lasting more than a few weeks because of compounding factors. Due to the scarcity of gasoline, there were long lines at gas stations. Adding to the gas shortages was the difficulty in delivering gas to gas stations because of blocked roads, landslides, etc. Additionally, the earthquakes that began on December 2019 resulted in power outages after the events and increased the system's vulnerability to outages throughout 2020. The baseline metrics were determined based on the discussion above and are shown in Table 11 and Table 12.

Table 11. Puerto Rico Community Baseline Analysis

Case	Backup Systems	Renewable Penetration	Diesel/Gas?	Required Fuel Storage?	Cost (electric rates, local generation)
Community Center Bldg	None	0	No	No	Utility: 20 cents/kWh
Residential customer with no emergency generator	None	0	No	No	Utility: 20 cents/kWh
Residential customer with emergency generator	Limited (typical generator capacity: 2 to 5 kW)	0	Yes	Small containers (typically 1 to 10 gallons)	Utility: 20 cents/kWh Power from gen. 70 cents/kWh*

* Calculation from Prof. Lionel Orama, ECE Department, UPRM

Table 12. Puerto Rico Community Baseline Analysis (Continued)

Case	GHG Emissions (estimated average 1.25 lbs CO2e per kWh for 2018)	Electric Power for Bedridden Persons, Life-Support Devices, and for the Elderly	Refrigeration for Medicines	Minimal Lighting	Ventilation
Community Center Bldg	None	No	No	No	No
Residential customer with no emergency generator	None	No	No	No	No
Residential customer with emergency generator	At least 20 lbs CO2e per day	Yes	Yes	Yes	Yes

5.2.4. *Mitigations*

Mitigation strategies were discussed and selected in meetings with the community board (2014-2019) and focus groups with community members (UPRM Solar Colloquia April 2017, focus group April 2018, NSF RAPID project #1810800). Preference was towards renewable and not gasoline/diesel options because of the multiple problems with fuel supply after hurricane Maria. Furthermore, emergency generators for residential use are not an economic option for long-term outages (weeks or months). Natural gas is not an option at the residential level in Puerto Rico because of lack of distribution infrastructure. The community approved a plan to start with a rooftop PV system for the CCB, and a few stand-alone rooftop PV systems as funding became available. All systems would be community owned. Based on the experience acquired with those initial PV systems, and contingent to funding, more rooftop PV systems would be installed, and further plans would be discussed for a community microgrid. That plan was used to prioritize the options and the type of analysis performed.

Based on the preferences from community members, UPRM researchers explored expanding the scope of the PV systems and substituting utility power with a portfolio of rooftop PV, storage, and demand response. The community is connected to the utility at a three phase 38 kV/4.16 kV distribution substation through a 1.3 mile, three phase 4.16kV distribution feeder as shown in Figure 18. Typical distribution line parameters corresponding to this feeder were used [31]. In consultation with the community board, the initial analysis would only include the 238 houses closest to the CCB, as well as the CCB to simplify the system modeling. The 238 houses are served through 20 single phase distribution transformers of various capacities (25, 50 or 75 kVA).

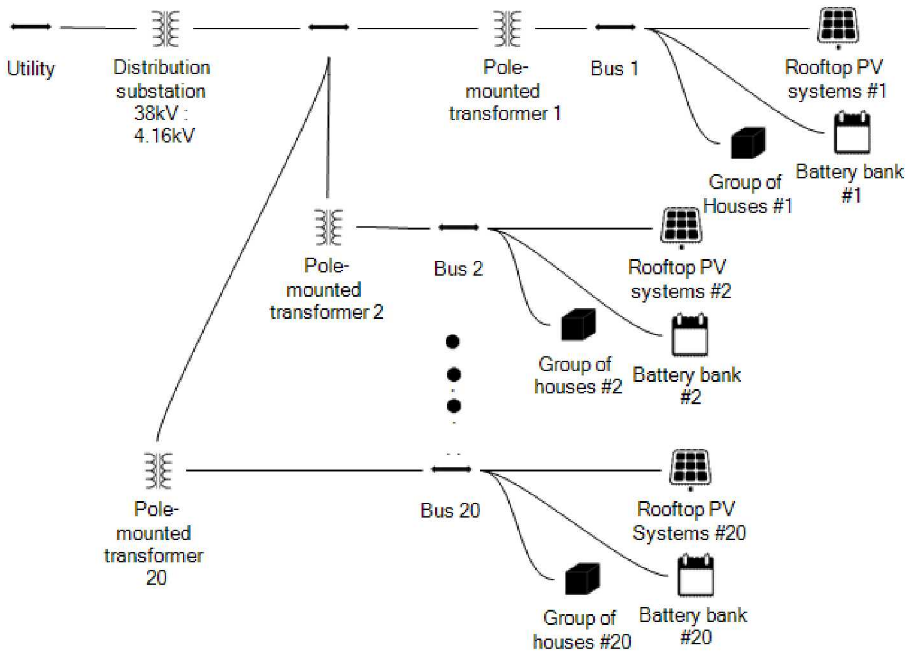

Figure 18. Representation of community distribution system and resilience nodes (20 groups of houses, each with aggregate PV and battery banks). Adapted from [6].

The community does not want to use existing, common-use, green areas for a large PV system. Thus, rooftop PV systems will be the main power sources. The distributed energy options available for the design were: rooftop PV systems, distributed storage, and demand response [32]. The critical loads identified by community members to meet critical residential needs (for one household) were a small refrigerator, ventilation (desk fans, ceiling fan), an LCD TV, a radio, lighting, and cellular phone charging. These loads were used to determine the minimum demand during emergency operations and the storage requirement as shown in Table 13.

Table 13. Minimal Energy Needs per Household

Level	Daily Demand	Days of Autonomy	Battery Depth of Discharge	Energy Storage Needed
Residential	4.582 kWh	1	40%	7.637 kWh

Two main scenarios were modeled and analyzed: a solar community (composed of stand-alone, residential PV systems connected through net metering), and a community microgrid (capable of disconnecting from the utility). For both scenarios, PV systems for the CCB and for the 238 houses closest to the CCB were considered [32]. To simplify the analysis, PV systems and energy storage were simulated as aggregated systems for the houses connected to each of the 20 transformers.

5.2.4.1. Solar Community

This option considered two start-up scenarios. The first one had nine households participating in a behind the meter solar community, with only four PV systems: three on individual rooftops and the other on the community center. The other scenario had 10 PV systems shared among a solar community of 20-50 households. These start-up scenarios represent a "solar community" operation. The design for this stage included individual rooftop PV systems and storage for critical load operation. It is assumed that the community members are well-organized and have reached a set of rules ("social agreement") on how the benefits of the solar community would be distributed. The initial investment could be provided from interested participants, a community loan, or donations. Each house with a rooftop PV system would have an individual net metering agreement with the utility. The most vulnerable community members (bedridden, elderly or other people with special needs) will have priority for initial PV systems. The rules for participant selection would be decided openly in community meetings. Eventually, the economic benefits generated from the installed PV systems would be distributed among the solar community participants following previously set rules.

The results from those two start-up scenarios were used to develop the study for a larger solar community and for the community microgrid of 238 houses [32]. Electric energy use data from previous UPRM design projects were combined with census data to obtain an estimate of energy use and allocation of types of households. Table 14 shows the load profiles for different types of households.

Table 14. Daily Demand by Size of Household [9]

Demand Profile	# of Persons	Daily Demand (kWh)	# of Households
1	6	33	20
2	5	22	70
3	4	15	67
4	2	10	24
5	1	5.75	57
		Total	238 houses

Under blue-sky conditions, the PV systems would be connected to the utility through individual net metering arrangements. Under black-sky conditions, minimal power would be provided for a subset of houses, prioritizing bedridden, elderly or other people with special needs. Neighbors with PV systems would share refrigeration and other services (e.g., charging cell phones) with those without PV systems as part of the "social agreement" within the solar community, acting as "resilience shelters" for their neighbors. Bedridden, elderly, or other people with special needs would share the services from their PV systems only after their critical life-support needs are met.

An example of the PV systems designed for demand profile #2 (from Table 14) used 12 PV panels (330 W each, for a total of 3.96 kW of power) for a maximum energy output of 19.8 kWh (assuming 5 hours of peak sun for Southern Puerto Rico). That information was used to design each residential PV system for the majority of the houses (167 of 238) based on rooftop area available (from visual inspection of satellite images).

Cost calculations were kept simple. Using information from actual PV quotes, UPRM researchers estimated the range of installed costs (as of 2018) shown in Table 15. For a typical PV system (3.96 kW), the cost would be around $11,000 (using the lower range of costs). Lead-acid batteries were assumed, at a quoted cost of $200 per kWh (quote from a PV contractor in Puerto Rico). Rounding the minimum storage needs per household identified earlier to 8 kWh, that would mean $1,600 per battery bank, for a total of $12,600 per PV system. The analysis was shared with the community board and used in various proposals to funding agencies.

Table 15. 2018 Rooftop PV Costs in Puerto Rico [6]

Component/Task	Cost ($/W)
PV panels	0.71
Inverter	0.18
Charge controller	0.07
Balance of system	0.45
Sub-total (do-it-yourself)	1.41
Installation (estimate)	0.40 to 1.50
Design, permitting (estimate)	1.00 to 2.20
Total	2.81 to 5.11

5.2.4.2. Community Microgrid

The solar community could evolve into a community microgrid where the 238 houses and the CCB could operate as an independent system, disconnected from the utility (either under blue-sky or black-sky conditions). For microgrid operation, the total amount of storage would be different than for the solar community case. In the solar community each PV system has separate storage designed to meet critical needs for each stand-alone PV system. In a microgrid, storage services are shared among all houses, and more storage would be needed to help balance supply/demand in both connected and disconnected modes. Microgrid operation also has additional costs related to communications and control equipment. The design of those additional systems and their costs were not part of the UPRM analysis. The regulation on microgrids in Puerto Rico initially establishes that a community microgrid must produce at least 75% of its energy from non-fossil fuel sources. Thus, 75% of the maximum expected demand from the 238 houses should come from the rooftop PV systems. The remaining 25% was assumed to come from the utility, under blue-sky, interconnected conditions through a constant block of energy contracted with the utility. During outages or emergencies, the microgrid would have enough distributed energy resources to operate in stand-alone mode [32]. However, under emergency conditions, the total demand is reduced and the ability to serve all 238 houses depends on the amount of solar energy available during the day and the state of charge of the batteries. As part of the social agreement that is needed, the community would have rules with respect to the distribution and use of available energy under various scenarios (e.g., sunny vs. cloudy days). The levels of energy use and the required energy storage would depend on the community's willingness to be flexible in their demand under dark sky scenarios. The recommended levels from UPRM's studies for the microgrid were 12.8 kWh of storage per house and 25-33% demand response. More details about demand response and storage are given in the Improvement Analysis section.

Demand response strategies need to be implemented in the community microgrid to reduce the variations seen by the grid, to reduce storage costs, and also to ensure proper operation in stand-alone mode. Demand response also helps reduce the storage requirements and thus the microgrid costs. For example, varying demand response from 10% to 30% would represent cost savings of around $16,000 to the community. This information was shared with the community since a change in energy consumption patterns could result in economic benefits for their community microgrid. Besides helping under stand-alone mode, demand response can also help during cloudy days when batteries are not charged completely, resulting in a violation of the contracted load with the utility during the night [32].

Power flow analyses were performed for the microgrid operation with a simplified 200-house community microgrid. Power flow studies provided further evidence of the technical feasibility of different microgrid scenarios. The main result from these simulations was the need for 12.8 kWh of storage per house, in order for the microgrid to operate properly. The demand response level assumed for that level of storage was between 25 and 33%. If the community is not willing or able to reduce their demand by those aggressive percentages, then the storage required would be larger and thus the cost of the overall system would increase [31], [33], [34].

5.2.4.3. Metrics for Mitigation Cases

The metrics in the following tables were estimated from the results obtained from UPRM's solar community and community microgrid studies. Table 16 and Table 17 contain the metrics for each case as they apply to the residences within the community. Table 18 and Table 19 contain the metrics for the CCB. Note that the metrics for the CCB are the same for both mitigation cases and have been combined into a single row.

Table 16. Residential Mitigation Metrics

Case	Backup Systems	Renewable Penetration	Diesel/Gas?	Cost	Electric Rates
Residential Baseline	None	0	No	No	Utility: 20 cents/kWh
Solar Community	167 rooftop PV systems & 8 kWh storage	86% of 3828 kWh (total daily demand)	No	$12,600 per PV system	10 cents/kWh LCOE without storage
Community Microgrid	167 rooftop PV systems & 13 kWh storage	86% of 3828 kWh (total daily demand)	No	$13,600 per PV system + microgrid controls cost	10 cents/kWh LCOE without storage

Table 17. Residential Mitigation Metrics (Continued)

Case	GHG Emissions (estimated average 1.25 lbs CO2e per kWh for 2018)	Electric Power for Bedridden Persons, Life-Support Devices, and for the Elderly	Refrigeration for Medicines	Minimal Lighting	Ventilation
Residential Baseline	None	No	No	No	No
Solar Community	At least 4133 lbs CO2e *saved* per day	Yes	Yes	Yes	Yes
Community Microgrid	At least 4133 lbs CO2e *saved* per day	Yes	Yes	Yes	Yes

Table 18. Community Center Mitigation Metrics

Case	Backup Systems	Renewable Penetration	Diesel/Gas?	Required Fuel Storage?	Cost (generation, electric rates)

Case	Backup Systems	Renewable Penetration	Diesel/Gas?	Required Fuel Storage?	Cost (generation, electric rates)
Community Center Baseline	None	0	No	No	Utility: 20 cents/kWh
Community Center with PV (Solar Community & Community Microgrid	Rooftop PV, storage (10 kWh)	5 kW	No	No	10 cents/kWh (PV LCOE without storage)

Table 19. Community Center Mitigation Metrics (Continued)

Case	GHG Emissions (estimated average 1.25 lbs CO2e per kWh for 2018)	Electric Power for Bedridden Persons, Life-Support Devices, and for the Elderly	Refrigeration for Medicines	Minimal Lighting	Ventilation
Community Center Baseline	None	No	No	No	No
Community Center with PV (Solar Community & Community Microgrid	At least 28 lbs CO2e *saved* per day	Charging for portable medical devices	Yes	Yes	Yes

5.2.5. *Improvement Analysis*

The proposed mitigations, either the solar community or the community microgrid, would allow this community to meet the minimum critical needs through the CCB and also through houses with PV. Furthermore, besides delivering black-sky benefits, the solar community or the microgrid would deliver a reduction in GHG emissions and a 75% reduction in the dependence on fossil fuels. These distributed alternatives also represent more resilient alternatives than centralized infrastructure [35], which has proven vulnerable to the extreme winds from hurricanes and the effects of earthquakes. The community microgrid has the advantage of sharing available energy resources among all 238 houses. However, a microgrid is more complex to manage and is more expensive than a solar community that only has stand-alone PV systems as shown in the previous section.

The analyses from UPRM helped the community secure initial funds for community outreach and education. With help from UPRM's capacity building activities, the community was able to negotiate the installation of a 5 kW PV system as part of the recovery initiatives after hurricane Maria. Furthermore, the community secured a grant to install up to 10 small stand-alone PV systems with batteries, following one of the recommendations from the UPRM studies.

Sandia's integrated resilience methodology was used in this use case as a framework to inform future distributed solar energy investments in this Puerto Rican community. Applying the integrated methodology was relevant and useful since resilience is now a major community goal after hurricane Maria and the 2019-2020 earthquakes. UPRM data and results from previously completed electric energy analyses for the community were used as input for the integrated methodology in this use case. The UPRM studies looked at distributed energy options for the community and focused on the community's sustainability and self-sufficiency goals. The integrated methodology expanded that perspective to a threat-informed resilience analysis that would provide stakeholders more information to decide which resilience options to implement.

The communications infrastructure sector was included in the initial steps of the analysis because this sector was severely impacted by hurricane Maria and mentioned during focus group discussions. As data becomes available regarding communications metrics for the baseline analysis, that sector could be included in the mitigation analysis. An interesting mitigation idea proposed by UPRM faculty was the use of portable, rapidly deployable cellular phone "repeater" stations, powered by PV systems.

Sandia's resilience tools can be used to expand and fine-tune the mitigation options from the previous UPRM studies. For example, instead of aggregating at the level of the twenty transformers, clusters of critical needs might be identified. Sandia's Resilient Node Cluster Analysis Tool (ReNCAT) can be applied to both scenarios, yielding Pareto fronts that can be used to select the best combinations of resilient nodes. Once new resilience nodes are identified, Sandia's Microgrid Design Toolkit (MDT) can be used to identify the optimal microgrid design that addresses the community's needs. This would greatly improve the recommendations made in the previous UPRM study, which only looked at three possible microgrid designs. MDT considers multiple technology combinations and optimizes designs for both resilience and blue-sky scenarios. Furthermore, the integrated methodology can be applied in the future to the entire community, and not just the 238-houses subset described in this use case.

5.3. Integration Example 3: Multi-Infrastructure Notional Analysis

The third integration example introduces a fictional township called Great Junction, to illustrate how the integrated methodology can be applied to perform resilience analysis. Though notional, this example covers how each of the steps in the resilience framework would be executed to evaluate potential mitigations to improve resilience for the township.

5.3.1. Scope and Goals

This integration example represents the fictional township of Great Junction. Great Junction is a small township with a population of about 10,000 residents. The township has an elected mayor who runs the small city government, police, and combined fire/ambulance services. The township also has a publicly owned water treatment plant that uses water obtained from the river on the northeast corner of the town. Wastewater is processed by a wastewater treatment plant and discharged in the southwest corner of town. The township is electrically served by a private cooperative, High River Coop, with two substations (A and B) and five feeders. Only two feeders (B2 and B3) are fed with underground cables in the town center area, with B2 located in a slightly elevated area above the 100-year flood plain. A map of Great Junction and a layout of its power distribution are shown in Figure 19.

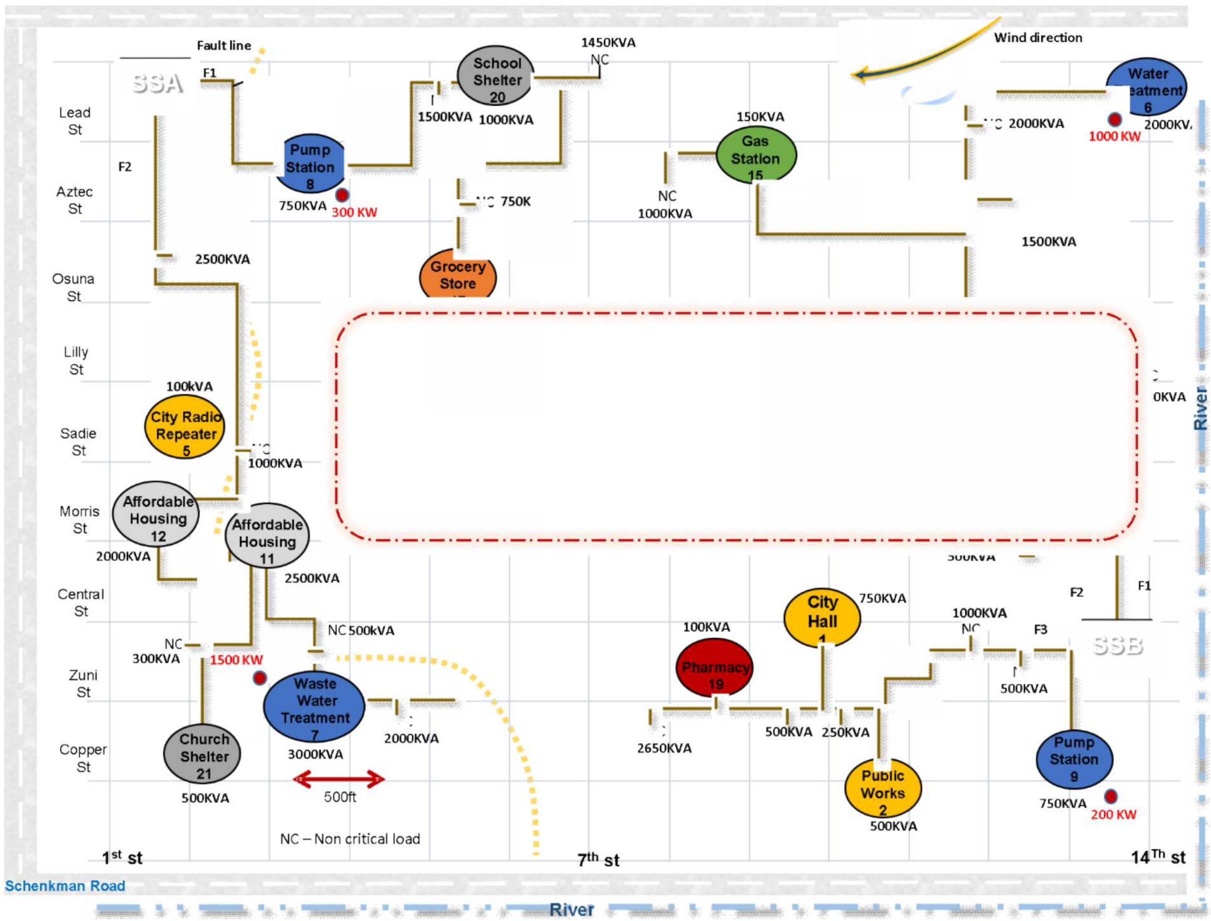

Figure 19. Great Junction Map and Power Distribution Layout

The township is serviced by a cell tower operated by a cell phone provider who also provides a less used wired service and a dedicated city telecom network for emergency dispatch centered from a fire/dispatch center. There is also a privately-owned natural gas company which provides services primarily for heating in the winter as well as for other small businesses and residences in the town. The township has several important privately-run businesses including a hospital, a pharmacy, grocery stores, and gas stations. Vulnerable populations exist in senior and affordable housing facilities, and the township has designated a school, a church, and a large parking garage as potential temporary shelter areas in the event of an emergency. Table 20 shows critical facilities and services within Grand Junction and their key characteristics.

Table 20. Great Junction Critical Services and Facilities

S#	Service	F#	Facilities	Substation Feeder	Peak Load (kW)	Backup Generation (kW)
1	City Critical	1	City Hall	B3	750	None
1	City Critical	2	Public Works	B3	500	None
1	City Critical	3	Fire Station	B2	500	150
1	City Critical	4	Police Station	B2	500	150
1	City Critical	5	City Radio Repeater	A2	100	None
2	Water	6	Water Treatment	B1	2000	1000
2	Water	7	Wastewater Treatment	A2	3000	1500
2	Water	8	Pump Station A	A1	750	300
2	Water	9	Pump Station B	B3	750	200
3	Housing	10	Senior Housing A	B1	1500	None
3	Housing	11	Affordable Housing A	A2	2500	None
3	Housing	12	Affordable Housing B	A2	2000	None
4	Medical	13	Hospital	B2	2000	1250
5	Communications	14	Cell Tower	B2	500	None
6	Gas	15	Gas Station A	B1	150	None
6	Gas	16	Gas Station B	B2	150	None
7	Food	17	Grocery A	A1	1500	None
7	Food	18	Grocery B	B2	1000	None
8	Pharmacy	19	Pharmacy	B3	100	None
9	Shelter	20	School Shelter	A1	1000	None
9	Shelter	21	Church Shelter	A2	500	None
9	Shelter	22	Garage	B1	750	None

The township is considering upgrading its critical services to better withstand emergency conditions. The current mayor and city leaders applied for and were able to obtain a $5M grant to provide funds, with additional funds available if they are able to obtain private partnerships in the project, to upgrade the existing electrical infrastructure to mitigate against the occurrence of anticipated future threats to the city services. The list of known threats and their historical impacts is given in Table 21.

Table 21. Great Junction Threats and Historical Impacts

Threat	Historical Impacts
Flooding	Great Junction located 30 miles inland from Atlantic Coast—experienced extensive flood damage 60 years ago from 100-year flood
Earthquake	Known fault line runs through city—no recorded earthquakes in known history
Windstorms, Blizzards, and Ice Storms	Winter storms from northeast cause wind damage and outages to power services with overhead lines

To come up with a set of overall resilience goals and determine the best way to use the grant funds for resilience improvements, the mayor coordinated a set of meetings with key stakeholders including city personnel, the utility High River Coop, and select representatives of key city services. They concluded that flooding posed the highest known risk and that funds should be used to focus resilience improvements on mitigating the impacts of future floods while still including other known risks in the analysis. An independent consultant firm was hired, with continuous input and guidance from a steering committee with representatives from key city stakeholders, to conduct a baseline analysis of how the township would be affected by an anticipated flood, what mitigation measures should be considered, and the expected effectiveness of each mitigation option considered.

5.3.2. Metrics

In consultation with township leaders, the consultant firm derived a list of performance metrics to use to evaluate resilience improvements. In the event of a major flood, it was deemed that resilience improvements should be effective for a minimum of three days and a maximum of one week, after which time state and federal resources would be expected to supplement requirements.

Evaluation of mitigation options will be based on metrics associated with improving the availability of the set of critical services listed in Table 20 relative to the existing baseline system including:

- Emergency response (City critical services that dispatch and deploy during emergencies)
- Critical services that most immediately impact community needs (medical, pharmacy, water, communications)
- Shelter for vulnerable populations (senior and affordable housing plus other scattered populations that cannot easily evacuate or shelter in place during a flood, and require access to critical services for the duration of the emergency)
- Other services like food and groceries (included if all other services can be met and resilience improvements can be made by adding these services without significant costs to the options considered)

Resilience options that improve these critical services to meet the needs of the township during a flood emergency, meet the three-day minimum, and have low associated costs, will be considered the most viable options to pursue. Options that improve resilience and can simultaneously provide additional blue-sky benefits such as additional revenue streams during normal operations will also be considered.

5.3.3. Baseline Analysis

The historical information about the distribution system and critical facilities in Table 22 is used for a baseline analysis of the township:

Table 22. Great Junction Asset Information

Asset	Location	Characteristics
Substation A	Fed from transmission feeders closer to the ocean	Likely to be disrupted by hurricanes that cause major flooding
Substation B	Fed from inland transmission feeders	Less likely to be disrupted by hurricanes
Feeders A1 & B1	Northern part of township; overhead	Subject to prevalent gusty winds, least reliable feeders historically
Feeders B2 & B3	Underground	Most reliable feeders, outages rare

Note that the part of the township fed by feeder B2 is located at a higher elevation and is the least likely area in town to be directly impacted by flooding.

Based on the historical information above, the impact of a flood on the baseline system can be assessed. It is estimated that substation A will be taken out of service by a hurricane, and as a precaution it is assumed that substation B will also be out of service. Therefore, only services with backup generators will be available initially. The following summarizes the current state of backup generation in Great Junction:

- Emergency response: Only the fire and police stations have backup power
- Critical services that most immediately impact community needs: The hospital and water systems have backup power, the cell tower and pharmacy do not
- Shelter: Existing senior and affordable housing do not have backup generation

Though some facilities have backup generation that's adequate to meet critical needs, not all have enough fuel storage to meet the three-day minimum. Some generators are older than others and may differ in their expected reliability during an outage. There are also a few locations where backup generator equipment needs to be hardened to be able to withstand flooding and provide power to critical facilities.

There are multiple tools that can be used to do the actual baseline analysis, as well as the improvement analysis, in a more formal and quantitative manner. For example, Sandia-developed tools like the Resilient Node Cluster Analysis Tool (ReNCAT) and MDT can be used to evaluate where resilience upgrades should be located within a region, as well as evaluate performance and cost metrics to analyze how improvements compare to the baseline system. These tools require inputs for the system to define the threat being analyzed (such as 100-year flood data which can be obtained from federal agencies such as FEMA), as well as feeder and equipment performance and reliability data from utilities. There are related tools which can evaluate the blue-sky benefits of resilience options, providing stakeholders with a way to generate revenue streams for resilience options. There may be other ancillary benefits to the system depending on the resource, such as additional emergency power sources which could be used in the system to mitigate potential power shortages or reduce costs of peak power demands.

5.3.4. Mitigations

The following options were considered to mitigate and improve the baseline system to meet Great Junction township's goals to be resilient for a minimum of three days to a major flood occurrence:

- Upgrades to fuel storage capabilities, hardening of generators in flood zones, and select replacement of older generators
- If feasible, develop microgrids around the township in areas that supply critical services using a combination of new and existing generation
- Where microgrids are not feasible, install new generation for critical services to meet the minimum three-day requirement

For all mitigation options, natural gas generators are preferred over diesel generators unless they are cost prohibitive. The analysis should also consider renewables such as PV and battery energy storage if they directly benefit resilience of provide auxiliary benefits like revenue streams that offset costs.

A number of mitigation options were evaluated based on the performance metric requirements and the available mitigation guidelines. Required upgrades deemed necessary for fuel storage needs, generation hardening, and generation replacement, were costed at $1.3M. This left $3.7M of the remaining funds for other resilience projects. However, a public-private partnership with the communication cell tower included could provide an additional $200K to available funds, and a partnership with the pharmacy another $100K, bringing the overall remaining budget to $4M.

Cost estimation involved estimating all of the costs required to implement each improvement option (referred to as project capital costs). These include the initial equipment purchase costs; the design costs for a design firm to survey the electrical system, do supporting analysis, and create design drawing to outline the changes in the existing grid necessary to implement the design; the engineering costs for additional support to review and oversee the design and construction phases;

and the construction costs including the labor costs to install and test the equipment and any overhead associated with a general contractor assigned to oversee the construction. Another set of costs which need to be considered but are not calculated below are the operation costs for ongoing fuel supply, maintenance, and operation of the new equipment. There are numerous estimation methods used to calculate costs. The biggest variables in cost besides the types of equipment considered (types of generations, renewables, etc.) will be labor costs which depend on the region where the work is done, and the overhead costs based on the types of permitting, regulations, etc., that must be obtained prior to working on a project. It is important to properly estimate these costs by allowing some contingency in the estimates to increase the likelihood that the costs of the actual project will align with the initial project estimates.

Taking into account the remaining budget, the microgrid projects in Table 23 were designed and costed. All microgrids assume the use of natural gas generators. If using diesel generators, the cost would be 30% less.

Table 23. Great Junction Microgrid Projects

Microgrid Feeder	Included Facilities	Cost
Feeder B1	Senior Housing, Water Treatment	$1.2M
Feeder B2	Fire Station, Cell Tower	$0.8M
Feeder B3	Public Works, City Hall, Pharmacy	$1.6M
Feeder A1	Pump Station, School Shelter, Grocery Store	$1.8M
Feeder A2	City Radio Repeater, Affordable Housing (2 units), Church Shelter, Wastewater Treatment	$3.5M

Besides the microgrids, the standalone projects in Table 24 were formulated, and costs determined as alternatives if microgrids weren't feasible for these facilities. Again, the costs assume the use of natural gas generators and would be 30% less with diesel generators.

Table 24. Great Junction Standalone Projects

Feeder	Standalone Facility	Cost
Feeder B1	Senior Housing	$0.5M
Feeder B3	Public Works	$0.5M
Feeder B3	City Hall	$0.7M
Feeder A1	School Shelter	$0.3M
Feeder A2	City Radio Repeater	$0.1M
Feeder A2	Affordable Housing (2 units)	$0.7M each
Feeder A2	Church Shelter	$0.2M

There was also one renewable/storage project considered as a possible feasible option. It consisted of 300kW of rooftop PV and 150kWH of energy storage deployable in multiple locations at a cost of $0.8M and yearly revenue of $150K.

5.3.5. Improvement Analysis

After all of the mitigation options were evaluated, the projects in Table 25 were approved by Great Junction township based on the following considerations:

Table 25. Approved Projects for Great Junction

Approved Project	Included Facilities	Cost	Justification
Feeder B2 Microgrid	Fire Station, Cell Tower	$0.8M	Meets critical needs with public-private partnership
Feeder B3 Microgrid	Public Works, City Hall, Pharmacy	$1.6M	Meets critical needs with public-private partnership
Feeder B1 Backup Generator	Senior Housing	$0.5M	Meets critical needs for vulnerable populations
Feeder A1 Backup Generator	School Shelter	$0.3M	Meets critical needs for vulnerable populations
Feeder A2 Backup Generator	City Radio Repeater	$0.1M	Meets critical needs for emergency response
Renewable/Storage Project	300kW rooftop PV, 150 kWh energy storage	$0.8M	Energy storage deployable in multiple locations, $150K/yr revenue

In addition to the approved projects, the required upgrades deemed necessary for fuel storage needs and generation hardening and replacement came to $1.3M. The total for the projects is $5.4M of which $5M is obtained from grants, $0.3M from public-private partnerships, and the small remainder is obtained from township funds. Since requirements could be met using preferred natural gas generation, no diesel generation options were considered even though it would have lowered costs. Affordable housing requirements could not be met but it was deemed that a subset of that population could be temporarily moved to available rooms in the school shelters or senior housing as a backup. Figure 20 below shows on the Great Junction map where these solutions would be applied.

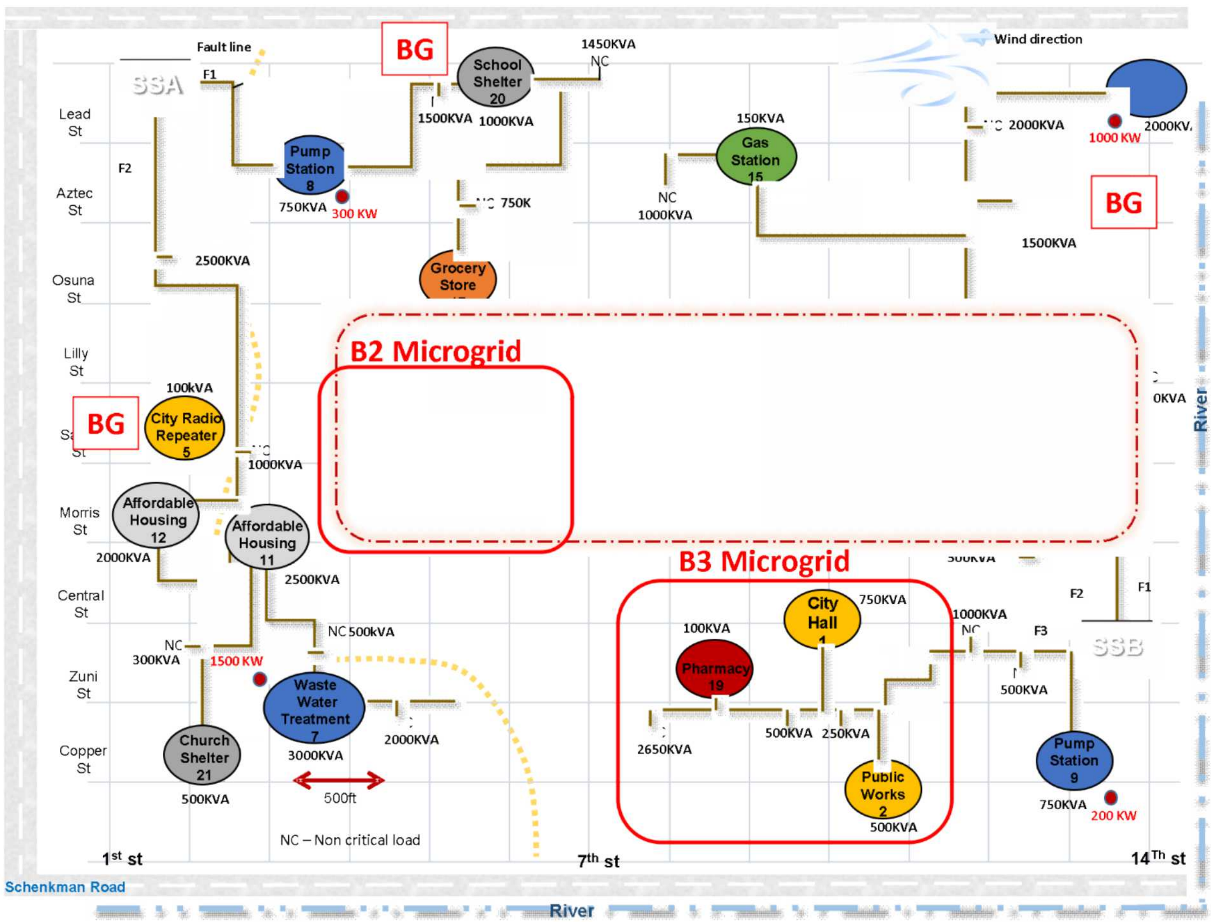

Figure 20. Approved Resilience Project Locations for Great Junction

5.4. Lessons Learned

As is illustrated by the three use cases, the details of how the integrated resilience methodology is applied to projects can vary greatly depending on the specifics of individual projects including stakeholders, types of infrastructure analyzed, available data, community goals, and mitigation options. The framework is broad enough to allow for this flexibility while still guiding the analysts and partners through a cohesive analysis and providing valuable metrics and options to meet resilience goals and objectives. Despite differences in application, there were similar lessons learned across the use cases that are important to keep in mind during future analyses.

The first key for a successful project is to carefully define the scope and goals for the project, including identifying all the important critical infrastructures and associated facilities that need to be included in the analysis. Even if the focus is strictly on a single infrastructure sector, it is still important to consider the impacts of other infrastructure sectors that could impact the analysis either directly or indirectly. The best way to avoid missing information in developing a plan to address resilience is to have as complete as possible a set of community stakeholders (public and private) and infrastructure stakeholders (energy, water, communications, etc.) either directly involved or in an advisory role. This ensures a broad perspective and increases awareness of non-technical considerations. Even with a broad team, data is not always readily available or may require some integration and validation. Larger teams do have the downside of making the timing of integrated analysis difficult, as one sub-team may be producing required analysis input for another sub-team, but there is still an overall benefit from involving a diverse set of stakeholders and analysts. Stakeholders and SMEs also benefit from the new connections that are made during the analysis process.

The next key is to carefully define the metrics and the best ways to evaluate the metrics for resilience improvements through both analytic tools and models, as well as the use of the best available data or conservative estimates if data cannot readily be obtained for the analysis. The temptation to allow each technology/domain to do its own separate analysis is strong since identifying common metrics and relevant threats is challenging but efforts should be made to maintain an integrated approach to resilience solutions. The analysis should also consider future growth or other anticipated changes to the community that can impact the analysis as well as how energy, water or other infrastructure costs may affect the analysis. To address the design basis threat in which resilience improvement are to be applied, it is best to look at the worst case and also more probable but still severe scenarios in order to make decisions on appropriate and realistic levels of resilience.

Lastly, the analysis should account for all associated costs, not just the equipment itself. Contingencies should be factored in for the costs as well as for the lead times and schedules to anticipate what overruns might possibly occur, and to evaluate which ones can be tolerated for the installation of a system. A successful resilience project should also include plans for continual monitoring and maintenance of the completed system including anticipated operational costs for the new resilient system. Part of the monitoring of the resilient system is tracking how well the metrics anticipated in the design of the system actually match the performance of the system with resilient improvements to ensure that these improvements have occurred.

6. CONCLUSION

This report documents, demonstrates, and extends Sandia's Integrated Methodology for Energy and Infrastructure Resilience Analysis. This integrated methodology highlights the unique contributions of Sandia's approach to resilience analysis. First, the method is explicitly threat-informed, drawing on Sandia's extensive expertise in both intentional and natural hazards. Second, it is consequence-focused, considering a range of technical, social, economic, and national security impacts. Third, it is performance-based, using modeling and simulation to evaluate system-level impacts of disruptions and potential mitigations. Finally, it is attentive to infrastructure dependencies and interdependencies, leveraging Sandia's experience across critical infrastructure sectors.

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APPENDIX A. TOOLS TO SUPPORT RESILIENCE ANALYSIS

A.1. RAP Tools [3]

Tool	Description	Reference
FEMA HAZUS Model	GIS-based software model which produces loss estimates for earthquakes, floods, hurricanes, and tsunamis	https://www.fema.gov/hazus
STEEP Analysis	Categorize and analyze social, technological, economic, environmental, and political metrics	https://pestleanalysis.com/what-is-steep-analysis/
Open Space Technology	Process for communities to identify critical issues, voice passions and concerns, learn, and take collective responsibility for finding solutions	https://openspaceworld.org/wp2/what-is/
Analytic Hierarchy Process (AHP)	Method used to support expert determinations of which kinds of consequences are prioritized	https://www.transparentchoice.com/analytic-hierarchy-process

A.2. ICPIA Tools [5]

Tool	Description	Reference
Emulytics™	Suite of emulation, modeling, and analysis tools for exercises and training that include forensics, predictive simulation, and real-time dynamic defense	https://energy.sandia.gov/programs/electric-grid/cyber-security-for-electric-infrastructure/
SCEPTRE	Modeling and simulation capabilities to simulate, emulate, and include hardware in the loop to more effectively analyze potential impacts from cyber attacks	https://energy.sandia.gov/programs/electric-grid/cyber-security-for-electric-infrastructure/grid-cyber-vulnerability-assessments/
Siemens PSS/E	PSS/E allows for transmission system analysis and planning. The software is applicable to many technical areas, including transient stability simulation, optimal power flow, node-breaker modeling, and steady-state voltage stability.	https://new.siemens.com/global/en/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html

Tool	Description	Reference
FASTMap	Tool that allows various spatial data at any spatial resolution to be quickly viewed by stakeholders	https://energy.sandia.gov/download/43011/

A.3. DRC Tools [6]

Tool	Description	Reference
System Definition Tools		
FASTMap	Tool that allows various spatial data at any spatial resolution to be quickly viewed by stakeholders.	https://energy.sandia.gov/download/43011/
ArcGIS	Geographic information system for working with maps and geographic information.	https://www.arcgis.com/index.html
Stakeholder Elicitation Methods for Threats and Goals		
Prioritization and Resource Allocation Decision Environment (PARADE)	Enables enterprise-wide prioritization of security and resilience investments. Metrics are then prioritized and used in a mathematical model which provides an optimal, cost-effective schedule of technology investments and mitigations over time based on performance improvement against these metrics. The model combines expert elicitation via the Analytic Hierarchy Process (AHP) and a Mixed-Integer optimization model.	
Risk-Informed Management of Enterprise Security (RIMES)	Characterizes targets by how difficult it would be for adversaries to exploit each target's vulnerabilities to induce consequences. RIMES focuses on a security risk metric based on the degree of difficulty an adversary will encounter to successfully execute the most advantageous attack scenario. The degree of difficulty is plotted against the level of consequences if the attack were successful.	

Tool	Description	Reference
IdeaScale	Software for stakeholders to share ideas and comments.	https://ideascale.com/service/idea-management/
	Threats/Disruptions	
FEMA Hazus	GIS-based software model which produces loss estimates for earthquakes, floods, hurricanes, and tsunamis.	https://www.fema.gov/hazus
ArcGIS	Geographic information system for working with maps and geographic information.	https://www.arcgis.com/index.html
	Component, Infrastructure, Multi-infrastructure Impacts	
Water Network Tool for Resilience (WNTR)	Sandia-developed Python package designed to simulate and analyze the resilience of water distribution networks.	https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2017/178883r.pdf
	Baseline & Improvement Resilience Metrics	
ICE Calculator	Tool to estimate interruption costs and/or the benefits associated with reliability improvements.	https://www.icecalculator.com/home
Regional Economic Accounting (REAcct)	Rapidly provides order-of-magnitude estimates (by nation, region, or sector) of a disaster's potential economic severity, expressed as changes to gross domestic product (GDP), due to short-term disruptions.	https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2016/163361m.pdf
Prescient	Sandia-developed software toolkit that uses stochastic programming to perform power system production cost model simulations.	https://energy.sandia.gov/tag/prescient/
Technology Management Optimization (TMO)	TMO software optimizes user-defined problems using a genetic algorithm. It can be used to determine optimal design for power generation and distribution systems.	https://www.sandia.gov/CSR/tools/tmo.html
Whole System Trades Analysis Tool (WSTAT)	Sandia-developed decision support optimization tool that integrates subsystem models into a holistic system view, mapping critical design choices to consequences relevant to stakeholders.	https://www.sandia.gov/CSR/tools/wstat.html
	Technology Screening	

Tool	Description	Reference
Resilient Node Cluster Analysis Tool (ReNCAT)	Sandia-developed tool to analyze services provided by infrastructure within a region and suggest portfolios of potential microgrid locations that minimize societal burden at least cost.	https://www.sandia.gov/news/publications/labnews/articles/2019/08-30/Puerto_Rico_grid.html
LPNORM (OD&O)	Software tool for designing resilient distribution grids to support DOE's goal of "10% reduction in the economic costs of power outages by 2025."	https://www.electric.coop/nreca-grid-modernization-laboratory-consortium-funded-projects/
REEDS	Capacity planning model that simulates the evolution of the bulk power system, including generation and transmission	https://www.nrel.gov/analysis/reeds/index.html
Resilience Mitigations Identification		
Microgrid Design Toolkit (MDT)	The MDT is a decision-support tool that aids microgrid planners and designers in quantitative analysis to meet objectives and constraints for efficiency, cost, reliability, and environmental emissions.	https://energy.sandia.gov/download-sandias-microgrid-design-toolkit-mdt/
QSTS	Quasi-static time-series (QSTS) power flow simulations require accurate and computationally efficient methods to address long computational times of up to 120 hours per simulation when unbalanced distribution feeders are modeled. The methods and tools developed demonstrate multiple pathways for speeding up the QSTS computation using new and innovative methods for advanced time-series analysis, faster power flow solvers, parallel processing of power flow solutions, and circuit reduction. The target performance level was achieved with year-long high-resolution time series solutions run in less than 5 minutes within an acceptable error.	Final technical report in review as of September 2020
Distributed Energy Resources Customer Adoption Model (DER-CAM)	DER-CAM is an economic and environmental model of customer DER adoption that helps to minimize the cost of operating on-site generation and combined heat and power systems.	https://gridintegration.lbl.gov/der-cam
REOpt	Techno-economic design support platform to optimize energy systems. Recommends optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, and energy performance goals.	https://reopt.nrel.gov/

Tool	Description	Reference
Hybrid Optimization of Multiple Energy Resources (HOMER)	HOMER optimization model software simplifies the task of designing hybrid renewable microgrids by providing easy-to-use simulation, optimization, and sensitivity analysis capabilities. The tool is commercially available through HOMER Energy.	http://homerenergy.com/software.html
QuESt	Sandia-developed open source, Python-based application suite for energy storage simulation and analysis	https://energy.sandia.gov/tag/quest/
Mathworks MATLAB	MATLAB is a commercially available interactive environment that allows the user to explore and visualize ideas and collaborate across disciplines including signal and image processing, control systems, and communications. MATLAB can be used to model energy consumption to build smart power grids. Its capabilities include data analysis for visualization, algorithm development, numeric computation, and application development.	https://www.mathworks.com/products/matlab.html
Mathworks Simulink	Tool to design and simulate systems and their components.	https://www.mathworks.com/products/simulink.html
Mathworks Simscape Electrical (formerly SimPowerSystems)	Provides component libraries for modeling and simulating electronic, mechatronic, and electrical power systems.	https://www.mathworks.com/products/simscape-electrical.html
LabView	LabVIEW is a development environment designed to accelerate the productivity of scientists and engineers by reducing test times, translating ideas into reality, and delivering business insights based on collected data. Applications include instrument control, embedded control and monitoring systems, automated test and validation systems, and acquiring and analyzing measurement data.	https://www.ni.com/en-us/shop/labview.html
Xyce	Xyce is an open source, SPICE compatible, high-performance analog circuit simulator that is capable of solving extremely large circuit problems by supporting large-scale parallel computing platforms. Xyce is released under the GNU General Public License can be downloaded at https://xyce.sandia.gov/downloads/sign-in.html.	https://xyce.sandia.gov/

Tool	Description	Reference
Grid PV	Models and simulates the integration of distributed generation into the electric power system and determines the impacts on the distribution system for highly variable generation	https://pvpmc.sandia.gov/applications/gridpv-toolbox/
CYME Power Engineering Software	The CYME Power Engineering Software consists of advanced applications and libraries for either transmission/industrial or distribution power network analysis. Applications for distribution network/system analysis include network configuration optimization, long-term dynamics analysis, secondary grid network analysis, and reliability assessment. The software is commercially available.	http://www.cyme.com/software/#dist
OpenDSS	OpenDSS is an open source simulation tool that supports nearly all frequency domain (sinusoidal steady-state) analyses performed on electric utility power distribution systems, as well as new types of analyses that are designed to meet future needs related to smart grid and renewable energy research.	http://smartgrid.epri.com/SimulationTool.aspx
GridLAB-D	GridLAB-D is a power distribution systems simulation and analysis tool capable of simulating interactions between business systems, physical phenomenon, markets and regional economics, and customer interactions to determine how they each affect the power system.	http://www.gridlabd.org/
Siemens PSS/E	PSS/E allows for transmission system analysis and planning. The software is applicable to many technical areas, including transient stability simulation, optimal power flow, node-breaker modeling, and steady-state voltage stability.	https://new.siemens.com/global/en/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html
GE PSLF Dynamic Tools	The Dynamic Analysis Tools package for Concorda PSLF allows users to perform transient stability analysis for multiple events on cases containing up to 80,000 buses. The software is commercially available.	http://www.geenergyconsulting.com/practice-area/software-products/pslf
PowerWorld Simulator	PowerWorld Simulator simulates high voltage power system operation. Its power flow analysis package is capable of solving systems of up to 250,000 buses. It is commercially available from PowerWorld Corp.	http://www.powerworld.com/products/simulator/overview

Tool	Description	Reference
Matlab Power System Analysis Toolbox	Matlab toolbox for electric power system analysis and simulation.	http://faraday1.ucd.ie/psat.html
	Multi-Metric Optimization	
Prioritization and Resource Allocation Decision Environment (PARADE)	Enables enterprise-wide prioritization of security and resilience investments. Metrics are then prioritized and used in a mathematical model which provides an optimal, cost-effective schedule of technology investments and mitigations over time based on performance improvement against these metrics. The model combines expert elicitation via the Analytic Hierarchy Process (AHP) and a Mixed-Integer optimization model.	
Prescient	Sandia-developed software toolkit that uses stochastic programming to perform power system production cost model simulations.	https://energy.sandia.gov/tag/prescient/
Resilient Node Cluster Analysis Tool (ReNCAT)	Sandia-developed tool to analyze services provided by infrastructure within a region and suggest portfolios of potential microgrid locations that minimize societal burden at least cost.	https://www.sandia.gov/news/publications/labnews/articles/2019/08-30/Puerto_Rico_grid.html
LPNORM (OD&O)	Software tool for designing resilient distribution grids to support DOE's goal of "10% reduction in the economic costs of power outages by 2025."	https://www.electric.coop/nreca-grid-modernization-laboratory-consortium-funded-projects/

A.4. ESDM Tools [4]

Tool	Description	Reference
	Commercial Power Grid Analysis Packages (mainly Transmission)	
GE PSLF Dynamic Tools	The Dynamic Analysis Tools package for Concorda PSLF allows users to perform transient stability analysis for multiple events on cases containing up to 80,000 buses. The software is commercially available.	http://www.geenergyconsulting.com/practice-area/software-products/pslf

Tool	Description	Reference
Siemens PSS/E	PSS/E allows for transmission system analysis and planning. The software is applicable to many technical areas, including transient stability simulation, optimal power flow, node-breaker modeling, and steady-state voltage stability.	https://new.siemens.com/global/en/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html
PowerWorld Simulator	PowerWorld Simulator simulates high voltage power system operation. Its power flow analysis package is capable of solving systems of up to 250,000 buses. It is commercially available from PowerWorld Corp.	http://www.powerworld.com/products/simulator/overview
Power Systems Computer Aided Design (PSCAD)	PSCAD allows users to build, model, and simulate power systems. Features include online plotting functions, controls and meters, which allow the users to alter system parameters during a simulation and view the effects while the simulation is in progress.	https://www.pscad.com/software/pscad/overview
Commercial Power Grid Analysis Packages (mainly Distribution)		
EasyPower	The EasyPower product suite consists of Windows-based electrical software tools for designing, analyzing, and monitoring electrical power systems. Packages include Protective Device Coordination, Arc Flash Hazard, and Automated Design.	https://www.easypower.com/products/easypower?/products/EasyPower/EasyPower_family.php
CYME Power Engineering Software	The CYME Power Engineering Software consists of advanced applications and libraries for either transmission/industrial or distribution power network analysis. Applications for distribution network/system analysis include network configuration optimization, long-term dynamics analysis, secondary grid network analysis, and reliability assessment. The software is commercially available.	http://www.cyme.com/software/#dist
Generic Power Grid Analysis Packages		
Mathworks MATLAB	MATLAB is a commercially available interactive environment that allows the user to explore and visualize ideas and collaborate across disciplines including signal and image processing, control systems, and communications. MATLAB can be used to model energy consumption to build smart power grids. Its capabilities include data analysis for visualization, algorithm development, numeric computation, and application development.	https://www.mathworks.com/products/matlab.html

Tool	Description	Reference
Mathworks Simulink	Simulink is a block diagram environment for multi-domain simulation and model-based design. It is integrated with MATLAB, allowing for the incorporation of MATLAB algorithms into models. The software is commercially available.	https://www.mathworks.com/products/simulink.html
Mathworks Simscape Electrical	Simscape Electrical (formally SimPowerSystems) provides component libraries and analysis tools for modeling and simulating electrical power systems. Its models can be used to develop control systems and test system-level performance. The software is commercially available.	https://www.mathworks.com/products/simscape-electrical.html
Open Distribution System Simulator (OpenDSS)	OpenDSS is an open source simulation tool that supports nearly all frequency domain (sinusoidal steady-state) analyses performed on electric utility power distribution systems, as well as new types of analyses that are designed to meet future needs related to smart grid and renewable energy research.	http://smartgrid.epri.com/SimulationTool.aspx
LabVIEW System Design Software	LabVIEW is a development environment designed to accelerate the productivity of scientists and engineers by reducing test times, translating ideas into reality, and delivering business insights based on collected data. Applications include instrument control, embedded control and monitoring systems, automated test and validation systems, and acquiring and analyzing measurement data.	https://www.ni.com/en-us/shop/labview.html
Xyce	Xyce is an open source, SPICE compatible, high-performance analog circuit simulator that is capable of solving extremely large circuit problems by supporting large-scale parallel computing platforms. Xyce is released under the GNU General Public License can be downloaded at https://xyce.sandia.gov/downloads/sign-in.html.	https://xyce.sandia.gov/
Microgrid & Distribution Resilience Analysis Packages		
Microgrid Design Toolkit (MDT)	The MDT is a decision-support tool that aids microgrid planners and designers in quantitative analysis to meet objectives and constraints for efficiency, cost, reliability, and environmental emissions.	https://energy.sandia.gov/download-sandias-microgrid-design-toolkit-mdt/

Tool	Description	Reference
Technology Management Optimization (TMO)	TMO software optimizes user-defined problems using a genetic algorithm. It can be used to determine optimal design for power generation and distribution systems.	https://www.sandia.gov/CSR/tools/tmo.html
Performance Reliability Model (PRM)	The PRM evaluates the performance of a microgrid design, focusing on the behavior of a microgrid when operating in islanded modes following extreme weather events. PRM and TMO are embedded in the MDT tool.	https://www.sandia.gov/CSR/tools/mdt.html
GridLAB-D	GridLAB-D is a power distribution systems simulation and analysis tool capable of simulating interactions between business systems, physical phenomenon, markets and regional economics, and customer interactions to determine how they each affect the power system.	http://www.gridlabd.org/
Distributed Energy Resources Customer Adoption Model (DER-CAM)	DER-CAM is an economic and environmental model of customer DER adoption that helps to minimize the cost of operating on-site generation and combined heat and power systems.	https://gridintegration.lbl.gov/der-cam
Hybrid Optimization of Multiple Energy Resources (HOMER)	HOMER optimization model software simplifies the task of designing hybrid renewable microgrids by providing easy-to-use simulation, optimization, and sensitivity analysis capabilities. The tool is commercially available through HOMER Energy.	http://homerenergy.com/software.html
Renewables Alternative Power System Simulation (RAPSim)	RAPSim is an extendable framework supportive of users' implementation of their own grid object models and grid controlling algorithms.	http://sourceforge.net/projects/rapsim/
ETAP Microgrid	ETAP Microgrid monitors, predicts, manages, and optimizes energy supply and demand for small-scale energy systems through distributed energy technologies with intelligent software.	https://etap.com/solutions/microgrid
SICAM Microgrid Controller	SICAM Microgrid Controller offers automated planning, forecasting, modeling, and real-time optimization for controlling all operating resources within a microgrid.	https://new.siemens.com/global/en/products/energy/energy-automation-and-smart-grid/microgrid/sicam-microgrid-controller.html
Pyomo	Pyomo (formerly Coopr) is a collection of open-source optimization-related Python packages, which supports a set of optimizing capabilities for formulating and analyzing optimization models.	http://www.pyomo.org/

Tool	Description	Reference
System of Systems Analysis Toolset (SoSAT)	SoSAT is a tool for modeling and simulation of multi-echelon operations and support activities of a system of systems. As a stochastic simulation, SoSAT characterizes sensitivity changes to all platforms, support systems, processes, and decision rules as well as platform reliability and maintainability properties.	https://www.sandia.gov/CSR/tools/sosat.html
Consequence Modeling	Sandia has used systems dynamics software (such as PowerSim Studio) to track microgrid performance under varying load scenarios. Consequence modeling helps to guide design teams toward optimal Energy Surety Microgrid design.	http://prod.sandia.gov/techlib/access-control.cgi/2013/136185.pdf
Open EI	Open EI is an open data platform that provides energy information and links data together. Open EI offers data sets on smart grids, utilities, and various forms of renewable energy, as well as a forum to discuss this data.	https://openei.org/wiki/Main_Page
Microgrid & Distribution Resilience Test Beds		
Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid Testbed	The microgrid testbed was designed to demonstrate an advanced approach for integrating multiple distributed energy resources (DERs) into a utility's distribution system or power grid.	https://certs.lbl.gov/
Center for Smart Grid Applications, Research and Technology (CSMART)	CSMART is a lab focused on researching, testing, and analyzing smart grid technologies in a real-world environment. It aims to leverage capabilities from academia, industry, and utilities to determine the best ways to deploy and support advanced smart grid technologies in an effort to manage renewable, energy storage, and microgrids in a secure and reliable environment.	https://web.iit.edu/wiser/csmart-center-smart-grid-applications-research-and-technology
National Electric Grid Reliability Test Bed	This testbed has a utility-scale transmission system and distribution systems that can be configured to various power grids.	https://inl.gov/research-programs/grid-resilience/
MIT Energy Initiative Facilities	The facilities offer a laboratory-scale microgrid to investigate questions from computer simulation studies. Focus areas include determining which components to use and how best to operate them to meet demand, and how to disconnect and reconnect from a central power grid without voltage instability.	http://energy.mit.edu/research/

Tool	Description	Reference
Distributed Energy Resources Test Facility (DERTF)	Located at the National Wind Technology Center near Boulder, CO, DERTF is a laboratory designed for interconnection and systems integration testing. The facility includes generation, storage, and interconnection technologies, as well as electric power system equipment capable of simulating a real-world electric system.	https://www.nrel.gov/esif/distributed-energy-resources-test-facility.html
Energy Systems Integration Facility (ESIF)	ESIF houses a collection of capabilities that support the development, evaluation, and demonstration of innovative clean energy technologies. Specialty research capabilities include systems integration, manufacturing and material diagnostics, high performance computing and analytics, and prototype and component development. ESIF offers laboratories that allow researchers to interconnect energy generation and storage systems with the utility grid, test system performance, and perform system experiments involving building-to-grid interactions.	https://www.nrel.gov/esif/distributed-energy-resources-test-facility.html
Complete System-Level, Efficient & Interoperable Solution for Microgrid Integrated Controls (CSEISMIC)	CSEISMIC is a microgrid testbed at DECC that employs an ORNL algorithm which directs automatic transition on and off the main grid. The major benefits of the microgrid controller are improvements to reliability, efficiency, stability, and economics of the microgrid.	https://github.com/ORNLPES/CSEISMIC
Distributed Energy Communications & Controls (DECC)	DECC is a laboratory that can test multiple distributed energy systems in a real-world distribution system and demonstrate the ability of these technologies to provide dynamic reactive power locally. The goal of the lab is to work with the power industry, manufacturers, and universities to develop local control for producing reactive power from microturbines, fuel cells, and reciprocating engines.	https://www.ornl.gov/content/system-integration
Reactive Power Lab	The Reactive Power Lab was established to demonstrate that distributed resources can provide reactive power locally for power factor correction and voltage regulation through low-cost controls and minimal communications using either inverters or synchronous machines. The lab's work is conducted under the DECC project and laboratory.	

Tool	Description	Reference
PPL Electric Utilities Power Lab	The PPL Electric Utilities Power Lab includes a microgrid testbed at Penn State Harrisburg is based on the norms of IEEE 1547, an interconnection standard, which enables studies of the impact of interconnecting DER with the electrical grid. Research on the testbed is focused on integration of distributed energy sources; intelligent protection schemes for detecting and preventing outage, islanding, and blackouts; creating new microgrid solutions for residential and industrial applications; and intelligent real-time demand side management based on renewable energy uncertainty.	https://sites.psu.edu/microgridtestbedpsh/
Distributed Energy Technologies Laboratory (DETL)	DETL is a 480V, three-phase microgrid with interconnections to the utility grid and various distributed energy resources. The lab is involved in research on generation, storage, and load management at the systems and component levels, exploring advanced materials, controls, and communications to achieve a reliable and low-carbon electric infrastructure.	https://energy.sandia.gov/programs/renewable-energy/solar-energy/photovoltaics/distributed-energy-technologies-lab-detl/
Smart Grid Demonstration and Research Investigation Lab	This facility focuses on developing power system operation and control algorithms utilizing smart grid data and real-time validation. The objective is to produce reliable, secure and economic smart grid operations.	https://sgdril.eecs.wsu.edu/

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