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Final Technical Report: Designing Resilient Communities: A Consequence-Based Approach for Grid Investment Report Series

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ABSTRACT

As part of the project "Designing Resilient Communities (DRC): A Consequence-Based Approach for Grid Investment," funded by the United States (US) Department of Energy's (DOE) Grid Modernization Laboratory Consortium (GMLC), Sandia National Laboratories (Sandia) partnered with a variety of government, industry, and university participants to develop and test a framework for community resilience planning focused on modernization of the electric grid. This report provides a summary of the development, description, and demonstration of the resulting Resilient Community Design Framework.

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Further appreciation is offered to the Department of Energy and the Grid Modernization Laboratory Consortium for recognizing the importance of resilient communities when addressing the modernization of our nation's electric grid.

We appreciate all their efforts and look forward to further collaborations in the future.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
BCA	Benefit Cost Analysis
BEV	Battery Electric Vehicle
BRAC	Base Realignment and Closure
CHP	Combined Heat and Power
CLT	Community Land Trust
CMP	El Caño Martín Peña
CoSA	City of San Antonio
COTS	Commercial Off-The-Shelf
CYME	CYME Power Engineering Software
DBT	Design Basis Threat
DCFC	Direct Current Fast Charging
DER-CAM	Distributed Energy Resources Customer Adoption Model Tool
DETL	Distributed Energy Technologies Laboratory
DOE	Department of Energy
DRC	Designing Resilient Communities
EMP	Electromagnetic Pulse
ENLACE	The Corporación del Proyecto ENLACE del Caño Martín Peña
EPA	Environmental Protection Agency
EV	Electric Vehicle
EVFC	Electric Vehicle Fast Chargers
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
GIS	Geographic Information System
GMD	Geomagnetic Disturbance
GMLC	Grid Modernization Laboratory Consortium
GridLab-D	Power Distribution System Simulation and Analysis Tool
HAZUS	GIS Based Natural Hazard Analysis Tool
ICE Calculator	Interruption Cost Estimate Calculator
IDP	Integrate Distribution Plan
IEEE	Institute of Electrical and Electronics Engineers
IOUs	Investor Owned Utilities
IRP	Integrated Resource Plan
LPNORM	Optimal Resiliency Model Software Tool
LVAT	Laboratory Value Analysis Team

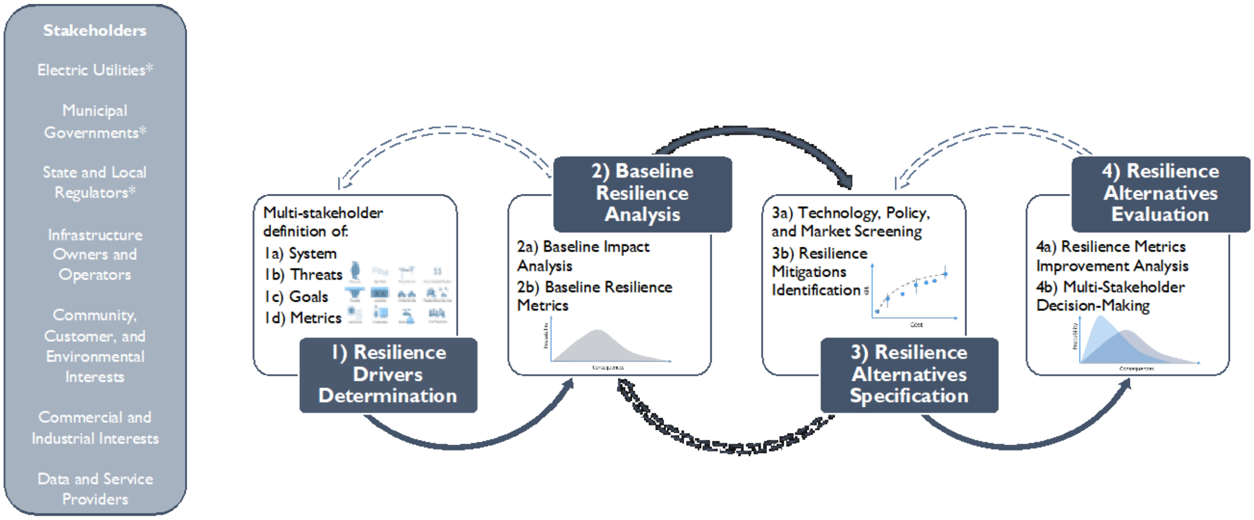
Abbreviation	Definition
MDT	Microgrid Design Toolkit
MSC	Microgrid Sizing Capability
NARUC	National Association of Regulatory Utility Commissioners
O&M	Operation and Management
OECD	Organization for Economic Cooperation and Development
OpenDSS	Electric Power Distribution System Simulator
PGA	Peak Ground Acceleration
PHEV	Plug-In Hybrid Electric Vehicle
PPD-21	Presidential Policy Directive-21
PREB	Puerto Rico Energy Bureau
PREC	Puerto Rico Energy Commission
PREPA	Puerto Rico Electric Power Authority
PRESCIENT	Prescient is a software package for simulating electricity grid operations.
PRM	Performance Reliability Model
PSLF	Positive Sequence Load Flow Software
PSS/E	Power System Simulator for Engineering
PUC	Public Utility Commissions
PV	Photovoltaic
ReEDS	Regional Energy Deployment System Capacity Planning Tool
ReNCAT	Resilience Node Cluster Analysis Tool
REOpt	Renewable Energy Optimization Tool
SAG	Stakeholder Advisory Group
Sandia	Sandia National Laboratories
SME	Subject Matter Expert
SUNY	State University of New York
TEB	Tiered Energy Buildings
TMO	Technology Management Optimization
UPRM	University of Puerto Rico Mayaguez
US	United States
USFS	United States Forest Service
USGS	United States Geological Survey
WNTR	Water Network Tool for Resilience
Xyce	Xyce Parallel Electronic Simulator

EXECUTIVE SUMMARY

The "Designing Resilient Communities (DRC): A Consequence-Based Approach for Grid Investment" project, funded by the US Department of Energy's (DOE) Grid Modernization Laboratory Consortium (GMLC), sought to enable more resilient communities through consequence-based approaches to grid investment planning via two related goals. First, in collaboration with key stakeholders, to design a framework that aligns community resilience and grid investment planning through a novel consequence-based approach. Second, through iterative implementation and refinement of the framework and analysis of associated technology, policy, and market dynamics, to establish a clear, actionable path toward widespread adoption of this consequence-based resilience planning approach among electric utilities, municipal governments, and energy regulators. These goals were realized through project workstreams organized under four tasks:

- Task 1: Development of a framework for alignment of community resilience planning and grid investment planning
- Task 2: Implementation, demonstration, and validation of the Resilient Community Design Framework in practice
- Task 3: Investigation of alternative regulatory frameworks for incentivizing efficient resilience investments and monetizing resilience benefits
- Task 4: Hardware demonstration of the "resilience node" concept

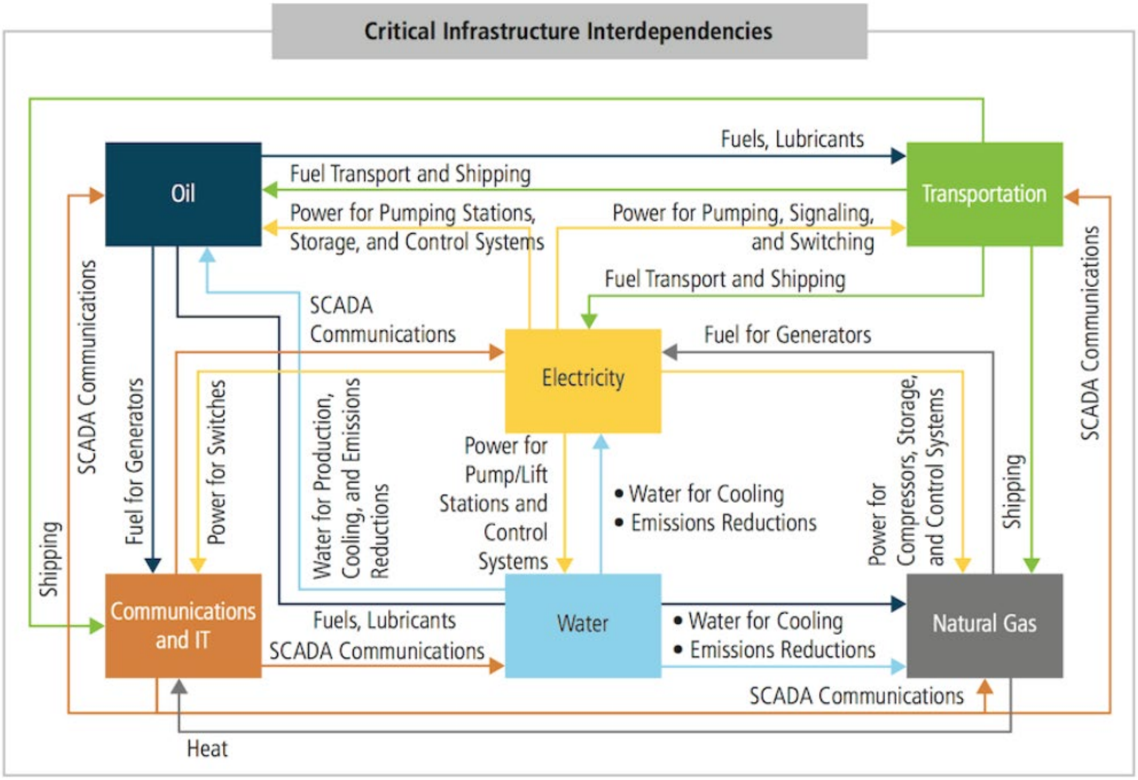
This report summarizes the DRC project across these four tasks, with a focus on the development, description, and demonstration of the Resilient Community Design Framework (depicted below) via engagement with a broad set of stakeholders, novel research and analysis, and framework and hardware demonstration case in New York .



1. INTRODUCTION

1.1. Motivation

The energy sector is one of 16 critical infrastructure sectors designated in Presidential Policy Directive-21 (PPD-21) [1]. This designation recognizes the criticality of these sectors to the functioning of the United States (US) economy, society, and national security [1]. The electricity subsector has been recognized as particularly critical because of its interdependencies with other critical infrastructure sectors, as depicted in Figure 1 [2, 3, 4].



Key critical infrastructure interdependencies represent the core underlying framework that supports the American economy and society. The financial services sector (not pictured) is also a critical infrastructure with interdependencies across other major sectors supporting the U.S. economy.

Acronyms: supervisory control and data acquisition (SCADA).

Figure 1: Electricity System Centrality for Critical Infrastructure Resilience (source: [2])

The consequences of major disruptions to the electric power system—such as those experienced during Superstorm Sandy, Hurricane Maria, and Winter Storm Uri—exemplified its criticality and focused attention on strategies to promote its resilience. Despite substantial interest in the topic of critical infrastructure resilience, definitions vary widely in the literature [5, 6, 7, 8, 9, 10, 11, 12] and among practitioners [13, 4]. This report utilizes the definition of resilience established in PPD-21: "…the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [1]. This definition exemplifies the unique temporal dimensions of resilience, as depicted in Figure 2, which encompasses system performance before, during, and after a disruptive event. Notably, this definition of resilience does not specify the temporal scale of each disruption, whether they be fast-acting acute hazards such as hurricanes, or slow-moving chronic hazards such as sea level rise. However, the electric power industry has increasingly focused on acute hazards in the practice of "resilience planning," whereas slow-moving chronic hazards are addressed using other terms such as "climate adaptation." This distinction is important to note when working across stakeholder domains.

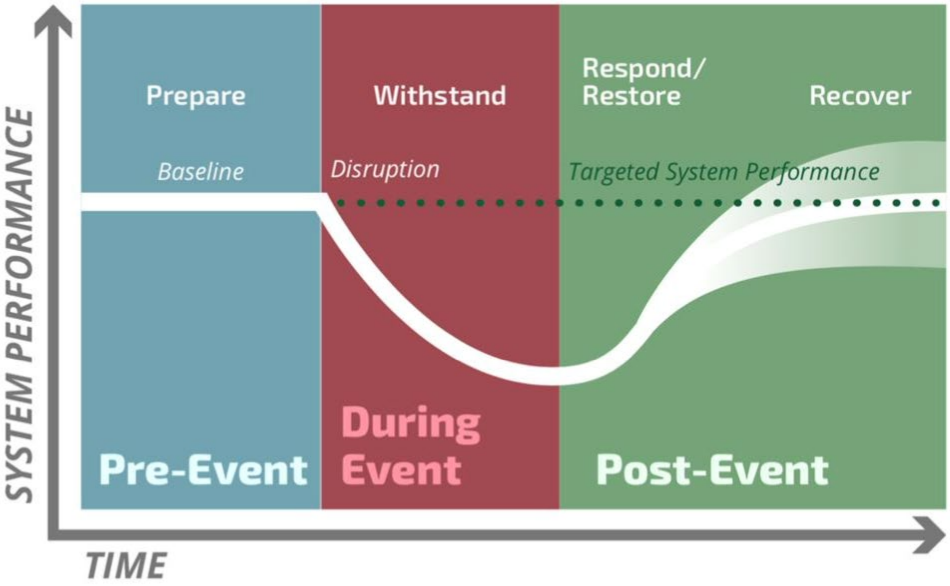


Figure 2: Resilience Curve and Timeline (source: [4])

Resilience, using this definition, is an extension of the concept of reliability. Power system planners and utility regulators have well-established reliability planning metrics, approaches, and criteria. Although resilience extends reliability in the sense that is it concerned with system performance given a disruption, the approaches and metrics used for reliability are insufficient and indeed may be inappropriate for resilience planning for two related reasons. First, measuring and mitigating extreme values is often the motivation for resilience analysis, as contrasted with reliability analysis which may focus on the higher probability but lower consequence impacts (e.g., shorter duration or less widespread power outages). These widespread and longer-duration outages are historically rare, and each major event is somewhat unique in manifestation. The usage of major event days to delineate the difference between reliability and resilience is a positive first step. This means that approaches relying primarily on historic behaviors to predict future performance are fraught, and a more fundamental understanding between system performance and these consequences must be developed. Second, consequences to society, the economy, and national security scale nonlinearly with longer duration and more widespread power disruptions [4]. Therefore, approaches to resilience planning must be developed and utilized that explicitly address these consequences. Moreover, consequence valuation must be dynamic, unlike in reliability planning where attempts to quantify economic consequence, for example, often focus on a static value-of-lost-load metric.

To plan for improvements in consequence-focused resilience [14], changes to planning practices for both transmission and distribution systems are likely necessary to incorporate social and economic impacts more directly. Planning at the distribution level is likely to be the first to incorporate more direct community input since distribution planning fundamentally occurs with a more local scope. The myriad stakeholders and the diverse market and policy contexts involved in distribution system planning and operation add complexity to the technological and methodological aspects of electric grid resilience planning. In particular, aligning electric grid modernization investment planning with community resilience planning is a key challenge for enabling a more resilient distribution system, and in turn, more resilient communities.

1.2. Report Purpose and Overview

The "Designing Resilient Communities (DRC): A Consequence-Based Approach for Grid Investment" project, funded by the US Department of Energy's (DOE) Grid Modernization Laboratory Consortium (GMLC), addresses the aforementioned challenge of aligning electric grid modernization investment planning and community resilience planning. This report summarizes the advancements made by the DRC project, focusing on the development, description, and demonstration of a framework for community resilience planning applied to modernization of the electric grid. It begins with an overview of the DRC project, including the project goals, stakeholders, and key accomplishments (Section 2). It then describes the iterative framework development and stakeholder engagement processes before turning to a detailed description of the framework, including steps, stakeholders, and tools (Section 3). The report then summarizes framework implementation, demonstration, and validation through three application and demonstration cases (Section 4), followed by a discussion of opportunities for future framework iteration and implementation focusing on alternative regulatory frameworks for resilience (Section 5). It then details the hardware demonstration case of the resilience nodes concepts (Section 6). It concludes with a discussion of lessons learned and areas for future work (Section 7). The appendices provide a repository of relevant tools and DRC project publications. Technical reports and journal articles produced as part of the DRC project and are summarized in Table 15, which provides a mapping to the relevant task(s) and a link to the materials.

2. DRC PROJECT OVERVIEW

Sandia National Laboratories (Sandia) partnered with a variety of government, industry, and university partners in the development and demonstration of a framework for community resilience planning focused on modernization of the electric grid. To address the gap between community and electric utility resilience planning, the DRC project investigated how coordinated grid investment can support resilient community design and how electric utilities of various configurations can plan for resilience and benefit from grid resilience investments. This section provides a summary of the DRC project goals, stakeholders, and accomplishments.

2.1. DRC Project Goals and Tasks

The DRC project sought to enable more resilient communities through consequence-based approaches to grid investment planning through two related goals. First, in collaboration with key stakeholders, to design a framework that aligns community resilience and grid investment planning through a novel consequence-based approach. Second, through iterative implementation and refinement of the framework and analysis of attendant technology, policy, and market dynamics, to establish a clear, actionable path toward widespread adoption of this consequence-based resilience planning approach among electric utilities, municipal governments, and energy regulators. These goals were realized through project workstreams organized under four tasks:

- Task 1: Development of a framework for alignment of community resilience planning and grid investment planning
- Task 2: Implementation and validation of the Resilient Community Design Framework
- Task 3: Investigation of alternative regulatory frameworks for incentivizing efficient resilience investments and monetizing resilience benefits
- Task 4: Hardware demonstration of the "resilience node" concept

2.2. DRC Project Stakeholders

Deep collaboration among a broad set of stakeholders was essential to the DRC project's success. As Figure 3 depicts, Sandia engaged a variety of government, industry, and university partners with shared interest and expertise in community resilience planning and electric grid modernization. Sandia formed a Stakeholder Advisory Group (SAG) to inform the development of the Resilient Community Design Framework and to serve as a community of practice for connecting local government, utility, and regulator activities focused on resilience and addressing shared challenges in consequence-focused resilience planning. The SAG consisted of stakeholders from municipal governments and electric utilities, spanning multiple regions, regulatory environments, and utility structures. Over the course of the project, the SAG included representatives from six jurisdictions[1]. In addition, Sandia engaged three sets of demonstration partners to enable the implementation and validation of the Resilient Community Design Framework and the hardware demonstration for the resilience node concept: the City of San Antonio and CPS Energy, the El Caño Martín Peña Communities, and National Grid. To support framework development and demonstration, as well as investigation of alternative regulatory frameworks and the hardware demonstration, Sandia also engaged several project partners, including State University of New York (SUNY) at Buffalo, Synapse Energy Economics (Synapse), Bosque Advisors, Clemson University, and New Mexico State University. Other organizations, such as the National Association of Regulatory Utility

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[1] New York City (ConEdison), Honolulu (Hawaiian Eclectic Company), Norfolk (Dominion Energy), Atlanta (Southern Company), Los Angeles (Los Angeles Department of Water and Power), and Boston (Eversource).

Commissioners (NARUC) and the 100 Resilient Cities organization also collaborated with SAG members and contributed expertise to the project.

Figure 3: Designing Resilient Communities Project Stakeholders

The SAG and other project stakeholders served three critical roles in the DRC project. First, they provided feedback on unique aspects of their operating contexts that enable or discourage alignment of community resilience planning and electric grid modernization. Second, they informed the technical and regulatory solution space for the project and provided research, analysis, and advice to support the establishment of a clear, actionable path toward widespread adoption of this consequence-based resilience planning approach among electric utilities, municipal governments, and energy regulators. Third, they enabled information exchange about emerging technologies that can provide grid resilience and addressed how these technologies can provide community resilience.

In particular, as discussed in Section 3, the SAG played an instrumental role in the design, validation, and implementation of the Resilient Community Design Framework. SAG members provided information about the challenges and opportunities their unique jurisdictions and organization have faced in grid resilience planning, which helped frame the gap analysis for the framework. SAG members also provided feedback on several drafts of the framework, enabling an iterative and collaborative framework development process. SAG members suggested direction for analysis and designs being performed with demonstration partners, supporting framework validation. Finally, discussions among SAG members, demonstration partners, and project partners facilitated information exchange about emerging methodologies, technologies, and strategies to enhance the intersection of grid and community resilience, thereby supporting ongoing implementation of the framework.

3. TASK 1: DEVELOPMENT OF A FRAMEWORK FOR ALIGNMENT OF COMMUNITY RESILIENCE PLANNING AND GRID INVESTMENT PLANNING

Pursuant to Task 1, the DRC project developed several iterations of the Resilient Community Design Framework. Moreover, throughout the project the Sandia team and DRC project and demonstration partners maintained ongoing interaction with the SAG. As noted above, this engagement with the SAG both informed the design and refinement of the Resilient Community Design Framework and enabled the development of an internal community of practice for connecting local government, utility, and regulator activities focused on resilience and addressing shared challenges in consequence-focused resilience planning. The SAG met five times over the course of the project and "lessons learned" were captured following each meeting. The first meeting, held in July 2018 in Washington, D.C., focused on learning about the challenges different stakeholders face in grid resilience planning and developing a "shared language" for key concepts. The second meeting, held in January 2019 in Los Angeles, CA, focused on resilience metrics (and their limitations) as well as the broader policy and market contexts for resilience. The third meeting, held in July 2019 in New York, NY, focused on eliciting stakeholder feedback on an updated, more detailed framework and discussing progress on framework application and demonstration cases. The fourth meeting, held in January 2020 in Washington, D.C., focused on moving from the final framework description to framework implementation. In lieu of a fifth in-person meeting, a webinar and two virtual workshops were held in April and June 2021, respectively, to summarize project accomplishments and identify opportunities for ongoing collaboration among project stakeholders. In addition to these meetings, the Sandia project team, SAG members, and other project stakeholders also collaborated throughout the project via an electronic communication platform, SAG-led working groups (which included a working group focused on Defining, Valuing, and Measuring Resilience and another working group focused on Rethinking Regulatory Frameworks and Utility Business), and related symposia.

3.1. Framework Development Process

To enable more resilient communities through consequence-based approaches to grid investment planning and to establish a clear, actionable path toward widespread adoption of this consequence-based resilience planning approach among electric utilities, local governments, and energy regulators, the DRC project produced the Resilient Community Design Framework. The framework aligns community resilience planning and grid investment planning through a novel consequence-based approach. The framework was developed, implemented, and refined in close collaboration with project stakeholders (Section 2.2). The framework was informed by the DRC application and demonstration cases (Section 5) and analyses of attendant technology, policy, and market dynamics (Section 6). This section describes the framework development process.

3.1.1. Preliminary Framework Design and Feedback

The development of the Resilient Community Design Framework was an iterative process. The initial version of the framework was produced during the first six months of the project. This early framework draft leveraged Sandia's longstanding experience with resilience analysis for critical infrastructure sectors [15], adapting the steps and stakeholders to reflect the unique the institutional contexts for community resilience planning. Depicted in Figure 4, this early version of the framework consisted of four steps and the engagement of a broad range of stakeholders, including local governments, electric utilities, state and local regulators, community groups, and infrastructure owners. The preliminary framework consisted of the following four steps:

1. Determination of resilience drivers: determining the threats to which the community wishes to be more resilient, the infrastructure systems that matter most, and how to measure consequence to the community.
2. Community resilience analysis: understanding the current community risk (in the determined unit of consequence) to extreme events for each threat over a planning horizon.
3. Specification of resilience alternatives: proposing alternative technology investments, utility business models, and regulatory frameworks that help mitigate the events and improve performance and reduce costs based on the consequence-focused resilience metrics.
4. Evaluation of resilience alternatives: evaluating resilience planning options based on criteria such as resilience benefits, as well as co-benefits accrued during normal or "blue sky" days and over very long time horizons.

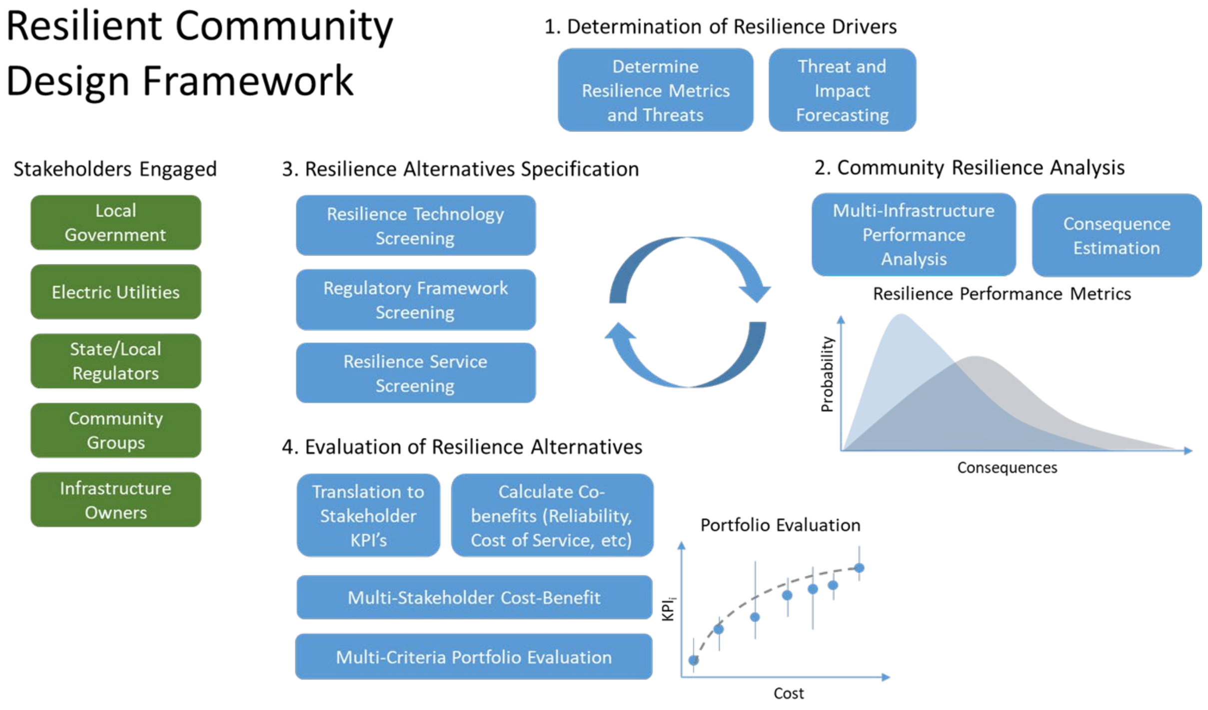


Figure 4: Preliminary Resilient Community Design Framework

Over the course of the first year of the project, members of the SAG, demonstration partners, and project partners provided feedback on the draft framework. As described in Section 2.2, the SAG played an instrumental role in the design, validation, and implementation of the Resilient Community Design Framework. During the July 2018 SAG meeting in Washington, D.C., the January 2019 SAG meeting in Los Angeles, CA, and engagements between meetings, the SAG provided input on the unique aspects of their operating contexts that enable or discourage alignment of community resilience planning and electric grid modernization. This information about the challenges and opportunities faced in grid resilience planning helped frame areas for further development of the framework. Specifically, the July 2018 SAG meeting included a guided brainstorming session on significant threats to resilience and resilience planning challenges, resulting in several key themes that helped inform project workstreams. The January 2019 SAG meeting focused on resilience metrics and provided critical information about the metrics used to quantify system performance and gaps associated with translating these performance metrics into more consequence-focused measures of economic, social, and national security impacts (presentations from SAG members were organized around a template with core definitions and framing questions, enabling systematic comparisons across operating contexts). Moreover, following the January 2019 meeting, members of the SAG formed working groups focused on "Defining, Valuing, and Measuring Resilience" and "Rethinking Regulatory Frameworks and Utility Business Models," which enabled Sandia, members of the SAG, demonstration partners, and project partners to further iterate on framework development and implementation.

3.1.2. Revised Framework Design and Feedback

Drawing on feedback from the SAG and ongoing developments in the working groups and other project tasks, a revised version of the framework was developed between the second and third SAG meetings. Depicted in Figure 5, this revised version of the framework consisted of the same basic four steps as the draft framework, but with an expanded set of intermediate steps and a broader set of stakeholders engaged. The revised framework consisted of the following four steps:

1. Resilience drivers determination: multi-stakeholder definition of the system and area of interest, threats to resilience, resilience goals, and resilience metrics.
2. Baseline resilience analysis: assessing potential disruptions from identified threats and the effects these would have on system performance as well the resulting consequences as represented by selected resilience metrics.
3. Resilience alternatives specification: identifying alternative technology investments, regulatory frameworks, and utility business models that may improve resilience and selecting candidate mitigations to be evaluated.
4. Resilience alternatives evaluation: assessing the effects of selected mitigations on system performance and calculating resilience metrics, which can be used to co-optimize among candidate mitigation portfolios across several planning dimensions such as affordability and sustainability.

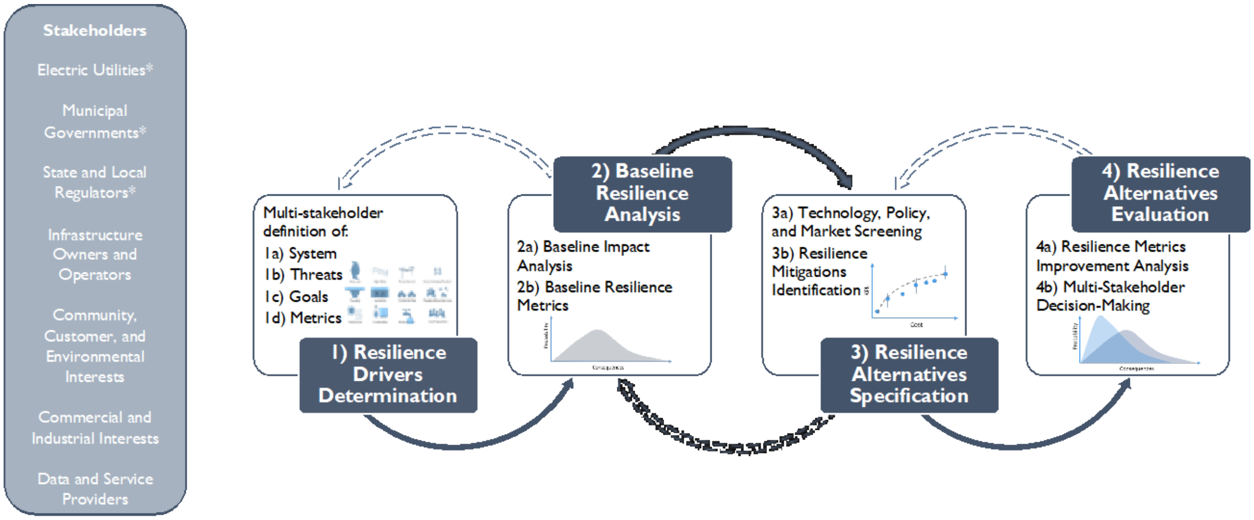


Figure 5: Revised Resilient Community Design Framework

This revised framework was provided to project stakeholders in advance of the third SAG meeting, along with a template for project partners to report out on application cases using the framework to describe steps of their resilience analysis processes. During the July 2019 SAG meeting in New York, NY, stakeholder feedback was elicited on the updated framework and application cases, which both supported framework validation and provided direction for analysis and designs being performed with project partners. The January 2020 SAG meeting in Washington, D.C., focused on moving from the final framework draft to framework implementation, with an emphasis on emerging methodologies, technologies, and strategies to enhance grid resilience. Together, this feedback informed the technical and regulatory solution space for the project and provided research, analysis, and advice to support to establish a clear, actionable path toward widespread adoption of this consequence-based resilience planning approach among electric utilities, municipal governments, and state and local regulators.

3.2. Final Framework Description

The Resilient Community Design Framework is an analytical framework for aligning energy investments with the resilience goals of local or municipal governments; identifying and evaluating technology options for achieving these resilience goals; and assessing policy- or market-based incentives for electric utilities' investments in community resilience. This section describes the framework, providing details about its four steps—resilience drivers determination, baseline resilience analysis, resilience alternatives specification, and resilience alternatives evaluation—as well as the most relevant stakeholders and potential tools for each step. A summary of this more detailed version of the Resilient Community Design Framework is depicted in Figure 6 below and discussed in the subsequent sections.

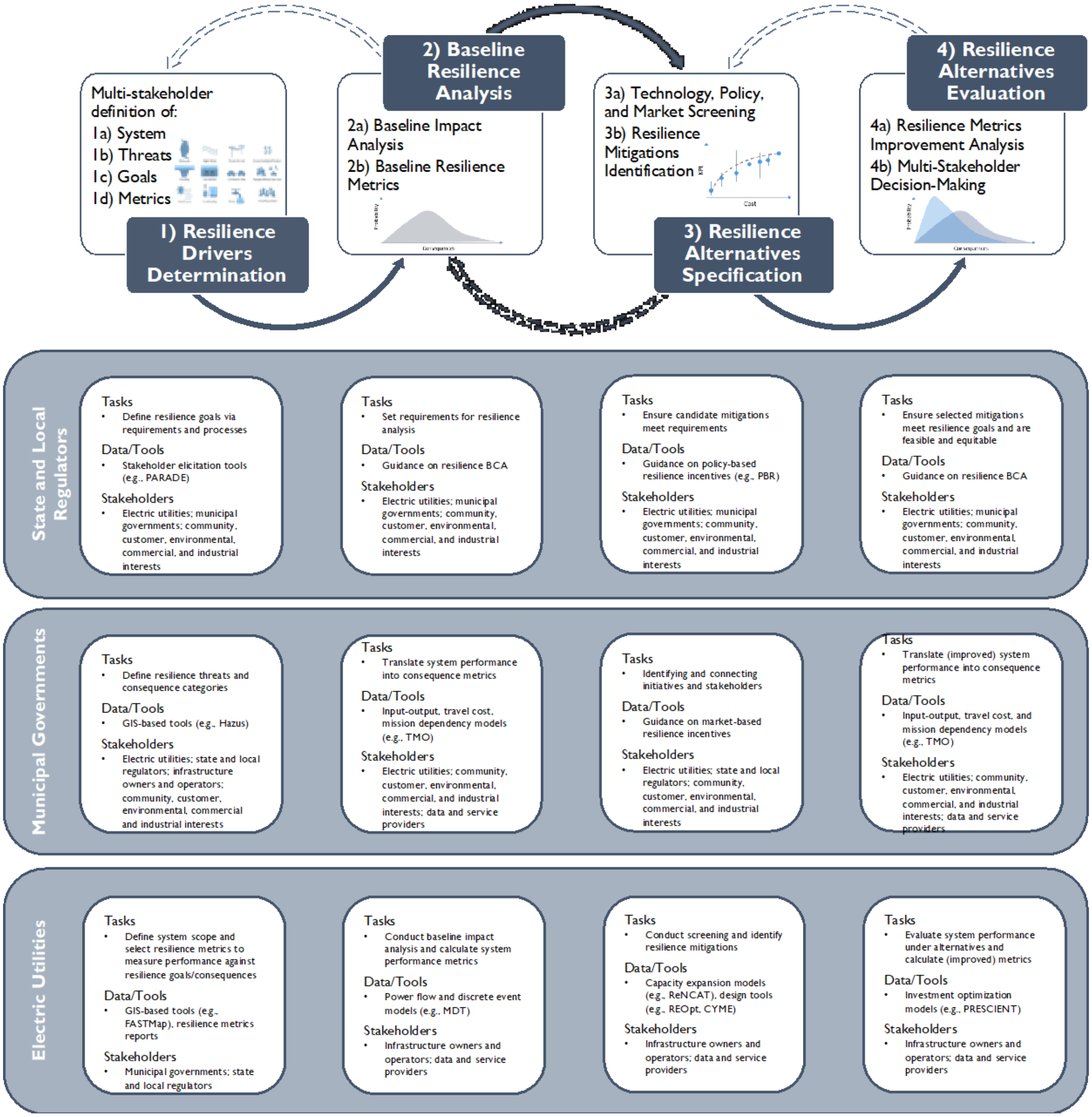


Figure 6: Resilient Community Design Framework Steps, Stakeholders, and Tools

A central feature of the Resilient Community Design Framework is the treatment of resilience planning for the electric power grid as a multi-stakeholder process, which requires coordination among electric utilities, local governments, and state and local regulators as well as engagement of a broad set of additional stakeholders, including community, customer, and environmental interests, infrastructure owners and operators (for both interdependent and enabling infrastructure), commercial and industrial interests (for both the electric power sector and supporting industries, such as insurance), and data and service providers (to provide resilience data and analysis as well as policy, market, and technology intelligence). Recognizing that resilience analysis may be computationally intensive and require the development of novel capabilities, each section also discusses existing data and tools that may support resilience analysis (for another survey of infrastructure resilience analysis tools, see [15]) as well as key analytical challenges. Finally, because the framework is designed to both inform resilience analysis given the current system state and to help identify and accelerate the transition to a more ideal future state, the following sections include metrics, tools, and mitigations spanning various maturity levels.

3.2.1. Step 1: Resilience Drivers Determination

The first step of the Resilient Community Design Framework is the resilience drivers determination, which consists of multi-stakeholder definition of the system, the threats to resilience, various stakeholders' resilience goals, and resilience metrics.

3.2.1.1. Step 1 Process

3.2.1.1.1. Define System Scope

A system scope can be defined by geographic or jurisdictional boundaries in addition to the infrastructures or sectors most important to the resilience planner. Attentiveness to the temporal scope is also important, particularly as it pertains to the selection of a planning horizon over which performance will be assessed or accrued. This sub-step should identify the specific planning processes that are common practice in the jurisdiction and the role of resilience therein. A non-exhaustive set of examples for system planning paradigms is summarized in Table 1. For example, a utility-led investment planning process—such as an integrated resource plan or distribution plan—may include resilience objectives alongside reliability, efficiency, and/or sustainability objectives.

Table 1: Example Planning Processes that May Include Resilience Objectives

Utility Led	City Led	Regulator Led
• Integrated Resource Plan • Integrated Distribution Plan • Integrated Grid Plan • Rate Case	• Sustainability Plan • Resilience Plan • Emergency Management Plan	• Rulemaking (e.g., Performance-Based Regulation) • Study

3.2.1.1.2. Prioritize Resilience Threats

Resilience is contextual. Systems that are resilient to hurricanes may not be resilient to cyber-attacks or earthquakes. Because resilience is contextual, the threats to the system's resilience should be specified and roughly prioritized. Alternatively, threat-agnostic approaches use a vague description of impacts to the system and plan around reducing consequences without specifying specific causes of those impacts. The threat-specific approach can be modified to include an "other/non-specified" threat, thereby merging threat-specific and threat-agnostic approaches.

Table 2 provides examples of potential threats, organized into three major categories: natural threats (e.g., hurricanes), intentional or accidental threats (e.g., cyberattack or human error, respectively), and structural threats (e.g., aging infrastructure). The Resilient Community Design Framework can incorporate a variety of resilience priorities and underlying threats, but it particularly focused on acute threats. As described in Section 1, chronic threats, which are higher probability but lower consequence, are being incorporated into electricity grid planning paradigms such as reliability and efficiency planning, as well as considered in the context of sustainability objectives (e.g., integrating decarbonization or water usage objectives into resource planning). Acute threats, which are lower consequence but have the potential for much higher consequences to society, have received less consideration in traditional planning processes and necessitate new analytical frameworks to account for both their distinctive spatial and temporal scopes and potential consequences to communities.

Once threats to the system are identified, a high-level prioritization should be accomplished to define which threats will be assessed in more detail within the planning process. Many jurisdictions have performed hazard vulnerability assessments that can be leveraged for this task [16]. Referencing the feedback process arrows in Figure 5, the hazard prioritization will become more mature in each subsequent iteration through the planning framework, as all stakeholders become more knowledgeable about the threat-specific risk posture of the grid.

Table 2: Threats for Electric Grid Resilience (compiled from [15])

Natural	Intentional/Accidental	Structural
• Hurricane • Geomagnetic Disturbance • Earthquake • Landslide • Tsunami • Tornado • Extreme temperature • Flooding • Wildfire • Drought	• Cyberattack • Electromagnetic Pulse Attack • Kinetic/physical attack • Human error	• Aging infrastructure • Economic/market shocks • Regulatory/policy changes • System complexity

3.2.1.1.3. Define Resilience Goals

The resilience goals defined as part of this sub-step should be as detailed as possible and attentive to the system's ability to prepare, withstand, respond, and/or recover to the threats identified in the previous step of the framework, as well as to the types of consequences that the planners intend to capture. For example, resilience goals may relate to decreasing the magnitude of a performance disruption below a level deemed unacceptable. Goals may also specify that the planner intends to focus on decreasing resilience-derived consequences to the economy, society, and/or national security [4]. In addition to defining resilience goals, this sub-step should encompass specification of the other goals relevant to the planning process in which resilience may be embedded. For example, goals related to sustainability may focus on decreasing greenhouse gas emissions while goals related to efficiency may focus on the affordability of energy services for different customers.

3.2.1.1.4. Select Resilience Metrics

The final sub-step is identifying metrics (e.g., critical load not served, recovery costs, access to community lifeline services, mission assurance) associated with the consequence categories (e.g., engineered system performance, economic, social, and national security) that correspond to the planning goals. Metrics for resilience can broadly be categorized as attribute-based or performance-based. Attribute-based metrics focus on identifying and quantifying system features or characteristics that are believed to improve performance (i.e., what makes the system more resilient?). Performance-based metrics focus on quantifying actual (or simulated) system performance during and following a disruption. [17]. Table 3 provides examples of attribute- and performance-based metrics for electric grid efficiency, sustainability, and resilience.

Table 3: Comparison of Attribute- and Performance-based Metrics for the Electric Power Grid

	Efficiency	Sustainability	Resilience
Attribute-based	• Number of efficient gens • Efficient water heaters deployed	• Renewable capacity • PV / battery recycling capacity	• kW on microgrids • Miles of hardened conductor
Performance-based	• Energy affordability • Total cost of service	• Absolute greenhouse gas emissions or emissions intensity • Total water usage	• kWh not served to critical customers during disruptions • Social burden due to lack of services

The Resilient Community Design Framework necessitates the use of performance-based metrics to compare system performance with and without a disruption (i.e., baseline resilience analysis) in Step 2 and to evaluate the impact of potential mitigations on performance (i.e., improvement analysis) in Step 3. Moreover, our research team concludes that selecting consequence-focused performance metrics, both for individual infrastructures such as the power grid and for multi-infrastructure analysis, can enable a more holistic accounting of the benefits of potential resilience investments, or inversely, the costs associated with disruptions. For example, a common performance-based resilience metric for the electric grid is the amount of energy unserved to customers during a disruptive event, but such a metric can be extended to capture the social (e.g., social burden), economic (e.g., gross production losses), or national security (e.g., performance of missions ensuring national security) consequences of these outages. Examples of resilience metrics by consequence category and level of maturity are provided in Table 4 below. The level of maturity differentiates those metrics that are accessible today but may be less able to fully represent the consequences of resilience from those that require additional development but will enable more accurate quantification of system resilience and associated consequences.

Table 4: Resilience Metrics for the Electric Power Grid

	System Performance	Economic Consequences	Societal Consequences	National Security Consequences
Higher Maturity ↓ Lower Maturity	• Energy not served (and derivatives thereof) • Quantity and duration of customer outages • Restoration efficiency	• Repair and recovery costs • Value of lost load (residential, commercial, industrial customer damage functions) • Business interruption costs	• Critical load not served • Quantity and duration of outages for critical services • Social burden to access critical services	• Quantity and duration of outages for critical services • Mission assurance

Developing these consequence-focused performance metrics for the electric power grid is an active area of research for Sandia and its partners [4, 15]. For example, the recently released "Resilience Metrics for Informing Decisions Associated with the Planning and Operation of the North American Energy System" report provides a detailed survey of metrics for the energy system, characterized by type (i.e., performance-based, attribute-based), spatial scope (i.e., asset, facility, infrastructure, multi-infrastructure), temporal scope (i.e., pre-event [prepare], during event [withstand], immediately post-event [respond/restore], post-event [recover]), threat (i.e., natural, manmade, systemic, threat-agnostic) and performance and consequence (system performance, economic, social, and national security) [4]. Similarly, the Sandia "Integrated Methodology for Energy and Infrastructure Resilience Analysis" report extends these performance-based metrics to other critical infrastructure sectors [15]. As part of the DRC project, Sandia and project partners published a new report on "Performance Metrics to Evaluate Utility Resilience Investments", which included the principles for well-designed performance metrics depicted in Table 5, and a white paper was developed describing a detailed methodology [18] for the social burden metric, which is visually depicted in Figure 7. The social burden metric quantifies the effort that society must expend to achieve a basic level of life-sustaining capability, as aligned with the human welfare-focused human capabilities framework of Sen [19] and Nussbaum [20].

Table 5: Principles for Well-Designed Performance Metrics (source: [Appendix B.3.2.])

Principles	Description
1. Tied to Performance Areas	Performance metrics should enable utilities to convey whether progress in performance areas is achieved.
2. Clearly Defined	There should be a description of and methodology for quantifying the performance metrics, including data definitions and formulas. Also, responsibility for measuring, calculating, reporting, and verifying the metrics and how often these tasks will be performed should be established.
3. Comparable	Performance metrics should have applicable baselines. Baselines are used on a going-forward basis for context, illuminate the level to which data fluctuates over time, and inform the extent to which the observed fluctuations are acceptable, or if changes are desired or necessary.
4. Readily Available	Performance metrics should be available, obtainable, and updatable without substantial difficulty. Readily available information includes data that is currently reported for compliance with existing industry standards. It also includes data that can be gathered without imposing new and/or excessive costs, technologies or methodologies, and administrative burdens on both utilities and regulators.
5. Objective	Performance metrics should address outcomes over which the utility has some degree of control. Exogenous factors often have an impact on the measurement of resilience. While controlling for all these factors may not be an option, stakeholders should make their best attempt to control for as many factors as possible and reasonable. This is especially important if the utility’s performance will be attached to financial rewards or penalties. Otherwise, the extent to which the utility’s actions brought about the result will not be clear, and proceedings to set incentives may be contentious.
6. Easily Interpreted	Performance metrics should be easy for stakeholders to understand and communicate to others. Naming conventions should be intuitive, calculations should be transparent, and definitions should be memorable.
7. Verifiable	Performance metrics should lend themselves to evaluation and verification wherever possible. Metrics that require costly studies or complex calculations or models to validate and update may not have value.

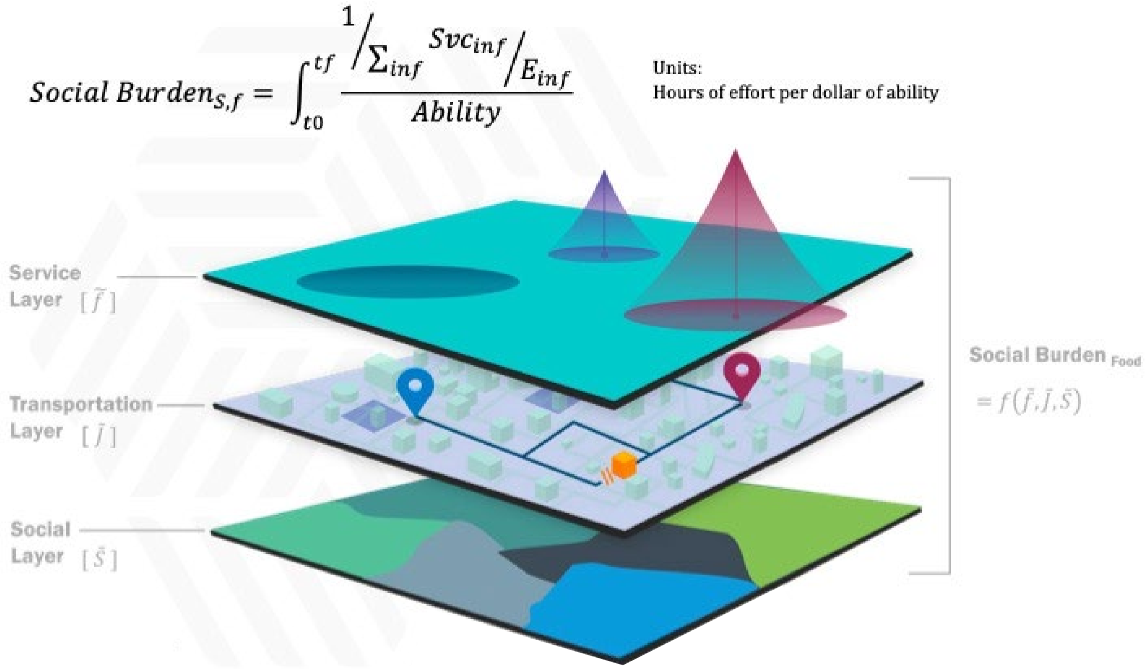


Figure 7: Social Burden Metric

3.2.1.2. Step 1 Stakeholders

The primary stakeholders for the first step of the framework are local governments, electric utilities, and state and local regulators. While defining resilience drivers is necessarily a multi-stakeholder process, regulators (and their political principals) will play a key role in establishing overarching resilience requirements as well as the contours of the planning processes in which resilience is embedded, which may in turn shape resilience goals. Local governments will define threats and consequences, potentially in consultation with citizens (e.g., via community, customer, and environmental interest groups), local businesses (e.g., via commercial and industrial interest groups), and infrastructure owners and operators for interdependent and enabling infrastructure (e.g., water providers). Utilities will define the system scope and translate resilience goals and consequences into decision-relevant performance metrics.

3.2.1.3. Step 1 Tools, Data, and Analytical Challenges

There are several GIS-based tools that can support system scoping, such as HAZUS, or the All Hazards Analysis framework [21]. Stakeholder elicitation methods—such as analytic hierarchy process, Delphi technique, multi-attribute utility theory, nominal group technique, risk assessment matrix, notice and comment processes—can enable multi-stakeholder identification and prioritization of resilience threats and goals. Threat characterization may be supported through myriad threat-specific tools and data sources, including those available for floods (e.g., Federal Emergency Management Agency (FEMA) FIRMs, hydrological modeling), earthquakes (e.g., United States Geological Survey (USGS) PGA estimates), landslides (e.g., USGS susceptibility), wildfires (e.g., FEMA/United States Forest Service (USFS) first data), cyber-attacks (e.g., event-based characterization), physical attacks (e.g., criticality and vulnerability estimates), and electromagnetic pulse/geomagnetic disturbance (EMP/GMD) (e.g., atmospheric modeling and electromagnetic coupling modeling). These tools, techniques, and data sources vary in their accessibility to the community energy resilience planning stakeholders identified in Figure 6.

Ongoing work, including the work at DOE national laboratories and with project partners, will support the identification of resilience metrics and the methodologies and data required to implement them. Nonetheless, performance-based consequence-focused resilience metrics are novel and will require ongoing development in terms of both data collection and methodology validation. Moreover, given the myriad interests and the salience and complexity of topics involved, a key challenge in this step is reaching consensus among stakeholders regarding the definition system scope, prioritization of goals, and selection of metrics.

3.2.2. Step 2: Baseline Resilience Analysis

The second step of the Resilient Community Design Framework is the baseline resilience analysis, which involves assessing potential disruptions from identified threats and the effects on system performance and the resulting consequences as represented by selected resilience metrics. Baseline resilience is assessed in a "business as usual" scenario assuming only current trends, policies, and investments are in place, which serves as a point of comparison for the subsequent framework steps.

3.2.2.1. Step 2 Process

3.2.2.1.1. Assess Baseline Impacts

This step begins with assessing the baseline infrastructure service impacts to the population, which entails using historical data combined with simulation models to forecast potential disruptions from identified threats and the resulting component, infrastructure, and multi-infrastructure impacts. As Figure 8 depicts, the baseline impacts can be represented as a probability distribution of potential consequences, with the tail of the distribution representing the lower probability but higher consequence impacts (or "tail risks"), such as long duration widespread power outages. In this step, the consequences are in the units of system performance—e.g., energy not served during the course of each disruption analyzed. Measuring and mitigating these extreme values is often the motivation for resilience analysis, as contrasted with reliability analysis that may focus on the higher probability but lower consequence impacts (e.g., shorter duration or less widespread power outages).

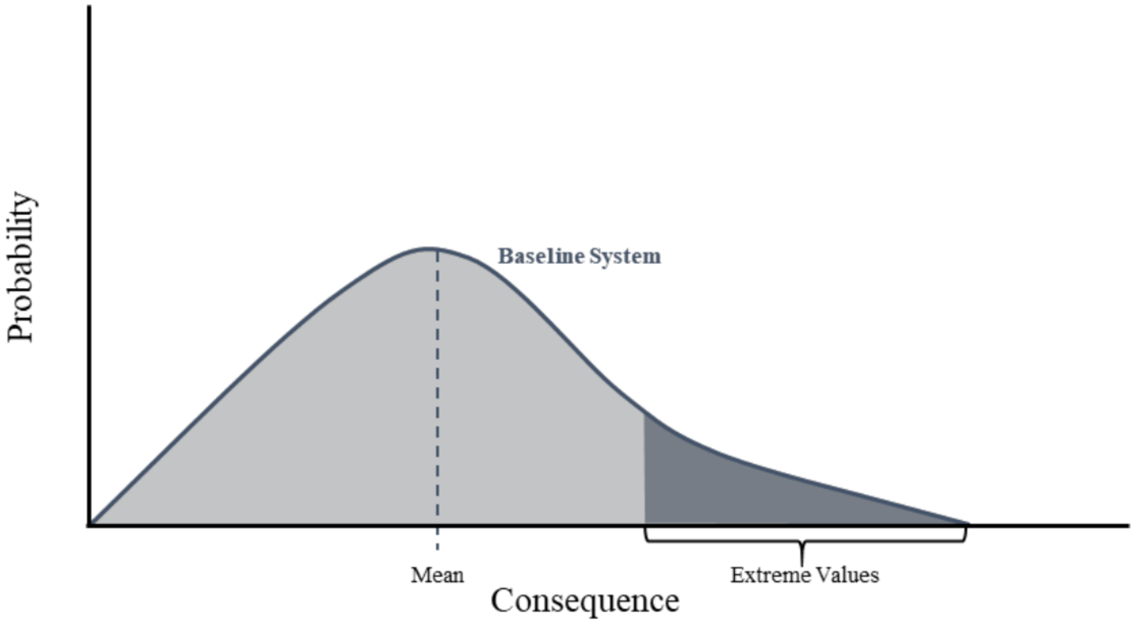


Figure 8: Representation of Baseline System Performance (source: [15])

3.2.2.1.2. Calculate Baseline Resilience Metrics

Having modeled the component, infrastructure, and multi-infrastructure impacts of potential disruptions, the baseline resilience metrics can be calculated. Consequence-focused resilience metrics translate degradation of infrastructure system performance into economic, social, and national security consequences. These baseline resilience metrics represent the system performance and resulting consequences from the disruptions without any mitigations such as new investments or policy changes.

3.2.2.2. Step 2 Stakeholders

The primary stakeholders involved in the second step of the framework are electric utilities, municipal governments, and state and local regulators. Regulators may set requirements for resilience analysis, stipulating the balance between the technical rigor and analytical burden. Electric utilities—potentially in consultation with interdependent and enabling infrastructure owners and operators—will conduct the baseline impact analysis, translating selected threats into system performance metrics. Local governments—in consultation with community, customer, and environmental interests and commercial and industrial interests—will translate these system performance metrics into more consequence-focused metrics based on the local situation. Depending on the primary stakeholders' resources and internal capabilities, data and service providers may also be engaged in this step.

3.2.2.3. Step 2 Tools, Data, and Analytical Challenges

Tools such as the FEMA HAZUS can support the translation of threats into potential disruptions [21]. Modeling component, infrastructure, and multi-infrastructure impacts can be achieved with Geographic Information System (GIS) fragility models and tools such as WNTR (as an example for potable water delivery systems [22]). These models can leverage utility outage data (e.g., Outage and Asset Management Systems) and the federally-curated EAGLE-I dataset [23]. Physics-based models may also be used for impact analysis.

Translating these disruptions into performance metrics for the grid (e.g., unserved load) may involve static and dynamic power flow models, discrete event models (e.g., the Microgrid Design Toolkit [24]), statistical models, and simplified/surrogate models. Although the preliminary focus of the framework is on the electric grid, this step may be expanded to interdependent infrastructures (e.g., natural gas, water, communications, wastewater, transportation, food and agriculture), which will necessitate additional tools.

Consequence-focused resilience performance metrics can be populated through various modeling approaches. For economic consequences, input-output modeling, computable general equilibrium, and macro-econometric models may be used, and existing economic value of service interruption models (e.g., ICE Calculator [25]) may be employed. For social consequences, need-based travel cost modeling may be employed, and/or existing measures of health impacts (e.g., quality-adjusted life years) may be extended. Promising new approaches to social consequence estimation such as the social burden approach are also emerging. Finally, for national security, mission dependency modeling and energy assurance for critical mission functions assessments (e.g., TMO [26]) may be employed.

There are several analytical challenges to overcome in the second step. For example, component-level impact is difficult to predict with high confidence for some threats. In addition, performance-based resilience metrics will be a new paradigm in many jurisdictions, adding complexity to the data gathering and planning processes. Moreover, there are relatively few models available for cross-infrastructure impact analysis. Capabilities to extend infrastructure performance to societal, economic, and national security consequences have experienced increased investment recently, yet still require validation and increased confidence through application and testing.

3.2.3. Step 3: Resilience Alternatives Specification

The third step of the Resilient Community Design Framework is the resilience alternatives specification, which involves identifying alternative technology investments, regulatory frameworks, and utility business models that may improve resilience and selecting candidate mitigations to be evaluated.

3.2.3.1. Step 3 Process

3.2.3.1.1. Screen Technology, Policy, and Market Conditions

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 over time. As jurisdictions evolve their application of the framework, non-investment alternatives such as alternative regulatory frameworks, can also be analyzed.

3.2.3.1.2. Select Resilience Mitigation(s) to Evaluate

Having completed this screening, the next step is to specify potential resilience mitigations, which consist of potential planning, operational, and policy actions that enhance the system's ability to prepare, withstand, respond, and/or recover. Examples of these potential resilience enhancements are depicted in Table 6. Planners may choose to select a single mitigation to evaluate, multiple mitigations to compare, or portfolios of mitigations to evaluate and/or compare.

Table 6: Potential Resilience Enhancements for the Electric Power Grid

	Technology and Infrastructure	Regulatory Mechanisms	Utility Business Models
Higher Maturity ↓ Lower Maturity	• Vegetation management • Replacement parts • Physical spacing and barriers • Grid hardening • Supplemental heating and hot water systems • Backup generation • Distributed energy resources • Physical security • Cyber security and system controls • Advanced metering infrastructure and controls • Transmission and distribution grid automation and controls • Microgrids and resilience nodes	• Integrating resource planning • Tariffs and programs to leverage private investment • Alternative lines of business for utilities • Enhanced cost recovery • Securitization • Performance-based regulation • Stress testing	• Microgrid-as-a-service • Resilience-as-a-service

Sandia expects the initial implementation of the framework will focus on technology and infrastructure investments, however, in future phases the framework may be designed to explore alternative regulatory mechanisms or utility business models to enhance resilience. Ongoing DRC work with project partners seeks to better understand these potential regulatory mechanisms and utility business models. As discussed further in Section 5, Sandia and project partner Synapse produced a report as part of the DRC project that identifies regulatory mechanisms to enable investments in electric grid resilience, which includes case studies of performance-based regulation in Hawaii, integrated planning in Puerto Rico, leveraging private investment and alternative lines of business for utilities in Vermont, enhanced cost recovery in New Jersey, and securitization in California. Similarly, and discussed in Section 5.8, Sandia and project partner Bosque Advisors produced a report exploring the use of stress testing to enhance grid resilience and sustainability, drawing on lessons learned from "regulating for resilience" in other sectors broadly and the application of stress testing to financial institutions specifically.

3.2.3.2. Step 3 Stakeholders

The primary stakeholders for the third step are electric utilities, local governments, and state and local regulators. Local governments play a key role in identifying and connecting initiatives as well as opening new opportunities. Electric utilities conduct technology, policy, and market screening and select potential resilience mitigations. State and local regulators ensure that designs address resilience goals. In addition, the screening and mitigations identification may be supported by engagement with policy, market, or technology data and service providers, interdependent and enabling infrastructure owners and operators, as well as community, customer, and environmental interests and commercial and industrial interests.

Coordination among these stakeholders will be essential to overcome potential misalignment between policy design and technology investment planning. Moreover, technology, policy, and market issues can overlap and influence each other in unexpected ways, so determining the optimal number of portfolios to explore the problem space at the needed level of complexity is not trivial.

3.2.3.3. Step 3 Tools, Data, and Analytical Challenges

As described above, the envisioned initial application of the framework will focus on technology-based mitigations. There are various capacity expansion modeling tools that can support technology screening for the distribution (e.g., ReNCAT [27], LPNORM [28]) and transmission (e.g., ReEDS [29]) systems. In addition, there are myriad tools that can support the identification of resilience mitigations, including high-level initial design tools (e.g., MDT [30], DER-CAM [31], REOpt [32]) and tools to support down-selection for operational feasibility at the component (e.g., Simscape Electrical [33], LabView [34], Xyce [35]), distribution (e.g., CYME [36], OpenDSS [37], GridLab-D [38]), and transmission (e.g., PSS/E [39], PSLF [40], PowerWorld [41]) levels.

3.2.4. Step 4: Resilience Alternatives Evaluation

The fourth and final step of the Resilient Community Design Framework is the resilience alternatives evaluation, which consists of assessing the effects of selected mitigations (from Step 3) on system performance and calculating resilience metrics. These resilience metrics can then be used to co-optimize or analyze tradeoffs among candidate mitigation portfolios including additional performance dimensions such as affordability or sustainability if those dimensions were selected in Step 1.

3.2.4.1. Step 4 Process

3.2.4.1.1. Evaluate Improvements in Resilience Metrics with Mitigation(s)

Improvements in resilience metrics are evaluated by calculating consequence-focused performance metrics (repeating Step 2) with mitigations (identified in Step 3). The same tools and approaches used in Step 2 would apply in this step as well. As depicted in Figure 9, comparing the baseline and improved system performance enables users to analyze how alternative mitigations affect both the mean and extreme values. Often, the goal of resilience analysis is to "crush the tail"—in other words, to reduce the probability of the highest consequence disruptions—while shifting the overall probability distribution to the left. The additional step of translating these changes in system performance associated with a given mitigations into consequence metrics enables users to quantify the benefit streams associated with various mitigations.

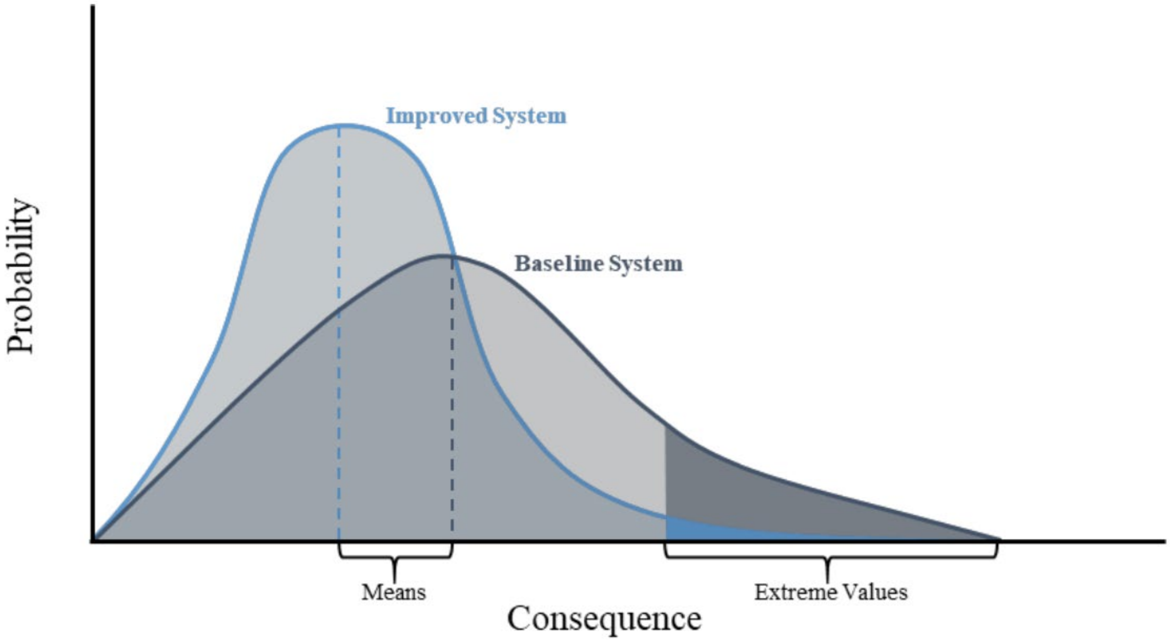


Figure 9: Representation of Improved System Performance (source: [15])

3.2.4.1.2. Optimize Resilience Investment Portfolio

Recognizing that there might be multiple stakeholders and multiple metrics involved, final selection may involve renegotiating weights for various resilience metrics with relevant stakeholders and prioritizing investment portfolios through multi-dimensional optimization. This sub-step may require additional tools and approaches beyond those used in Step 2.

3.2.4.2. Step 4 Stakeholders

The primary stakeholders involved in the fourth step are electric utilities, municipal governments, and state and local regulators. Electric utilities—potentially in consultation with interdependent and enabling infrastructure owners and operators—will evaluate performance under resilience alternatives, translating selected threats and mitigations into (improved) system performance metrics. Municipal governments—in consultation with community, customer, and environmental interests and commercial and industrial interests—will reevaluate consequences given resilience alternatives, translating the (improved) system performance metrics into (improved) consequence-focused metrics. Regulators will ensure that the final portfolio of mitigations meet resilience goals and are both feasible and equitable. Key challenges for this step involve the fact that resilience benefit streams are generally not internalized explicitly in current planning and policy processes, thus explicitly quantifying and allocating benefits represents a new paradigm for participants. In addition, final investment selection can appear opaque to communities, especially when quantifiable metrics and approaches are either not used or not well-understood, as such, interaction with affected stakeholders is essential to create shared understanding and collective support of outcomes

3.2.4.3. Step 4 Tools, Data, and Analytical Challenges

The same data and tools used in Step 2 may be employed in Step 4 to compare baseline system performance to system performance with candidate mitigations. In addition, economic analysis tools may be used to inform the choice among candidate mitigations. For resilience metrics that can be readily monetized (i.e., translated into dollars), benefit-cost analysis (BCA) provides a systematic framework to determine whether the benefits of candidate mitigations exceed the costs. For resilience metrics that cannot be readily monetized, cost effectiveness analysis provides a systematic framework to determine the most cost-effective mitigation(s) to achieve a given level of benefit (e.g., improved system resilience). Sandia and project partner Synapse produced a comprehensive guide to economic analysis of resilience costs and benefits which may support this step, including the guiding principles depicted in Table 7. In addition, tools such as ReNCAT [27], LPNORM [28], and PRESCIENT [42] may support optimization across investment portfolios. Finally, there are technical challenges associated with incorporating consequence-based resilience metrics into multi-objective investment optimization, especially as it relates to the size of the optimization problem becoming unwieldy for existing computational resources. Approaches that use multi-criteria decision analysis techniques as mentioned in Step 1 may eliminate the need to perform detailed performance-based co-optimization for some stakeholders

Table 7: Principles for Benefit Cost Analysis and Implications for Resilience (source: [Appendix B.2.3])

Principle	Description	Implications for Resilience
Treat Utility Resources Consistently	All utility resources should be compared using consistent methods and assumptions to avoid bias across resource investment decisions.	All resilience investment options should be evaluated using BCA.
Align with Policy Goals	Jurisdictions invest in or support energy resources to meet a variety of goals and objectives. The jurisdiction-specific BCA test should therefore reflect this intent by accounting for the jurisdiction's applicable policy goals and objectives.	If resilience is a policy goal, resilience costs and benefits should be captured.
Ensure Symmetry	Asymmetrical treatment of benefits and costs associated with a resource can lead to a biased assessment of the resource. To avoid such bias, benefits and costs should be treated symmetrically for any given type of impact.	If resilience costs are included, resilience benefits should be as well.
Account for Relevant Impacts	BCA tests should include all relevant impacts including those that are difficult to quantify or monetize.	Some resilience benefits may be hard to quantify but they should not be ignored or given no value.

Principle	Description	Implications for Resilience
Conduct Forward-Looking, Long-Term, Incremental Analyses	BCA should be forward-looking, long-term,25 and incremental to what would have occurred absent the investment. This helps ensure that the investment in question is properly compared with alternatives. The analysis should consider the entire lifetime of the investment so it can capture the full costs and benefits associated with the solutions under consideration.	The benefits of resilience investments may not be experienced frequently or soon.
Avoid Double-Counting Impacts	BCA present a risk of double-counting benefits and/or costs. All impacts should therefore be clearly defined and valued to avoid double- counting.	The delineation by perspective can help avoid counting the same impact twice.
Ensure Transparency	Transparency helps ensure engagement and trust in the BCA process and decisions. BCA practices should therefore be transparent, where all relevant assumptions, methodologies, and results are clearly documented and available for stakeholder review and input.	Resilience costs and benefits should be clearly named and defined.
Conduct BCAs Separately from Rate and Bill Impact Analyses	BCA answer fundamentally different questions than rate and bill impact analyses, and therefore should be conducted separately from the rate and bill impact analysis.	As the cost of some resilience investments may be high, rate and bill impacts are an important, but separate consideration.

3.3. Framework Iteration and Implementation

Although the framework steps are discussed sequentially in this section, there are opportunities for further exploration of feedback among them and iteration as technology, policy, and market conditions evolve. For example, as depicted by the dashed arrows in Figure 6, there may be a feedback loop between the policy or market screening and the identification of metrics. In addition to these feedbacks within the process, Sandia envisages the implementation of the framework will be iterative. For example, as depicted in Figure 10, the first implementation may focus on technology investments as resilience mitigations, but as policy or market conditions evolve, the second implementation may focus more on potential regulatory frameworks or utility business models. Opportunities for future application of the framework drawing on lessons learned from DRC project analyses of technology, policy, and market dynamics for resilience are discussed in Section 5.

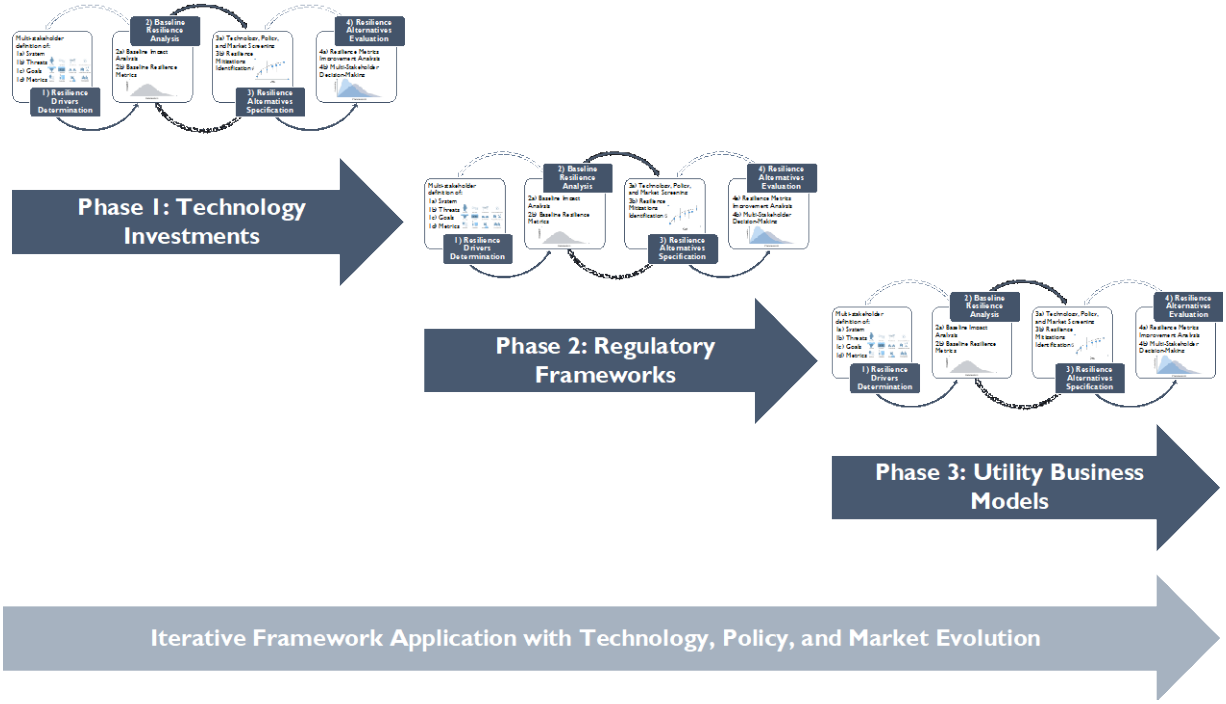


Figure 10: Iterative Application of Resilient Community Design Framework

4. TASK 2: IMPLEMENTATION AND VALIDATION OF THE RESILIENT COMMUNITY DESIGN FRAMEWORK

The DRC project implemented and validated the Resilient Community Design Framework via two application cases: the first application case was in San Antonio, Texas and the second was in El Caño Martín Peña communities in Puerto Rico. In San Antonio, Sandia worked with the municipal government and the utility, CPS Energy, to conduct analysis resulting in microgrid siting and sizing to provide community resilience in a future with high electric vehicle penetration. In Puerto Rico, Sandia and project partners worked with the El Caño Martín Peña communities to conduct a conceptual design of "resilience nodes" for co-optimal blue and black-sky performance with a goal of improving community outcomes.

Through these application cases and related research, the DRC project also significantly improved consequence-focused resilience metrics and associated approaches. Rather than using metrics such as hours-not-served as a proxy for community impacts, the team developed a methodology for quantifying and evaluating the *consequences* of unserved load for the people in the affected system via the social burden metric. These application cases and related research established tighter connection between theory, data collection, and modeling for consequence-based resilience metrics. The Resilient Community Design Framework provides standard approach to operationalize these metrics in planning processes, and in turn to more fully understand and therefore better predict and evaluate the value of resilience for people within a community; including diverse people in diverse communities where not everyone experiences disruptions the same way.

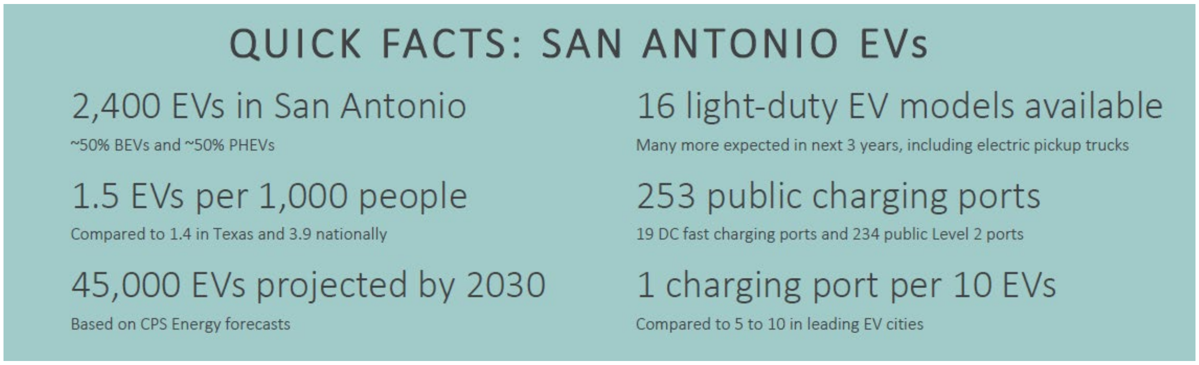
4.1. CPS Energy & City of San Antonio, San Antonio, TX

The City of San Antonio (CoSA) is the seventh largest city in the U.S. spanning over 465 square miles with 1.5 million residents [43]. CPS Energy, the electric utility for the CoSA and portions of surrounding counties, is the nation's fifth largest municipal electric utility with over 830,000 customers served [44]. Early in the DRC project, Sandia partnered with CPS Energy and the CoSA to demonstrate the application of the Resilient Community Design Framework for a city-utility pair. CPS Energy's status as a municipal utility gives it unique advantages that may allow it to efficiently justify investments that demonstrably benefit community resilience. Namely, because CPS Energy is municipally owned, it is regulated by a Board of Trustees who are elected by the San Antonio City Council. This structure gives CPS Energy a natural and direct connection to the goals and needs of city government. Nationwide, municipal utilities and cooperative utilities may be the first adopters of the DRC consequence-focused resilience planning paradigm for this reason.

Early conversations with CPS Energy and the CoSA focused on existing mechanisms for grid resilience investment planning and community resilience planning. Three city offices provided direction and feedback in scoping the analysis: the Office of Sustainability, the Office of Emergency Management, and the Office of Equity. The CoSA has established a joint Climate Adaptation and Mitigation plan called SA Climate Ready [45]. This plan establishes a strategy to prepare citizens for the impacts of climate change, including investment in infrastructure resilience. Improving social equity is also a major component of the plan. Across the CoSA offices engaged in the DRC project, all were supportive of a more quantifiable link between grid resilience and community resilience. CPS Energy, as well, was supportive of this approach. However, grid investment planning involves a complex set of roles at any electric utility. No single group or planning process at CPS Energy is responsible for community-focused resilience investment planning[2].

To support evolving efforts at CPS Energy focused on improving grid and community resilience, the DRC project focused on piloting a valuation approach at a smaller scale that could be extended in the future. The goal was to showcase distribution system investments for a small region of the CoSA that could be demonstrably linked to improvements in a community resilience metric. Discussions with all stakeholders focused on types of investments that might realistically be made in the next five years. Through these discussions, a focus on electric vehicle (EV) infrastructure and Electric Vehicle Fast Chargers (EVFCs) emerged.

Partially catalyzed by the 2018 Volkswagen settlement [46], the CoSA and CPS Energy are undergoing a major planning initiative to support EV infrastructure, both for city fleet and private vehicles. As outlined in a study [47] commissioned by the CoSA Office of Sustainability, city-wide conversion of the transportation fleet from gas to electric is a goal shared by CoSA and CPS Energy. High-level facts summarizing existing EV conditions in CoSA are shown in Figure 11. Stakeholders seek to increase adoption rates and facilitate fleet conversion as optimally as possible. Supporting the siting of DC Fast Chargers (DCFCs) is one of the primary mechanisms to do so. This presents a host of challenges and opportunities in infrastructure planning. Until engagement with the DRC project, neither CoSA nor CPS Energy were quantifiably incorporating resilience into EV planning. Discussions with the stakeholders centered around whether the siting and sizing of DCFCs might change if equitable improvement in community resilience were an additional objective, and whether additional investments in the grid such as microgrids could be co-located with DCFCs to further augment community resilience cost-effectively. Sandia, CoSA and CPS leveraged the Resilient Community Design Framework, defined in Section 3, to demonstrate how EV infrastructure and distribution grid infrastructure planning could incorporate these concepts.



QUICK FACTS: SAN ANTONIO EVs

2,400 EVs in San Antonio
~50% BEVs and ~50% PHEVs

16 light-duty EV models available
Many more expected in next 3 years, including electric pickup trucks

1.5 EVs per 1,000 people
Compared to 1.4 in Texas and 3.9 nationally

253 public charging ports
19 DC fast charging ports and 234 public Level 2 ports

45,000 EVs projected by 2030
Based on CPS Energy forecasts

1 charging port per 10 EVs
Compared to 5 to 10 in leading EV cities

Figure 11: Electric vehicle statistics as of 2019 for battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) in the City of San Antonio [47]

The shared goal of the CoSA and CPS Energy to accelerate adoption of EVs is partly dependent on developing the EV charging infrastructure so that it is at least as accessible, reliable, and convenient as gasoline fueling. However, a simple one-to-one conversion from gasoline stations to electric charging stations would ignore the important differences between EVs and fossil-fueled vehicles. Broadly, a sound analysis requires evaluating the ancillary benefits that come with charge site

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[2] Winter Storm Uri caused extreme consequence to CoSA residents and CPS Energy customers in February 2021. This was toward the end of the DRC analysis' timeline, and data from the event did not influence the results. Since that time, CPS Energy has increased its focus on resilience planning. In their recent rate case with the Board of Trustees, CPS Energy highlighted weatherization and infrastructure resilience as priority investment areas that will be supported by the 3.85% rate increase [70].

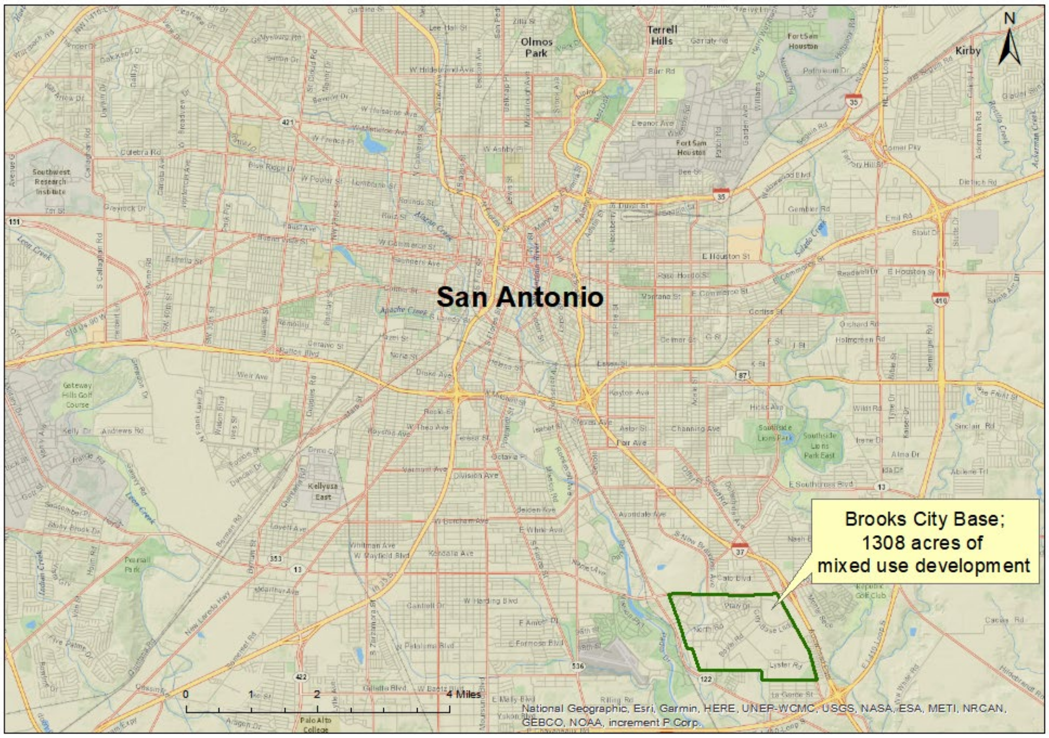
investments and associated back-up generation. It considers not just "blue sky" benefits, defined as those that improve performance during normal conditions, but also "black sky" benefits, defined as improvements in performance during more extreme or off-nominal conditions. For example, planning for improved grid performance subject to extreme storm conditions should consider the availability and accessibility of grid, transportation, and community resources during those conditions. Incorporating as much information as possible about likely threat conditions is a cornerstone of the Resilient Community Design Framework.

Resilience events, in this analysis, are defined as low-probability, high-consequence events that are commonly not fully addressed under traditional power system reliability-focused planning. Examples might include massive wildfires, cyber-attacks, or crippling winter storms that exceed design standards. Sandia's goal for this case study was to validate the framework and show its applicability in enabling communities to improve resilience through deliberate EV infrastructure siting.

The process followed the Resilient Community Design Framework as detailed in the following subsections. The process was started by gathering information about the system including electric feeder data and locations for service-providing facilities. Then an estimate was made of future conditions based on the design year 2040. An analysis was then performed to generate a design basis threat (DBT) and estimate its impact on the system, including impact on both EV infrastructure needs as well as the grid. Any site is typically subject to manmade and natural potential threats. A resilience analysis can be done as threat-agnostic, but in this case, to evaluate specific characteristics of the system, the work is threat-specific. The DBT is simply the term used to describe the threat(s) deemed to be the basis of design and analysis. Using simulation models and the Resilience Node Cluster Analysis Tool (ReNCAT) [18], an evaluation was made of the resilience benefit of co-locating chargers at a variety of critical infrastructure sites where microgrids might be installed to mitigate loss and suffering due to the design basis event and resulting concurrent power outage. ReNCAT uses a genetic algorithm to analyze the distribution system and determine which of these to power via microgrids during a grid outage to minimize social burden (see Figure 7) at least cost. ReNCAT analyzes feeders by sub-section, isolated by existing and potential/theoretical switch locations, where each section may contain both critical and non-critical loads. ReNCAT evaluates the total improvement to social burden for each alternative and compares against the corresponding capital cost. Analysts can then look at each solution produced by ReNCAT and evaluate the microgrid cost-to-value tradeoffs. A detailed snapshot of these tradeoffs is included in B.1.

4.1.1. CoSA Resilience Drivers Determination

Brooks City Base (Brooks), Figure 12, was identified as an ideal study site within San Antonio. Brooks is a new development area on the site of a former Air Force Base [48] that was realigned as part of the Base Realignment and Closure (BRAC) program. It is a 1,308-acre mixed-use community with goals for innovative development. The site hosts residential, commercial, and industrial facilities that together provide an ideal sample set to evaluate the framework and methodology used to assess resilience potential associated with EV infrastructure expansion.



Brooks City Base; 1308 acres of mixed use development

National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Figure 12: Brooks City Base located in southeast San Antonio

A base model was developed using GIS to collect, tabulate, and evaluate the electric distribution system from the substation and all relevant service facilities (e.g., hospitals, groceries, hotels, etc.) as depicted in Figure 13. Brooks has four major feeders that service a range of customer types. Information was gathered with CPS Energy and the CoSA to determine the demand on each feeder sub-section, the types of service-providing buildings in the area, and the service capacity of these buildings (e.g., large vs. small grocery stores). Details about the resident population were collected primarily from U.S. Census data[3]. Exclusion zones were identified using FEMA floodplain mapping. Exclusions zones are defined as areas excluded from potential microgrid siting locations due to acute local hazard-prone characteristics.

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[3] https://www.census.gov/data/datasets.html

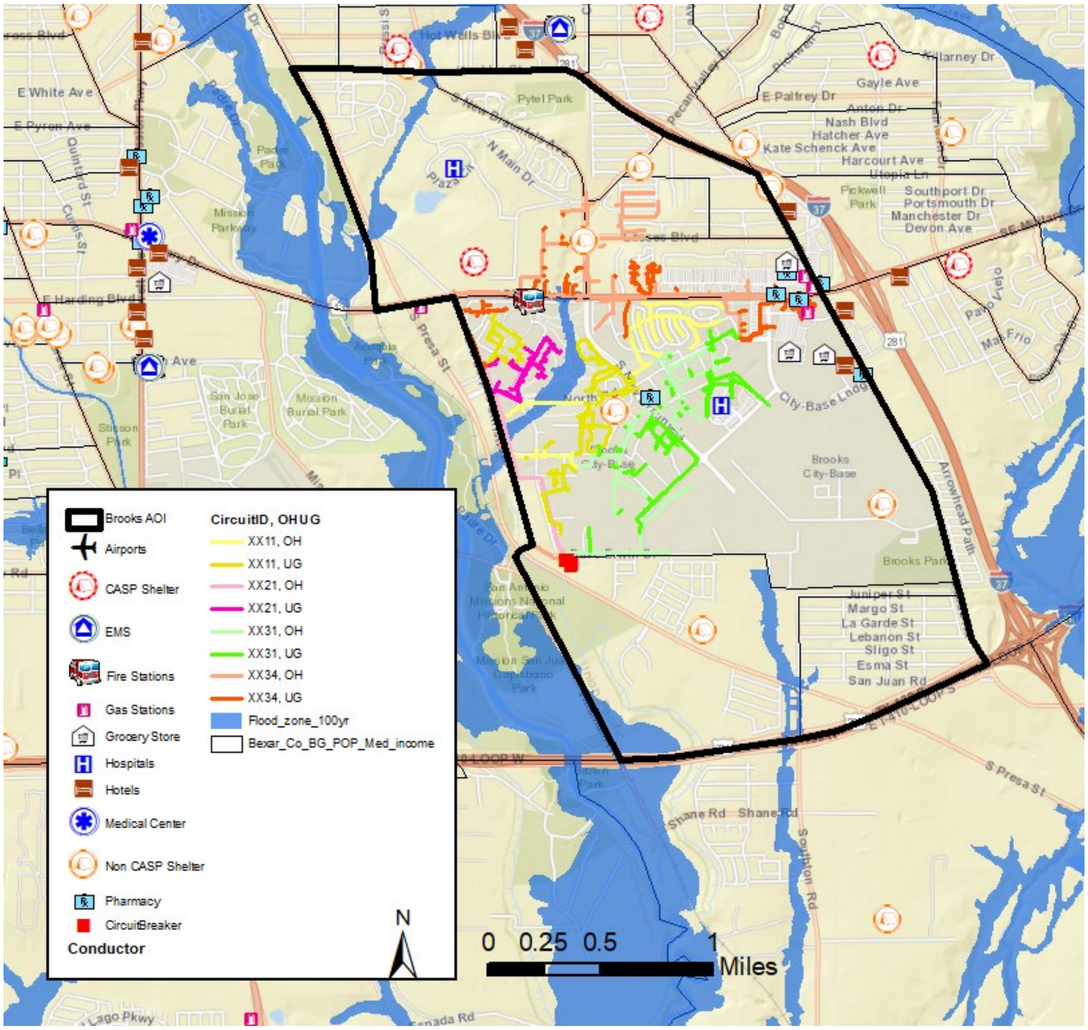

Figure 13: Area of interest boundary around Brooks with feeder data and critical infrastructure

Having collected the necessary information about the design site, the CoSA Office of Sustainability together with CoSA Emergency Management personnel and CPS Energy subject matter experts supported discussion around DBT determination, opportunities for infrastructure investment, and leveraging the analysis to evaluate trade-offs. Having the existing conditions clearly determined, it was possible to quantify and assess the impacts of alternative microgrid investment portfolios.

Sandia facilitated multiple conversations over several months to evaluate the impacts and consequences to viable threats, ultimately defining a single threat scenario around which to develop a resilience analysis. This DBT describes the threat scenario that results in a disruption to system performance. The project team worked through a range of extreme event scenarios, ultimately selecting a major storm event concurrent with a 14-day power outage. In the design scenario, a hurricane in the Gulf of Mexico forces neighboring coastal communities to evacuate inland toward San Antonio. A percentage of these evacuees seek refuge in Brooks. Based on historic averages, expected travel patterns, and the sheltering capacity of Brooks, the estimated number of evacuees arriving in the area is 2,000. The resident (baseline) population is projected to be 4,500 in the design year 2040. A subset of these people will drive EVs [49]. Estimates for the number of EVs in the system were developed based on observed adoption rates [47]. These percentages were used to approximate the number of EVs in Brooks (either BEV, or PHEV). Both types require periodic charging and, though different in terms of range and demand, are combined in the model as one set of charge-seeking vehicles.

4.1.2. *CoSA Baseline Resilience Analysis*

After establishing the DBT and existing conditions for the study area, a discrete-event simulation representing EV charge patterns was built to estimate the added wait time resulting from a sudden increase in the population as evacuees enter the system. Figure 14 shows the FlexSim[4] model logic and output that was generated using the evacuation scenario developed earlier in the framework. It was assumed that a total of 200 EVs (146 Residents, 54 Evacuees) need charging infrastructure. This value is simply a first pass estimate, a quantity that begins to reveal impacts to the system during a disruption. The model is scalable. The simulation spanned 14 days, running 2000 Trials for each scenario (3, 5 and 10 EVFCs). Based on expected 2040 technology [50], EV range estimates were as follows: each vehicle can conservatively travel 230 miles with a full charge. Charge rates were assumed to be: 10 minutes from 0-50%; another 18 minutes from 50-80%; 30 minutes to complete the charge from 80-100%. It was assumed that 40% of daily miles are driven 6-9am, 20% driven between 9am and 4pm and 40% between 4 and 9pm. This makes it possible to identify the number of EVFCs needed during the DBT that results in reasonable wait time without installing so many that EVFCs sit unused a disproportionate amount of the time. The estimated optimal number for this configuration was five EVFCs. As indicated in Figure 14, providing three EVFCs in this scenario would result in extremely long wait times for the first two days of disruption, while any more than five EVFCs reaches a point of diminishing returns.

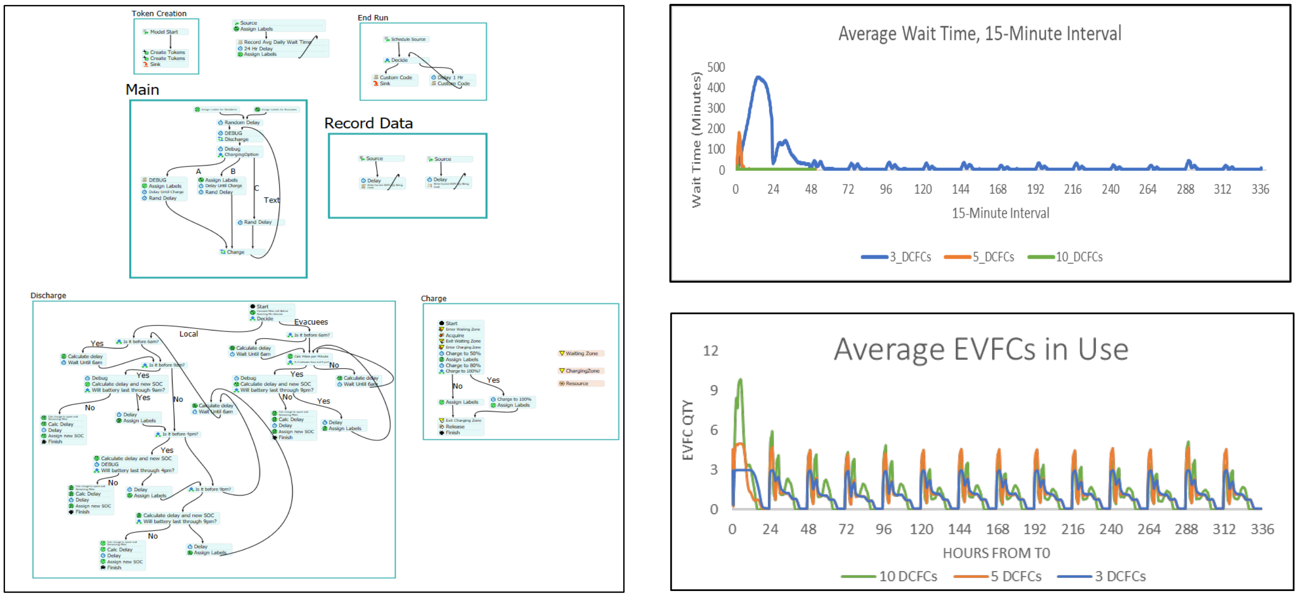

Figure 14: FlexSim modelling process and logic; wait times and average utility of EV chargers based on number of chargers available

ReNCAT inputs commonly include grid topology data, various cost information, existing and candidate switch locations (enabling isolation for microgrids), and information about the size, capability, and type of critical service-providing assets in the study region. For this analysis, a new feature was added to ReNCAT that incorporates EV queuing times dependent on the number of

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[4] Commercial off-the-shelf (COTS) Discrete-Event Simulation software. https://www.flexsim.com/

EVFCs supported by microgrids or other backup power technologies. This allowed the modeling team to provide a clearer understanding of the EV charging impact to social burden.

4.1.3. CoSA Resilience Alternatives Specification and Evaluation

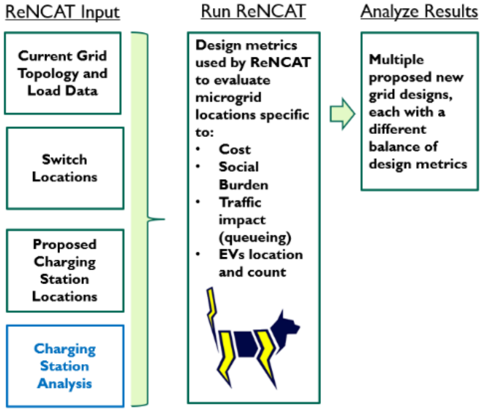
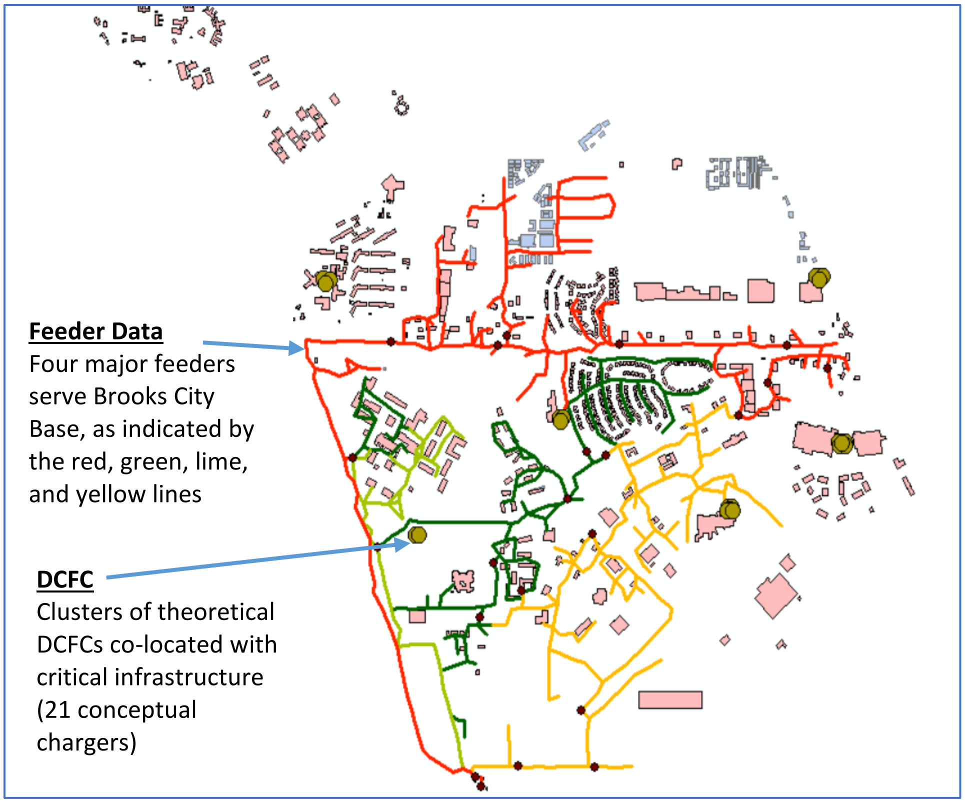


Figure 15: ReNCAT inputs, calculation, and results

Using the information gathered in the earlier phases of the framework, inputs were formatted for ReNCAT as detailed in Figure 15. The EV charging infrastructure queuing model established a tradeoff curve between average wait time and the number of EVFCs online in the study area. Using this information, ReNCAT supports determination of the siting and the number of EVFCs that should be supported by resilient power investments across the study area. Additionally, ReNCAT can reflect the social burden benefit of co-locating EVFCs with other service-providing facilities on microgrids. As defined in Figure 7, the social burden enables a quantitative assessment of a specific community's *ability* to access basic needs and the associated *effort* required. Qualitatively, it is straightforward to understand that installing EV charging stations near other service-providing facilities is more socially efficient during disaster conditions than installing them in remote locations. Within this project, the goal was to quantitatively determine where co-location with other services is most advantageous in a manner useful for cost-benefit analysis. There are two quantifiable components of the link between microgrid siting and social resilience benefits. First, clustering facilities in a microgrid enables more effective use of backup power resources and minimizes the distribution infrastructure that would need to be hardened for this social benefit. Second, people derive advantages from co-locating resources in emergency situations because it minimizes their need to travel in order to meet their needs and obtain services. If several services are available in one location supported by a microgrid, the uncertainty of where to go is minimized, which should significantly decrease time spent acquiring basic needs and services, minimizing social burden and overall stress. However, even for a study area as small as Brooks, optimizing co-siting of EVFCs and critical infrastructure-serving microgrids is challenging due to dimensionality. The problem breaks down to choosing how to support approximately five EVFCs among 21 potential locations, compounded with 25 feeder sub-sections and nearly 60 critical infrastructure assets.

Twenty-one possible EV chargers were identified across five qualifying locations (Figure 16). Recall that only five EVFCs are necessary to acceptably limit charging wait times during a power outage. ReNCAT is able to consider which of the optional 21 chargers would best decrease wait times and how co-locating these chargers with service-providing facilities could enable an overall reduction in social burden. This allowed optimization of social burden versus cost to identify microgrid locations that would minimize queueing for EV charging and would benefit other facilities on the same feeder; aggregating the social burden across all services including EV charging.



Feeder Data
Four major feeders serve Brooks City Base, as indicated by the red, green, lime, and yellow lines

DCFC
Clusters of theoretical DCFCs co-located with critical infrastructure (21 conceptual chargers)

Figure 16: GIS model of Brooks feeders and facilities, including proposed DCFC locations

The results of the analysis are summarized in the Pareto-optimized frontier graph shown in Figure 17. Each portfolio computed by the model includes number of microgrids, location of microgrids, cost for entire portfolio, list of infrastructure being powered, name plate generation capacity, social burden score, and the switching configuration necessary to achieve islanded status. Along the Pareto frontier, microgrid configurations of varying size are used to "buy down" social burden. This provides an objective approach to making decisions about EV charging infrastructure location as a function of a larger set of critical assets.

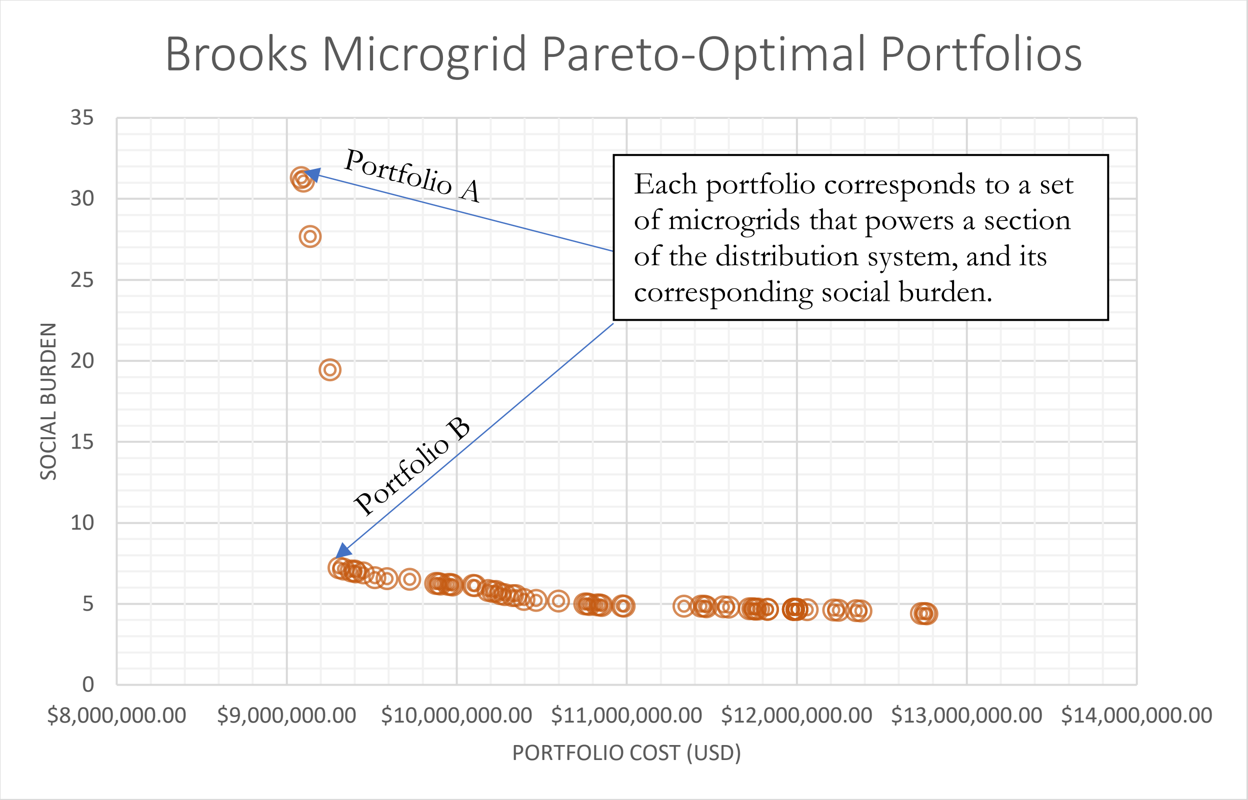
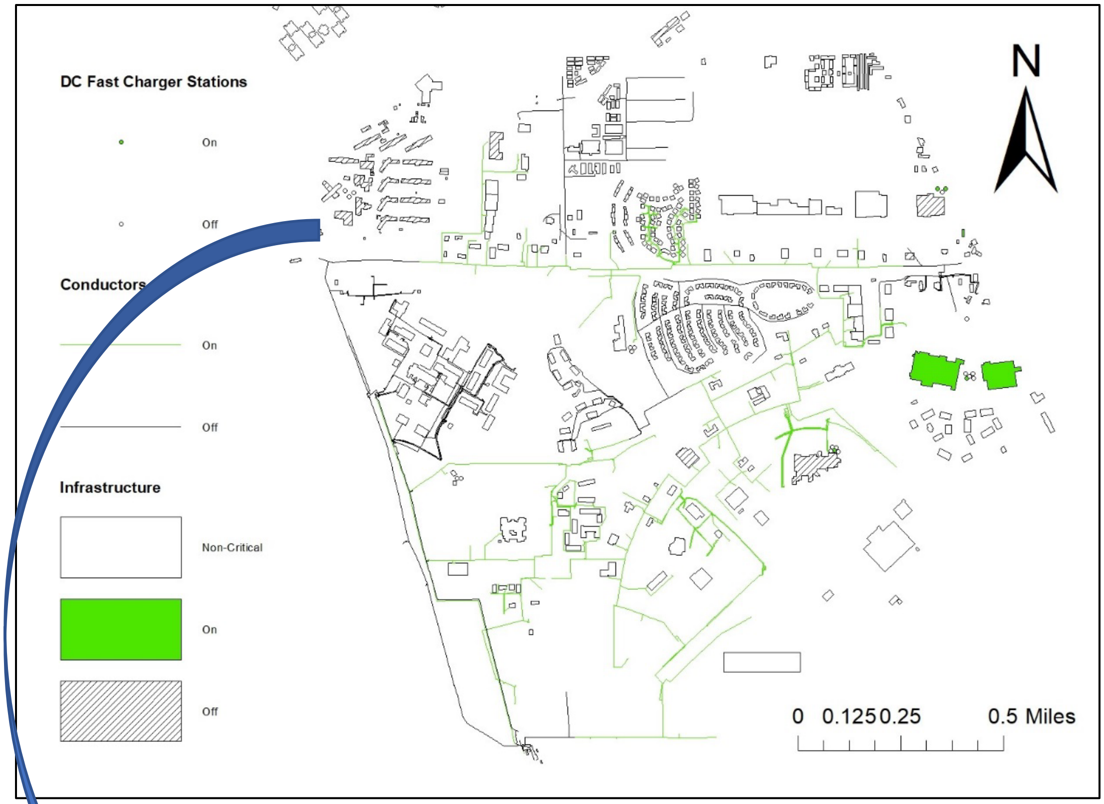


Figure 17: Pareto-optimized portfolios for Brooks showing social burden reduction as a function of energy resilience investment. Portfolio A and B are detailed below.

Evaluating public EV infrastructure as part of the overall system that provides basic needs and services during disruptions enables a holistic assessment of how microgrids can support overall community resilience. Analysts can explore the Pareto frontier and quickly assess where return on investment starts to diminish in terms of further reduction of social burden. As shown in Figure 18 and Figure 19, the configuration difference between Portfolio A and Portfolio B is primarily gained by adding the facilities in the northwest quadrant of Brooks, including one additional EVFC. Investing in the incremental expansion of microgrid infrastructure defined by Portfolios A and B benefits the entire area, but not equally. As shown in Figure 19, the census block group in the northwest quadrant, which, not coincidentally is the population group with the lowest average income, stands to see the greatest reduction in social burden between Portfolios A and B.

Portfolio A



Portfolio B

Figure 18: Additional powered facilities selected to lower social burden

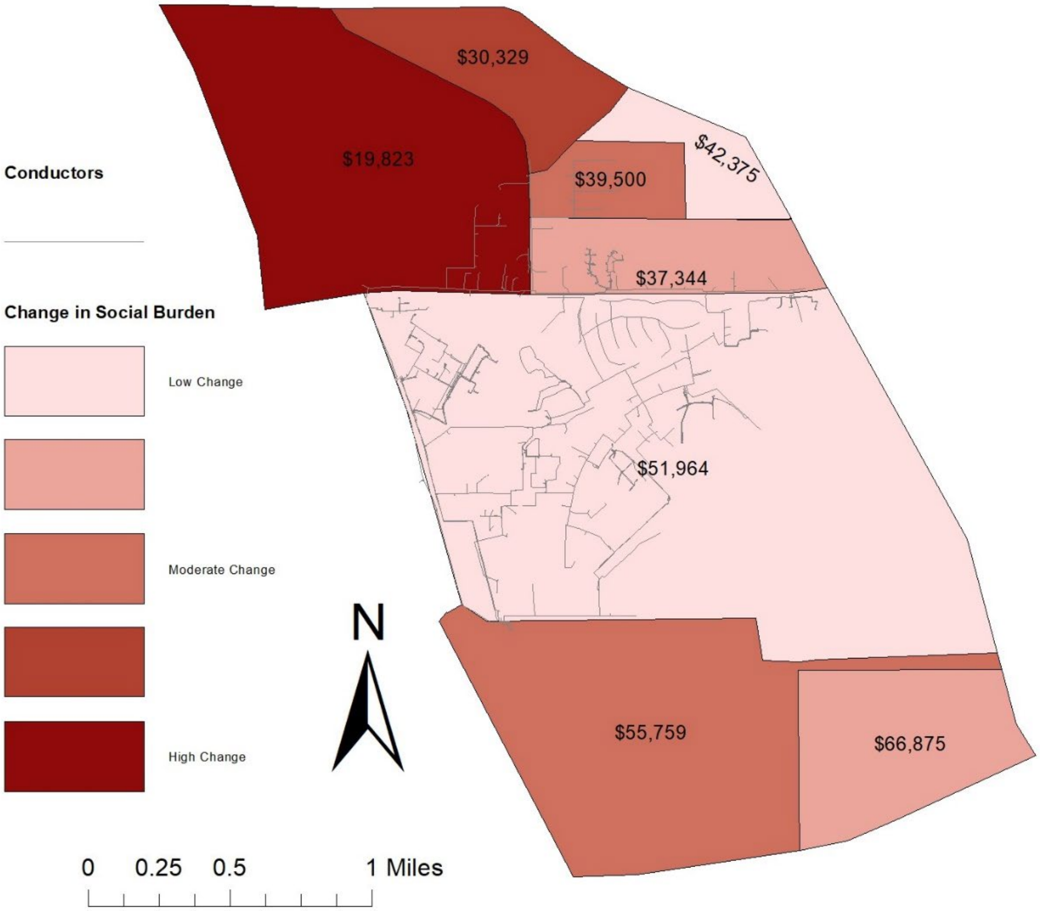


Figure 19: Change in social burden by census block group (average household income noted) between Portfolio A and Portfolio B in Figure 18.

4.1.4. CoSA Application Case Conclusions

This analysis achieved the goal to incorporate EVFCs as critical infrastructure and quantitatively understand the opportunities for improving resilience across the community as a function of EV infrastructure expansion. As noted above, until engagement with the DRC project, neither CoSA nor CPS Energy were quantifiably incorporating resilience into EV planning. Sandia, CoSA and CPS Energy leveraged the Resilient Community Design Framework to demonstrate how EV infrastructure and distribution grid infrastructure planning could incorporate equitable improvement in community resilience as an additional objective. As intended, this analysis is scalable to a much larger region, which could inform and justify citywide investment in both EVFCs and microgrids.

4.1.5. Synthesis of Lessons Learned

The EV adoption patterns and charging habits of future society are still somewhat unpredictable. It's possible to make reasonable assumptions based on observable trends, but the future state of vehicle electrification is evolving and timelines are uncertain. Models that can be scaled up or down in response to policy and market shifts is key. This is important both to anticipate infrastructure needs during blue sky days, but also to anticipate infrastructure impacts and needs during resilience events.

The DRC framework enabled this team to develop a comprehensive appreciation for the role of transportation electrification within the greater context of energy resilience. It is important to quantify the impacts to neighboring communities during an outage when a significant portion of transportation is electric.

The following take-aways highlight what was learned about this system and about the process, including opportunities to expand this research and gain additional insight.

- Stakeholder engagement and information sharing, as defined and supported by the DRC framework, is critical. This cannot be overstated. The energy and transportation sectors touch every person in a community. Efforts to gather input cannot be limited to infrastructure data, although this is also critical. Scenario planning, impact assessment, near-and-long term plans for development, these are all invaluable insights into the system that cannot be well understood without input from city personnel, electric utility experts, emergency management leaders, and others. A systematic, persistent, and patient approach is necessary if findings are to encapsulate the true implications of energy resilience in the system.
- Sensitivity analysis as a function of EV adoption would be a logical next step. The volumes of EVs assumed to move into Brooks City Base could be expanded to reveal tipping points. Meaning, there is some number of EVs that result in the need to install not only additional charge ports but will affect the overall microgrid locations by influencing the locations of resilience nodes. Further study to understand saturation volumes of EVs within the system would be of value.
- The area of interest for this work was relatively small. Having now verified the approach, a citywide energy resilience analysis would enable visibility into how neighboring communities might influence one another. Performing a social burden analysis that captures the full diversity of a city as large and diverse as San Antonio would result in identifying feeders throughout the system that not only provide electricity to the most impactful services, but would help point out equitable locations for future public EV charge station.

4.2. El Caño Martín Peña Communities, San Juan, PR

The El Caño Martín Peña (CMP) communities constitute about 5,000 homes supporting around 18,000 residents along the Martín Peña Channel—a 3.75-mile-long tidal channel in San Juan, Puerto Rico connecting the San Juan Bay at its west to the Laguna San Jose [51] to its east, as depicted in Figure 20. It is San Juan's most densely populated area [52]. The CMP communities were selected as a demonstration partner for DRC through consultation with University of Puerto Rico at Mayaguez collaborators about potentially underserved communities in Puerto Rico that could benefit from better alignment between energy investment and community resilience planning, while demonstrating how the Resilient Community Design Framework might be applied by communities that commonly have limited interaction with their electric utility.

Figure 20: Location of the CMP communities engaged in the DRC demonstration study [Image credit: US EPA].

4.2.1. CMP Resilience Drivers Determination

The primary drivers for resilience investment needs in the CMP communities stem from the condition of the channel, the history of the community, and the organizational structures that have arisen to support the community. The CMP communities largely were settled by squatters settling along the banks of the Martín Peña Channel in the 1930s and 40s due to rapid migration of Puerto Ricans from rural areas seeking a better quality of life [53]. Over time, these settlers filled the surrounding mangrove swamps to establish residence, and the resulting sedimentation and sewage has polluted, channelized, and obstructed the Martín Peña Channel, as depicted in Figure 21. During rainstorms and hurricanes, much of the CMP communities experience flooding that can be contaminated with sewage. To exacerbate this resilience challenge, the communities are economically challenged—more than fifty percent of the population lives below the national poverty line [54].

Figure 21: Evolution of settlements along the Martín Peña Channel have led to channelization[5].

Two intersecting opportunities are driving requirements and opportunities for CMP to invest in improving resilience. First, the ENLACE Project Corporation was created by Law 489 in 2004, establishing the foundation for a Comprehensive Development and Land Use Plan and designating CMP as a special planning district within San Juan. ENLACE's statutory mission is to develop and implement this comprehensive land use plan for the community. Second, the Caño Martín Peña Ecosystem Restoration Project resulted in a major dredging plan to restore proper flow between the San Juan Bay and the Laguna San Jose, with support from the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers to implement the dredging plan [55]. The comprehensive land use plan and the dredging plan converge toward a need for redevelopment. To restore the channel to its appropriate capacity, residents must be encouraged to relocate away from key restoration areas near the channel. Many residents prefer to stay within the district if they are to relocate. To support this relocation, ENLACE is investigating and implementing select redevelopment opportunities for more modern, safe, resilient, yet affordable, housing. Importantly, if this housing and the surrounding services are not resilient to the key driving hazards, ENLACE and the community will have trouble encouraging the relocation and may not be able to implement the ecosystem restoration.

To determine how energy investment could improve the resilience of the CMP communities, while enabling both the channel restoration and the activities of the comprehensive land use plan, Sandia, the University at Buffalo, and the University of Puerto Rico at Mayaguez engaged key stakeholders representing the communities in a series of both in-person and web-based interactions between 2019 and 2021, in addition to surveying the communities directly in 2021. The major stakeholders engaged include:

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[5] Top image from 1936 received from EPA

- **ENLACE:** Officially titled The Corporación del Proyecto ENLACE del Caño Martín Peña, ENLACE is responsible for overseeing and implementing the CMP comprehensive land use plan for the CMP special planning district.
- **The Community Land Trust (CLT):** The Fideicomiso, or Community Land Trust, for the CMP communities separates the value of the land from that of the buildings and holds the land in perpetuity on behalf of community members for approximately 200 out of the 450 acres within CMP.
- **G-8:** The Grupo de las Ocho Comunidades Aledañas al Caño Martín Peña, or G-8, is a non-profit that represents residents in decision-making activities that affect CMP. The G-8 consists of twelve organizations which represent both the CMP special planning district as well as the Cantera Peninsula. The Cantera Peninsula is not within the special planning district, nor were they engaged as part of the Sandia study. The G-8 oversee both ENLACE and the CLT.

The in-person and virtual meeting engagements focused on progressing through the Resilient Community Design Framework to arrive at energy system investment options that could best improve community resilience. In addition to engaging the community stakeholders, the Olin Corporation was also engaged due to their role supporting redevelopment planning for ENLACE. The following three sections outline the progression of these engagements and the associated analysis.

Resilience, and specifically energy resilience, is not the only goal of the CMP communities. Notably, the solutions in the comprehensive land use plan and more specifically the housing redevelopment initiatives must also achieve affordable and safe living conditions. Sustainability is also a goal, although the stakeholders have not firmly determined how potential tradeoffs between energy sustainability and other goals will be evaluated. For instance, in several interactions, stakeholders articulated that solutions would not be pursued at all if they did not reach a certain level of affordability and resilience, whereas energy sustainability was conveyed as a benefit that would add to a plan's desirability without being a set requirement. Metrics useful for quantifying each of these dimensions were discussed with the stakeholders, and the analysis focused on the following:

- **Affordability**: net present value of all energy-related expenditures
- **Sustainability**: energy-associated greenhouse gas emissions
- **Resilience**: energy availability (the probability of service during disruptions) for critical loads as defined by stakeholders and the project team

4.2.2. CMP Baseline Resilience Analysis

The CMP communities have multiple resilience challenges and hazards. Flooding and high wind speeds associated with hurricane events are a paramount, acute hazard. The economic condition of many residents exacerbates these challenges and leads to additional vulnerabilities such as energy-dependent health conditions. A depiction of the 100-year flood zone as determined by FEMA and other sources, along with the household median income for each census block group within the CMP communities is shown in Figure 22.

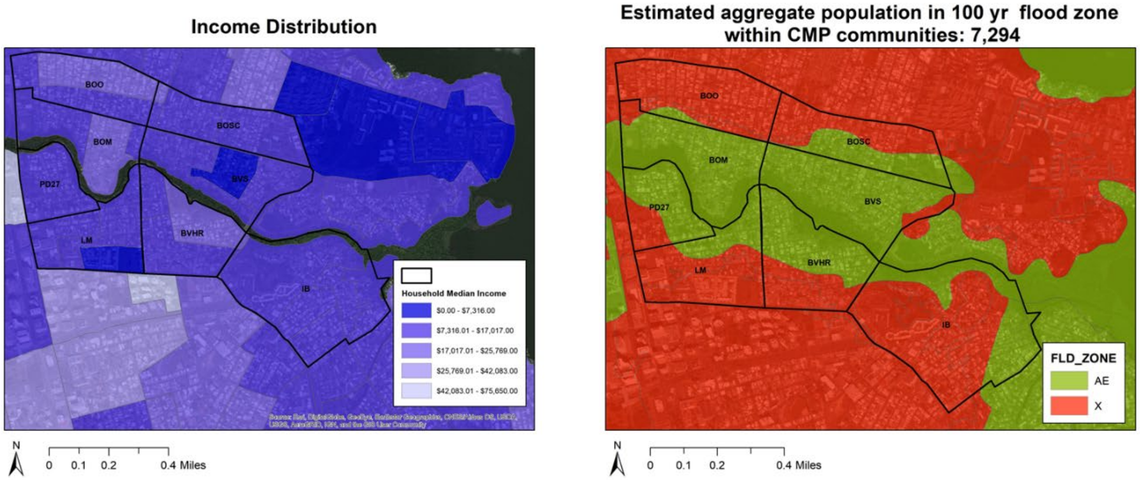

Figure 22: Depiction of the 100-year flood zone as determined by FEMA, along with the household median income for each census block group within the CMP

A discussion of CMP's community resilience as a function of energy resilience must include the experiences of the communities following hurricanes Irma and Maria in 2017. These hurricanes hit less than two weeks apart, and Maria especially caused extreme wind damage after her eye passed directly over Puerto Rico. Residents [56] were left without electric power for weeks to months, and dependent infrastructure systems such as communications, water, wastewater, and financial services were also unavailable for extended periods. Residents dealt with extreme flooding contaminated with waste and severe structural damage, with approximatley 1,200 homes becoming roofless and several more completely destroyed [52]. However, the G-8 and the CMP residents benefited from a high degree of community social cohesion after the storm. Residents organized and helped each other, often going door-to-door to tally needed items and delivering these items from a supply chain operating out of the ENLACE building. Because of the community organization built over time, leaders already knew which residents had specific needs and were able to prioritize these community members. Perhaps unlike other communties in San Juan, most CMP residents felt safe staying in their community during the recovery period due to trust in these organizations and each other. Items or services reported to be in particularly short supply during this period include tarps, batteries, bug repellant or nets, food, water, fuel, insulin and other medicines, and ice. Many residents reported spending much of their time during the recovery period in lines waiting for these items and services. Also relevant to energy system design, some people would leave their homes due to noise from fossil fuel generators.

Over the course of several meetings with CMP stakeholders, the social burden resilience metric was discussed in detail. Stakeholders aligned with the concept of the social burden metric describing much of the burden experienced by their communities following major acute disruptions—e.g., more of the community's time spent accessing basic human services as compared to normal days. Sandia performed a baseline social burden estimate across all infrastructure services and shared this with the stakeholders to discuss the burden on a "blue sky" day without any facilities being compromised, as depicted in Figure 23. Many of the infrastructures providing services are along CMP's perimiter, largely to the north, west, and south. Some services, such as medical clinics, are disproportionately available on one side of the channel. Residents reported commonly walking to access these services, even during normal days, because of the lack of reliable transportation services.

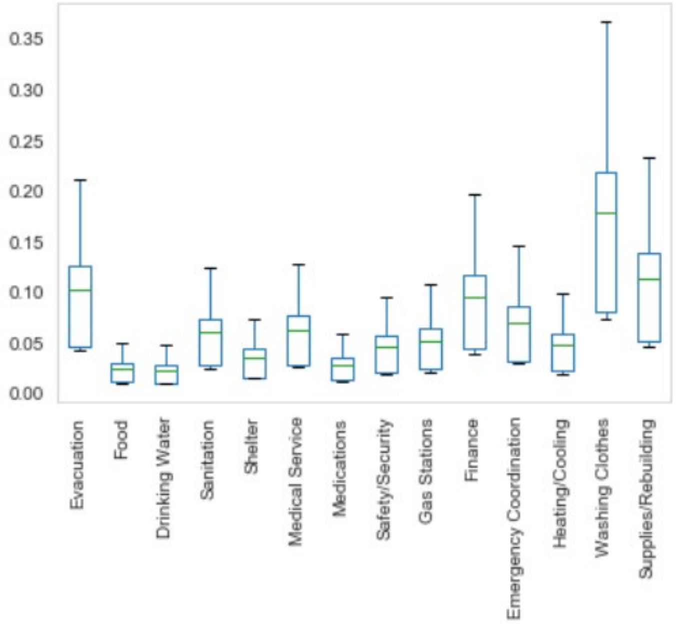

Figure 23: Baseline social burden estimate across all infrastructure services

4.2.3. *CMP Resilience Alternatives Specification*

Energy investment will be necessary to provide the appropriate level of resilience supporting the comprehensive land use plan and, more specifically, the housing redevelopments necessary for ecosystem restoration. A major design consideration for specifying energy investment alternatives is the role of the serving electric utility—Puerto Rice Electric Power Authority (PREPA)—in supporting the resilience of CMP. Stakeholders expressed concern that the PREPA investment process appeared high-level and opaque to CMP residents. Stakeholders were unsure whether PREPA could consider some of the unique needs of CMP—such as the need to support housing redevelopment and new critical infrastructure such as flood pumps—in the utility's island-wide investment planning process. The DRC project team, therefore, focused primarily on energy investments that could be made unilaterally by the CLT and community members themselves. Through other initiatives, Sandia continues to partner with PREPA and others in a more centralized fashion on recovery efforts coordinated and supported by the US DOE and FEMA.

In 2018, the Puerto Rico Energy Commission (PREC)—which is now the Puerto Rico Energy Bureau (PREB)—arrived at a microgrid ruling in CEPR-MI-2018-0001 that set guideposts for microgrid development and interconnection by non-utility parties [57]. These so-called "third-party microgrids" were determined to be allowed to sell excess energy and services to neighboring customers, with rates approved by PREC on a project-by-project basis. However, PREC did not rule whether these third-party microgrids should be allowed to lease PREPA assets. Leasing local distribution infrastructure during outage conditions could decrease capital costs for third party microgrids if rules are put in place to ensure safety is maintained. The microgrid ruling also creates special distinction of renewable microgrids that consist 75% of renewables, and combined heat and power (CHP) microgrids that consist of at least 50% CHP generation.

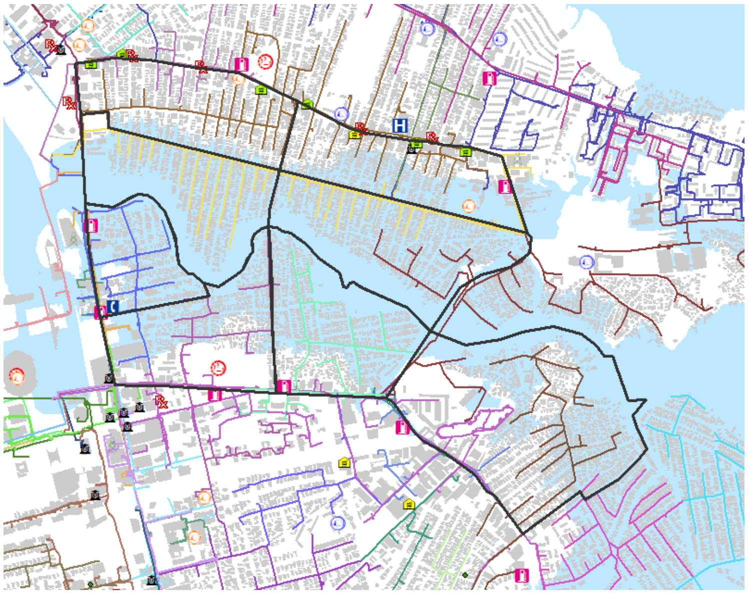

Figure 24: CMP area infrastructure

Because of the parameters described in the 2018 microgrid ruling, along with the CMP stakeholders unique resilience needs associated with housing redevelopment and community service provision, the DRC project team and the stakeholders together decided to develop conceptual designs for investment alternatives that meet the definition of renewable microgrids set by PREC and do not utilize any PREPA assets. In-depth, in-person discussion in February 2020 arrived at three distinct types of "third-party" microgrids that would support community needs as defined by the three metric categories for sustainability, affordability, and resilience:

- **Critical infrastructure microgrids**: developed in partnership with local businesses such as grocery stores, clinics, and hardware stores, and could also support public resilience infrastructure such as drainage pumps and emergency shelters.
- **Housing redevelopment microgrids:** support the housing redevelopments being developed by ENLACE and may also provide select services to the broader community.
- **Institutional microgrids:** support large institutional buildings or groups of buildings that serve the community during major disruptions, such as schools, community centers, and the ENLACE building.

Non-microgrid energy resilience investments are also being considered by the CMP stakeholders, such as redeveloping several new homes with solar and battery backup throughout the district. However, these are often relatively straightforward and do not require advanced design considerations that would benefit from the DRC project team's expertise.

Several locations for each of these types of microgrids were identified and discussed with the CMP stakeholders. Based on engineering judgement of the DRC project team and additional discussion with the Olin team, as well as iterative feedback from the CMP stakeholders, a down-selected set of locations for each of the types was developed and shared. Decreasing social burden during major disruptions was a factor in determining the locations, but additional considerations also came into play such as land availability and minimization of right-of-way crossings for the microgrids. The housing redevelopment microgrid type was elevated as the most important for the DRC project to analyze, since the electrical design might heavily influence other design work underway. Additionally, potential locations for potential PREPA-owned microgrids were also identified, and scope was developed for the Puerto Rico Recovery projects in partnership with the University of Puerto Rico Mayaguez (UPRM). Those results are not highlighted in this report.

4.2.3.1. Developing a Conceptual Design for Housing Redevelopment Microgrids

To demonstrate the tradeoffs in design considerations and feed into ENLACE's comprehensive planning, a single site was selected as being representative of the design considerations for housing redevelopment microgrids throughout the district. This site, the Barbosa 211 redevelopment, is highlighted in Figure 25. At the time of analysis, initial plans for the redevelopment were targeting up to 206 housing units, with about 65% of those being town homes and 35% being apartments. The redevelopment would support several accessible units for elderly and disabled community members. On the first floor facing the major throughfare, commercial spaces could house service-providing businesses such as a small market or pharmacy. Some publicly accessible space and institutional capacity could be available for meetings, emergency coordination, or other community functions. All of these plans remained high level and in discussion with the G-8 at the time of the DRC analysis.

Figure 25: Barbosa 211 Location

The DRC team sought to develop and refine alternative conceptual designs of Barbosa 211's energy system, employing several advanced capabilities to do so. Following the Resilient Community Design framework, additional detailed steps once the site of interest was established are:

- Establish and characterize DBTs for resilience goals and metrics
- Project microgrid load over a planning horizon in both blue sky (normal day) and black sky (DBTs) conditions
- Determine options for generation and other microgrid components
- Optimize several designs for blue sky goals and metrics
- Optimize several designs for black sky goals and metrics
- Iterate to converge upon final conceptual design

For this process, the DRC team employed Sandia's Microgrid Design Toolkit (MDT), which develops intelligent conceptual designs for stakeholders that have a large set of design options and want to consider tradeoffs between resilience, sustainability, and affordability goals. To support MDT, the Tiered Energy in Buildings (TEB) [58], [59] tool was developed to create load profiles that can reflect both blue-sky (normal day) and black sky (during DBTs) behavior of load.

To establish the DBT, the DRC team and the CMP stakeholders discussed historic drivers of outage and increased (worsened) social burden. In addition to hurricanes, other major storms, earthquakes, and general power system failures were raised as threats of concern. Since no outage data were available at the time of analysis, the DRC team relied on anecdotal evidence by CMP stakeholders as well as the subject matter expertise of UPRM researchers. Table 9 outlines the outage parameters that were used for the set of DBTs. These outage parameters are used for the black sky design accomplished by MDT's Performance Reliability Model (PRM). To build Table 9, discussions were had with the stakeholders and research partners as to how frequently they might expect outages lasting certain duration ranges to recur. For example, starting with short durations, it was gleaned that outages lasting one to two days occur on average once a year. As the discussion turned to longer durations, stakeholders shared insights on how they did not diminish the thought of these less-probable outages, but instead remained comfortable with their educated guesses. Because MDT-PRM simulates microgrid behavior over thousands of representative years, even the 1-in-500 recurrence frequency outage (lasting an entire year) can be investigated alongside more probable events.

Table 8: Outline of outage parameters used for DBTs

DBT Frequency (yrs)	Duration (days)	Duration Range	1000 Year Sim Occurences	Total Sim Outage Duration (days)	Percent of Total Sim Time
1	2	1-2 days	1000	2000	0.55%
10	14	7-14 days	100	1400	0.38%
50	40	30-60 days	20	800	0.22%
100	180	4-8 months	10	1800	0.49%
500	365	8-16 months	2	730	0.20%
		Totals:	**1132**	**6730**	**1.84%**

Once the DBT was established, sets of topologies for the microgrid were presented and discussed. The final modeled topology is shown in Figure 26. Since the Barbosa 211 development, and most housing redevelopments in CMP, would be relatively densely constructed, Sandia subject matter experts deemed it appropriate to assume that the microgrid could consist of a single node, or bus. This indicates that location of assets such as generators and switches within the redevelopment footprint is less important to the resilience of the microgrid than the selection, capacity, and capabilities of those assets. Furthermore, a discussion was held about the types of loads on the microgrid. Load was broken into four unit types—residential apartments, residential townhomes, commercial, and institutional. Within each unit type, different tiers of load were determined. Tier 1 consists of only that load which would be necessary for basic human needs, while tier 3 consists of the lowest priority that designers would still prefer to keep online during grid-islanded conditions. Finally, designers are least concerned with supporting load designated as non-critical.

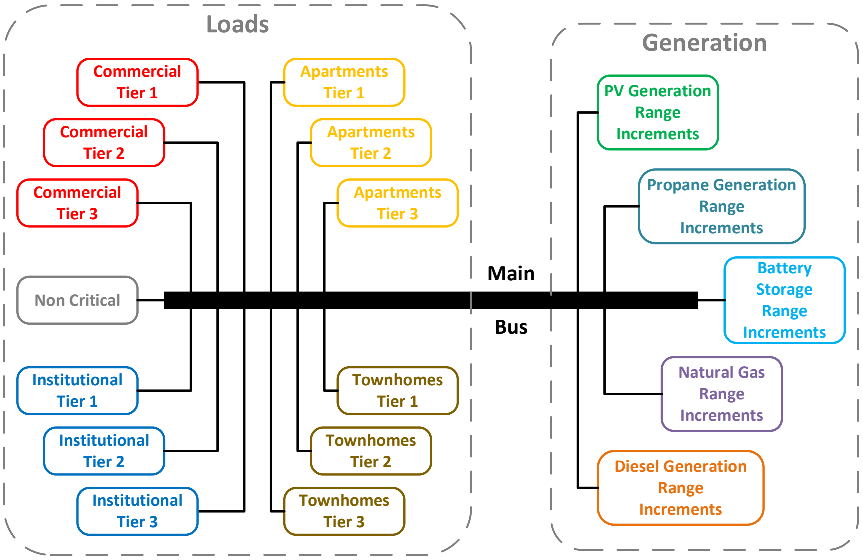

Figure 26: Final topology model

After creating the load taxonomy, the DRC team developed and applied the TEB tool to build annual load profiles at hourly resolution for each unit type and each tier. TEB is unique in that it builds separate load profiles for blue sky and black sky conditions. It also uses a simplified model of thermal systems in units, which can be calibrated to accurately reflect the interaction between loads (for example, between heat emitted by refrigeration and increased cooling load). For this CMP demonstration, not all the capabilities of TEB were exercised. Load use propensity and occupancy were kept constant across blue sky and black sky conditions. Figure 27 depicts a stacked tier 1, 2, 3 and non-critical load, across two 24-hour periods (a minimum load day and a maximum load day) for all units combined across Barbosa 211. The peak load is estimated to be approximately 580 kW for all loads together and 130 kW for only the Tier 1 loads.

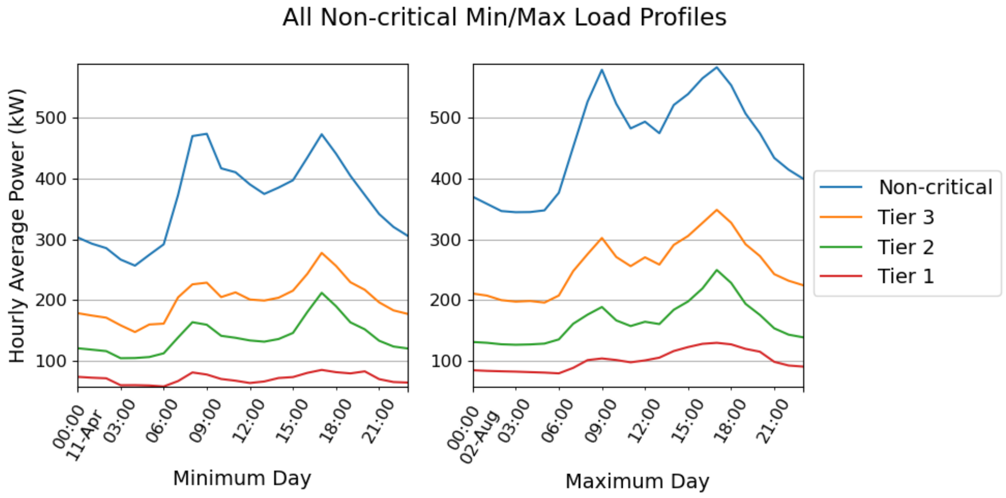

Figure 27: Stacked tier 1, 2, 3 and non-critical load, across two 24-hour periods (a minimum load day and a maximum load day) for all units combined across Barbosa 211

4.2.4. CMP Resilience Alternatives Evaluation

A benefit of MDT is that literally billions of alternatives may be considered simultaneously using optimization techniques if objectives are clearly defined. Therefore, concrete alternative designs do not need to be built beforehand for the blue sky and black sky optimization steps. The MDT deploys a different optimization approach for the blue sky design (the Microgrid Sizing Capability, or MSC) as opposed to the black sky design (the PRM).

4.2.4.1. Blue Sky Optimal Design Analysis

Utilizing the MSC, a blue sky optimal design was developed for Barbosa 211. Several unique market conditions impact this design. First, retail electricity rates in Puerto Rico are among the highest in the United States and were assumed to average 0.224 $/kWh for the planning horizon of 20 years. There are no time of use rates or demand charges assumed, but net metering is allowed with an end-of-year true-up. This means that generation surpluses from the microgrid from month-to-month could be credited at the full retail rate, but any surplus at the end of the year would be credited at a reduced rate of 0.07 $/kWh. To reflect the goals of PREB and of the CMP communities, designs were not allowed that did not meet the microgrid ruling definition of "renewable microgrids," and therefore 75% of all blue sky energy generated by the microgrid must come from renewable resources. A discount rate of 6.5% was assumed based on a discussion with the stakeholders about their weighted cost of capital.

With these assumptions, including the installed cost of simple (non-grid-forming) photovoltaic (PV) generation in Puerto Rico, the optimal microgrid design for the affordability metric alone is a 2.3 MW-AC rooftop PV system. By initial estimates this design utilizes all rooftop space at Barbosa 211 and may require PV systems placed on nearby spaces as well. No other technologies other than perhaps building efficiency (not considered as an investment option) are net beneficial. Table 11 shows the annual cash flow and emissions metrics for this system as compared to the baseline. Emissions figures are calculated based on avoiding historic PREPA emissions per kWh as calculated by their 2019 emissions figures. In the baseline run with no investment, Barbosa 211 would pay approximately $800,000 in energy purchases per year, and the PREPA system would emit around 2,500 metric tonnes of CO_2 per year to serve that load. With the rooftop 2.3 MW-AC PV system, over the course of the year as many kWh of electricity are generated by this system as are consumed by Barbosa 211. Annual expenditures amount to the operations and maintenance (O&M) costs on the PV system, plus the fixed fees on the PREPA bill which are not shown. Because this system offsets 100% of the energy consumed by Barbosa 211, it also offsets nearly all CO_2 emissions.[6]

Table 9: Annual cash flow and emissions metrics for PV system as compared to the baseline

Investment Annual Cash Flows		
Fuel Cost	$	-
O&M Cost	$	(43,150)
CO2 Charges	$	-
Energy Purchases	$	(435,830)
Energy Sales (at 0.224)	$	435,830
Energy Sales (at 0.07)	$	33
Demand Charges	$	-
Net Annual Cash Flow	**$**	**(43,117)**
Carbon Emissions (tonne/yr)		
Local CO2 Emissions		0.0
Utility CO2 Emissions		1374.6
Offset CO2 Emissions		-1374.9
Net CO2 Emissions		**-0.3**

Baseline Annual Cash Flows		
Fuel Cost	$	-
O&M Cost	$	-
CO2 Charges	$	-
Energy Purchases	$	(802,049)
Energy Sales (at 0.224)	$	-
Energy Sales (at 0.07)	$	-
Demand Charges	$	-
Net Annual Cash Flow	**$**	**(802,049)**
Carbon Emissions (tonne/yr)		
Local CO2 Emissions		0.0
Utility CO2 Emissions		2529.7
Offset CO2 Emissions		0.0
Net CO2 Emissions		**2529.7**

Table 12 shows the 20-year net present value of the 2.3 MW-AC rooftop PV system at Barbosa 211 using the discount rate of 6.5%. With the capital cost of this system assumed to be 1,800 $/kW, a $4.1M up-front investment nets a 20-year net present value of +$3.9M, and offsets over 2,500 metric tonnes CO_2 per year. These evaluation metrics were shared with the ENLACE team and the Olin consultants, representing the blue sky optimal design.

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[6] To precisely calculate the PREPA CO_2 emissions that a PV system would offset, a more detailed calculation could be performed that estimates the PREPA carbon intensity per kWh for each hour of each day based on generation resources dispatched by the utility.

Table 10: 20-year net present value of the 2.3 MW-AC rooftop PV system at Barbosa 211

Net Present Value of Investment		
NPV of Baseline Cash Flows	$	(8,837,387)
NPV of Investment Cash Flows	$	(475,090)
NPV Annual Cash Flow v. Base	**$**	**8,362,297**
CapEx of Investment	$	(4,132,800)
NPV of EOL Salvage Investment	$	234,575
Total CapEx	**$**	**(3,898,225)**
Net Benefit v. Baseline	**$**	**4,464,072**
CO2 Emissions v Baseline (tonne/yr)		**-2530.0**

4.2.4.2. Black Sky Optimal Design Analysis

Once a blue sky optimal design was developed, the MDT-PRM was employed to develop optimal options for black sky systems. This is the system that would be most cost effective only for times in which the microgrid is running islanded from PREPA. One of the major differences with a microgrid operating in this "islanded" mode is that it must balance the power generated with the load at all times, as opposed to the blue sky system which can in effect use the grid as a battery.

To determine technology options available for generation on the Barbosa 211 microgrid, the DRC team researched available generation technologies and their costs as built in San Juan, Puerto Rico. The UPRM team's expertise designing distributed generation solutions in Puerto Rico was invaluable for this analysis. Table 10 shows the generation options considered, as well as the unit capacities, capital costs, reliability parameters, and any capacity limits due to space constraints. Notably, while there is no natural gas distribution system in Puerto Rico, a liquified natural gas distributor is now in business. Delivery trucks are currently dispatched from the EcoElectrica LNG terminal near Poncé on the south side of the island, and due to debris, the supply chain cannot be guaranteed immediately following major hurricanes. It was assumed that a minimum realistic generator size eligible to contract with this service would be 1 MW.

Table 11: Black sky generation options, including the unit capacities, capital costs, reliability parameters, and any capacity limits due to space constraints

Asset Type:	Range:	Increments:	MTBF (h):	MTTR (h):	Capital Cost:
PV	50kW-1MW	50/100/500kW and 1MW	8468	55	$1800/kW
Lithium-Ion Batteries	50-500 kW	50/100/500 kW (4-hour batteries)	8000	168	$2604/kW
Diesel Generators	50kW-1MW	50/100/500kW and 1MW	10,500	37	$850/ kW
Natural Gas Generators	1MW	1MW	30000	6	$1000/kW
Propane Generators	50kW-1MW	50/100/500kW and 1MW	30000	6	$2750/kW

Table 13 shows the results of the MDT-PRM analysis for black sky optimization. Objectives for the optimization were to reach as close to energy availability objectives for tier 1, 2, and 3 loads as possible (99.5%, 95.5%, and 85% respectively) at least capital cost. The MDT-PRM employs an algorithm which outputs a pareto frontier, resulting in multiple investment options that are each optimal for performance at their CapEx price point. As can be seen by these results, the least expensive option that meets all requirements for serving critical load is a set of three 100 kW propane generators. The more expensive options on the pareto frontier improve service to tier 3 loads and to non-critical loads during disruptions. Notably, propane generators are a common investment in several optimal black sky portfolios unless the designer values serving the non-critical load. In that case, a single 1 MW natural gas generator complemented by a small amount of solar PV becomes cost effective.

Table 12: Results of the MDT-PRM analysis for black sky optimization

Nothing Fixed, Updated Load Shedding Scheme											
Config#	Availability				Variable Selections (kW)					Total Installed Capacity (kW)	Total Purchase Cost ($M)
	Tier 1	Tier 2	Tier 3	NC	PV	Natural Gas	Diesel	Li-Ion Battery	Propane		
1003	99.95%	99.95%	96.87%	4.66%	0	0	0	0	300	300	$0.825M
627	99.96%	99.95%	97.89%	10.06%	0	0	50	0	300	350	$0.871M
759	99.95%	99.94%	99.69%	6.63%	0	0	0	50	300	350	$0.955M
109	99.98%	99.96%	99.90%	12.66%	50	0	50	50	300	450	$1.091M
1805	99.98%	99.97%	99.98%	99.98%	100	1000	0	0	0	1100	$1.18M

4.2.4.3. Blue and Black Sky Co-Optimal System Design

To arrive at a blue and black sky co-optimal system, the DRC team relied on unique features of these designs that allow for simplification of the co-optimal design step. First, for the blue sky optimal design, solar PV is the only generation technology considered that has any blue sky value whatsoever. Second, the solar PV on its own can provide some value in black sky simulations but must be combined with flexible resources such as fossil generators or batteries to meet the black sky objectives. Therefore, the DRC team developed a co-optimal design by “locking in” the 2.3 MW solar PV system and allowing MDT-PRM to optimize for black sky objectives by complementing that system with additional generation. Furthermore, after the designs were shared with the CMP stakeholders, feedback was received that diesel generators are much less desirable than propane or natural gas because of the high amount of noise they create while running. During Maria, for instance, several residents reported leaving the district in search of temporary housing because the noise from individual diesel generators was unbearable. A set of final co-optimal conceptual designs are shown in Table 14. In this case, some co-optimal designs can take advantage of the PV during black sky conditions to meet objectives with less total fossil generation capacity than the black sky optimal systems and a higher rate of return over 20 years. Also notable is that in configurations 53 and 55, nearly 100% of tier 1, 2, and 3 critical load is met. This may simplify the electrical circuit design of the housing redevelopment and ultimately result in a less expensive microgrid cost.

Table 13: Final co-optimal conceptual designs

PV Fixed 2300 kW, Propane and Batteries Variable, Updated Load Shedding Scheme										
Config#	Availability				Variable Selections (kW)			Total Installed Capacity (kW)	Total Purchase Cost ($M)
	Tier 1	Tier 2	Tier 3	NC	PV	Li-Ion Battery	Propane		
73	99.99%	98.88%	83.72%	47.36%	2300	0	200	2500	$4.69M
67	99.55%	99.41%	87.50%	47.59%	2300	50	200	2550	$4.82M
61	99.77%	99.63%	95.85%	47.41%	2300	100	200	2600	$4.95M
55	99.96%	99.94%	99.57%	55.90%	2300	0	300	2600	$4.965M
53	99.98%	99.96%	99.94%	59.20%	2300	50	300	2650	$5.095M

After discussing the various co-optimal designs and different follow-on design considerations with the CMP stakeholders, the DRC team recommends configuration 55 or 53, depicted in the bottom two rows of Table 14. This allows the microgrid to "group" tier 1, 2, and 3 into a single critical load circuit instead of using a more complex microgrid controller to optimize service across these tiers in real time. The difference between these designs is a single 50 kW, 4-hour lithium-ion battery, which could provide additional resilience benefits not considered here, and could capitalize on future alternative rate structures. To finalize costs, designers should consider that the total capital expense in these tables includes all generation capital costs, but not the "balance of microgrid" costs such as controllers, protection, switchgear, and circuitry. However, since Barbosa 211 is essentially greenfield development without major right-of-way concerns, these costs should be relatively small compared to the generation costs.

To summarize, the co-optimal design for Barbosa 211 is a 2,300 kW-AC rooftop PV system and three 100 kW propane generators, with an option for additional 50 kW battery system. For the primary design metrics, this system results in:

- **Affordability:** Capital expenditure between $4.9 to $5.1M plus balance of microgrid costs. Net present value based on a 6.5% discount rate of approximately +$3.6 M over 20-year planning horizon compared to no energy investments.
- **Sustainability:** Avoided greenhouse gas emissions equal to 2,530 metric tonnes CO_2 per year, equating to 50,600 metric tonnes avoided over the 20-year planning horizon (not considering emissions during black sky operations).
- **Resilience:** All tier 1, 2, and 3 loads served over 99% of the time during outage conditions, including the year-long outages considered in the DBT. Non-critical loads could be served during mostly daylight hours.

4.2.5. CMP Application Case Conclusions

The Barbosa 211 microgrid conceptual design represents a heavily stakeholder-driven design of a microgrid for community needs, and effectively exercised much of the Resilient Community Design Framework in a different way than it might be employed by electric utilities and regulators. Several conclusions are applicable more broadly for applications of the framework:

- The MDT analysis capability became more of the focus of the analysis as opposed to ReNCAT or other design tools because the CMP stakeholders had fewer options for investment and therefore were ready to focus on the options that they knew could be feasible. This is important when considering future users of both toolsets.
- At several junctures, community feedback greatly altered the analysis approach which impacted the final design. Diesel was eliminated only after seeing the relatively minor cost increases for other feasible options. Greenhouse gas emissions became a secondary driver for the design next to resilience and affordability. Pursuers of place-based energy transition initiatives nation-wide can use this experience as a data point when creating the model for how to deliver impact to communities.
- Under current regulatory structures in Puerto Rico, namely available rate tariffs, the 2018 microgrid ruling, and the net energy metering policies, behind-the-meter investments are largely driven toward rooftop solar PV. However, the microgrid ruling opens the door for these solar PV investments to be complemented with microgrid technologies at a local scale, resulting in a small decrease in the cost of resilience investments when coupled with the value of solar PV. Larger third party microgrids where right-of-way must be crossed remain relatively disincentivized. Other rate structures, such as larger demand charges or time of use rates, could drastically alter the co-optimal design for Barbosa 211.
- The simplicity of the retail electricity market in Puerto Rico allowed for relatively straightforward co-optimization of a conceptual microgrid design. In fact, this conceptual design would be nearly co-optimal for similarly sized microgrids regardless of application in Puerto Rico. This assertion can be tested as the national labs continue to perform DOE-sponsored analysis in partnership with PREPA, LUMA, and other stakeholders.

5. TASK 3: INVESTIGATION OF ALTERNATIVE REGULATORY FRAMEWORKS FOR INCENTIVIZING EFFICIENT RESILIENCE INVESTMENTS AND MONETIZING RESILIENCE BENEFITS

Pursuant to Task 3, Sandia collaborated with Synapse, Bosque Advisors, NARUC, and other project stakeholders to investigate alternative regulatory frameworks for incentivizing efficient resilience investments and monetizing resilience benefits. Sandia and project partners conducted research and engaged stakeholders to understand how regulatory existing regulatory approaches enable or inhibit resilience investments and to identify best practices for both designing regulatory frameworks for resilience and quantifying resilience benefits within utility regulatory and investment processes. This research and engagement resulted in seven interrelated technical reports, a journal article, two academic conference presentations, and a co-sponsored workshop (see Table 15), providing a comprehensive assessment of the following topics:

- Regulatory strategies for resilience spanning multiple sectors, jurisdictions, levels of government, resilience hazards, and policy instruments (Section 5.1)
- Community and utility experiences with grid resilience planning across various state regulatory structures, regions, threat types, and community sizes (Section 5.2)
- Electric utility regulator perspectives on grid and community resilience challenges and opportunities (Section 5.3)
- Existing regulatory mechanisms that could be used to enhance grid resilience (Section 5.4)
- Strategies to quantify electric grid resilience via BCA (Section 5.5)
- Resilience-oriented performance metrics for the electric grid (Section 5.6)
- Public purpose microgrids to enhance resilience (Section 5.7)
- Methodology and policy framework for "stress testing" utilities to enhance electricity system sustainability and resilience (Section 5.8)
- Lessons learned about developing alternative regulatory frameworks for incentivizing efficient resilience and investments and monetizing resilience benefits (Section 5.9)

The collaborative workstreams under Task 3 iteratively build on each other. For example, early research on the policy landscape and engagements with communities, utilities, and regulators highlighted challenges and opportunities that subsequent work on regulatory frameworks addressed including gaps, new mechanisms, metrics, and evaluation approaches. The research conducted as part of Task 3 was informed by engagements with the SAG in Task 1 and demonstration partners in Task 2. The resulting insights and publications not only shaped the Resilient Community Design Framework, as discussed in Section 3, but also offer next steps that communities, utilities, and regulators can undertake to advance both quantification of resilience benefits and efficient investments in resilience. In particular, recognizing that regulatory processes benefit from the consideration of simplified information and inputs, the reports produced as part of Task 3 summarize, streamline, and distill complex information into informative and decision-useful formats for regulators. This section discusses the outcomes and lessons learned from each of the major work streams discussed under Task 3.

5.1. “Regulating for Resilience” Policy Landscape

As part of early efforts to understand potential regulatory frameworks for resilience, Sandia collaborated with Bosque Advisors to conduct a survey of regulatory approaches to defining, evaluating, and promoting resilience. Recognizing the novelty of “regulating for resilience” and the potential for learning across institutional contexts, the survey included policies spanning multiple sectors (e.g., energy, financial services, communications, water), jurisdictions (e.g., local/state, national, cross-national, and international), and threats (e.g., natural disasters, intentional attacks, economic shocks, aging infrastructure). A review of relevant scholarly literature was also conducted to better contextualize these policy developments. The resulting analysis of some 240 policies and some 70 academic and gray literature sources suggests that while policies prioritizing resilience (as a concept) are widespread, there remains considerable work to effectively design and implement policies to promote resilience (in practice). This research and analysis resulted in the compendium of relevant resources for the DRC project and the identification of six themes that shaped subsequent work under Task 3 as well as the development of the Resilient Community Design Framework under Task 1.

First, definitions of resilience in policies are heterogenous and subjective. Many of the policies purportedly addressing resilience do not provide a precise definition of resilience, and among those that do, myriad conceptualizations of resilience emerged. The survey suggests that framing, rather than substance, often determines a policy’s “relevance” with respect to resilience. On one hand, there are policies that define resilience as an objective, but neither define resilience metrics nor prescribe an implementation strategy. On the other hand, there are many policies that may enhance resilience (e.g., building codes, cybersecurity standards) but are not explicitly framed as such. Moreover, scholars have observed that regulatory strategies for resilience can be substantive or procedural (e.g., ex post regulatory impact assessment) [60], with the latter being potentially easier to design but harder to detect in a substantively focused survey. Thus, intentionality, specificity, and consistency are clear gaps in policy and underscore the challenge of defining and measuring resilience in practice and the criticality of the multi-stakeholder approach to resilience definitions envisioned in Step 1 of the Resilient Community Design Framework (Section 3.2.1).

Second, there is a disconnect between resilience prioritization and implementation in policy frameworks. As with policy frameworks for other emergent issues, there is an apparent disconnect between policy commitments (e.g., via executive directives, strategic plans) and policy implementation (e.g., via rules, standards) for resilience. A key challenge is moving from policy commitments and programs to rulemaking and standard setting, particularly for sectors in which non-governmental actors are owners and operators and thus policy commitments may not be enforceable without legislative mandates or delegation of authority to regulators. Gaps in implementation underscore the importance of attentiveness to institutional constraints for research and development efforts focused on resilience definitions, metrics, and valuation approaches, underscoring the importance of the iterative application of the Resilient Community Design Framework to enable both incremental and idealized expansion as technology, policy, and market conditions evolve (Section 3.3).

Third, regulation for resilience is nascent in theory and practice. In the academic and gray literature, the importance of regulation in achieving resilience is well documented, but actual regulation for resilience is not well developed in theory or in practice. There is a substantial body of literature on resilience that references the role of regulation, but relatively little work on regulation designed to address resilience issues. The policy survey suggests that these gaps in the literature reflect practice, for which there are insufficient regulatory developments to evaluate resilience approaches systematically across sectors, but episodic progress in certain sectors, often following large disruptions (e.g., natural disasters, financial crises) [61]. One potential explanation for this gap is the absence of analytical frameworks for resilience. For example, a study by the NARUC found that state electric utility regulators tend to deal with resilience events qualitatively because existing quantitative frameworks (e.g., for reliability) are not parametrized for long-duration widespread outages [62]. Another explanation is the absence of legal frameworks for resilience. For example, scholars have argued that because regulatory law is largely ex ante, it is poorly equipped to address emergent risks and thus new legal frameworks that enable more adaptive approaches are needed [60]. At the same time, scholars have observed that the regulation of resilience will largely depend on existing government arrangements [60], suggesting potential opportunities to leverage existing policy processes and analytical capabilities. While addressing legal frameworks for resilience is beyond the scope of the DRC project, the Resilient Community Design Framework directly addresses gaps related to analytical frameworks for resilience. Moreover, subsequent work as part of Task 3 explores policy frameworks, given existing regulatory authorities and governance arrangements, for embedding resilience analysis in electric utility regulatory processes (Section 5.8).

Fourth, resilience programs are comparatively more developed and may inform policy strategies. Resilience regulation lags resilience programs, both internationally and domestically. At the US federal level, much of the resilience activity has been programmatic (e.g., see the Government Accountability Office's 2017 summary of federal efforts to enhance grid resilience [63]) and similar trends were observed cross-nationally and internationally (e.g., see the many European Union funded projects on resilience [64]). There are government-funded projects, initiatives, and voluntary standards for which the line between policy and program is blurred. Scholars have argued that because of challenges with formal legal frameworks for resilience, policies have more often been codified in voluntary or private standards than law [60]. Moreover, programs may directly affect resilience—such as those focused on providing funding to bolster disaster preparedness—or may inform subsequent policies. In the international standard space, the line between policies and frameworks/metrics is also blurred (e.g., United Nations Disaster Risk Reduction). Given this substantial overlap, analyses of policy progress on resilience must be attentive to the role of programmatic efforts in advancing resilience goals.

Fifth, policies often conflate resilience causes and consequences. Resilience policies can be segmented by cause (i.e., threats to resilience) and/or consequence (i.e., unit of analysis for resilience effects), and often policies focus on one or the other, rather than both. With respect to causes, natural disasters seem to have garnered the most work domestically and internationally, although there has also been some episodic-driven interest in financial market shocks (and more broadly, policies focusing on economic and social resilience among Organization for Economic Cooperation and Development (OECD) countries [65]) both domestically and internationally. With respect to consequences, the most prominent binding standards internationally focus on financial markets (e.g., resilience of systemically important banks), whereas in the US much of the current focus is on resilience of critical infrastructure, with some policy focusing on environmental resilience. This finding underscores the importance of evaluating opportunities for learning across regulatory approaches to resilience where there are shared causes, consequences, or underlying challenges as explored in subsequent work under Task 3 (Section 5.8).

Sixth, resilience issues and institutions are highly interconnected and interdependent. Although there is a substantial body of work on community resilience, some of which is multi-level (e.g., state and local), there are key gaps with respect to the interconnectedness and interdependence of resilience planning across the community, national, and international levels. This suggests potential inattention to cascading threats and highlights the benefits associated with more integrative analysis across multiple levels and sectors. Although resilience issues are interconnected and interdependent, regulatory authorities tend to be fragmented, creating coordination and collaboration challenges across sectors and levels [61]. Identifying effective coordination and collaboration mechanisms—as with resilience definitions, metrics, and valuation approaches—requires attentiveness to institutional constraints, motivating further work on coordination strategies for grid resilience under Task 3 (Section 5.8).

The survey and analysis provided a holistic understanding of the regulatory landscape for resilience and highlighted key gaps in existing regulatory strategies for resilience that informed the refinement and implementation of the Resilient Community Design Framework and project efforts more broadly. For example, gaps in implementation suggest a need for more widely accepted definitions, metrics, and valuation approaches. Similarly, a clear area for research and development is the maturation of tools and methodologies that operationalize resilience metrics, as well as strategies to align policy goals with operational constraints. While standardization enables multi scale-analysis, specialization enables incorporation of unique institutional contexts [61]. Where systemic risk is a concern, interconnectedness with broader complex systems may need to be part of the community-level analysis; however, the drivers of resilience may vary at the community level. Thus, analysis of coordination and collaboration mechanisms is another clear gap that the Resilient Community Design Framework helps address through its multi-stakeholder implementation approach. Indeed, the literature consistently notes the importance of inclusive and deliberative stakeholder engagement in the design, evaluation, and implementation of resilience regulation [61, 60].

5.2. Community and Utility Experiences with Resilience Planning

To complement the more macro perspective of the aforementioned survey, Sandia collaborated with Synapse on a series of case studies of community and electric utility pairs engaging in resilience planning. To understand and document the challenges and opportunities experienced by communities and electric utilities aligning their energy-related resilience efforts, Synapse conducted semi-structured interviews to better understand the landscape of resilience planning both within and across jurisdictions. Interviews were conducted with representatives of six community and utility pairs having pre-existing working relationships on energy-related resilience efforts. The sample of communities and their utilities were selected to represent diversity across utility regulatory structure, region, threat types, and community size. They included: Hoboken, New Jersey and Public Service Electric and Gas Company; Norfolk, Virginia and Dominion Energy; Salt Lake City, Utah and Rocky Mountain Power; Tallahassee, Florida and the City of Tallahassee Electric Utility; Los Angeles, California and the Los Angeles Department of Water and Power; and Cordova, Alaska and the Cordova Electric Cooperative.

Interviews were semi-structured with separate but related series of standardized questions provided to utility and community representatives. The utility representatives interviewed were utility managers, lead or principal power system engineers, or staff responsible for grid investment planning and modernization efforts and directly involved in resilience efforts at the utility. The community representatives interviewed were leading resilience efforts for municipal governments as Chief Resilience Officers or Mayors. Several key findings emerged from these case studies.

First, communities and utilities were experiencing increased interest in and commitment of resources for energy-related resilience. While the types of threats they experienced varied widely, the risks and consequences these communities and utilities face in the past, present, and in the future drove them to improve engagement, advance processes, further decision-making, and in many cases invest in projects. However, no process used by the communities and utilities was the same. The different processes used by communities and utilities allowed each one to make progress in its own way. For example, the resilience activities of communities located in Utah, Virginia, and New Jersey were propelled by state leadership while the cities of Norfolk, Tallahassee, Hoboken, and Los Angeles were leading by convening a broad group of stakeholders including utilities to develop resilience plans. Los Angeles and Norfolk were expanding existing processes to include resilience, such as sustainability and climate planning, economic development initiatives, and neighborhood revitalization projects. The utilities interviewed were expanding their resilience services and offerings, particularly related to storm hardening, critical load prioritization, and backup power options. Grid modernization and non-wires alternatives proceedings in some jurisdictions were providing additional opportunities for more comprehensive planning.

Second, communities and their utilities differed in their definitions of resilience and ways of assessing their performance on resilience, consistent with themes from the "regulating for resilience" survey (Section 5.1). Communities, utilities, and utility regulators lacked a shared framework for evaluating costs and benefits for a wide variety of potential resilience measures. Moreover, in most circumstances, resilience-related investments needed to provide benefits on blue-sky (normal) and black-sky (resilience event) days to be implemented. The finding that investments needed to be assessed for both resilience and reliability benefits informed the structure and content of the performance metrics report and associated template, discussed in Section 5.6. While jurisdictions should have some flexibility in customizing their performance metrics to address local circumstances and needs, some standardization of key performance metrics was helpful for context and comparison in electric utility proceedings. As a result, the performance metrics report evolved into more of a user guide for implementing performance metrics and a suite of potential metrics for consideration and the template evolved from a quantification of several resilience related performance metrics for one utility to a broader suite of performance metrics for further evaluation in different jurisdictions and discussion about how they could best be applied. The lack of adoption and application of a standard approach for quantifying resilience costs and benefits was also identified as a gap by interview participants, which informed confirmed the scope of the BCA report discussed in Section 5.5. The BCA approach needed to be applied to a wide range of resilience solutions and to demonstrate how to combine blue and black sky costs and benefits for a series of potential investments into a single benefit-cost ratio to inform decision-making.

Third, communities and utilities more experienced with resilience planning continued to express resource challenges in getting to fully integrated planning that considers resilience, with other initiatives and investments competing for staff time and investment dollars. In some cases, communities served by Investor Owned Utilities (IOUs) had the resources to engage more in utility processes. However, many communities served by IOUs with large service territories faced logistical challenges working together on resilience planning. This finding informed the scope of regulatory mechanisms report, discussed in Section 5.4, highlighting that the report needed to explore a broad range of regulatory approaches beyond integrated planning. In particular, the report seeks to investigate the opportunities in current and future planning processes for robust community participation, consideration of the costs and benefits of a wide range of potential resilience solutions, and development of customizable solutions to meet different communities' needs.

The full report, titled *"The Resilience Planning Landscape for Communities and Electric Utilities,"* is available in Appendix A.

5.3. Electric Utility Regulator Perspectives on Resilience

To better understand electric utility regulators' perspectives on resilience and key challenges in "regulating for resilience", Sandia and Bosque Advisors collaborated with NARUC and the DOE's Office of Electricity to convene a workshop on "Regulating for Resilience" for electric utility regulators, which was held during the 2019 NARUC Annual Meeting and Education Conference in November 2019. The workshop was attended by some 60 participants, including public utility commissioners and their staff, federal and state government agencies, infrastructure owners/operators, interest groups, and research and consulting organizations.

Through facilitated breakout and large group discussions, workshop participants explored various themes including (1) defining and measuring resilience, (2) regulatory approaches for resilience, (3) resilience mitigations and investments, and (4) valuing resilience. The following sections summarize key questions and insights that emerged from the thematic breakout discussions as well as cross-cutting findings, which serve to both substantiate the general themes that emerged from the case studies, landscape survey, and literature review, and provide a more nuanced understanding of PUC challenges and opportunities in addressing resilience.

With respect to defining and measuring resilience, participants explored how existing definitions were operationalized, for example, whether resilience metrics were threat-agnostic or threat-informed, considered acute and/or chronic threats, and were attribute or performance-based (and if the latter, whether they also measured consequence). The discussion revealed that PUCs are very attuned to the importance of consequence-focused metrics, and highlighted needs related to prioritizing critical loads—which might include those serving drivers of economic activity in a given area—and measuring health and safety impacts. The discussion also underscored the importance of considering how the selection and implementation of particular metrics affect energy equity (e.g., via restoration prioritization). Moreover, reflecting the broader interdependencies theme of the workshop, the metrics breakout group identified the need to jointly consider electricity and natural gas outages in the winter (and attentat challenges with defining outage duration for fuel security requirements) and identified opportunities for learning across water and other infrastructures sectors.

With respect to valuing resilience, participants explored how resilience is prioritized relative to other goals/mandates (e.g., reliability, sustainability), how different resilience metrics and consequences are prioritized, and the methodological and implementation challenges associated with valuing resilience. The discussion revealed that while resilience valuation could be supported through better understanding of prior events, accessing and analyzing historical event data can be challenging. Moreover, for certain events there are no historical examples from which to draw insights and opportunities for inference may be limited by variation in threats and operating environments across states. Another discussion noted that even with available data, PUCs may not be sure what questions to ask in the data collection or analysis stages. Moreover, PUCs need to consider utilities' privacy concerns, for example, related to disclosing cybersecurity vulnerabilities. Relatedly, resilience valuation should make the costs and benefits of resilience tangible. The "value" of resilience is most salient to those communities that have experienced a recent disruption. Critically, valuation must reflect multiple stakeholder perspectives and include consideration of affordability for ratepayers, impacts to taxpayers, and a suite of societal values. Existing valuation approaches tend to capture only a subset of all relevant perspectives (e.g., ICE Calculator produces estimates of customers' "value of lost load," a metric of direct economic impact derived from contingent valuation surveys). Moreover, valuation should be objective and not be dominated by a specific stakeholder's perspective

With respect to resilience mitigations and investments, participants explored what potential resilience mitigations exist (e.g., physical, policy, procedural), how potential investments should be evaluated, what would be needed to feel confident that the mitigations could be applied, and whether there are "no-regrets" high "bang-for-the-buck" investments. The discussion illuminated that PUCs have an opportunity to lead resilience conversations. Specifically, convening represents a "high bang-for-buck investment" that could enable broader stakeholder recognition and public interest, thereby serving as a precursor to more formal utility investment processes. These stakeholder engagements could discuss resilience objectives and options, employing accessible language and focusing on opportunities for partnership. Successfully implemented, such engagements could inform utilities' planning processes and regulators' decision-making process. However, involving multiple stakeholders is not a silver bullet and there are challenges that must be addressed for productive engagement, for example, it is difficult for people to "transcend" past practices in favor of the common good and to ask people to prioritize investments in one area over another. Another high "bang-for-buck investment" is jointly exercising incident response and recovery capabilities. Utilities and their stakeholders may derive key benefits from practicing their plans together—utilizing scenarios that involve high-consequence threats—to identify gaps, overlaps, and inconsistencies. Additionally, there is an opportunity to educate non-energy stakeholders on issues specific to the grid (e.g., the special permitting treatment that qualifying resilience resources may receive under Emergency Support Function 14) as well as to inform state emergency management office processes. A final high 'bang-for-buck investment" involves consideration of micro-approaches to resilience, such as updating local zoning requirements to "build in" resilience.

With respect to regulatory approaches for resilience, participants explored how commissions are currently incorporating resilience into regulatory processes and how, given existing authorities and resources, commissions could further incorporate resilience into regulatory processes. The discussion also considered how the regulatory process in which resilience is embedded affects how it is measured (e.g., BCA requirements), which aspects of resilience involve entities outside the commission, and the key stakeholders and (existing or needed) coordination mechanisms. The discussion revealed that Public Utility Commissions (PUCs) are still defining resilience and their roles in regulating it. While PUCs have clear regulatory authorities for reliability, PUCs do not fully understand their authorities for resilience. PUCs may be hesitant to act without a clear legislative mandate and suggested the need for an inventory of states' authorities for resilience (underscoring the breadth of the "regulating for resilience" survey in Section 5.1). Moreover, PUCs do not fully understand what existing practices or investments may fall under the "resilience" umbrella and suggested value in identifying existing expenditures proposed in rate cases that may promote resilience; delineating benefits across reliability and resilience dimensions is a key challenge. Plus, there are many potential regulatory strategies to incorporate resilience, but feasibility depends on underlying authorities. Examples of identified mechanisms include focused resilience proceedings, guidance/approval for investment planning, guidance/approval for utility pilots, rate cases, research/focused staff investigations, and convening stakeholder workshops/meetings (these and other regulatory mechanism are explored in Sections 5.4 and 5.8). As discussed in the context of valuation, concerns about data availability and privacy are paramount.

Relatedly, PUCs cannot address resilience on their own and, reflecting a broader theme of the workshop and indeed a core motivation of the DRC project, the discussion noted that stakeholder coordination is essential. In particular, PUCs need to work with their federal counterparts (e.g., transmission-distribution coordination is a challenge and federal funding is a potentially underutilized opportunity), state emergency management agencies (e.g., understanding state agencies vs. PUCs authorities in emergencies is needed), and state legislatures (e.g., some PUCs seem themselves as resilience policymakers, while others see themselves as implementers of policy set by legislatures). Scenario-based and road mapping exercises have been a useful coordination mechanism, but there is a need for more frequent and detailed exercises (the role of scenario-based exercises in gird resilience planning is discussed in Sections 5.8).

Through these discussions, several cross-cutting findings emerge that are particularly relevant to the development of regulatory frameworks for resilience as part of the DRC project. First, all of the participating utilities and all but one PUC are, or expect to be, involved in at least one resilience proceeding. Many other stakeholders reported being involved in resilience proceedings via the provision of research, benchmarking, best practices, and/or technical assistance for PUCs, utilities, and other stakeholders. This finding suggests a broad understanding of what constitutes a resilience proceeding among PUCs, consistent with the findings of the landscape survey. Second, the electric grid has myriad stakeholders, and mechanisms and incentives for stakeholder coordination vary. PUCs have an opportunity to serve as conveners of various stakeholders, including infrastructure owners/operators, state/local policymakers, community and business interest groups, and citizens/customers. Third, PUCs are concerned about not only threats to electric grid resilience, but also resilience threats affecting and emerging from interdependent infrastructure systems. Given their jurisdiction over multiple infrastructures (e.g., electricity, natural gas, water, telecommunications), PUCs may be uniquely able to advance multi-infrastructure resilience analysis and to facilitate learning across infrastructures. While state-of-the-art resilience analysis capabilities are of interest to PUCs, many are in the early stages of defining, measuring, valuing, and regulating resilience. More than anything, PUCs need help to just "get started" and would value strategies to initiate conversations with relevant stakeholders to build shared understanding of the issues. Together these findings underscore the value of Resilient Community Design Framework for developing multi-stakeholder resilience analysis and highlight the need to develop both incremental and idealized regulatory frameworks—and associated metrics and valuation approaches—for resilience.

The agenda and a summary memo for the "Regulating for Resilience" workshop are available upon request and the workshop slides link is in Appendix A.

5.4. Regulatory Mechanisms for Resilience

To address issues identified by PUCs, communities, and utilities, Sandia collaborated with Synapse on a report exploring how regulatory mechanisms may enable investments in electric utility resilience. Given that cost-of-service regulation may fail to provide utilities with adequate guidance or incentives regarding community priorities for infrastructure hardening and disaster recovery, the focus of this research was identifying and characterizing other regulatory mechanisms that electric utility regulators can use to align utility, customer, and third-party investments with regulatory, ratepayer, community, and other stakeholder resilience interests and priorities. The report explores several regulatory mechanisms—performance-based regulation, integrated planning, tariffs and programs to leverage private investment, alternative lines of business for utilities, enhanced cost recovery, and securitization—and provides examples of how these mechanisms have been applied to resilience.

The report characterizes the desired outcomes for key regulatory objectives including: continuity of electric service (i.e., adequacy, preparedness, and efficient process), ensuring reasonable rates (i.e., investment diversity, balancing costs with benefits, and stable, reasonable rates and bills), customer equity (i.e., consideration of vulnerability and differential cost allocation), in the public interest (i.e., stakeholder input and consideration of other policy objectives), and measured and measurable (i.e., performance measurement and evaluation). It identifies regulatory mechanisms that are used or can be adapted to improve the resilience of the electric system and provides a case study of each mechanism. Additionally, it summarizes findings across the case studies based on level of achievement of desired outcomes for each regulatory objective. Finally, it suggests how these regulatory mechanisms might be improved and applied to resilience moving forward.

The report concludes that the included regulatory mechanisms are not currently structured or applied to effectively address resilience, nor do incentives align well with the resilience goals of ratepayers and community representatives. Overall, the research indicated that application of regulatory mechanisms to resilience investments is in the early stages and case studies are few and far between. Where regulatory mechanisms are applied to resilience, goals other than resilience were the primary drivers and resilience was not well integrated. Additionally, resilience was not a regulatory objective in one of the case studies.

Moreover, the limited data thus far suggest that, as applied to date, no single mechanism achieved all regulatory objectives and associated desired outcomes. Additionally, no regulatory objectives and associated desired outcomes were achieved by all the mechanisms. Lastly, all the regulatory mechanisms fell short in two areas: first, requiring consideration of and comparison of the full range of investments utilities and third parties can make to address resilience challenges (referred to as investment diversity) and second, partnering with stakeholders and considering their viewpoints (referred to as stakeholder input). Thus, as currently implemented, each mechanism had shortcomings and therefore did not enable full resilience investments. With improvement, these regulatory mechanisms had the potential to address resilience goals, however, multiple approaches likely need to be implemented together to address resilience more fully.

The full report, titled *"Regulatory Mechanisms to Enable Investments in Electric Utility Resilience,"* is available in Appendix A.

5.5. Integrating Resilience into Benefit Cost Analysis

Valuing resilience was a key theme at the "regulating for resilience" workshop (Section 5.3) and across engagements with stakeholders more broadly. In response, Sandia collaborated with Synapse on the development of a report detailing best practices for integrating resilience into BCA, providing an approach that electric utilities, electric utility regulators, and communities can use to evaluate the costs and benefits of a wide range of grid resilience investments holistically and transparently. Specifically, the report extends the 2020 "National Standard Practice Manual for Benefit-Cost Analysis of Distributed Energy Resources" to grid resilience investments. The framework presented in the resulting report is a resilience-inclusive BCA that recognizes that resilience is one of several goals when planning grid investments; given that resilience may not be the only or primary reason for making the investment and that there may also be costs and benefits that are not resilience-related.

Prior research [62] and interviews for the landscaping report confirmed that BCA was regularly applied to some types of grid investments, but the application of BCA to grid resilience investments was still nascent. Indeed, resilience was increasingly cited in connection with grid investment proposals and plans, but the resilience-related costs and benefits of grid resilience investments were typically not fully identified, infrequently quantified, and almost never monetized. Moreover, regulators were hesitant to approve some types of grid resilience investments without complete assessments of the resilience-related costs and benefits.

The BCA report addresses these gaps by providing the following: naming and definitions for the costs and benefits that were relevant to grid resilience investments; a catalogue of the many types of grid resilience investments; an illustrative example of how to include these resilience impacts in a BCA; other considerations that were relevant to BCA for grid resilience investments, including the probability of occurrence, temporal and locational variability, and interactive effects; a summary of metrics and data needed to quantify the costs and benefits of resilience; and guidance on next steps for implementation of BCA for resilience investments.

The report also identified next steps suggesting that regulators, utilities, communities, and other stakeholders work together to advance BCA practices for investments that can achieve grid resilience, among other goals and identified roles and responsibilities for each. Regulators can direct utilities to undertake BCA of investments, including resilience investments, in all relevant proceedings, including integrated resource planning, (integrated) distributed system planning, grid modernization, non-wires alternatives, energy efficiency, and renewable energy proceedings. Regulators can also develop standardized BCA principles and practices that assess grid investments comprehensively and consistently for their jurisdiction, including identifying policy priorities, constructing a Jurisdiction Specific Test, discussing approaches for accounting for non-monetized benefits, considering the processes and proceedings that warrant a resilience-inclusive BCA. Additionally, regulators direct utilities to take the lead on collecting and organizing resilience data by establishing resilience performance metrics. Utilities can develop a full inventory of costs and benefits pertinent to resilience in investment proposals; assess resilience costs and benefits, especially those that are most impactful. Utilities can also act as a central repository for the data and lead the reporting of resilience performance metrics. Communities and other stakeholders can support utilities by providing resilience-related data that utilities cannot readily access. Finally, utilities, communities, and other stakeholders, such as research institutions, can conduct research and analysis to address gaps in data needed to understand costs and benefits of grid resilience investments.

The report concludes that proactive integration of grid resilience investments into existing regulatory processes and practices can increase the capacity of jurisdictions to respond to and recover from the consequences of extreme events. With improvements to BCA, utilities and regulators can better understand the costs and benefits of grid resilience investments. Utilities can present a range of options for regulatory consideration and regulators can evaluate these options. The report also includes a section on data needs which identified a series of potential performance metrics to support benefit-cost analysis that were integrated into the performance metrics report.

The full report, titled *"Application of a Standard Approach to Benefit-Cost Analysis for Electric Utility Resilience Investments"* is available in Appendix A.

5.6. Resilience-Oriented Performance Metrics

As discussed throughout this report, performance metrics define the information that utilities, regulators, communities, and other stakeholders can use to monitor grid performance of resiliency investments. However, there is no established set of standard performance metrics for resilience, and many of the metrics that have been proposed in the literature required extensive data, modeling, and analysis to develop. In response, Sandia collaborated with Synapse to develop a report to help jurisdictions in defining and establishing performance metrics for resilience based on readily available data.

The report provides: a roadmap of the performance mechanism development process, which identifies and names the steps in the process, discusses the sequence of the steps, defines key terminology associated with each step, and categorizes the steps as necessary or optional; a list and discussion of seven principles for developing well-designed performance metrics; a menu of performance metrics for grid resilience and associated discussion, for consideration by utilities and their regulators; and an Excel based template visualizing these performance metrics in the form of reporting frameworks for utilities to track their performance and provide ongoing updates to regulators and other stakeholders.

These metrics focus on annual event-level, customer-level, and system-level performance, and break out performance into key customer and geographic subsegments. The menu of metrics contained in the report Excel-based template is intended to provide a starting point for utilities, regulators, and stakeholders to develop metrics that are tailored to the needs and data available in a given jurisdiction, and quantified with reasonable effort. Because these metrics are achievable, they served as a bridge between current best practices for resilience quantification and the consequence-focused metrics being developed (as discussed in Section 3.2.1.1.4), providing opportunities for both incremental and idealized approaches to measuring resilience performance.

The report concludes that utilities can lead the development of resilience performance metrics, which in turn can be proposed to regulators and suggests a process by which this can be achieved. First, regulators and utilities can hold a technical session to review the suggestions in the Excel-based template and identify resilience performance metrics of interest. Second, once a regulator approves the utilities' proposed resilience performance metric reporting template, utilities can populate the metrics using actual data and review the calculations and outputs with regulators and other stakeholders at a subsequent technical session. Third, utilities can formally file baseline performance metrics in the proceeding of their regulators' choosing and with a frequency that makes sense for that jurisdiction. Fourth, once the baseline data is established, the utility, regulator and other stakeholders can work together to identify performance metrics that need improvement and discuss the level of improvement desired. Fifth, utilities can explore many investment options to achieve the goals. Utilities can offer programs to promote customer implementation of measures that achieve the desired improvement. Utilities can also implement measures directly to achieve the desired levels of improvement. Utility investment proposals should identify the resilience performance metrics of interest and the impacts of the potential investments on the resilience performance metrics. Sixth, after utilities select investments to pursue and implement the measures, resilience performance metrics can demonstrate the impact of the investments. Finally, the report also suggests ongoing review and update of the performance metrics to document progress, allow for adjustments, and identify new opportunities over time.

The full report, titled *"Performance Metrics to Evaluate Utility Resilience Investments"* is available in Appendix A.

5.7. Public Purpose Microgrids for Resilience

Resilient public purpose microgrids—defined as microgrids that serve public interests in island mode on extreme event days, in addition to interconnected mode on normal days—were identified as a technology of broad interest by the SAG and discussions with communities and utilities in interviews for the landscaping report. However, a literature review revealed that microgrid project proponents are coming before PUCs to request electric ratepayer funding to cover part or all the costs. Utility regulators have rarely approved ratepayer investments in microgrids, whether they were designed to improve resilience or not. Building on this insight, Sandia collaborated with Synapse on a report that identifies the features of microgrids, including potential resilience value, which were apt to receive electric utility regulatory approval and ratepayer funding. The resulting report focuses on microgrids that were in operation and received approval to apply utility ratepayer funding towards a portion of the cost.

Specifically, the report uses the key regulatory objectives for achieving resilience from the regulatory mechanisms report to define the term "resilient public purpose microgrid" and characterize five project types; provides a case study and findings for each project type; summarizes findings across the case studies; and proposes next steps. The report finds that implementation of individual demonstration projects provides important insights into the development of utility system-wide resilient public purpose microgrids in the areas of service strategies, project design guidance, and funding sources and levels. Several thematic strengths and weakness were also identified in the case studies, such as resilience as a specific, measurable goal, alignment with utility system needs (addressing siting and sizing), explicit provision of community needs, application of ratepayer funding, and multi-project assessment and prioritization.

The report concludes that resilience investments such as microgrids can be funded by ratepayers when one or more of the following are achieved: when the load to be served is critical, when needs beyond the host customer (such as utility and community needs) are met, when the normal day benefits of the project exceed the costs, and when other funding sources can be applied to cover all, or a portion of, the additional costs related to resilience. Additionally, strategically directed and properly planned portfolios of resilience investments, rather than infrequent one-off projects, will likely be required to add resilience to the utility system.

Moreover, public purpose microgrid project proposals could be stronger with direction from regulators, including utility system requirements related to siting and sizing of microgrids and the availability of ratepayer funds. Regulators can provide guidance for utilities and project proponents to refer to as they develop microgrid project proposals that are resilient and serve public interests. Defining replicable categories of projects, or project types, can help evolve proposals from individual projects to suites of solutions. Building from the project examples identified in this report, regulators can use these inputs to define replicable, recognizable project types which can lead to development of more standardized regulatory processes and practices for ongoing project review.

There are many opportunities to advance resilient public purpose microgrid project development and regulatory review, to the benefit of regulators, utilities, communities, and other stakeholders. With explicit guidance from regulators, project proponent teams including utilities and communities can propose better projects, and more of them. Project types that are well defined and broadly replicable can streamline regulatory review. Projects that excel at achieving key regulatory objectives should be eligible for ratepayer contributions to cover a portion or all the costs. Regulatory proceedings including, but not limited to, integrated system planning, grid modernization, and non-wires alternatives can then focus on the level of ratepayer contribution and cost allocation to different beneficiaries through novel rate designs. Some regulators may be apprehensive that total ratepayer contributions may become unwieldy using this approach. However, there are safeguards that can be put in place to address this concern. For example, caps for certain types of investments can be established to set reasonable limits. These limits should be based on outputs from modeled scenarios in planning proceedings that are specifically designed to address and improve resilience.

The full report, titled *"The Quest for Public Purpose Microgrids for Resilience: Considerations for Regulatory Approval,"* is available in Appendix A.

5.8. "Stress Testing" to Enhance Grid Resilience

A key theme across the research conducted under Task 3 is that developing regulatory frameworks for incentivizing efficient resilience investments and monetizing resilience benefits is not only a challenging analytical undertaking, but also requires navigating complex governance arrangements. As the landscape survey demonstrates (Section 5.1), progress on regulatory strategies for resilience across sectors is uneven and, as the workshop with regulators and related research underscores (Section 5.3), many resilience issues span the jurisdictions of different local, state, regional, and national entities. As such, regulatory framework for electric grid resilience should both incorporate opportunities for translation of best practices across sectors and enable coordination among the myriad stakeholder that determine and depend upon grid resilience. To address this opportunity, Sandia collaborated with Bosque Advisors to analyze opportunities for cross-sector learning in performance-based approaches to "regulating for resilience." Specifically, this research explores how post-global financial crisis regulatory strategies for measuring and managing financial systemic risk—and in turn, promoting the resilience of the financial system—could inform regulatory strategies for electric grid resilience. Recognizing the opportunity for translation across sectors and disciplines, this research provides an approach for leveraging the Resilient Community Design Framework to inform regulatory and utility investment decisions for resilience and makes five related contributions to the broader academic and applied discourse on regulating for electric grid resilience.

First, it builds upon the survey of resilience policies and literature discussed in Section 5.1 to explore and address the gap between the policy prioritization of resilience and the exploration of regulatory strategies for resilience in the literature, which inhibits regulatory implementation practices. Consistent with findings in Section 5.1, this research defines "regulating for resilience" broadly as encompassing the design, implementation, and evaluation of policies to enhance resilience. It identifies two key analytical and governance challenges associated with "regulating for resilience," which are particularly relevant to the energy and financial services sectors broadly and electric utility and banking regulation specifically. The first challenge is bridging system-level policy goals (i.e., energy or financial system resilience) and institution-level policy instruments (i.e., utility or bank risk regulation). The second challenge is tailoring these institution-level requirements to the idiosyncratic risk profiles of individual firms, based on performance of critical functions (e.g., supplying electricity or intermediation).

Second, it explores how financial regulators have addressed the analytical and governance challenges associated with "regulating for resilience" and provides a comprehensive assessment of the evolution, application, and evaluation of a core regulatory tool: financial stress testing. Financial stress tests are scenario-based modeling exercises to prospectively assess the resilience of a financial institution's balance sheets to hypothetical future adverse macroeconomic and financial market conditions. Stress tests are well-institutionalized in the U.S. regulatory system and are used for both risk measurement and management by assessing how hypothetical scenarios would affect individual firms and the financial system as well as informing calibration of prudential regulations and participating firms' risk management processes. The research demonstrates how stress testing has enabled bank regulators to partially address the challenges associated with "regulating for resilience" by providing a methodology to calibrate regulatory requirements (i.e., capital buffers) to the risk profiles of individual banks based on a dynamic evaluation of both performance and process. It also shows how they can analyze the accumulation and propagation of systemic risk and the consequences of potential regulatory responses. Finally, it summarizes how post-global financial crisis reforms, including stress testing, have resulted in better capitalized and managed banks, increased attentiveness to systemic risk, and a more resilient financial system.

Third, given the shared analytical and governance challenges faced by bank and electric utility regulators and leveraging lessons learned from financial stress testing, this research demonstrates how stress testing can be used to advance regulatory frameworks for grid resilience. Electric utility stress tests would be scenario-based modeling exercises to prospectively evaluate utility resilience to different hypothetical threat scenarios and to evaluate potential resilience investments via performance-based metrics. Utility stress tests could inform risk measurement and management by evaluating utility performance and processes for preparing for, adapting to, withstanding, and recovering rapidly from hypothetical hazards as well as informing prioritization and regulatory oversight of investments to bolster resilience (and potentially other goals, such as sustainability) and helping institutionalize "resilience thinking" in planning and operational decisions. Moreover, the implementation of electric utility stress tests could inform the development of resilience standards, incorporation of resilience analysis into state and local regulatory processes and enable regional and national coordination and integration. Thus, stress testing could help electric utility regulators overcome the analytical and governance challenges associated with "regulating for resilience." The first challenge is tailoring requirements (e.g., investment incentives) to the idiosyncratic risk profiles of individual utilities, based on simulated or actual performance of critical functions under adverse conditions (i.e., delivering electricity to all [priority] loads) and stress testing could provide regulators with a methodology for evaluating potential investments based on resilience benefits that accounts for the idiosyncratic risk profiles of individual utilities. The second challenge is bridging system-level policy goals (i.e., energy sector resilience) and institution-level policy instruments (e.g., electric utility investment approvals) and stress testing could provide utility regulators with a methodology for localized resilience investment prioritization, that informs, and is informed by, regional or national-level assessments of resilience.

Fourth, it leverages the Resilient Community Design Framework to develop a novel methodology and an actionable policy framework for embedding stress testing in electric utility investment strategies and regulatory processes, as summarized in Figure 28. It explores how stress testing could be designed by regulators in coordination with DOE national laboratories and other stakeholders (left of Figure 3), implemented by utilities (middle of Figure 3), overseen by state and local utility regulators (top of Figure 3), and coordinated across federal and regional stakeholders to both ensure technological feasibility and enable system-level aggregation and analysis. It uses a notional example to demonstrate how the proposed methodology could be used to evaluate and enhance grid resilience through a hypothetical utility stress test focused on the effects of a hurricane on distribution system infrastructure performance and associated economic and social consequences.

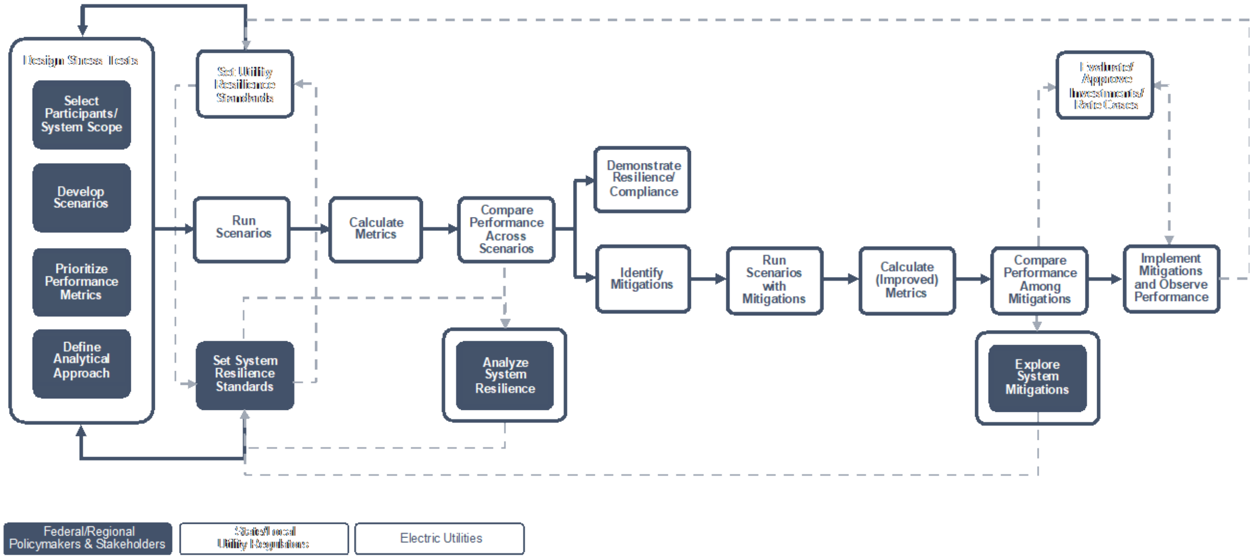

Figure 28: Proposed stress testing framework for electric utilities (Source: [66])

Finally, this research explores the relationship between resilience and environmental sustainability, observing that in the context of the electric grid they are potentially complementary system goals with distinctive temporal dimensions and distributional considerations for which stress testing might support both quantification of tradeoffs and adjudication among diverse stakeholder values. The notional example highlights how, for example, concurrent quantification of resilience and decarbonization benefits of candidate investments might enable more optimal mitigations that siloed analysis, consistent with feedback from regulators, communities, and other stakeholders throughout the DRC project. Moreover, focusing on the relationship between resilience and environmental sustainability underscores the benefits of cross-sector regulatory coordination. For example, stress testing is becoming an essential risk measurement and management tool for financial regulators' approaches to measuring and managing climate-related (systemic) financial risks, which are concentrated in emissions-intensive and climate-sensitive sectors like the electric power sector [67], underscoring opportunities for regulatory coordination in multi-sector analyses of climate-related risk and resilience.

The full report, is available upon request and a derivative journal article, titled *"From Systemic Financial Risk to Grid Resilience: Embedding Stress Testing in Electric Utility Investment Strategies and Regulatory Processes"* published in the Journal of Sustainable and Resilient Infrastructure [66] is available online, and slides from several academic conferences at which it was presented are also available online.

5.9. Synthesis of Lessons Learned

The Task 3 research and engagement investigating alternative regulatory frameworks for incentivizing efficient resilience investments and monetizing resilience benefits highlights five key themes.

First, despite substantial policy and practitioner interest in grid resilience, the multi-stakeholder adoption of consistent definitions of and measurement strategies remain key impediments to the development of regulatory frameworks for resilience. There are opportunities to build on relevant national frameworks—such as the Institute of Electrical and Electronics Engineers' (IEEE's) Reliability Standards and FEMA's National Risk Index—to provide greater standardization of resilience definitions and metrics while enabling regional flexibility. There is also a need to develop and document a standardized definition of criticality that focuses on critical services (rather than critical loads), recognizing that there may be differences in which services are deemed critical to which communities. Definitions of critical services should include consideration of disadvantaged and vulnerable communities, for example, services that alleviate social burden. Moreover, measuring resilience should reflect consequences to society, even when those consequences are relatively low probability.

Second, resilience planning does not occur in a vacuum and thus regulatory frameworks for resilience should both consider the role of resilience in existing planning processes and enable multi-objective decision-making, particularly to account for tradeoffs or complementarities among resilience, environmental sustainability, and equity goals. For some jurisdictions, existing planning processes and regulatory mechanisms may enable incorporation of resilience. For others, however, new planning paradigms and novel regulatory mechanisms may be needed. There is also a need for guidance on multi-criteria decision making that weighs and balances existing regulatory objectives with new objectives such as equity, sustainability, and resilience. Improving resilience performance may or may not improve energy equity and environmental sustainability. With respect to energy equity, grid planning processes can be inaccessible to vulnerable and disadvantaged communities, which often bear disproportionate burden of long duration widespread outages (e.g., due to slower restoration times), and thus planners need to both dedicate resources to proactively engaging and incorporating the perspectives of these communities in resilience planning processes (procedural justice) and assessing how alternative resilience investments would affect grid performance and consequences for these communities (i.e., distributive justice). With respect to environmental sustainability, while fossil fuel-based backup generation is currently often a least-cost resilience solution, community microgrids with renewable distributed generation and storage resources can be designed to cost effectively enhance both resilience and sustainability objectives (e.g., by supporting decarbonization).

Third, there is no one-size-fits-all approach to resilience mitigation investments and regulatory frameworks must balance blue and black sky performance as well as more local versus more global solutions. Utilities will need to develop solutions that can be customized to better meet the needs and values of communities with different priorities and vulnerabilities. For example, addressing the resilience needs of disadvantaged populations and environmental justice communities may require a different set of solutions than addressing the resilience needs of commercial customers. In most circumstances, resilience-related investments will need to provide benefits on blue and black sky days. Resilience investments can be evaluated and compared via BCA using the framework developed in this report, but approaches for more fully quantifying and monetizing the distribution of resilience benefits need to be expanded and refined. Moreover, microgrids play an important role in resilience, but project types need to be well defined and excel at achieving key regulatory objectives to be eligible for ratepayer contributions to cover a portion or all the costs.

Fourth, regulatory frameworks for resilience should incorporate diverse stakeholder perspectives and reflect the roles and responsibilities of regulators, utilities, communities, and other stakeholders in resilience planning processes. There is an opportunity for regulators, utilities, and communities to pilot the next-generation collaborative approaches identified through the project and each play an important role in advancing resilience planning. Regulators can direct utilities to assess resilience in relevant grid planning processes, develop standardized principles and practices for resilience quantification, direct utilities to collect data and report resilience data and metrics, and provide guidance for utilities and project proponents (e.g., for resilience public purpose microgrids). Utilities can take the lead on developing and populating performance metrics, screening and optimizing project ideas for utility system impacts, acting as project owners or support third-party project owners in technologies that advance resilience, and proposing rate structures or riders to collect the appropriate portion of total costs from ratepayers. Communities can assist with characterizing threats and quantifying consequences, providing data and input to regulators and utilities to avoid or minimize lost opportunities, and informing utilities and regulators of federal, state, and local legislation, policies, and funding sources relevant to these projects. Community leaders can also represent groups or demographics of people who are disproportionately favored or conspicuously absent from discussions. Other stakeholders can advocate for important outcomes such as community resilience, sustainability, customer rights and protections, equity, and environmental justice by working with utilities and others to conduct new research and analysis to fill gaps in current understanding.

Fifth, regulatory frameworks for resilience may require novel governance arrangements to enable coordination across jurisdictions, regions, and sectors. There is an opportunity to continue cross jurisdictional discussion and collaboration through a forum for regulators, utilities, community members, and other stakeholders focused on a more specific topic area of broad interest. There is broad interest in continuing to discuss how utilities can incorporate resilience into IRP and other planning processes, and establishing a forum could enable participants to exchange ideas, cultivate best practices, and discuss methodologies with a goal of developing several broadly relevant and replicable use cases as well as a menu of options for incorporating these use cases into decision making. The implementation of these use cases could follow the pilots in leading jurisdictions and culminate in broader involvement by a larger pool of jurisdictions. There is also need to identify ways to merge top-down federally funded and coordinated efforts e.g., through DOE, FERC, DHS, and HUD)) with bottom-up initiatives that are led by communities. Analytical and governance frameworks to support benchmarking and improving resilience across sectors and jurisdictions is an active area of research [66].

6. TASK 4: HARDWARE DEMONSTRATION OF "RESILIENCE NODES" CONCEPT

Sandia and project partners addressed technical challenges in Task 4 that covered clean resilience nodes and completed a hardware demonstration of adaptive protection on a resilience node. One of the key challenges for clean inverter-based microgrids is the ability to safely protect them. While distributed energy resources can impact distribution system protection, there are potential solutions using machine learning, traveling wave, and adaptive protection. To overcome technical challenges in clean resilience nodes, Sandia collaborated with New Mexico State University on modeling grid forming inverters for protection studies, and on installing, testing, and validating designs using power hardware in the loop for demonstration at Sandia's Distributed Energy Technologies Laboratory (DETL). Additionally, Sandia is collaborating with Clemson University on adaptive protection designs for inverter-dominated microgrids, also for demonstration at Sandia's DETL. Sandia is also working with National Grid on a hardware demonstration of adaptative protection on a resilience node. The demonstration seeks to enhance the resilience of the Old Forge and involves a >70-mile microgrid powered by a large battery energy storage system and includes five substations in the microgrid, all connected with a 46 kV sub-transmission line.

Please reference the separately published SAND report: *"Final Technical Report: Designing Resilient Communities: Hardware demonstration of resilience nodes concept"*.

7. CONCLUSION

The Designing Resilient Communities project contributed to understanding and internalizing several facets of the resilience externality. Namely, this project has broken ground to demonstrate a more systematic and quantitative connection between the goals of communities and electric utility planners. The project has done so across several dimensions:

- Reviewed a broad landscape of resilience planning practices across jurisdictions, and identified examples of utilities and communities working together to define resilience goals and approaches, including by employing quantitative resilience metrics.
- Provided a forum for representatives of city governments and the electric utilities that serve them to discuss resilience objectives and approaches and associated challenges and opportunities, with. Collected feedback from this advisory group (the SAG) on all elements of the DRC research.
- Broadened the perspectives of the SAG through strategic engagement with public utility commissions, academics, and other subject matter experts.
- Developed a framework for aligning community resilience planning and grid investment planning, including defining roles for key stakeholders (e.g., electric utilities, municipal governments, utility regulators) and identifying key methodologies and tools.
- Advanced research into the social consequences of major electricity outages, further establishing, verifying, and validating the social burden metric. More deeply connected the social burden metric to underlying capabilities approach theory of human development.
- Performed two case studies applying the Resilient Community Design Framework. These case studies showcased the current utility of socially focused, equity-informing resilience planning approaches and tools.
- Developed additional functionality to support the Resilient Community Design Framework, such as the explicit impact of EV charging locations on social burden within a microgrid-enabled resilience node citing tool suite. The Resilience Node Cluster Analysis Tool (ReNCAT) and the Microgrid Design Tool (MDT) are central to this tool-suite.
- Created and connected practical resilience planning and measurement approaches to ideal, theory-supported foundations. Namely, developed a BCA approach and resilience metrics portfolio that is achievable by utilities, PUCs, and local governments using today's data and tools. This approach and these metrics are inspired by the theoretical underpinning behind social burden and other more "ideal" planning approaches.
- Overcame several technical challenges that enable the use of renewable-based microgrids in support of a "resilience node" strategy for community-focused resilience investment. Namely, developed advanced planning approaches that consider both protection and control schemes for systems that are dominated by a mix of grid-forming and grid-following inverters.

By connecting all of these efforts, several high-level takeaways can be established:

- There are no examples of states, local governments, and electric utilities that together have fully internalized social benefits of electricity resilience investments. However, there are promising elements that can be used to build from. Hawaii's microgrid tariff and performance-based regulation discussions, California's Resiliency and Microgrid Working Group, and New York's community-focused resilience efforts within the broader Reforming the Energy Vision initiative are three among several examples collected within this project.
- Reducing the social consequences of disruptions to electricity systems are broadly the primary goal of local governments that have yet to be quantifiably internalized within electric utility planning and state commission regulatory approaches. Thus, consequence-focused resilience metrics and measurement processes are critical areas for future work.
- There is value in connecting public and private sectors on the topic of enabling market-driven resilience investment. Over the project, it was observed that simply convening these stakeholders creates progress, for example, the language used by utility and city representatives begins to converge over a series of meetings. An appreciation for systemic challenges of which all parties are elements within begins to outweigh previously held perceptions over the course of these constructive dialogues.
- Neither a top-down nor a bottom-up resilience planning approach will capture the entirety of the resilience benefit stack. Top-down approaches that consider centralized and interdependent large-scale infrastructure must be combined with bottom-up approaches that utilize community input and often consider more localized infrastructure. Emergency managers within local governments may be naturally biased in their current approaches by the levers that they have control over—e.g., public emergency services and disaster recovery infrastructure. Use of the social burden metric and the Resilient Community Design Framework appear to alleviate these biases.
- There are several component technical analysis challenges that have been revealed over the course of the DRC project, and some progress made toward overcoming them:
    - <u>Proving the counterfactual impacts of an energy resilience investment</u>: To properly verify the benefits of an investment are being delivered to the population, it is necessary to describe the consequences that would have been experienced if that investment were never made. Because of the complexities of the grid, interdependent infrastructures, and human behavior, adequately proving this counterfactual condition is a deeply difficult problem. Furthermore, near misses can be an issue. For instance, many investments may not only shorten outage durations, but limit outages altogether or arrest what may otherwise have been a widespread or cascading outage. Utilities, commissions, state and local governments may have difficulty identifying when a counterfactual analysis is necessary due to these
    - <u>Dissecting the role of the grid within overall social consequence of a disruption</u>: Major power outages often coincide with other direct impacts of extreme events, such as damage to buildings, communications outages, etc. Assessing the amount to which a power outage contributed to negative social consequences of a disruption remains a challenge.
    - <u>Tracking consistent resilience progress annually</u>: Testing the resilience of the grid is, by the very nature of resilience, a rare activity. Much of the value of a resilience investment may be returned during one or two events during that investment's lifetime. Tracking the performance of these types of investments in order to prove that they are worthwhile cannot be done annually or perhaps even over a decade. Therefore, if resilience is to be included

within—for example—a performance-based regulatory construct, additional analyses must be performed to estimate an investments' hypothetical or projected benefit. The "stress testing for grid resilience approach describes in Section 5.8 provides an example of one such analysis paradigm.

    - Addressing both acute and chronic disruptions within a single resilience planning framework: Although the utility industry increasingly focuses on the impacts of acute hazards, and hence, outages, under the banner of resilience planning, public representatives often use a broader definition of resilience that includes slower-evolving chronic hazards. Different tools are required to incorporate these chronic stressors than those developed for acute shocks.

Finally, beneficial future directions that can further contribute to aligning utility investment incentives with public resilience goals were discussed during the fifth and final SAG meeting. Those future directions are summarized as:

- Further incorporation of equity within the Resilient Community Design Framework: Meeting attendees proposed using social burden to integrate resilience within an equity-focused planning framework. Additional tenets of equity beyond distributional can be incorporated, such as procedural equity.
- Building a more robust and more community-engaged resilience node planning practice: The potential social resilience solution of "resilience nodes" continues to be a promising investment direction that both local government representatives and electric utilities are highlighting. Attendees proposed developing a community forum and a methodology for stakeholder engagement to complement the existing social burden driven analysis developed through this project.
- Advancing regulatory decision support for social resilience evaluation: Attendees proposed developing a national forum to develop regulatory guidance for integrating social resilience into multi-objective utility planning processes, for example, by extending scenario analysis requirements for IRP/IDP to reflect resilience, decarbonization, and equity metrics in addition to standard cost and reliability objectives.
- Expanding the definition of critical load: The social burden metric can be used to develop a more dynamic, socially explicit definition of load criticality. Attendees proposed demonstrating the social burden metric within the jurisdiction of SAG partners to better understand the social resilience importance of certain types of utility customers. This direction could synergize with efforts of existing resilience programs (e.g., HUD CDBG, FEMA BRIC) which target investment in infrastructure that can prove social resilience benefits.

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APPENDIX A. DRC PUBLICATIONS

Table 14: DRC Publications and Articles

Citation	Task	Source
The Resilience Planning Landscape for Communities and Electric Utilities (Synapse/Sandia)	3	https://www.osti.gov/biblio/1782684
Performance Metrics to Evaluate Utility Resilience Investments (Synapse/Sandia)	3	https://www.osti.gov/biblio/1821803
Application of a Standard Approach to Benefit-Cost Analysis for Electric Utility Resilience Investments (Synapse/Sandia)	3	https://www.osti.gov/servlets/purl/1821803
Regulatory Mechanisms to Align Utility Investments with Resilience (Synapse/Sandia)	3	https://www.osti.gov/biblio/1808934
Public Purpose Microgrids for Electric Grid Resilience: Considerations for Electric Utility Regulatory Approval (Synapse/Sandia)	3	https://www.synapse-energy.com/sites/default/files/The_Quest_for_Public_Purpose_Microgrids_for_Resilience_SAND%202021_8207_19-007.pdf
Regulating for Resilience Workshop, 2019 NARUC Annual Meeting and Education Conference (Bosque Advisors/Sandia)	3	https://www.naruc.org/meetings-and-events/naruc-annual-meetings/2019-annual-meeting/presentations/ (see NARUC/DOE Sandia Regulating for Resilience Workshop PDF)
From Financial Systemic Risk to Grid Resilience: Embedding Stress Testing in Electric Utility Investment Strategies and Regulatory Processes article (Bosque Advisors/Sandia)	3	https://doi.org/10.1080/23789689.2021.2015833
Final Technical Report: Designing Resilient Communities: Hardware demonstration of resilience nodes concept	4	https://www.osti.gov/servlets/purl/1902867

APPENDIX B. TASK 2 ANALYSIS DETAILS

B.1. CPS Energy & City of San Antonio, San Antonio, TX

Section 4.1of this report describes a trade-off analysis enabled by ReNCAT analysis. Solutions (also called Portfolios) are defined by a microgrid that powers a subset of services during a resilience event. It is assumed that during this resilience event there is a complete outage of the main power system and the only electrification in the system is due to islanded microgrids.

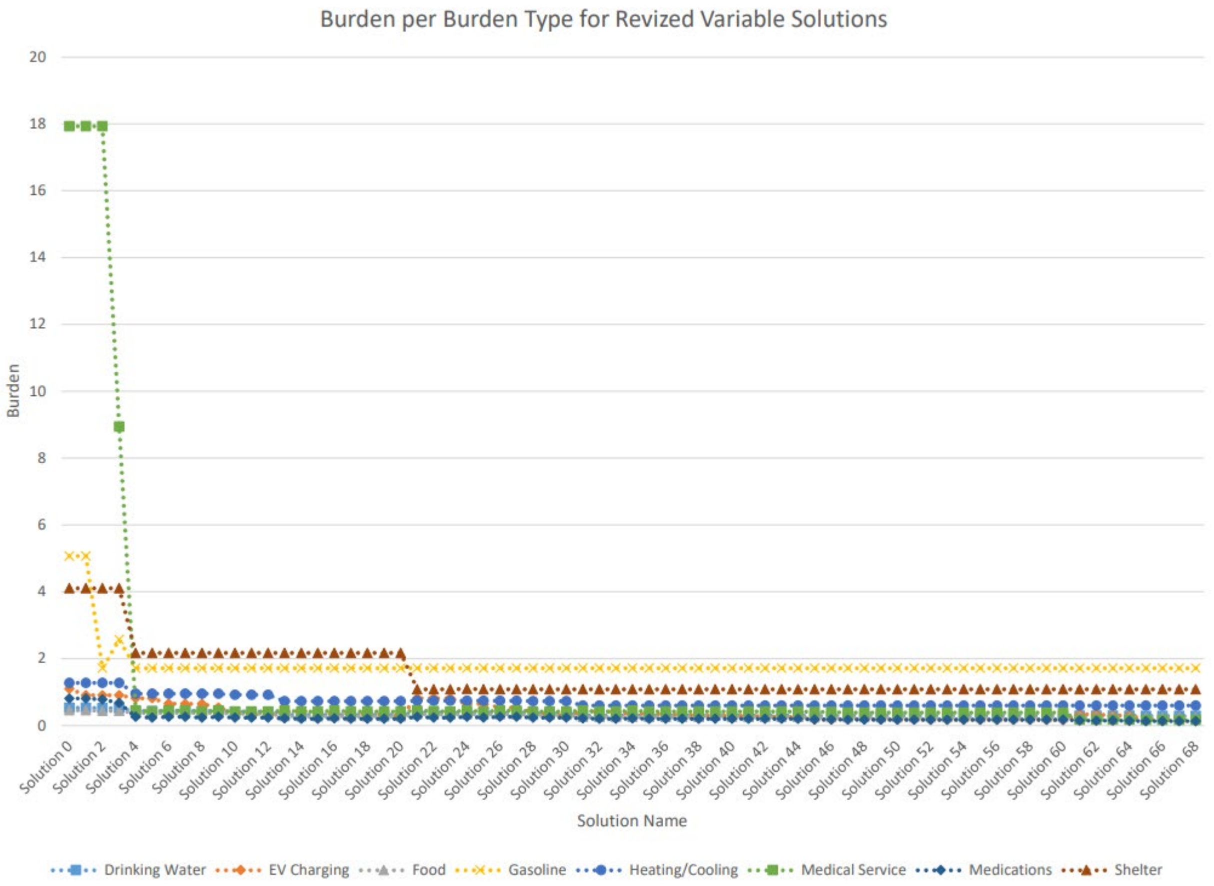

Figure 29: Burden by Solution Services within Portfolios – Full Burden Scale

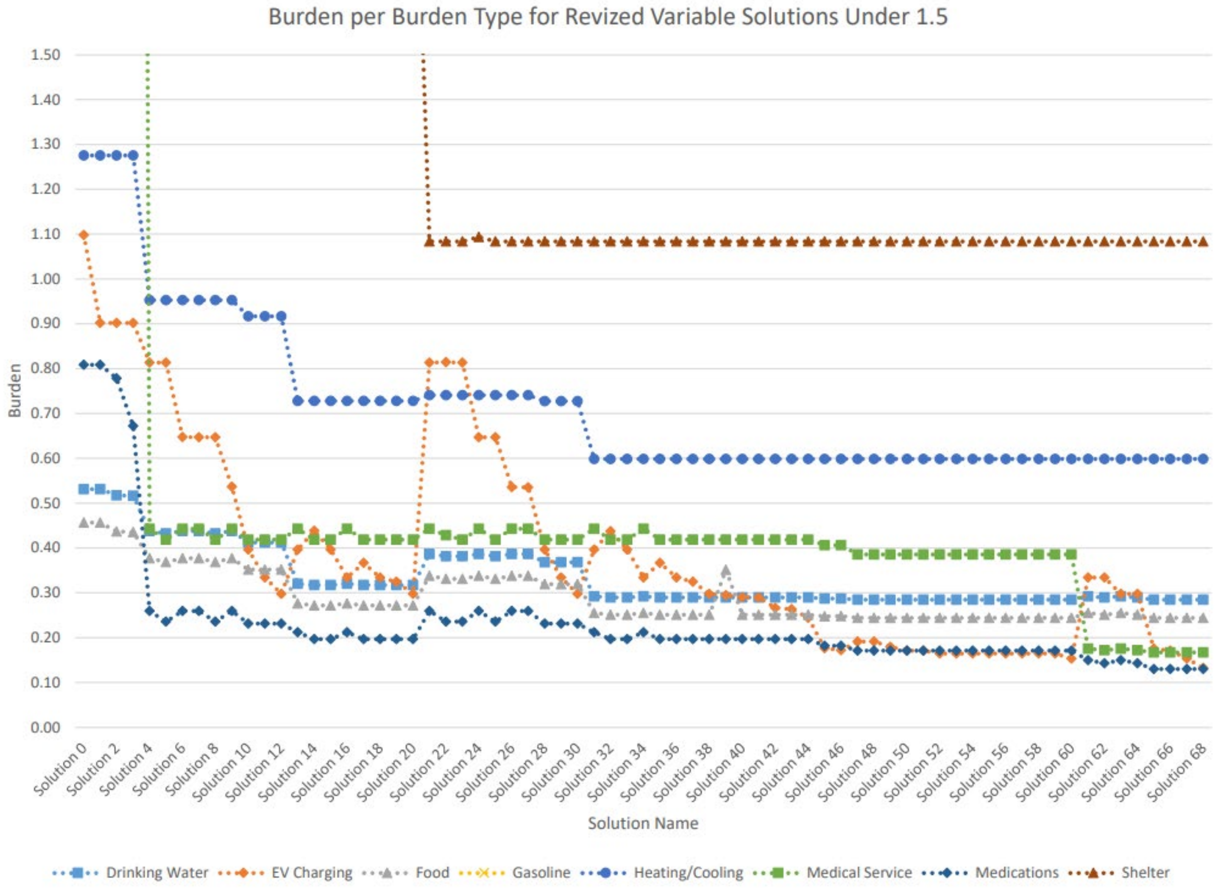

Figure 30: Burden by Solution Services within Portfolios – Reduced Burden Scale

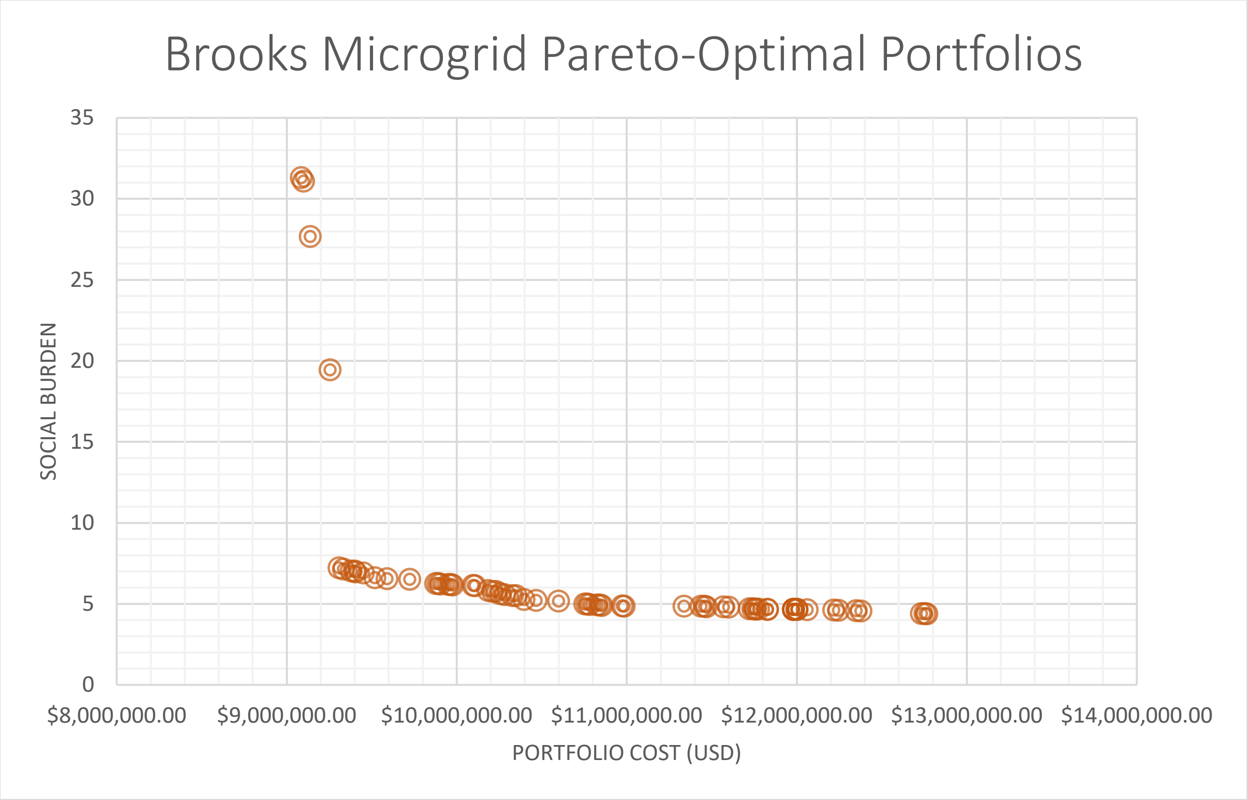

Figure 31: Pareto-optimal graph of ReNCAT solution set

Figure 29-Figure 31 above show the different social burden scores for each pareto-optimal portfolio in this simulation. These social burden values are for the entirety of Brooks City Base (though burden for each census block group is available) and are separated into eight key aspects of social burden: drinking water availability, EV charging accessibility, food availability, gasoline accessibility, accessibility to climate control, medical service availability, medication availability, and shelter availability. A low social burden is desired. The relationship between economic feasibility and these specific aspects can be seen by comparing all above figures. As the amount spent increases, the overall social burden decreases, though some individual aspects may fluctuate in either direction. There is also an overall pattern of diminishing returns, with many of the individual aspects of social burden plateauing after the inflection point or "knee" of the pareto-optimal portfolio.

APPENDIX C. RESILIENCE ANALYSIS TOOLS REPOSITORY

Task	Tool	Description	Reference
Step 1: Resilience Drivers Determination			
System Definition	FASTMap	Tool that allows various spatial data at any spatial resolution to be quickly viewed by stakeholders.	https://www.osti.gov/servlets/purl/1649836
	ArcGIS	Geographic information system for working with maps and geographic information.	https://www.arcgis.com/index.html
Goals Definition	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.	https://www.osti.gov/servlets/purl/1643662
	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.	https://www.osti.gov/servlets/purl/1831596
Threats Definition	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

Task	Tool	Description	Reference
Step 2: Baseline Resilience Analysis & Step 4: Resilience Alternatives Specification			
Baseline & Improved Impacts Assessment	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 & Improved Resilience Metrics Calculation	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/center-for-systems-reliability/tools/tmo/
Step 3: Resilience Alternatives Specification			
Technology Screening	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.osti.gov/servlets/purl/1880920
	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.cooperative.com/programs-services/bts/Documents/Reports/Report-LPNORM-Project-Final-Report-Nov-2019.pdf
	REEDS	Capacity planning model that simulates the evolution of the bulk power system, including generation and transmission.	https://www.nrel.gov/analysis/reeds/

Task	Tool	Description	Reference
Resilience Mitigations Identification for Evaluation	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.	https://www.osti.gov/servlets/purl/1773234
	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/
	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

Task	Tool	Description	Reference
	QuESt	Sandia-developed open source, Python-based application suite for energy storage simulation and analysis	https://www.sandia.gov/ess/tools-resources/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/

Task	Tool	Description	Reference
	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://www.siemens.com/global/en/products/energy/grid-software/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

Task	Tool	Description	Reference
	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
	MATLAB Power System Analysis Toolbox	MATLAB toolbox for electric power system analysis and simulation.	http://faraday1.ucd.ie/psat.html
Step 4: Resilience Alternatives Evaluation			
Optimize Resilience Investment Portfolio	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.	https://www.osti.gov/servlets/purl/1643662
	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

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