RESILIENCE BENEFITS FROM DISTRIBUTED ENERGY RESOURCES:

A TECHNICAL WHITEPAPER ON SYSTEMATIC PORTFOLIO EVALUATION OF DER PROJECTS FROM A RESILIENCE VIEWPOINT

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OPEN ENERGY SOLUTIONS

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Executive Summary

The increase in frequency and severity of weather events in many areas, coupled with growing demands for electricity and a lower tolerance for interruptions, has created unprecedented challenges for electric utilities in maintaining grid reliability and resilience. The two-year period from January 2023 to December 2024 witnessed fifty-five separate billion-dollar weather disasters in the United States, each causing significant power outages and economic disruption.

In compliance with North Carolina Utilities Commission Renewable Energy Portfolio Standards (NCUC: REPS), Duke Energy Corporation initiated an internal study to develop and apply a framework for analyzing Duke Energy's portfolio of potential distributed energy resource (DER) projects in NC and quantifying resilience benefits. This whitepaper presents the framework developed as part of this study by Duke Energy Corporation and Open Energy Solutions for systematically evaluating and quantifying the resilience benefits of DER and microgrid projects.

The methodology combines traditional reliability metrics with risk assessment techniques and community impact analysis to create a holistic evaluation framework. This approach addresses a critical gap in the industry: the lack of standardized methods for incorporating resilience benefits into DER project business cases. Through systematic screening using a dual-index assessment, this framework enables utilities to make data-driven investment decisions that emphasize both grid resilience and community benefits.

1. Introduction and Problem Statement

1.1. The Escalating Resilience Challenge

The modern electric grid faces an unprecedented array of challenges that threaten its fundamental reliability and resilience. Severe weather events have increasingly emerged as a primary driver of grid vulnerability.

The National Oceanic and Atmospheric Administration (NOAA) documented twenty-seven individual weather-related billion-dollar disaster events in 2024 alone (following twenty-eight in 2023) - both represent a significant increase from historical averages and highlight the growing economic impact of grid disruptions.

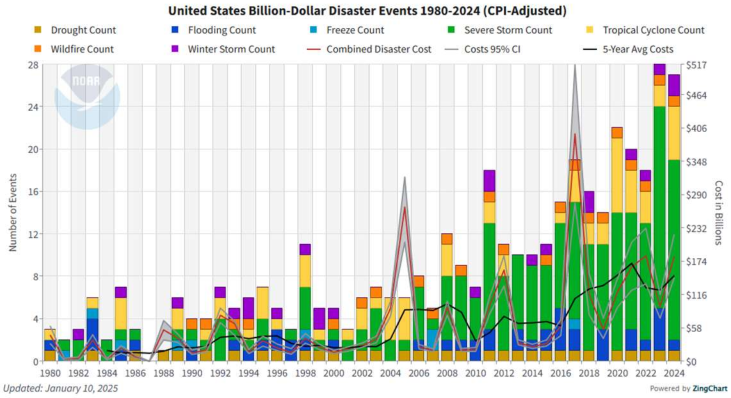


Figure 1: # of Events and Annual Costs (Source NOAA National centers for Environmental Information)

Traditional approaches to grid planning have historically focused on reliability metrics such as the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) to support the investment thesis. While these metrics provide valuable insights into system performance, they fail to capture the full spectrum of resilience benefits that distributed energy resources can provide, particularly during severe weather events and other major disruptions.

1.2. The Distributed Energy Resource Opportunity

Distributed energy resources, including solar photovoltaics, battery energy storage systems, and microgrids, coupled with other tools like self-healing technology, offer unique capabilities to enhance grid resilience. Given their distributed nature across the grid, DERs can help provide localized power during grid outages, reduce stress on transmission and distribution infrastructure, and enable faster restoration of critical services. However, the business case for DER investments has traditionally relied on conventional value streams such as energy arbitrage, demand charge management, and ancillary services.

The challenge facing utilities is the lack of standardized methodologies for quantifying and monetizing resilience benefits. Without robust frameworks for evaluating these benefits, utilities may underinvest in resilience-enhancing technologies, potentially leaving communities vulnerable to increasingly severe weather events and other disruptions.

1.3. Research Objectives

This whitepaper presents a data-driven framework developed to address these challenges following a methodical approach to achieve the following:

- Develop a systematic methodology for screening and prioritizing DER projects based on resilience potential
- Create quantitative metrics for assessing disruption risk and community vulnerability
- Establish approaches for valuing resilience benefits that complement traditional economic analysis
- Provide a replicable framework that can be adapted across different utility service territories
- Demonstrate the practical application of the framework through real-world case studies

2. Literature Review and Industry Context

2.1. Evolving Definitions of Grid Resilience

The concept of grid resilience has evolved significantly over the past decade, with various industry organizations and regulatory bodies developing formal definitions. The Department of Energy defines resilience as "the ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions." The Federal Energy Regulatory Commission emphasizes "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.". The National Association of Regulatory Utility Commissioners (NARUC) defines resilience as “robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event.”

Significantly, all these definitions share common themes around evaluating resilience based on four core capabilities: preparation and planning, absorption of disruptions, adaptation to changing conditions, and rapid recovery. Presidential Policy Directive 21 explicitly identifies these four components as essential elements of resilient infrastructure systems and can also be seen in NARUC’s illustration of the resilience trapezoid (Fig 2).

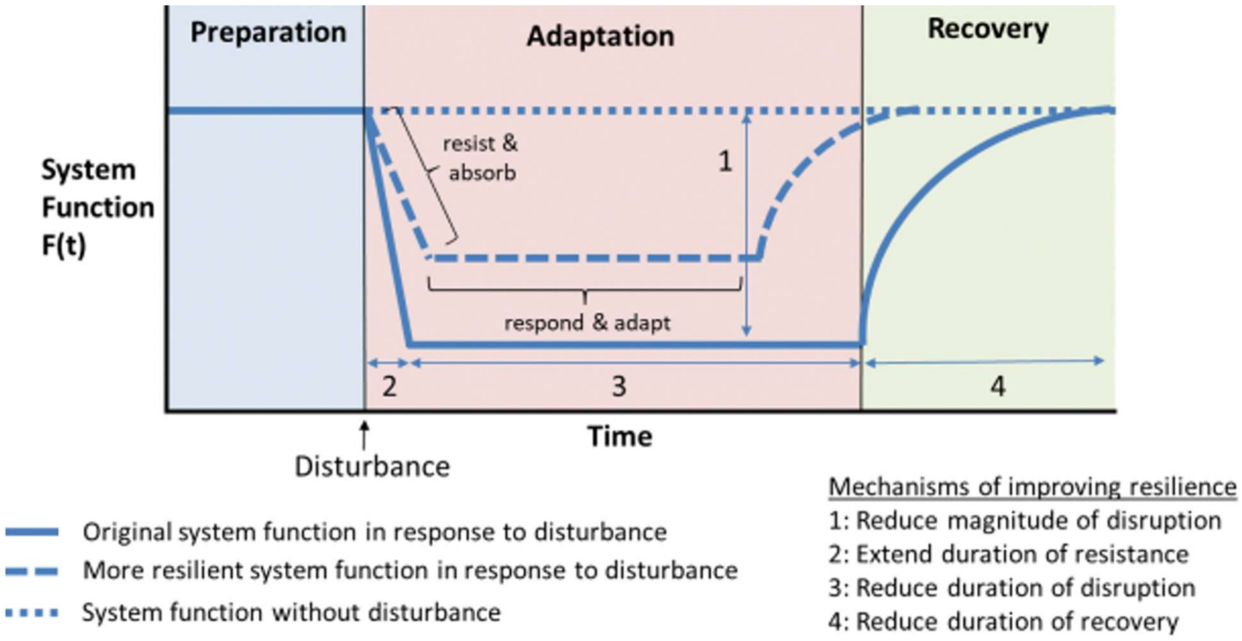


Figure 2: Resilience Trapezoid, Source NARUC Energy Resilience Reference Guide

2.2. Leveraging Microgrids and DER to Enhance Resilience

From the standpoint of capital investments in power system infrastructure, improvements in resilience usually come down to two levers that utilities can control:

1. Hardening the electrical power system which involves physically changing hardware (such as poles and transformers) to make it less susceptible to damage during major events ('Resist and Absorb' in Fig 2)
2. Enhancing the ability of the power system to respond, adapt and recover faster during major events

Investments to 'harden' the electrical system (through pole replacements, transformer upgrades, vegetation management, and similar programs) are accounted for in the utility's traditional capital planning and O&M budgeting activities.

Enhancing the power system to 'respond, adapt and recover' is the area where non-wires alternatives can play a significant role. Clean energy microgrids are one of the tools available to improve the adaptability and recoverability of the bulk power system. Specifically in the context of improving resilience, microgrids can be used to:

1. Reduce the magnitude of the disruption through grid-forming microgrids and DER backup facilities (i.e., absorb)
2. Extend the capability to resist and absorb through planned islanding in advance of an anticipated major disruption
3. Reduce duration of disruption and recovery (e.g., black start operations, islanded operations, event impact analysis, and restoration support)

2.3. Current State of Microgrid and DER Deployment

A brief survey of the national landscape of microgrid projects shows initiatives focused on improving community resilience.

Microgrid	Type	Scale	Why Interesting
Goleta Load Pocket	Non-Utility	200 MW solar + 400 MWh energy storage	Coordinated community effort to solve resilience challenges arising from transmission line vulnerability to natural disasters (earthquakes, fires etc.)
Marcus Garvey Apartments	Non-Utility	500 kW PV + 400 kW fuel cell + 300 kW/1,200 kWh battery	Strong utility / non-utility coordination, significant operational benefits, and improved resilience in an underserved community
Montgomery County, MD	Non-Utility	Public Safety Headquarters microgrid can produce 11M kWh of electricity / year	Strong utility / non-utility coordination, targeted resilience benefits for critical facilities, energy-as-a-service offering by Schneider / AlphaStruxure, Duke Energy Renewables (now Deriva Energy) as asset owner
ComEd Bronzeville Microgrid	Utility	750 kW PV + 500 kW battery	One of the largest and most prominent utility-owned and executed renewable microgrid projects, designed to power emergency shelters and serve immobile populations during major events.
Green Mountain Power Stafford Hill Solar Farm and Microgrid	Utility	2.5 MW solar + 4 MW / 3.4 MWh battery	Utility owned, first microgrid to provide power solely through solar and battery backup, standard wholesale market value levers (demand mgmt. + ancillaries) augmented by community resilience benefits
PEPCO Largo MD Microgrid	Utility	1.18 MW Solar PV + 1.85 MW battery storage ($26 M projected cost)	Would have been one of the largest utility owned microgrids, community resilience benefits cited, ICE calculator used for ‘resilience’ benefits, project rejected by PSC due to no funding or deal participation by third parties and inequitable rate impacts on program non-participants

Analysis of pioneering microgrid projects reveals both the potential and challenges of current approaches to resilience-focused DER deployment. While these projects demonstrate qualitative benefits from the perspective of community resilience, proving cost-effectiveness at scale and quantifying resilience benefits remains an industry challenge. Most documented projects focus on traditional value levers such as demand management and ancillary services, with resilience benefits often cited but rarely quantified in business case analyses.

2.4. Regulatory and Policy Context

While the regulatory environment for grid resilience investments varies significantly across jurisdictions, several trends are emerging. State utility commissions are increasingly recognizing the need for resilience-focused investments, and some are working to develop specific frameworks for evaluating and approving such projects. The Federal Energy Regulatory Commission has also emphasized the importance of resilience in its oversight of bulk power system reliability.

Environmental justice considerations have become increasingly a part of the utility planning processes, driven by the growing recognition of the potentially disproportionate impact of power outages on vulnerable communities. While these considerations were originally initiated at the federal level (as evidenced by the former DOE Justice40 program), several states have subsequently maintained and are even seeking to expand these considerations for regulatory policy at the state level.

3. Methodology Overview

3.1. Framework Architecture

The developed framework employs a systematic, multi-stage approach to evaluate DER project opportunities across an entire utility service territory. The methodology consists of seven primary stages:

1. **Portfolio Development:** Systematic screening of distribution feeders to identify high-value DER opportunities
2. **Framework Definition:** Establishment of evaluation criteria and analytical structure
3. **Resilience Valuation:** Quantification of economic benefits from avoided outages and improved recovery
4. **Disruption Risk Assessment:** Development of multi-factor risk indices for individual feeders
5. **Community Impact Analysis:** Integration of social vulnerability and environmental justice factors
6. **Results Integration:** Synthesis of technical and community factors into prioritized project portfolios
7. **Validation and Performance Measurement:** Ongoing assessment of framework effectiveness

3.2. Data Integration Strategy

The framework leverages multiple data sources to create a comprehensive assessment capability – typical data sources are listed below:

Utility Operational Data: Historical reliability metrics, customer demographics, load profiles, and infrastructure characteristics from the utility's operational databases.

Federal Risk Assessment Data: FEMA National Risk Index providing county level data metrics and scoring historical exposure to 18 natural hazard types, including hurricanes, floods, wildfires, and severe storms.

Social Vulnerability Data: Center for Disease Control and Prevention Social Vulnerability Index incorporating 36 indicators across four themes: socioeconomic status, household characteristics, racial and ethnic minority status, and housing type and transportation.

Environmental Justice Data: Data from Department of Energy's Justice40, or applicable state level initiatives that provide burden indicators at the census tract level for environmental and energy justice considerations.(Note: While Justice 40 has been discontinued by the current Federal Administration, the mapping data for each census tract is still available through various websites such as justice40.cnt.org. Additionally, the framework can be adjusted as needed to accommodate the specific community impact metrics of interest in the state's regulatory environment).

Economic Impact Data: Regional economic models including IMPLAN (Impact Analysis for Planning) and Bureau of Labor Statistics county-level employment data for assessing economic consequences of power outages.

3.3. Analytical Approach

The analytical approach, illustrated in figure 3 below, employs a dual-index approach that balances technical risk assessment with community impact evaluation. This methodology recognizes that optimal resilience investments must consider both the likelihood and magnitude of disruptions (Disruption Risk Index) and the community consequences of those disruptions (Community Risk Index).

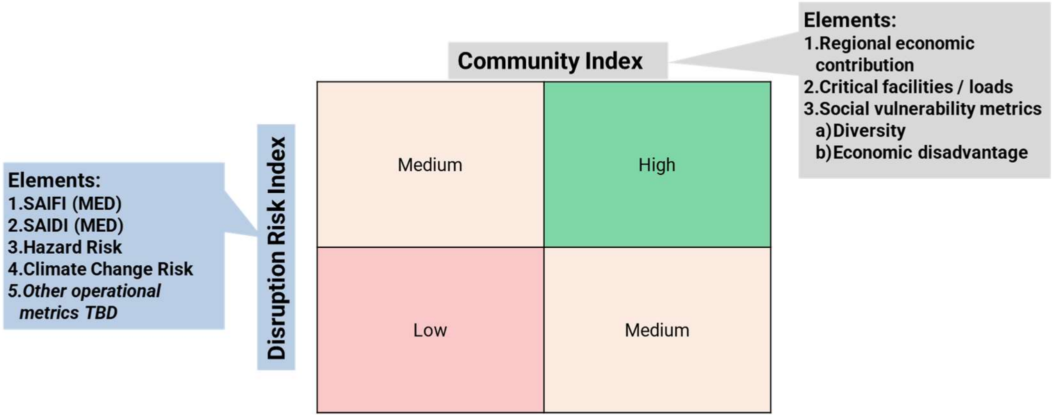


Figure 3: Portfolio Analysis Framework

While the Disruption Risk Index quantifies the probability and severity of power outages based on historical reliability data, infrastructure characteristics, and external risk factors, the Community Risk Index assesses the potential impact of outages on vulnerable populations, critical facilities, and regional economic activity.

4. Quantifying the Value of Resilience

Quantifying the economic value of grid resilience investments presents significant methodological and practical challenges that extend far beyond traditional utility cost-benefit analyses. These challenges create barriers to optimal investment decisions and stakeholder alignment.

This section discusses some of the challenges and general methodologies that can be applied to the problem of quantifying resilience. The specific implementation of valuation techniques at Duke Energy are discussed in section 8.

4.1. Fundamental Valuation Complexities

The core challenge lies in translating resilience capabilities into quantifiable and predictable economic benefits that can be used as the basis for justifiable capital expenditures. Unlike traditional infrastructure investments, where benefits may be predictable and more directly observable, resilience investments provide value primarily through avoiding future costs that may never materialize. This creates several interconnected problems:

Customer Impact Variability: The value customers place on avoiding power interruptions varies dramatically across customer segments, geographic regions, and time periods. Residential customers may value evening outages differently than daytime disruptions, while industrial customers face vastly different cost structures depending on their production processes, inventory management capabilities, and ability to implement backup systems.

Temporal and Seasonal Dependencies: The economic impact of power interruptions fluctuates significantly based on timing factors. Summer cooling loads, winter heating demands, and peak business hours all influence the actual cost of lost load. Additionally, the day of the week and time of year can dramatically alter both the direct costs to customers and the broader economic ripple effects.

Stakeholder Perception Alignment: Building consensus among diverse stakeholder groups requires addressing fundamentally different perspectives on resilience value. Customers may not perceive the same benefits that utilities anticipate from resilience investments, creating challenges for rate recovery and public support. This misalignment often stems from the preventative nature of resilience benefits—customers do not experience the outages that were avoided.

4.2. Operational and Economic Uncertainties

Several key areas require further study and stakeholder education to improve resilience valuation accuracy:

Non-wires Alternative (NWA) Asset Integration: While approved capital spending for resilience improvements can lead to increases in customer rates, the operational and support costs for NWA assets compared to traditional alternatives remain poorly understood. Distribution grid operators need new capabilities to operate these assets efficiently and at scale, and the learning curve costs are difficult to predict.

Benefit Realization Timelines: The timeline for when benefits (both hard and soft) from investments become tangible for customers varies significantly across different resilience investments. Some benefits may be immediately apparent, while others may only become clear during rare, but severe, events.

Equity and Cost Allocation: Determining fair cost allocation presents ongoing challenges, as the principle that ratepayers receiving resilience benefits should bear the associated costs is complicated by the community-wide and regional nature of many resilience improvements.

4.3. Valuing Resilience

The common metric used in the industry for valuing resilience, specifically the value that customers and stakeholders may place on resilience is termed Value of Lost Load (VOLL).

The Value of Lost Load (VOLL) is the estimated maximum amount that customers with firm contracts for electric supply would be willing to pay to avoid a disruption in their electricity service. The value of these losses can be expressed as a customer damage function (CDF) defined below:

Loss (\$/kW) = ƒ (duration, season, time of day, notice)

Note that VOLL is not controlled or dictated by the utility and does not include utility's cost-benefit analysis.

As can be inferred from the CDF above, the valuation is heavily reliant on the specific circumstances and the customer's perception thereof. While multiple approaches have been developed to estimate VOLL, each comes with distinct advantages, limitations, and appropriate applications. An overview of each of the methods is provided below:

Survey-Based Approaches

Survey methodologies directly gather customer preferences and willingness-to-pay information through structured questionnaires and choice experiments. The most widely used tool in this category is the Interruption Cost Estimate (ICE) Calculator, which has become the de facto standard for VOLL calculations used in utility capital program evaluations.

ICE Calculator Implementation: The ICE Calculator uses survey-derived customer interruption cost data to estimate VOLL across residential, small commercial and industrial (C&I), and medium/large C&I customer segments. Key input requirements include service territory characteristics, customer counts and usage patterns by segment, reliability metrics with and without proposed improvements, and outage distribution patterns by time of day and season.

The tool's strength lies in its ability to estimate customer interruption costs for various power interruption scenarios without requiring extensive external data. Results are straightforward to understand and communicate with stakeholders, making ICE particularly valuable for regulatory proceedings and public engagement.

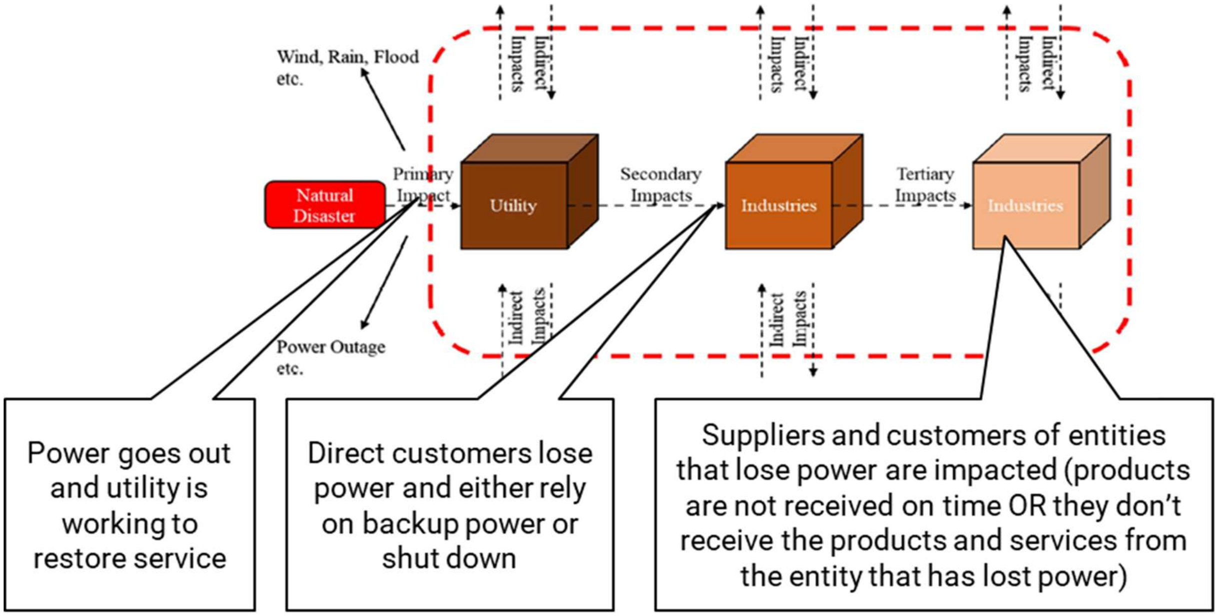
Limitations and Constraints: Survey approaches face several inherent challenges that limit their accuracy and applicability. Significant resources are required to conduct statistically valid surveys, and cognitive biases can skew respondent cost estimates due to the hypothetical nature of the scenarios presented. Respondents may lack awareness of the full consequences of power interruptions, particularly for longer-duration events or cascading failures.

Most critically, current survey data primarily addresses shorter-duration outages and may not capture the exponential increase in costs associated with extended disruptions. Customer segmentation remains basic, with C&I customers categorized simply as construction, manufacturing, and other sectors, which may not reflect the true diversity of interruption costs across different business types and operational models.

Macroeconomic Input-Output Modeling

Input-output (I-O) models, exemplified by tools like IMPLAN, use linear equations to model inter-industry relationships and economic flows within regional economies. These models can differentiate economic effects by sector and are particularly useful for estimating local, sector-level disruptions resulting from widespread power interruptions.

Methodological Framework: I-O models leverage fixed coefficients that represent economic relationships between different industries and sectors. When power interruptions disrupt one sector, the model traces the impacts through supply chains and inter-industry dependencies to estimate total economic effects. Regional downscaling capabilities allow for location-specific analysis that reflects local economic structures and dependencies.



Power goes out and utility is working to restore service

Direct customers lose power and either rely on backup power or shut down

Suppliers and customers of entities that lose power are impacted (products are not received on time OR they don't receive the products and services from the entity that has lost power)

Figure 4: Secondary Economic Impacts of Power Disruption

Source: I-O Case Study - Economic Impact Assessment of Severe Weather–Induced Power Outages in the US_ASCE_2021

Applications and Industry Usage: Duke Energy and other utilities have successfully employed I-O modeling to estimate secondary economic impacts for specific infrastructure projects, including strategic undergrounding initiatives across multiple jurisdictions. As part of its 2018 grid improvement initiative, Duke Energy utilized I-O modeling in conjunction with other economic tools to quantify regional benefits of grid investments.

Model Limitations: I-O approaches assume fixed relationships between economic sectors, which may not accurately reflect adaptive behaviors during actual outage events. The models focus primarily on demand-side multiplier effects, potentially providing upper-bound estimates that overstate true economic impacts. Additionally, I-O models do not directly estimate residential load value and may ignore adaptive actions customers take during extended outages to minimize their losses.

Computable General Equilibrium (CGE) Modeling

CGE models represent the most sophisticated approach to VOLL estimation, using microeconomic principles to create comprehensive, non-linear representations of entire economic systems. Tools like REMI enable analysis of complex market interactions and substitution behaviors that simpler models cannot capture.

Advanced Capabilities: CGE models can account for substitution behavior across multiple customer classes, adjust for different resilience options, and provide appropriate analysis for longer-duration outages. They incorporate both demand-side and supply-side factors within a non-linear framework that can represent market flexibility in response to power interruptions.

These models can also account for non-linear damage functions that better represent how interruption costs escalate with duration, and they include direct and indirect economic interactions across all sectors.

Implementation Challenges: CGE models require significantly more data than I-O approaches, and sufficient data to drive accurate models is often unavailable. Model validation presents ongoing challenges, and the models may lack reliable forecasting ability for unprecedented scenarios. The assumption of return to equilibrium may not hold during severe or extended disruptions, and perfect knowledge assumptions (that are inherently factored into modeling of substitution behavior) may not reflect real-world information constraints.

As a result, CGE models can yield over-resilient responses that make them lower-bound estimates of economic effects, potentially undervaluing the true costs of power interruptions.

Empirical Data Approaches

Outage Studies: Analysis of historical major outage events provides actual data on power interruption costs, potentially the most accurate assessment of specific outage impacts. However, these studies require significant analytical resources and are limited by data availability. Additionally, given the unique context and circumstances around each major disruption, comparability and consistency across different studies is not guaranteed, making comparative analysis challenging.

Insurance Data Analysis: Some research has leveraged loss data collected by insurance companies based on actuarial analysis of power interruption claims. While this data represents actual losses rather than hypothetical survey responses, it suffers from self-selection bias and is often difficult to obtain from insurance providers.

As discussed above, while there are several different methodologies that can be leveraged to place a valuation on resilience, each comes with its own set of implementation challenges. Section 6.5 elaborates the methodology applied in this study to augment traditional VOLL calculations to include secondary impacts.

5. Technical Framework Development

As introduced in section 3.3, the study employed a dual index approach to evaluate the intersection of the technical risk of major events to a circuit and the impact to communities serviced by the circuit if the risk were to materialize. The dual indices were subsequently utilized to screen potential DER projects at a community / region level and identify the ones with the greatest impact for further feasibility analysis.

The following sections provide an overview of the factors included in the development of the two indices.

5.1. Portfolio Screening Methodology

The initial screening process begins with screening the utility's population of distribution circuits using available metrics on circuit demographics and reliability. This comprehensive approach ensures that no potentially high-value opportunities are overlooked while maintaining analytical efficiency.

Several different techniques (as described below) were employed to identify a subset of circuits most likely to benefit from a resilience investment.

Statistical Analysis of Reliability Metrics: The screening process employs statistical analysis to identify "problem circuits" with performance significantly below system averages. Specifically, feeders with 5-year average SAIDI (System Average Interruption Duration Index) more than one standard deviation above the mean are flagged for detailed analysis.

Multi-Year Pattern Recognition: The methodology identifies "repeat offender" circuits with consistently poor performance across multiple years, indicating systemic issues that may benefit from DER solutions.

Combinatorial Assessment: Multiple screening criteria, applied simultaneously to identify feeders that meet multiple risk factors, indicating higher potential for resilience benefits.

This screening process typically identifies 3-5% of total feeders annually for detailed analysis, creating a manageable portfolio for comprehensive evaluation while focusing resources on the highest-potential opportunities.

5.2. Disruption Risk Index Development

The Disruption Risk Index represents a multi-factor, objective measure of the likelihood and magnitude of service disruptions. While the specific components included in the calculation and relative weightings may vary based on each utility's operations data, the index generally incorporates five primary components:

Reliability Metrics Foundation:

The foundational elements of disruption risk index leverage traditional reliability indices that include the impact of major event days, notably:

- Customer Average Interruption Duration Index (CAIDI) including Major Event Days (MED)
- Customer Average Interruption Duration Index excluding Major Event Days
- Historical patterns of interruption frequency and duration

Note that while system indices (SAIFI and SAIDI) are traditional drivers of reliability-based analysis, customer-based metrics provide a more direct measurement of customer impacts

Scale and Impact: These include factors to weigh the index based on number of customers served by a circuit, load characteristics, etc.

- Total number of customers served by each feeder
- Number and percentage of commercial and industrial customers
- Load characteristics and consumption patterns

External Risk Factors: These include factors that weigh the index based on the historical risk of natural hazards and /or the challenges of restoration (e.g., hard to reach areas) following a major event

- FEMA National Risk Index scores for natural hazard exposure
- Historical frequency of weather-related outages
- Geographic and topographic risk factors

Infrastructure Vulnerability: These include factors to scale the risk based on the condition of the underlying distribution infrastructure (such as age/composition of poles, last vegetation management etc.)

- Age and condition of distribution infrastructure
- Exposure to vegetation-related outages
- Proximity to transmission facilities and interdependencies

Climate Risk: Integration of climate and severe-weather related projections of outage events and evolving risk patterns.

The underlying goal of the disruption risk index calculation is to develop a data-driven approach to identify those circuits serving customers that are likely to experience outage durations significantly greater than the utility's mean duration during major events

5.3. Community Risk Index Methodology

The Community Risk Index employs a multi-dimensional approach to assess community vulnerability and the potential impact of power outages on different populations. The index incorporates four primary components:

Social Vulnerability Assessment: Utilizing the CDC Social Vulnerability Index (SVI), which incorporates thirty-six burden indicators organized into four themes:

- Socioeconomic status (poverty, unemployment, income, education)
- Household characteristics (age, disability, single-parent households)
- Racial and ethnic minority status
- Housing type and transportation access

Data granularity at the census tract level enables precise mapping of vulnerable populations to specific distribution feeders.

Critical Facilities and Infrastructure:

Evaluation of circuits based on the distribution to emergency services and distance to backup facilities if the primary facility is out.

- Emergency services (police, fire, emergency medical services)
- Healthcare facilities (hospitals, nursing homes, dialysis centers)
- Educational institutions and community centers
- Water treatment and communication facilities
- Transportation infrastructure and fuel distribution

Economic Impact Assessment: Regional economic modeling using IMPLAN and Bureau of Labor Statistics data to quantify:

- Direct economic losses from commercial and industrial customer outages
- Indirect economic impacts on supply chains and dependent businesses
- Employment effects and wage losses
- Regional economic multiplier effects

Environmental Justice Integration: Incorporation of indicators representing the equitable consideration of environmental equity in project prioritization.

While specific factors and actual weightings of components may vary, the Community Risk Index scores aim to identify those communities that face significantly greater economic and social impacts during extended outages.

6. Implementation and Case Study Results

The overall methodology described in sections 5 through 7 was applied to Duke Energy's North Carolina distribution system, encompassing approximately 3,000 distribution feeders serving diverse geographic regions and customer types. The analysis revealed significant variation in both disruption risk and community vulnerability across the service territory

6.1. North Carolina Distribution System Analysis

Portfolio Screening

The initial screening of 3,000 feeders leveraged a combination of approaches to identify ‘high-value circuits for DER projects. The criteria leveraged for initial screening was based on statistical analysis of circuit reliability metrics of interest such as:

- Five-year SAIDI (MED) more than one standard deviation from mean
- Circuit identification on problem circuit / trouble-feeder lists

The initial screen identified about 3-5% of the circuit population as the most interesting for DER projects.

Individual feeder analysis revealed that traditional reliability metrics alone provide insufficient information for resilience investment decisions. Many feeders with moderate reliability performance showed high resilience value potential due to serving critical facilities or vulnerable populations.

To that initial dataset of 100-150 feeders, we applied additional screens to further down-select circuits likely to realize the highest value from DER projects. Examples included metrics such as:

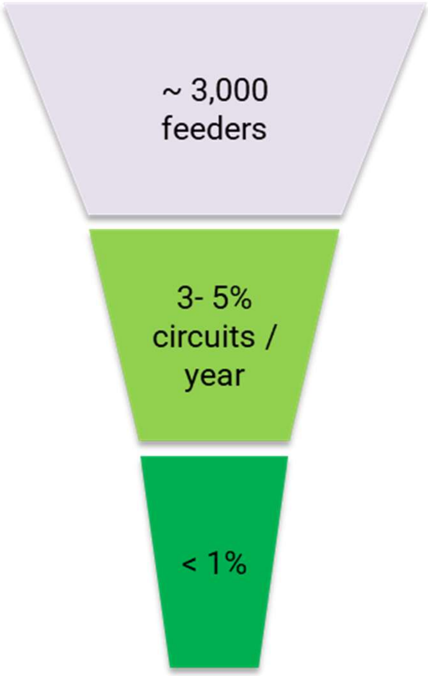


Figure 5: Portfolio Screening

- Historical annual VOLL calculations greater than threshold
- SAIFI(MED), representing frequency of disruptions greater than one standard deviation from mean
- Repeat offenders on 5-year trouble feeder lists

Additionally combinatorial analysis such as geographical proximity of circuits and identification of specific circuits on multiple screens was used to further reduce the target circuit lists for DER project definition, analysis, and prioritization.

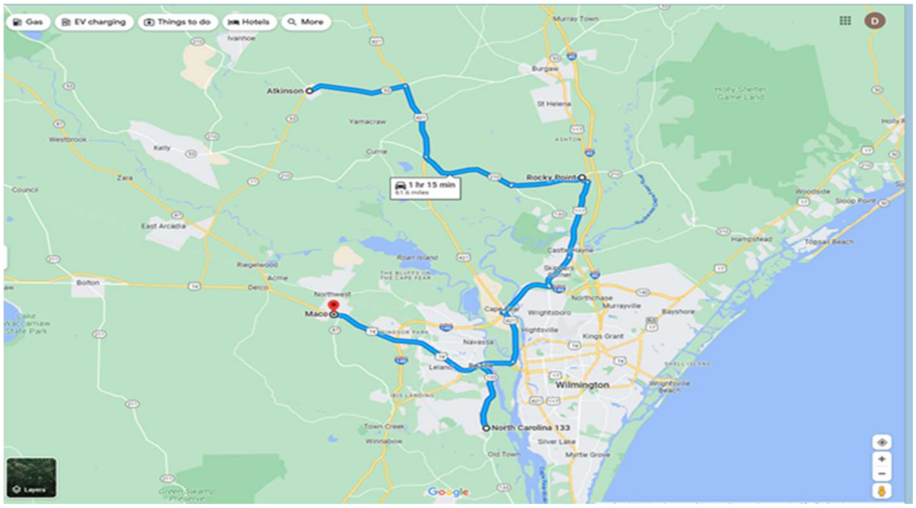
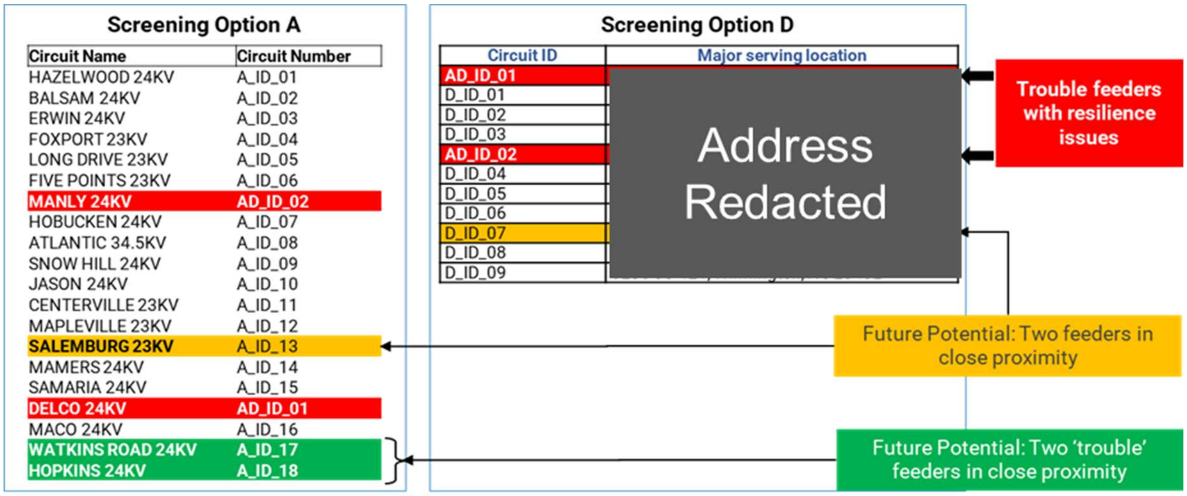


Figure 6: Circuits in Proximity Serving Common Regions



Screening Option A

Circuit Name	Circuit Number
HAZELWOOD 24KV	A_ID_01
BALSAM 24KV	A_ID_02
ERWIN 24KV	A_ID_03
FOXPORT 23KV	A_ID_04
LONG DRIVE 23KV	A_ID_05
FIVE POINTS 23KV	A_ID_06
MANLY 24KV	**AD_ID_02**
HOBUCKEN 24KV	A_ID_07
ATLANTIC 34.5KV	A_ID_08
SNOW HILL 24KV	A_ID_09
JASON 24KV	A_ID_10
CENTERVILLE 23KV	A_ID_11
MAPLEVILLE 23KV	A_ID_12
SALEMBURG 23KV	A_ID_13
MAMERS 24KV	A_ID_14
SAMARIA 24KV	A_ID_15
DELCO 24KV	**AD_ID_01**
MACO 24KV	A_ID_16
WATKINS ROAD 24KV	**A_ID_17**
HOPKINS 24KV	**A_ID_18**

Screening Option D

Circuit ID	Major serving location
AD_ID_01	
D_ID_01	
D_ID_02	
D_ID_03	
AD_ID_02	
D_ID_04	
D_ID_05	
D_ID_06	
D_ID_07	
D_ID_08	
D_ID_09	

Address Redacted

Trouble feeders with resilience issues

Future Potential: Two feeders in close proximity

Future Potential: Two 'trouble' feeders in close proximity

Figure 7: Combinatorial Analysis

The end results of portfolio screening identified approximately thirty feeders (1% of total) for detailed analysis and prioritization using the dual-index framework.

6.2. Applying the Framework

Disruption Risk Index Calculation

The initial calculation methodology for developing the disruption risk index was based on:

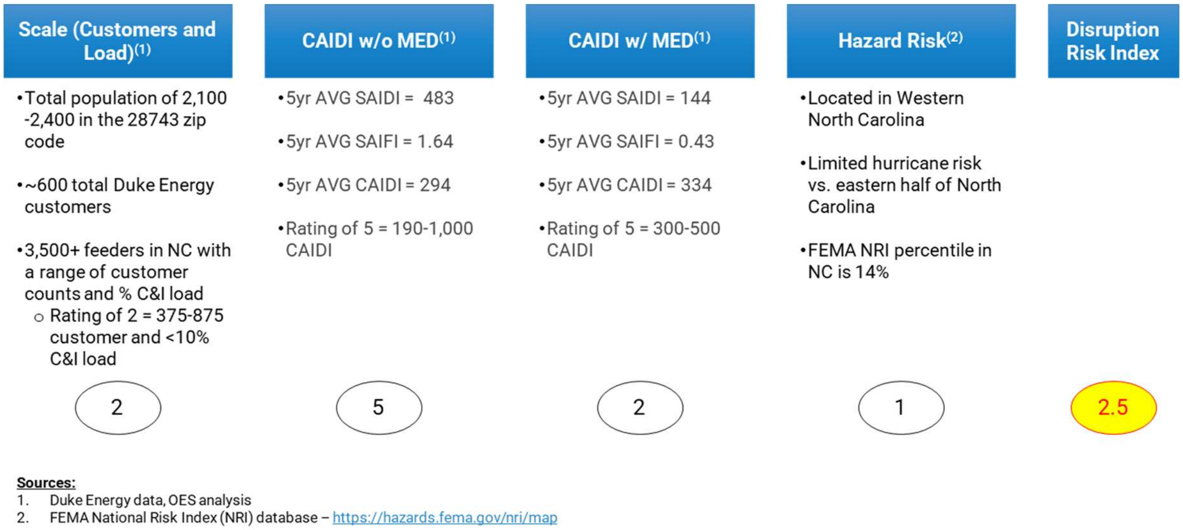
- Equal weight of each input component
- Linear scoring of each of the input components (between 1 and 5 with 5 being the highest)

- Summation of linear scores from individual components into a composite score between 1 and 5, with 5 indicating the highest likelihood of disruption during major events

The specific components included in the initial calculation methodology applied to Duke Energy's NC distribution circuits included the following:

- Number of customers served: Feeders with larger number of customers, highest rankings for feeders with 6,000+ customers
- Commercial and Industrial customer count: Larger number (or %) of non-residential customers / load is an indicator of higher consumption and higher VOLL when both direct and indirect impacts are considered. Feeders with the highest scores had 50+ C&I customers
- Scale: Relative weighting factor applied to # of customers and # of C&I customers – a larger scale would imply the need for a higher cost of resilience solution
- CAIDI without MED: The highest scores identified feeders with CAIDI greater than five hundred minutes
- CAIDI with MED: the highest scores identified feeders with CAIDI (including major event days) approaching 1,000 minutes
- Hazard Risk: Based on FEMA National Risk Index reflecting historical risk exposure to eighteen natural hazard types. NRI provides a percentile ranking for the county at a national and state level. Highest rankings were used for counties in the 80-99 percentile range

The example in the figure below illustrates how the framework was applied to calculate the disruption risk index to a feeder in Duke Energy's distribution service territory.



Scale (Customers and Load)(1)	CAIDI w/o MED(1)	CAIDI w/ MED(1)	Hazard Risk(2)	Disruption Risk Index
• Total population of 2,100 -2,400 in the 28743 zip code • ~600 total Duke Energy customers • 3,500+ feeders in NC with a range of customer counts and % C&I load ○ Rating of 2 = 375-875 customer and <10% C&I load	• 5yr AVG SAIDI = 483 • 5yr AVG SAIFI = 1.64 • 5yr AVG CAIDI = 294 • Rating of 5 = 190-1,000 CAIDI	• 5yr AVG SAIDI = 144 • 5yr AVG SAIFI = 0.43 • 5yr AVG CAIDI = 334 • Rating of 5 = 300-500 CAIDI	• Located in Western North Carolina • Limited hurricane risk vs. eastern half of North Carolina • FEMA NRI percentile in NC is 14%	
2	5	2	1	2.5

Sources:
1. Duke Energy data, OES analysis
2. FEMA National Risk Index (NRI) database – https://hazards.fema.gov/nri/map

Figure 8: Calculating Disruption Risk

Community Impact Index Calculation

The community index calculation for Duke Energy Carolinas was based on four components:

- Economic Impact: Combining interruption cost estimates from ICE calculator with secondary / downstream impacts modeled using IMPLAN, the size of the local economic output (IMPLAN) and county employment data (US Bureau of Labor Statistics)
- Critical Loads: Ranking feeders based on distribution to emergency services with the highest rating used for feeders serving officially designated critical facilities and community-identified priority locations.
- Social Vulnerability: Using CDC's SVI database to score communities on a percentile ranking based on four themes: socio-economic status, household composition / diversity, minority status and language and access to affordable housing and transportation. Highest scores indicated communities with the highest percentiles of social vulnerability (80-99 percentile) at a national level

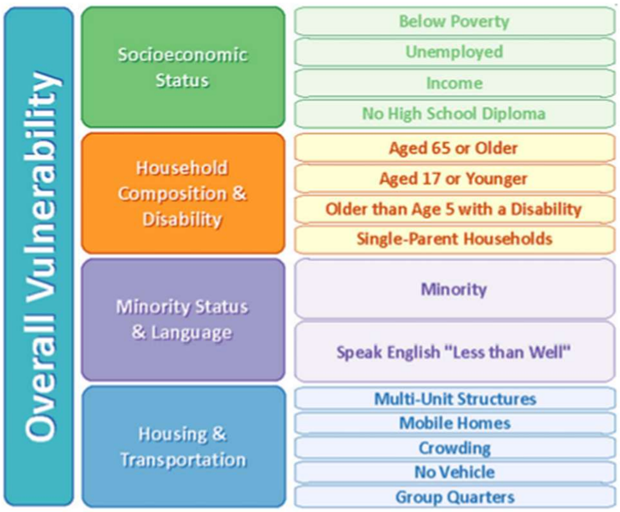
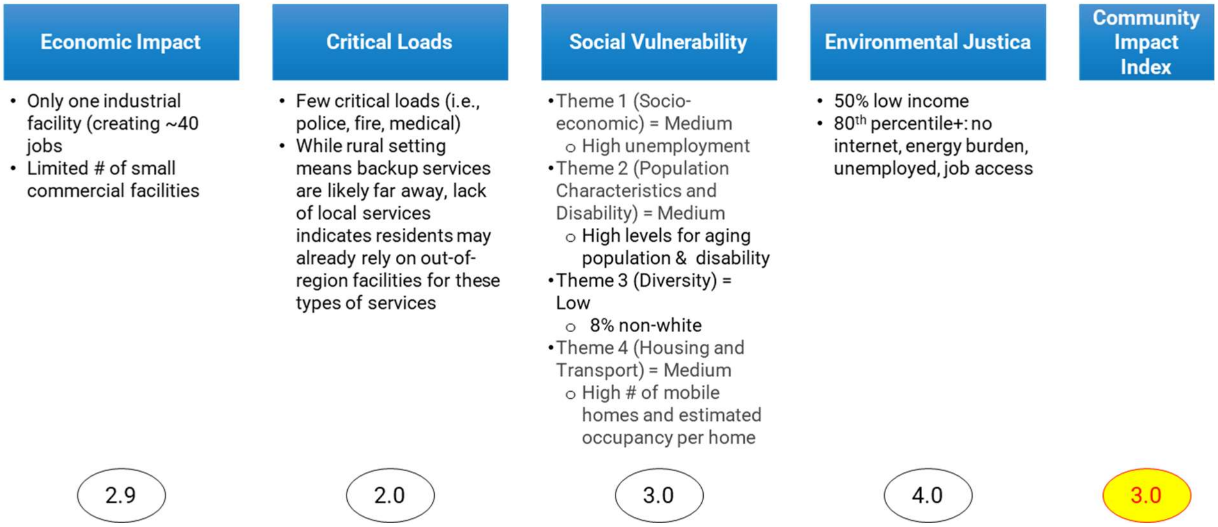


Figure 9: CDC's SVI Themes and Input Factors

- DOE Justice: A similar scoring to SVI, based on percentile ranking of a community at the national level based on thirty-six burden indicators.

The scoring of each component was on a linear scale between 1 and 5, with 5 being the most impactful.

The example below illustrates how the community index was calculated for a representative community within the service territory.



Economic Impact	Critical Loads	Social Vulnerability	Environmental Justica	Community Impact Index
• Only one industrial facility (creating ~40 jobs • Limited # of small commercial facilities	• Few critical loads (i.e., police, fire, medical) • While rural setting means backup services are likely far away, lack of local services indicates residents may already rely on out-of-region facilities for these types of services	•Theme 1 (Socio-economic) = Medium o High unemployment •Theme 2 (Population Characteristics and Disability) = Medium o High levels for aging population & disability •Theme 3 (Diversity) = Low o 8% non-white •Theme 4 (Housing and Transport) = Medium o High # of mobile homes and estimated occupancy per home	• 50% low income • 80th percentile+: no internet, energy burden, unemployed, job access	
2.9	2.0	3.0	4.0	3.0

Figure 10: Calculating the Community Impact Index

6.3. Results and Validation Against Historical Data

The analysis above yielded a disruption risk index associated with a circuit and community impact index that applied to specific census tracts or communities. Applying the indices in a consistent manner requires a geospatial mapping activity that maps the circuits to impacted communities. For this study, we denoted this common intersection as a *region*.

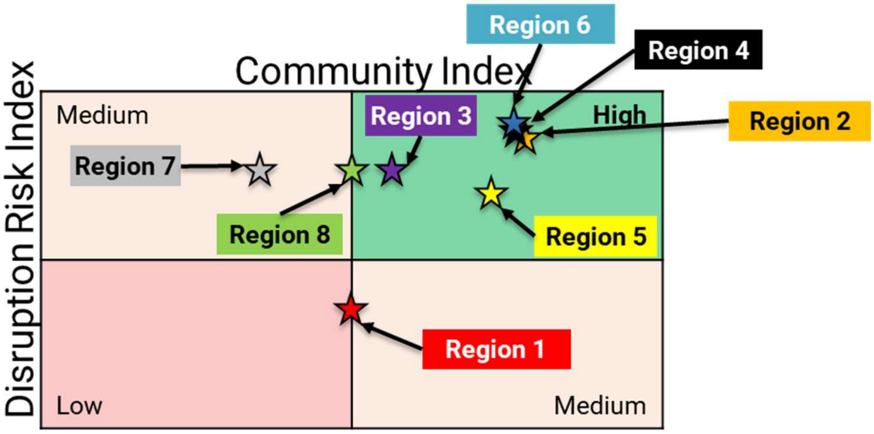
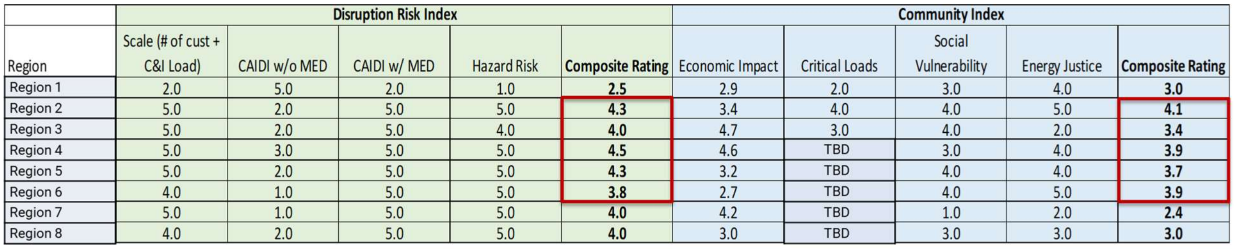


Figure 11: Duke Energy Carolinas, Preliminary Portfolio Analysis

As illustrated in figure 11 that shows the evaluation of eight regions, the preliminary analysis classified regions based on the combination of disruption risk and community impact. These regions ranged from high disruption risk with high community impact to low disruption risk with low community impact, with several intermediate combinations.

The dual-index approach enabled systematic prioritization of investment opportunities, with highest priority given to feeders showing both high disruption risk and high community impact. Based on the combination of disruption risk and community impact, this approach identified approximately five regions for detailed feasibility studies.



	Disruption Risk Index					Community Index				
Region	Scale (# of cust + C&I Load)	CAIDI w/o MED	CAIDI w/ MED	Hazard Risk	**Composite Rating**	Economic Impact	Critical Loads	Social Vulnerability	Energy Justice	**Composite Rating**
Region 1	2.0	5.0	2.0	1.0	**2.5**	2.9	2.0	3.0	4.0	**3.0**
Region 2	5.0	2.0	5.0	5.0	**4.3**	3.4	4.0	4.0	5.0	**4.1**
Region 3	5.0	2.0	5.0	4.0	**4.0**	4.7	3.0	4.0	2.0	**3.4**
Region 4	5.0	3.0	5.0	5.0	**4.5**	4.6	TBD	3.0	4.0	**3.9**
Region 5	5.0	2.0	5.0	5.0	**4.3**	3.2	TBD	4.0	4.0	**3.7**
Region 6	4.0	1.0	5.0	5.0	**3.8**	2.7	TBD	4.0	5.0	**3.9**
Region 7	5.0	1.0	5.0	5.0	**4.0**	4.2	TBD	1.0	2.0	**2.4**
Region 8	4.0	2.0	5.0	5.0	**4.0**	3.0	TBD	3.0	3.0	**3.0**

Figure 12: Disruption Risk and Community Impact by Region

The framework's effectiveness was validated through analysis of historical major events in Duke Energy's service territory. The analysis demonstrated that feeders identified as high-risk by the framework experienced longer outage durations during major events and served more vulnerable customers.

Additionally, the framework also provided insights on prior DER projects implemented in the Carolinas. In the above table, Region 1 included a completed non-wire alternative microgrid project in the Western Carolinas, which aimed to improve resilience for a community load pocket served by a single feeder and lacking good alternatives for secondary feeders. While the project in Region 1 had significant merits from a business and operations standpoint, a data-driven approach as laid out in this whitepaper would not have identified this area as a high priority from a resilience standpoint.

6.4. Stakeholder Engagement and Validation

The framework underwent stakeholder review involving Duke Energy’s operations personnel and regulatory staff from NCUC: REPS. This review process helped to validate both the technical approach as well as the interest amongst regulatory stakeholders in adopting such data-driven techniques.

Operational Validation: Distribution system operators confirmed that the framework's identification of high-risk feeders aligned with their operational experience and knowledge of system vulnerabilities.

Community Validation: Emergency management staff at the utility also confirmed that the Community Risk Index accurately reflected their understanding of vulnerable populations and critical facility locations.

6.5. Economic Valuation Approach

Our research employed a hybrid approach to estimating the Value of Lost Load (VOLL) that incorporated both direct customer impacts and indirect economic consequences. This approach recognized that traditional VOLL calculations may underestimate the true economic value of resilience improvements.

The two components of VOLL were estimated as follows:

Direct Customer Impact Assessment:

- Residential customer interruption costs based on customer surveys and willingness-to-pay studies using the ICE calculator
- Commercial and industrial customer costs based on production losses, spoilage, and business interruption
- Sector-specific impact multipliers reflecting varying vulnerability to power outages

Indirect Economic Impact Analysis:

- Regional economic multiplier effects using IMPLAN input-output models
- Supply chain disruption costs and cascading economic impacts
- Tourism and service sector impacts in the affected regions
- Long-term economic development implications

7. Industry Implications and Applications

While the focus of this study was to implement a DER portfolio screening methodology for Duke Energy Carolinas, the resulting framework can be tailored and applied to the industry as a whole and leveraged as a means of engaging communities and regulators.

7.1. Utility Application

The framework provides utilities with a systematic yet flexible approach to resilience investment decision-making that addresses multiple business and operational needs.

Utilities can implement a structured approach to develop and update their candidate project list on an annual basis, building a 3-5 year portfolio of potential projects across their service territory. At the same time, the flexibility in the framework allows utilities to:

1. Prioritize metrics and weightings appropriate to their service region and decide which projects to advance to the detailed feasibility analysis and capital allocation stages
2. Focus on the community impacts relevant to the communities in their service area
3. Engage regulators and stakeholders with transparent, data-driven metrics to justify ratepayer funded capital investments

Investment Planning and Portfolio Optimization:

- Develop project portfolio for the medium term using the dual-index framework to forecast capital investment needs.
- Systematically prioritize resilience investments for detailed feasibility analysis, cost benefit analysis, executive support, and regulatory approval
- Integrate resilience benefits into traditional utility planning processes
- Allocate limited capital resources analyzing costs, benefits, and mitigation of risks to the grid

Community Assessment and Engagement

- Incorporate social vulnerability index factors most relevant to the utility’s power system and communities affected with appropriate emphasis on economic, infrastructure, health, and social factors, potentially integrating with utility customer class data

- Apply, modify, and weigh the 36 DOE Justice40 burden indicators incorporated in the framework to appropriately account for the burdens most relevant to the served communities

Regulatory and Stakeholder Engagement:

- Quantify the business case for resilience investments using well established metrics (such as VOLL)
- Integrate community impact analysis and benefits for proposed DER investments
- Leverage the data-driven methodology for transparency and objectivity in regulatory approval of rate funded investment decisions

Operational Integration:

- Integration with existing utility planning and operations processes
- Compatibility with established reliability and performance metrics
- Support for emergency preparedness and post-event response

7.2. Regulatory Implications

The framework provides regulators with tools and methodologies for evaluating utility resilience investments and ensuring prudent resource allocation.

Rate Case and Investment Approval:

- Standardized methodology for evaluating resilience benefits for DER investment proposals
- Objective criteria for comparing alternative investment options
- Framework for assessing cost-effectiveness and desirability of resilience improvements

Policy Development:

- Evidence-based foundation for resilience policy development
- Quantitative analysis supporting resilience standards and requirements
- Framework for evaluating utility resilience plans and strategies

7.3. Broader Industry Applications

The framework's methodology can be adapted for application across different utility types, service territories, and regulatory environments.

Scalability and Adaptability:

- Flexible framework structure accommodating different utility sizes, characteristics, and operational priorities
- Right-size to available data and priorities – utilities can select the metrics and weightings that make the most sense in their current operations context.
- Adaptable to different geographic regions and climate risk profiles
- Compatible with various regulatory frameworks and policy environments

Industry Standardization Potential:

- Foundation for incorporation into industry-wide resilience evaluation initiatives led by regulatory bodies and national laboratories
- Basis for peer utility comparison and benchmarking
- Framework for collaborative resilience planning across utility boundaries

8. Future Research and Development

8.1. Framework Enhancement Opportunities

Several areas for framework enhancement have been identified through initial implementation and stakeholder feedback.

Augment Portfolio Analysis

In the initial iteration, our methodology used a simple average score calculation assuming a linear distribution of data to develop disruption and community indices. More sophisticated scoring mechanisms may involve using statistical analysis of the distribution of data and placing higher weights on outliers.

Additionally, the framework would benefit from augmentations to include additional resilience metrics and assets-at-risk evaluation in the calculation of disruption risk index.

The community impact index would benefit from a structured evaluation of critical facilities based on traditional facility classification schemes (Tiers 1-4) and the impact of downtime to community resilience (service continuity during emergency events, shelter capacity, economic impacts, public safety, and health consequences).

Expanded Data Integration

The framework can also be improved by integration of relevant federal, state, and utility-specific data sources, in conjunction with data service APIs. As an example, when evaluating the impact of a critical service facility, one factor that could be incorporated is the drive time to the closest alternative (using API services from providers such as Google Map and OpenStreetMap)

Advanced Analytics Integration

While the analytical techniques utilized in the development of the framework were based on available historical data from one utility, a collaborative approach across multiple utilities could yield a rich data set that allows implementation of machine learning models for predicting disruption risk and community impacts

Adapting to DER Propagation

The current iteration of the framework does not consider the adoption of DER, V2G, standby generation, alternate distribution circuits, and planned grid modernization investments in the evaluation of disruption risks and community impacts. For example, community load pockets served by circuits with above-normal disruption risk may also have significant propagation of DER resources. In such cases, the existence of alternate sources of supply needs to be factored into the calculation of the two indices to appropriately lower the attractiveness of a new project in the area.

8.2. Research Priorities

Priority research areas having the greatest potential for advancing this framework further are discussed below:

Economic Valuation Refinement

While the current framework addresses the limitations of VOLL calculation techniques using input-output modeling, it suffers from the limitations that it assumes static / fixed economic relationships. To address these constraints, additional research is needed in the areas of:

- Advanced VOLL estimation methodologies incorporating behavioral economics and social costs such as,
    - Healthcare and public safety impacts from prolonged outages
    - Educational disruption costs for schools and students
    - Transportation and communication system impacts
    - Environmental and public health consequences
- Integration of insurance and risk management perspectives
- Development of market-based resilience valuation approaches
- Integration of uncertainty analysis into economic valuation to provide risk-adjusted estimates of resilience benefits

Incremental Value of Resilience

In the initial iteration of the framework, VOLL is calculated as an absolute value for the purpose of analysis. However, in the context of incremental costs for improved performance scenarios enabled by DER investments, the incremental value of resilience improvements (with respect to the as-is or base case) may be a better metric.

Baseline Scenario Development: Historical outage patterns and costs provide the foundation for baseline scenarios, adjusted for projected climate change impacts and evolving risk patterns.

DER Performance Modeling: Technical analysis of DER capabilities during outage events, including:

- Critical load support duration and capacity
- Restoration acceleration through distributed generation
- Grid stabilization benefits during recovery operations

Incremental Benefit Quantification: The difference between baseline and DER-enabled scenarios provides the quantified resilience value for investment analysis.

Sensitivity Analysis

The framework could be extended to incorporate comprehensive sensitivity analysis to address uncertainty in key parameters and assumptions. This analysis includes:

Parameter Sensitivity:

- Variations in VOLL estimates across different customer classes and regions
- Climate change impact uncertainty ranges
- Performance and cost assumptions for DER technology

Scenario Analysis:

- Multiple future climate and weather scenarios
- Different regulatory and policy development paths
- Technology cost evolution scenarios

Integration of Community Impacts

The current methodology focuses on portfolio screening and prioritization. An area of suggested research is to extend the methodology to better incorporate community benefit evaluation and engagement in the project feasibility evaluation. The goal would be to go beyond traditional cost-benefit analysis to include:

- Enhanced methodologies for quantifying community resilience benefits such as, evaluation of per capita benefits in lieu of absolute values
- Integration of community resilience into the utility planning process
- Development of participatory planning and assessment approaches based on quantified community benefits and evaluation of community indicators such as SVI and environmental justice
- Integration of resilience planning with broader community and regional planning processes

Performance Measurement Metrics

A key area of research is the development of metrics to evaluate project performance. Some areas include:

- Microgrid performance metrics such as Islanding Event Summary, PV and Storage Asset Performance, Actual vs Forecast Performance
- Advanced metrics for resilience performance assessment augmenting traditional reliability indicators to also include measurements based on legs of the resilience trapezoid and continuity of critical services
- Integration of customer satisfaction measures

9. Conclusions and Recommendations

9.1. Key Findings

This research introduces the feasibility and value of systematic approaches to quantifying resilience benefits from distributed energy resource investments. Several key findings emerge from the framework development and implementation:

Quantification enables better decision-making: The framework demonstrates that resilience benefits can be systematically quantified and integrated into utility investment decision-making processes. This quantification enables more informed resource allocation and better alignment of investments with community needs.

Community impact integration is essential: Traditional utility planning approaches focused primarily on technical and economic factors may miss important community resilience needs. The integration of social vulnerability and environmental justice factors ensures more equitable and effective resilience investments.

Multi-factor assessment provides data-driven decisions: The dual-index approach combining technical risk assessment with community impact analysis leads to objective, data-driven decisions that can be evaluated using objective metrics, as compared to traditional approaches focused solely on reliability metrics or economic factors.

Validation confirms predictive value: Preliminary validation against historical events demonstrates that the framework provides meaningful predictive value for identifying high-risk situations and prioritizing investments with maximum resilience benefit.

9.2. Closing Observations

The framework presented in this white paper aims to advance the systematic evaluation of distributed energy resource investments for grid resilience. By combining technical analysis with community impact assessment, the framework enables utilities to make more informed decisions that enhance both grid reliability and community resilience.

The preliminary implementation of this framework at Duke Energy demonstrates its practical value and scalability. The methodology's emphasis on objective metrics, multiple data sources, and stakeholder engagement provides a foundation for broader industry adoption and continued advancement.

As severe storms and climate events continue to intensify the challenges facing electric utilities, frameworks like this will become increasingly essential for ensuring that investments in grid modernization and distributed energy resources deliver maximum benefit to both utilities and the communities they serve. The continued development and refinement of these approaches will be critical for building a more resilient and equitable energy future.

References and Data Sources

- Centers for Disease Control and Prevention Social Vulnerability Index
- FEMA National Risk Index
- National Oceanic and Atmospheric Administration Climate Data
- Department of Energy Justice40 Initiative
- Duke Energy operational databases and reliability metrics
- IMPLAN regional economic modeling system
- Interruption Cost Estimate (ICE) Calculator
- Bureau of Labor Statistics employment and economic data
- IEEE reliability standards and utility industry benchmarks

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