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Reviewing Benefit-Cost Analyses of Electricity Resilience Projects

A Guide for Regulators with Key Elements to Scrutinize

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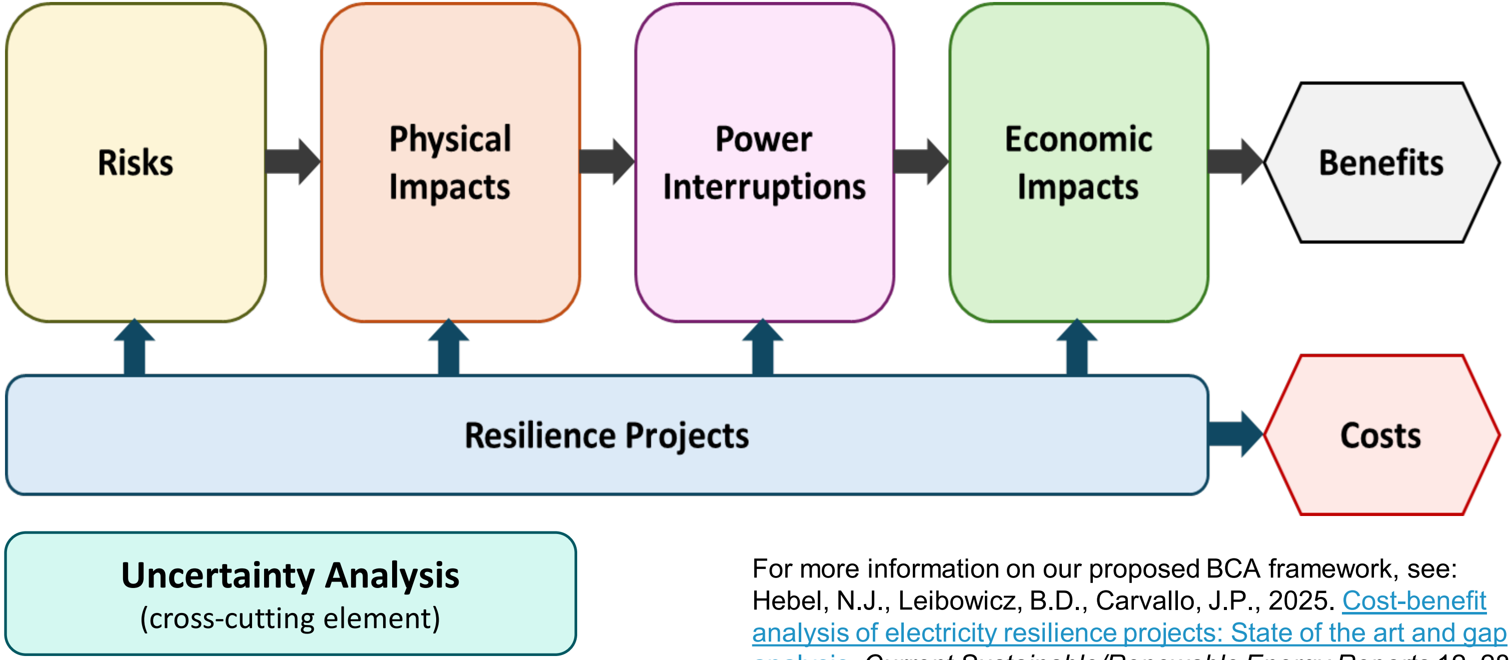
What This Guide Intends to Do:

- Benefit-cost analysis (BCA) is a widely used approach for assessing whether investments and operational strategies are economically justifiable. However, each project is different and BCA methods and assumptions vary considerably
- We offer guidance to help the Vermont Department of Public Service (PSD) and the Vermont Public Utility Commission (PUC) examine and interpret the BCAs that utilities will likely submit under the proposed resilience framework
- In particular, we identify some of the key methodological choices and assumptions that utilities will likely have to make, and which the PSD and PUC should scrutinize to evaluate the overall quality of the BCA
- We also provide links to resources, references, and examples that can be consulted to compare a utility's methods, assumptions, and input and output data values to existing expert guidance, available tools, and practical examples of electricity resilience BCA

Caveats and Disclaimers:

- This guide does not impose any requirements on the BCAs performed by Vermont utilities
  - Rather, the guidance contained herein is intended to help the PSD and PUC evaluate the thoroughness and logic of any submitted BCA
- Our identification of key methodological choices and assumptions to scrutinize is tailored to what we expect will be the most common and typical BCA approaches that Vermont's utilities follow
  - A utility may choose to follow a less typical BCA methodology that is not addressed as directly by the guidance offered in these slides. In this case, the lack of alignment between our guidance and the BCA methodology should not be viewed as a negative (or positive) signal about the methodology's soundness

Visual Summary: BCA Framework with Major Elements



For more information on our proposed BCA framework, see: Hebel, N.J., Leibowicz, B.D., Carvallo, J.P., 2025. Cost-benefit analysis of electricity resilience projects: State of the art and gap analysis. *Current Sustainable/Renewable Energy Reports* 12, 28.

Outline: BCA Elements and Key Questions

BCA Element(s)	Key Question	Slides
Resilience Projects	At what level of spatial granularity is the BCA performed, and is it suitable for the decision-making context?	7,8
Risks	What risks to resilience are included within the scope of the analysis?	9,10
Risks	What does the utility assume about the severities and frequencies with which the events will occur?	11,12
Physical Impacts & Power Interruptions	How does the utility translate risk events into power interruptions?	13,14
Physical Impacts & Power Interruptions	How does the utility incorporate the impacts of resilience interventions?	15,16
Power Interruptions	How does the utility estimate energy not served (ENS) based on the power interruptions it projects?	17,18

Outline: BCA Elements and Key Questions

BCA Element(s)	Key Question	Slides
Economic Impacts	How does the utility value the economic impacts of power interruptions in dollars?	19,20
Benefits	What other benefits, beyond avoided power interruptions, does the utility estimate and value?	21,22
Costs	How is the cost of implementing the resilience project estimated? What supporting evidence is provided?	23,24
Benefits & Costs	How does the utility calculate the BC ratio?	25,26
Uncertainty Analysis	Does the utility conduct any form of uncertainty analysis, and how does uncertainty affect the BCA's conclusions?	27,28

Key Question: At what level of spatial granularity is the BCA performed, and is it suitable for the decision-making context?

Detailed Questions	Comments
Does the analysis occur at the whole program/service-territory-wide level? Or does the analysis divide the system into several zones, feeders, circuits, etc.?	• Note that it is possible that a BCA could include analyses at multiple levels of granularity • A geographically broad BCA could allow some individual projects with negative net benefits to go forward, but this would also allow for some flexibility to enhance resilience for more costly-to-serve (e.g., rural) customers
Does the BCA group together different types of resilience interventions, or does it analyze the costs and benefits of different project types separately?	• Different resilience interventions may protect against different threats and have different vulnerabilities, but in some cases the performance of one resilience intervention is affected by other interventions or upgrades

Key Question: At what level of spatial granularity is the BCA performed, and is it suitable for the decision-making context?

Resources, References, and Examples

- CenterPoint Resilience Plan: Example of program-level BCA. Potential investments are grouped by type (e.g., Distribution Hardening, Lateral Hardening), regardless of circuit/location.
- Entergy Storm Plan: Uses project-level BCA to determine which individual projects have positive benefit-cost ratios (BCRs) but does not report results at the individual project level. Projects with BCR>1 are then grouped together for further analysis.

Key Question: What risks to resilience are included within the scope of the analysis?

Detailed Questions	Comments
What types of weather events are included in the analysis and how is their inclusion justified?	
Does the analysis limit its scope to only “extreme” resilience-type events or does it also include more typical weather threats to reliability? Does the methodology distinguish between these types of risks?	• “Extreme” types of events have different statistical properties compared to “typical” weather events, so it is useful to characterize them separately
Does the analysis only include the types of events that have occurred historically, or does it include any “new” event types that could begin to significantly afflict Vermont in the future, such as wildfires?	
Does the analysis address physical attacks? Cyberattacks? Failures of other infrastructure networks that affect power systems, such as gas supply lines?	

Key Question: What risks to resilience are included within the scope of the analysis?

Resources, References, and Examples

- Climate READI Climate Data User Guide (EPRI): Includes an overview of weather and climate hazards to the power system and a review of different sources of climate projections
- CenterPoint Resilience Plan: Begins with a resilience risk assessment, which includes both natural hazards (such as extreme wind, extreme temperatures, and flooding) and other hazards such as physical attacks and cybersecurity threats

Key Question: What does the utility assume about the severities and frequencies with which the events will occur?

Detailed Questions	Comments
Does the utility assume that future events will be statistically similar to historically observed events, or does it project forward – either by "scaling" historical severities / frequencies up or down, or by using some type of downscaled climate projections?	• Data needs and uncertainty from historical vs. forward-looking events are markedly different • This is a good area to leverage the expertise of the Vermont State Climatologist, University of Vermont, etc. to examine whether a utility's assumptions about the future are credible
What quantitative values for frequency and severity are assumed, how were they obtained, and is any uncertainty analysis conducted?	

Key Question: What does the utility assume about the severities and frequencies with which the events will occur?

Resources, References, and Examples

- CenterPoint Resilience Plan: Uses a combination of historical data and downscaled global climate models to assess variability and future risks
- Entergy Storm Plan: Uses Monte Carlo simulation to create 1000 potential futures over a 50-year period from a database of storm probabilities based on modified historical data
- ClimRR Tool: Provides dynamically downscaled climate projections from Global Climate Models, including precipitation and wind speed

Key Question: How does the utility translate risk events into power interruptions?

Detailed Questions	Comments
Does the utility explicitly model the vulnerability of its power infrastructure to risk events and/or power system operations in various system states? Or does it rely on past experience, rules of thumb, etc. to map event characteristics to the resulting power interruptions?	
How does the utility estimate the durations of the interruptions that occur? Are the estimated durations staggered (i.e., they account for stages of recovery affecting different customers) or aggregated?	• Staggered estimates characterize the varying outage durations experienced by different customers, more realistically describing the restoration process and its resilience impacts

Key Question: How does the utility translate risk events into power interruptions?

Resources, References, and Examples

- Climate READI (EPRI): Includes a referenced inventory of Fragility Curves, which allows users to filter by asset and threat types. Also provides information on various adaptation strategies and a template for assessing asset vulnerability
- Entergy Storm Plan: The analysis includes a Storm Impact Model which calculates "likelihood of failure (LOF)" scores for each asset at the circuit protection level for different types of storms

Key Question: How does the utility incorporate the impacts of resilience interventions?

Detailed Questions	Comments
How does the utility represent the effects of its proposed resilience interventions on power interruptions and incorporate them into its analysis?	• If the BCA explicitly models electric infrastructure assets, then resilience interventions could reduce asset failure probabilities for a given risk event • If the BCA directly translates risk events into power interruptions, then resilience interventions could reduce power interruptions by assumed percentages; these stylized, high-level assumptions should be scrutinized
If this utility or others in Vermont have undertaken the same type of resilience project before, how well did they perform empirically? Do the utility's assumptions about the project's interruption-mitigating effects align well with historical performance data from similar projects?	

Key Question: How does the utility incorporate the impacts of resilience interventions?

Resources, References, and Examples

- Entergy Storm Plan: The resilience impacts of grid hardening measures are captured in the Storm Impact Model component of the analysis, where applying a hardening measure to a part of the system reduces its Likelihood of Failure relative to the status quo scenario
- CenterPoint Resilience Plan: The analysis generally allows projects to enhance resilience by (1) reducing the frequency of outage events, (2) reducing the number of customers impacted by an outage, and/or (3) reducing the durations of outages. Using mode (1) as an example, for assets in a given class (e.g., distribution poles in the Coastal region), a hardened version of the asset will have a higher failure threshold (e.g., wind speed) than a baseline version, and thus have a lower annual probability of failure

Key Question: How does the utility estimate energy not served (ENS) based on the power interruptions it projects?

Detailed Questions	Comments
How does the utility establish the counterfactual of how much electricity its customers would consume should power be fully available?	
Does the utility disaggregate the total ENS by customer segment, interruption duration, etc.?	• This disaggregation would allow more specifically targeted VOLL estimates to be applied and for consideration of how the resilience project's benefits would be distributed across customer groups
How do calculations of ENS in future years account for load growth due to population growth, economic growth, electrification, etc.?	
What sensitivities for the ENS are developed and reported?	• Avoided ENS is a key resilience benefit; sensitivities may be important to understand the range of performance for the strategy under evaluation

Key Question: How does the utility estimate energy not served (ENS) based on the power interruptions it projects?

Resources, References, and Examples

- Entergy Storm Plan: The utility uses a power restoration model to estimate the durations of outages at the resilience project level, which is combined with customer data for the relevant circuit
- Avangrid BCA: Engineers conduct analyses to estimate percentage outage reductions and reduced restoration times achieved by various measures for each resilience circuit proposal
- CenterPoint Resilience Plan: Uses statistics for average amount of load at risk and outage duration for different types of asset failures to estimate energy not served

Key Question: How does the utility value the economic impacts of power interruptions in dollars?

Detailed Questions	Comments
If the analysis uses an assumed value of lost load (VOLL), is the VOLL well-tailored?	• Is it appropriate for the geographic area? • Does it represent different types of customers affected? • Does it reflect the duration and timing (e.g., summer vs. winter) of the interruption?
How does the assumed VOLL compare to VOLL estimates obtained by researchers, used in other practical examples, used by organizations and authorities in the region (e.g., ISO-NE), etc.?	
Does the analysis attempt to account for additional economic impacts not captured through VOLL surveys, e.g., by using a regional economic model?	• VOLL captures “direct” impacts to customers, but other methods recognize “indirect” economic impacts to society at large • If VOLL and economic modeling approaches are both included, there may be overlap in the economic impacts that each approach captures. Ensure clear delineation between the different methods

Key Question: How does the utility value the economic impacts of power interruptions in dollars?

Resources, References, and Examples

- LBNL ICE Calculator: Uses survey data to estimate interruption costs associated with reliability improvements
  - The accompanying Guidebook provides additional background, methodology details, and case studies that demonstrate how interruption cost data can be calculated and used
- CenterPoint Resilience Plan: Uses a single VOLL value for all resilience measures, which was increased from a previous analysis based on Texas PUC recommendations
- Gorman 2022: Synthesizes the VOLL estimation literature and discusses the application of VOLL in the context of BCA for grid-enhancing investments
- Macmillan et al. 2023: Reviews models used to estimate the costs of long-duration power interruptions, discussing each model’s strengths and weaknesses

Key Question: What other benefits, beyond avoided power interruptions, does the utility estimate and value?

Detailed Questions	Comments
Does the analysis incorporate avoided storm recovery and/or system restoration costs? If so, what is the source of these costs and how are they projected to evolve?	• In addition, if there are benefits attributed to reliability, ensure that these are defined and estimated distinctly from resilience benefits
Does the analysis incorporate avoided O&M costs (e.g., reduced needs for vegetation management)? If so, what is the source of these costs and how are they projected to evolve?	
Does the analysis include any aesthetic benefits (e.g., due to undergrounding)? If so, how are these benefits estimated?	
Does the analysis include cost savings due to reduced energy losses on lines, T&D investment deferral (e.g., due to battery storage), reduced capacity purchases, reduced transmission charges, etc.?	• Note that this is not an exhaustive list of the potential benefits that might be incorporated into a BCA. For any benefits that are included, note the sources of all input data assumptions

Key Question: What other benefits, beyond avoided power interruptions, does the utility estimate and value?

Resources, References, and Examples

- Larsen 2016: Provides an example of comprehensive BCA with benefit calculations for avoided aesthetic costs and impacts on lifecycle costs
  - Note that changes to O&M costs may potentially be considered as part of costs or benefits
- Zamuda et al. 2019: A high-level review of methods for quantifying and monetizing benefits for use in BCA
- Avangrid BCA: Incorporates avoided restoration costs, which are defined as capital and operating costs for the utility to restore power, in addition to avoided customer interruption costs
- Grid Modernization Laboratory Consortium (GMLC) Resilient Distribution Systems (RDS): Provides a taxonomy of different benefits and associated metrics for estimating them

Key Question: How is the cost of implementing the resilience project estimated? What supporting evidence is provided?

Detailed Questions	Comments
Has this type of project been implemented by this utility before, especially in recent years? What experience does the utility have?	• Experience with certain projects helps constrain the unexpected costs that could arise once solutions are designed and implemented • If the utility does not have direct experience, have other Vermont utilities implemented this type of project recently, and what were their costs?
What are possible drivers of cost uncertainty for each solution, and how does the analysis account for them (e.g., high- and low-cost estimates)?	
If cost estimates are taken from elsewhere (e.g., industry reports, utilities in other states), how credibly can they be applied to this utility in Vermont?	

Key Question: How is the cost of implementing the resilience project estimated? What supporting evidence is provided?

Resources, References, and Examples

- Kallay et al. 2021: Present potential costs that may be associated with the implementation of resilience measures
- LBNL Resilience Investment Guides*: Provide cost estimates for various technologies with references that may be useful for benchmarking
- Entergy Storm Plan: Outside consultant worked with Entergy to develop unit cost estimates, which were then adjusted by lengths and other location-specific cost drivers (e.g., vegetation, terrain)

* *After clicking the hyperlink, search for "resilience investment guides" to locate the relevant references*

Key Question: How does the utility calculate the BC Ratio?

Detailed Questions	Comments
Does the analysis quantify benefits and costs in appropriate and comparable units (e.g., net present values or annual equivalent values)?	
How are future benefits and costs discounted? What discount rate is used, and does the utility use the same rate for every cost and benefit?	
How is the baseline scenario defined? Are the assumptions about baseline costs and benefits credible and appropriately justified? Are they consistent with the assumptions for the alternate scenario(s) that involves proactive resilience interventions?	• It is important to note that the resilience project BCR is established relative to some baseline scenario. Therefore, the baseline scenario should be a clearly specified, realistic vision of what would happen if the proposed resilience project is not implemented

Key Question : How does the utility calculate the BC Ratio?

Resources, References, and Examples

- Entergy Storm Plan: Calculates the BCR as the sum of avoided restoration costs and avoided customer outage costs divided by project cost and then uses weighted values for different storm futures to calculate the final BCR for each hardening project
- Avangrid BCA: Estimates the 30-year value from the estimated project completion date, escalating all costs and benefits by 2% per year and discounting future cost and benefit streams to their present values at a rate of 6.4% per year
  - Discount rate is equal to the company’s after-tax Weighted Average Cost of Capital (WACC) for investments

Key Question: Does the utility conduct any form of uncertainty analysis, and how does uncertainty affect the BCA's conclusions?

Detailed Questions	Comments
Does the analysis conduct any sensitivity analysis to gauge the impact that individual assumptions may have on the BCR?	• This can help identify which assumptions warrant additional scrutiny
Does the analysis include scenario analysis, testing how different future scenarios (e.g., varying climate projections) may impact the BCR?	• Regulators may want to pay close attention to BCR ranges that include BCRs below and above 1 in different scenarios. A BCR range that is above 1 in all, or almost all, scenarios considered plausible provides solid evidence that a project would be net-beneficial
Is there a Monte Carlo simulation that produces a probability distribution over benefits?	• Monte Carlo simulations offer a comprehensive treatment of uncertainty compared to scenarios that are not assigned probabilities. However, specifying probability distributions for input assumptions can be challenging and the process is data and computationally intensive

Key Question: Does the utility conduct any form of uncertainty analysis, and how does uncertainty affect the BCA's conclusions?

Resources, References, and Examples

- CenterPoint Resilience Plan: Includes sensitivity analysis that shows how results vary with different VOLL values (see Appendix C)
- Larsen 2016: Example of a sensitivity analysis for comprehensive BCA. Includes sensitivity analysis for individual input assumptions as well as a Monte Carlo simulation

Final Thoughts: Keeping BCA in Perspective

- While high-quality BCAs can serve as important inputs to regulatory decisions on proposed resilience projects, regulators should not view BCAs as dispositive by themselves; regulators may want to consider a range of other factors before approving a project even if its BCR is greater than one
- For example, some benefits should naturally be passed on to customers through lower rates (e.g., avoided storm recovery costs), whereas other benefits that customers receive could come at the cost of higher electric bills (e.g., avoided power interruptions)
  - While in principle VOLL estimates reflect how customers assess this tradeoff between power interruptions and costs, they entail a number of limitations
- Beyond the BCR estimated through BCA, regulators might also want to consider the types of benefits, how they are distributed among the utility and its customers, rate impacts, alternative resilience strategies, etc. before making a final decision

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