Strategies for Valuing and Prioritizing Resilience Investments and Measuring Progress

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Resilience Training for States – Western Region

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Goals for today

Information Sharing

- Metrics in practice to facilitate project valuation and prioritization
- Valuation frameworks and measuring progress
- Examples of valuing and prioritizing a resilience strategy
- Links to references and a glossary

Method

- Presentation
- Discussion
- Interactive polls

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Availability of information

- **Regulatory processes lead to publicly-available information** that can be useful for (1) evaluating projects that have societal benefits and (2) measuring performance after the project has been installed
- For this reason, there tends to be more information in the public domain for regulated utilities and less so for other utilities

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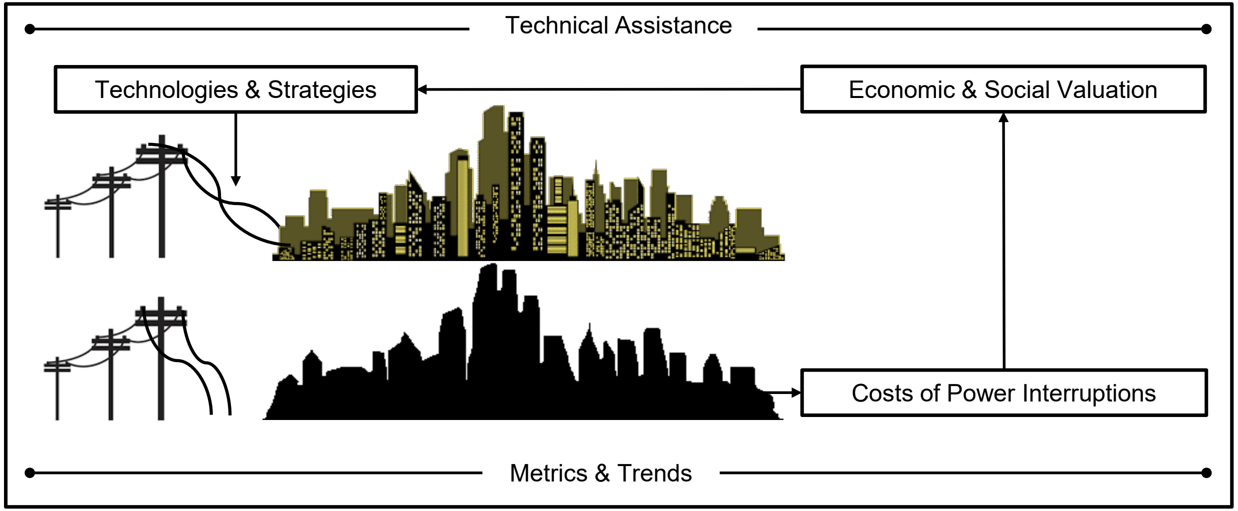
Metrics in Practice for Valuing and Prioritizing Resilience Projects

Metrics within context of project valuation and prioritization

Berkeley Lab's Portfolio of Resilience Activities



- **Metrics are important because they allow key stakeholders to assess the performance of systems before <u>or</u> after an investment**

- Some metrics (e.g., costs of power interruptions) are critical inputs into the value proposition for new projects

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Selected metrics in practice

State	Metric	Comments
California	IEEE 1366 reliability metrics, with and without major event days (MEDs)	● Circuit level and company-wide SAIDI ● Circuit level and company-wide SAIFI ● Circuit level and company-wide CAIDI ● Circuit level and company-wide MAIFI (see glossary) ● Top 1% of worst performing circuits (defined by circuit-level SAIDI and SAIFI excluding MEDs)
	Community Resilience Metric (CRM) (*mostly used for resilience planning)*	● A set of scores measuring the sensitivity and corresponding adaptive capacity of a particular community to potential loss of utility service ● Prioritizes the timing/order of adaptations based on socioeconomic indicators that approximate a community's resilience to power outages
	Risk-reduction and Risk-spend Spend Efficiency (*mostly used for resilience planning)*	● Estimation of the cost-effectiveness of initiatives based on risk-reduction benefits (calculated by probability and associated consequences) and costs for a specific solution
	Resiliency scorecard *(mostly used for resilience planning)*	● Scoring resiliency configuration characteristics including those that support state policy goals (e.g., mitigation measure characteristics (duration of backup, load capacity, fuel availability, emission levels))

Sources: CPUC (2016), CPUC (2021), SCE (2021), SCE (2023), SDGE (2023)

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Selected metrics in practice (2)

State	Metric	Description
Nevada	IEEE 1366 reliability metrics	● SAIDI, SAIFI, CAIFI
	Resilience metrics *(proposed)*	● Quantity of distributed resources available to respond to resilience events ● Compliance with Natural Disaster Protection Plan (NDPP) mandates ● Time to recover from service disruptions due to resiliency events ● Amount of load voluntarily reduced under emergency conditions
Washington	IEEE 1366 reliability metrics (*Circuit-level and system-wide*)	● SAIDI, SAIFI (with and without MED) ● Customers Experiencing Multiple Sustained and Monetary Interruptions (CEMSMI; number of customers experiencing more than a certain number of interruptions a year, including both momentary and sustained outages)
	Reliability metrics (*Circuit-level and system-wide*)	● CEMI-3 (customers experiencing more than three outages of 1 minute or more per year) ● Average outage duration ● Number of outage events per year ● Total customer outage hours ● Average number of affected customers per outage event ● Circuit performance indicator (CPI) to identify areas of greatest concern and worst performing circuits

Sources: NV Energy (2020), PUCN (2020), Watts et al. (2020), Pacific Corp (2021), AVISTA (2022)

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Selected metrics in practice (3)

State	Metric	Description
Idaho	IEEE 1366 reliability metrics	• SAIDI, SAIFI with and without MEDs, significant events • SAIDI and SAIFI by underlying causes • CEMSMI
	Reliability metrics	• Number of incidents by underlying causes • Worst performing circuits based on CPI • Reliability performance indicator (RPI)
Oregon	IEEE 1366 reliability metrics (*Circuit-level and system-wide*)	• SAIDI, SAIFI, CAIDI • $MAIFI_e$ (Momentary Average Interruption Frequency Index event, total number of momentary interruption events divided by the customer base for the relevant period)
	Reliability metrics	• Under-performing circuits (identified by CPI) • Customer minutes lost for incident (with of without MEDs) by cause and region • Customers in incident sustained (with or without MEDs)
	Resilience metrics *(mostly used for resilience planning purposes (benefit calculations))*	• Reduction in Near-Term Asset Risk (NTR) values (reduced annual risk value) • Reduction in Near-term Customers Minutes Interrupted • Reduction in expected outage durations and numbers

Sources: Rocky Mountain Power (2019), Portland General Electric Company (2022), ISEA (2023), Pacificorp (2023),

Selected metrics in practice (1)

State	Metric	Comments
Florida	IEEE 1366 reliability metrics	● SAIDI ● SAIFI ● CAIDI ● MAIFI (see glossary)
	L-Bar	● Average time it takes to restore power to all customers
	Customer-specific reliability metrics	● Customers experiencing multiple interruptions (customers experiencing more than X outages of 1 minute or more per year) ● Customers experiencing multiple momentaries ● Customer momentary events (customers affected by a momentary event)
	Customer interruption cost	● Florida Power and Light uses Berkeley Lab's ICE Calculator to estimate benefits of reducing SAIDI/SAIFI

Sources: Florida PSC (2013), FPL (2004), Florida PSC (2021)

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Interactive poll #1

What new metrics might be needed in your region to evaluate proposed or past investments in resilience?

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Valuation Frameworks and Measuring Progress

Selected economic and social valuation methods

Method	Units	Examples	Comments
Least-cost, best-fit	$ divided by a non-monetary value	X dollars invested in grid to avoid Y number of fatalities X dollars invested in grid to reduce SAIDI by Y minutes	• Presumes that an investment is needed and helps prioritize options to achieve objectives • Does not require monetization of any or all benefits of project
Cost-benefit analysis	$ divided by $	X dollars invested in grid leads to Y dollars in societal benefits	• Does not presume that an investment is needed • Allows for an apples-to-apples comparison of options • Can be extremely challenging to put a dollar value on some benefits

Source: Woolf et al. (2021)

Examples of information needed for valuing a strategy

Cost	Benefits: Non-monetized	Benefits: Monetized	Other
• Capital/installation • Annual operations and maintenance	• Avoided pollution • Avoided health/safety risk • Avoided damage to utility infrastructure • Reduction in frequency and/or duration of power interruptions • Avoided impacts to national security	• Avoided morbidity and mortality costs • Avoided capital and O&M costs to utility • Avoided interruption costs to customers • Avoided "spillover" effects to regional economy • Avoided aesthetic costs (if applicable)	• Real discount rate (or weighted average cost of capital) • Lifespan of strategy • Local, state, and federal incentives and rebates • Frequency and duration of power interruptions before and after investment • Detailed information about customers impacted

Forward- and backward-looking analyses

- Valuation activities can be conducted "ex ante" or "ex post"

Ex ante: "Based on forecasts rather than actual results"

Ex ante analysis is often used to identify a **proposed investment** and, in some cases, rank it among alternatives

- Undergrounding circuit 1234 has *expected* net benefits of $1M over its lifespan

Ex post: "Based on actual results rather than forecasts"

Ex post analysis is often used to measure progress or performance of an **investment that has already been made**

- Undergrounding circuit 1234 improved SAIDI and SAIFI by 21.2% and 19.4%, respectively.

Source: Oxford Dictionary (2023)

Interactive poll #2

What resilience valuation methods have you observed in your region?

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Examples of Valuing and Prioritizing Resilience Strategies

Example #1: Valuing a utility resilience strategy

- Berkeley Lab research into factors that impact long-term reliability of the U.S. power system led to research on the **value of undergrounding power lines**

- Increase in % share of transmission and distribution lines that are **underground has a statistically significant correlation with improved reliability/resilience** (Larsen et al. 2020)


Energy Policy

Distribution-level electricity reliability: Temporal trends using statistical analysis

Joseph H. Eto*, Kristina H. LaCommare, Peter Larsen, Annika Todd, Emily Fisher


Energy

Recent trends in power system reliability and implications for evaluating future investments in resiliency

Peter H. Larsen, Kristina H. LaCommare, Joseph H. Eto, James L. Sweeney

Components of valuation framework (1)

Despite the high costs attributed to power outages, there had been **little or no research to quantify both the benefits and costs of improving electric utility reliability/resilience**—especially within the context of decisions to underground T&D lines

- Study perspective:
  - Regulator who cares about maximizing private benefits
- Key stakeholders with standing:
  - Investor-owned utilities (IOUs), ratepayers, and all residents within service territory
- Policy alternatives:
  (1) Status quo (i.e., maintain existing underground and overhead line share)
  (2) Underground all T&D lines (i.e., underground when existing overhead lines reach end of useful lifespan)
- Why Texas?
  -Texas IOU service territories were selected due to (1) previous study evaluating costs and (some) benefits of undergrounding; (2) ready access to useful assumptions; and (3) public utility commission showing interest in undergrounding major portions of electrical grid

Source: Larsen (2016)

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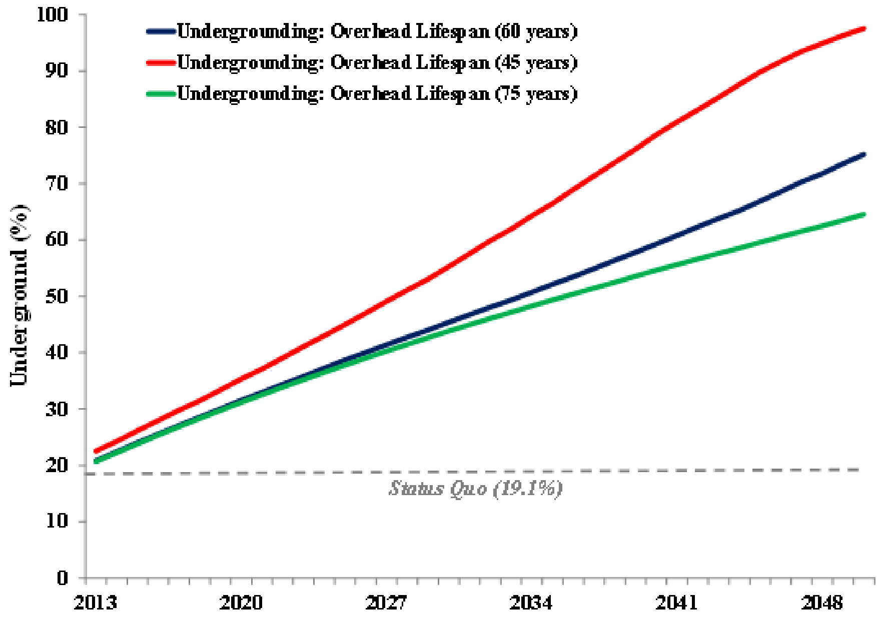
Components of valuation framework (2)

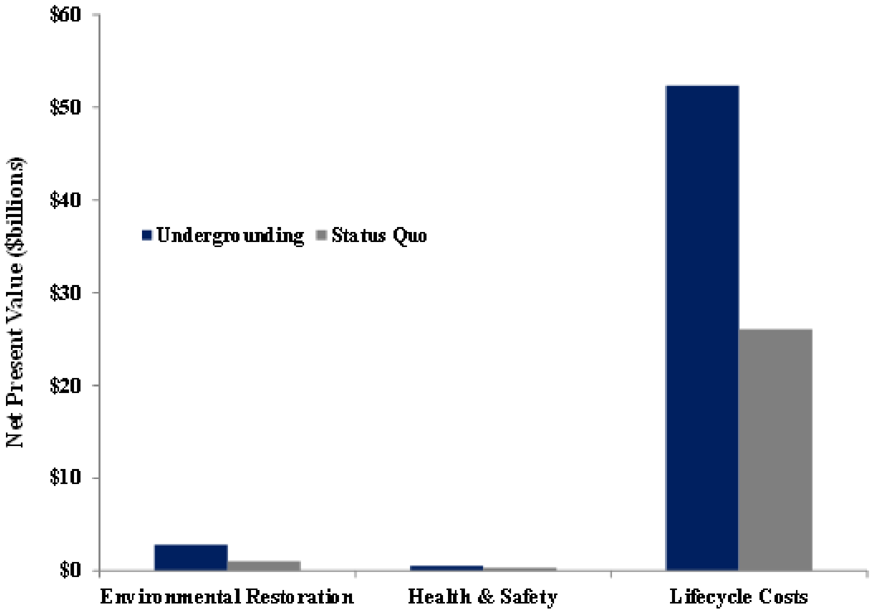
Key Stakeholders	Undergrounding Mandate	
	Selected Costs	**Selected Benefits**
IOUs	• Increased worker fatalities and accidents*	
Utility ratepayers	• Higher installation cost of underground lines***** • Additional administrative, siting, and permitting costs associated with undergrounding* • Increased ecosystem restoration/right-of-way costs**	• Lower operations and maintenance costs for undergrounding*
All residents within service area		• Avoided societal costs due to less frequent power outages*** • Avoided aesthetic costs**

* Denotes degree of impact on overall results

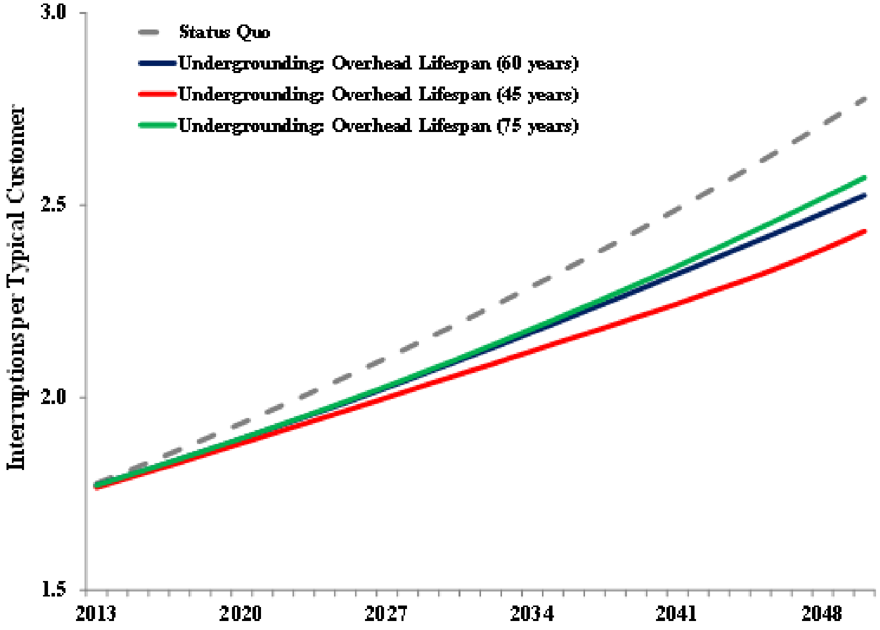
Can you spot the metrics included in this valuation framework?

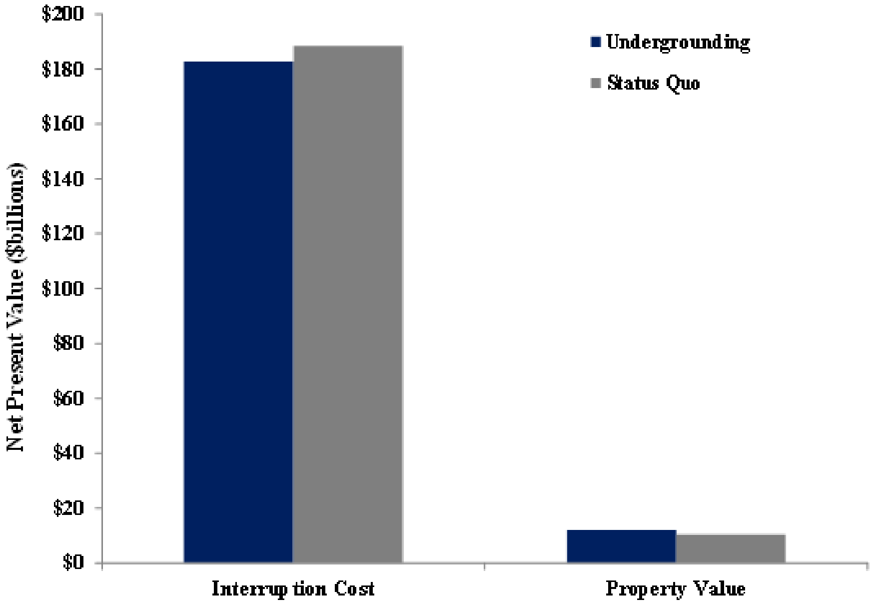
Estimated costs





Estimated benefits (1)





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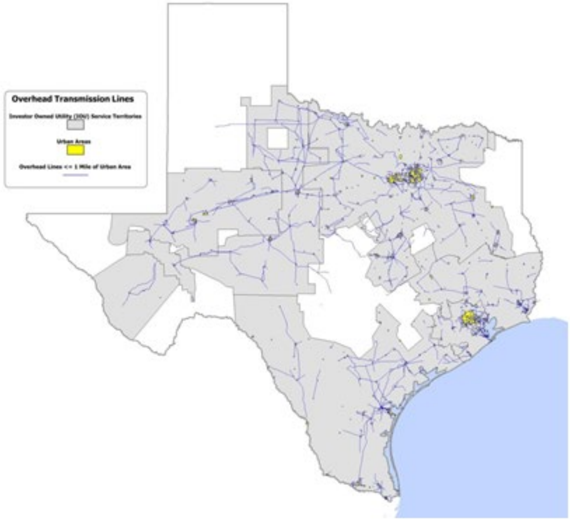
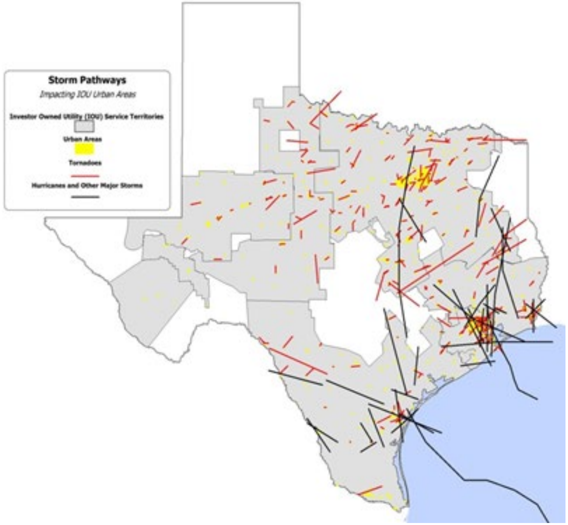
Estimated benefits (2)

The initial valuation indicated that **broadly mandating undergrounding when overhead T&D lines have reached the end of their useful life is not cost-effective for Texas IOUs.**





What are the minimum conditions necessary for a targeted undergrounding initiative to have positive net benefits?

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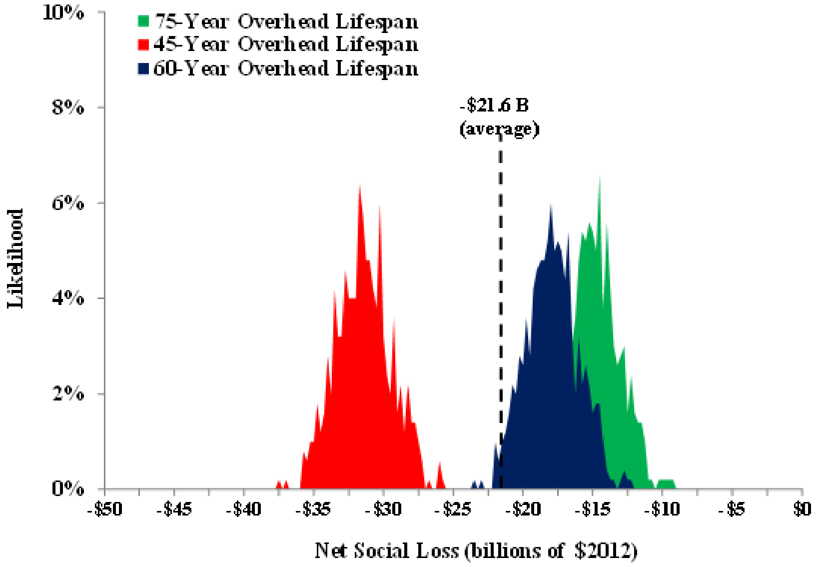
Valuation results

Impact Category	Undergrounding	Status Quo	Net Cost ($billions)
Environmental restoration	$2.8	$1.0	$1.8
Health & safety	$0.56	$0.31	$0.2
Lifecycle costs	$52.3	$26.1	$26.3
Total net costs (Undergrounding)			$28.3
Impact Category	**Undergrounding**	**Status Quo**	**Net Benefit ($billions)**
Interruption cost	$182.7	$188.4	$5.8
Avoided aesthetic costs	$12.1	$10.6	$1.5
Total net benefits (Undergrounding)			$7.3
Net Social Benefit (Undergrounding)			
Net social benefit (billions of $2012)			-$21.0
Benefit-cost ratio			0.3



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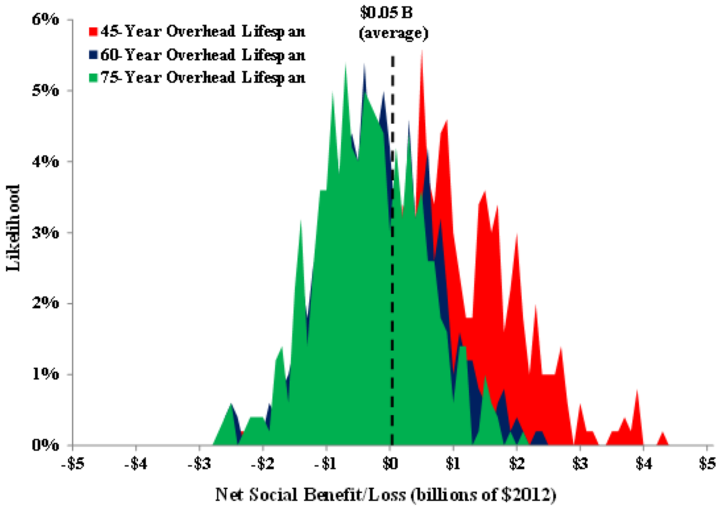
Possibility of net benefits

Texas policymakers <u>should</u> consider requiring that all T&D lines be undergrounded in places where:

- **there are a large number of customers per line mile** (e.g., greater than 40 customers per T&D line mile)
- **there is an expected vulnerability to frequent and intense storms**
- **there is the potential for economies of scale for installing underground T&D lines** (e.g., installation costs decrease each year)
- **overhead line rights-of-way are larger than underground line rights-of-way (i.e., less environmental footprint)**



"Electric utility providers should evaluate strategic, targeted undergrounding of distribution lines in limited, appropriate circumstances based on the exposure to the threat of severe winter events."
Source: [ORC (2021)]

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Example #2: Valuing a customer resilience strategy

- **Residential rooftop and storage systems (PVESS) can mitigate long duration interruptions** by providing backup power during power outages. This can reduce the economic and social impacts of power outages—a key resilience benefit.

- The benefit-cost ratio (BCRs) of PVESS varies by region, depending on the cost of PVESS, the value of lost load (VOLL), and the likelihood of long duration interruptions.

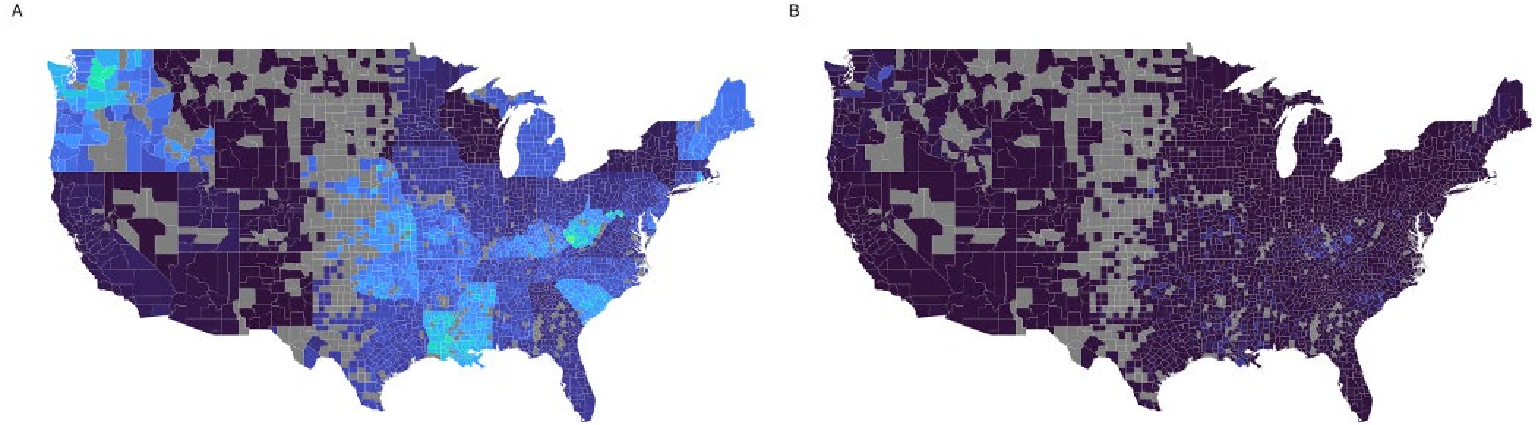
Key Research Questions

- What is the regional distribution of the ability of residential PVESS to mitigate resilience events (long duration interruptions lasting longer than 1 day)?
- Assuming regionally-differentiated PVESS costs and VOLL, what is the benefit-cost of storage investments on existing PV systems?
- How does this benefit-cost change considering Inflation Reduction Act (IRA) support?

Source: Baik et al. (2023)

PVESS mitigates customer interruptions

- States with a high frequency of resilience events (e.g., Louisiana, West Virginia) showed significant load loss without PVESS, while regions less impacted had lower loss
- **PVESS introduction mitigates or eliminates load loss across regions** (96% interruptions mitigated)



Left (A): w/o PVESS
Right (B): with PVESS

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Calculating the benefit-cost ratio

- **Benefits of storage investments in regions were assessed using load served, event frequency, duration, and state-level VOLL estimates**

- Benefit-cost ratio was computed by comparing benefits with annualized region-specific storage costs

$$BCR_{FIPS} = \frac{\sum_{1}^{m}\sum_{1}^{d}(VOLL_{FIPS} \times Expected\ number\ of\ resilience\ events_{m,d} \times Load\ served\ by\ PVESS_{m,d})}{Annualized\ cost\ of\ the\ PVESS\ system_{FIPS}}$$

$where\ d = resilience\ event\ duration\ interval\ (ranging\ from\ 1\ day\ to\ 10\ days),$

$m = month,$

$VOLL_{FIPS} = VOLL\ estimate\ assigned\ to\ each\ FIPS\ region\ belonging\ to\ each\ state$

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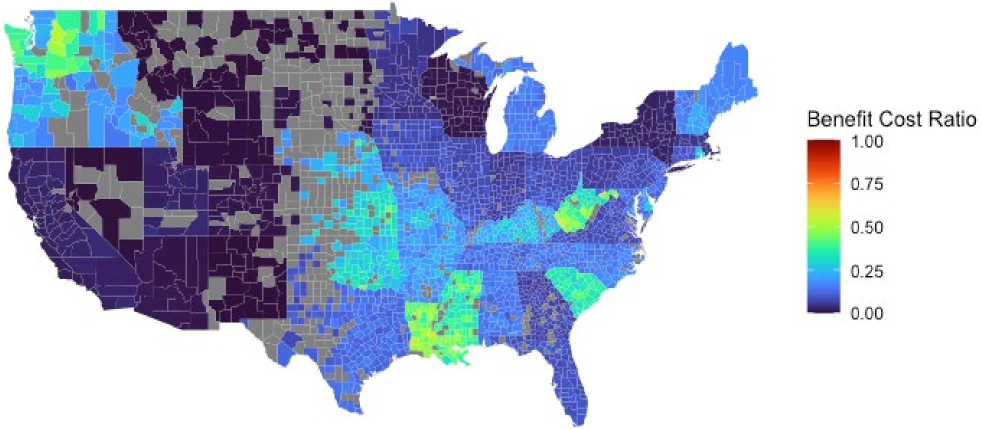
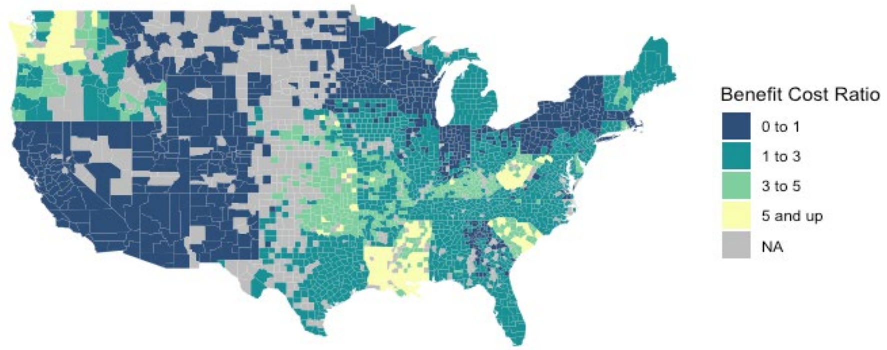
Distribution of benefit-cost ratios

- Resilience benefits from PVESS averaged 20% of total costs, ranging from 0% to 83% depending on load served, event frequency, duration, and state-level VOLL estimates
- However, **resilience was the only benefit considered in this research effort**
- **Other benefit streams are often included as part of the decision to install PVESS**



Importance of scenario/sensitivity analyses

- Scenario and sensitivity-based analyses communicate the range of possible outcomes given uncertainties
- Four scenarios were analyzed individually and collectively: two **storage cost** scenarios, a **high VOLL scenario**, and a **higher event frequency** scenario
- Individual scenarios achieve BCR > 1.0 in some states
- We also evaluated the **combined impact** of storage cost reduction, a high VOLL, and increased frequency of resilience events



- **Customers experiencing above-average long-duration event frequencies and higher VOLL are likely to observe resilience benefits greater than the cost of installing PVESS**

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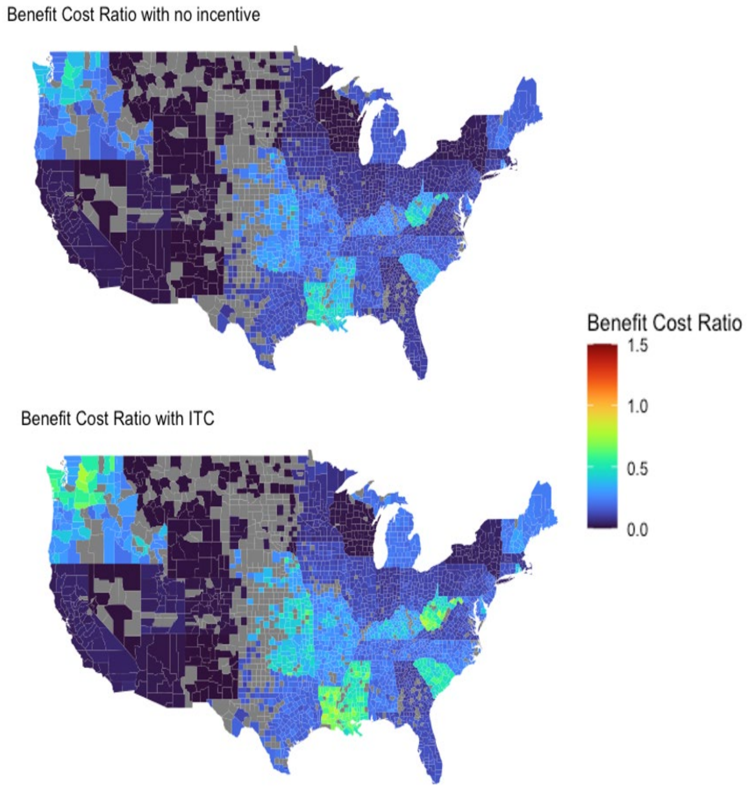
Impact of federal incentives

- **Incentives from the investment tax credit (ITC) were considered**
- Applying a 30% ITC reduction to storage acquisition costs improved BCRs by 50% compared to no incentives
- Notably, some regions (e.g., West Virginia, Louisiana) show higher BCRs, yet BCRs are still below 1
- If only considering the resilience benefit, the **ITC only incentivizes PVESS adoption for customers with high VOLL and higher frequency of long duration events**



Interactive poll #3

What challenges do you foresee when reviewing a utility's valuation and justification of a resilience investment?

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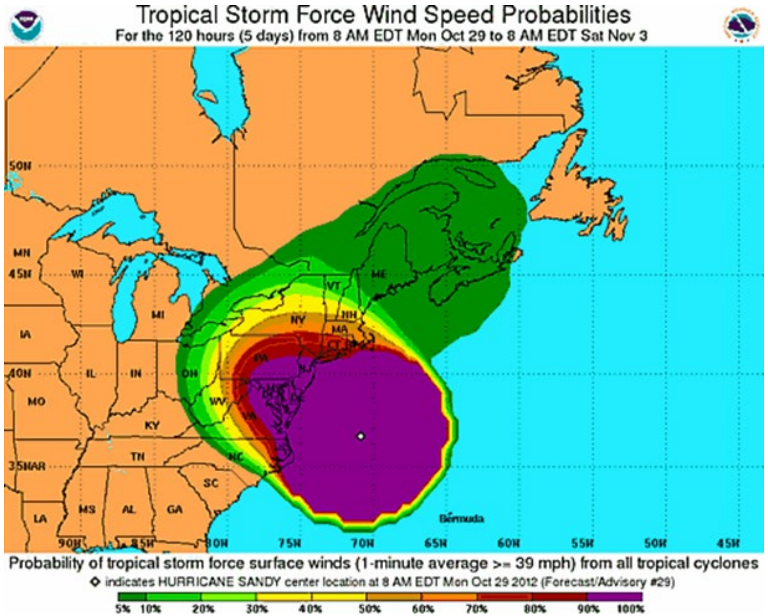
Example #3: Prioritizing a resilience strategy

- The U.S. Department of Energy Grid Deployment Office is sponsoring the development of "Resilience Spotlights" that feature examples of how organizations value and prioritize a specific project among a portfolio of proposed projects.

- The first spotlight focuses on activities in New York City in the immediate aftermath of Super Storm Sandy.

- Resilience spotlights will be accessible at the [DOE-GDO website.](#)



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Super Storm Sandy

- 20% of the city's land area was flooded, **exceeding FEMA's "100-year" floodplain** boundaries
- Loss of power to **> 2 million** Con Ed customers
- Full restoration took **~14 days**
- **Major equipment failure:** Con Ed's East 13th Street Substation flooded and failed due to record levels of storm surge.

Regulatory processes

- January 2013 (three months after storm): Con Ed proposed a **portfolio** of storm hardening projects in a general rate case filing.
- Many stakeholders in rate case had **opposing views**:
  - Hardening plan was too ambitious and expensive
  - Utility should develop a bigger "comprehensive and longer-term approach"
- **Key point of dispute:** What criterion should Con Ed use to evaluate hardening against flooding risks?
- Summer 2013: NYPSC ordered formation of a **Storm Hardening and Resiliency Collaborative** to work in parallel to rate case proceedings and consider:
  - Design standard
  - Approach to risk assessment and cost-benefit analysis

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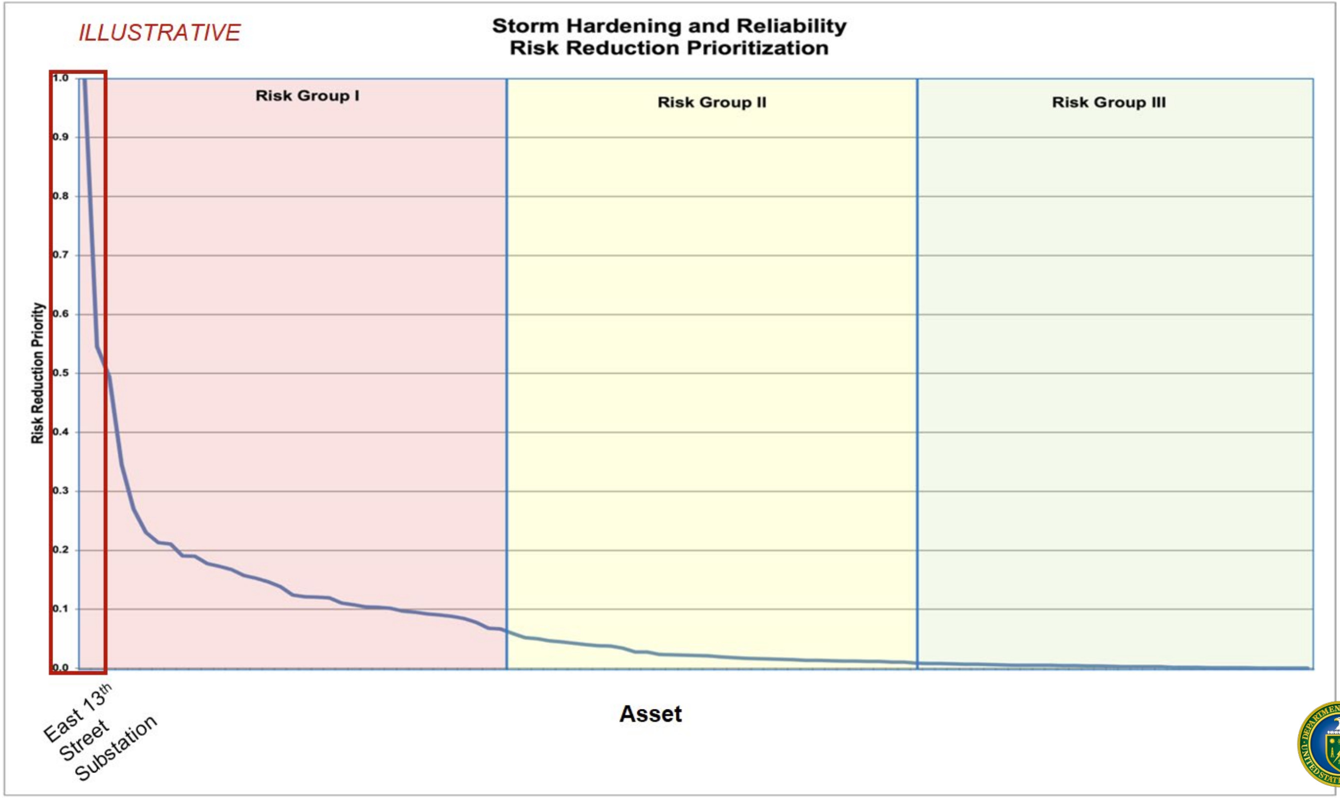
Project prioritization and valuation (1)

- The Collaborative developed a procedure for ranking the storm hardening projects that considered the following:

Probability: estimate likelihoods of significant storms and damage to infrastructure
Consequence: characterize physical and economic impacts of damage
Priority: run potential projects through models to rank them

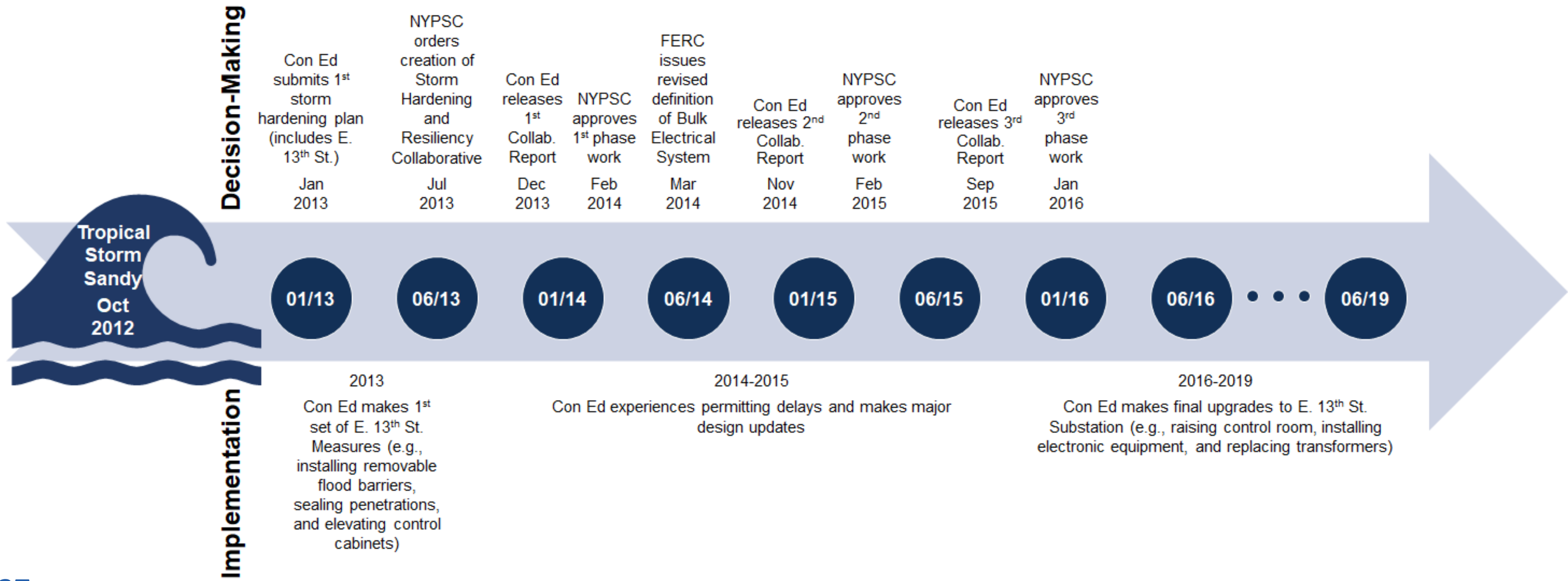
Models	Key Inputs
Risk Assessment and Prioritization Model	● Location-based flood probabilities provided by proprietary New York City inundation models ● Wind damage probabilities derived from historical wind gust frequency distributions ● Costs of storm hardening measures ● Estimated power interruption durations with and without hardening measures
Cost-Benefit Model	● Costs of storm hardening measures (from the Risk Assessment and Prioritization Model) ● Estimated power interruption durations with and without hardening measures (from the Risk - Assessment and Prioritization Model) ● Extrapolated avoided cost (i.e., value of lost load) estimates based on Lawrence Berkeley National Laboratory's ICE Calculator

Project prioritization and valuation (2)



Source: ConEd (2013)

Response timeline

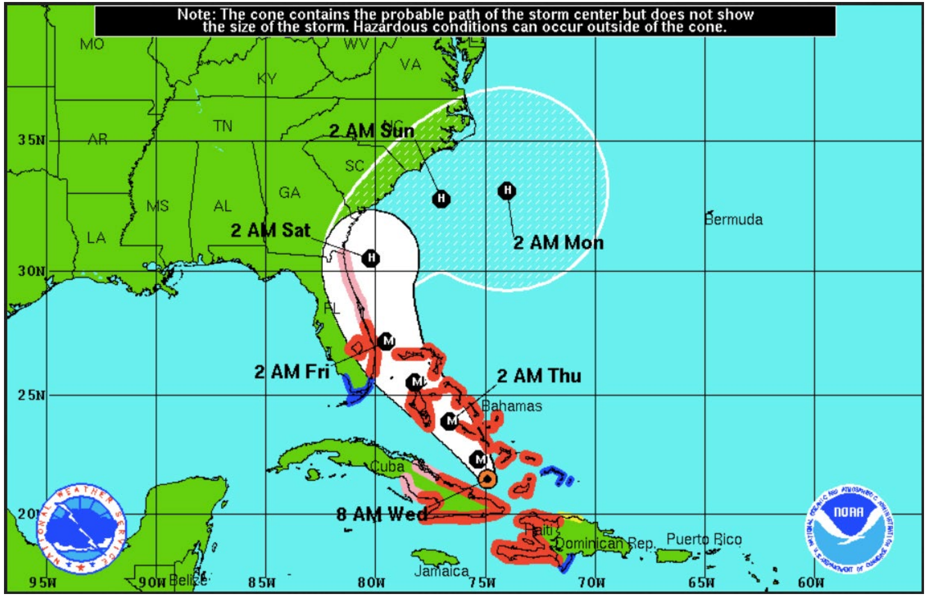


Example #4: Prioritizing a resilience strategy

- Regulations introduced in 2006-2007 **required that Duke and other Florida utilities begin systematically collecting data on the relative performance of underground and overhead lines** during extreme weather

- An especially severe hurricane season in 2016-2017 **demonstrated that underground lines were systematically less vulnerable** to disruption than overhead lines

- As a result, Duke Energy Florida (Duke) began a “Targeted Underground Program.”



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Regulatory and utility processes

- In 2019, Florida required that the state's electric energy utilities submit triennial "Storm Protection Plans" with **new requirements including cost and benefit estimation**, 10-year planning horizons, and more complete descriptions of proposed measures and implementation strategies.

- Duke began working closely with Guidehouse, Inc. to develop and implement a decision-support framework and software tool in their storm preparation planning.

Duke's three-part analytic framework

Risk modeling

Probabilistic weather modeling of storm scenarios using Monte Carlo methods, combined with spatial modeling of Duke distribution infrastructure, to estimate conditional probabilities of asset failures and the reductions in these probabilities as a function of storm hardening measures

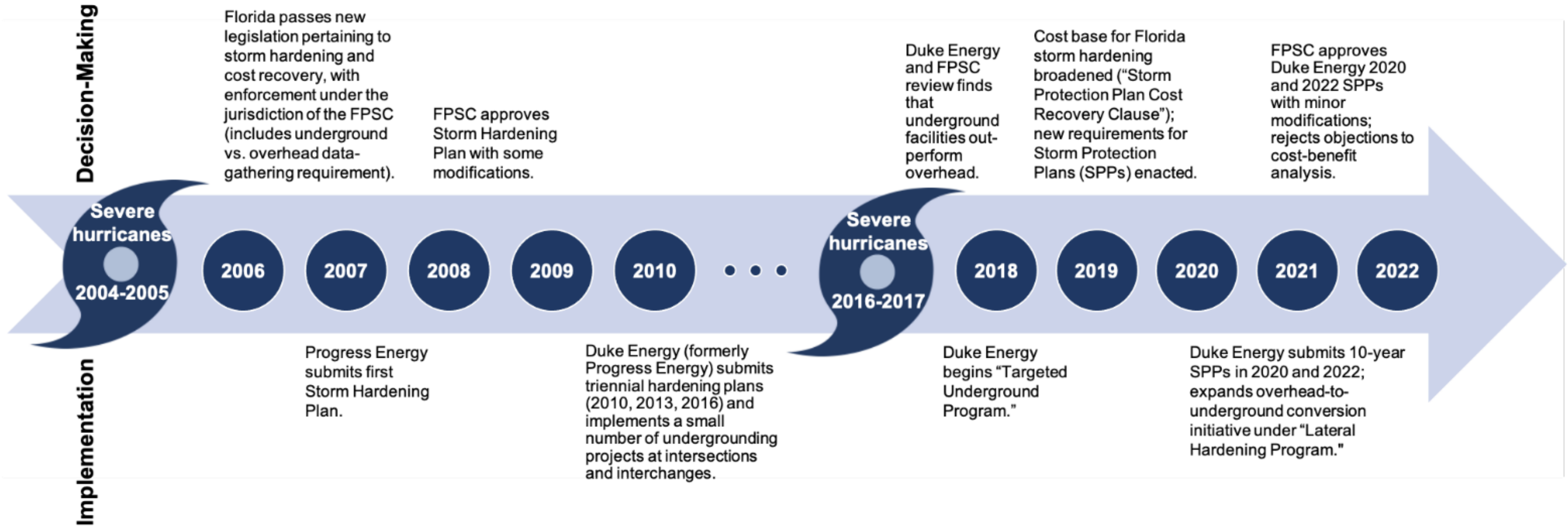
Benefit-cost modeling

Estimating Duke's capital and operations and maintenance costs of storm hardening measures and prospective utility benefits in the form of reduced future costs from avoiding damage to infrastructure and storm restoration activities; quantifying customer benefits in terms of projected reduced outage times by customer class, and applying avoided customer costs from Berkeley Lab's ICE Calculator, using the Calculator's 16-hour avoided cost estimates as a simplifying assumption for outage times greater than 16 hours

Decision analysis and prioritization

Calculating benefit-cost ratios and using them to rank projects and create a preferred portfolio, then applying funding and timing constraints, taking account of practical implementation constraints based on the judgment of Duke staff including subject matter experts

Response timeline



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Lessons learned

- Many, but not all, utility reliability and resilience investments are developed, proposed, and adjudicated in the **context of a general rate case**. This process is not always well-suited to addressing **novel, complex technical problems**.
- The need to address **low-probability/high-consequence events** requires flexibility in regulatory processes.
- **Collaborative work groups** can enable utilities to improve resilience planning methods and practice.
- **Requiring utilities to measure past performance** of underground lines has helped build confidence and justify future investments in this strategy.
- **Cost-benefit analyses** used in NY and FL could inform similar valuation and prioritization activities in other parts of the country.

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Interactive poll #4

What is the most important criteria for prioritizing one resilience strategy over another?

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Questions to ask

- Is the utility putting an economic value on reliability or resilience? If so, what tools or techniques are they using?
- Does the utility track the performance of past investments? Can you describe how this performance is tracked?
- What technology would the utility install if it could only install one type of technology to make the grid more resilient?
- What is the biggest challenge that the utility has faced when attempting to identify, prioritize, and justify a resilience project?

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Contact

https://www.energy.gov/gdo/grid-deployment-office

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Glossary of selected performance-based metrics

Metric	Description	Interpretation
SAIFI	System Average Interruption Frequency Index	Total number of interruptions that an average customer experiences over some time period
SAIDI	System Average Interruption Duration Index	Total number of minutes that an average customer is without power over some time period
CAIFI	Customer Average Interruption Frequency Index	Average number of interruptions per customer interrupted over some time period
CAIDI	Customer Average Interruption Duration Index	Time required to restore service for an average customer over some time period
MAIFI	Momentary Average Interruption Frequency Index	Total number of momentary interruptions (< 5 minutes) that an average customer experiences over some time period
MED	Major Event Day	Any day with a daily reliability metric that exceeds a statistically-defined threshold based on the previous five years of daily data (e.g., IEEE 1366 standard)

Source: CPUC (2021)

Useful references (1)

Baik, S., G. Barbose, J.P. Carvallo, C. Miller, W. Gorman, and M. Spears. 2023. Backup Power Performance of Solar-plus-Storage Systems during Routine Power Interruptions: A Case Study Application of Berkeley Lab's PRESTO Model. Link

Consolidated Edison Company of New York Inc (ConEd). 2013. Substation Hardening. Presentation; Appendix G in Consolidated Edison Company of New York Inc Storm Hardening and Resiliency Collaborative Report, December 4. Link

California Public Utilities Commission (CPUC). 2021. Electric System Reliability. Prepared by Julian Enis from the CPUC Energy Division, February 17. Link

Eto, J., K. Hamachi-LaCommare, H. Caswell, and D. Till. "Distribution System vs. Bulk Power System: Identifying the Source of Electric Service Interruptions in the U.S." *IET Generation, Transmission, and Distribution, Volume 13, Issue 5,* 12 March 2019, p. 717 – 723. Link

Florida Public Service Commission (PSC). 2013. Grid Reliability and Integrating Intermittent Energy Sources in Florida. Prepared by Commissioner Eduardo Balbis, May 21. Link

Florida Power and Light (FPL). 2004. Distribution Engineering Reference Manual, December. Link

Florida Public Service Commission (FPSC). 2021. Petition for Rate Increase by Florida Power and Light Company, September 21. Link

Georgia Power. 2019. Georgia Power's Strategic Overhead-to-Underground Conversions. Prepared by Robert Reepe for IEEE Insulated Conductors Committee Education Program, October 23. Link

Georgia Public Service Commission. 2022. Direct Testimony of Peter Hubbard of the Georgia Center for Energy Solutions, May 5. Link

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Useful references (2)

Jeffers, R., Hotchkiss, E., Hart, O., Jones, K., Shepherd, R. (2023) GDO Technical Assistance: Resilience Objectives and Metrics. Presentation to the US DOE Grid Deployment Office, National Renewable Energy Laboratory. February 2023. Future Link

LaCommare, K., P. Larsen, and J. Eto. 2017. Evaluating Evaluating Proposed Investments in Power System Reliability and Resilience: Preliminary Results from Interviews with Public Utility Commission Staff. LBNL Report 1006971. Link

Larsen, P., M. Lawson, K. LaCommare, and J. Eto. 2020. Severe weather, utility spending, and the long-term reliability of the U.S. power system. *Energy: The International Journal 198 (2020)*. Link

Larsen, P. 2016. A method to estimate the costs and benefits of undergrounding power systems. *Energy Economics* 60 (2016): *47-61*. Link

North Carolina Utilities Commission (NCUC). 2018. Direct Testimony of Caroline Golin on Behalf of the North Carolina Sustainable Energy Association, January 23. Link

North Carolina Utilities Commission (NCUC). 2020. Docket No. E-7, Sub 1213 and Docket No. E-7 Sub 1214 within Application for General Rate Case, February 18. Link

Office of Regulatory Staff (ORS). 2021. Report on the Resiliency of South Carolina's Electric and Natural Gas Infrastructure Against Extreme Winter Storm Events. Prepared by Guidehouse for the South Carolina Office of Regulatory Staff, December. Link

Presidential Policy Directive 21 (PPD-21). 2013. Critical Infrastructure Security and Resilience, February 12. Link

Rocky Mountain Institute/Regulatory Assistance Project (RMI/RAP). 2020. North Carolina Energy Regulatory Process, December 22. Link

Useful references (3)

U.S. Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response (U.S. DOE-CESER). 2023. Electric Disturbance Events (DOE 417). Link

U.S. Department of Energy Energy Information Administration (U.S. DOE-EIA). 2023. Annual Electric Power Industry Report (EIA 861). Link

Rocky Mountain Institute/Regulatory Assistance Project (RMI/RAP). 2020. North Carolina Energy Regulatory Process, December 22. Link

U.S. Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response (U.S. DOE-CESER). 2023. Electric Disturbance Events (DOE 417). Link

U.S. Department of Energy Energy Information Administration (U.S. DOE-EIA). 2023. Annual Electric Power Industry Report (EIA 861). Link

Woolf, T., B. Havumaki, D. Bhandari, M. Whited, and L. Schwartz. 2021. Benefit-Cost Analysis for Utility Facing Grid Modernization Investments: Trends, Challenges, and Considerations. Link

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