Valuing Resilience

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FAASSTeR Workshop and Seminar
Gainesville, Florida
June 25, 2019

NREL/PR-6A20-74258

Value of Resilience Research

- How can resilience be quantified?
- How is resilience valued?
- How is resilience monetized or incentivized?
- How is the value of resilience integrated into investment and/or operational decisions?

How Can Resilience be Quantified?

The Resilience Analysis Process defines a framework that can be used to derive resilience metrics via the following steps:

1. Specifying the specific system, threats and consequences of interest
2. Defining an analytical framework
3. Determining indicators (e.g., performance function and/or attributes)
4. Calculating resilience metrics to establish a current performance baseline and evaluate the expected performance improvements associated with a given resilience mitigation strategy

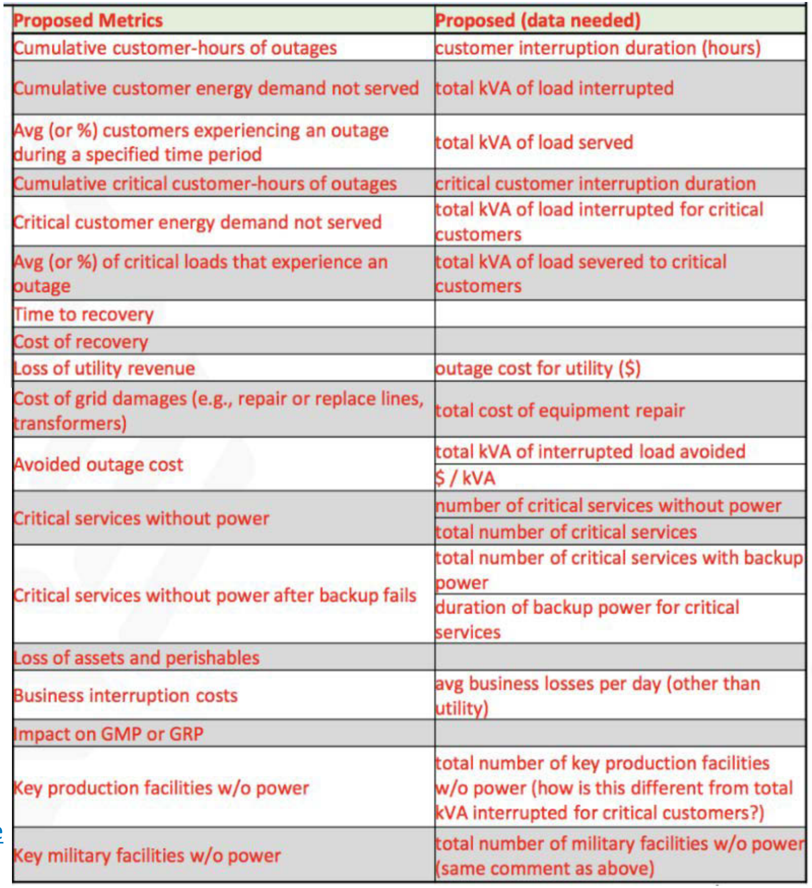
Figure 1. The Resilience Analysis Process.

https://www.energy.gov/sites/prod/files/2015/09/f26/EnergyResilienceReport_%28Final%29_SAND2015-18019.pdf

Quantifying Resilience Through Metrics

- Many resilience metrics have been developed, primarily from the perspective of the electric utility
- Most proposed metrics are immature, and none are widely agreed upon
- There is a need for metrics that go beyond reliability metrics
- There is no one definition or metric that can be applied broadly; depends on goals, context of the event, threats, scale, and perspective
- For quantitative analysis, it is preferable to use performance-based metrics that consider:
  - Likelihood and consequence of a given event and its corresponding consequences
  - Temporal evolution of an event

https://gridmod.labworks.org/sites/default/files/resources/GMLC1%201_Reference_Manual_2%201_final_2017_06_01_v4_wPNNLNo_1.pdf



Proposed Metrics	Proposed (data needed)
Cumulative customer-hours of outages	customer interruption duration (hours)
Cumulative customer energy demand not served	total kVA of load interrupted
Avg (or %) customers experiencing an outage during a specified time period	total kVA of load served
Cumulative critical customer-hours of outages	critical customer interruption duration
Critical customer energy demand not served	total kVA of load interrupted for critical customers
Avg (or %) of critical loads that experience an outage	total kVA of load severed to critical customers
Time to recovery	
Cost of recovery	
Loss of utility revenue	outage cost for utility ($)
Cost of grid damages (e.g., repair or replace lines, transformers)	total cost of equipment repair
Avoided outage cost	total kVA of interrupted load avoided $ / kVA
Critical services without power	number of critical services without power total number of critical services
Critical services without power after backup fails	total number of critical services with backup power duration of backup power for critical services
Loss of assets and perishables	
Business interruption costs	avg business losses per day (other than utility)
Impact on GMP or GRP	
Key production facilities w/o power	total number of key production facilities w/o power (how is this different from total kVA interrupted for critical customers?)
Key military facilities w/o power	total number of military facilities w/o power (same comment as above)

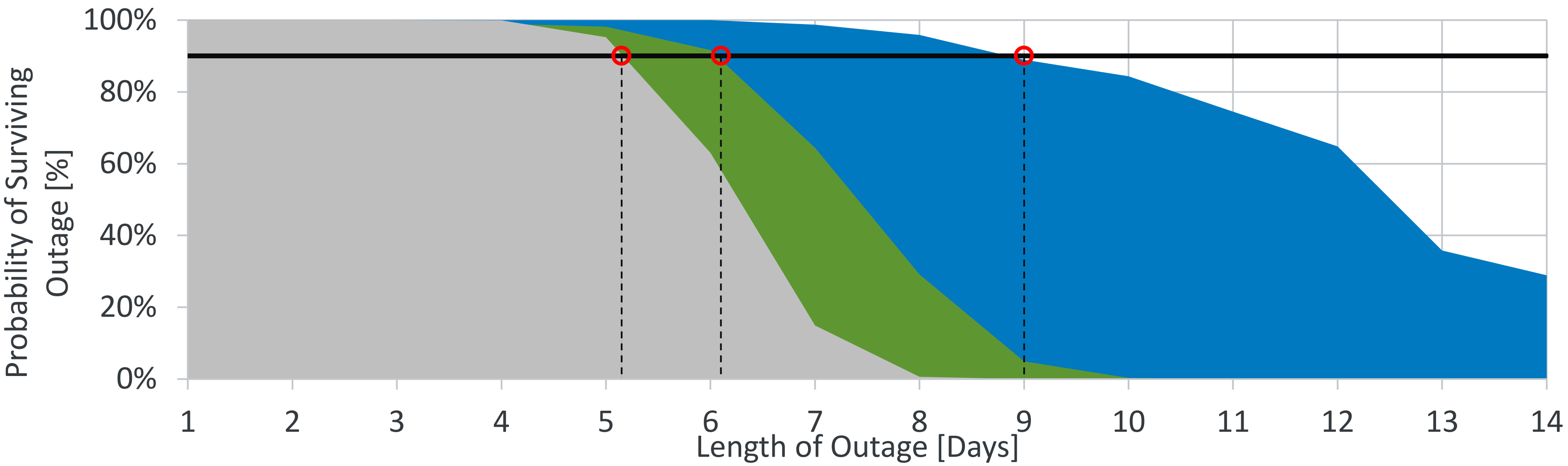
Unserved load
[kW, kWh, h, customer type]

Direct outage costs
[$, $/kW, customer type]

Indirect outage costs

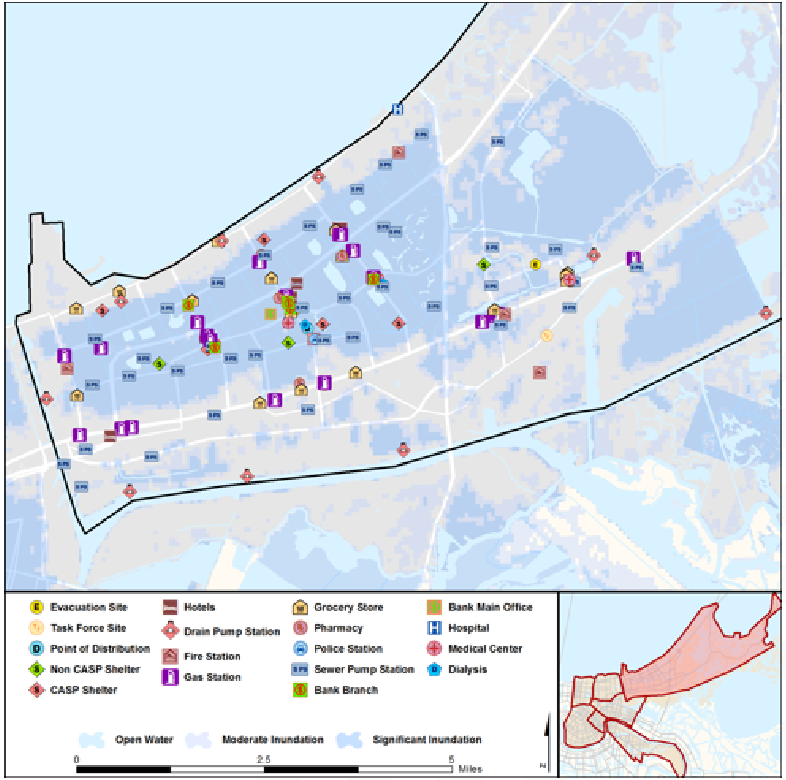
Quantifying Resilience: Days of Survivability

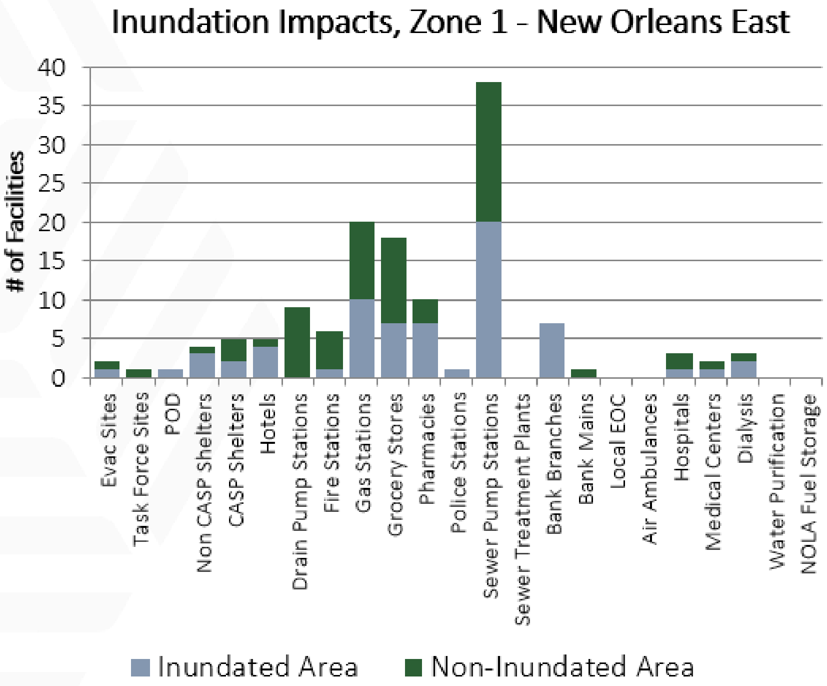
	Generator	Solar PV	Storage	Lifecycle Cost	Outage
1. Base case	**2.5 MW**	**-**	**-**	**$20 million**	**5 days**
2. Lowest cost solution	**2.5 MW**	**625 kW**	**175 kWh**	**$19.5 million**	**6 days**
3. Proposed system	**2.5 MW**	**2 MW**	**500 kWh**	**$20 million**	**9 days**



K. Anderson et al., "Increasing Resiliency Through Renewable Energy Microgrids". SCTE Journal of Energy Management Vol.2 (2) August 2017 pp.22-38. https://www.nrel.gov/docs/fy17osti/69034.pdf

Quantifying Resilience: Community Resilience





https://www.energy.gov/under-secretary-science-and-energy/articles/strengthening-community-resilience-new-orleans

How is Resilience Valued?

- Multiple resources provide data on the costs associated with potential resilience improvements
- Information on the *value* of resilience is limited
  - Metrics should be able to inform costs and benefits
  - We need to know more about what individuals and society are willing and able to pay to avoid the consequences of disruptive events

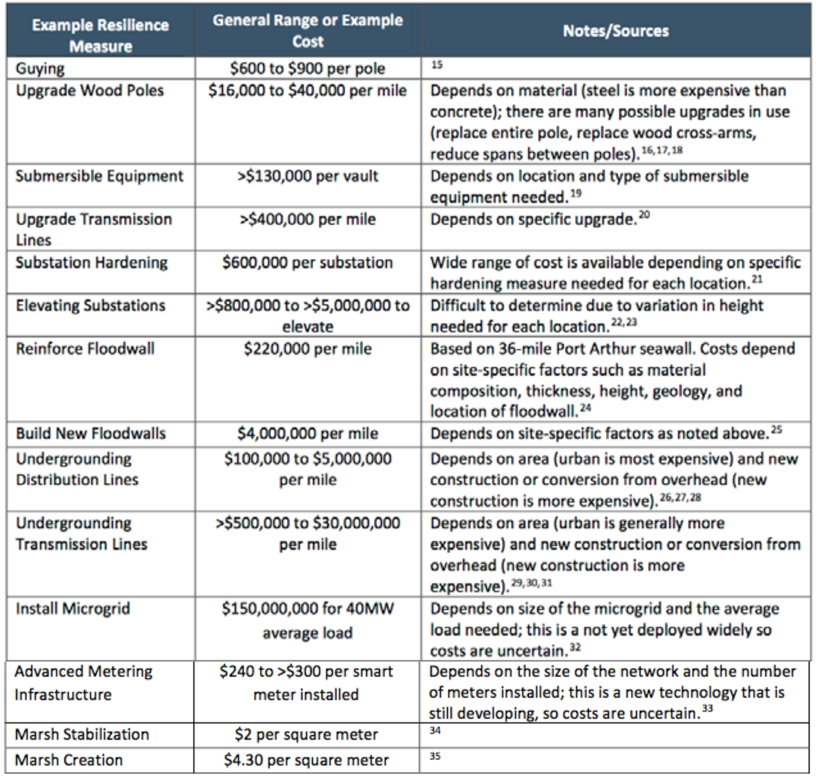


Table 12. Illustrative costs for selected resilience measures for utility assets.

Example Resilience Measure	General Range or Example Cost	Notes/Sources
Guying	\$600 to \$900 per pole	[15]
Upgrade Wood Poles	\$16,000 to \$40,000 per mile	Depends on material (steel is more expensive than concrete); there are many possible upgrades in use (replace entire pole, replace wood cross-arms, reduce spans between poles).[16,17,18]
Submersible Equipment	>\$130,000 per vault	Depends on location and type of submersible equipment needed.[19]
Upgrade Transmission Lines	>\$400,000 per mile	Depends on specific upgrade.[20]
Substation Hardening	\$600,000 per substation	Wide range of cost is available depending on specific hardening measure needed for each location.[21]
Elevating Substations	>\$800,000 to >\$5,000,000 to elevate	Difficult to determine due to variation in height needed for each location.[22,23]
Reinforce Floodwall	\$220,000 per mile	Based on 36-mile Port Arthur seawall. Costs depend on site-specific factors such as material composition, thickness, height, geology, and location of floodwall.[24]
Build New Floodwalls	\$4,000,000 per mile	Depends on site-specific factors as noted above.[25]
Undergrounding Distribution Lines	\$100,000 to \$5,000,000 per mile	Depends on area (urban is most expensive) and new construction or conversion from overhead (new construction is more expensive).[26,27,28]
Undergrounding Transmission Lines	>\$500,000 to \$30,000,000 per mile	Depends on area (urban is generally more expensive) and new construction or conversion from overhead (new construction is more expensive).[29,30,31]
Install Microgrid	\$150,000,000 for 40MW average load	Depends on size of the microgrid and the average load needed; this is a not yet deployed widely so costs are uncertain.[32]
Advanced Metering Infrastructure	\$240 to >\$300 per smart meter installed	Depends on the size of the network and the number of meters installed; this is a new technology that is still developing, so costs are uncertain.[33]
Marsh Stabilization	\$2 per square meter	[34]
Marsh Creation	\$4.30 per square meter	[35]

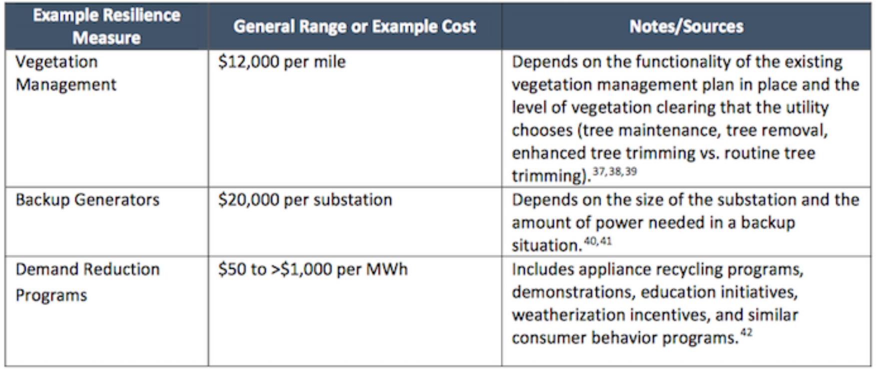


Table 13. Illustrative costs for selected resilience measures for utility operations.

Example Resilience Measure	General Range or Example Cost	Notes/Sources
Vegetation Management	\$12,000 per mile	Depends on the functionality of the existing vegetation management plan in place and the level of vegetation clearing that the utility chooses (tree maintenance, tree removal, enhanced tree trimming vs. routine tree trimming).[37,38,39]
Backup Generators	\$20,000 per substation	Depends on the size of the substation and the amount of power needed in a backup situation.[40,41]
Demand Reduction Programs	\$50 to >\$1,000 per MWh	Includes appliance recycling programs, demonstrations, education initiatives, weatherization incentives, and similar consumer behavior programs.[42]

https://www.energy.gov/sites/prod/files/2016/10/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf

Methods for Valuing Resilience

1) Cost of an outage
   a. Individual Site Characterization (Customer Damage Function)
   b. National Outage Survey (Interruption Cost Estimator)
   c. Insurance Valuation
2) Cost of other forms of emergency power

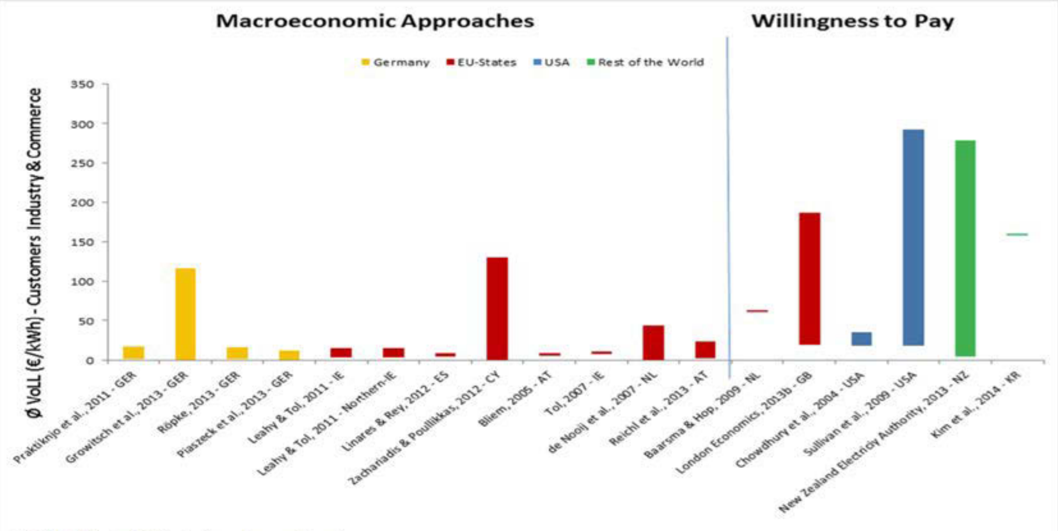
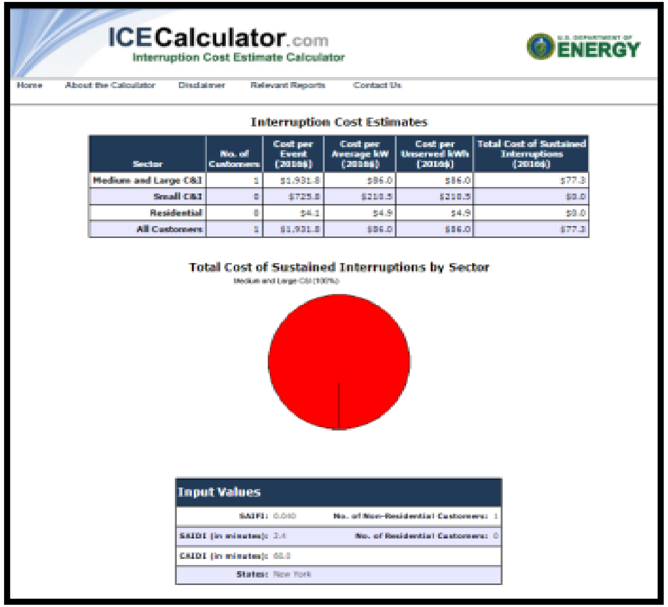


FIGURE 2 | Actual VoLL studies – Economic end users.

Schroder (2015). *doi: 10.3389/fenrg.2015.00055*



Interruption Cost Estimates

Sector	No. of Customers	Cost per Event (2016$)	Cost per Average kW (2016$)	Cost per Unserved kWh (2016$)	Total Cost of Sustained Interruptions (2016$)
Medium and Large C&I	1	$1,931.8	$86.0	$86.0	$77.3
Small C&I	0	$725.8	$210.5	$210.5	$0.0
Residential	0	$4.1	$4.9	$4.9	$0.0
All Customers	1	$1,931.8	$86.0	$86.0	$77.3

Total Cost of Sustained Interruptions by Sector

Input Values

SAIFI: 0.040 No. of Non-Residential Customers: 1

SAIDI (in minutes): 2.4 No. of Residential Customers: 0

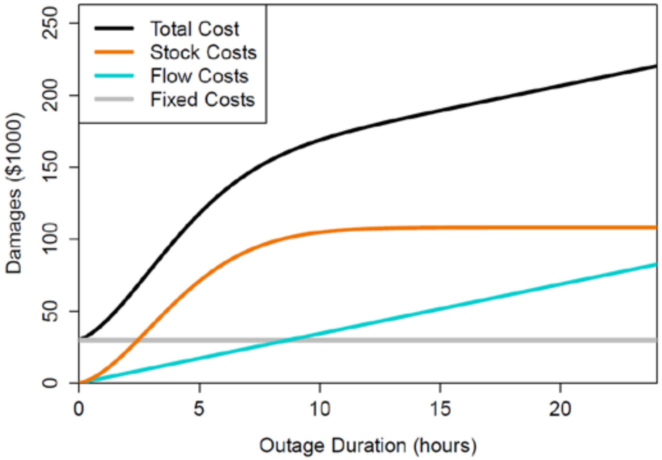
CAIDI (in minutes): 60.0

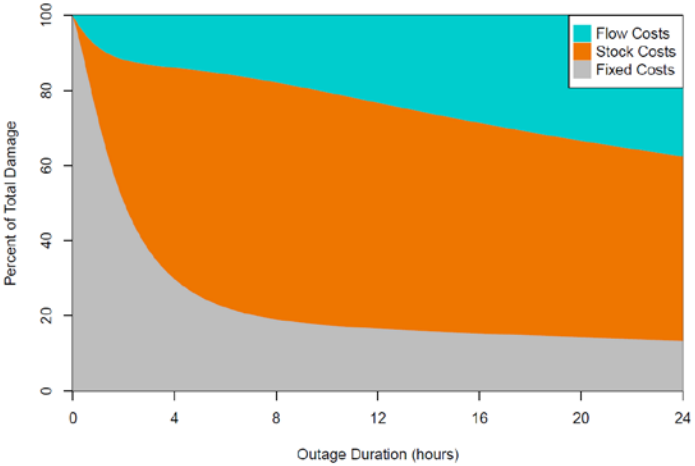
State: New York

https://icecalculator.com/home

Framework for Integrating Duration-Dependent Value of Lost Load in Energy Decisions

- Developed framework to estimate the customer cost of a power outage, accounting for outage duration
- Modeled various building types and estimated costs based on survey data
- Figures below show the total cost of a power outage over time and the composition of costs by category



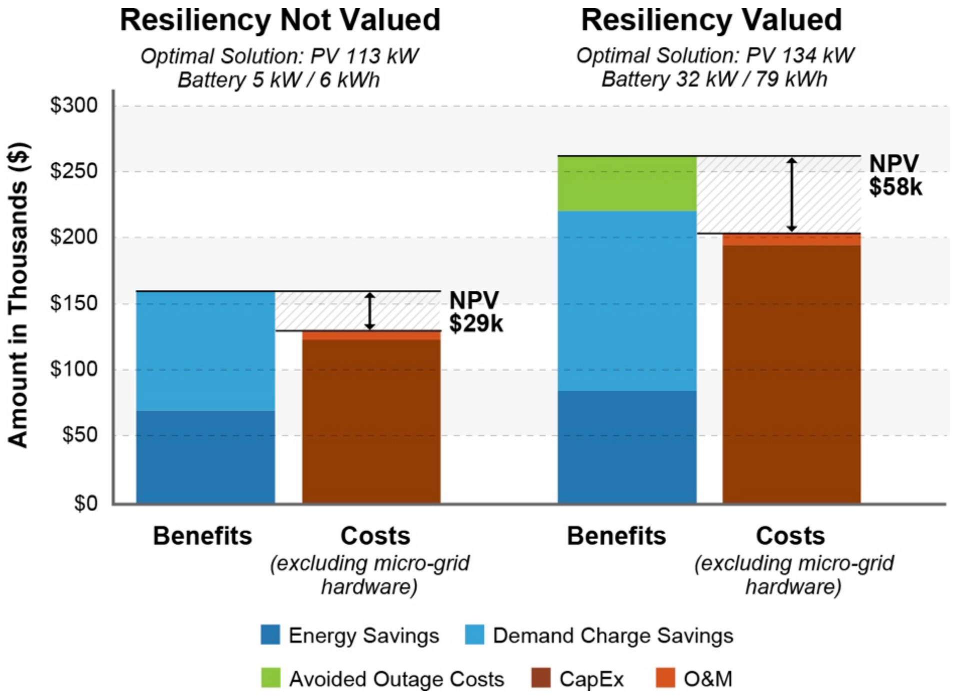


Ericson, S. & Lisell, L. Energy Syst (2018). https://doi.org/10.1007/s12667-018-0314-8

How Could Energy Decisions Change When Accounting for a Value of Resilience?

Implementing a value of resilience into a least-cost optimization can influence the "optimal" PV+storage system at a given site:

- Increases PV capacity
- Increases battery size and duration
- Increases the overall NPV

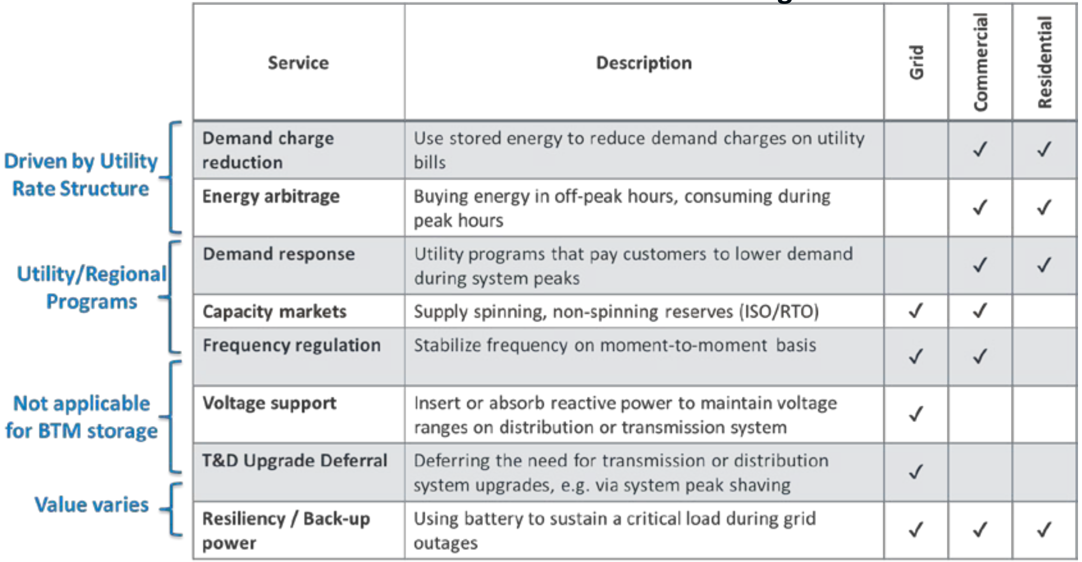


Laws, N. D., K. Anderson, N. DiOrio, X. Li, and J. McLaren (2018). "Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings." *Renewable Energy,* Volume 127, November 2018, pages 896-909. https://doi.org/10.1007/s12667-018-0314-8

Methods for Monetizing System Resilience

1) Grid services
2) Monthly resiliency payment from site host
3) Reduction in insurance premiums
4) Incentives
5) Internal risk mitigation (contingency planning)

Value streams for RE+storage



	Service	Description	Grid	Commercial	Residential
Driven by Utility Rate Structure	**Demand charge reduction**	Use stored energy to reduce demand charges on utility bills		✓	✓
	Energy arbitrage	Buying energy in off-peak hours, consuming during peak hours		✓	✓
Utility/Regional Programs	**Demand response**	Utility programs that pay customers to lower demand during system peaks		✓	✓
	Capacity markets	Supply spinning, non-spinning reserves (ISO/RTO)	✓	✓	
	Frequency regulation	Stabilize frequency on moment-to-moment basis	✓	✓	
Not applicable for BTM storage	**Voltage support**	Insert or absorb reactive power to maintain voltage ranges on distribution or transmission system	✓		
	T&D Upgrade Deferral	Deferring the need for transmission or distribution system upgrades, e.g. via system peak shaving	✓		
Value varies	**Resiliency / Back-up power**	Using battery to sustain a critical load during grid outages	✓	✓	✓

https://www.nrel.gov/docs/fy17osti/70035.pdf

Laboratory Value Analysis of 6 Resilient Distribution System Field Validations

Laboratory Value Analysis Team (LVAT)

Showcasing **RESILIENCE** field validation for six national lab-led projects across test sites in four regions

INL Idaho National Laboratory

- City of Cordova, Alaska

Lawrence Livermore National Laboratory

- Riverside Public Utility

Sandia National Laboratories

- San Antonio, Texas
- Massachusetts, National Grid

SLAC NATIONAL ACCELERATOR LABORATORY

- Santa Ana, CA
- Vermont Electric Co-op
- NRECA – City of Lancaster, CA; Southern Cal Edison; and Riverside Public Utility

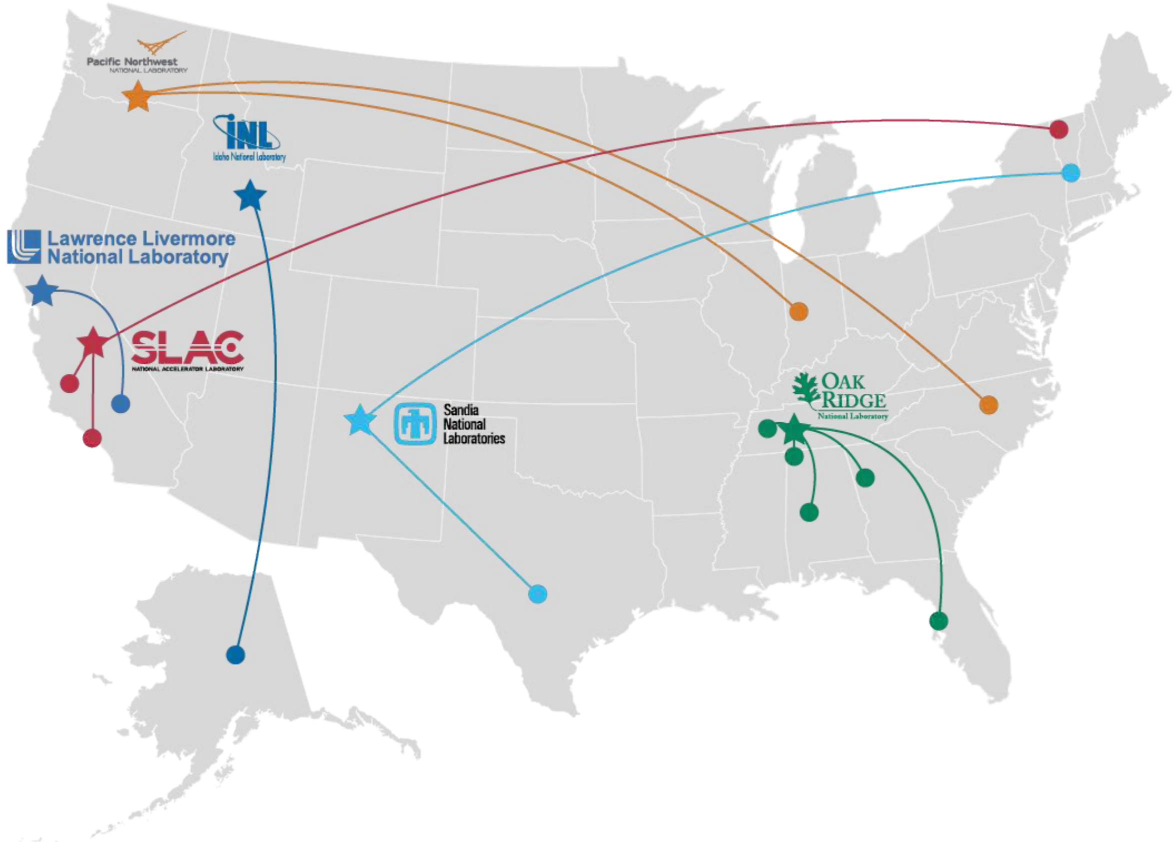
Pacific Northwest NATIONAL LABORATORY

- Anderson Civic Center at Duke University, Durham, North Carolina
- Muscatatuck Urban Training Center, Indiana

OAK RIDGE National Laboratory

- Birmingham, Alabama
- St. Petersburg, Florida
- Chattanooga, Tennessee
- Atlanta, Georgia
- Knoxville, Tennessee

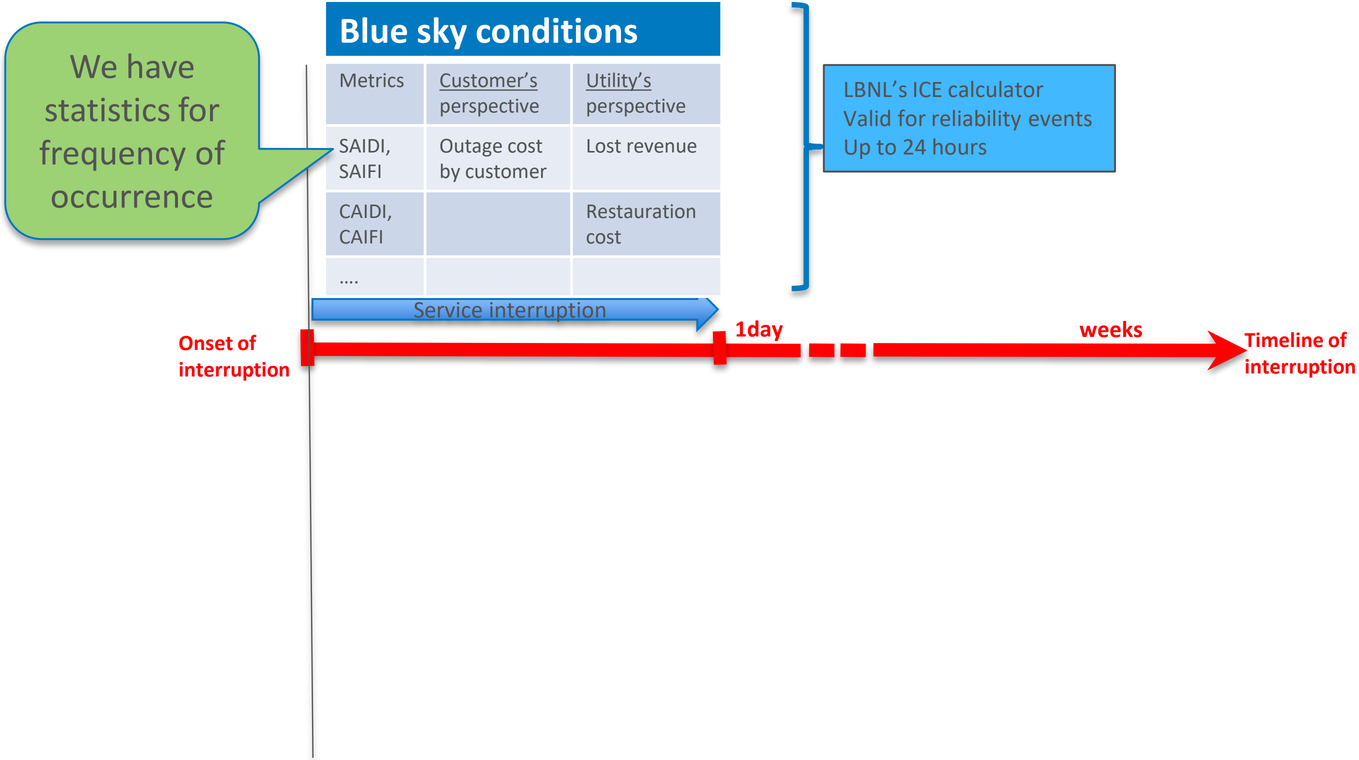
LVAT Analysis of Resilient Distribution System Field Validations



Challenges:

- Diverse technologies and systems to be valued
- Diverse locations - and market structures (e.g., vertically integrated IOUs versus muni)

Methodological Challenges



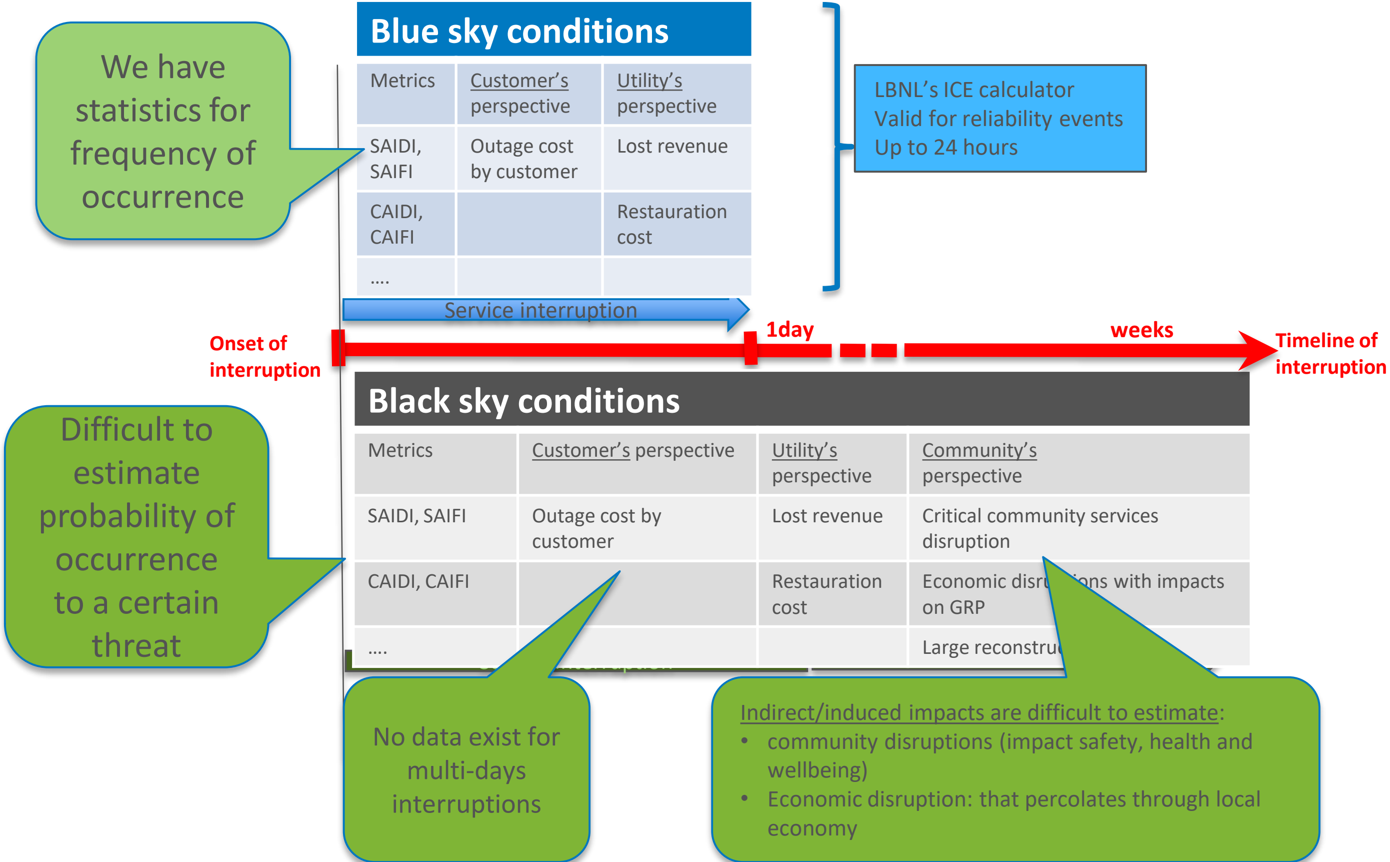
We have statistics for frequency of occurrence

Blue sky conditions

Metrics	Customer's perspective	Utility's perspective
SAIDI, SAIFI	Outage cost by customer	Lost revenue
CAIDI, CAIFI		Restauration cost
….		

LBNL's ICE calculator
Valid for reliability events
Up to 24 hours

Methodological Challenges



We have statistics for frequency of occurrence

Blue sky conditions

Metrics	Customer's perspective	Utility's perspective
SAIDI, SAIFI	Outage cost by customer	Lost revenue
CAIDI, CAIFI		Restauration cost
….		

LBNL's ICE calculator
Valid for reliability events
Up to 24 hours

Difficult to estimate probability of occurrence to a certain threat

Black sky conditions

Metrics	Customer's perspective	Utility's perspective	Community's perspective
SAIDI, SAIFI	Outage cost by customer	Lost revenue	Critical community services disruption
CAIDI, CAIFI		Restauration cost	Economic disr ons with impacts on GRP
….			Large reconstru

No data exist for multi-days interruptions

Indirect/induced impacts are difficult to estimate:

- community disruptions (impact safety, health and wellbeing)
- Economic disruption: that percolates through local economy

DOE Partnership for Energy Sector Resilience

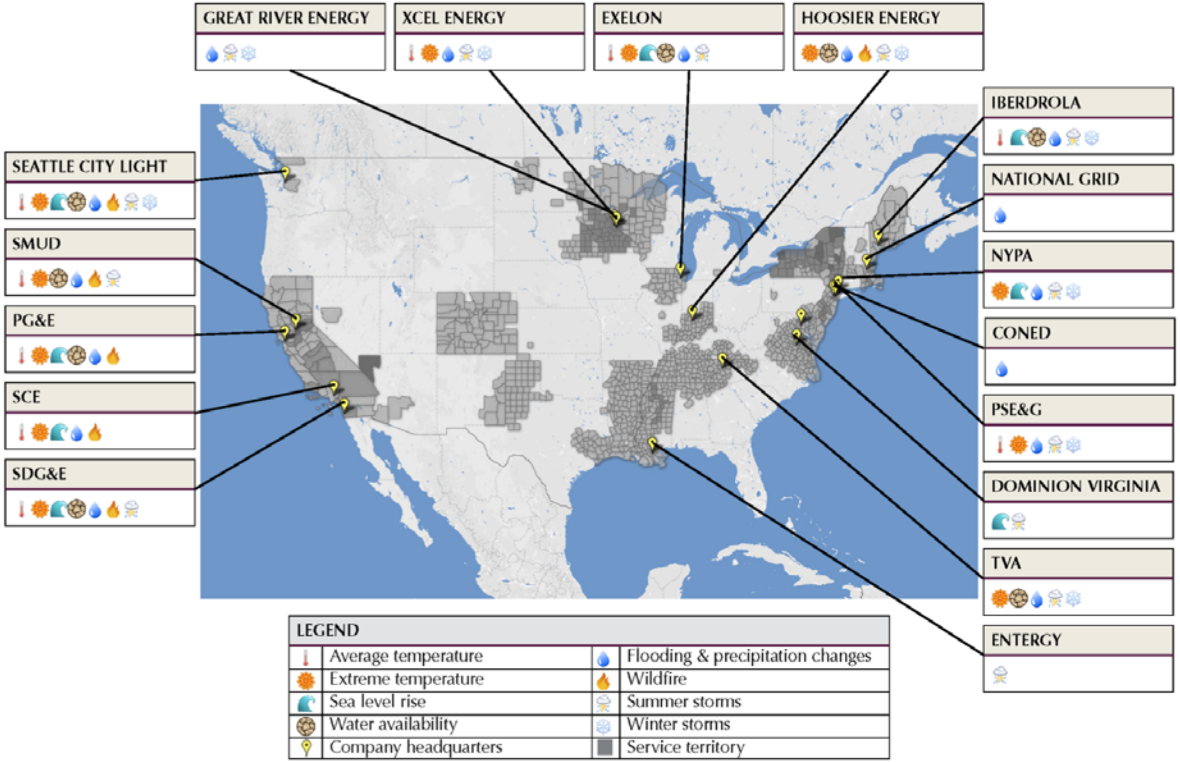
Evaluation Methods:

- Outage duration
- Service disruption to critical customers
- ICE Calculator
- Breakeven outage duration

Analysis Needs:

- Universal metrics
- Industry standards for quantifying benefits
- Better understanding of interdependencies

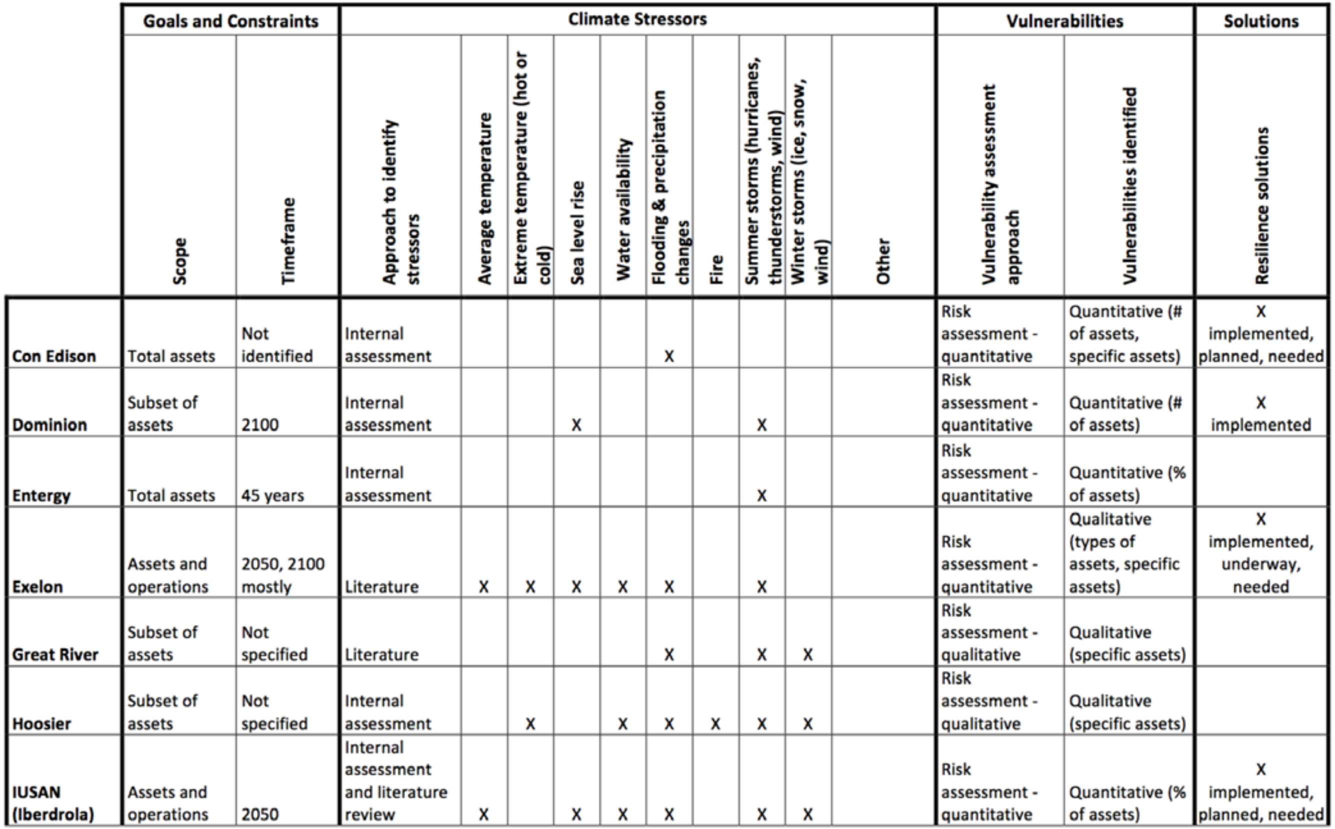
Figure 10: Specific climate change impacts examined by Partners in their vulnerability assessments



https://www.energy.gov/policy/initiatives/partnership-energy-sector-climate-resilience

DOE Partnership for Energy Sector Resilience

Table 1: Partner vulnerability assessment summary table



	Goals and Constraints		Climate Stressors										Vulnerabilities		Solutions
	Scope	Timeframe	Approach to identify stressors	Average temperature	Extreme temperature (hot or cold)	Sea level rise	Water availability	Flooding & precipitation changes	Fire	Summer storms (hurricanes, thunderstorms, wind)	Winter storms (ice, snow, wind)	Other	Vulnerability assessment approach	Vulnerabilities identified	Resilience solutions
Con Edison	Total assets	Not identified	Internal assessment					X					Risk assessment - quantitative	Quantitative (# of assets, specific assets)	X implemented, planned, needed
Dominion	Subset of assets	2100	Internal assessment			X				X			Risk assessment - quantitative	Quantitative (# of assets)	X implemented
Entergy	Total assets	45 years	Internal assessment							X			Risk assessment - quantitative	Quantitative (% of assets)	
Exelon	Assets and operations	2050, 2100 mostly	Literature	X	X	X	X	X		X			Risk assessment - quantitative	Qualitative (types of assets, specific assets)	X implemented, underway, needed
Great River	Subset of assets	Not specified	Literature					X		X	X		Risk assessment - qualitative	Qualitative (specific assets)	
Hoosier	Subset of assets	Not specified	Internal assessment		X		X	X	X	X	X		Risk assessment - qualitative	Qualitative (specific assets)	
IUSAN (Iberdrola)	Assets and operations	2050	Internal assessment and literature review	X		X	X	X		X	X		Risk assessment - quantitative	Quantitative (% of assets)	X implemented, planned, needed

https://www.energy.gov/policy/initiatives/partnership-energy-sector-climate-resilience

Summary and Conclusions

- Resilience metrics related to electricity supply are arguably more advanced (compared to other energy and non-energy sectors), but most metrics remain immature and none are universally adopted
- There are many helpful resources for establishing resilience goals, and information is readily available for the *costs* associated with various resilience investments
- Quantifying the *value* of resilience is ongoing in a variety of DOE-funded efforts, but this is a much more challenging task due to:
  - A lack of universally accepted metrics
  - The context-specific nature of benefits
  - The necessary data and detailed quantitative analysis needed to accurately determine the benefits associated with a given investment
- The National Laboratories and DOE's Partnership for Energy Sector Resilience have great resources for resiliency planning and valuation

Thank you

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the NREL Laboratory Directed Research and Development program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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