Power Systems Resilience

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National Renewable Energy Laboratory

Energy Efficiency and Conservation Block Grant Program Workshop

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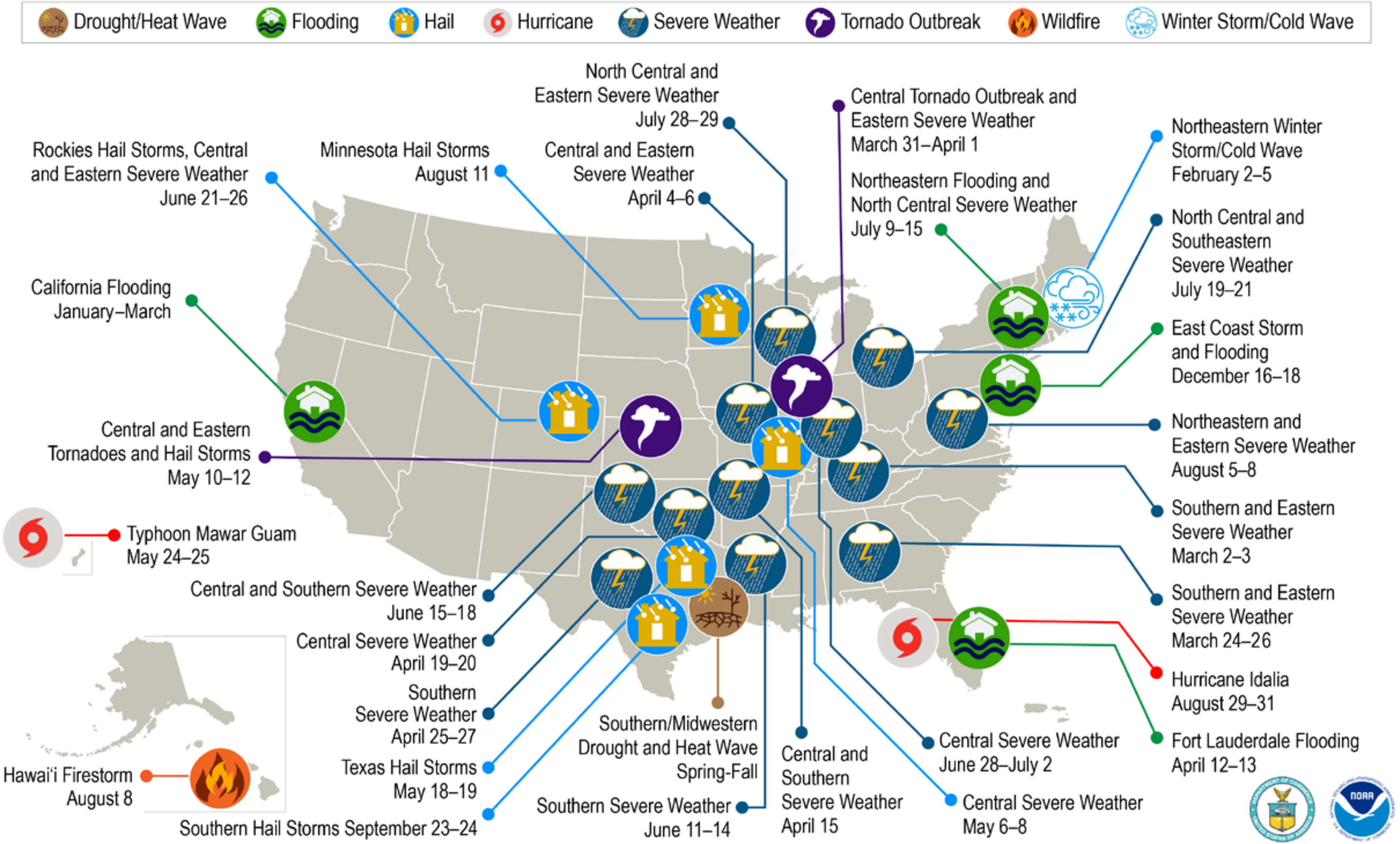
Outline

1. Welcome
2. Introduction
3. Drivers and Needs
4. Challenges to Resilience and Reliability
5. Strategies for Enhancing Resilience
6. Additional Resources
7. Conclusions and Final Questions

U.S. 2023 Billion-Dollar Weather and Climate Disasters



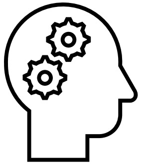
This map denotes the approximate location for each of the ***28 separate billion-dollar weather and climate disasters that impacted the United States in 2023.***

Illustration from NOAA National Centers for Environmental Information (NCEI). 2024. "U.S. Billion-Dollar Weather and Climate Disasters." https://www.ncei.noaa.gov/access/billions/.

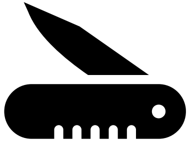
Key Takeaways

- Well-planned power systems can withstand and recover from disruptive events.
- Disruptions can be natural (storms, earthquakes) or man-made (cyberattacks, equipment failure).
- Mitigations focus on minimizing outages and restoring power quickly.
- Why is it important for everyone to understand the resilience of power systems?

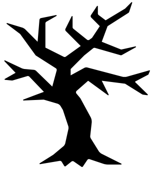
Resilient Power Systems



REFLECTIVE: Using past experience to inform future decisions.



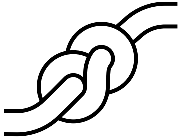
RESOURCEFUL: Recognizing alternative ways to use resources.



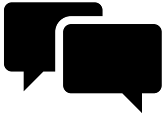
ROBUST: Well-conceived, constructed, and managed systems.

REDUNDANT: Spare capacity purposely created to accommodate disruption.

FLEXIBLE: Willingness and ability to adopt alternative strategies in response to changing circumstances.



INTEGRATED: Bringing together a range of distinct systems and institutions.



INCLUSIVE: Prioritizing broad consultation to create shared ownership in decision-making.

Illustrations from Microsoft stock images

Integrated Approach

Define Drivers and Needs

- Engage stakeholders.
- Identify mission drivers.
- Define resilience for mutual understanding.
- Develop metrics to access resilience readiness.
- Set specific resilience goals at the agency and site level.

Evaluate Current Operations and Risks and Identify Gaps

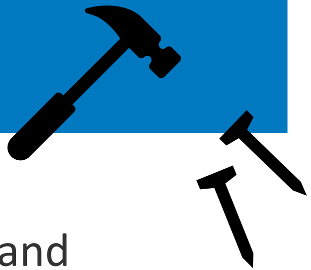
Identify Potential Solutions

Develop Roadmap and Prioritize Solutions

Implement and Measure Progress

Transfer Knowledge

Resilience Mitigation Framework



Emerging technologies can help address issues related to both resilience and reliability.

But start with **information**, **not solutions**.

Make **data-driven decisions** based upon **a clarity** of what you are trying to do and how you are measuring.

There are **multiple stakeholders** involved. Understanding how they articulate and measure *resilience* will influence the solution set.

Illustrations from Microsoft stock images

Role of Community Engagement

- Community involvement is important in building resilient power systems.
- Prioritize stakeholder consultation to create shared ownership in decision-making
- Individuals, businesses, and local governments can contribute to resilience efforts through energy efficiency and conservation, emergency preparedness, and support for infrastructure upgrades and grid modernization.
- How can you act in your own community to promote power system resilience?

Illustration from Microsoft stock images

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Resilience for

Resilience Hub Planning

- Identify hazards that the resilience hubs may face and address.
- Provide background information on social vulnerability and climate impacts.
- Identify populations who are at risk of disproportionate climate impacts due to social isolation and physical vulnerability characteristics (e.g., lack of transportation or internet).
- Align with best practices for reducing social vulnerability to climate impacts.

Illustration from Microsoft stock images

Notional hazards for community resilience hubs:

- Snow and ice as well as and windstorms can cause power outages leading to potential knock-on effects.
- Extreme heat events are becoming more prevalent with climate change and could reach up to 10 events per year. Many homes in the Western and Northwestern United States do not have air conditioning.
- Power outages are a hazard due to increased demand. In some parts of the United States, climate and hydraulic changes will likely alter hydroelectric supply, lowering it during summer.
- Air pollution from more frequent wildfires will worsen respiratory illnesses already experienced at higher rates in frontline communities, as well threaten power supply.

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- Define systems and baseline conditions.
- Assess risks based on vulnerabilities and likelihood of threats (past, current, and future).
- Develop resilience value and impact that is needed to reach identified goals.

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Our Power Grid: a Complex Web

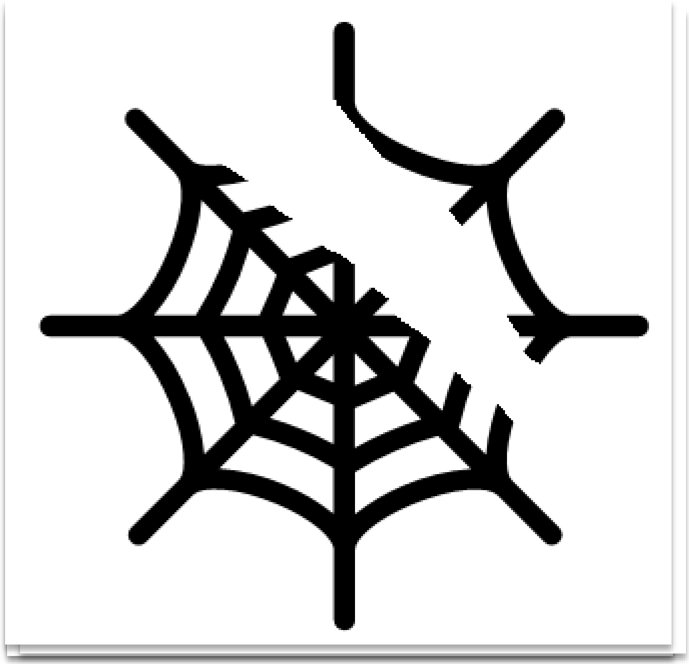
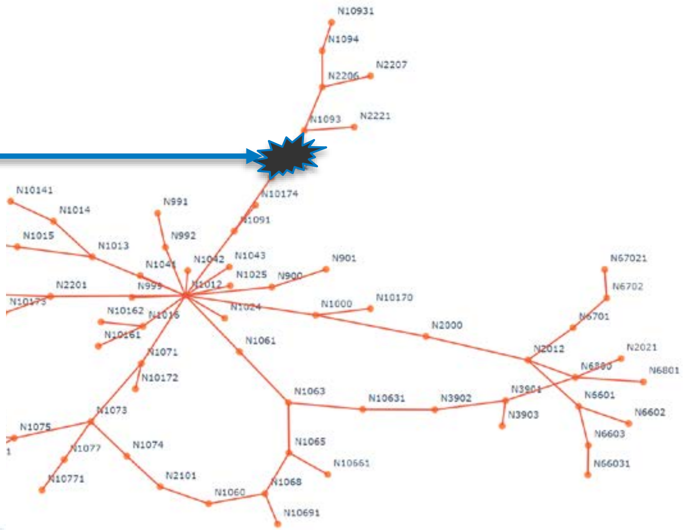


Illustration from Microsoft stock images

Illustration from U.S. Energy Information Administration

Our Distribution Grid: a Radial Hub and Spoke

Feeder outage

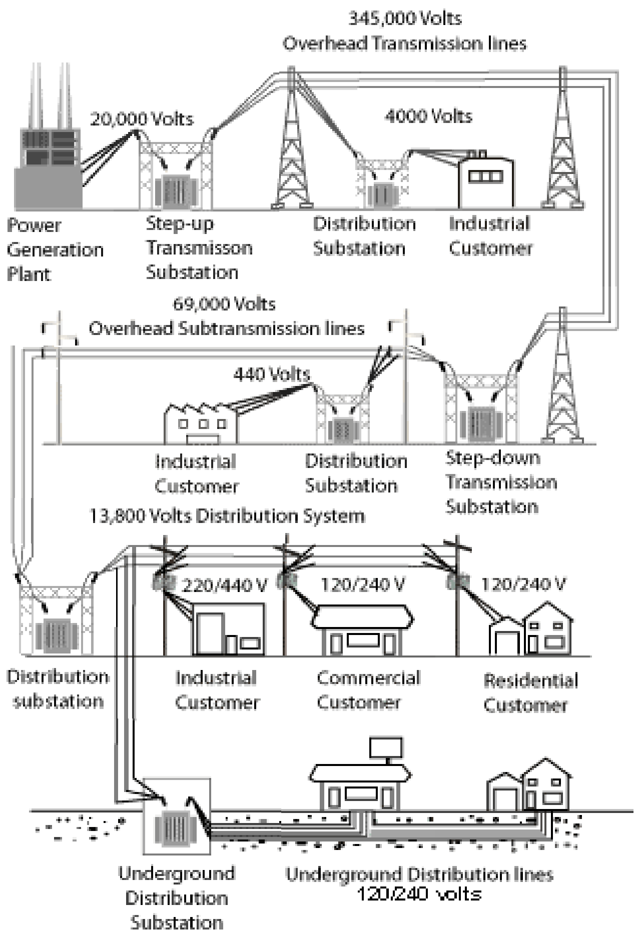


Distribution system model
Illustration by NREL

Source: Georgia Power

Understanding ^ Power Systems
Resilient

- What is *resilience* in the context of power systems?
- Why is it important to maintain electricity supply during normal and adverse conditions?
- How can power systems withstand disruptions like extreme weather, cyberattacks, or equipment failures?
- What are your options for insuring continuity of operations (survivability) if the grid does fail?



NREL Pix Library: Illustration from Schneider, Kevin, Emma Stuart, Murali Baggu, Michael Coddington, Juliet Homer, Lisa C. Schwartz, Joseph H Eto et al. 2017. "NECPUC Distribution Systems & Planning Training." https://emp.lbl.gov/publications/necpuc-distribution-systems-planning.

Impacts

EF5 storm originated in Mississippi.

Peak winds estimated at 200-plus mph.

Damage path: 132 mi (212 km).

Width: 1.25 mi (2 km).

Source: Tornado Recovery Action Council of Alabama. 2012. *Cultivating a State of Readiness: Our Response to April 28, 2011.* https://ema.alabama.gov/wp-content/uploads/2017/01/trac_report.pdf

More than 100 transmission lines affected (161 kV or higher).

275 mi (442 km) of conductor.

350-plus structures affected.

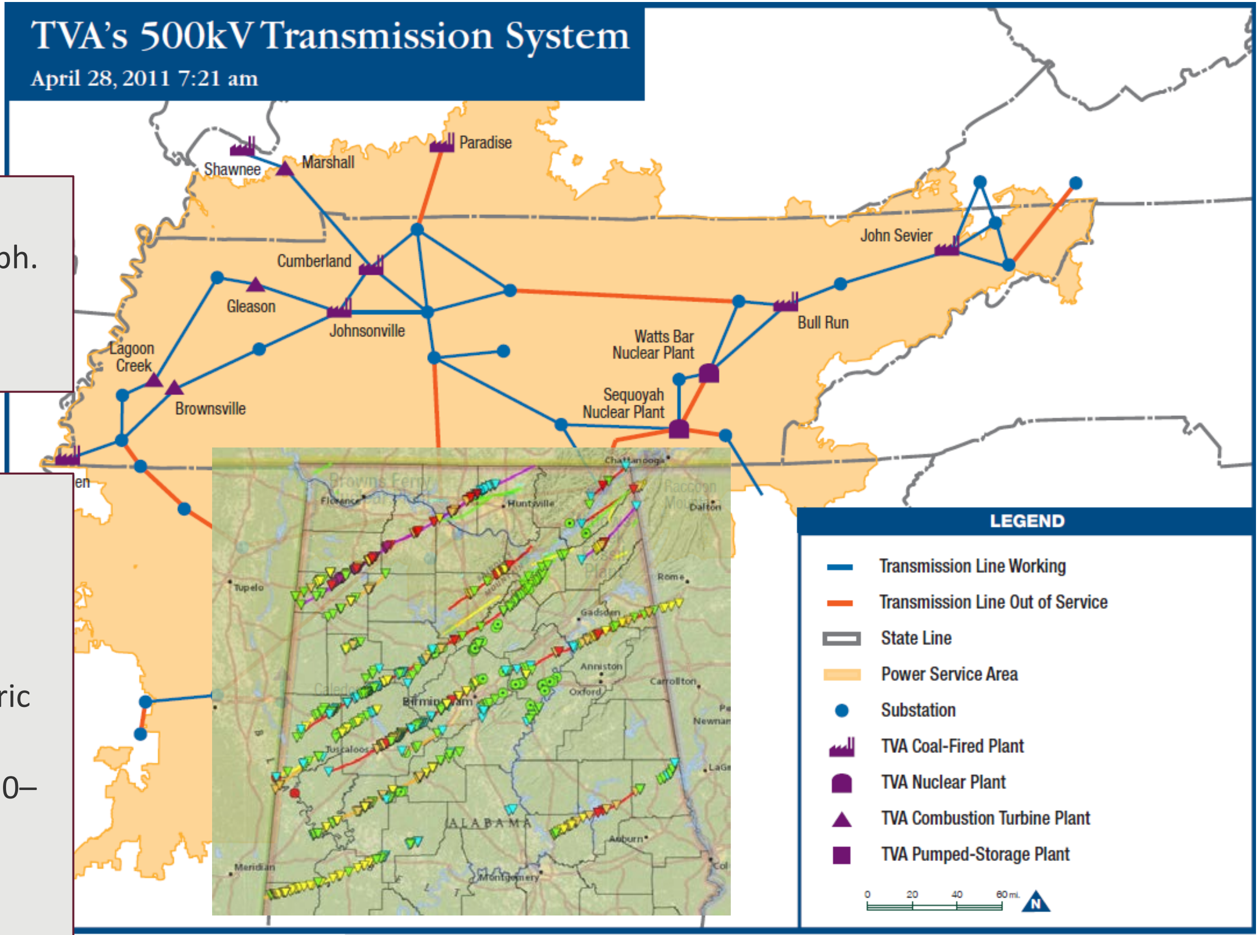
1.4 million pounds of steel (635 metric tons).

Tennessee Valley Authority cost: $150–$200 million.

850,000 customers without power.

Restoration: 65 days total.

Source: Tennessee Valley Authority news release. July 14, 2011.

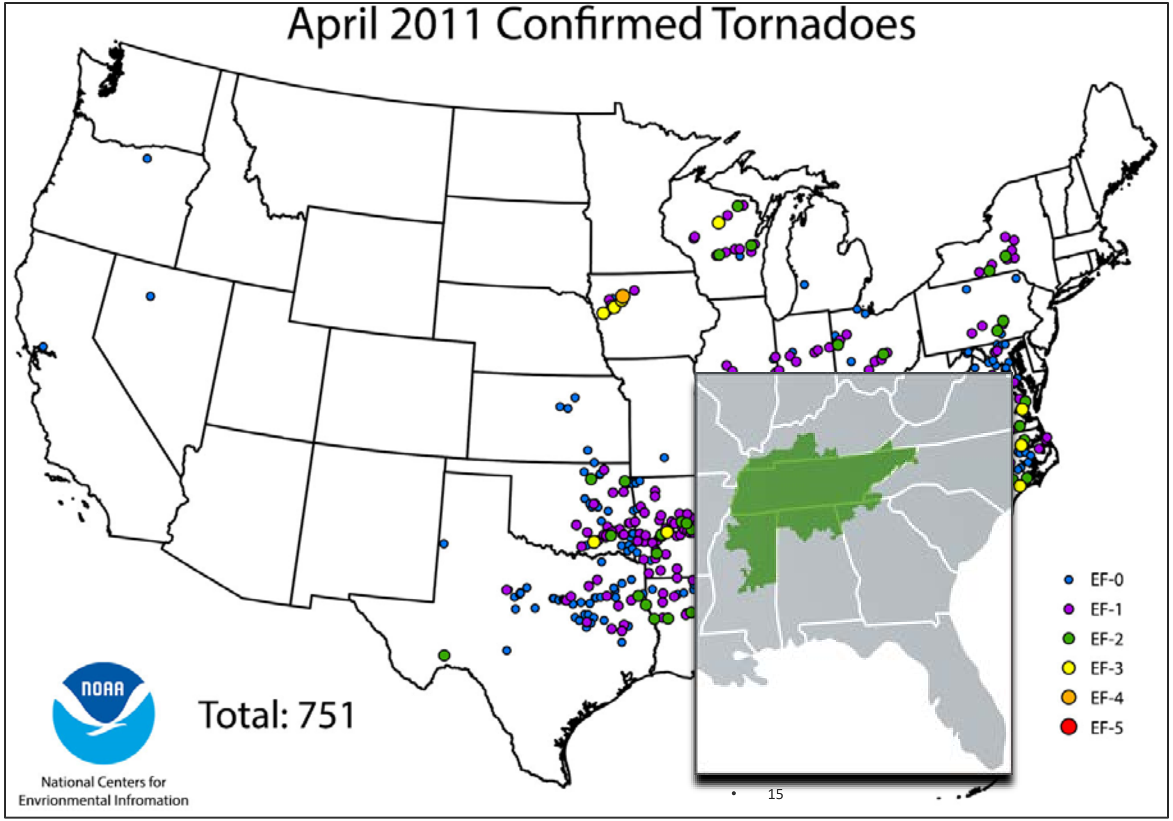


Tennessee Valley Authority transmission map image from Michael Ingram
Tornado paths image from weather.gov, accessed at https://www.weather.gov/bmx/event_04272011gis

Challenges to Power System Resilience

Five different storm systems.[1]

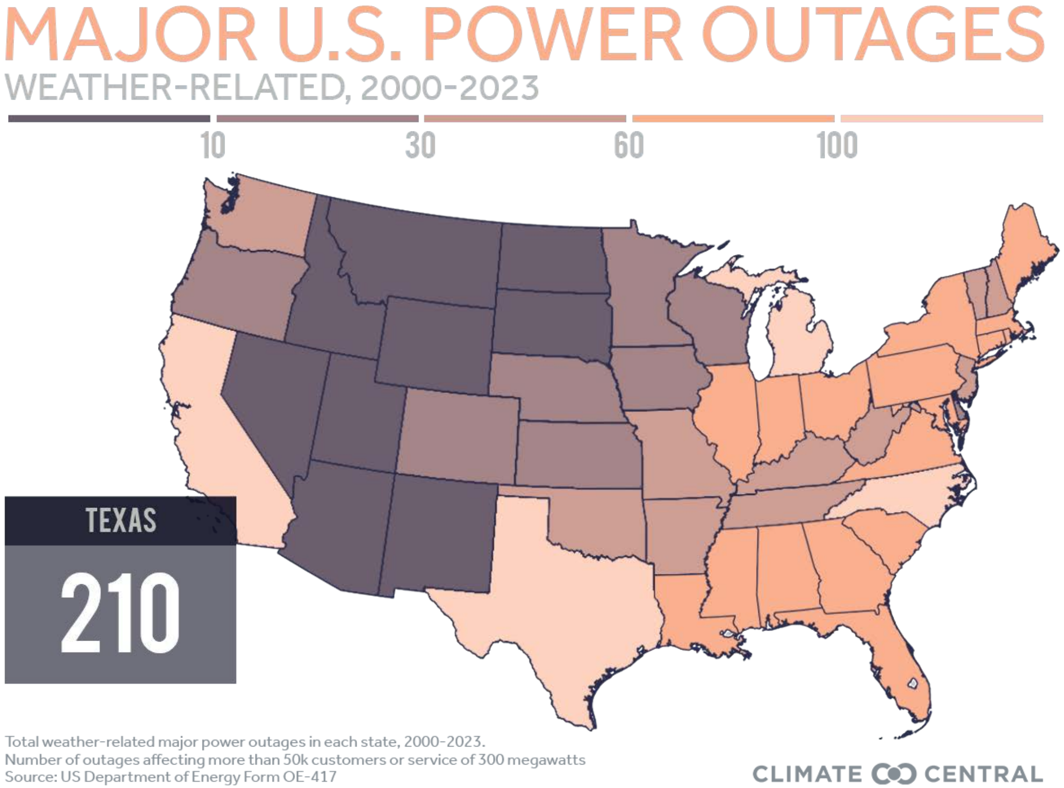
- April 4–5, 2011
  - 46 tornados, $3.2 billion
- April 8–11
  - 59 storms, $2.5 billion
- April 14–16
  - 177 storms, $2.4 billion
- April 19–20
  - 12-plus storms, $1.2 billion
- April 25–28
  - 343 storms, $12 billion.



Tornado map from National Centers for Environmental Information, https://www.ncei.noaa.gov/news/2011-tornado-super-outbreak
Tennessee Valley Authority territory map (animation) from www.tva.com.

[1] National Centers for Environmental Information. "Billion-Dollar Weather and Climate Disasters: Events." Aug. 2020. https://www.ncdc.noaa.gov/billions/events/US/1980-2020.

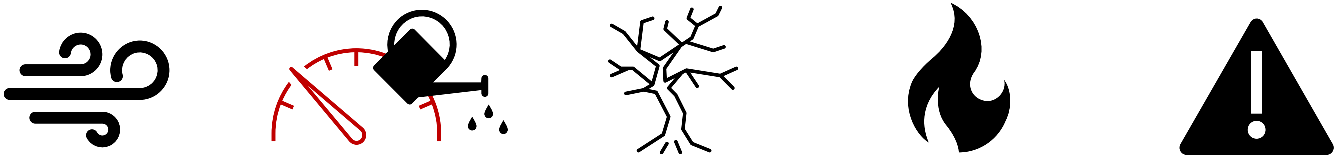
Weather-Related Power Outages



States With the Most Reported Weather-Related Power Outages (2000-2023)	
State	**Outages**
Texas	210
Michigan	157
California	145
North Carolina	111
Ohio	88
Louisiana	85
Virginia	83
Georgia	83
Pennsylvania	82
Florida	77
Alabama	76

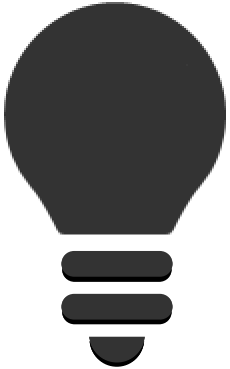
Source: Climate Central; https://www.climatecentral.org/graphic/weather-related-power-outages-rising?graphicSet=Weather+Outages+by+State&location=TX&lang=en

What is a Public Safety Power Shutoff?



High Winds | Low Humidity | Dry Vegetation | Fire Threat | Public Safety Risk

"High winds and other adverse weather conditions combine to increase the risk of wildfire. During windy conditions, flying debris can damage our power lines and create sparks that could cause ignition... a [public safety power shutoff] may be necessary to ensure the safety of our communities and employees."



Does your utility have a preemptive outage policy?

Source: San Diego Gas & Electric. 2020. "What is a PSPS? Public Safety Power Shutoffs Explained." https://www.sdgenews.com/article/what-psps-public-safety-power-shutoffs-explained.

Illustrations from Microsoft stock images

Anatomy of a Long Game

- Nine months before (spring 2015):
  - Initiated spear-phishing email campaign.
  - Installed BlackEnergy3 backdoor.
- Over many months:
  - Mapped network and harvested credentials.
  - Developed new serial-Ethernet converter firmware.
- On the day of the attack, December 23:
  - Launched a denial-of-service attack at a customer call center.
  - Entered supervisory control and data acquisition through hijacked credentials.
  - Interrupted service to 230,000 customers.
  - Wiped operator stations with KillDisk malware.
- One to six hours after:
  - Restored manually (breaker closures).

Illustration by the Government of Ukraine

"Ukraine is an example of how cyber systems used to operate and maintain interconnected networks…may be vulnerable to cyberattack."

Federal Energy Regulatory Commission, Docket No. RM16-18-000. 2016. "Cyber Systems in Control Centers." https://www.nerc.com/FilingsOrders/us/FERCOrdersRules/NOI_CyberSystems_20160721_RM16-18.pdf.

Source: U.S. Department of Homeland Security. 2016. "ICS Alert (IR-ALERT-H-16-056-01): Cyber-Attack Against Ukrainian Critical Infrastructure." https://us-cert.cisa.gov/ics/alerts/IR-ALERT-H-16-056-01#:~:text=SUMMARY,variety%20of%20critical%20infrastructure%20sectors.

Integrated Approach

Define Drivers and Needs

Evaluate Current Operations and Risks and Identify Gaps

Identify Potential Solutions

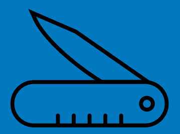
- Evaluate energy and water efficiency to optimize facilities and systems in a way that reduces overall demand.
- Evaluate infrastructure improvements to improve resiliency.
- Evaluate distributed energy and water generation opportunities (with islanding controls and storage).
- Conduct economic analysis that incorporates valuing resiliency.

Develop Roadmap and Prioritize Solutions

Implement and Measure Progress

Transfer Knowledge

Strategies for Enhancing Resilience



- Various strategies and technologies are used to improve power system resilience, including smart grids, microgrids, energy storage, and advanced monitoring systems.

- These solutions help mitigate risks and enhance the ability of power systems to bounce back from disruptions.

- Yes, they enhance resilience…but strategies also consider safety, economy, reliability, and environmental friendliness.

Illustration from Microsoft stock images

Resilience Matrix

Risks

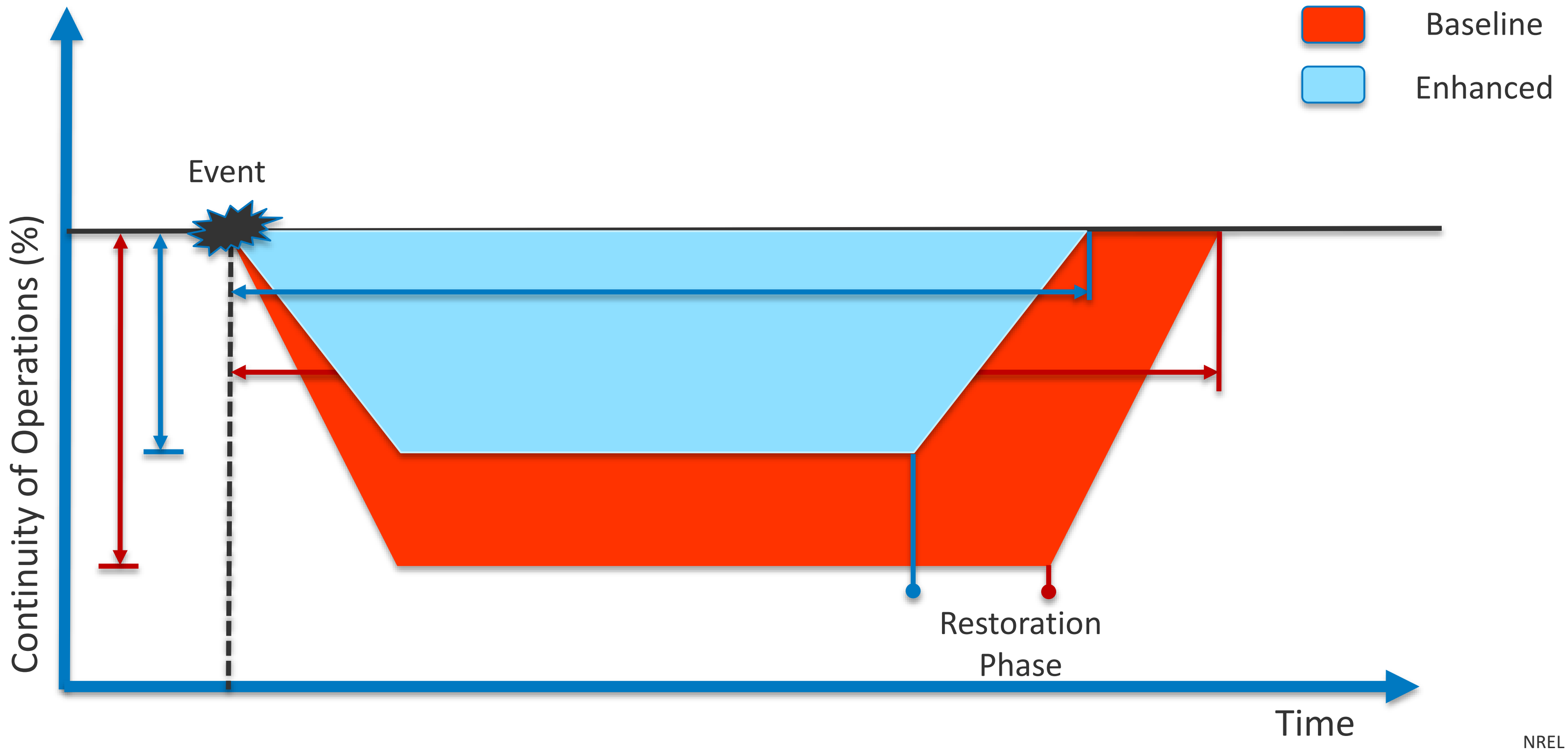
- Cyberattack
- Earthquake
- Electromagnetic pulse and geomagnetic disturbance
- Gas-electric interdependency
- Major equipment failure
- Physical attack
- Severe storms and severe flooding
- Single point failure
- Workforce and support (pandemic)
- Community resiliency.

Mitigation Plan

- Assess
- Prevention/hardening
- Detect/monitor
- Operating guides
- Recover/restore
- Emergency checklists
- Drills
- Operational integration.

Illustration edited from Microsoft stock images

Improving Resilience Performance



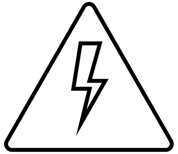
Threat-Agnostic Resilience Mitigations

Planning:

- Standards
- System models
- Threat characterization
- Vulnerability assessment
- System design
- Asset design
- Emergency preparedness (drills, planning).

Hardening:

- Transmission and distribution operations and maintenance
- Weatherization
- Configuration
- Grid modernization
- Generation fleet diversity
- Undergrounding
- Physical security
- Cybersecurity.



Event

Recovery:

- Spares and stores
- Mutual assistance
- Outage management
- Incident management
- Damage assessment
- Black start.

Survivability:

- Energy efficiency
- Microgrids
- Switching and isolation.

Illustrations edited from Microsoft stock images

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- Identify funding streams.
- Develop resilience action plan that provides an implementation road map for strategic funding and prioritization.

Implement and Measure Progress

- Implement projects and operational improvements based on prioritized road map; document project execution.
- Conduct project measurement and verification.
- Reevaluate resiliency metrics to assess resilience readiness.
- Review, revise, and approve resilience implementation plan based on evaluation of projects.

Transfer Knowledge

- Share lessons learned (successes, as well as failures).
- Give awards and recognition for successful projects and programs.
- Provide training on operational improvements.
- Implement feedback mechanisms to discuss challenges and solutions.

Prioritize Solutions and Measure Progress

- Estimate the impact of each mitigation measure's ability to:
  - Reduce the probability or level of outage frequency.
  - Limit the outage magnitude and duration.
  - Improve customers' operational continuity (survivability).

- Adjust the cost of the mitigation measure to reflect its co-benefits (if any) beyond resilience impacts. For example:
  - Transmission and distribution operations and maintenance has system capital and system efficiency benefits.
  - Energy efficiency has customer bill-saving, comfort, and emissions benefits.

- Assess value.

Relationship Between Reliability and Resilience

There are three operational phases to both reliability and resilience:

- Before event: Build or strengthen the system.
- During event: Manage events.
- After event: Restoration to normal.

Illustration from Microsoft stock images

Advanced Metering Infrastructure

Utility Use Cases[1,2]

- Load research
- Revenue protection
- Outage management
- Reliability indices
- Voltage regulation.

Resilience

- Service restoration
- Fault location (and isolation)
- Safety
- Performance management
- Microgrid design.

Source: U.S. Department of Energy. 2014. *Smart Grid Investments Improve Grid Reliability, Resilience, and Storm Responses.* https://www.energy.gov/sites/prod/files/2014/12/f19/SG-ImprovesRestoration-Nov2014.pdf.

Photo by NREL

[1] Dorr, D. 2015. *Survey for AMI Data Analytics: Summary Report.* Electric Power Institute.

[2] U.S. Department of Energy. 2016. *Advanced Metering Infrastructure and Customer Systems: Results from the Smart Grid Investment Grant Program.* https://www.energy.gov/sites/prod/files/2016/12/f34/AMI%20Summary%20Report_09-26-16.pdf .

Physical Resilience of Distributed Energy Resources

Technological categories of failure:

1. Photovoltaic module frame and laminate.
2. Module connection hardware.
3. Structural racking member.
4. Structural racking connections.
5. Racking foundations.
6. Electrical balance of systems.

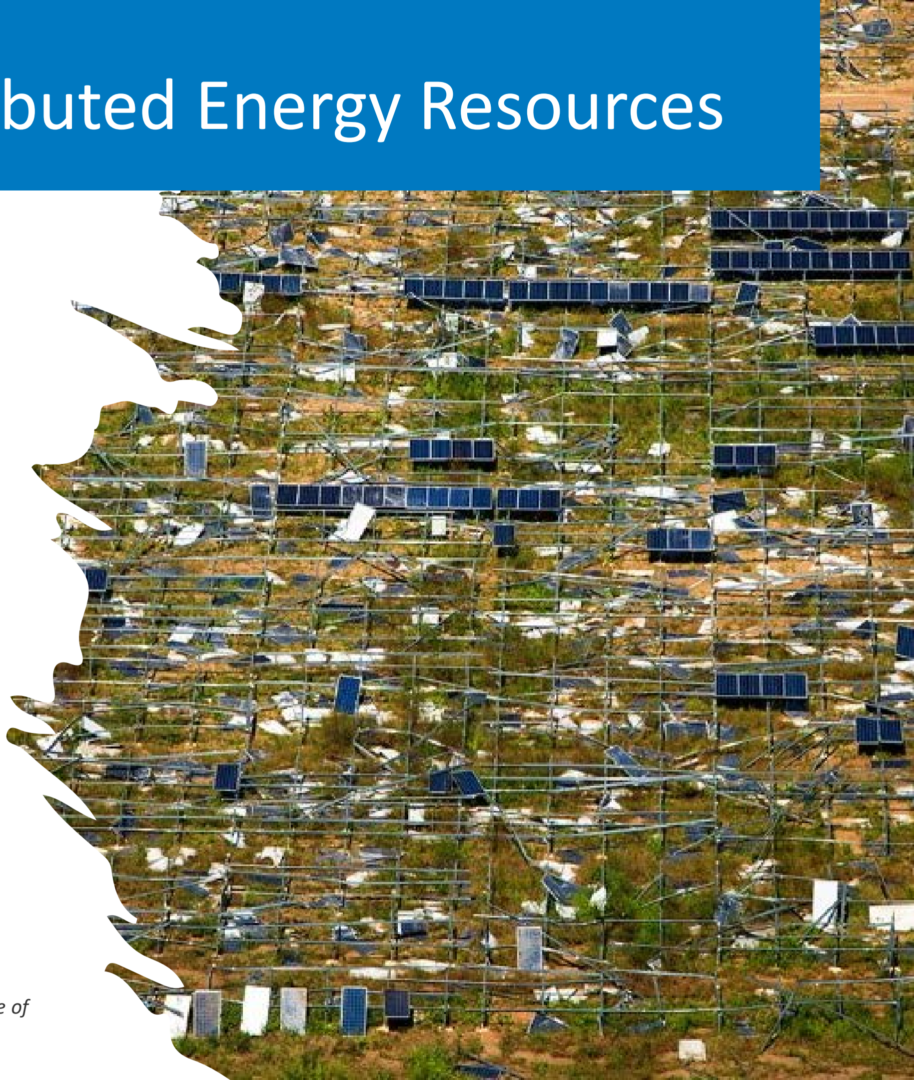


Photo from Erika P. Rodriguez

Source: Ingram, Michael. 2022. *Providencia Island White Papers: Potential for Increasing the Physical Resilience of Distributed Energy Resources*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-83563. https://www.nrel.gov/docs/fy23osti/83563.pdf.

Physical Security

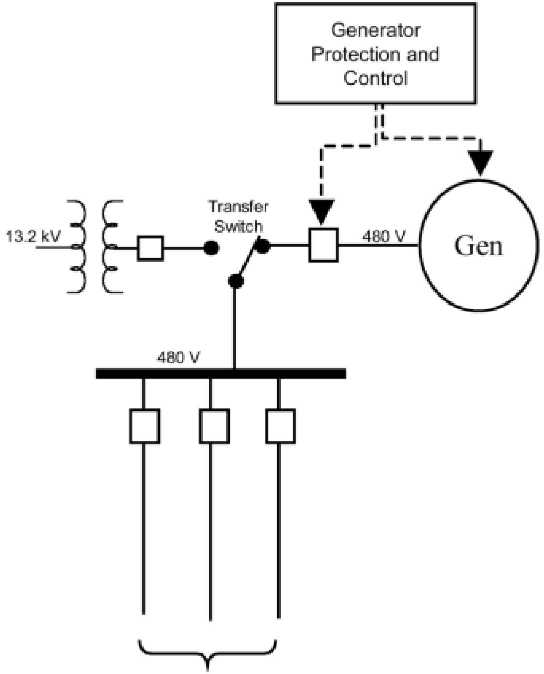
Of critical cyber systems[1]	Of critical grid assets[2]
(such as primary and backup control centers and substation control houses with external routable connectivity) Physical security plan documents: – **Measures** to secure "electronic security perimeter." – **Access** controls, monitoring, and logging. – **Implement** maintenance and testing for all physical security systems.	1. Deter/delay: perimeter structures, visual/audible alarms. 2. Detect: perimeter intrusion detection. 3. Assess: video management, access control. 4. Communicate: alerts and notifications. 5. Respond: course of action and dispatch.

April 16, 2013 attack on the Pacific Gas and Electric Company's Metcalf substation.

[1] North American Electric Reliability Corporation. *CIP-006 Physical Security of BES Cyber Systems.*
[2] North American Electric Reliability Corporation. *CIP-014 Physical Security.*

Backup Generator or Microgrid?

Backup Generator



Microgrid

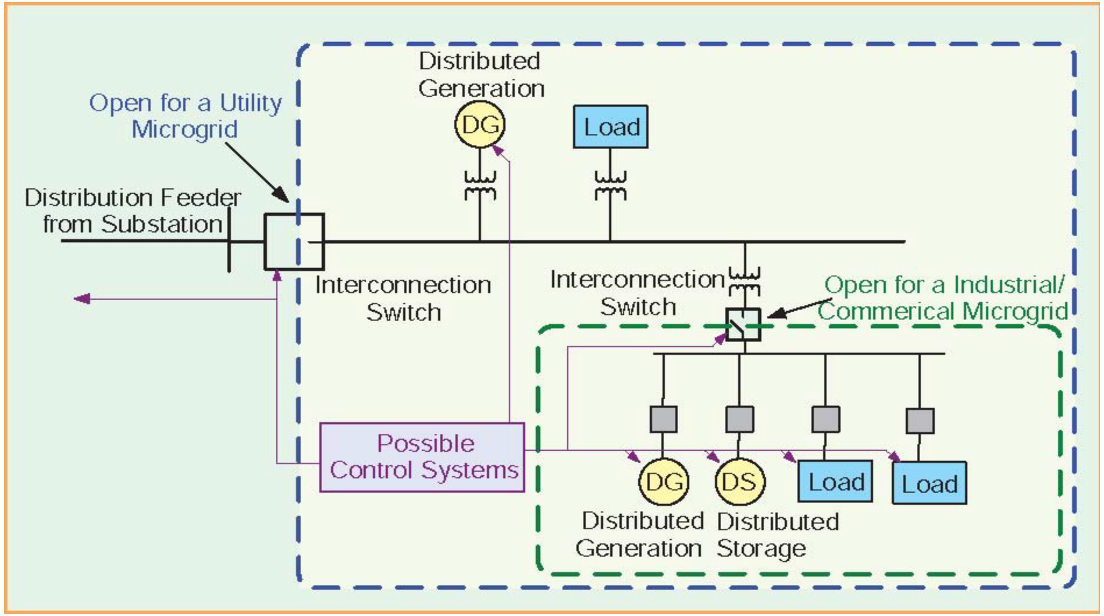


Illustration by NREL

Planning and Design of the Microgrid

- Yes, consider resilience. But also consider the safety, economy, reliability, and environmental friendliness of microgrids.
- Planners should consider the local load profile, energy demand, and energy resources.
  - Develop scalable solutions to meet forecasted growth.
  - Objectives should drive the solution set.
- Designers must incorporate analysis of protection and control, system security and stability, and power quality—**both in grid-tied and islanded modes**.
- Validate which designs meet objectives.
- Evaluate and compare schemes versus costs, benefits, and other considerations.

Resource: Institute of Electrical and Electronics Engineers. "IEEE Recommended Practice for the Planning and Design of the Microgrid." *IEEE Std 2030.9-2019:* 1-46. https://ieeexplore.ieee.org/servlet/opac?punumber=8746834.

Illustration from Microsoft stock images

Microgrid Planning-Level Information

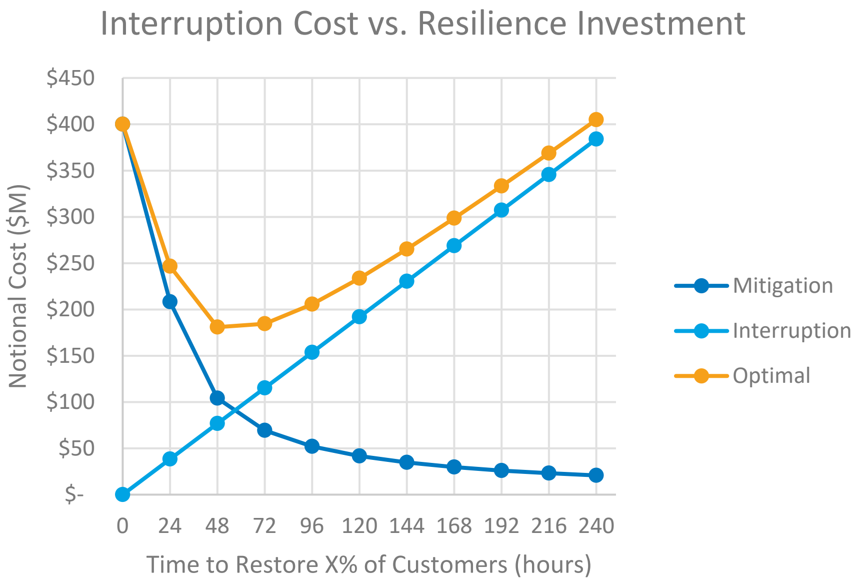
Data Type	Notes
• Objectives and "resiliency definition." • Copy of site continuity plan.	Relates to objectives and the type and extent of resiliency.
Mission-critical load identification and characterization: • Facilities: building numbers/locations identified on site plan. • Critical feeder/facility/building load information (submetering data). • Project list for planned or funded projects in critical load area. • Tenant facility considerations, including any available information on tenant critical loads.	Physical scope of energy security considerations.
Distributed resource (i.e., backup generators) characterization: • Existing generator ratings/nameplate data (including make/model). Typical information stored in site asset management system (i.e., Maximo).	Understanding of existing infrastructure and resources.
One-line diagrams and/or site distribution plans.	Understanding of site electrical infrastructure.
Load data (15-minute, 12 months preferred).	Understanding of peak and minimum loads, energy consumption, power factor, etc.

Checklist developed by National Renewable Energy Laboratory for federal clients.

Illustration from Microsoft stock images

Weighing Cost and Benefits

- Customer restoration framework (CR-90).[1]
  - Number of hours needed to restore service to 90% of customers.
- Mitigation costs include "hardening," deeper stores, and technology investments (e.g., microgrids, smart grid).



[1] Mihlmester, Phil, and Kiran Kumaraswamy. 2013. "What Price, Resiliency?" *Fortnightly Magazine:* 46-51.

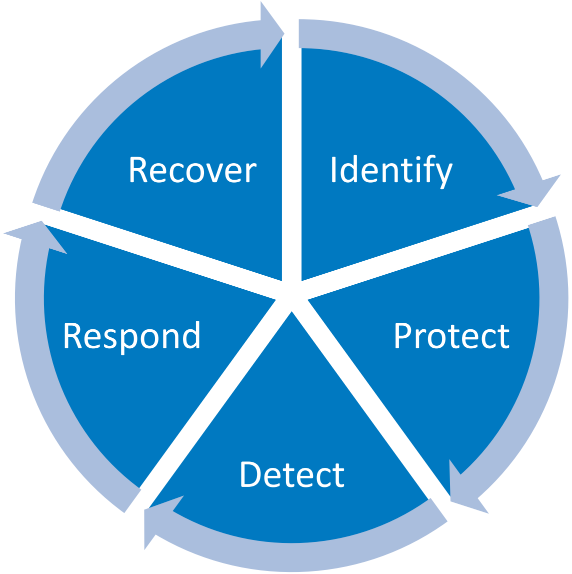
Additional Resource: Energy Resilience

Anderson, Kate, Eliza Hotchkiss, Lissa Myers, and Sherry Stout. 2019. *Energy Resilience Assessment Methodology.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-74983. https://www.nrel.gov/docs/fy20osti/74983.pdf.

Illustration by NREL

Additional Resources: Cyber Frameworks

- The U.S. Department of Energy: Electricity Subsector Cybersecurity Capability Maturity Model (ES-C2M2).
- The National Institute of Standards and Technology: Framework for Improving Critical Infrastructure Cybersecurity.
- The National Rural Electric Cooperative Association: Guide to Developing a Cyber Security and Risk Mitigation Plan.
- Ingram, Michael and Maurice Martin. 2017. *Guide to Cybersecurity, Resilience, and Reliability for Small and Under-Resourced Utilities.*



1. Risk management
2. Asset, change, and configuration management
3. Identity and access management
4. Threat and vulnerability management
5. Situational awareness
6. Information sharing and communications
7. Event and incident response, continuity of operations
8. Supply chain and external dependencies
9. Workforce management
10. Program management.

Illustration from Microsoft stock images

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Thank You

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