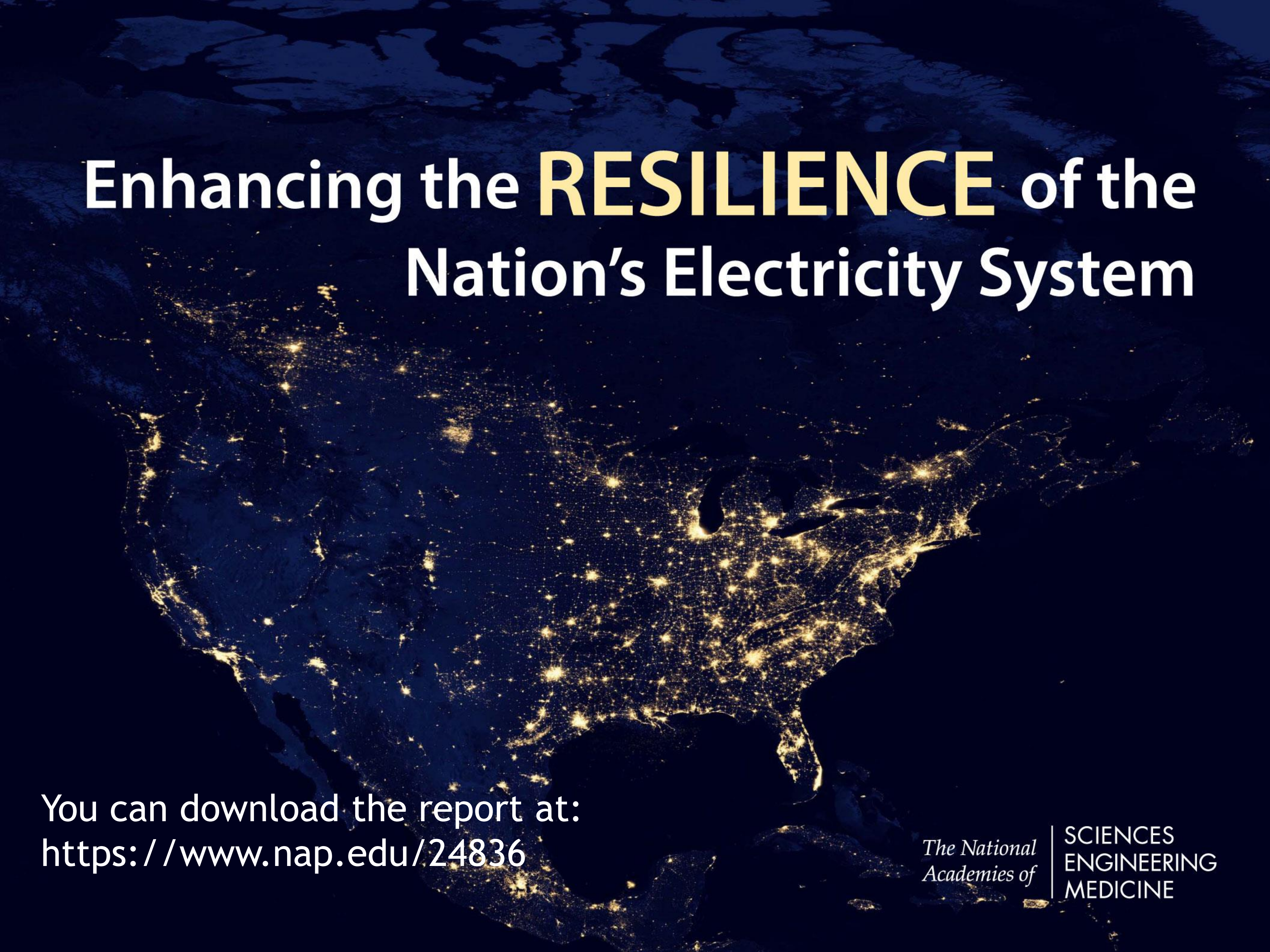


Enhancing the RESILIENCE of the Nation's Electricity System

You can download the report at:
https://www.nap.edu/24836

The National Academies of SCIENCES ENGINEERING MEDICINE

About the Study

At the request of Congress, the Department of Energy asked the National Academies of Sciences, Engineering, and Medicine to organize a study to identify technologies, policies, and organizational strategies to increase the resilience and reliability of the U.S. electricity system.

The committee members were expert volunteers from across various sectors. Over the course of 18 months, the committee collected input from stakeholders in academia, government, and industry before authoring their final report, which was independently peer-reviewed.

Download the complete report and the 4-page summary at:
https://www.nap.edu/24836

We had an excellent committee with very diverse expertise:

M. GRANGER MORGAN, *Chair*, NAS, Carnegie Mellon University, Pittsburgh, Pennsylvania
DIONYSIOS ALIPRANTIS, Purdue University, West Lafayette, Indiana
ANJAN BOSE, NAE, Washington State University, Pullman, Washington
TERRY BOSTON, NAE, PJM Interconnection LLC (Retired), Honolulu, Hawaii
ALLISON CLEMENTS, Goodgrid LLC, Salt Lake City, Utah
JEFF DAGLE, Pacific Northwest National Laboratory, Richland, Washington
PAUL DeMARTINI, Newport Consulting, Sausalito, California
JEANNE FOX, Columbia School of International & Public Affairs, New York City, New York
ELSA GARMIRE, Dartmouth College (Retired), Santa Cruz, California
RONALD E. KEYES, United States Air Force (Retired), Woodbridge, Virginia
MARK McGRANAGHAN, Electric Power Research Institute, Palo Alto, California
CRAIG MILLER, NRECA, Alexandria, Virginia
THOMAS J. OVERBYE, Texas A&M University, College Station, Texas
WILLIAM H. SANDERS, University of Illinois, Urbana-Champaign, Illinois
RICHARD E. SCHULER, Cornell University, Ithaca, New York
SUE TIERNEY, Analysis Group, Aurora, Colorado
DAVID G. VICTOR, University of California, San Diego, La Jolla, California

K. JOHN HOLMES, Study Director; Additional Staff: DANA CAINES, LINDA CASOLA, ELIZABETH EULLER, JORDAN D. HOYT, LaNITA JONES, JANKI U. PATEL, BEN A. WENDER, E. JONATHAN YANGER, JAMES J. ZUCCHETTO.

Most disruptions are brief and local

Most causes of power outages, such as lightning strikes, falling trees, squirrel electrocutions, or vehicles crashing into poles, cause little prolonged disruption to daily life. These events result in short term power outages, as evidenced by the median power outage in the United States lasting less than three hours in 2014. **Such outages are *not* the subject of this report. Our concern was wide-area outages of long duration.**

IEEE Benchmark Year 2015 Results for 2014 Data. IEEE Working Group on Distribution Reliability. Available at: http://grouper.ieee.org/groups/td/dist/sd/doc/Benchmarking-Results-2014.pdf, Accessed February 8, 2016.

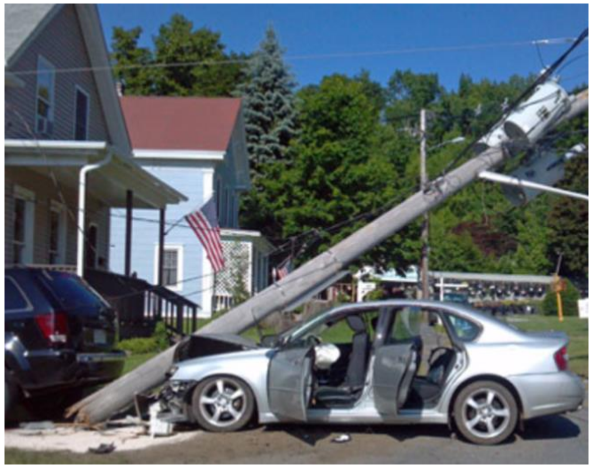
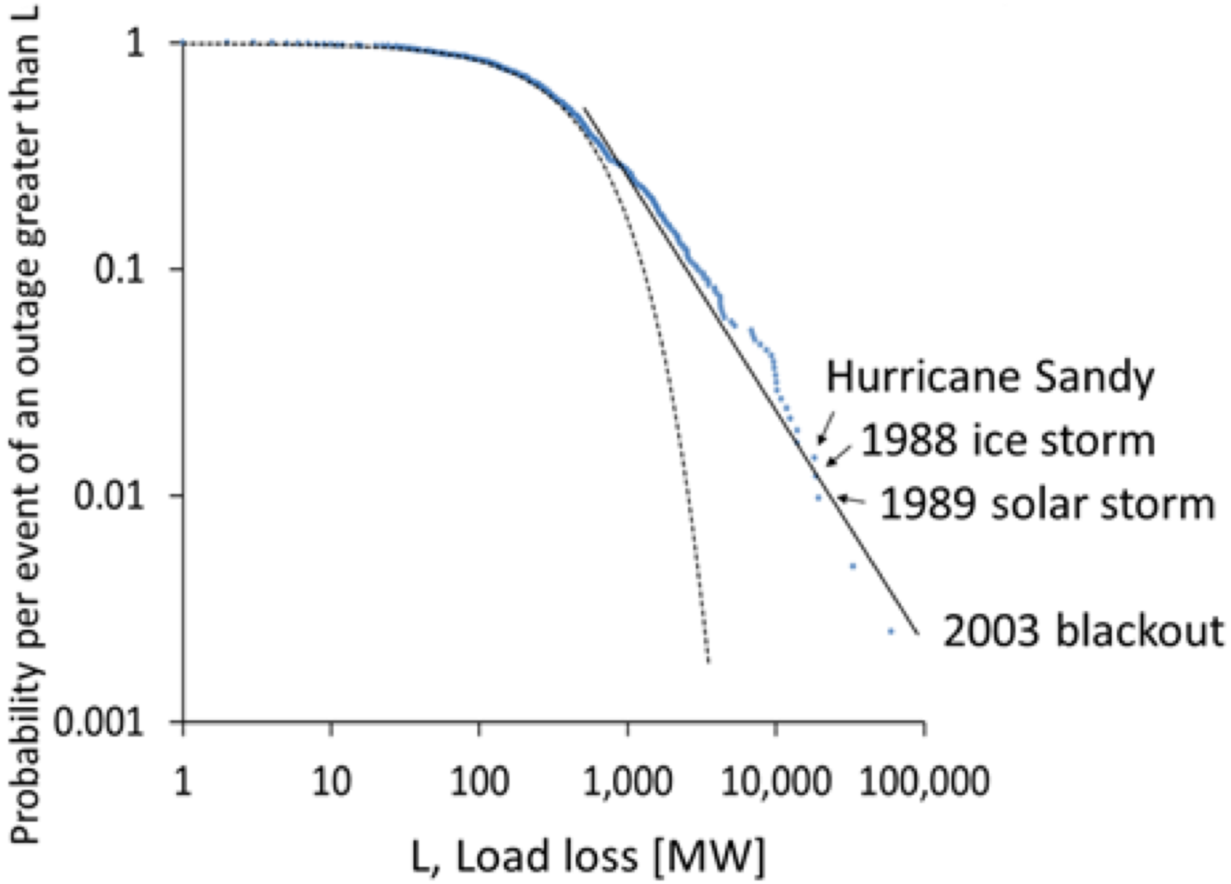


Image sources: wcvb.com; wikipedia; consumerwarningnetworrk.com; lightingsafety.com; rhizome.com

Large outages are more common than one might think



See page 1-5 of prepub for details

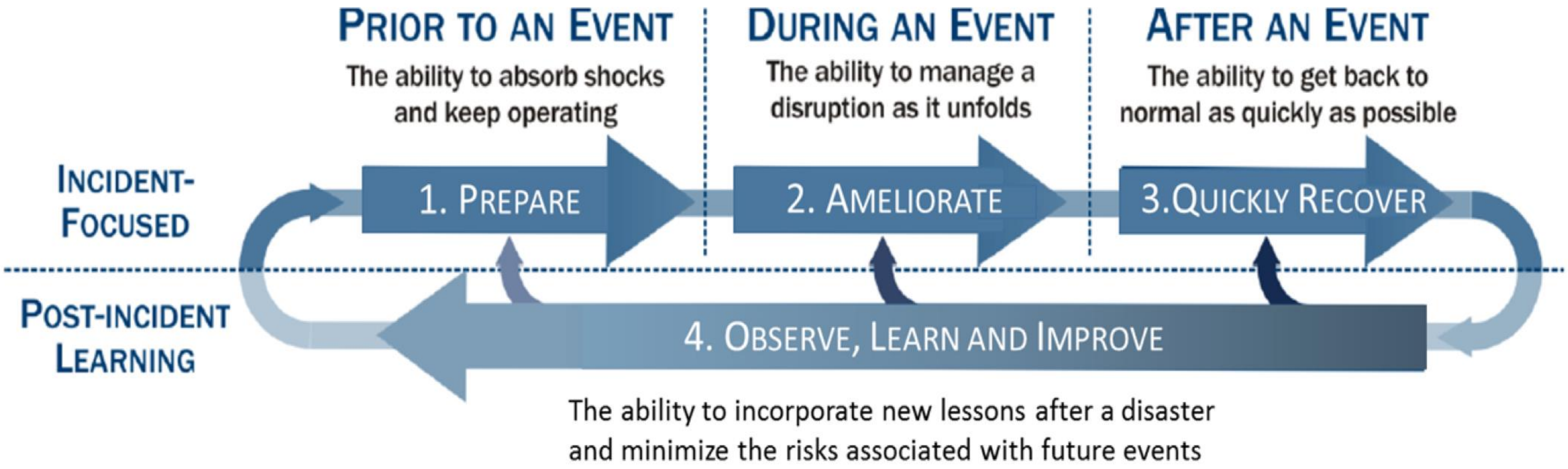
Resilience is Different than Reliability

The Random House Dictionary defines resilient as:

> "the power or ability to return to the original form, position, etc. after being bent, compressed, or stretched . . . [the] ability to recover from illness, depression, adversity, or the like . . . [to] spring back, rebound."

While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that large outages can occur, prepares to deal with them, minimizes their impact when they do occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future.

The Resilience Cycle



This framing was originally laid out in an article by S.E. Flynn in Foreign Affairs (2008). An earlier version of the diagram was produced by the National Infrastructure Advisory Council (NIAC, 2010). The committee modified it for our report

Organization of the report

Ch. 1
Introduction and Motivation

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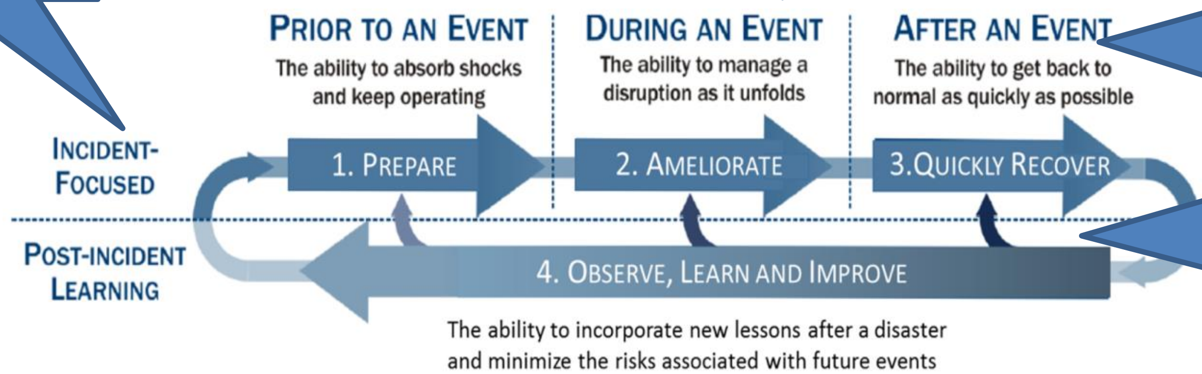
Restoring Grid Function After a Major Disruption



Chapter 1: Introduction and Motivation

1. **Electricity is critical to modern society:**

   "The modern world runs on electricity. As individuals, we depend on electricity to heat, cool, and light our homes; refrigerate and prepare our food; pump and purify our water; handle sewage; and support most of our communications and entertainment. As a society, we depend on electricity to light our streets; control the flow of traffic on the roads, rails, and in the air; operate the myriad physical and information supply chains that create, produce, and distribute goods and services; maintain public safety, and help assure our national security."

2. **For at least the next several decades, most customers will continue to depend on the** functioning of the large-scale, interconnected, tightly organized, and **hierarchically structured electric grid**.

3. While we should do all we can to minimize the possibility, **large outages of long duration have and *will* occur**.

Chapter 2: Today's grid and the evolving system of the future

This audience knows all this

- Introduction,
- Electric Industry Structure, Asset Ownership, and Operational Roles and Responsibilities
- Physical Structure and Operation of the High-Voltage Transmission Systems
- Physical Structure and Operation of the Distribution System,
- Metrics for Reliability and Resiliency
- Near-Term Drivers of Change and Associated Challenges and Opportunities for Resiliency
- Longer-Term Drivers of Change and Associated Challenges and Opportunities for Resiliency
- Sustaining and Improving the Resilience of a Grid that is Changing Rapidly and in Uncertain Ways

Metrics

Metrics for reliability are fairly straight forward because they involve looking at the statistics of past outages.

Standard reliability metrics include: **SAIFI** (System Average Interruption Frequency Index); **SAIDI** (System Average Interruption Duration Index). **CAIDI** (Customer Average Interruption Duration Index); **CAIFI** (Customer Average Interruption Frequency Index) and **MAIFI** (Momentary Average Interruption Frequency Index)

Developing metrics for resilience is extremely challenging because that involves assessing how well we are prepared for, and could deal with, very rare events, some of which have never happened.

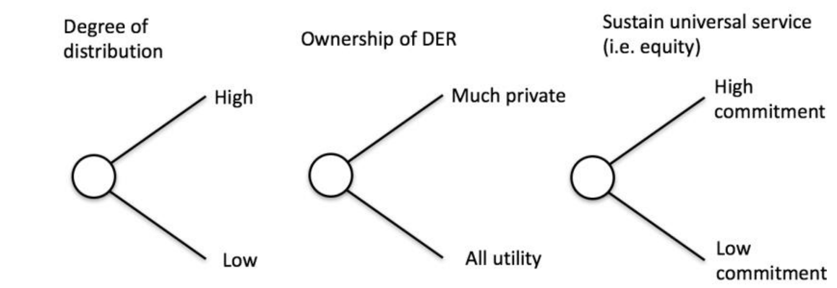
The report recommends that DOE work on improved studies to assess the value to customers of full and partial service during long outages as a function of key circumstances.

It also call for a coordinated assessment of the numerous resilience metrics being proposed.

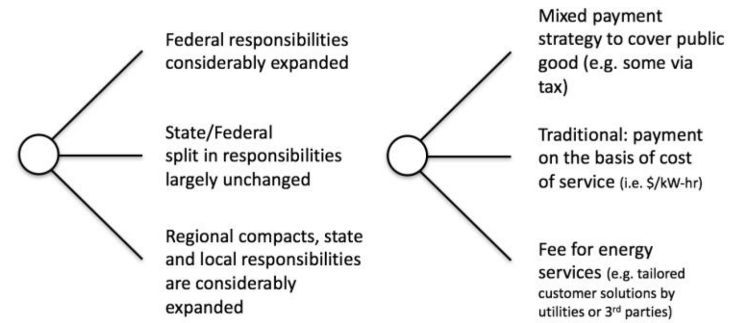
See page 2-26 to 2-32 for details

Future change

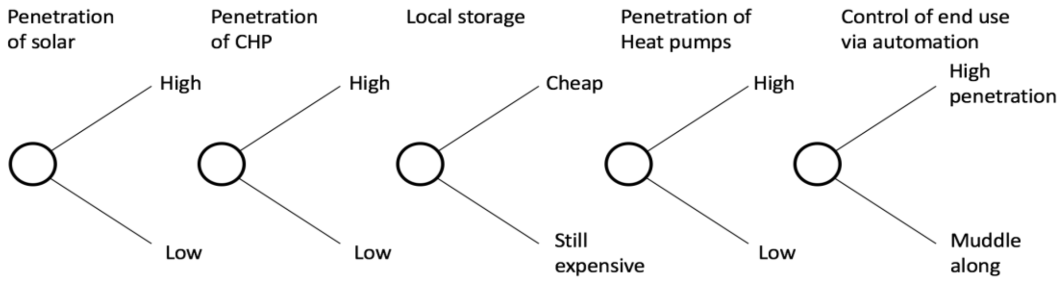
Distribution *vs* centralization



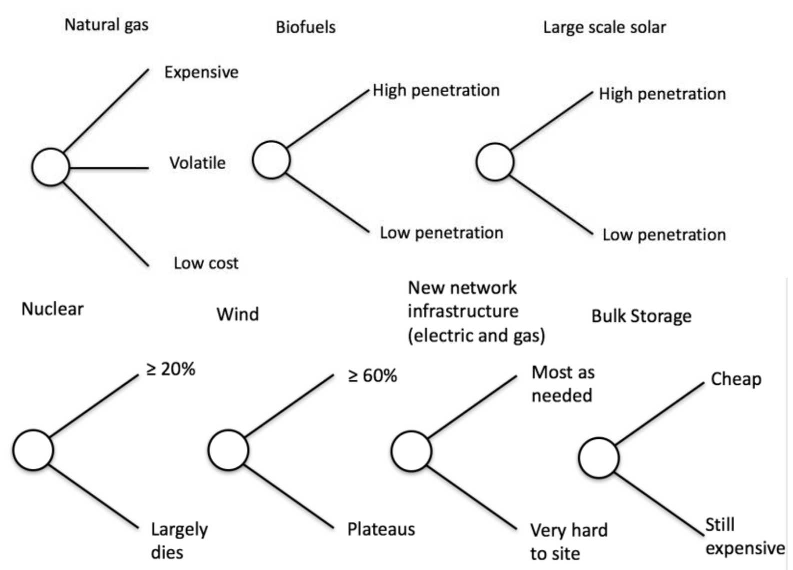
Regulatory Environment



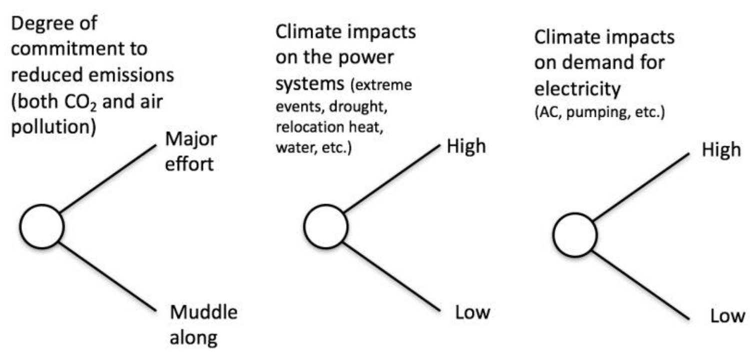
Distributed resources



Bulk energy



Climate/weather



We wrap up Chapter 2 with five summary observations

1. The grid is undergoing dramatic change…
2. Much of the hardware that makes up the grid is long lived…
3. No single entity is in charge of planning the evolution of the grid…
4. All players will be concerned about reliability…Only a few are…focused in a serious way on identifying growing system-wide vulnerabilities or identifying changes needed to assure resilience.
5. …virtually no one has a primary mission of building and sustaining increased system-wide resilience…

See page 2-55 to 2-56 of prepub for details

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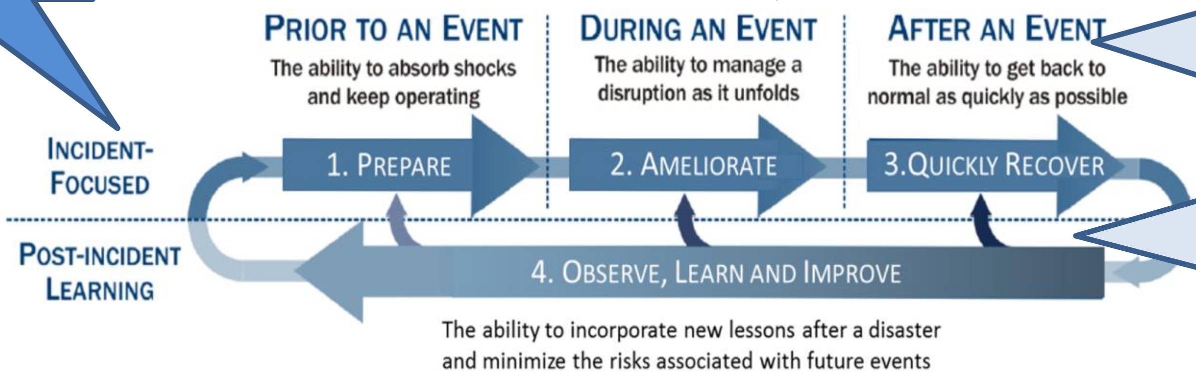

Chapter 3: The many causes of grid failure.

Introduction
Different Causes Require Different Preparation and Have Different Consequences
Reviewing the Causes of Outages
The Lifecycle of a Power Outage

- Human induced
  - Physical attack
  - Cyber attack
  - Operat(or/ion) error(s)
- Natural events
  - Drought and associated water shortage
  - Earthquake
  - Flood/storm surge
  - Hurricane
  - Ice storm
  - Pandemic
  - Regional storms and tornados
  - Space weather
  - Tsunami
  - Volcanic events
  - Wild fire

A few images can make this abstract description more real:

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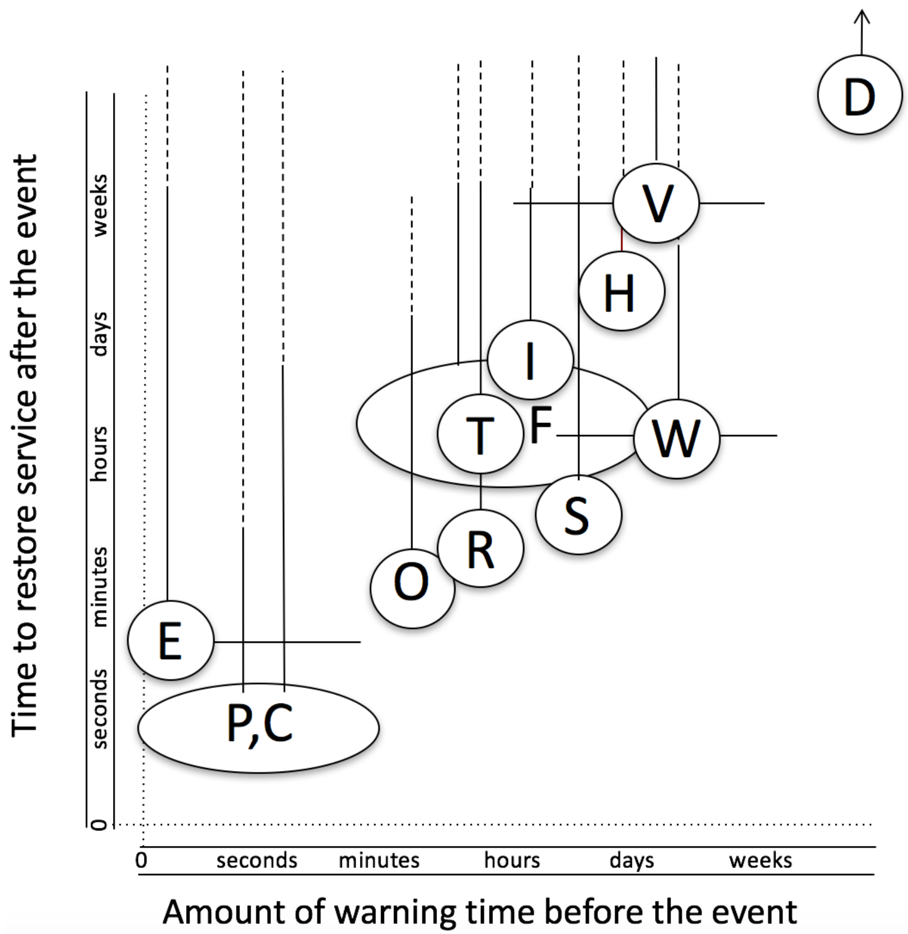
Images sources: NYT, NOAA, CBC, NWS, Thinglink, NCAR, teara.govt.nz

Warning and Restoration Times Vary for Different Threats



C = cyber attack (ranging from state/pro on left to good hacker on right)
D = drought and associated water shortage
E = earthquake (in some cases with warning systems)
F = flood/storm surge
H = hurricane
I = ice storm
O= major operator error
P = physical attack
R = regional storms and tornados
S = space weather
T = tsunami
V = volcanic events
W= wild fire

See page 3-2 of prepub for details

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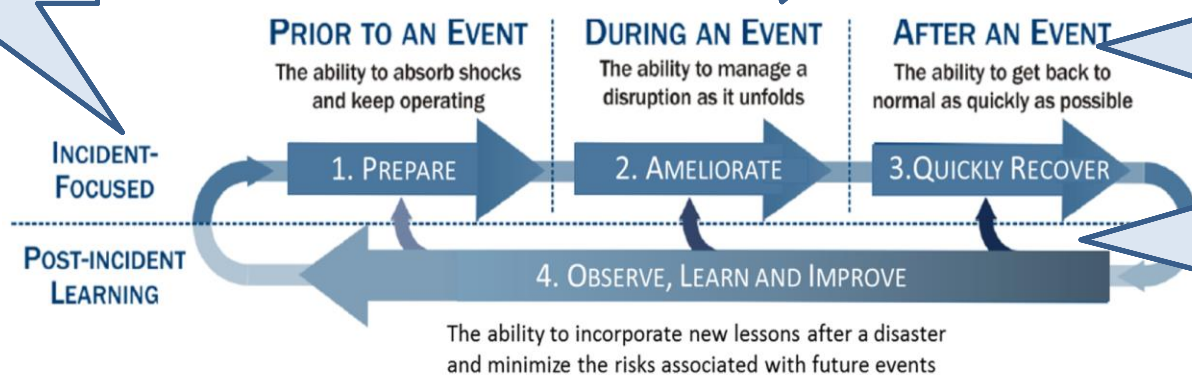

Chapter 4: Strategies to Prepare for and Mitigate Large-Area, Long-Duration Blackouts

Technology Opportunities to Enhance System Resilience

- Component hardening and physical security
- Distribution automation
- Better control/coordination of Distributed Energy Resources (DER)
- Enhanced modeling and simulation
- Wide area monitoring and control
- Intelligent load shedding / adaptive islanding
- System architectural considerations to reduce criticality of individual components
- Reducing dependency on supporting infrastructures
- Cyber resiliency

Cyber Resiliency

- The electric power system has become increasingly reliant on its cyber infrastructure.
- While much attention has been placed on grid *cybersecurity*, much less has been placed on grid *cyber resilience*.
- Protection alone as a mechanism to achieve cybersecurity is insufficient and can never be made perfect.
- Given that protection cannot be made perfect and the risk is growing, cyber resilience is critically important.
- Cyber resilience aims to protect, using established cybersecurity techniques, the best one can, but acknowledges that that protection can never be perfect and requires monitoring, detection, and response to provide continuous delivery of electrical service.
- Work to define cyber resilience architectures that protect, detect, respond, and recover from cyber attacks that occur is critically needed.

Climate/weather

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Recommendations from Ch. 4 to Enhance System Resilience

1. Grant programs that support utility efforts to enhance resiliency.
2. RD&D on technical, legal, and contractual challenges for DERs.
3. Research for modeling and mitigation of severe events.
4. Synthetic data models at realistic scale.
5. Use cases for intelligent load shedding using AMI and other technologies.
6. Technologies for sustaining critical functionality during degraded operations.
7. Awareness and information sharing between dependent infrastructures (e.g. w/ natural gas).
8. Wide area monitoring and control including enhanced situational awareness.
9. Standardized methods of sharing system status and health, including cyber systems.
10. Architecture designs that support resilience.

See page 4-8 to 4-38 of prepub for details

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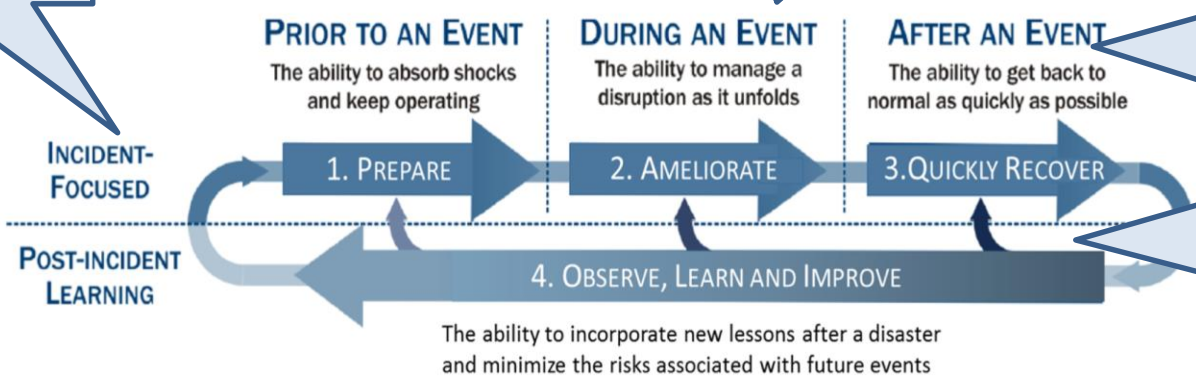


Chapter 5:Strategies for Reducing the Harmful Consequences from Loss of Grid Power

Experience suggests that a lot of the equipment designed to restore power service will not function reliably, especially in context of a long duration large area grid outage.

We need more work on advanced preparations for the use of non-traditional sources of back up.

Steps should also be taken to make it possible for those with roof top PV to obtain power during outages, and to use hybrid and fuel cell vehicles for distributed backup power

Images frim CAT; fslwfuels; Abley (1998), greentech media, GM.

Value to society

While there have been studies of the value of electric power in the context of short outages (≲ a day) we know very little about what society is willing to pay (and the value derived from) full or partial back-up service during large outages of long duration. Knowing that is a first step to more informed decision making.

Making "smart-grid" a reality

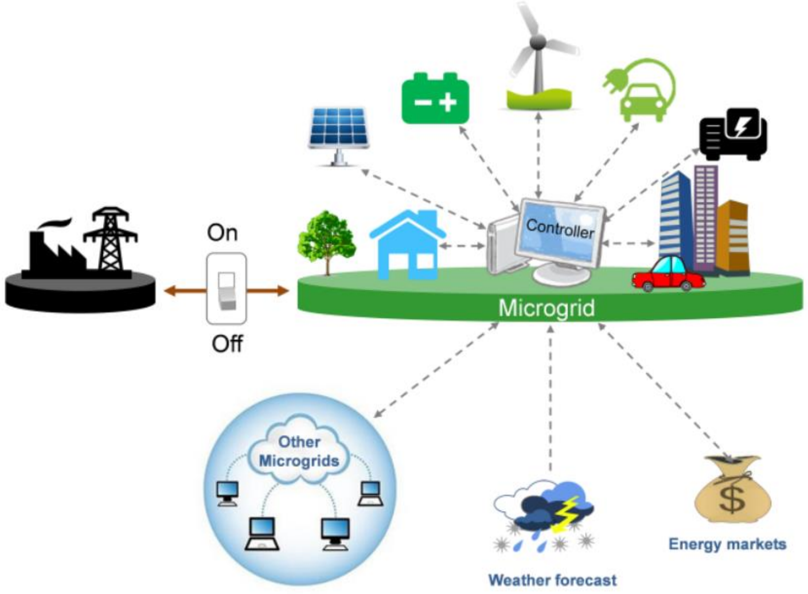
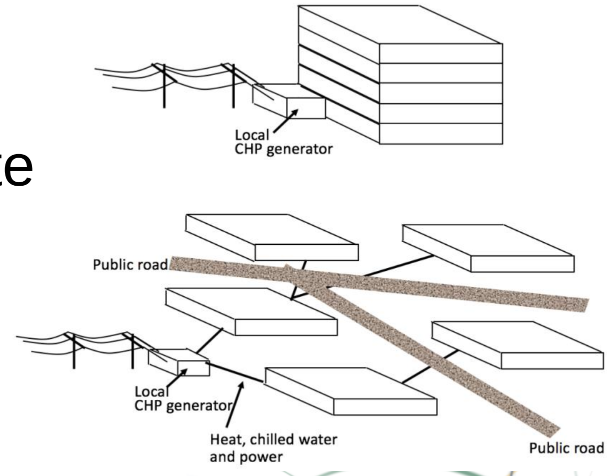


Image from Berkeley Labs

More work is needed on developing the ability for much expanded reliance on "smart grid" capabilities at and below the distribution level

- islanding
- public and private micro-grids



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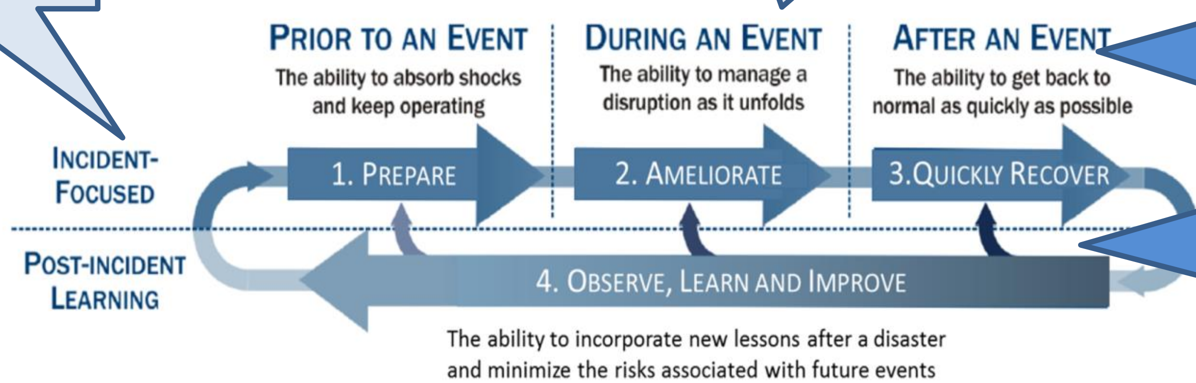

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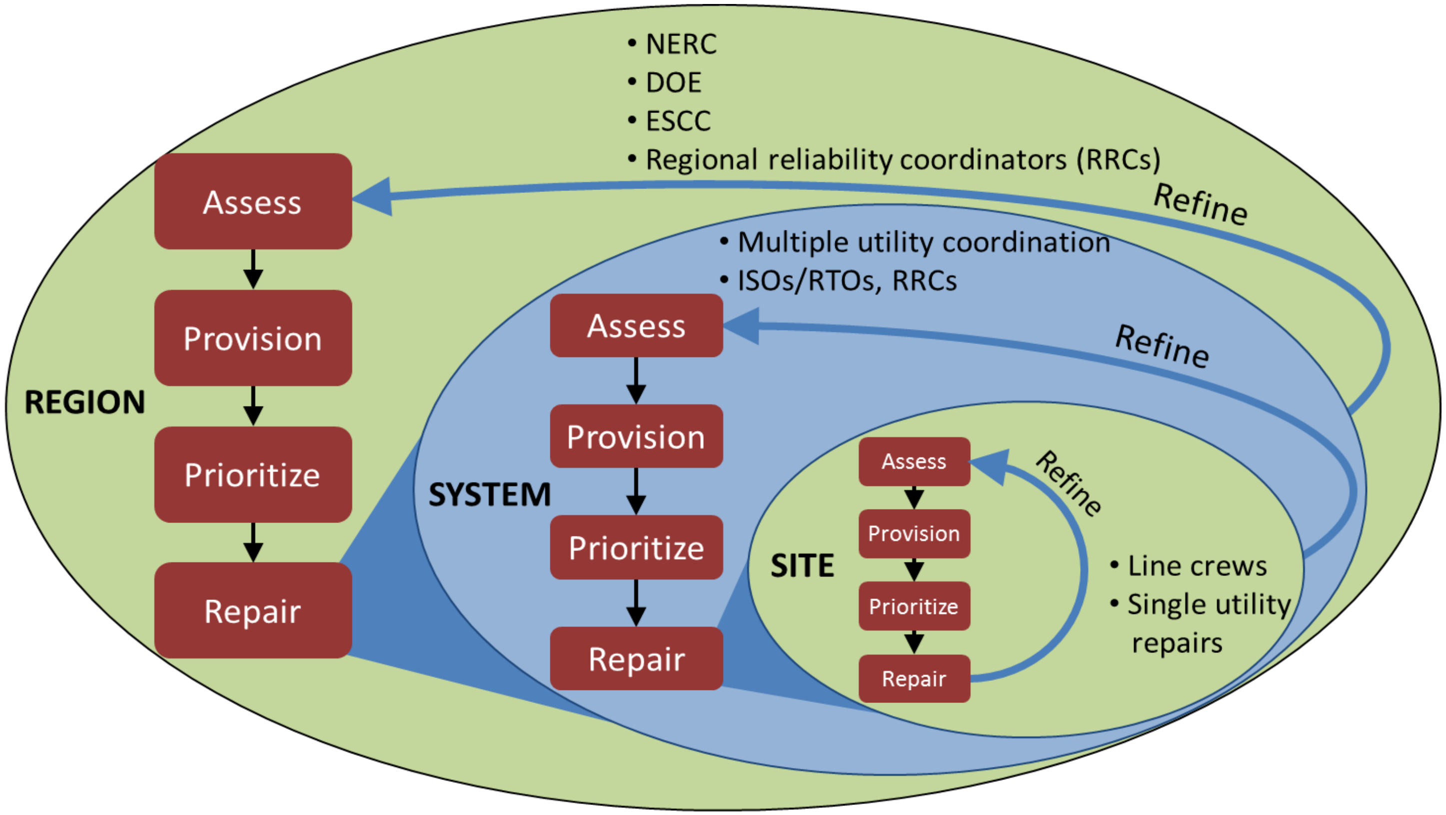
Chapter 6: Restoring Grid Function After a Major Disruption

A general model for electricity restoration:



Key Steps in the Restoration

- Plan
- Prepare
- Manage event
- Endure
- Restore
- Recover

These can be somewhat different depending on the hazard/event. But all can benefit from systematic collection and dissemination of lessons learned.

Some Recommendations from Chapter 6 for Enhancing Recovery

1. Coordinate universal credentialing for field crews
2. Collect and share lessons learned from prior events
3. Evaluate technical and contractual requirements for using DER to enhance restoration
4. Identify components for pre-emptive de-energizing
5. Seek new regulations to enable improved utilization of unmanned aerial vehicles
6. Stockpile flexible high voltage replacement transformers
7. RD&D for advanced large transformer designs
8. Better anomaly modeling/detection
9. Interagency coordination for large-scale cyber events and enhanced cyber security communication
10. Develop high performance testing environments
11. Conduct joint recovery exercises
12. Enhance investigation process

See page 6-4 to 6-38 of prepub for details

Overarching Recommendations

Emergency Preparedness Exercises that Include Multi-sector Coordination

Overarching Recommendation 1: Operators of the electricity system … should … conduct more regional emergency preparedness exercises that simulate accidental failures, physical and cyber attacks, and other impairments that result in large-scale loss of power and/or other critical infrastructure sectors …

See page S-5 of prepub for details

Implementing Available Technologies and Best Practices

Overarching Recommendation 2: Operators … should … more rapidly implement resilience-enhancing technical capabilities and operational strategies that are available today and to speed the adoption of new capabilities and strategies as they become available.

See page S-6 of prepub for details

DOE Supported Research is Critical

Overarching Recommendation 3: The Department of Energy (DOE) … should sustain and expand the substantive areas of research, development, and demonstration that are now being undertaken by the DOE's Office of Electricity Delivery and Energy Reliability and Office of Energy Efficiency and Renewable Energy, with respect to grid modernization and systems integration, with the explicit intention of improving the resilience of the U.S. power grid.

Resilient Physical Components

Overarching Recommendation 4: Through public and private means, the United States should substantially increase the resources committed to the physical components needed to ensure that critical electric infrastructure is robust and that society is able to cope when the grid fails…

See page S-7 of prepub for details

Cyber Resilience

Overarching Recommendation 5: [DOE], together with … [others] … should carry out a program of research, development, and demonstration activities to improve the security and resilience of cyber monitoring and controls systems, including the following:

- Continuous collection of diverse … data
- Fusion of sensor data with other intelligence information …
- Visualization techniques … [for] … situational awareness
- … generate real-time recommendations
- Restoration of control system and power delivery functionality …
- Creation of post-event tools for detection, analysis, and restoration …

See page S-8 of prepub for details

Envisioning Large-Scale Grid Failures

Overarching Recommendation 6: The Department of Energy and the Department of Homeland Security should jointly establish and support a "visioning" process with the objective of systematically imagining and assessing plausible large-area, long-duration grid disruptions that could have major economic, social, and other adverse consequences, focusing on those that could have impacts related to U.S. dependence on vital public infrastructures and services provided by the grid.

See page S-9 of prepub for details

National Implementation

Overarching Recommendation 7A: The Federal Energy Regulatory Commission and the North American Electric Reliability Corporation should establish small system resilience groups, informed by the work of the Department of Energy/Department of Homeland Security "visioning" process, to assess and, as needed, to mandate strategies designed to increase the resilience of the U.S. bulk electricity system.

See page S-9 of prepub for details

Regional, State, and Local Implementation

Overarching Recommendation 7B: The National Association of Regulatory Utility Commissioners should work with the National Association of State Energy Officials … to provide guidance to state regulators on how best to respond to identified local and regional power system-related vulnerabilities.

Overarching Recommendation 7C: Each state public utility commission and state energy office … should establish a standing capability to identify vulnerabilities, identify strategies to reduce local vulnerabilities, develop strategies to cover costs of needed upgrades, and help the public to become better prepared for extended outages.

See page S-10 of prepub for details

Thanks!

Download the full report and 4-page summary at: https://www.nap.edu/24836