ECEN 667
Power System Stability

Lecture 26: Electric Grid Resilience

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

Announcements

- Read Chapter 9
- Homework 6 is due on Tuesday December 3
- Final is at scheduled time here (December 9 from1pm to 3pm)

Resiliency Introduction

- Our modern society depends on a reliable electric grid with 40% of our energy transported in the form of electricity including most renewables
- Blackouts are costly, with some estimates of costs above $100 billion/year in the US.
  - Growing risk of catastrophic, long-term blackouts
  - Blackouts cannot be completely eliminated, but risk and impact can be reduced with a more resilient grid

Blackout misery

50 million affected in Northeast and beyond as power grid fails

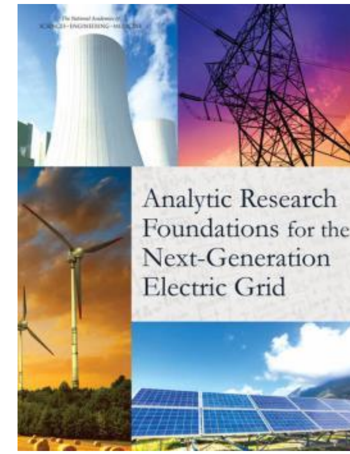
Transportation Many 'wait it out,' by air and land 4A | Scenes Moms in labor, cars stuck in car washes 5A | Impact Offices close, ATMs idle, cellphones jam 1B

Reliability and Resiliency

- Keeping the lights on involves designing and operating the electric grid with a goal of simultaneously increasing two related but ultimately different concepts: reliability and resiliency
- Reliability: suitable or fit to be relied on: dependable
  - One of the key benefits of interconnected electric grids
- Resiliency: an ability to recover from or adjust easily to misfortune or change
  - A key focus of electric grid protection systems almost from day one, but there is a more recent focus on acknowledging that large-scale blackouts cannot be totally prevented, so we must be able to bounce back

Two New National Academies Reports

- *Analytic Research Foundations for the Next-Generation Electric Grid*, 2016 [NAP 2016]
- *Enhancing the Resilience of the Nation's Electricity System*, 2017 [NAP 2017]
  - "While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future"



A Starting Point on Resilience: Will the Grid be Around?

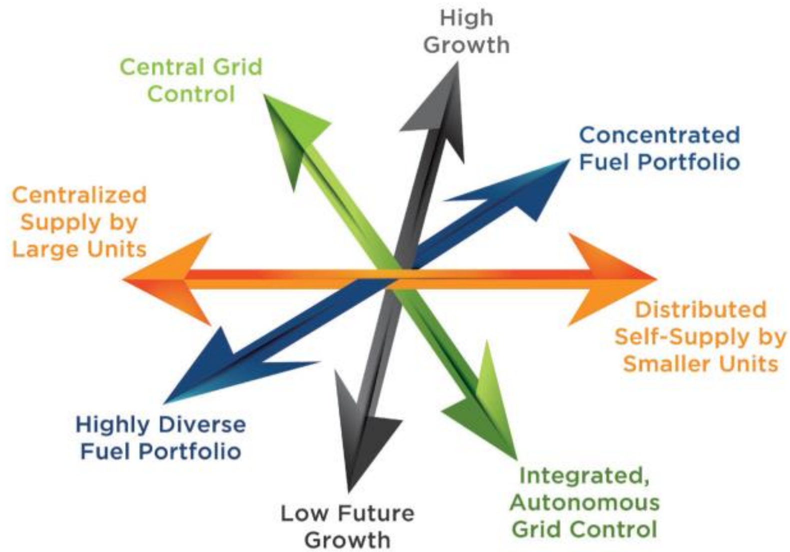
- When considering grid resilience it is important to ask, “Resilience of what?” and “Resilience to what?”
- In the NAE study group, we first discussed the question of whether the grid would gradually vanish, replaced by essentially all distributed resource
- **Finding:** “For at least the next two decades, most customers will continue to depend on the functioning of the large-scale, interconnected, tightly organized, and hierarchically structured electric grid for resilient electric service.”
- The answer to the of what question: Resilience of interconnected grids!

A Few Initial Thoughts

- The current electric grid already has a large amount of resiliency. However, we'll be addressing resiliency to what, and how to improve it
- The impact of blackouts is not linear!
  - Having 100 million people out of service can be more than tens times worse than 10 million out. A ten day blackout can be more than tens times worse than a one day blackout.
- Some quite bad things could impact the grid!
- We need to consider resiliency of the electric grid coupled with other infrastructures and ultimately society itself

How Will the System Change?

- In designing a resilient grid, it is important to look at the grid both of today, and tomorrow.
- However, in preparing for the future it is important to keep in mind the quote from NAP 2016, Chapter 5 from Winston Churchill, "It is always wise to look ahead, but difficult to look further than you can see."



- The goal is to economically "future proof" the system

Image Source: Figure 5.1, NAP 2016

Resilience To What?

- Electric grids are complex, and they are subject to a wide variety of different disturbances. Many occur regularly and some have never occurred
- The image shows the frequency of US bulk outages from 1984-2015; large events are more common than an exponential distribution would indicate

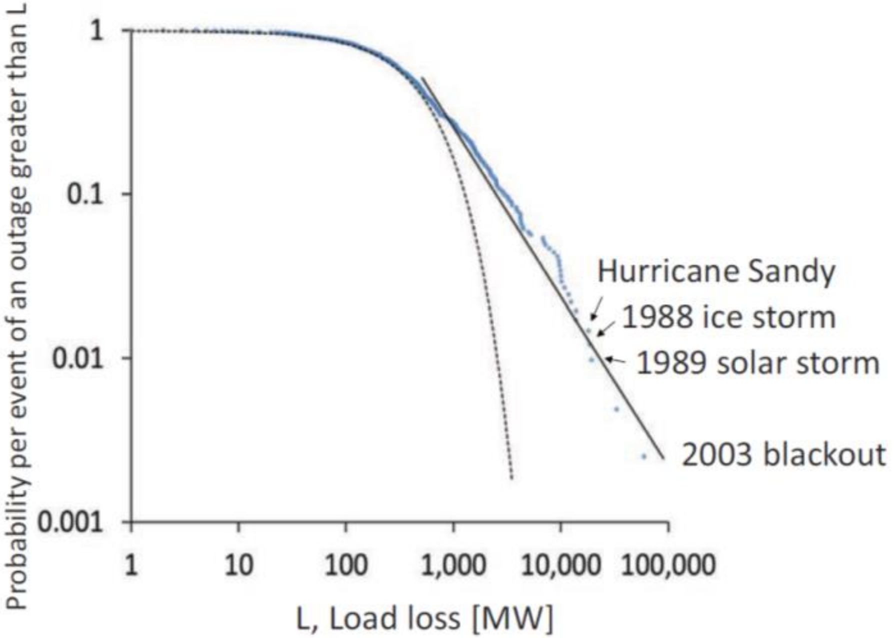
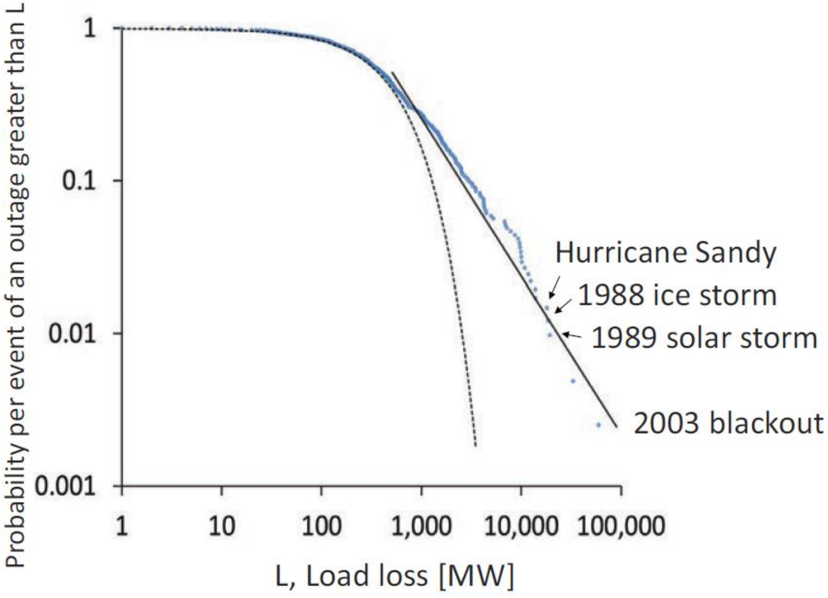


Image Source: Figure 1.1, NAP 2017

Probabilities of Rare Events

- When considering resilience to rare events, one needs to know the likelihood of the event. This requires considering probability distribution functions
- The image shows the frequency of US bulk outages from 1984-2015; large events are more common than an exponential distribution would indicate



Note the log-log scale

Image Source: Figure 1.1, NAP 2017

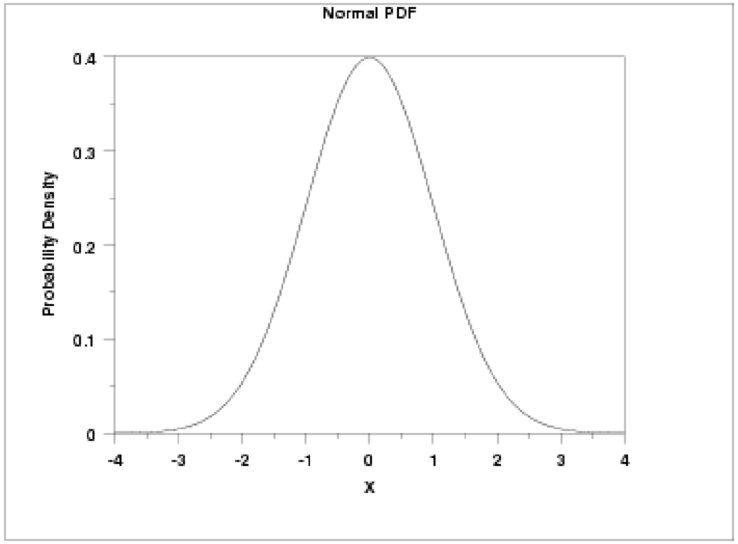
Probability Distribution Functions

- A probability distribution function (pdf) tells the likelihood of an event
- Most people are familiar with Gaussian (or normal) pdfs (i.e., the bell shaped curve)

$$pdf(x) = f(x) = \frac{e^{-(x-\mu)^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}}$$

u is the mean

σ is the standard deviation

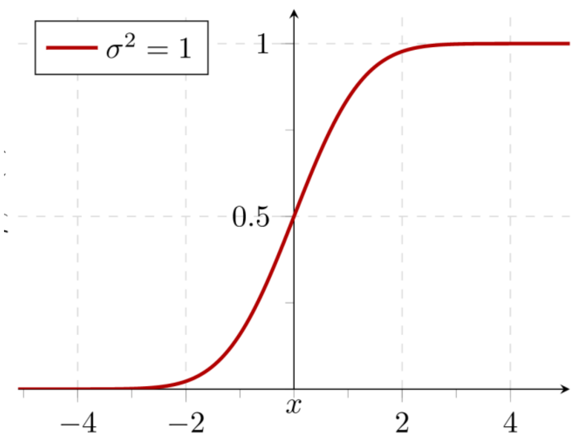


- 68% within one standard deviation, 99.7 within three

Image Source: www.itl.nist.gov/div898/handbook/eda/section3/eda3661.htm

Gaussian PDFs and Cumulative Distribution Function

- A Gaussian pdf has very few significant outliers
  - It has short tails
- The cumulative distribution function (cdf) tells the likelihood a value is less than a specified number of standard deviations
  - It is found by integrating the pdf
- Gaussian pdfs are useful for many things, but not in assessing rare events



Previous outage image is a cdf, integrated from the right

Image Source: upload.wikimedia.org/wikipedia/commons/1/15/Normal-distribution-cumulative-density-function.svg

Exponential PDFs

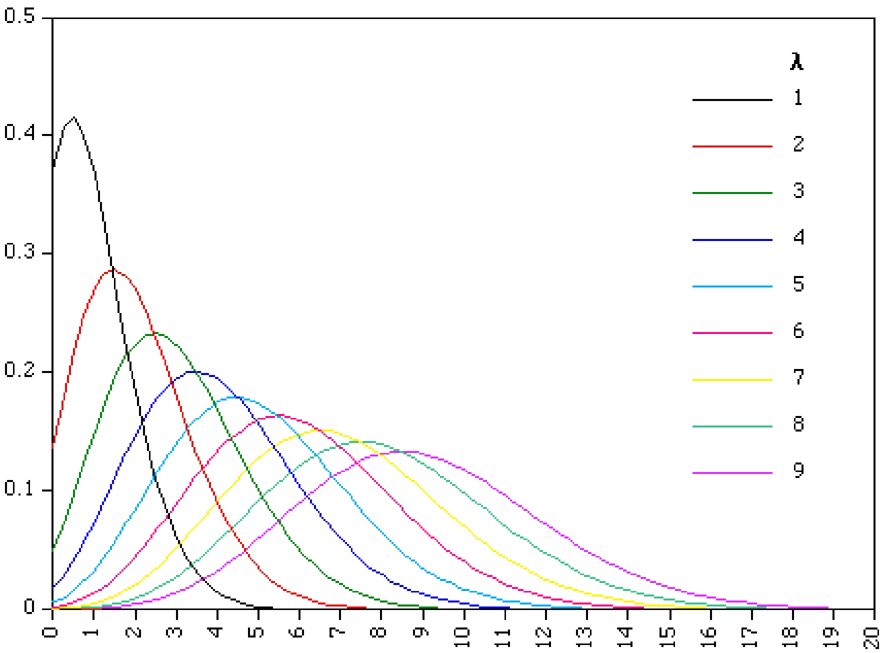
- An exponential pdf is often used to determine the amount of time until a event occurs. Uused when
  - Events occur with a known average, but the exact time between events is random
  - Events are independent of each other, but two events cannot occur at the same time
  - This is known as a Poisson Process.
  - It often applies to time but can be used in other situations
  - Many events have this characteristic. Such as calls to a call center, radioactive decay of atoms, webserver requests, trees per acre
  - It has much longer tails

Exponential PDFs

- Such an exponential pdf has the form

$$pdf(x) = f(x) = \lambda e^{-\lambda x}$$

λ is the decay parameter



- A cumulative density function can be found by integrating this pdf
- It would seem to be a useful approach for determining the risk of blackouts, but it does not match the data

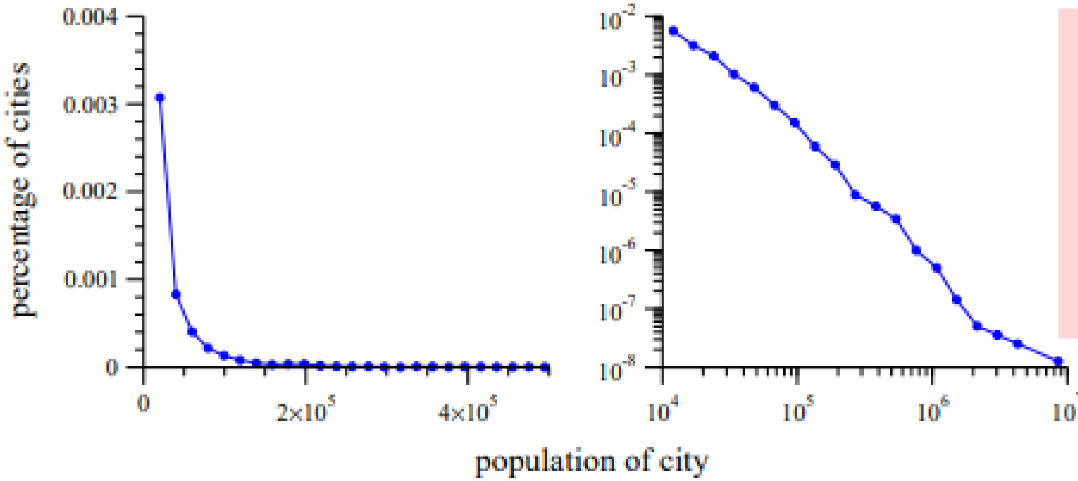
Image Source: deepai.org/machine-learning-glossary-and-terms/poisson-distribution

Power Law Distributions

- A power law pdf has a form
  $$pdf(x) = f(x) = Cx^{-\alpha}$$
  - This is often known as a Pareto distribution
- When plotted on a log-log scale the power law pdfs should give a straight line (with a negative slope)
- Many common things seem to follow a power law over a wide range of values. Examples include
  - Size of cities
  - Income
  - Earthquakes
  - Blackout sizes

Power Law Distributions

- The below image shows the pdf for cities by size; there are many small cities, fewer large cities



The well known 80-20 rule is a power law with an α of 2.16

- A characteristic of power laws is their scale invariance

$$f(\mathrm{b}\,x) = C\left(bx\right)^{-\alpha} = Cb^{-\alpha}x^{-\alpha}$$

Image Source: www-personal.umich.edu/~mejn/courses/2006/cmplxsys899/powerlaws.pdf

Power Law Distributions

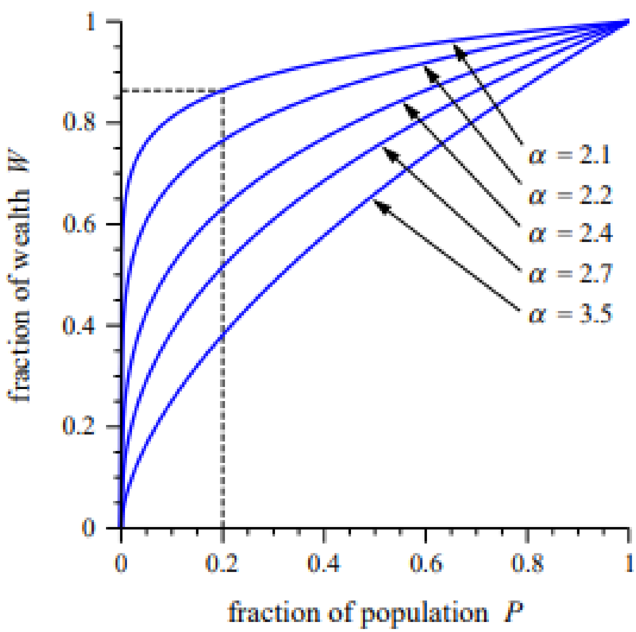
- Power law distributions have a well defined average only if α is > 2
- The first moment of a power law distribution is

$$\int xf(x)\,\mathrm{dx} = \int \mathrm{xCx}^{-\alpha}\mathrm{dx} = \int \mathrm{Cx}^{-\alpha+1}\mathrm{dx} = \frac{\mathrm{Cx}^{-\alpha+2}}{-\alpha+2} + \mathrm{Constant}$$

  - For the city example, this tells the number of people in the cities for various sizes
  - For blackouts it would tell the number of MWs lost by the various sized outages
- For α ≤ 2 this value is undefined, meaning the tail [rare events] dominates (for cities it is estimated to be about 2.3)

Power Law Distributions

- When considering a phenomena, it is useful to known 1) does it follow a power law, 2) if so over what range, and 3) what is it's α exponent



	quantity	minimum x_{min}	exponent α
(a)	frequency of use of words	1	2.20(1)
(b)	number of citations to papers	100	3.04(2)
(c)	number of hits on web sites	1	2.40(1)
(d)	copies of books sold in the US	2 000 000	3.51(16)
(e)	telephone calls received	10	2.22(1)
(f)	magnitude of earthquakes	3.8	3.04(4)
(g)	diameter of moon craters	0.01	3.14(5)
(h)	intensity of solar flares	200	1.83(2)
(i)	intensity of wars	3	1.80(9)
(j)	net worth of Americans	\$600m	2.09(4)
(k)	frequency of family names	10 000	1.94(1)
(l)	population of US cities	40 000	2.30(5)

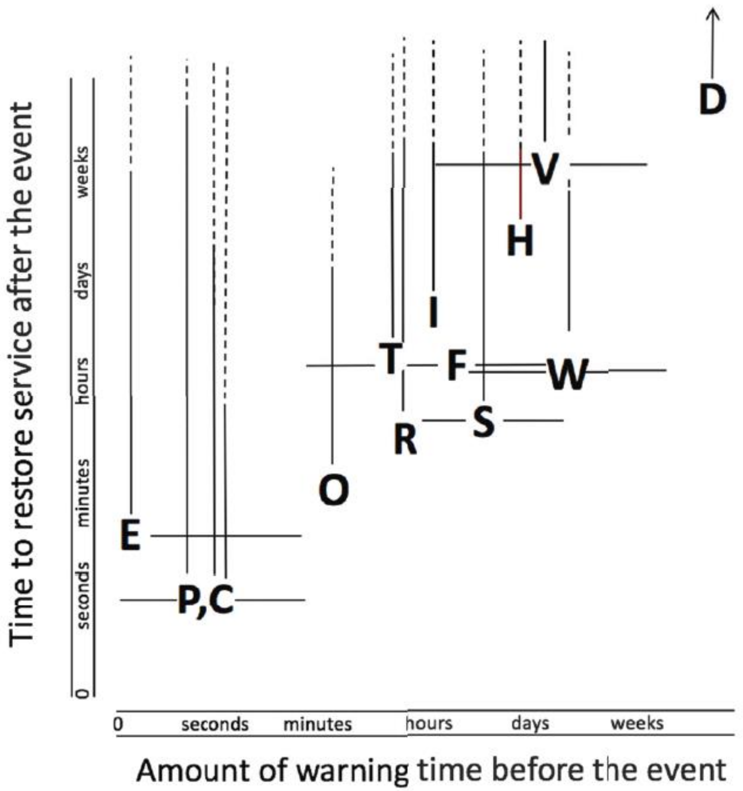
TABLE I Parameters for the distributions shown in Fig. 4. The labels on the left refer to the panels in the figure. Exponent values were calculated using the maximum likelihood method of Eq. (5) and Appendix B, except for the moon craters (g), for which only cumulative data were available. For this case the exponent quoted is from a simple least-squares fit and should be treated with caution. Numbers in parentheses give the standard error on the trailing figures.

Images Source: www-personal.umich.edu/~mejn/courses/2006/cmplxsys899/powerlaws.pdf

Application to Grid Resiliency

- Blackouts have been shown to have a power law distribution, with an α of close to the critical value of 2
  - This provides justification for devoting a substantial amount of resources to minimizing the likelihood of large events
- Grid resiliency needs to consider rare events, but some of these events have power law distributions
  - Geomagnetic disturbance size, earthquakes
  - However, some do not (EMPs, physical and/or cyber attacks)

Some Electric Grid Risks



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 operations error
P = physical attack
R = regional storms and tornados
S = space weather
T = tsunami
V = volcanic events
W= wild fire

FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

The Real Cause of Most Blackouts!

Photo source: http://save-the-squirrels.com

But mostly only the small ones in the distribution system

And Sometimes It's the Trees

Same Trees After "Trimming"

Resilience Event Size

- Grid resilience events can range from continental down to local

Most, but not all, events would likely be contained within a single electrical interconnect

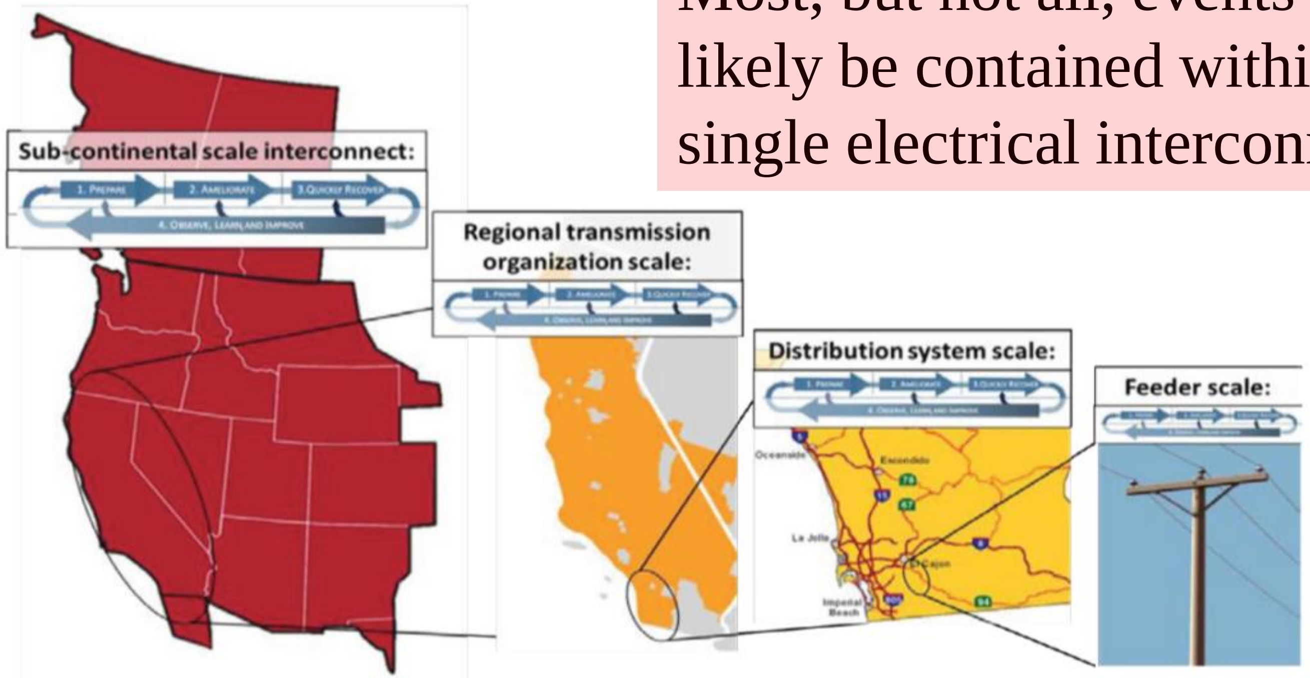


FIGURE 1.2 (A) A four-stage process of resilience based on a framing by Flynn (2008) and as illustrated by NIAC (2010); (B) In the case of the hierarchically organized power system, these concepts apply at several different levels of the system with different specific actions and lessons; and (C) Illustration of scales of resilience processes. SOURCE: Modified with permission from NIAC (2010).

Image Source: Figure 1.2, NAP 2017

Specific Risks Are Often Geographic: Example of Earthquake Risk

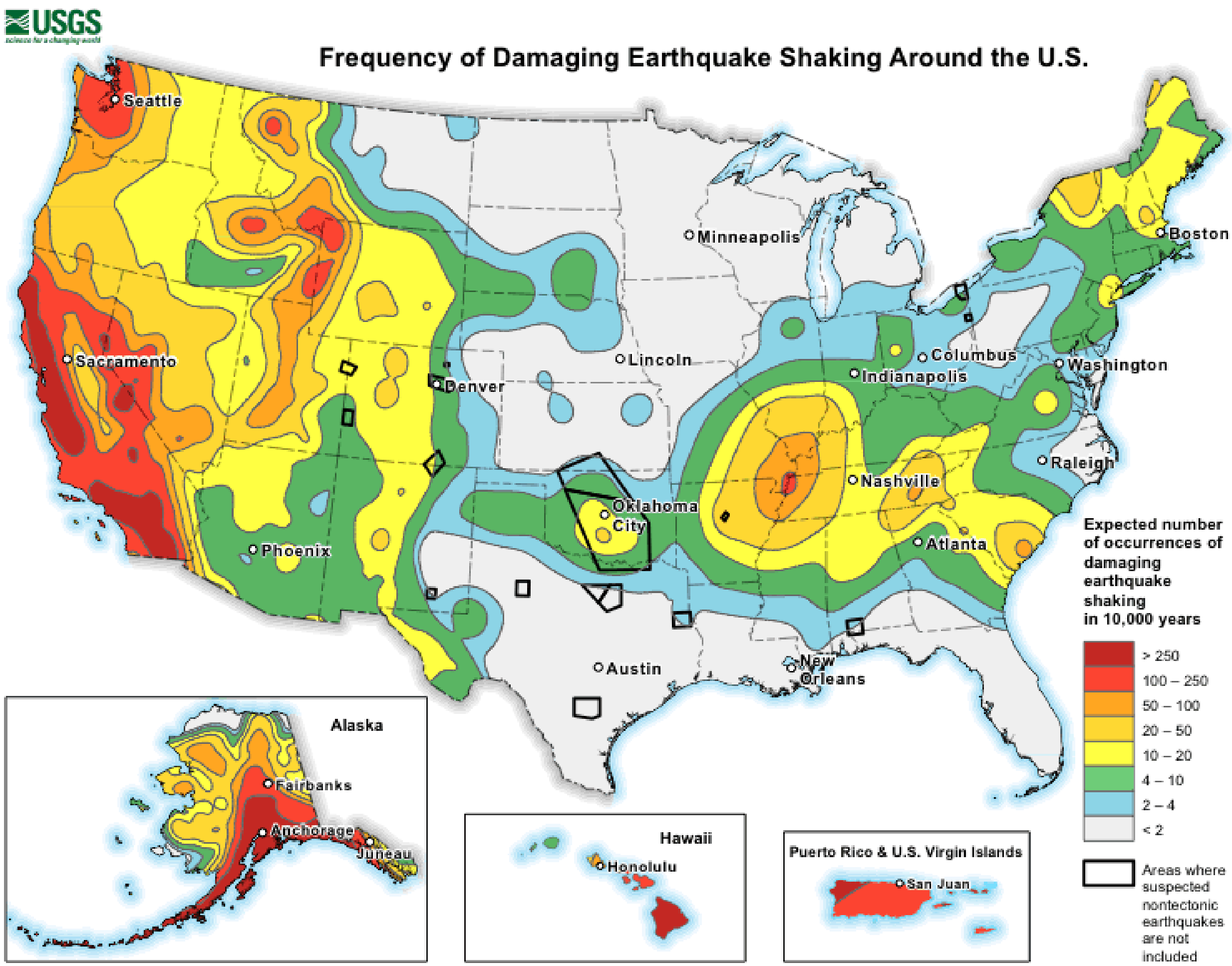
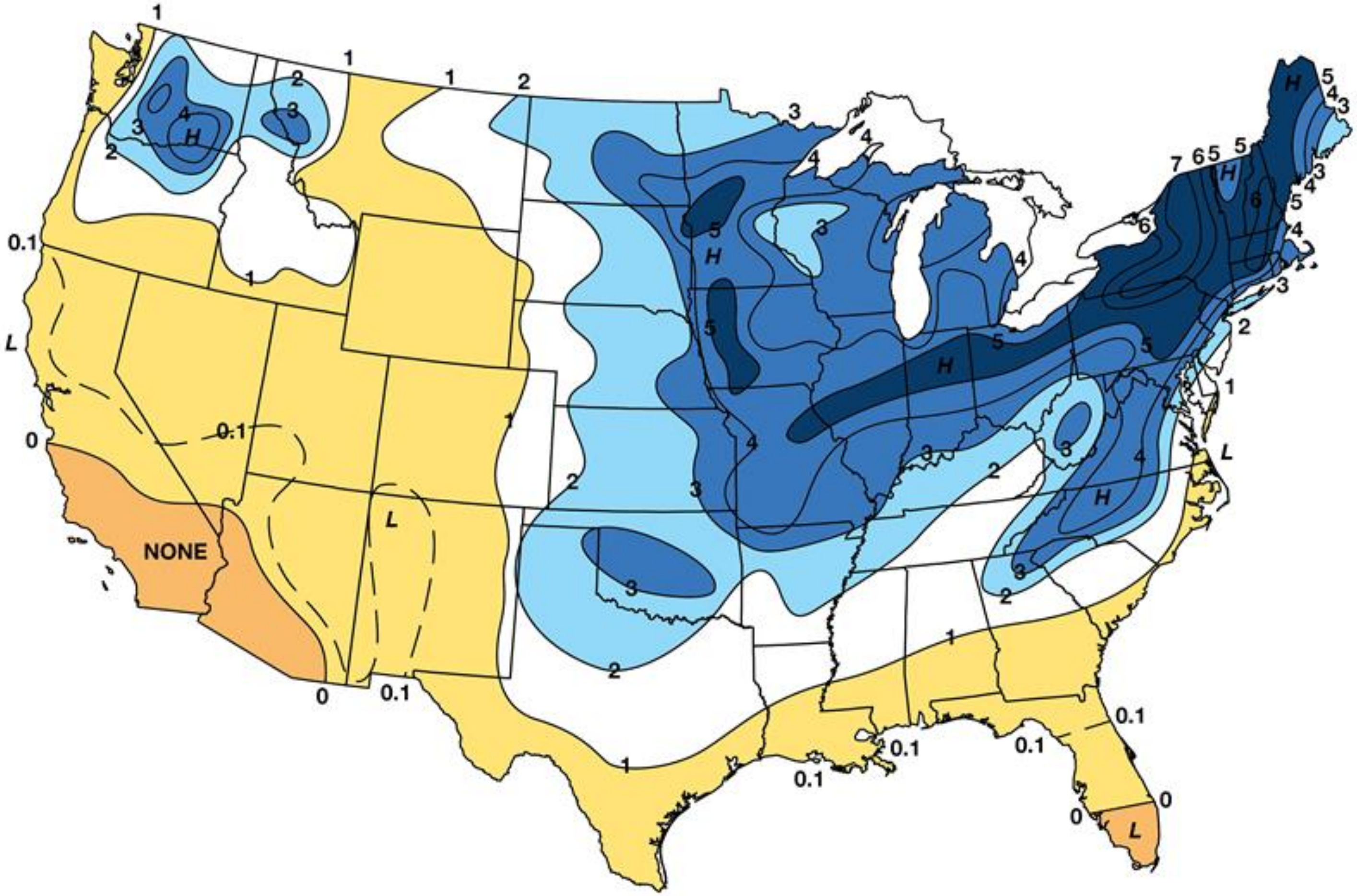


Image Source: earthquake.usgs.gov/hazards/learn/

Specific Risks Are Often Geographic: Example of Ice Storms



The average annual number of days with freezing rain, based on 1948-2000 data. *From Changnon and Karl, 2003.*

[Image Source: mrcc.illinois.edu/living_wx/icestorms/index.html](mrcc.illinois.edu/living_wx/icestorms/index.html)

High-Impact, Low-Frequency Events

- In order to enhance electric grid resiliency we need to consider the almost unthinkable events
- These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days

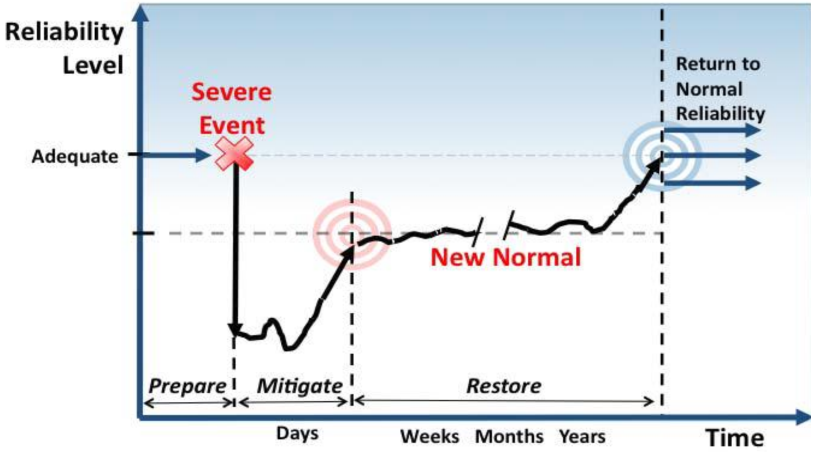


Image Source: NERC, 2012

  - Large-scale, potentially long duration blackouts
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

Major Considerations with Resiliency

- Understanding, and ultimately enhancing resiliency, requires consideration during three periods
  - Prior to an event
  - During an event
  - After an event
- All three require planning ahead of time and flexibility as events unfold

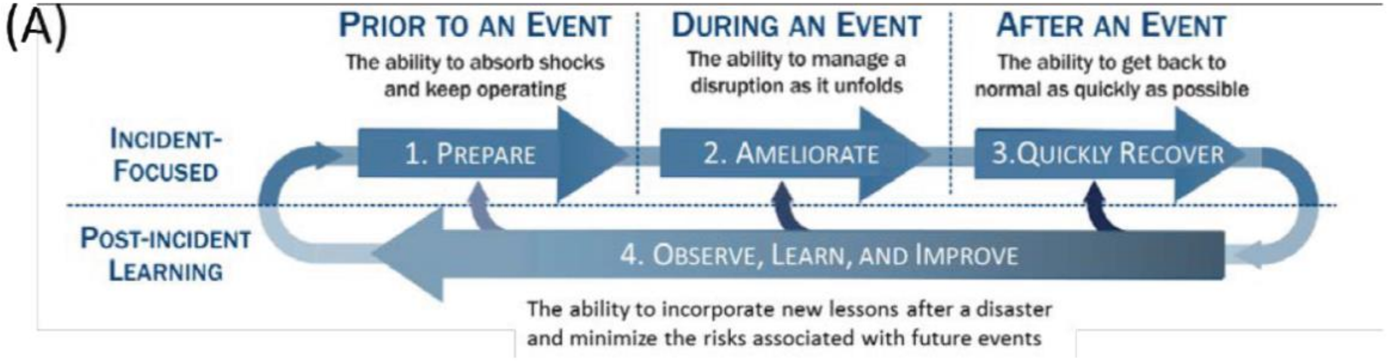


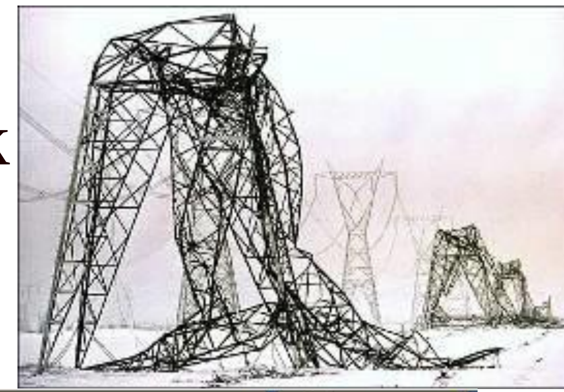
Image Source: Figure 1.2a, NAS, 2017

Challenges

- An all hazards approach to considering resiliency is crucial, but there is no a "one-size-fits-all" solution
- Identifying particular strategies to improve resiliency, to at least some degree, is relatively easy
- The challenge is developing appropriate priorities for actions, and determining the appropriate political and organizational support to make it happen
  - Just expecting electric utilities to make the investments necessary, while many are losing customer revenue to self-generation, might not be realistic

Examples of Larger-Scale or Long Duration Outages

- Quebec geomagnetic disturbance blackout of 1989
- Auckland, NZ 1998 five week blackout due to cable failures
- Northeast ice storm of 1998: A week long ice storm that resulted in more than three inches of ice on high voltage transmission lines, causing the collapse of 770 transmission towers and the replacement of 26,000 distribution poles



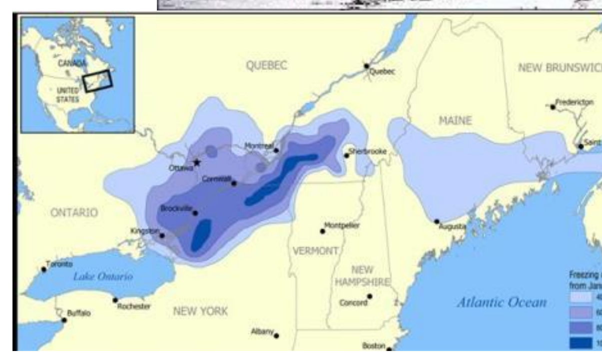


Image Source: https://www.rcinet.ca/en/2017/01/05/canada-history-jan-5-1998-the-deadly-ice-storm-of-the-century/

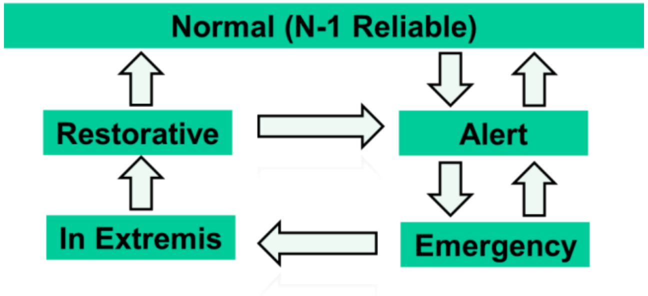
Examples of Larger-Scale or Long Duration Outages, cont.

- Northeast blackout from August 14, 2003
- Hurricane Katrina (2005) with loss of service to 2.7 million customers, with 250,000 still out after 4 weeks
- Superstorm Sandy (2012) with more than 8 million customers out, and about 10% still out after ten days
- Cyber attack on Ukrainian Electric Grid (2015)
- Hurricane Maria (2017) in Puerto Rico, with essentially a total loss of the grid

Image Source: IEEE Spectrum, P. Fairley, "Why Solar Microgrids May Fall Short in Replacing the Caribbean's Devastated Power Systems", October 2017

The Grid Needs to Be Resilient to Lots of Disturbances on Different Time Frames

- Events short and long-term
  - Lightning strikes can usually be cleared within seconds
  - But ice, tornados and hurricanes can bring large-scale damage over long timer periods
- Need to consider all operating conditions



Images from T. Rolstad and B.Don Russell

Image Derived From L.H. Fink and K. Carlsen, Operating under stress and strain, *IEEE Spectrum*, March 1978, pp. 48-53

Electric Grid Time Frames

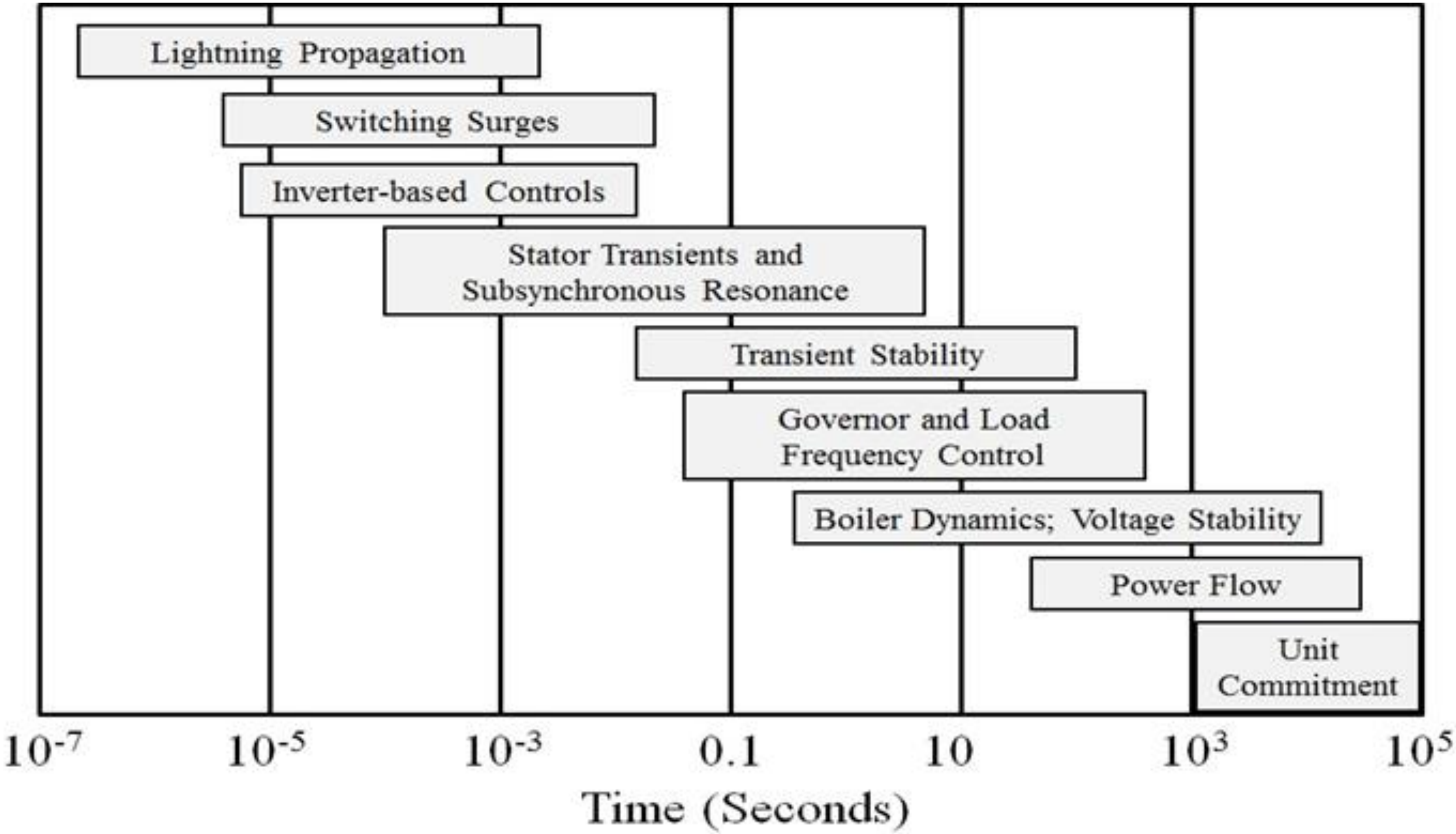


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

Developing Resiliency Metrics

- Currently there are a wide number of metrics to assess reliability. Examples include
  - SAIFI: "System Average Interruption Frequency" tells the number of times a customer is interrupted in a time period
  - SAIDI: "System Average Interruption Duration Index" tells the average interruption duration for customers served during a specific time period
- These reliability metrics can neglect major event days, which are events beyond the design and operational limits of a utility
- Reliability metrics provide only limited insight about resilience

US SAIDI for Year 2015 (Without Considering Major Events)

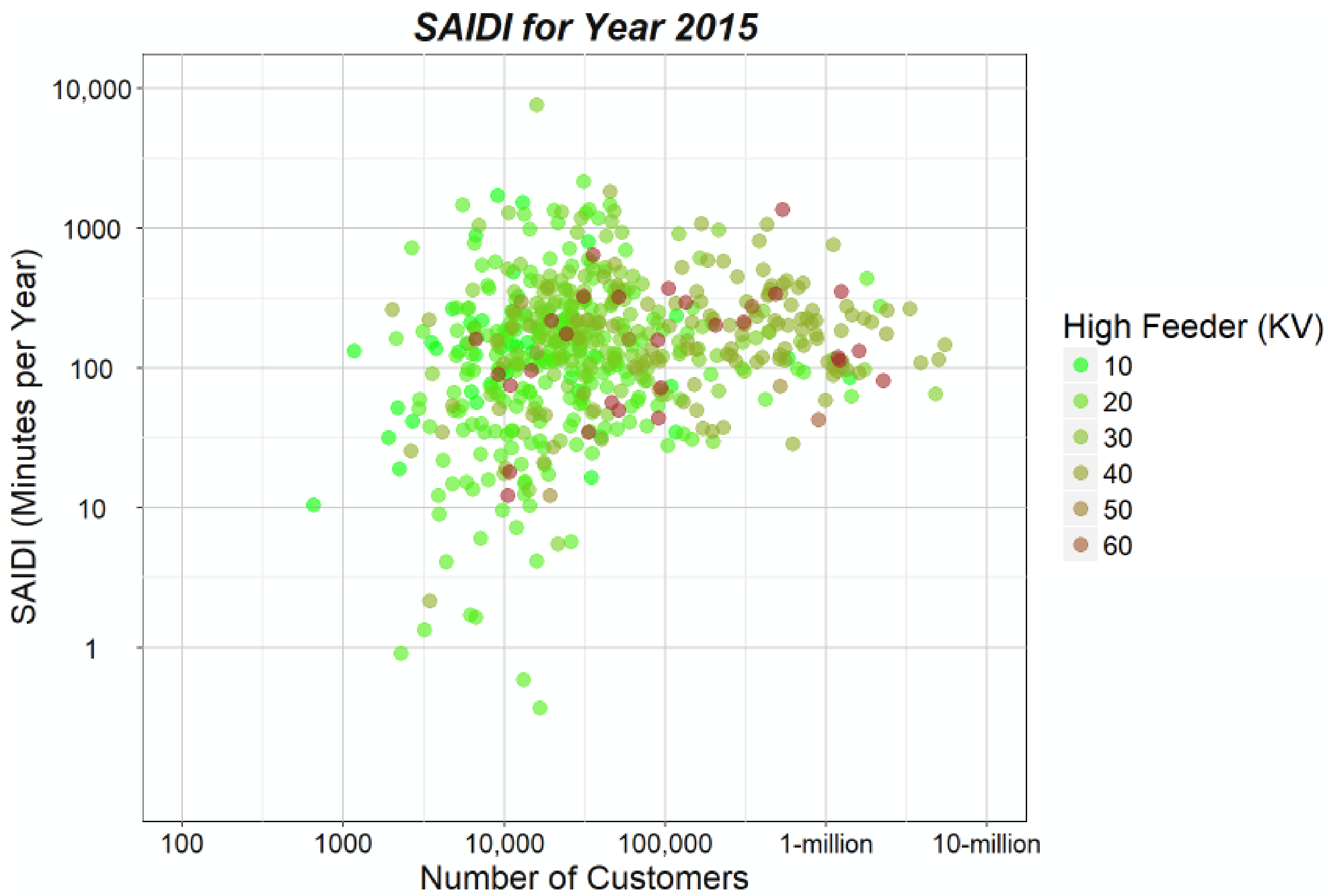


Image Source: rpubs.com/marcelMerchat/304554

Developing Resiliency Metrics

- True resiliency metrics are much less developed, partially because there is a lack of history with large-area, long-duration outages
- A number have been proposed, with one example "Resilience Metrics for the Electric Power System: A Performance-Based Approach" from Sandia, 2017

Figure 1. The Resilience Analysis Process.

Image Source: Figure 1 of the 2017 Sandia Report

Economic Valuation of Resilience

- While certainly challenging, metrics are needed to help determine the value of resilience to society
  - If we need to improve resiliency, someone needs to pay
- This is becoming a more challenging problem as more customers provide self-generation
  - Is the ability of some customers to self generate, at least for a period of time, a net gain to the grid's resiliency? How does one assess the resiliency of their systems?
- Given that both reliability and resilience are often desired, their needs to be a co-optimization of their benefits.

Challenges with Resiliency Research

- Need for realistic electric grid models and data
- In many places worldwide access to data about the actual power grid is restricted because of needs for confidentiality (e.g., in US critical energy infrastructure [CEII])
  - Data and models are sometimes available through NDAs, but ability to publish and distribute results is limited
- To do effective research, and to drive innovation, researchers need access to common, realistic grid models and data sets
  - Scientific principle of reproducibility of results

Challenges with Resiliency Research

- Even with NDAs, getting full model data is difficult. For example power flow models are the easiest, then transient stability, then remedial action schemes
- Because many resiliency scenarios are coupled with other systems (e.g., weather, earthquakes, GMDs, EMPS, cyber) there is a need for electric grid geographic coordinates
  - Up until recently accurate substation latitude and longitude data wasn't widely available
- A partial solution is to use the synthetic grids introduced early in the semester; the highly detailed ones allow coupling with other infrastructures

Challenges with Resiliency Research

- Even when using synthetic grids, resiliency research can be sensitive
  - Some severe electric grid risks are human caused
  - Assessing the resiliency of the grids to such events could requiring determining effective ways to harm the grid (to use a football analogy, to play could defense you need to know that the offense can do)
- The potential exists that some scenarios could be discovered that don't have effective remedies

Strategies to Prepare For and Mitigate Large- Area, Long-Duration Blackouts

- While events may vary, there a number of broad approaches that can be used to help improve resilience

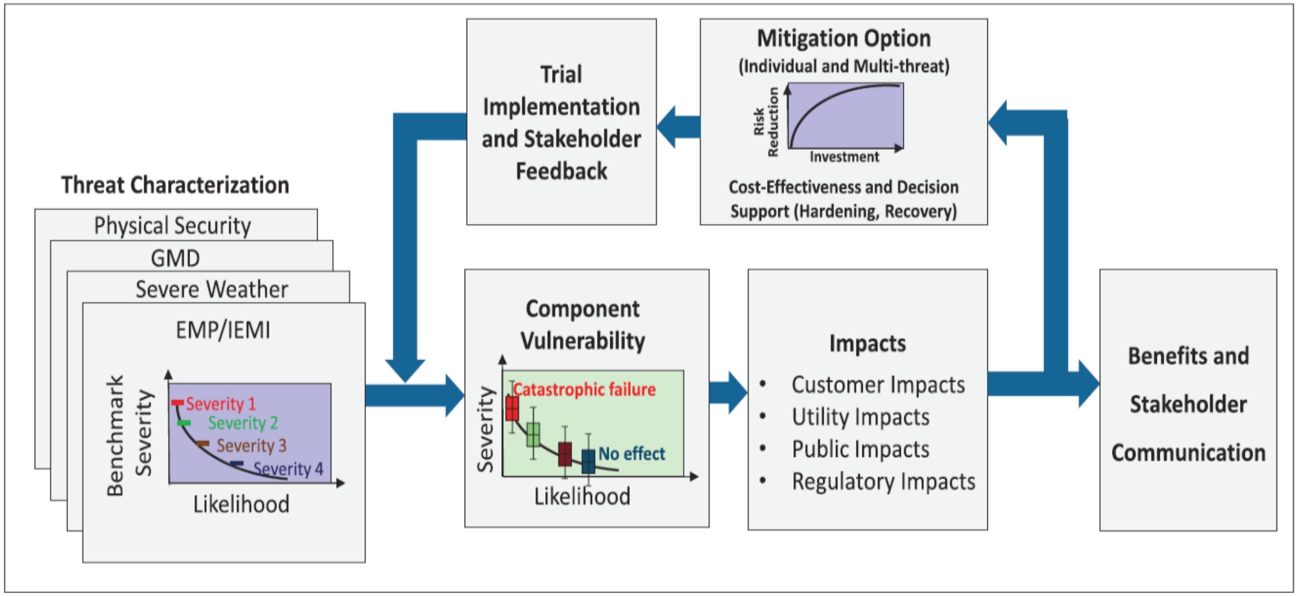


FIGURE 4.1 The process of considering and mitigating individual component vulnerability based on cost-performance optimization.
NOTE: GMD, geomagnetic disturbance; EMP, electromagnetic pulse; IEMI, intentional electromagnetic interference.
SOURCE: Courtesy of the Electric Power Research Institute. Graphic reproduced by permission from the Electric Power Research Institute from presentation by Rich Lordan to the NCSL-NARUC Energy Risk & Critical Infrastructure Protection Workshop, Transmission Resiliency & Security: Response to High Impact Low Frequency Threats. EPRI, Palo Alto, Calif.: 2016.

Image Source: Figure 4.1, NAS, 2017

Component Hardening, Physical Security

- Electric grids are comprised of components, and resiliency can be enhanced by hardening particularly vulnerable components
  - Transmission lines in likely icing location, undergrounding some lines, transformers with better handling of geomagnetically induced currents (GICs), water protection
  - This needs to be done considering the cost versus benefit
  - Vegetation management should also be considered
- Physical security is an area of increased concern, with unmanned aerial vehicles being a fast rising threat

Distribution System Automation

- Distribution systems have traditionally been radial, with little ability for dynamic reconfiguration
- This is rapidly changing, with growing use of distribution automation
- A finding of the NAS 2017 was, "While many distribution automation technologies are available that would enhance system resilience, their cost of deployment remains a barrier, particularly in light of challenges in monetizing the benefits of such installations."

Distributed Energy Resources (DERs)

- DERs are devices in the distribution system that can provide power
  - This could be isolated backup power, power only when grid connected, or the ability to function as an autonomous microgrid
- DERs can be used to delay or eliminate additions to the bulk grid
- The value of DERs is enhanced if 1) there is some potential for grid control, and 2) they have the ability to operate isolated from the grid [such as solar PV with battery storage]
- Fault ride through capability is of growing importance

Enhancing Bulk Grid Simulations to Handle HILF Scenarios

- The stressed operation associated with the high impact, low frequency events presents modeling challenges
- Luckily, over the last several years the software is being enhanced to deal with these situations
  - My next presentation goes in-depth on geomagnetic disturbance (GMD) and high altitude electromagnetic pulse (HEMP) modeling
- There is also a need to consider high voltage transmission system design that lessens the likelihood of cascading outages

Adaptive Islanding

- One promising resiliency technique is to design interconnected grids to split (island)
  - This is known as controlled islanding and can be enhanced to be adaptive islanding
  - A distribution system example is a microgrid
- The islands need to be chosen so they have sufficient generation to match load
- Often control is still centralized
- A more involved islanding issue is to setup the grid so smaller parts can function with full autonomy

Final Thoughts: Designing for Societal Resiliency

- The grid will likely fail, so society needs to be ready
- The grid is designed to be black-started
- Chapter 5 of NAS 2017 covers strategies for reducing the harmful consequences of loss of grid power
  - The gist is to have sufficient backup power and fuel sources, with electric vehicles a potential source of energy
- Chapter 6 covers grid restoration
  - Some useful books on restoration (and other topics) are available for free download at https://www.eiscouncil.org/Library.aspx
- Individuals should be prepared for potentially long-term power outages