Enhancing the Resilience and Sustainability of Large-Scale Electric Grids

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TEXAS A&M UNIVERSITY

Our Energy Future Could be Quite Bright!

- My professional goal is to help in the development of a sustainable and resilient electric infrastructure for the entire world.
- Electric grids are in a time of rapid transition, with lots of positive developments including the addition of large amounts of renewable generation, and lots of good engineering challenges
- I think our electric energy future could be quite bright, and it is a great time for students entering the field!!
- There are lots of concerns with this transition, particularly in dealing with electric grid resilience

Overview

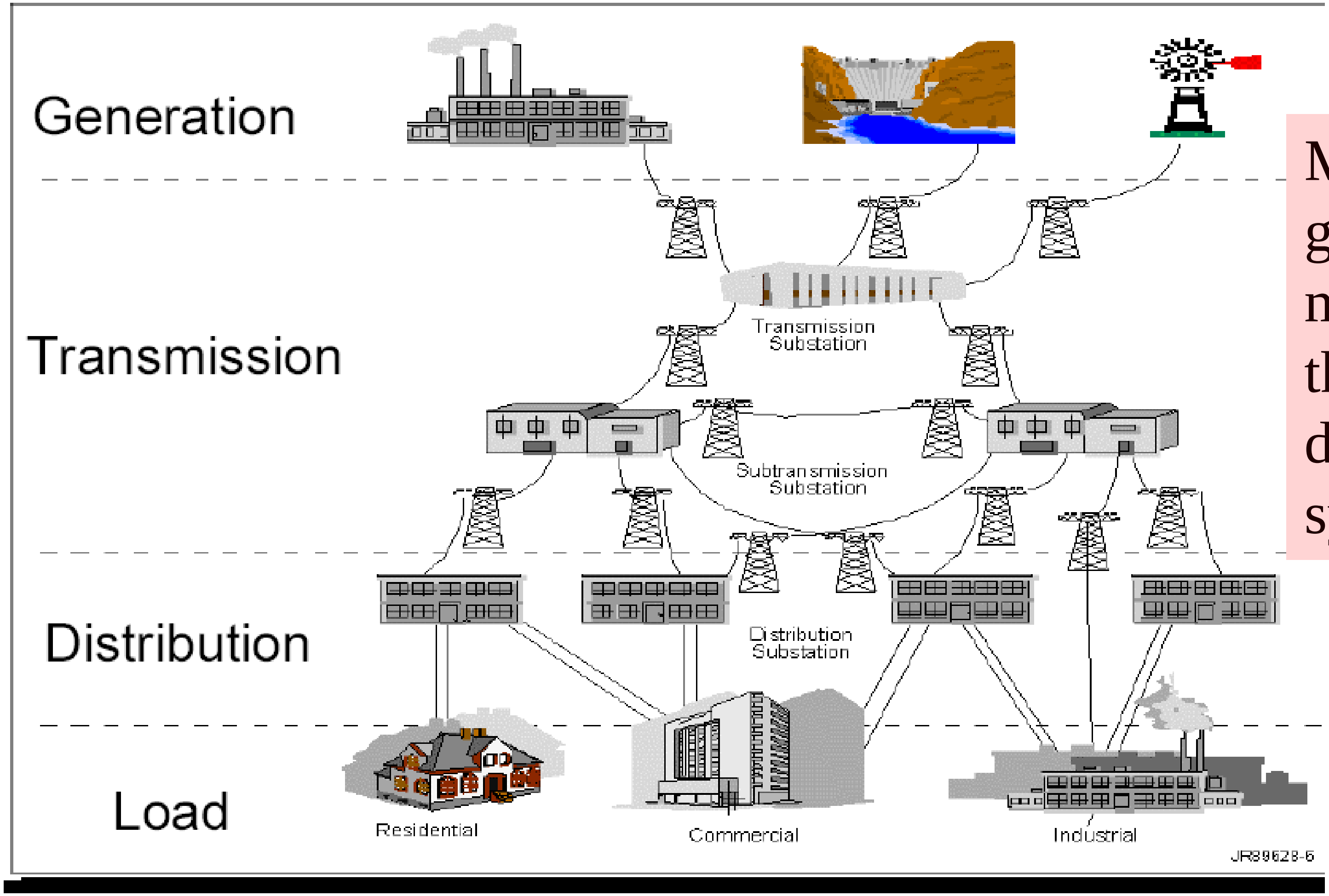
- Interconnected electric grids are going to play a key role in the development of a sustainable energy future
  - In the North America about 40% of our energy transported as electricity, a value that should be increasing as transportation becomes more electrified
- In order to achieve this vision of a bright future, we need to increase the reliability and resiliency of the electric grid as we become more sustainable

My favorite 8/14/03 blackout hoax picture

Rare Events

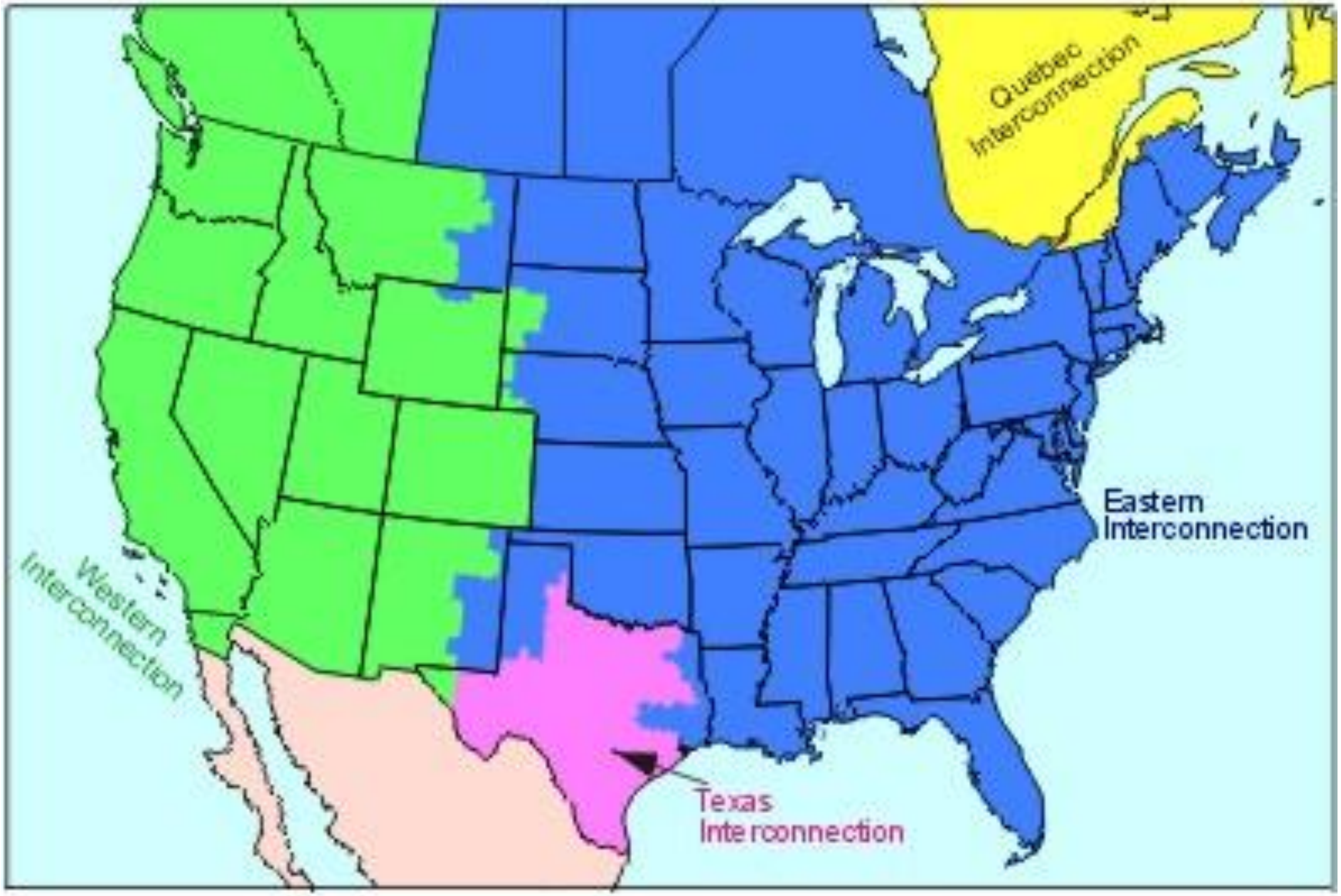
- A good part of resiliency is resilience to rare events with a large impact, which are rare but collectively not as rare as we often think
  - I got interested in this area partially through reading the book, *The Black Swan: Second Edition: The Impact of the Highly Improbable* by Taleb (2010)
- Rare events both affect us as individuals, and as a society; focus here is on large-scale societal events affecting the electric grid
- We need to diligently study these events with a goal to reduce their impact and/or likelihood in a fiscally responsible manner

Electric Grid Basics



More generation is moving into the distribution system;

North America Grid Interconnections



All Three US Grids Are 60 Hz, But Are Not Usually At the Same Value

- Images show the frequency during the 2020 Super Bowl

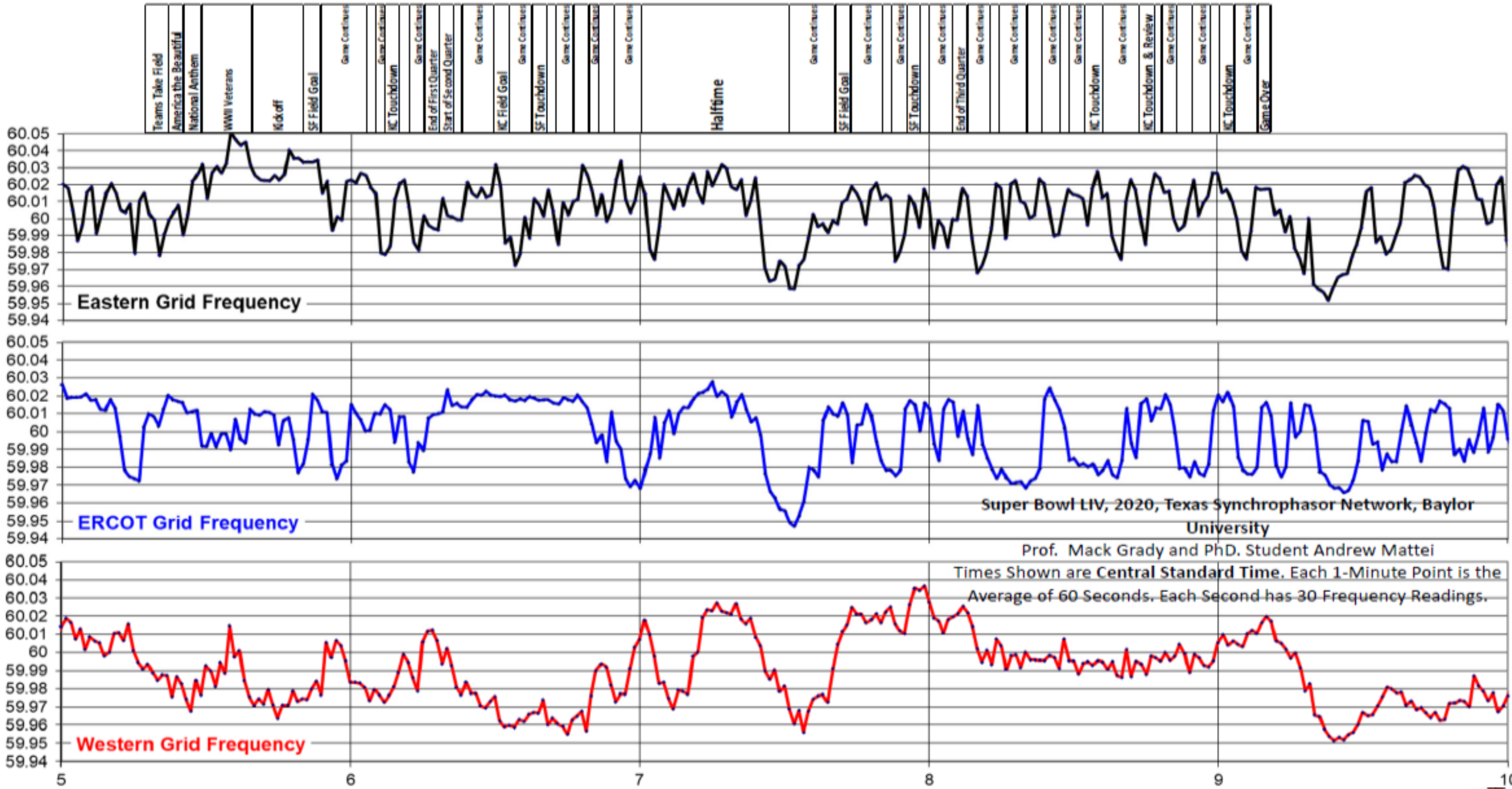
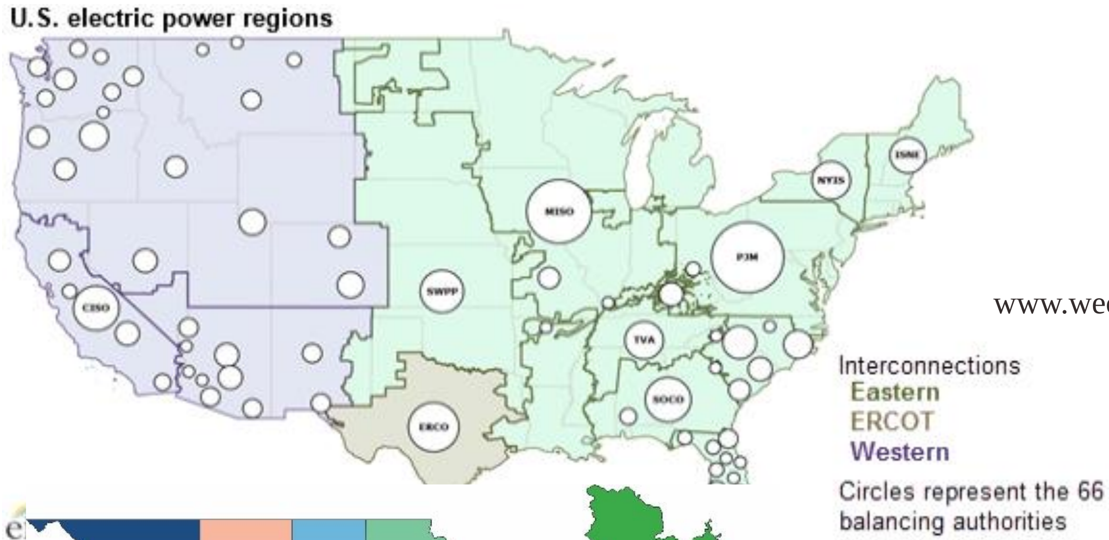
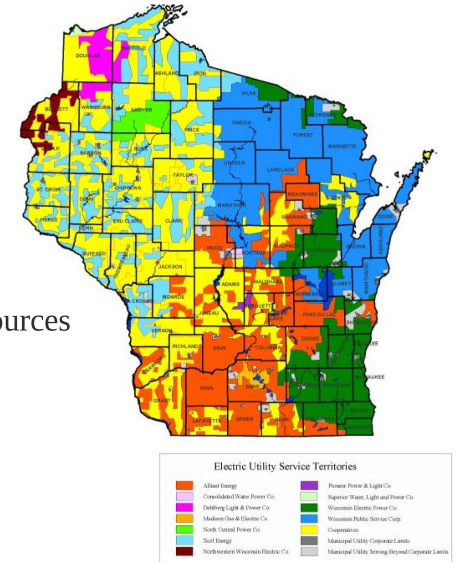


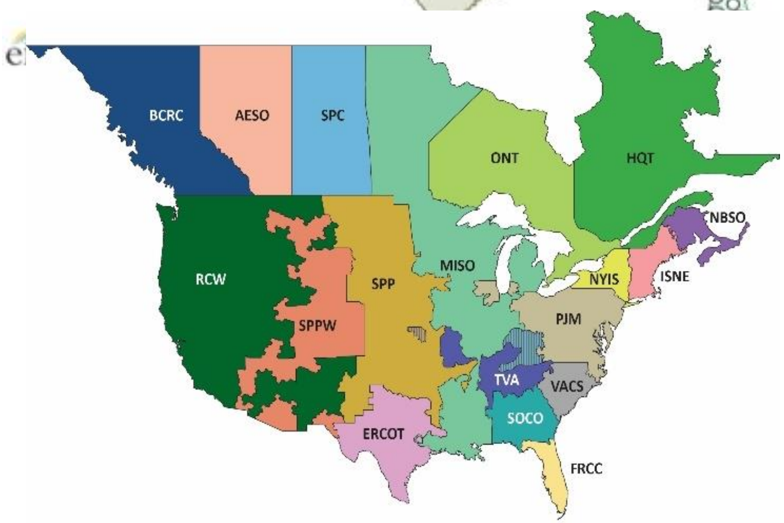
Image from Prof. Mack Grady of Baylor University

US Balancing Authorities, Reliability Coordinators and Electric Utilities





www.weca.coop/resources



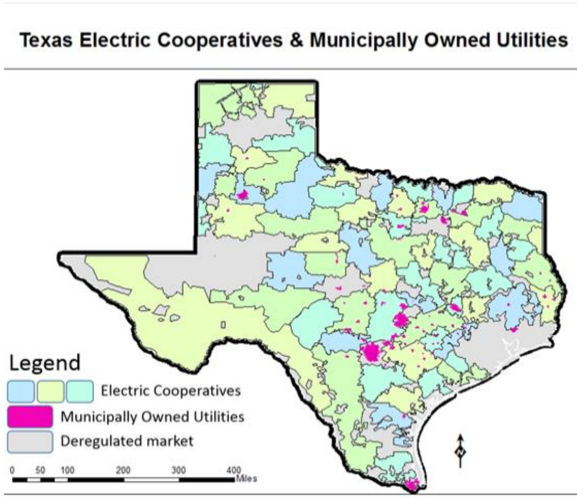


Image Sources: www.eia.gov/todayinenergy/detail.php?id=27152,
www.nerc.com/pa/rrm/TLR/Pages/Reliability-Coordinators.aspx

Electric Grid Time Frames

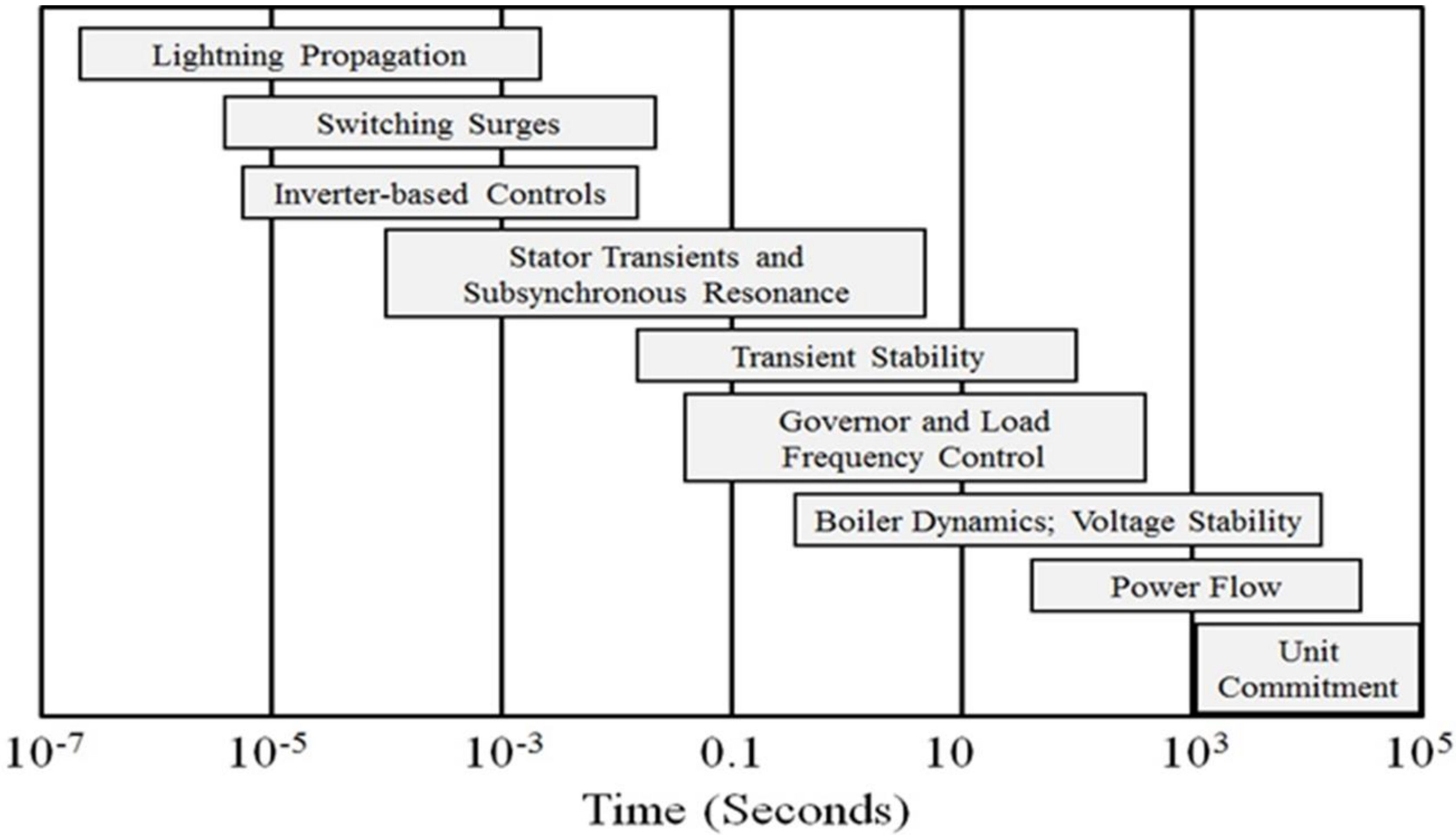


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

Important Electric Grid Considerations

- Electricity cannot be economically stored
  - Generation must be continually adjusted to match changes in electric load and losses
- Electric power flows on high voltage transmission lines cannot usually be directly controlled
  - Control is mostly indirect, by changing generation

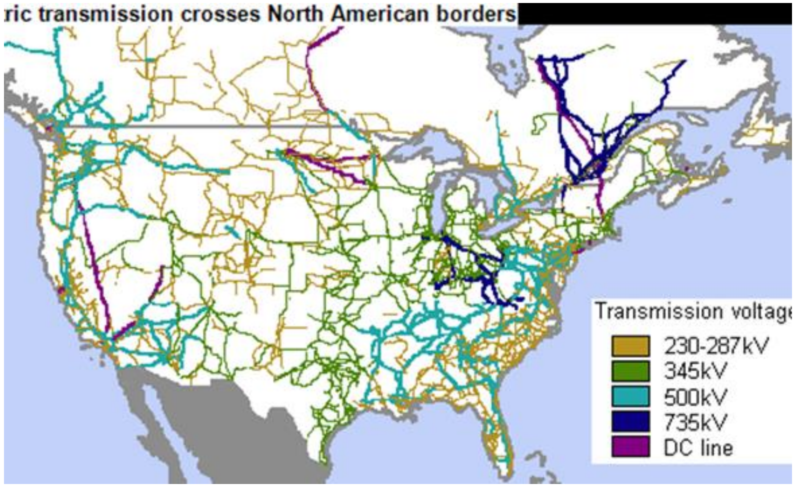
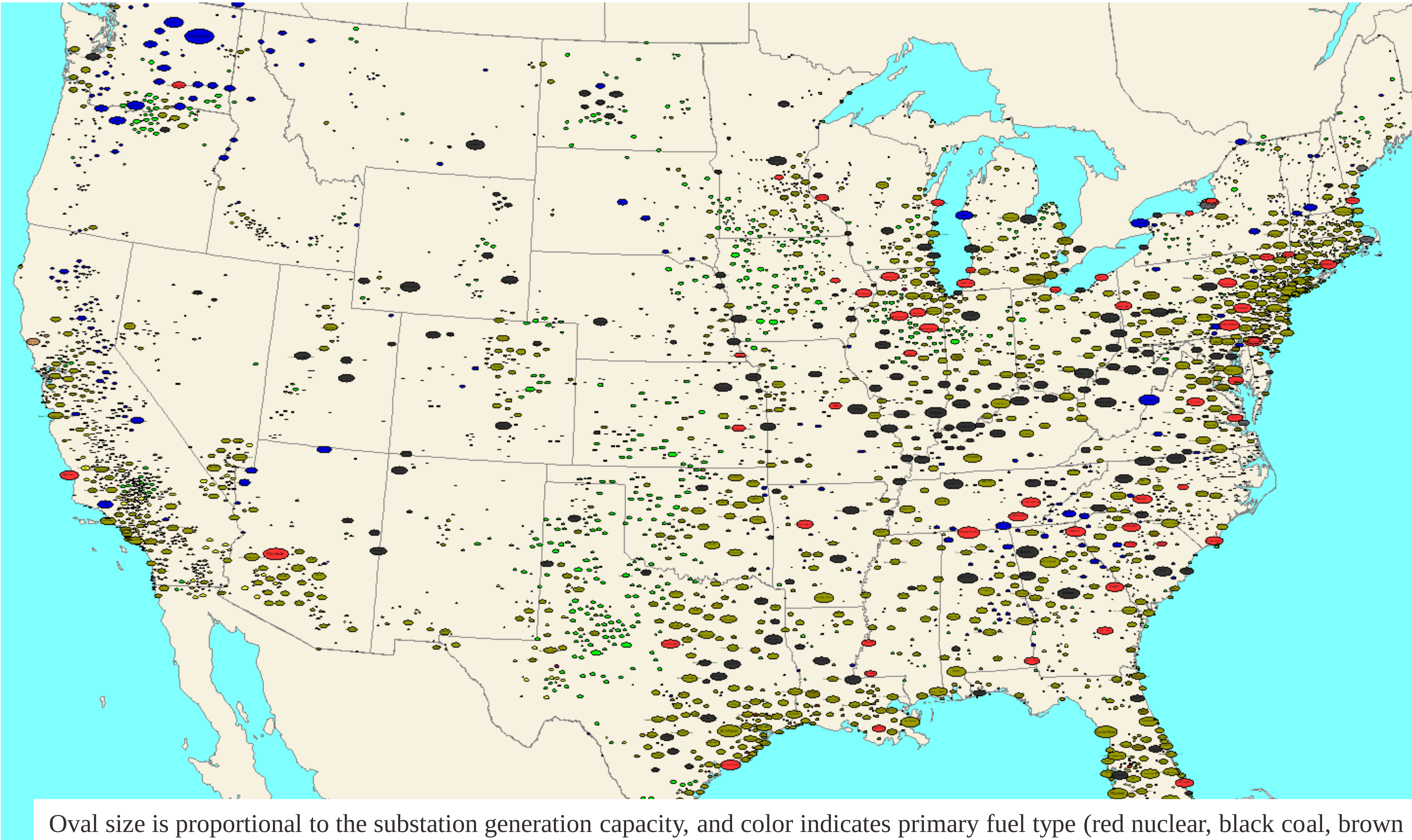


Image: US Energy Information Administration

- Customers have been in control of their load
- Transmission system has finite limits; often operated close to its limit for economic reasons

US Generator Fuel Type Diversity (2019)



Oval size is proportional to the substation generation capacity, and color indicates primary fuel type (red nuclear, black coal, brown natural gas, blue hydro, green wind, yellow solar). Image shows public data from EIA Form 860;

Changing Sources of Generation

- In the US and worldwide the sources of electricity are rapidly changing

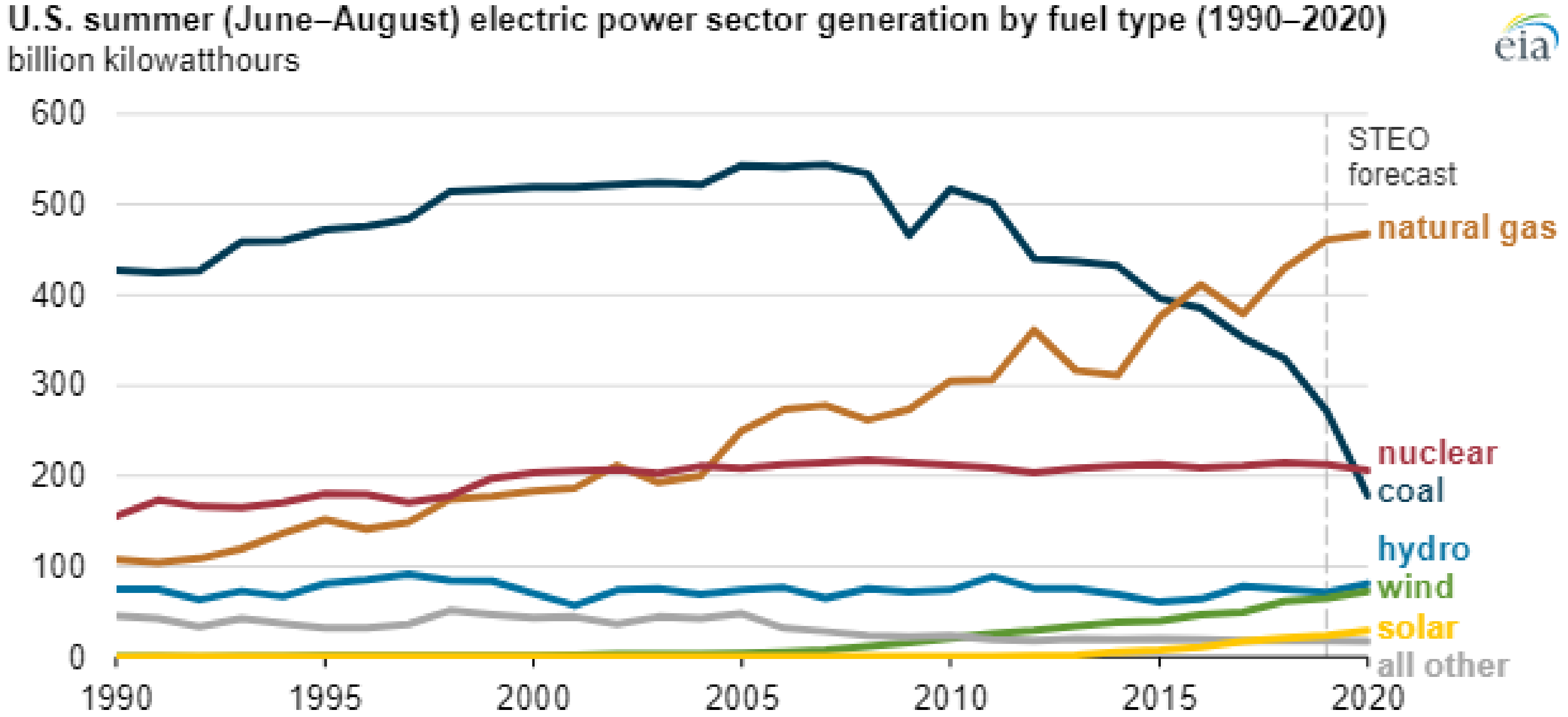


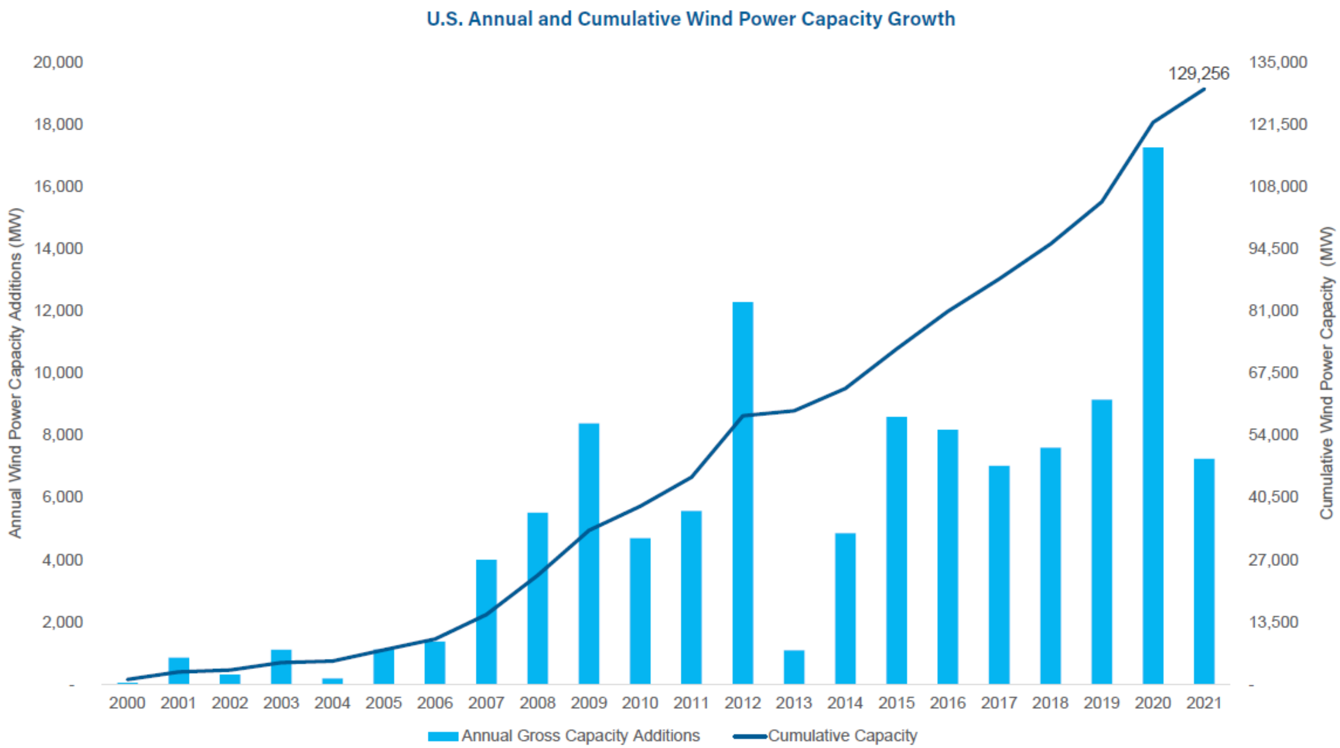
Image Source: www.eia.gov/todayinenergy/detail.php?id=44055

US Annual and Cumulative Wind Power Capacity Growth

LAND-BASED WIND ACTIVITY

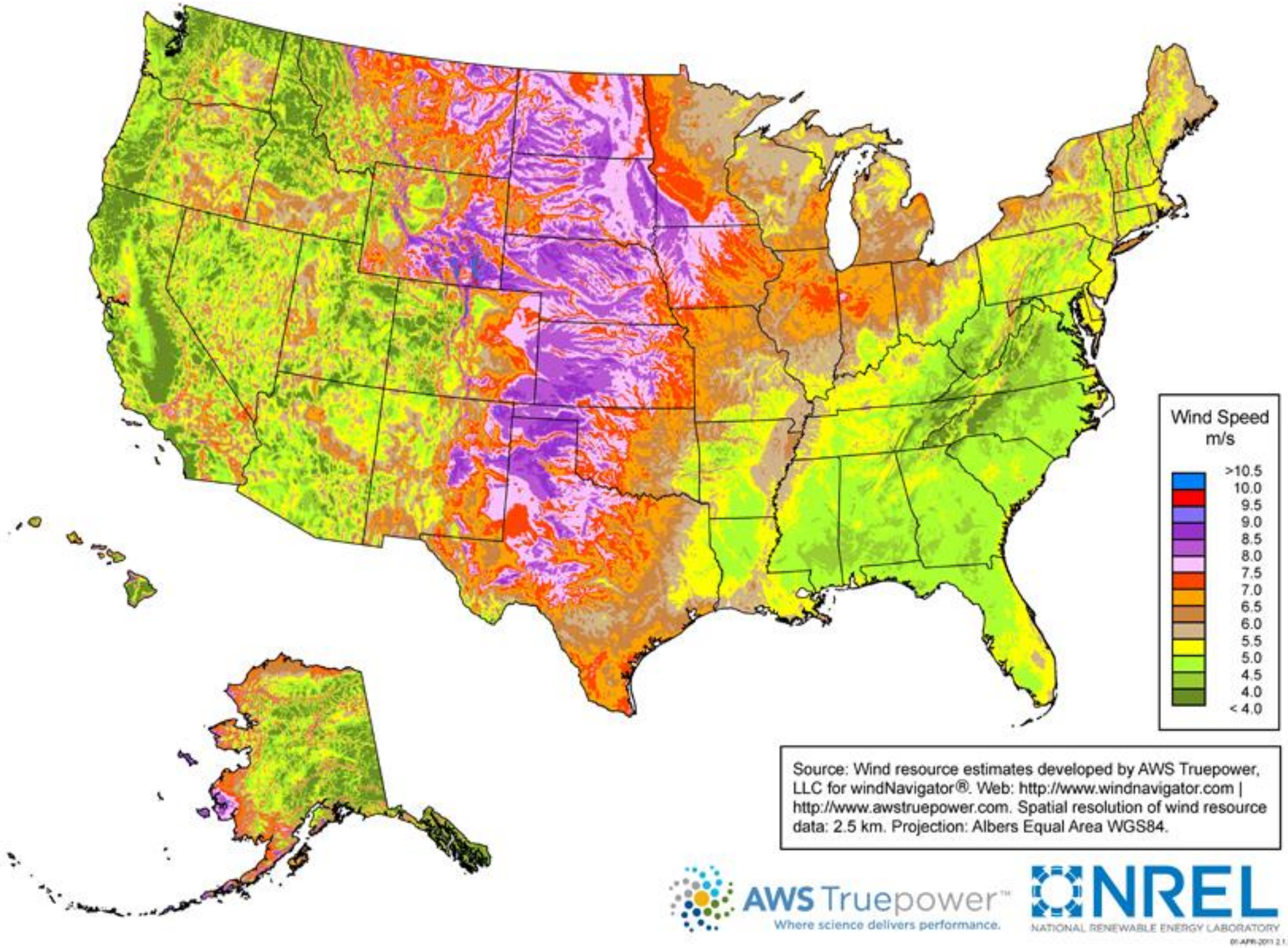
Over 1.5 GW of land-based wind online in Q3

- The wind industry installed 1,551 MW of new capacity. Total wind capacity installed in 2021 through September is now 7,248 MW.
- The volume of wind projects that came online in the third quarter is lower than pervious quarters this year, and lower than third quarter installations in recent years. This is due to projects originally planned to be online in the third quarter being pushed to a later date. Some developers cited supply chain issues as the reason for this delay.
- Ørsted's 367 MW Western Trail wind farm was the largest project to start commercial operation in the third quarter.
- Year-to-date the industry added 37 projects across 18 states totaling 7,248 MW, an increase of 15% compared to the first three quarters of 2020.
- The average size of wind projects installed in the third quarter was 129 MW.

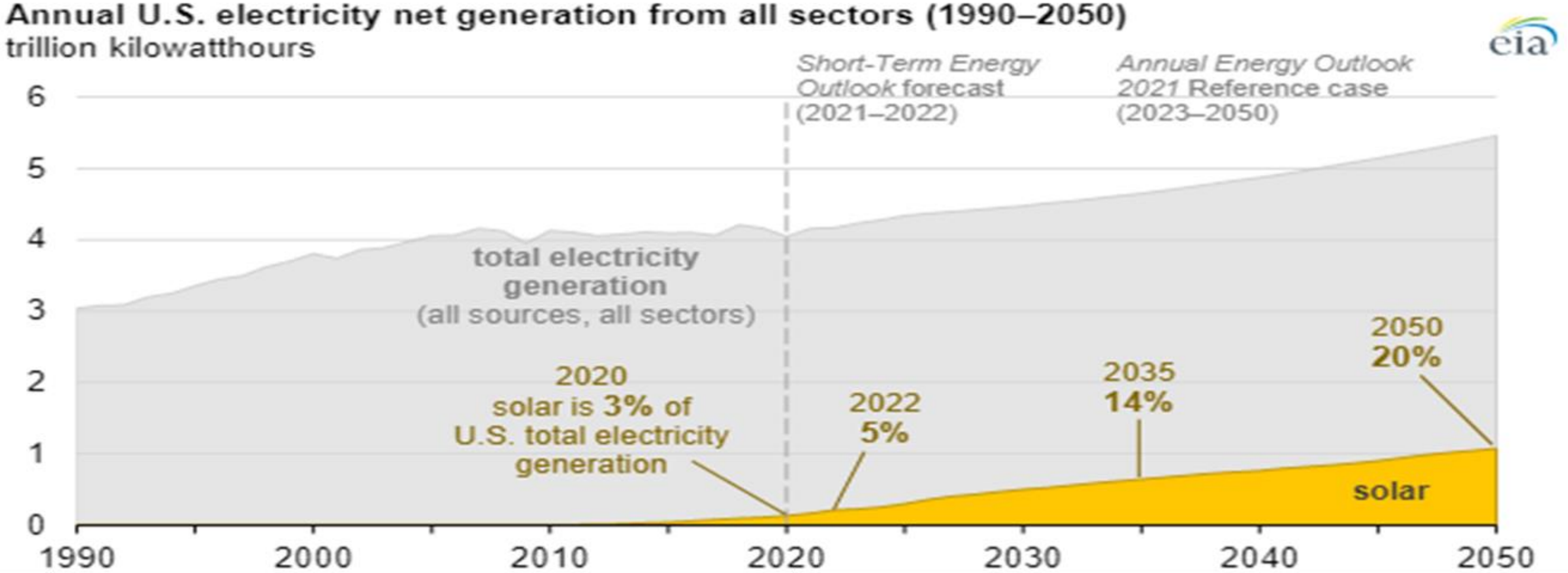


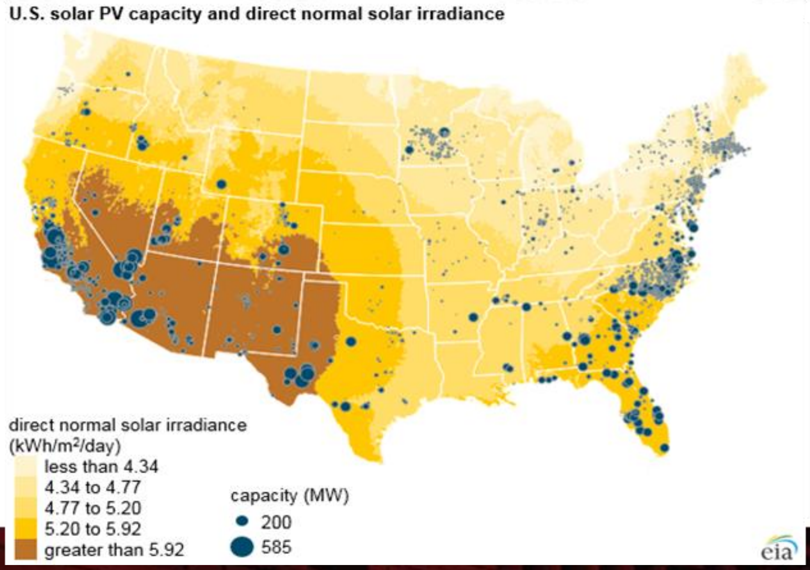
Source: American Clean Power Quarterly, 2021 Q3

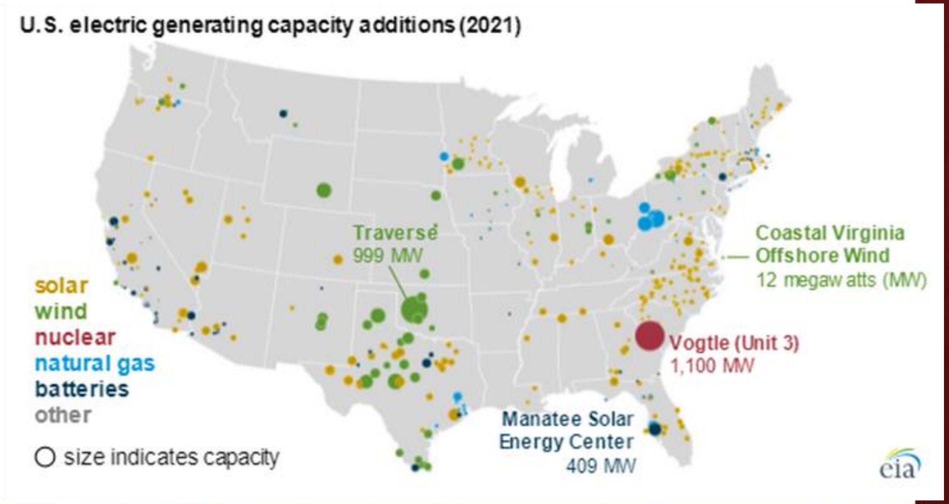
US On-Shore Wind Resources



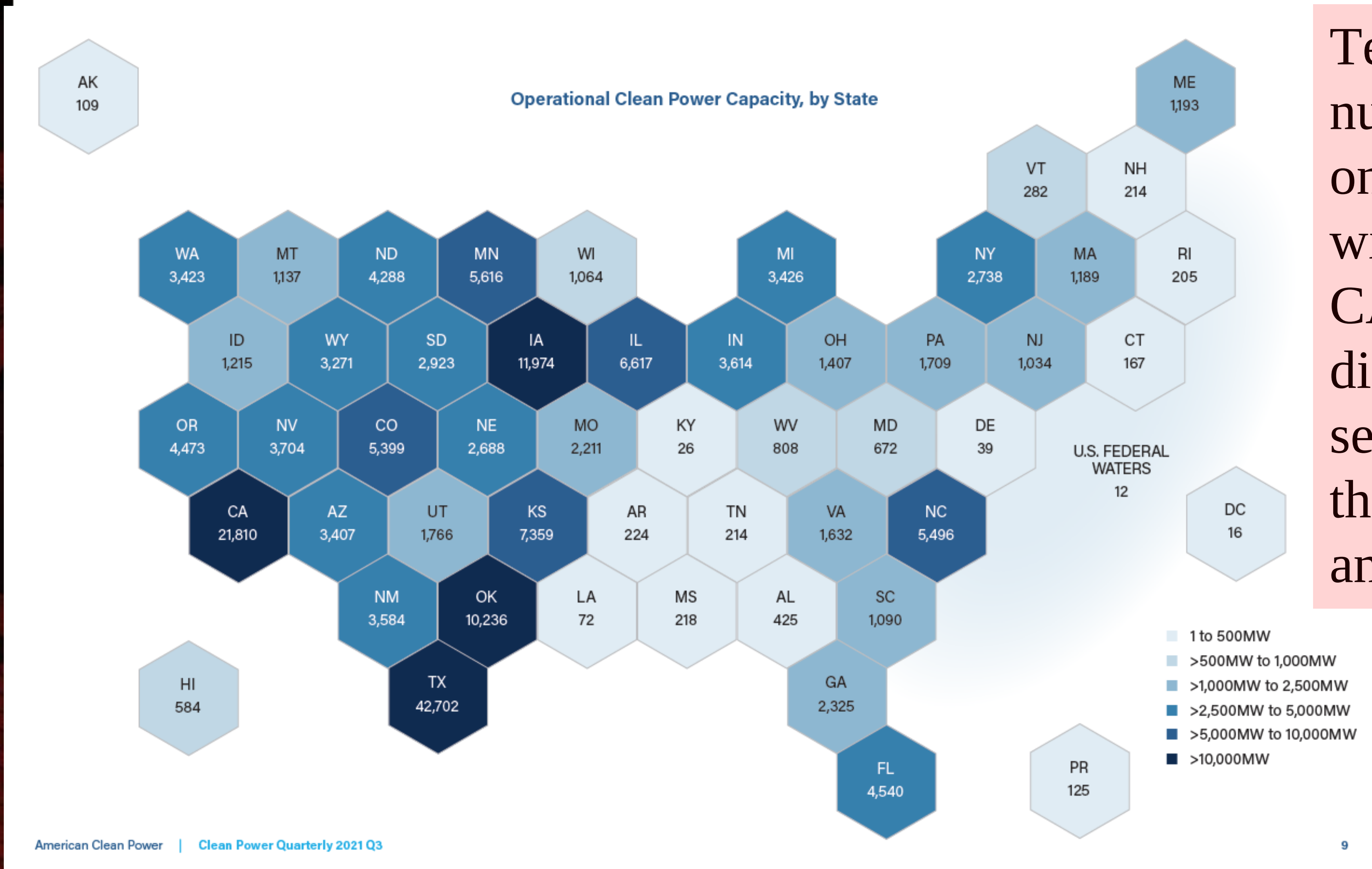
US Solar Generated Electricity







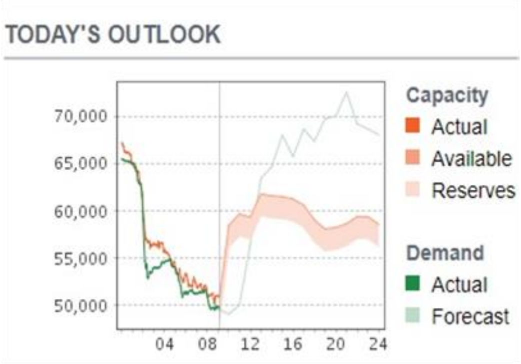
2021 Wind/Solar Capacity by State



Texas is number one, with CA a distant second, then IA and OK

Texas Near Blackout, February 2021

- Starting on Feb. 14, 2021 statewide Texas had temperatures at near record low levels.
- At 1:25am on 2/15 ERCOT had 10.5 GW of load shed and had more than 30 GW of generation forced off the system
  - Frequency dipped below 59.4 Hz
- In March newspapers reported much of the lost generation was due to paperwork failures and lack of situational awareness in how the coupled infrastructures were working together

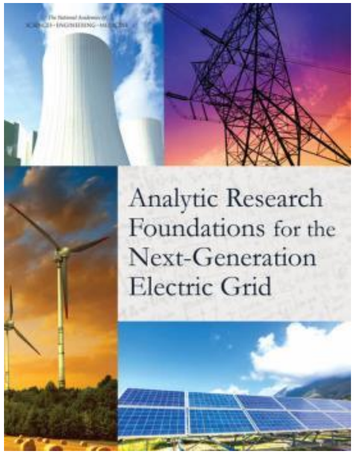


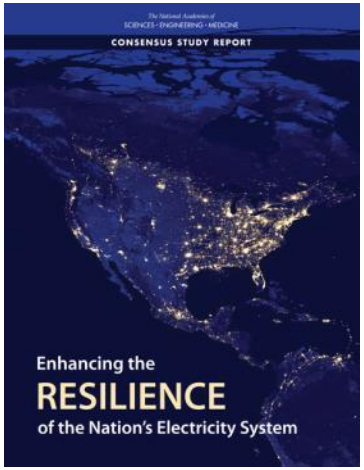
Reliability and Resiliency

- 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 US National Academies Reports

- Analytic Research Foundations for the Next-Generation Electric Grid, 2016
- Enhancing the Resilience of the Nation's Electricity System, 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"
- Focus here is on resiliency



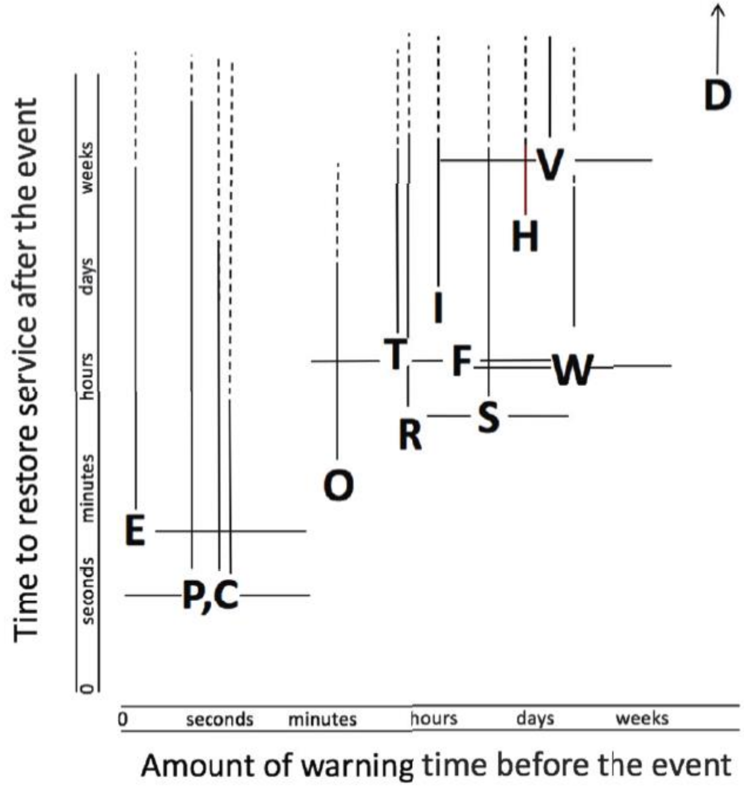


The Real Cause of Most Blackouts!

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

But mostly only the small ones in the distribution system

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

Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

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

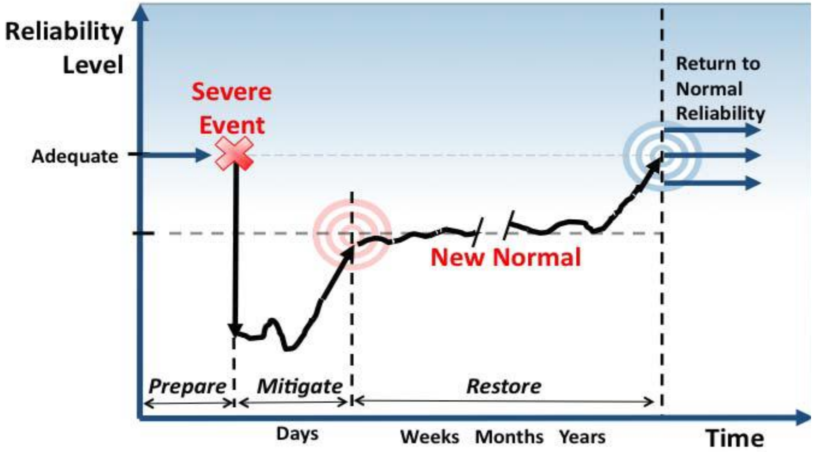


Image Source: NERC, 2012

  – 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

What is Grid Resilience?

- Merriam Webster Dictionary (resilience in general)
  – “An ability to recover from or adjust easily to misfortune or change”
- FERC
  – “The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event”

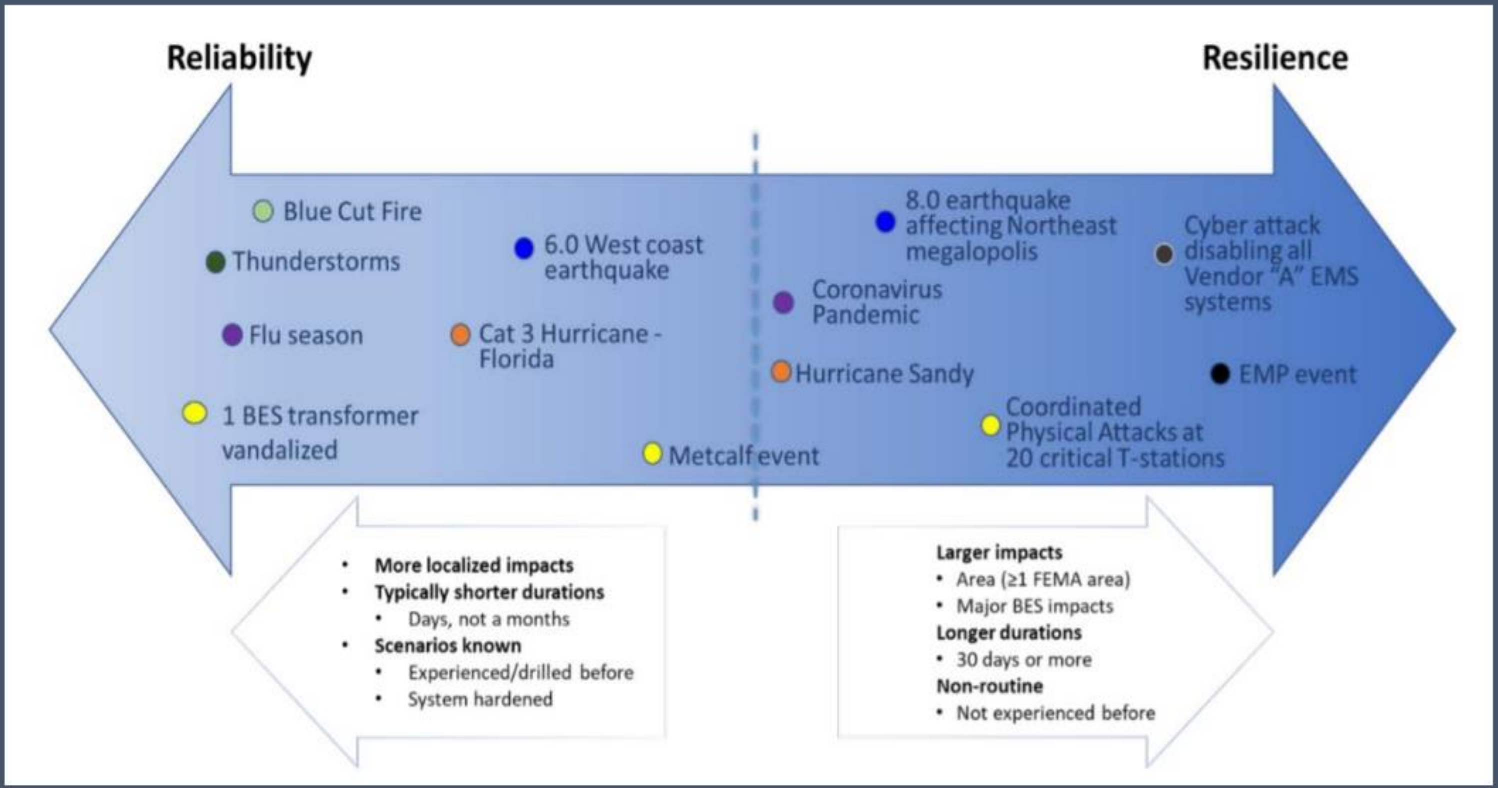
These definitions are from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021

What is Grid Resilience? Cont.

- National Association of Regulatory Utility Commissioners (NARUC)
  - “Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event”
- EPRI & North American Transmission Forum (NATF)
  - The ability of the system and its components (… equipment and human …) to minimize damage and improve recovery from non-routine disruptions, including High Impact, Low Frequency (HILF) events, in a reasonable amount of time”

These definitions are from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021

Reliability – Resilience Continuum



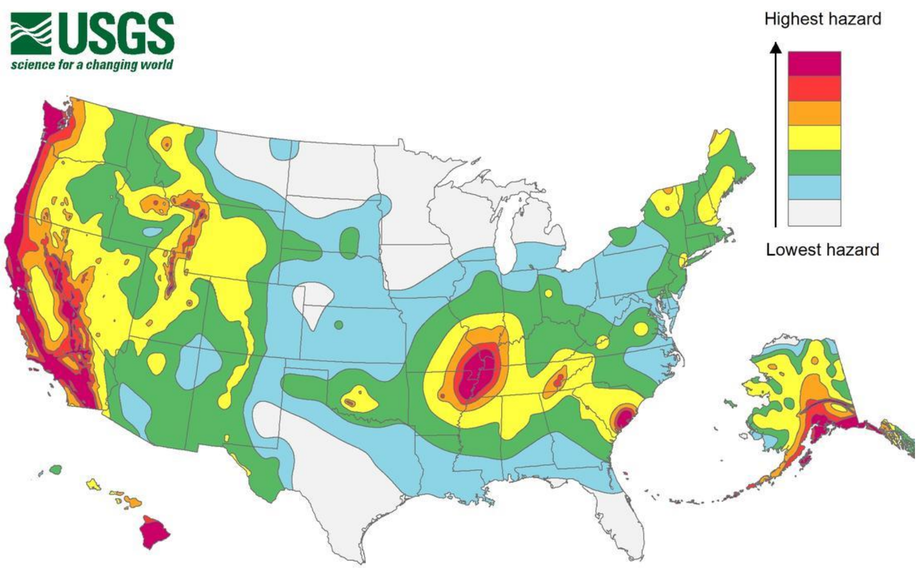
Credit: NATF TRMM Users Guide

Slide is from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021; credit NATF

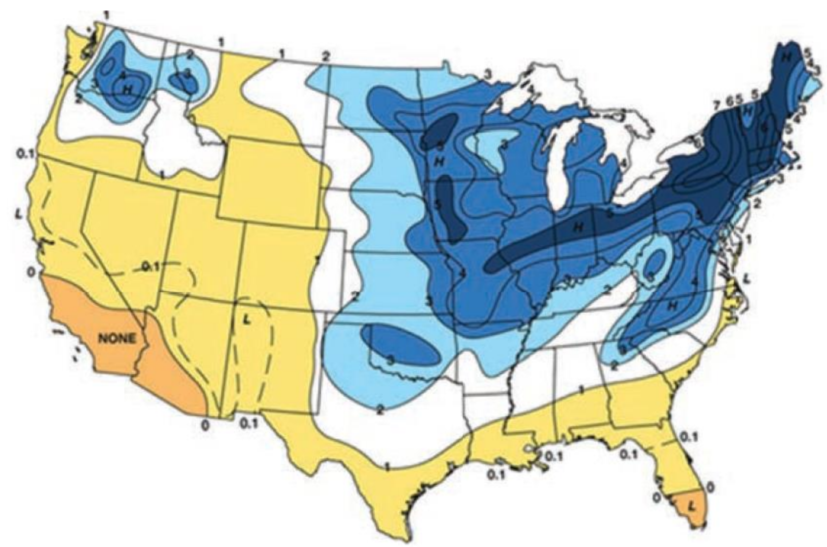
Resilient to What?

- A key question on resiliency is to determine the likely threats
  - Some are geographic, and may are hard to quantify

Earthquake Risk

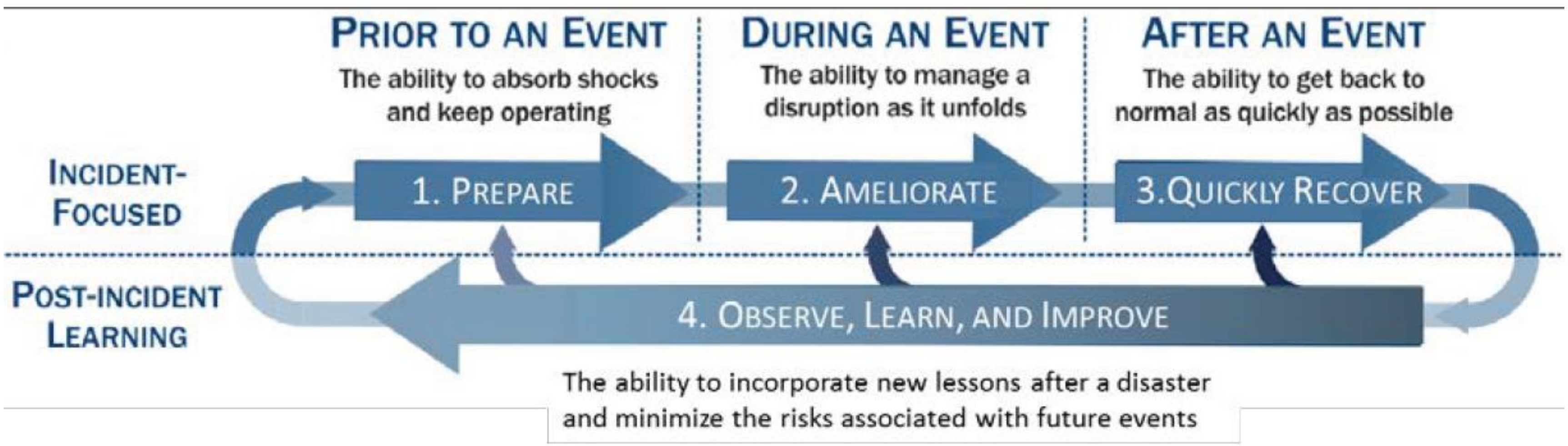


Freezing Rain Risk



Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

Four Stage Resilience Process



This is presented as Figure 1.2a in the National Academies' *Enhancing the Resilience of the Nation's Electricity System* report (2017), and is originally from S.E. Flynn, "America the resilient: Defying terrorism and mitigating natural disasters." *Foreign Affairs*, vol. 87: 2–8 (2008) and as illustrated by the National Infrastructure Advisory Council (NIAC) in 2010.

ATM

How to Approach HILF Events

- The goal in studying HILFs is seldom to replicate a specific event
  - Many have not occurred, and within each class there can be great variability (e.g., a physical attack)
- Nor is it to ensure there is no loss of service
- Rather, it is to be broadly prepared, and to be able to do at least a reasonable cost/benefit analysis
- HILF simulations can help in preparing for the unexpected
- Several techniques, such as improved control room rare event situational awareness and better black start procedures, are generally applicable

HILF Two Main Categories

- HILF events can be divided into two broad categories: 1) those not caused by human agents, and 2) those caused by human agents
- Modeling the non-human events is somewhat easier because the goal is to (at least generally) replicate what has occurred, or what could occur
- With human agent events the challenge is to protect the grid from potential events, without exposing vulnerabilities to an adversary or giving out potential mechanisms of attack
- Synthetic grids are good for both; next slides present synthetic grids and give two examples

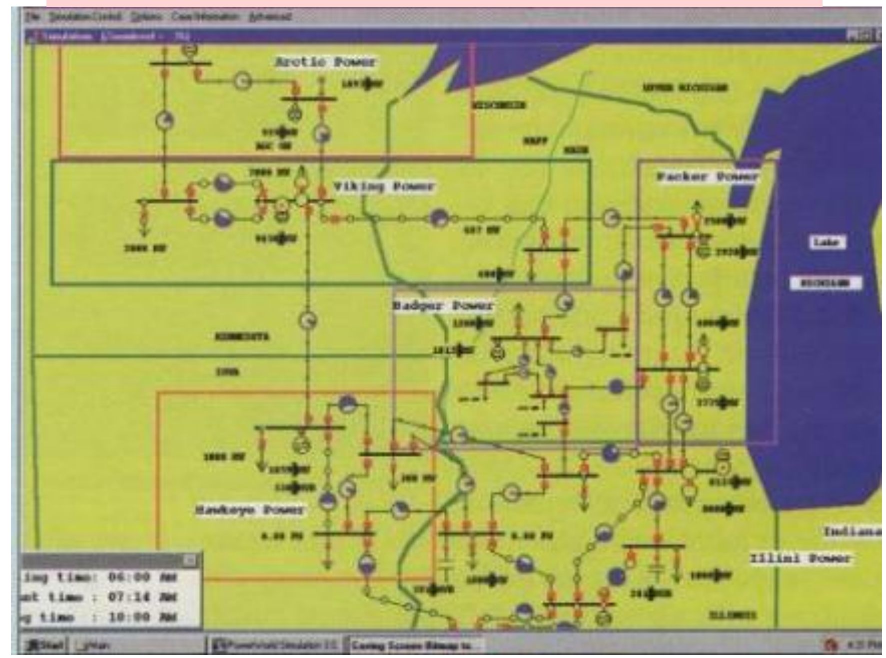
Synthetic Models and Resilience

- Access to actual power grid models is often restricted (CEII), and this can be a particular concern with data analysis, visualization and resilience studies since there purposes is are provide insight into the model, including weaknesses
  - Models cannot be freely shared with other researchers, and even presenting results can be difficult
- A solution is to create entirely synthetic (fictitious) models the mimic characteristics of actual models
  - Kudos to the US DOE ARPA-E for funding work over the last six years in this area; TAMU and UW-Madison are leaders in this area; "realistic but not real"

Early Synthetic Grids

- Synthetic electric grids are models of electric grids that do not represent any actual electric grid

A pseudo-geographic grid



A non-geographic grid

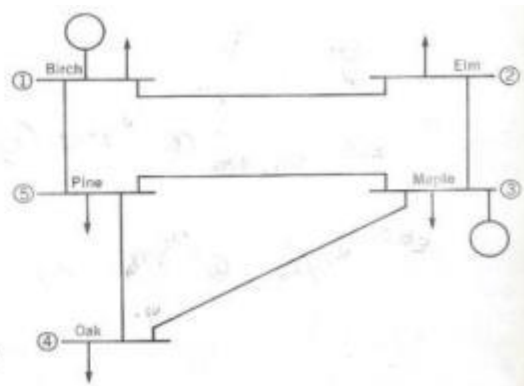


Figure 8.1 One-line diagram for Example 8.1.

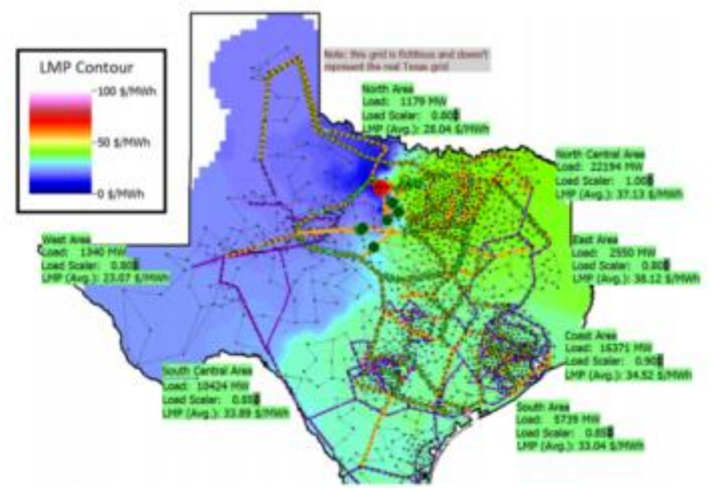
Left Image Source: W.D. Stevenson, *Elements of Power Systems*, Fourth Edition, McGraw-Hill Book Company New York, 1982 (the first edition was in 1955)

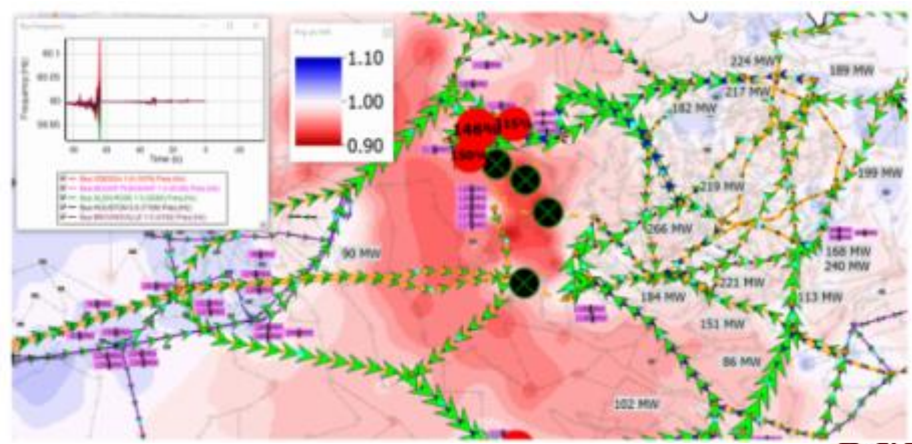
Larger-Scale Synthetic Models

- There are now synthetic grid models that go up to an 82,000-bus one grid modeling the contiguous US (CONUS)
  - Most synthetic grids have embedded geographic coordinates; the TAMU ones are available at **electricgrids.engr.tamu.edu**
- Geographic coordinates in actual electric grid models has increased rapidly over the last few years, driven in part by their requirement for geomagnetic disturbance (GMD) impact studies

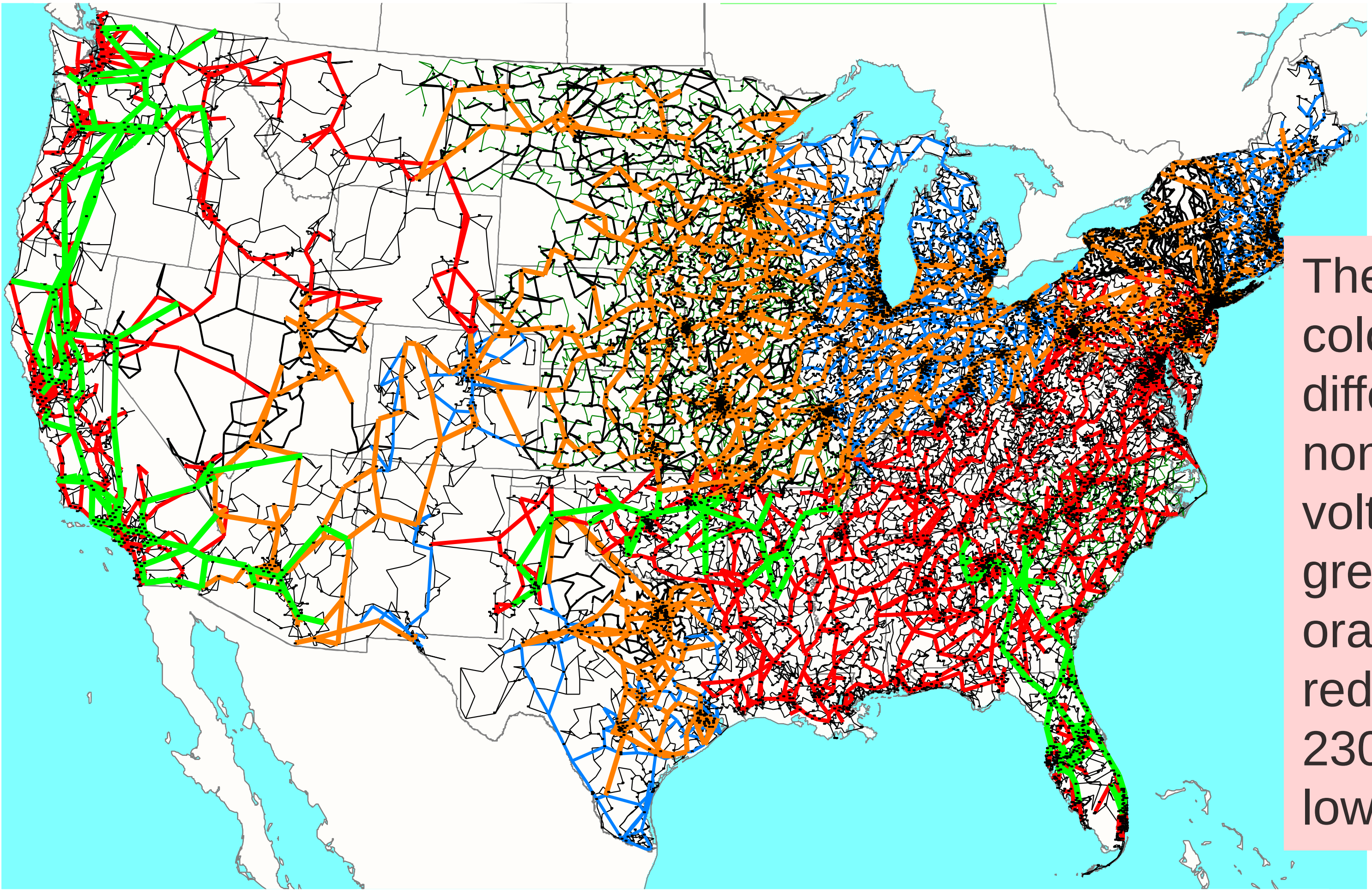
2000 Bus Texas Synthetic Grid

- This fictional grid, which has 2000 buses, is designed to serve a load similar to the ERCOT load with a similar geographic distribution
  - The grid was designed using a 500/230/161/115 kV transmission to be different from the actual grid
  - Public generator information is used





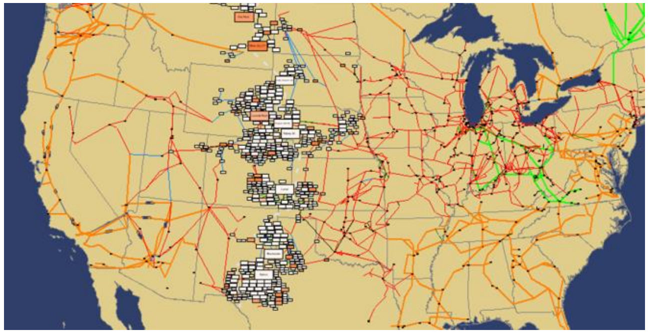
82,000 Bus Synthetic Grid



The different colors indicate different nominal kV voltages, with green 765, orange 500, red 345, blue 230, black lower.

Resilience and Grid Size

- There is no optimal ac grid size for resiliency
  - Larger grids can share resources but can also cascade
  - We recently finished a study looking at joining the North American Eastern and Western Interconnects; there are no major showstoppers to doing this



- Probably the most effective approach is to have grids the can flexibly breakup into smaller grids (known as adaptive islanding)
- UW-Madison and TAMU are starting a project looking at climate change impacts on grid modeling

HILF Event Example: Geomagnetic Disturbances (GMDs)

- GMDs are caused by solar corona mass ejections (CMEs)
- A GMD caused a blackout in 1989 of Quebec
- They have the potential to severely disrupt the electric grid by causing quasi-dc geomagnetically induced currents (GICs) in the high voltage grid
- Until recently power engineers had few tools to help them assess the impact of GMDs
- GMD assessment tools are now moving into the realm of power system planning and operations engineers

GMD Overview

- Solar corona mass ejections (CMEs) can cause changes in the earth's magnetic field (i.e., dB/dt). These changes in turn produce a non-uniform electric field at the surface
  - Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they are almost dc
  - 1989 North America storm produced a change of 500 nT/minute, while a stronger storm, such as the ones in 1859 or 1921, could produce 2500 nT/minute variation
  - Storm "footprint" can be continental in scale

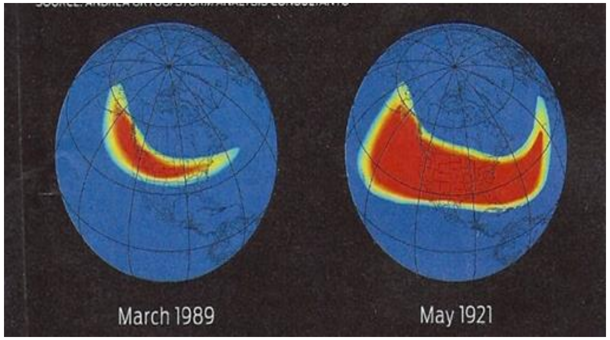


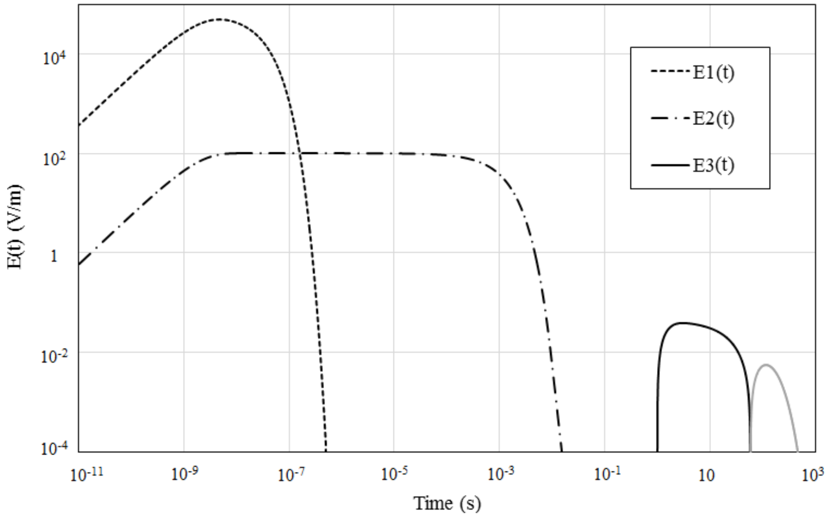
Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

Electric Fields and Geomagnetically Induced Currents (GICs)

- The induced electric field at the surface is dependent on deep earth (hundreds of km) conductivity
  - Electric fields are vectors (magnitude and angle); values expressed in units of volts/mile (or volts/km);
  - A 2500 nT/minute storm could produce 5 to 10 volts/km
- The electric fields cause GICs to flow in the high voltage transmission grid
- The induced voltages that drive the GICs can be modeled as dc voltages in the transmission lines.
  - The magnitude of the dc voltage is determined by integrating the electric field variation over the line length
  - Both magnitude and direction of electric field is important

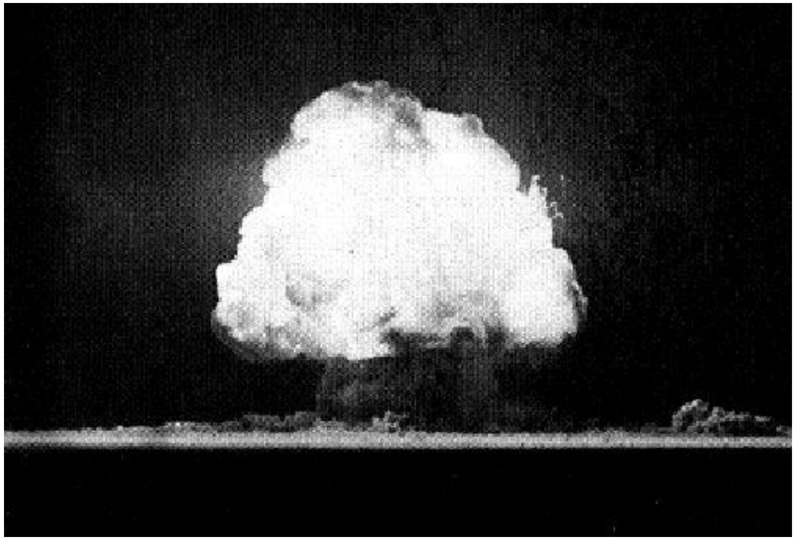
HILF Example: Nuclear EMPs

- Broadly defined, an electromagnetic pulse (EMP) is any transient burst of electromagnetic energy
- High altitude nuclear explosions can produce continental scale EMPs; called HEMPs
- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
  - E1 impacts electronics, E2 is similar to lightning, E3 is similar to a very large, but short duration GMD



Nuclear EMP History

- The presence of EMPs was theorized by Enrico Fermi prior to the first explosion in July 1945
  - Many wires were shielded, but still some data was lost due to EMP
- British called it “radioflash” in their tests in early 1950’s due to the presence of “clicks” heard on radios
- Operation Hardtack tests in 1958 (up to 80 km in altitude) further demonstrated HEMP impacts



Trinity Explosion, July 16, 1945, 20 kilotons of TNT
source: Los Alamos Lab

Nuclear EMP History: Starfish Prime

- Starfish Prime was an explosion of a 1.44 megaton nuclear weapon at an altitude of 400 km over the Pacific Ocean in July 1962
  - Part of series of tests known as Operation Fishbowl
  - The EMPs were much larger than expected, driving instruments off scale
  - Impacts seen in Honolulu (1445 km away), including knocking out about 300 street lights, setting off alarms, and damaging a microwave link
  - Some low earth orbit satellites were also damaged

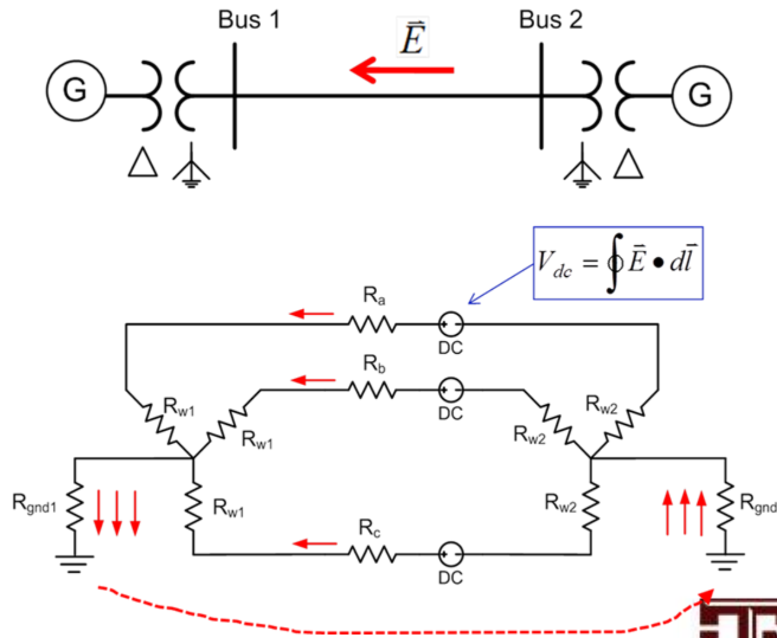
Starfish Prime observed on Maui in 1962, Source US EMP Commission Report from July 2017

HEMP Threats to Electric Grids

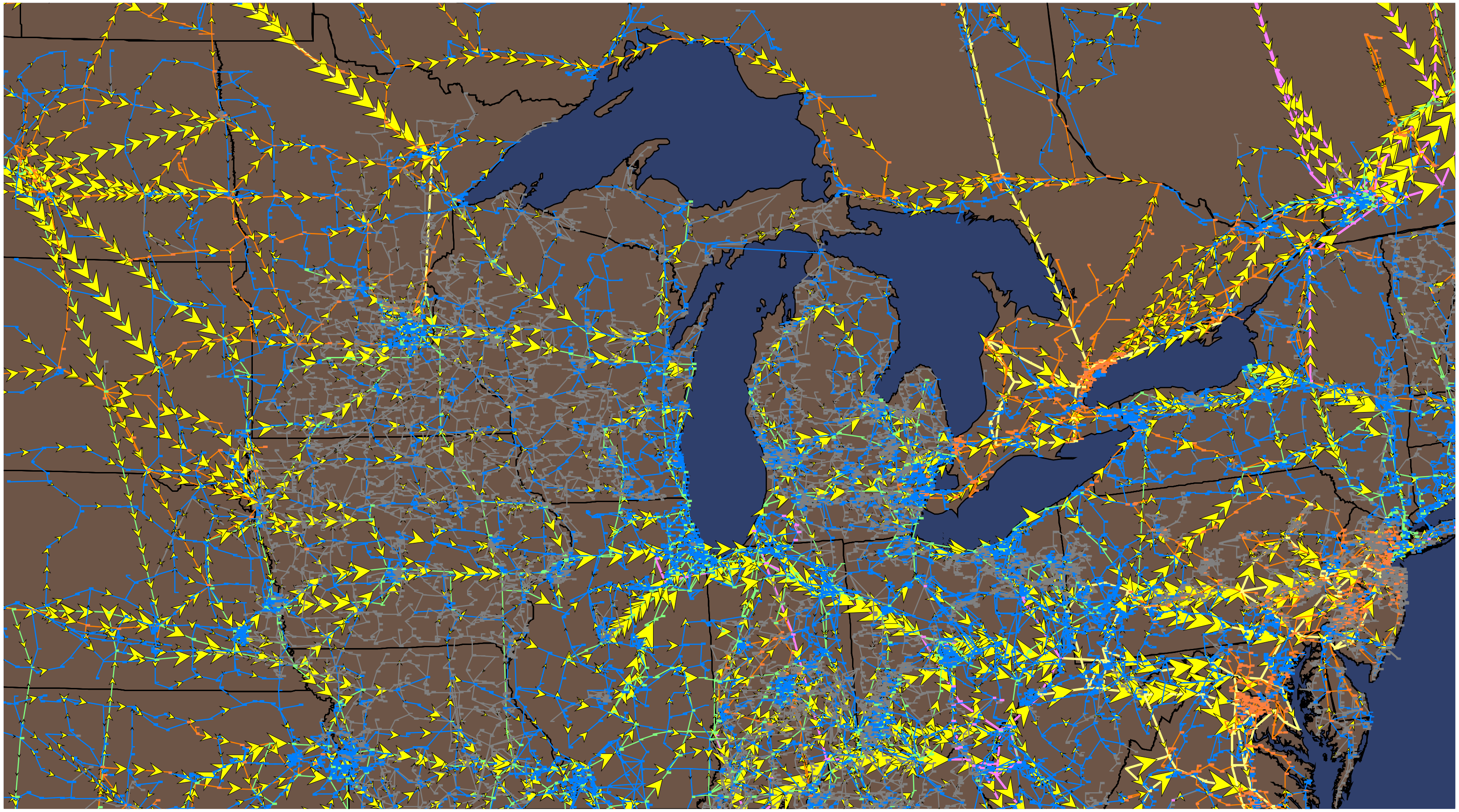
- E1: Partial loss of load and generation, possible damage to protection system (< one microsecond)
- E2: Voltage impulses on transmission lines and possible insulator flashover (< 0.1 second)
- E3: GIC → half-cycle transformer core saturation →
  - harmonics → excess reactive power losses → possible voltage or transient instability → immediate loss of critical loads; harmonics could damage equipment
  - excess transformer heat → possible damage or long-term degradation to individual components → long-term power supply constraints for critical loads
- Longer-term: potential cascading grid collapse and/or equipment damage

Geomagnetically Induced Currents (GICs)

- Both GMDs and HEMPs cause electric fields, with values dependent on the deep earth conductivity
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows

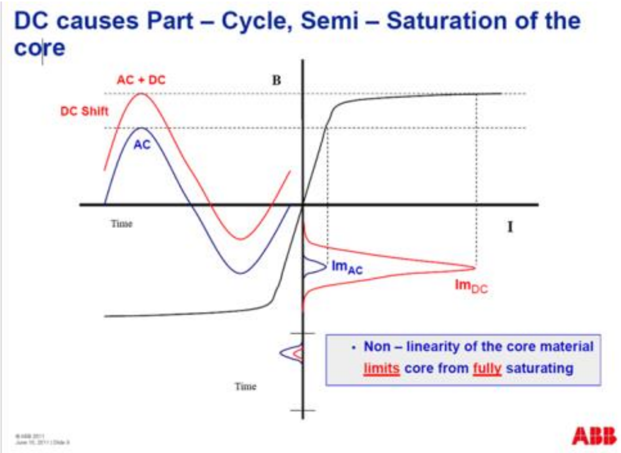


Simulated GICs in High Voltage Transmission Grid

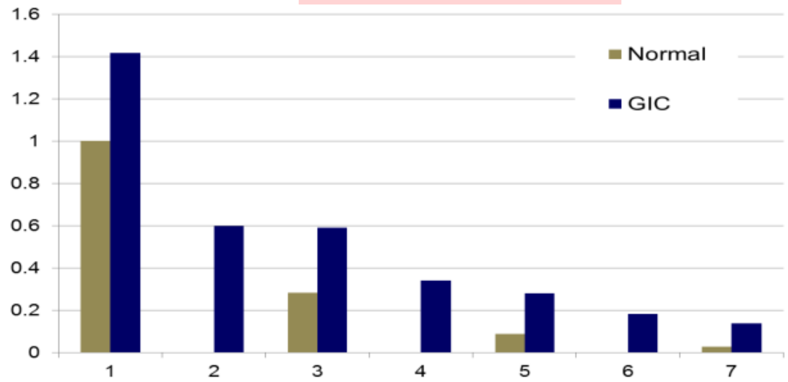


Transformer Impacts of GICs

- The superimposed dc GICs can push transformers into saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence (e.g., power flow and transient stability) these harmonics can be represented by increased reactive power losses in the transformer



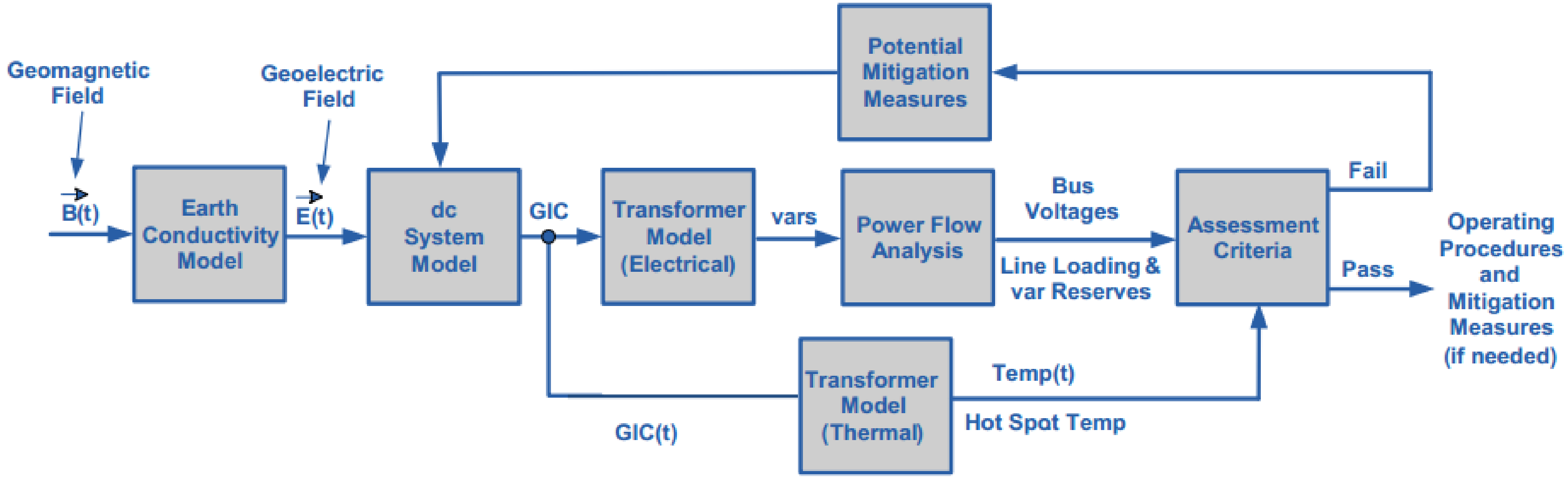
Harmonics



Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011

Overview of GMD Assessments

In is a quite interdisciplinary problem



The two key concerns from a big storm are 1) large-scale blackout due to voltage collapse, 2) permanent transformer damage due to overheating; similar concerns due to HEMPs

Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

The Impact of a Large GMD From an Operations Perspective

- Would be maybe a day warning but without specifics
  - Satellite at Lagrange point one million miles from earth would give more details, but with less than 30 minutes lead time
  - Could strike quickly; rise time of minutes, rapidly covering a good chunk of the continent

- Reactive power loadings on hundreds of high voltage transformers could rapidly rise

The Impact of a Large GMD From an Operations Perspective

- Increased transformer reactive loading causes heating issues and potential large-scale voltage collapses
- Power system software like state estimation could fail
- Control room personnel would be overwhelmed
- The storm could last for days with varying intensity
- Waiting until it occurs to prepare would not be a good idea!

Example EMP GIC Visualization for a 2000 Bus Synthetic Grid

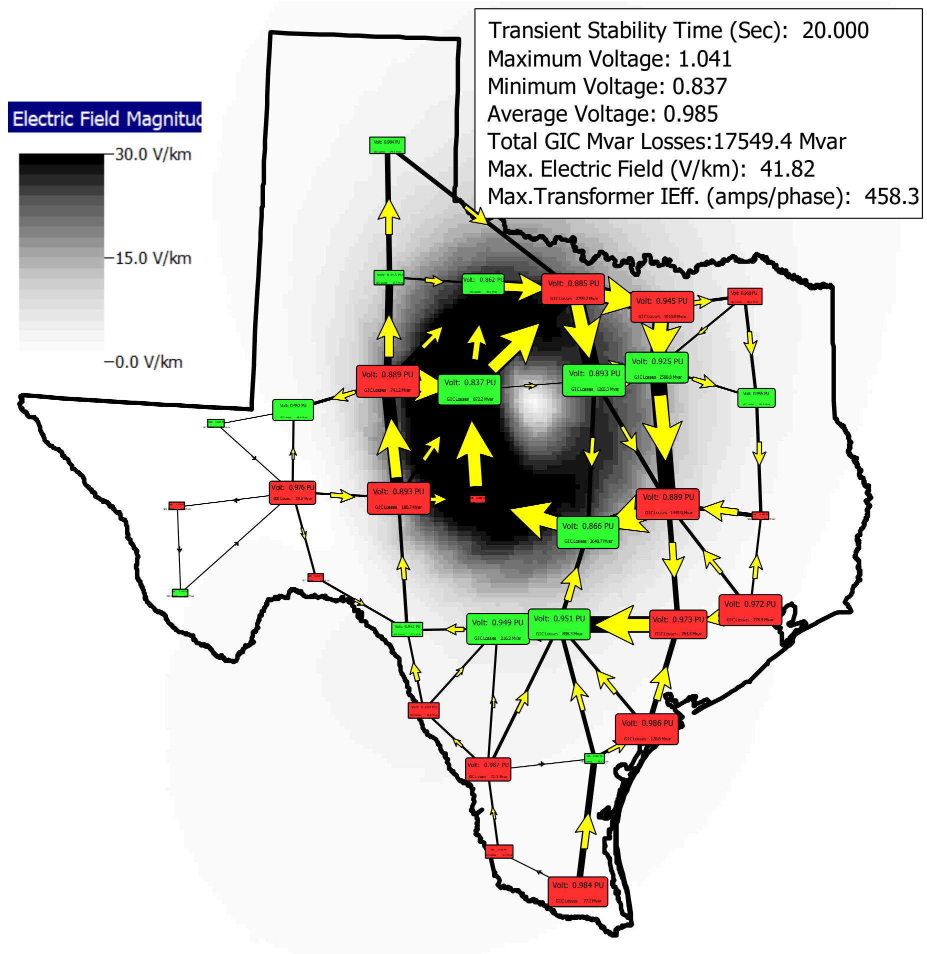


Image shows the GICs during an EMP event. The black/white contour shows the spatial variation in the electric field, the yellow arrows the aggregated GIC flows (using the technique of [a]), and the green/red boxes the GICs flowing out of and into the ground.

[a] T.J. Overbye, J. Wert, K. Shetye, F. Safdarian, and A. Birchfield, “Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids,” Kansas Power and Energy Conference (KPEC), Apr. 2021; available oneline at overbye.engr.tamu.edu/publications/

GIC Mitigation

- Tools are needed to determine mitigation strategies
  - Cost-benefit analysis
- GIC flows can be reduced both through operational strategies such as opening lines, and through longer term approaches such as installing blocking devices

- Redispatching the system can change transformer loadings, providing margins for GICs
- Algorithms are needed to provide real-time situational awareness for use during GMDs

Resiliency and Renewables

- As renewables make up an increasing percentage of our generation, there is growing concern about outlier weather events that could curtail large amounts of generation
  - A traditional droughts can impact hydro and the cooling on some thermal units
  - “Wind droughts” can impact wind energy production; Europe experienced a partial wind drought in late 2021
  - Unusually long periods of cloudy weather negatively impact solar power generation
- Fuel source diversity can help, and can additional transmission to help with geographic diversity

Resiliency and Coupled Infrastructures

- As our society becomes more dependent on electricity, short and small duration blackouts become more concerning, and large-scale, long duration outages can be catastrophic
- Electric grids have been coupled with other infrastructures (e.g., natural gas, cyber, water) and these couplings are growing, particularly with transportation as it electrifies
- We need more research and simulations considering those couplings

Some Specific Recommendations to Enhance Resilience

- A “visioning” process is needed to imaging and assessing plausible high impact events
- The electric grid operators need to do exercises to better simulate high impact scenarios
- More physical components are needed, including replacement transformers and backup power
- More research, development and demonstration is needed, including a focus on cyber and HILFs
- Resilience groups are needed throughout the industry and government to raise awareness

Source: National Academies 2017 “Enhancing the Resilience of the Nation’s Electricity System”

Conclusion

- The electric grid is crucial to our society, and for decades into the future we will be relying on it
- A perfect electric grid is impossible, and we need to be prepared for long-term, wide-area blackouts
- However, much can and should be done to reduce to reduce this risk
- A broad, sustained effort is needed in this area including the entire electric grid sector
- Synthetic electric grids will play a crucial role in this effort

Thank You!   Questions?

- This presentation is at overbye.engr.tamu.edu/