Enhancing the Resilience and Sustainability of Electric Grids (Including ERCOT Impacts of Winter Storm Uri)

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Acknowledgments

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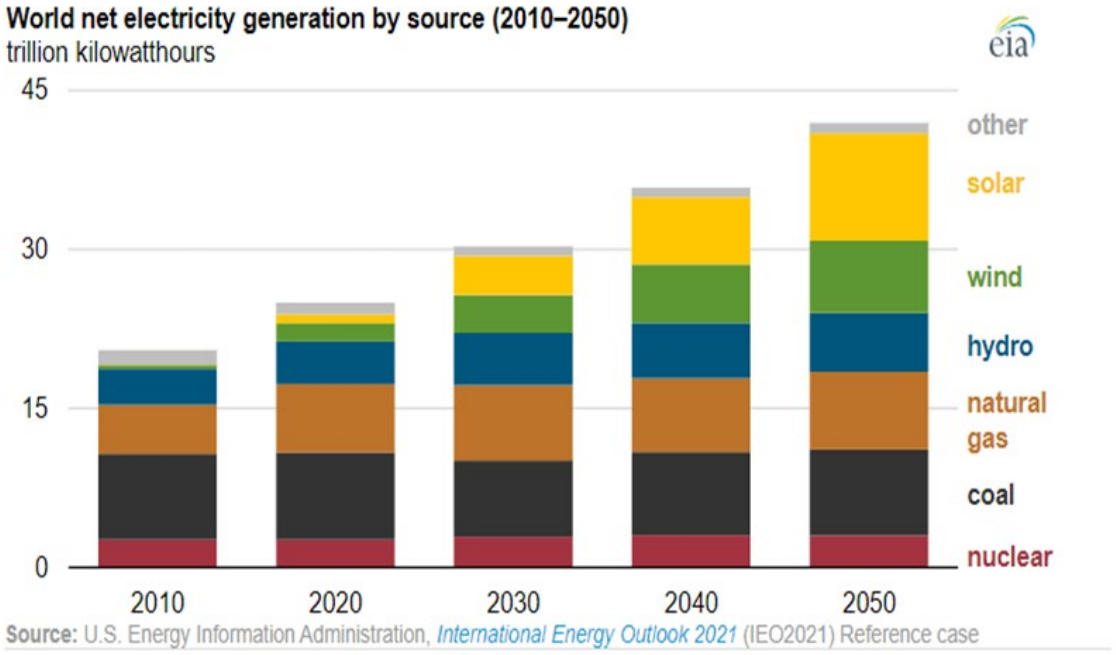
- Slides also include contributions from many of my students, postdocs, staff and colleagues at both TAMU and UIUC
- The views presented here are my own

Greetings from the Texas A&M Energy and Power Group (EPG)

This is from the Fall 2022 EPG dinner held at Dr. Kate Davis's house on Oct 1, 2022

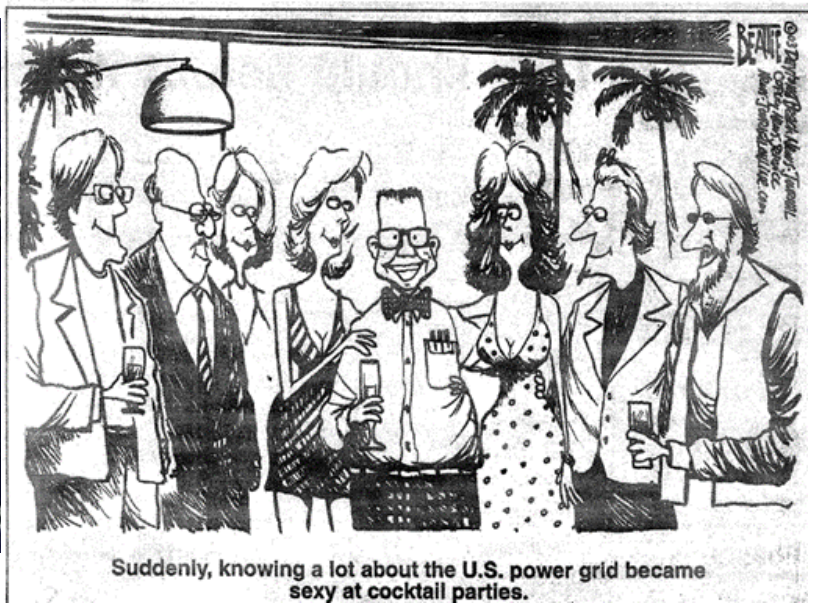
A Bright Electric Future

- Our electric energy future could be quite bright!
- Electric grids worldwide are in a time of rapid transition, with many positive developments including the addition of large amounts of renewable generation, transportation electrification, smart grid controls, etc.
  - The grid of the future is likely to be quite different from the one of the recent past
- There are lots of good engineering challenges and it is a great time for students entering the field!!



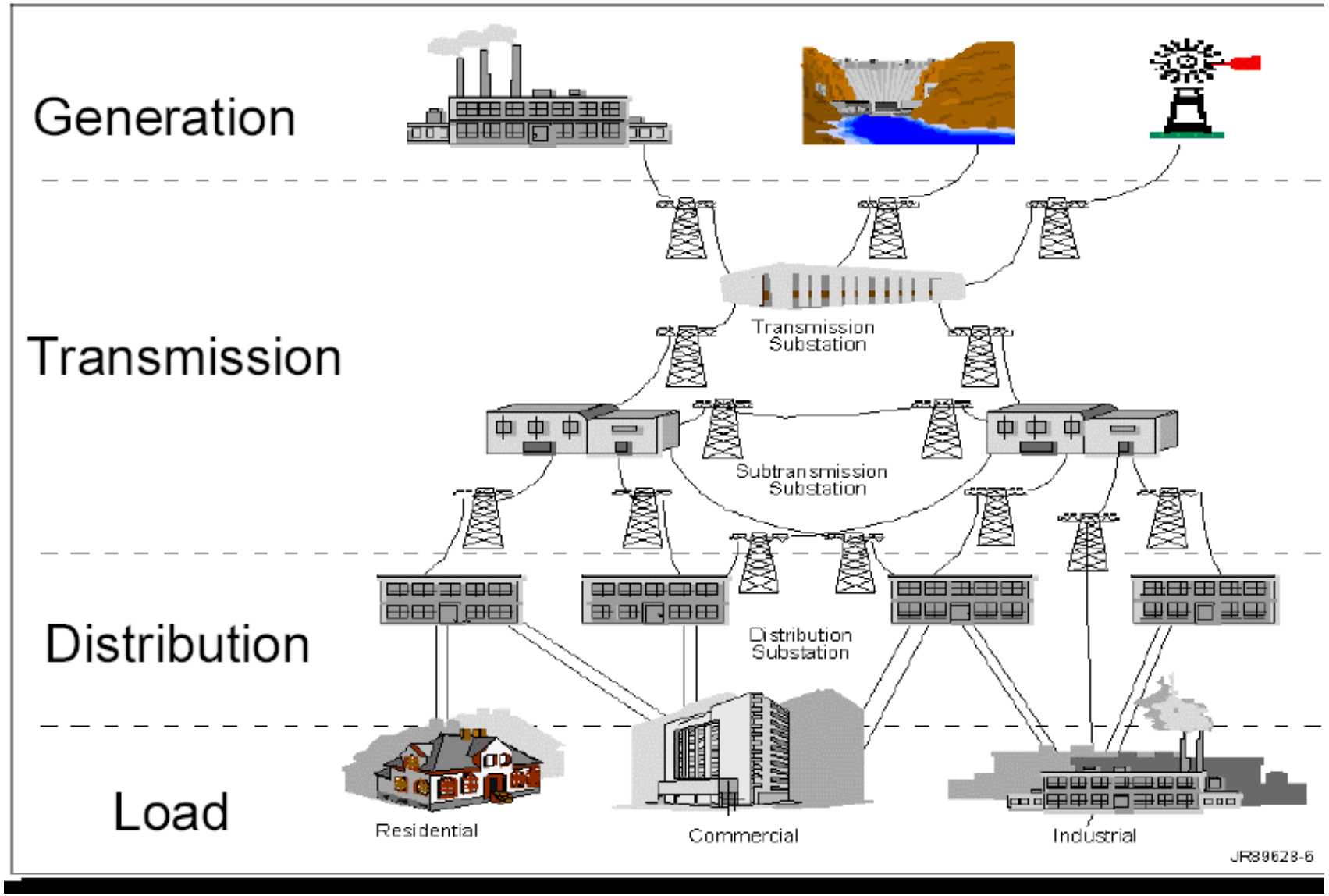
Overview

- 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 the 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



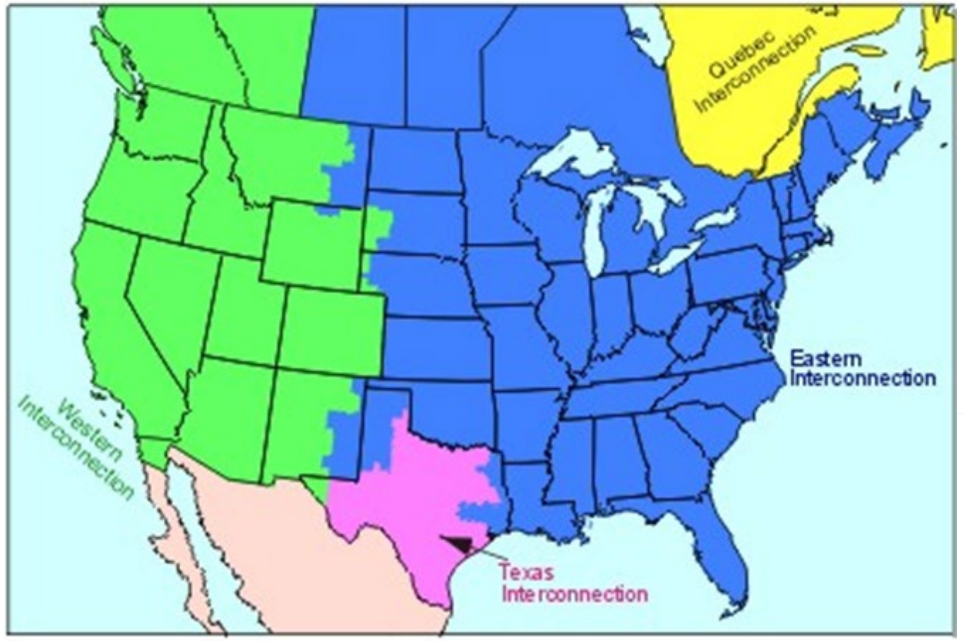
My favorite 8/14/03 blackout hoax picture and cartoon

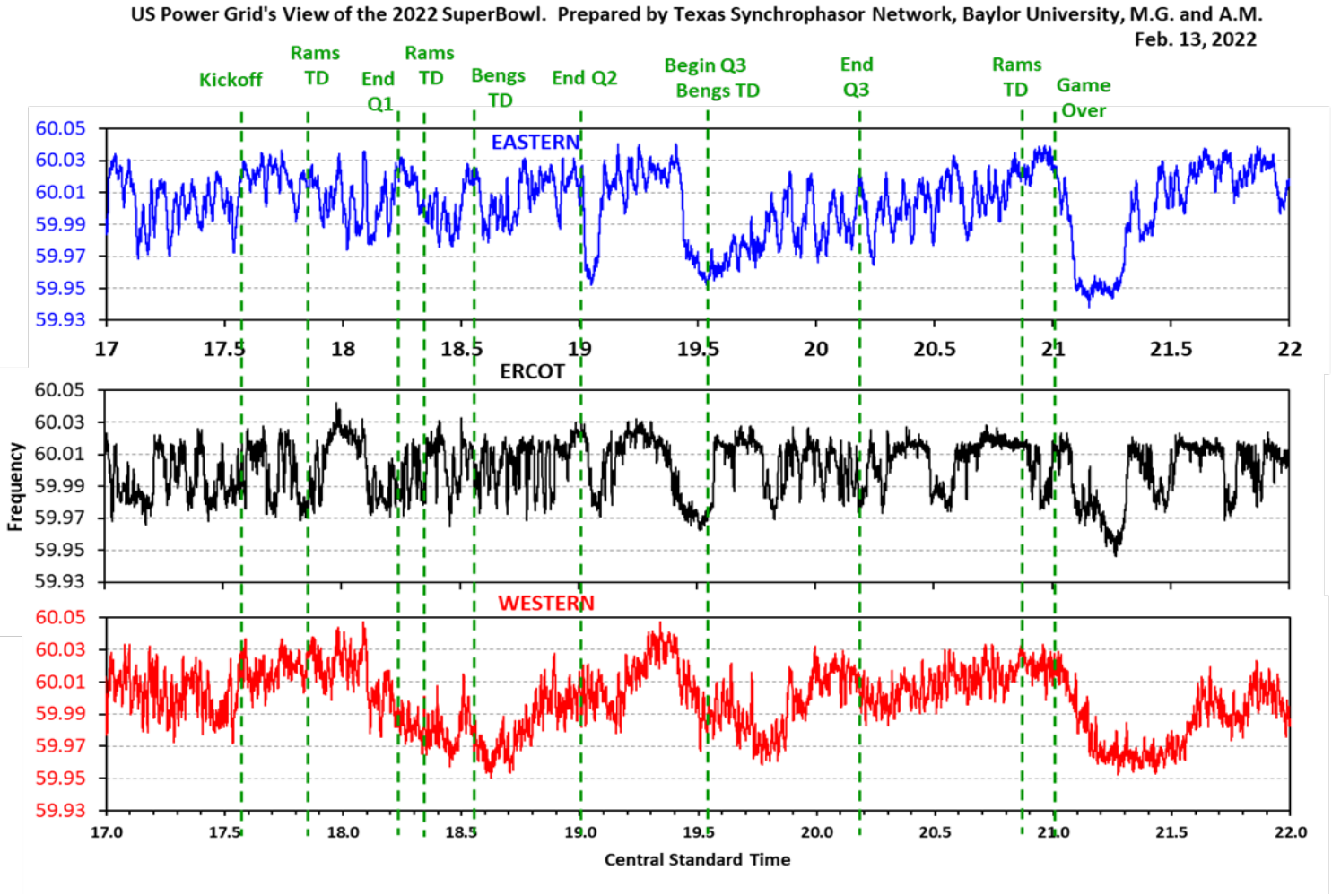
Electric Grid Basics



More generation is moving into the distribution system;

Asynchronous Grids Have Slightly Different Frequencies (USA 2/13/22)





Frequency image from
Prof. Mack Grady
of Baylor University

Electric Grid Time Frames

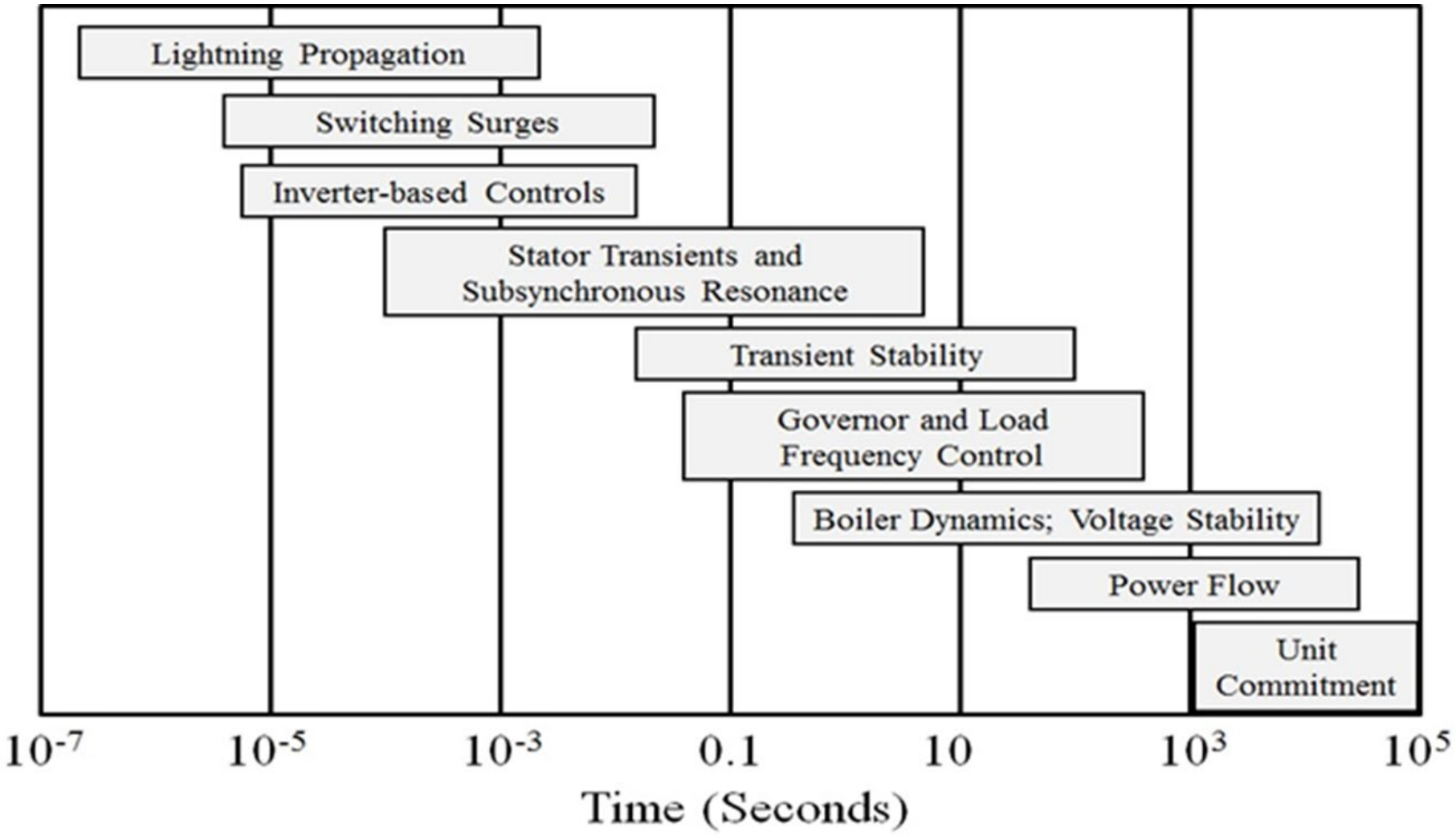


Image: Sauer, P.W., M. A. Pai, *Power System Dynamics and Stability*, Stripes Publishing, 2007

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
- Customers have been in control of their load

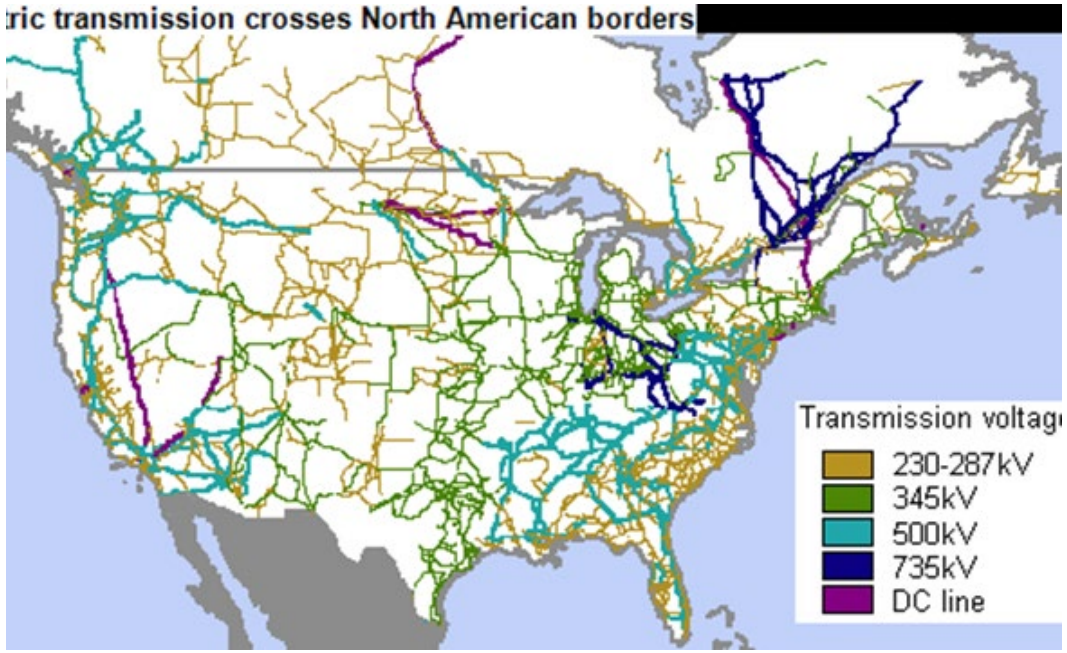


Image: US Energy Information Administration

- Transmission system has finite limits; often operated close to its limit for economic reasons

Changing Sources of Generation

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

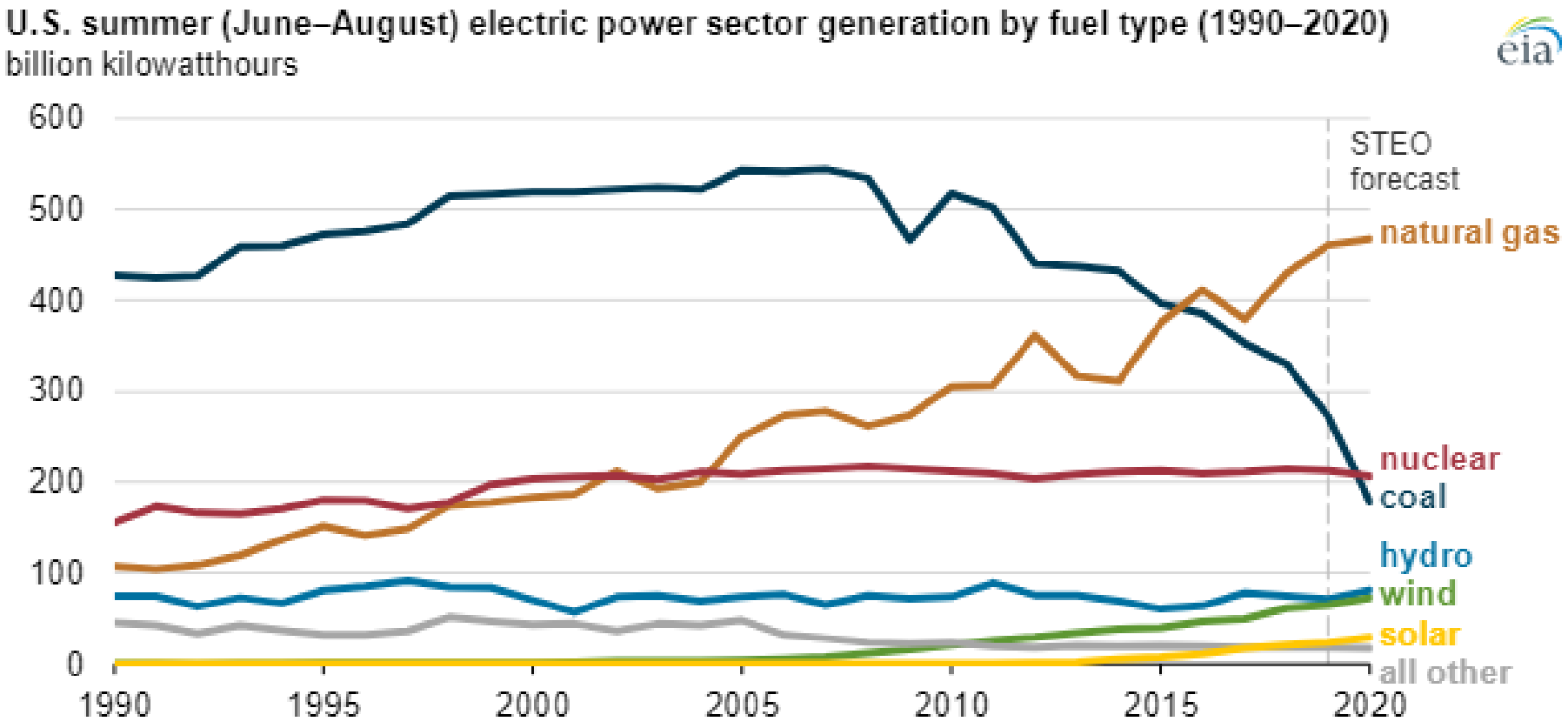
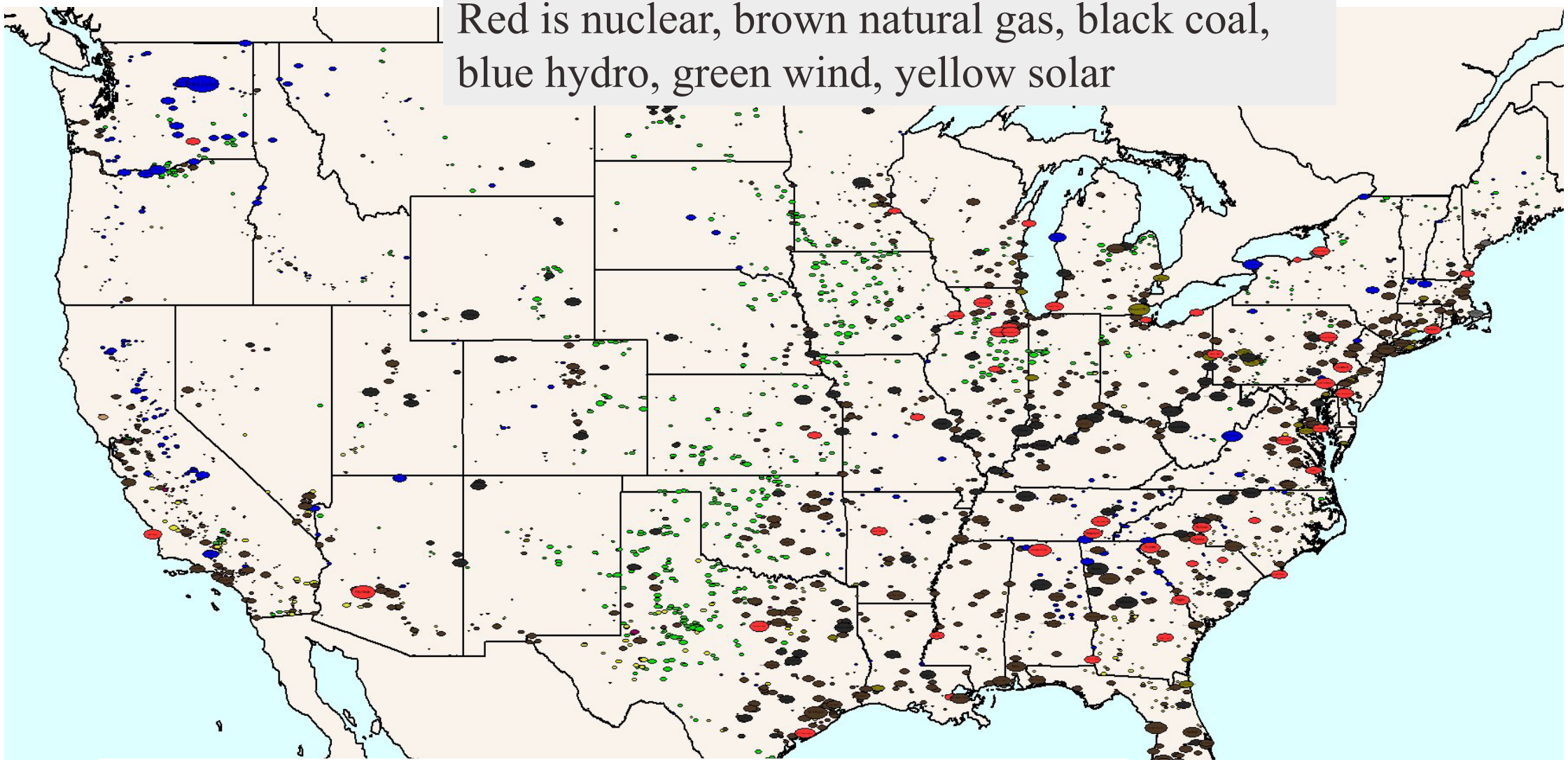


Image Source: www.eia.gov/todayinenergy/detail.php?id=44055

US Generation by Fuel Type (2021)

Red is nuclear, brown natural gas, black coal, blue hydro, green wind, yellow solar



Oval size is proportional to the substation generation; image shows public data from EIA Form 860, 2021

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

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

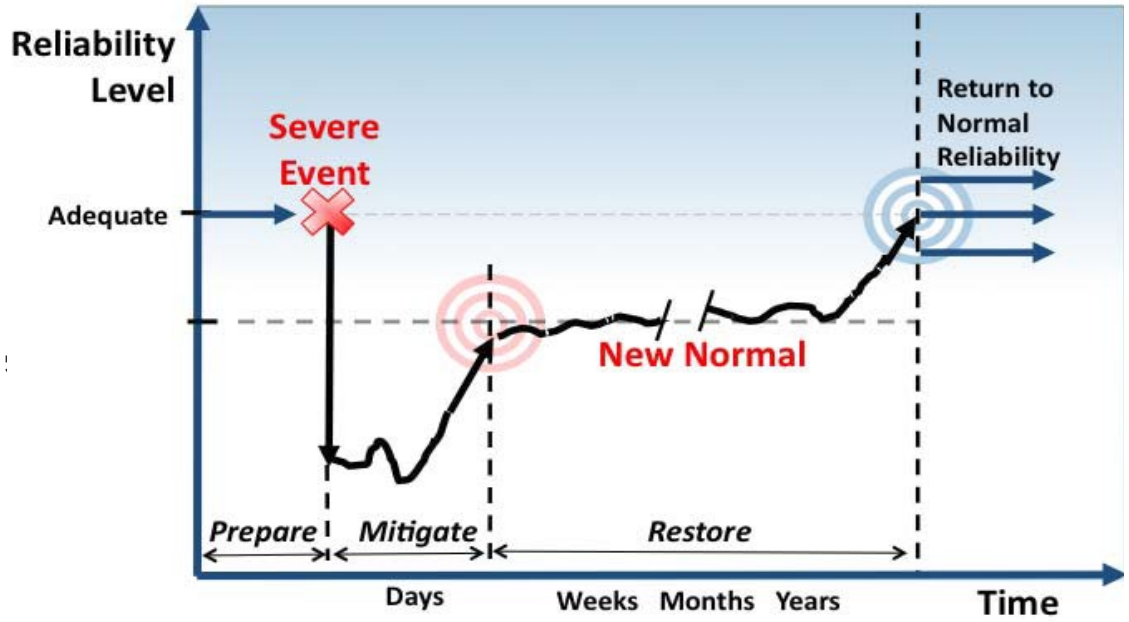


Image Source: NERC, 2012

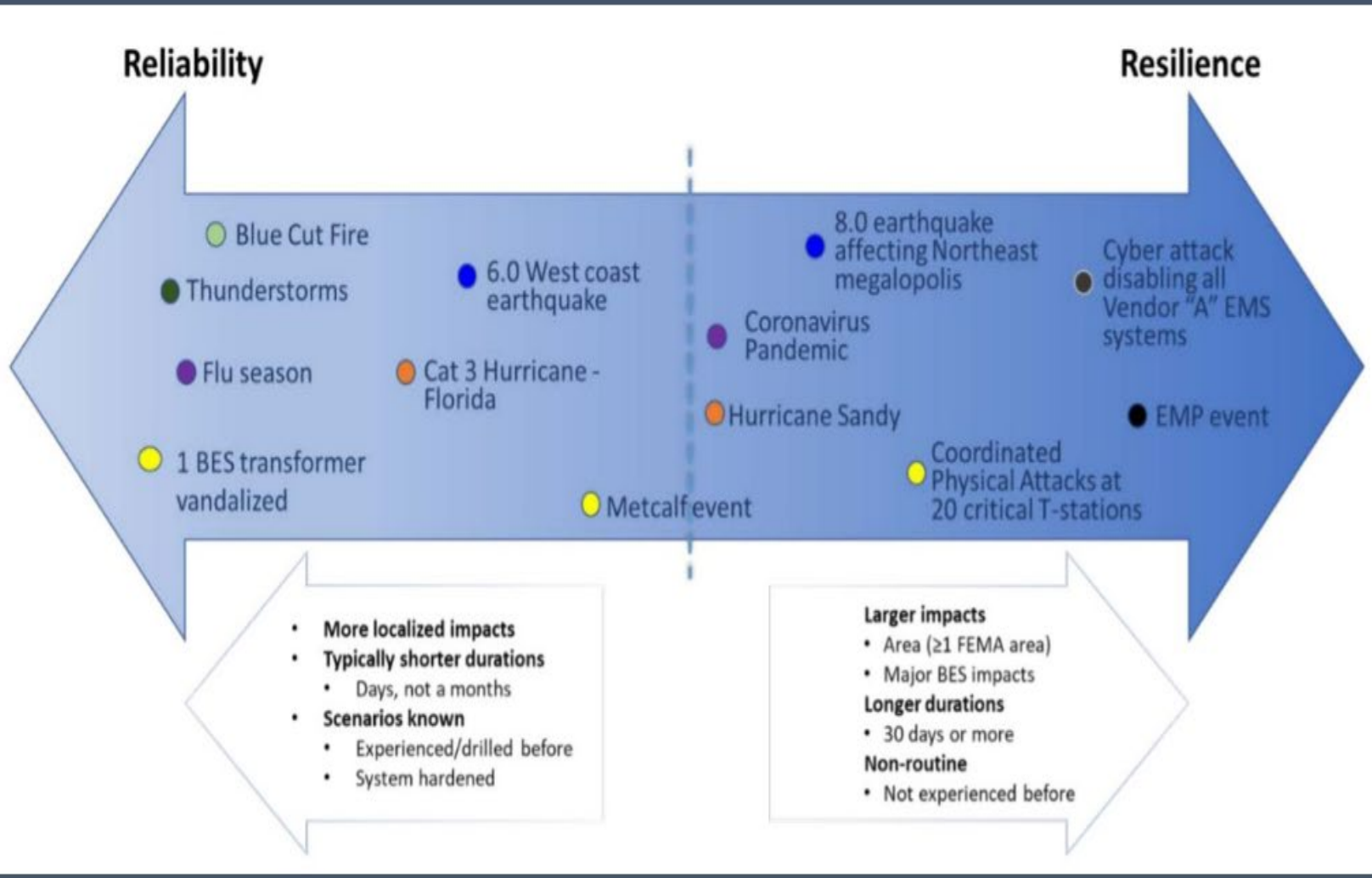
  - Large-scale, potentially long duration blackouts
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs

What is Grid Resilience?

- Merriam Webster Dictionary (resilience in general)
  - "An ability to recover from or adjust easily to misfortune or change"
- 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, Nov/2021

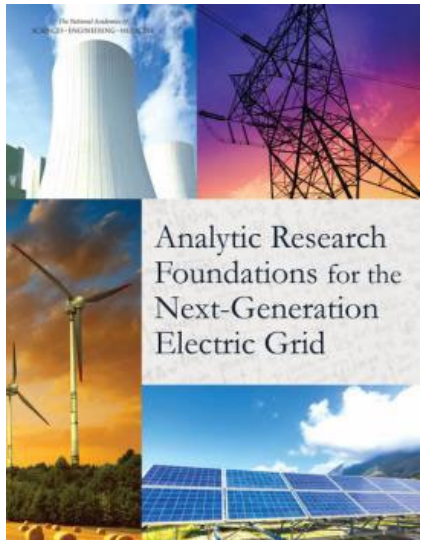
Reliability – Resilience Continuum

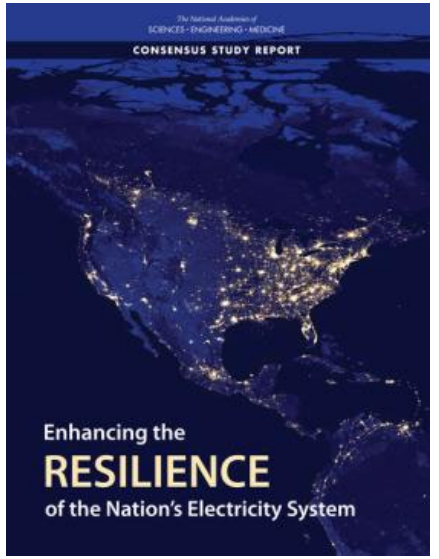


Slide is from the 53rd North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, November 2021; credit NATF

Several Recent Reports on Resiliency

- *Analytic Research Foundations for the Next-Generation Electric Grid*, 2016
  - Make everything as simple as possible but not simpler [maybe from Einstein]
- *Enhancing the Resilience of the Nation's Electricity System*, 2017
- US Department of Energy Transmission Innovation Symposium, May 2021
  - www.energy.gov/oe/transmission-innovation-symposium
- Focus here is on resiliency

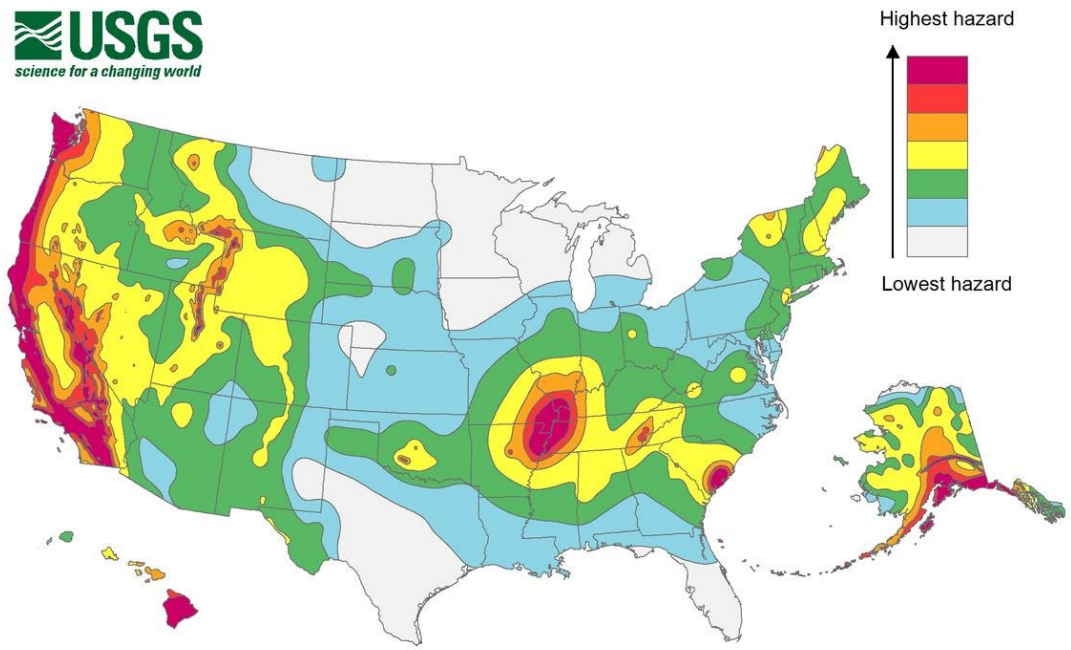




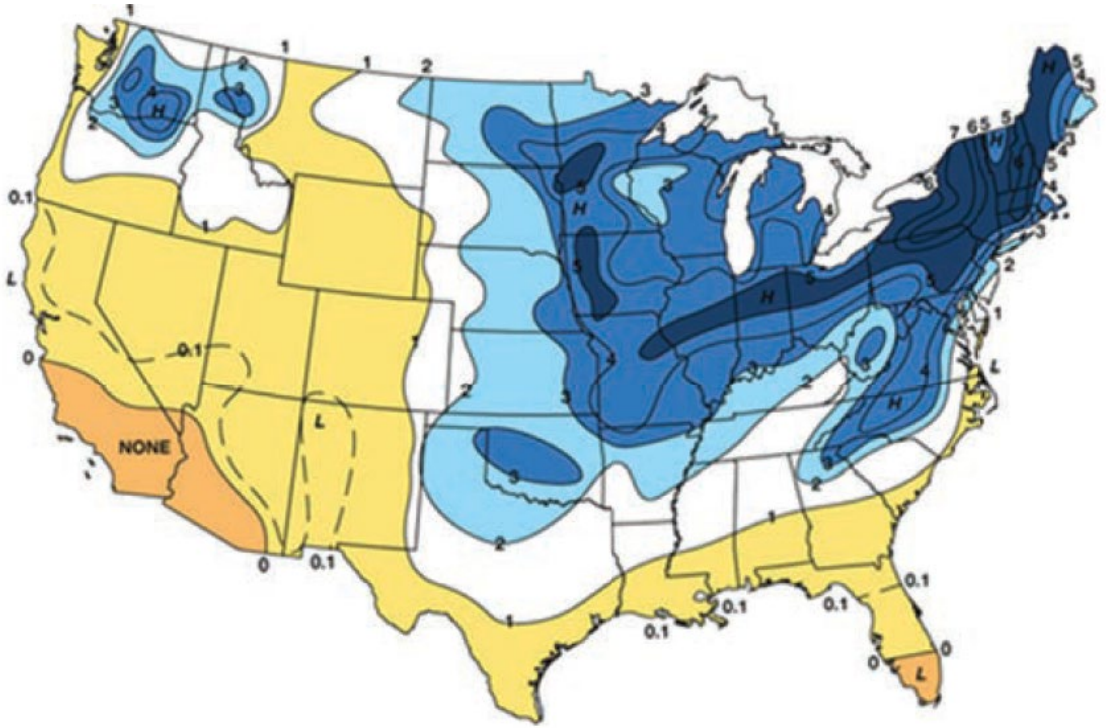
Resilient to What?

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

Earthquake Risk

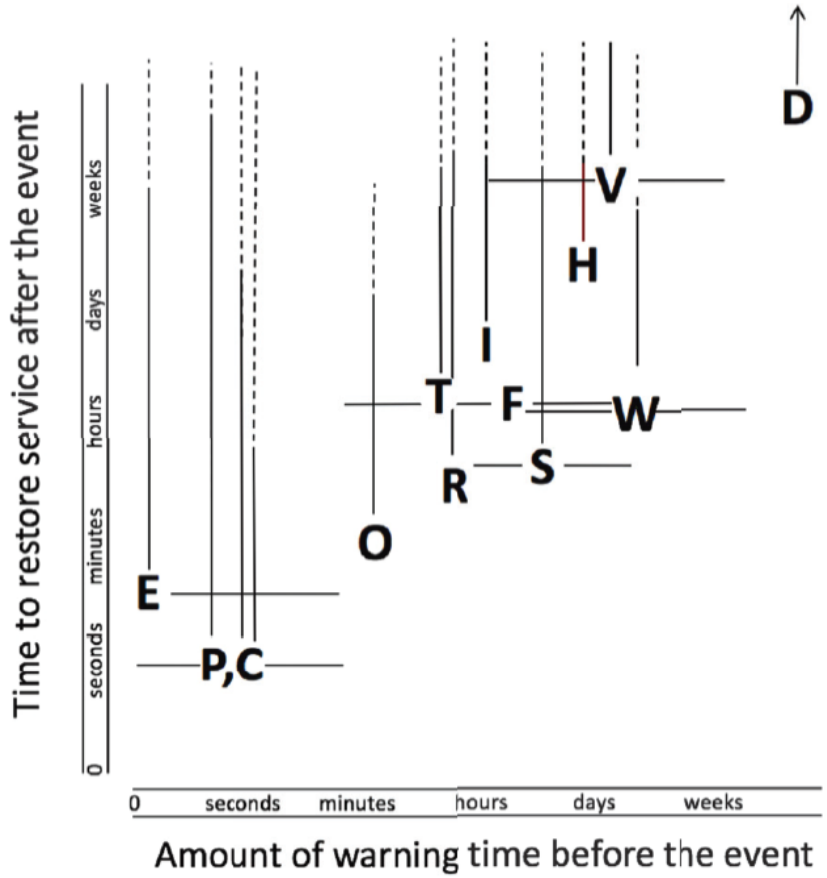


Freezing Rain Risk



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

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

This image does not mention cold weather, though it is discussed in the 2017 report

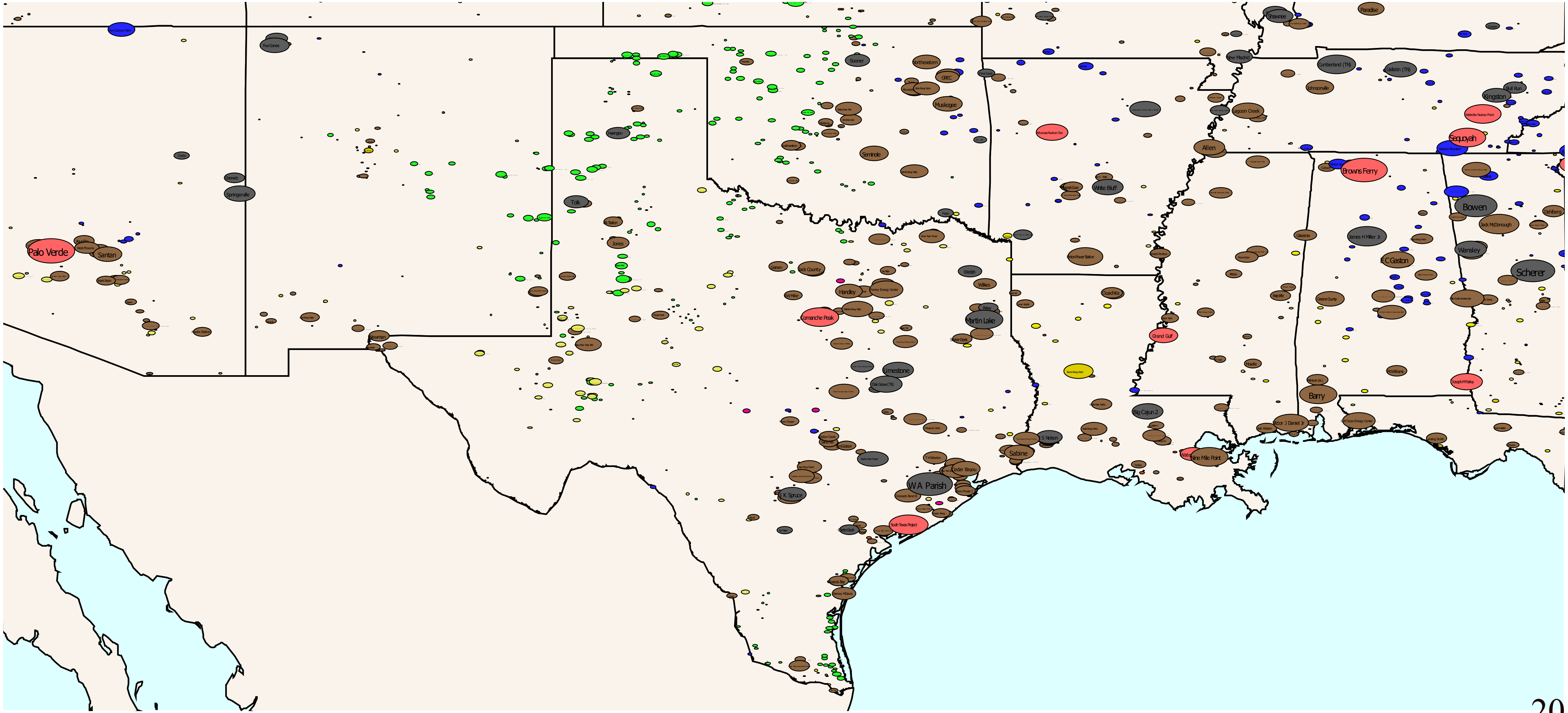
Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

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

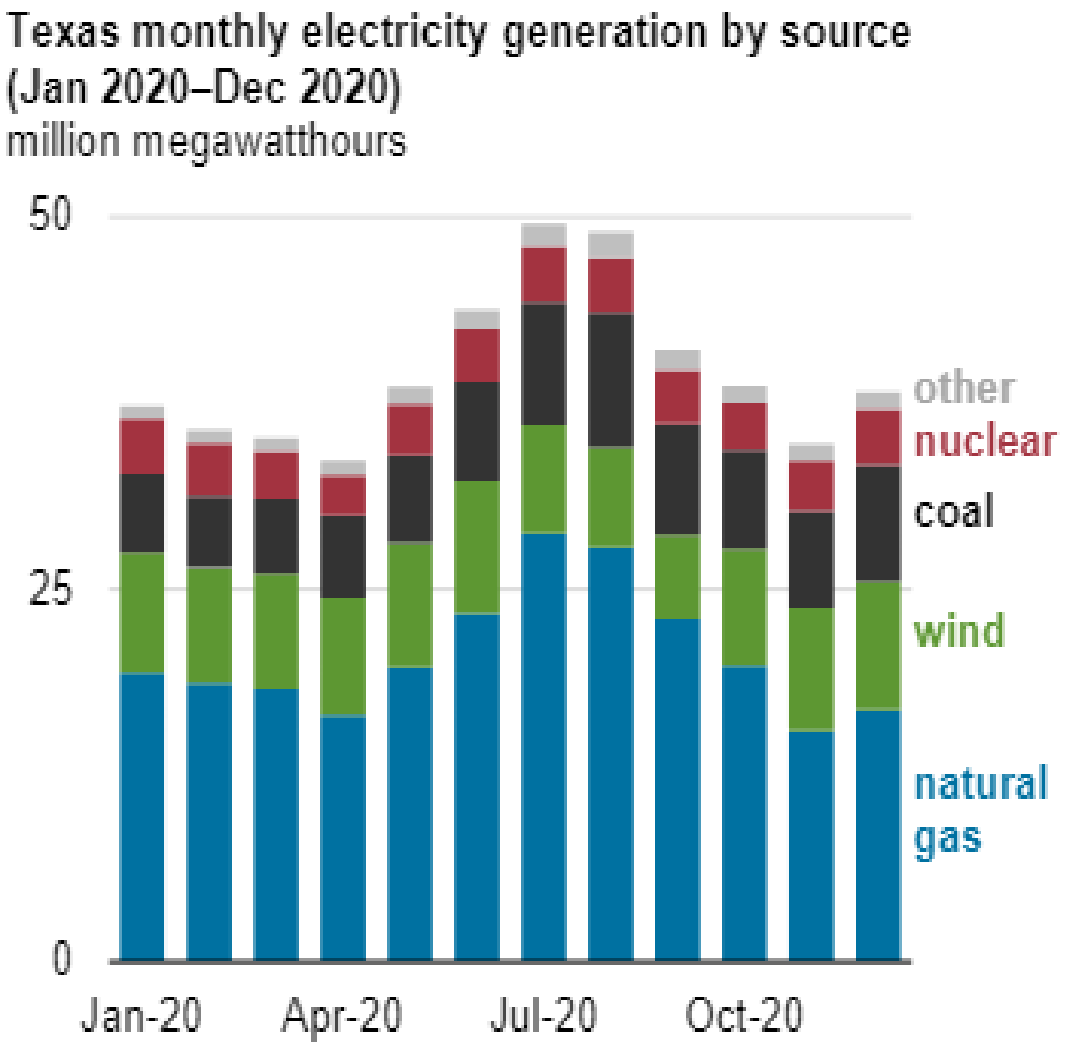
Texas Near Blackout, February 2021

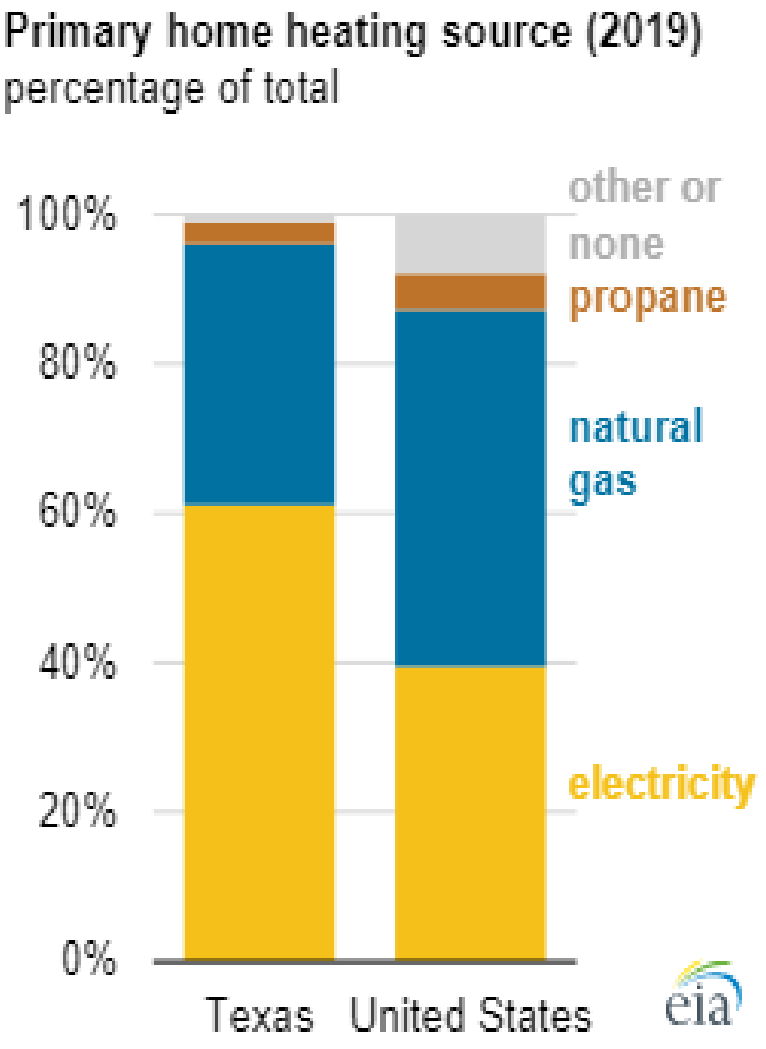
- Unfortunately, electric grids often make the news for all the wrong reasons!
- Starting on Feb 14, 2021 statewide Texas had temperatures much below avg., though not record cold
  - In College Station on Feb 15 is low was 9°F and very windy (and 5°F on Feb 16); avg. high is 65°F and low of 45°F
  - Our record low is -3°F (1/31/1949), our coldest February temperature was 5°F (2/5/1951) and last single digit was 9°F (12/22/1989)
- This stressed many infrastructures including the ERCOT electric grid

Zoomed View of Generation Sources, 2021



Texas Generation and Home Heating Sources

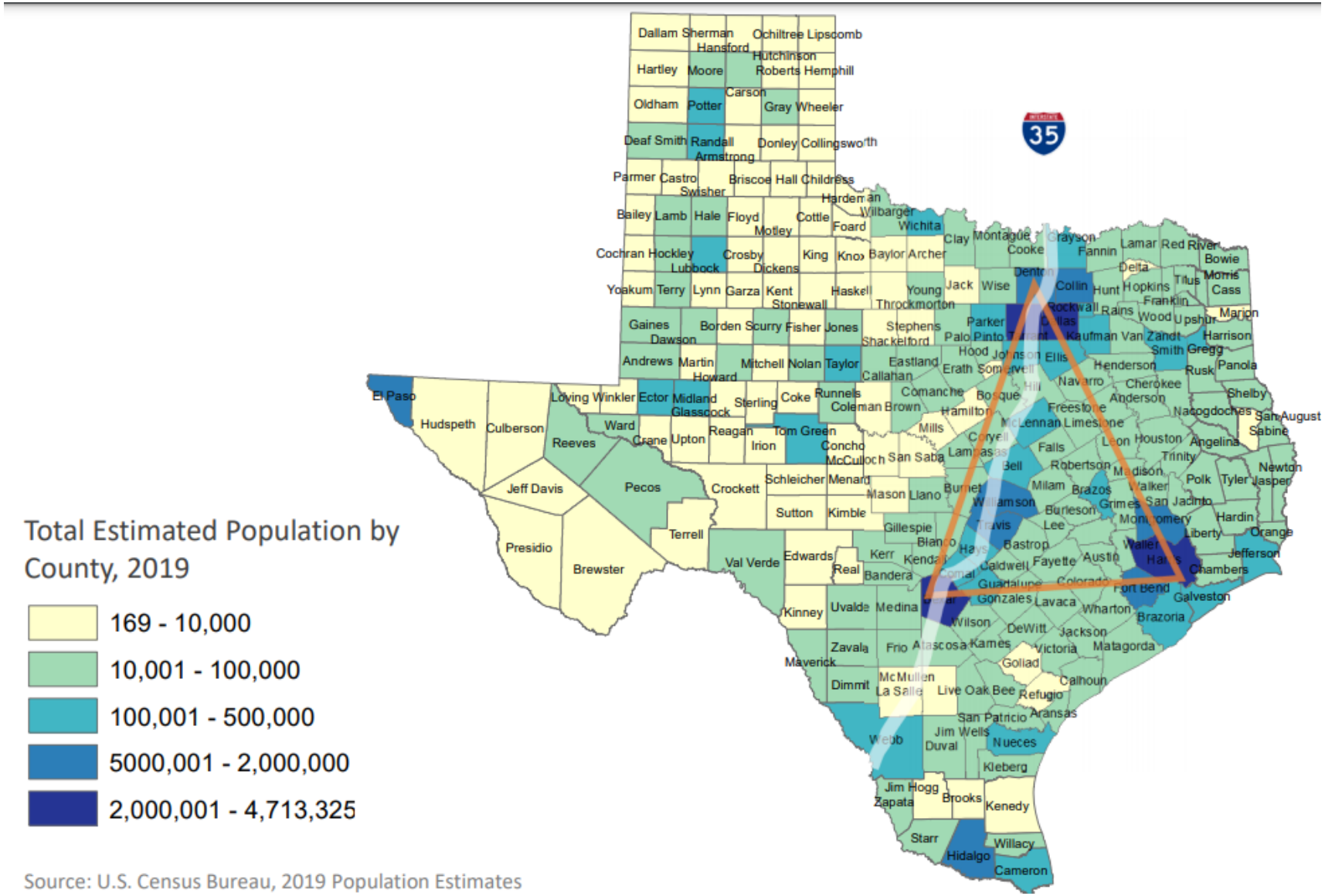




Texas population is growing, increasing 16% from 25.1 million in 2010 to 29.2 million on 2020

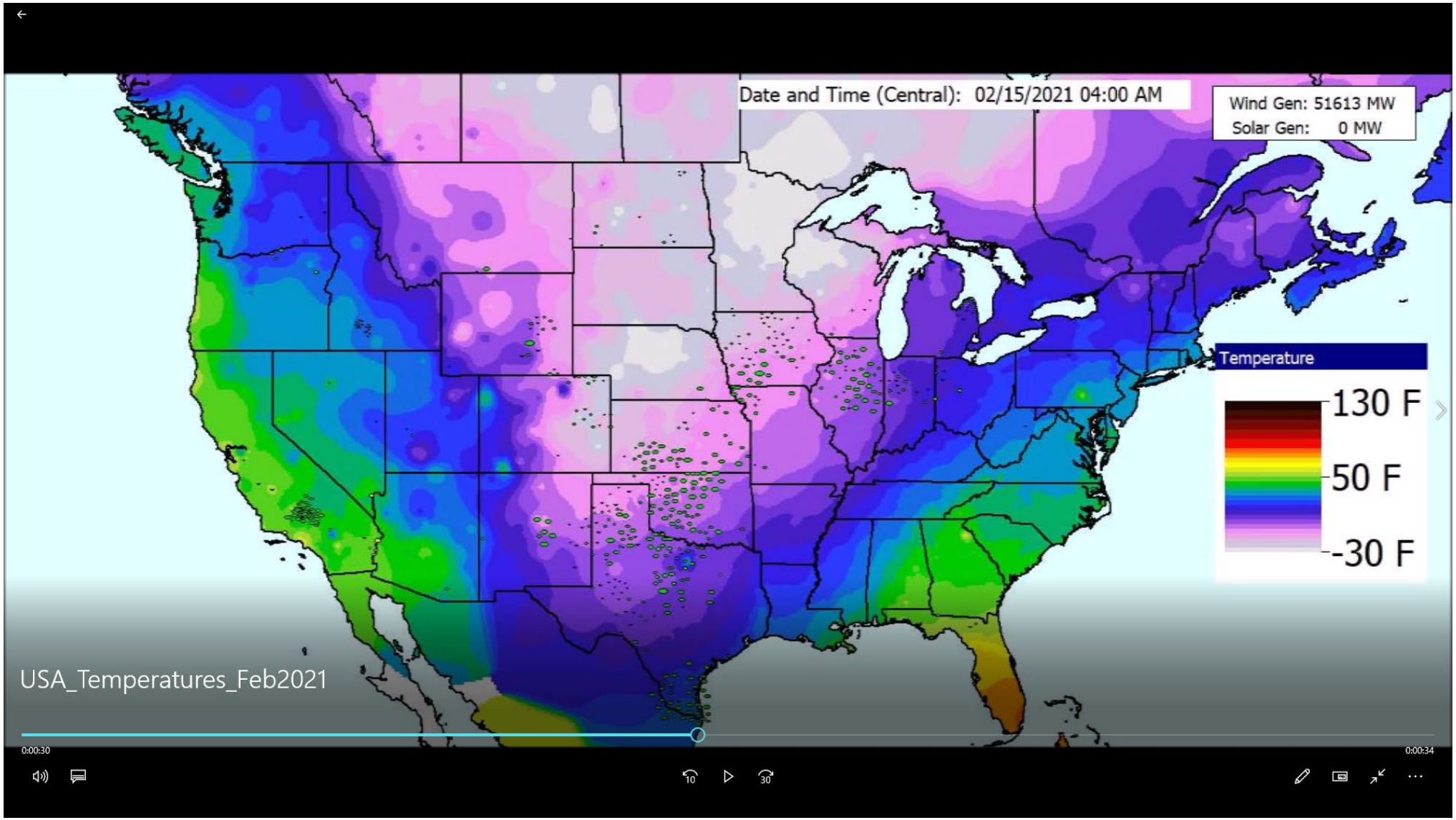
Image Source: www.eia.gov/todayinenergy/detail.php?id=47116

Texas Population Density



85% of population is along or east of the I35 corridor (DFW to Waco to Austin to San Antonio to Laredo)

Visualization of Temperatures, Feb 11 to 18, 2021



ERCOT Generation Feb 11-18, 2021

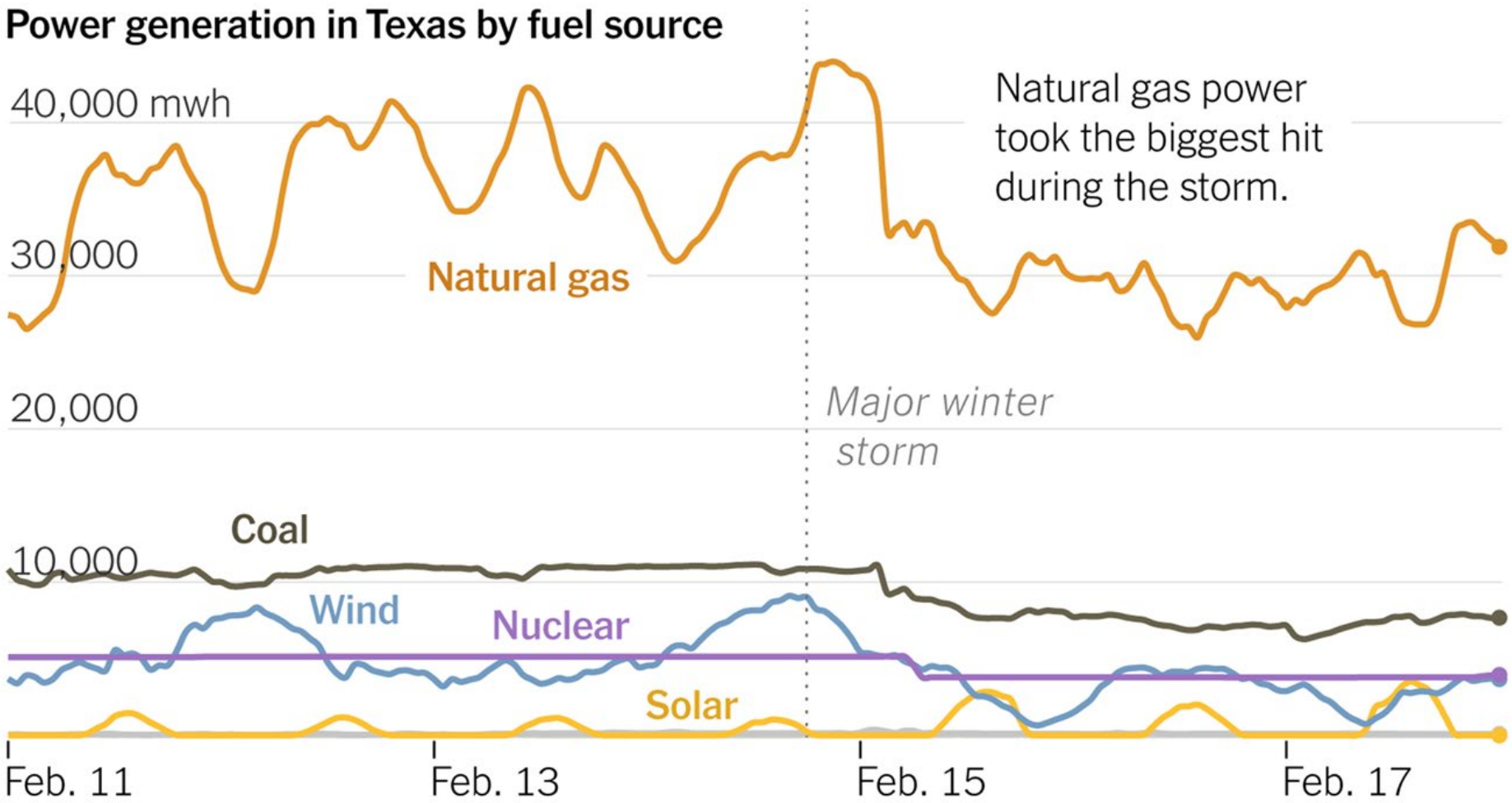
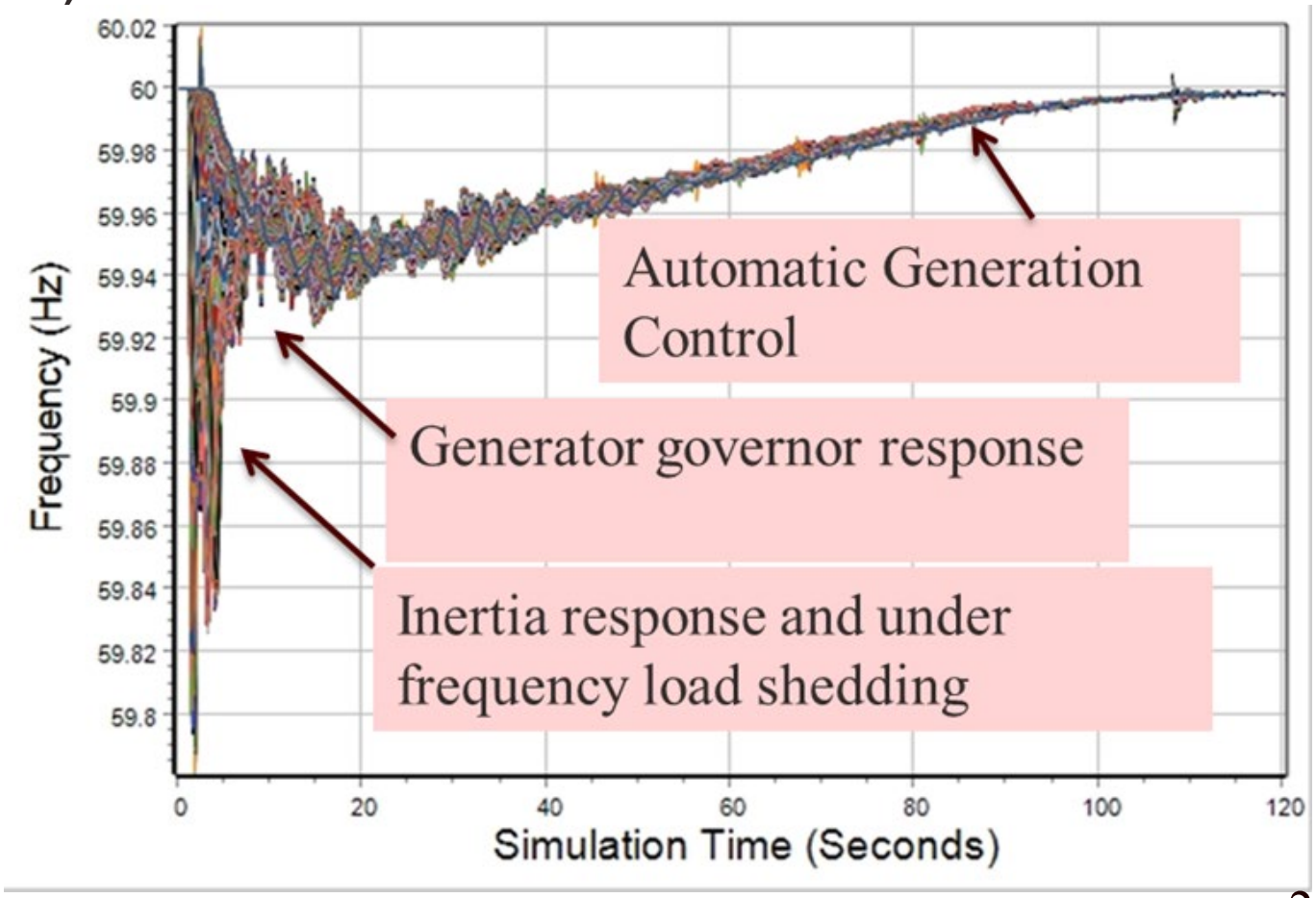


Image source: New York Times, Feb 23, 2021

Quick Aside: Power System Dynamic Response to Load/Gen Mismatch

- An electric grid frequency is constantly changing, but it usually within a few mHz of desired (e.g., 60 Hz)
- Too much generation increases the frequency and too little decreases it
- All grid elements have the same average frequency but during disturbances the frequency can oscillate



ERCOT Frequency, Feb 15, 2021

Rapid Decrease in Generation Causes Frequency Drop

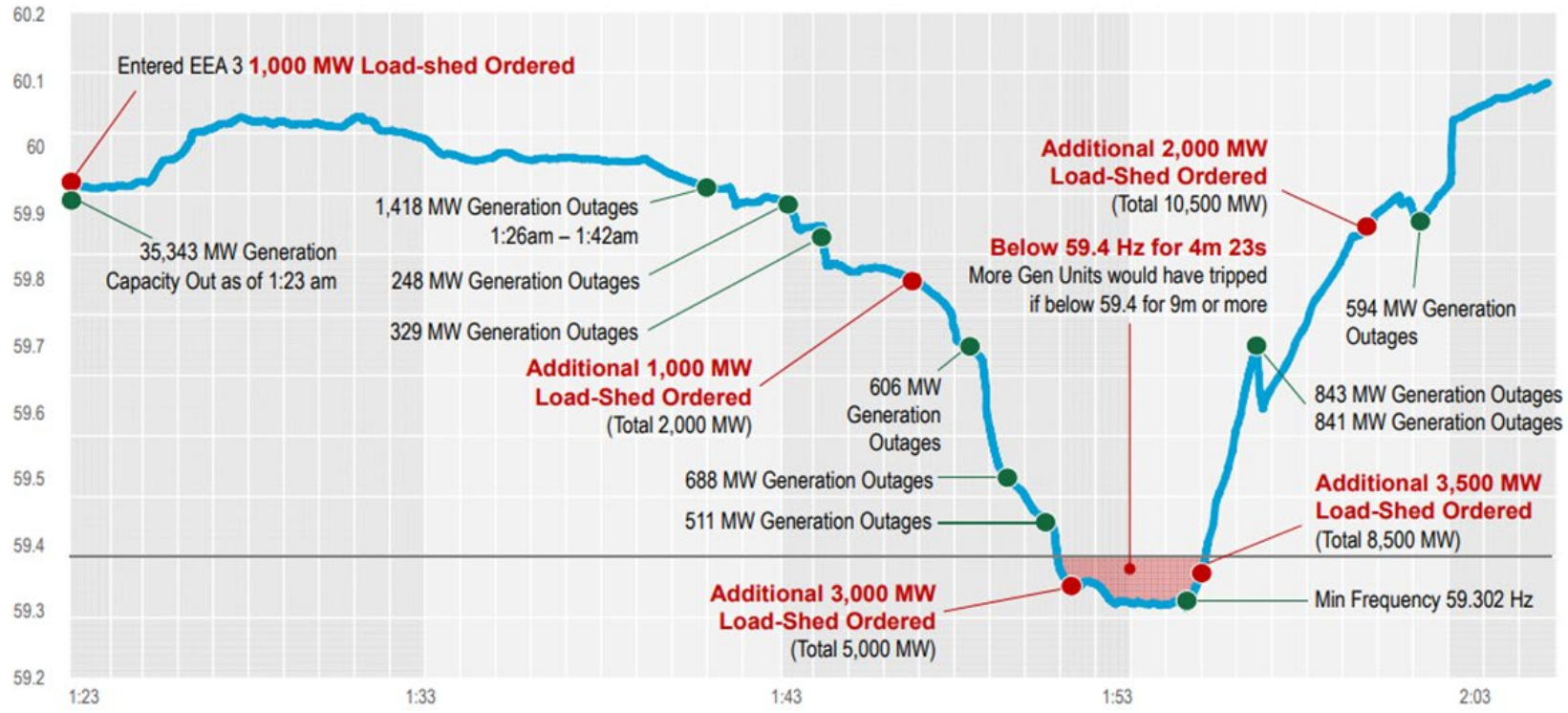


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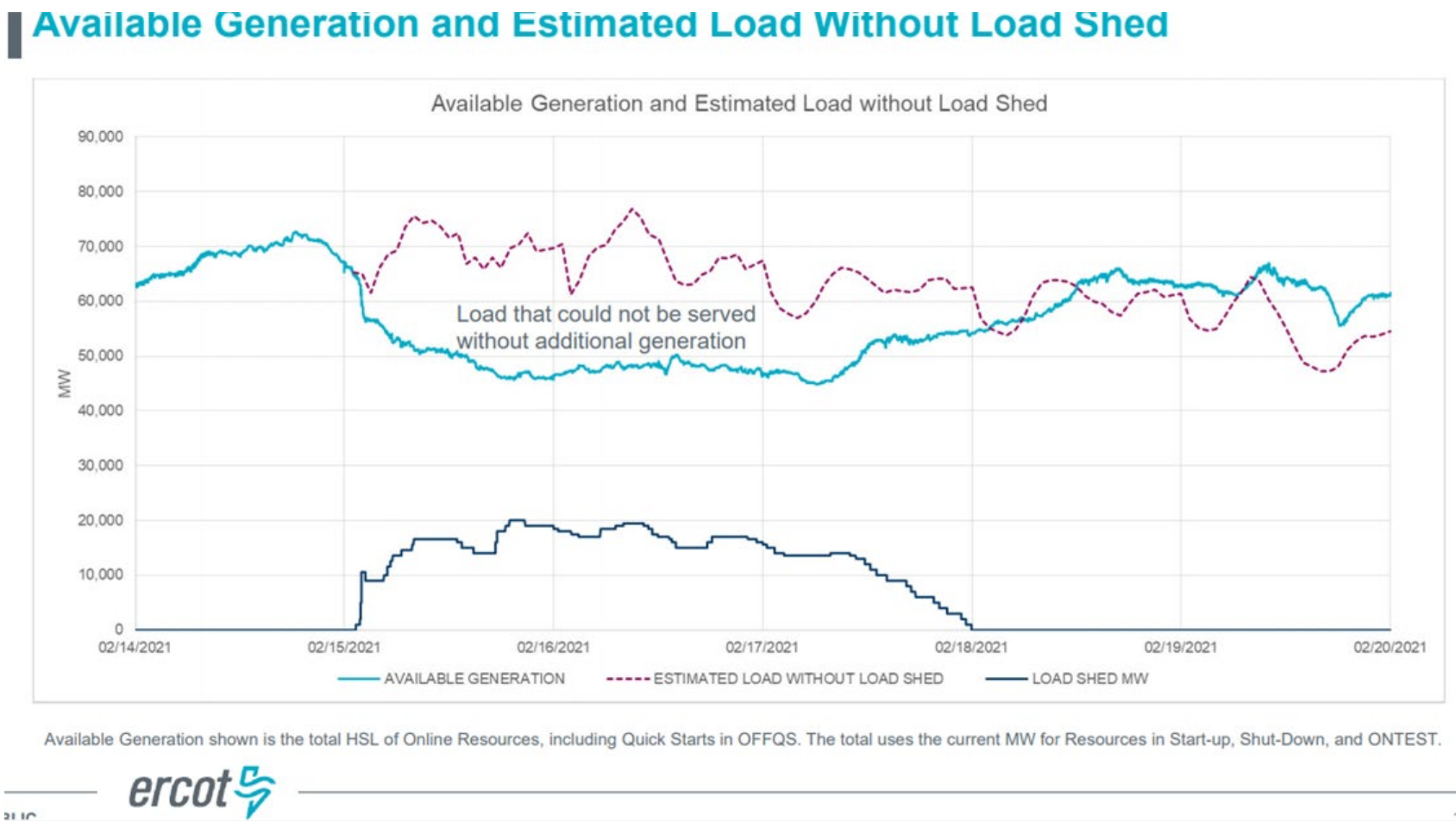
Image source: ERCOT Presentation by Bill Magness, February 25, 2021

ERCOT Load Shed and Rotating Blackouts

- The vast majority of the lost load was due to load shed and then rotating blackouts

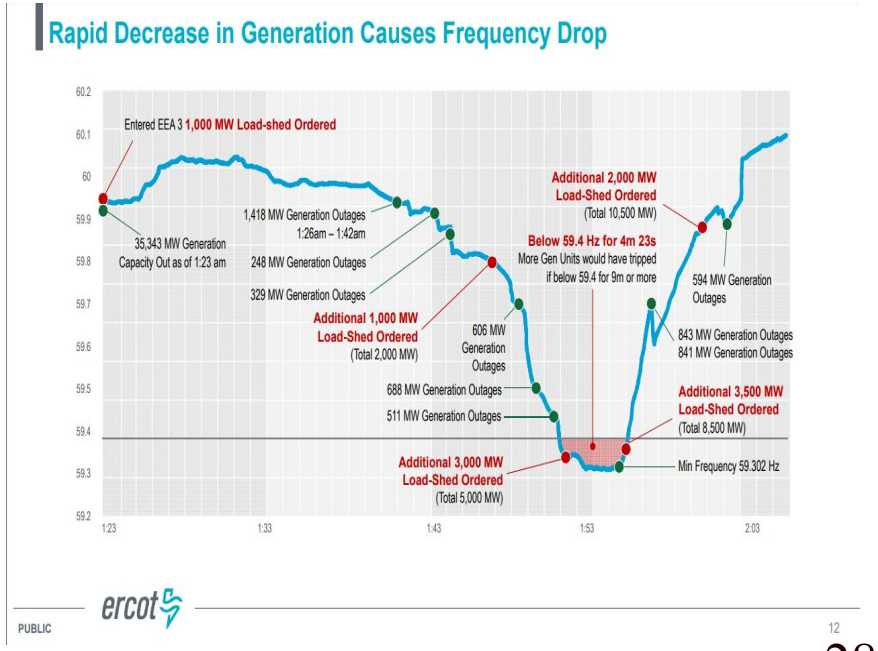


At the time the ERCOT peak load had been 74.8 GW (summer); winter peak of 69.2 GW was set on 2/14/21 (previous winter peak was 65.9 GW). A new peak of 80 GW was set on 7/20/22.

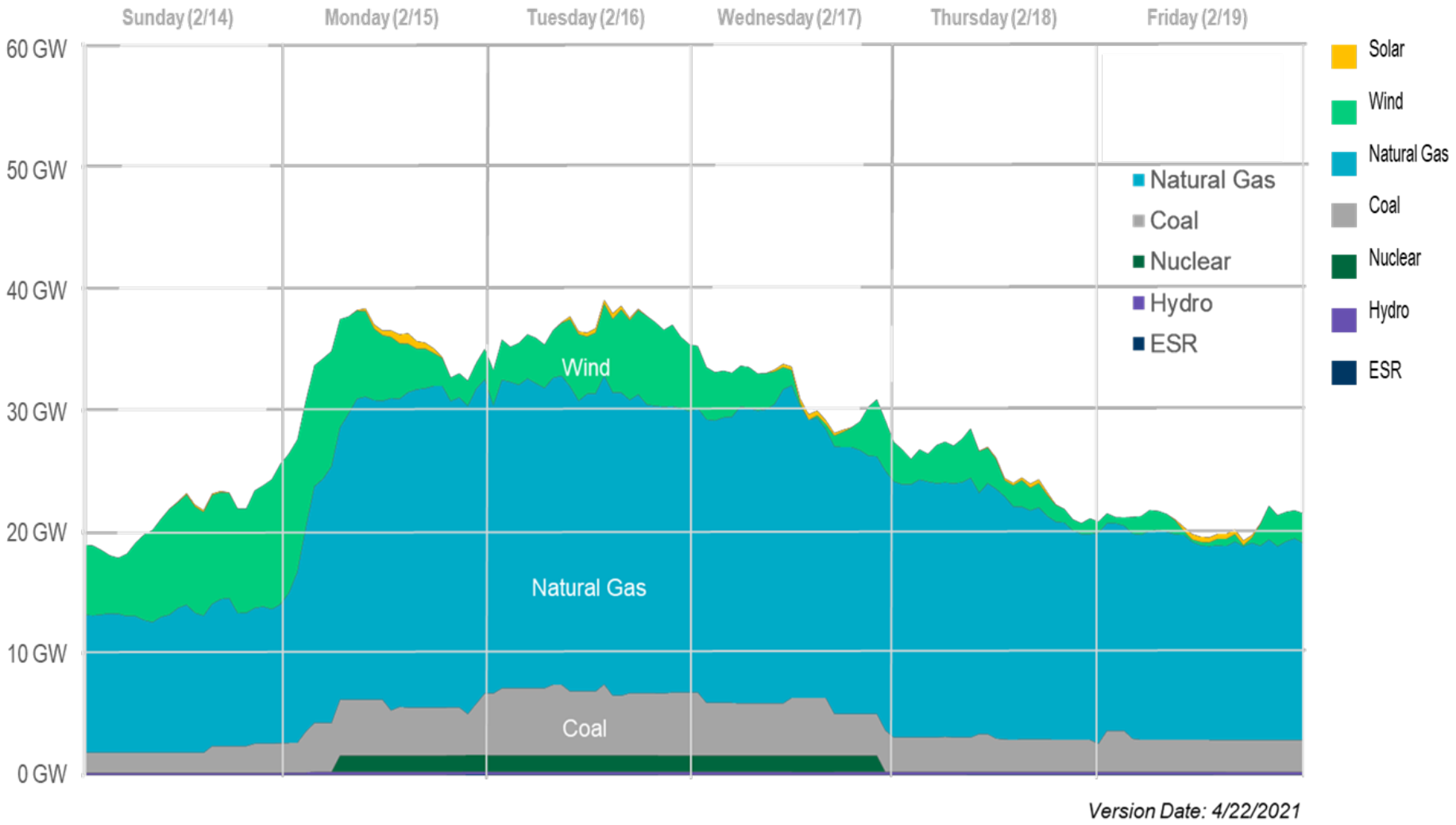
Image source: ERCOT Presentation by Bill Magness, February 25, 2021

How can Grids Cascade?

- ERCOT reported that they were minutes away from a catastrophic blackout that would have taken down the entire grid, requiring many days to restore
- Grids can cascade due to a number of different reasons with many related to the transmission grid flows and voltages
- For ERCOT the situation was the prolonged (minutes) low frequency would have result in generators tripping due to under frequency resulting in a cascading collapse in the frequency and hence the entire system



How Much Generation was Lost?



Wind and solar MW values based on estimated lost output due to outages and derates from slides 15 and 16.

This slide correctly recognizes that much of the wind capacity that was not available due to the cold, would not have been generating much because of low wind.

Winterizing Wind Turbines

- In general wind turbines can operate in quite low temperatures
- However, most of the wind turbines in Texas were not configured with the systems needed to deal with low temperatures
  - They mostly were not available because of turbine blade icing
- Wind turbines can be winterized with systems such as heated blades or coatings; packages can also be installed to protect the gearbox and motors, such as adding heating to the nacelle

Background: Why is ERCOT Separate?

- ERCOT operates asynchronous from the rest of North America, but has high voltage dc (HVDC) ties with the Eastern Interconnect and Mexico
- The advantage is ERCOT avoids some federal regulation. The legal basis for this is complex, based on the US Constitution, the Federal Power Act, the 5/4/76 midnight connection, other legislation, court rulings, and FERC decisions

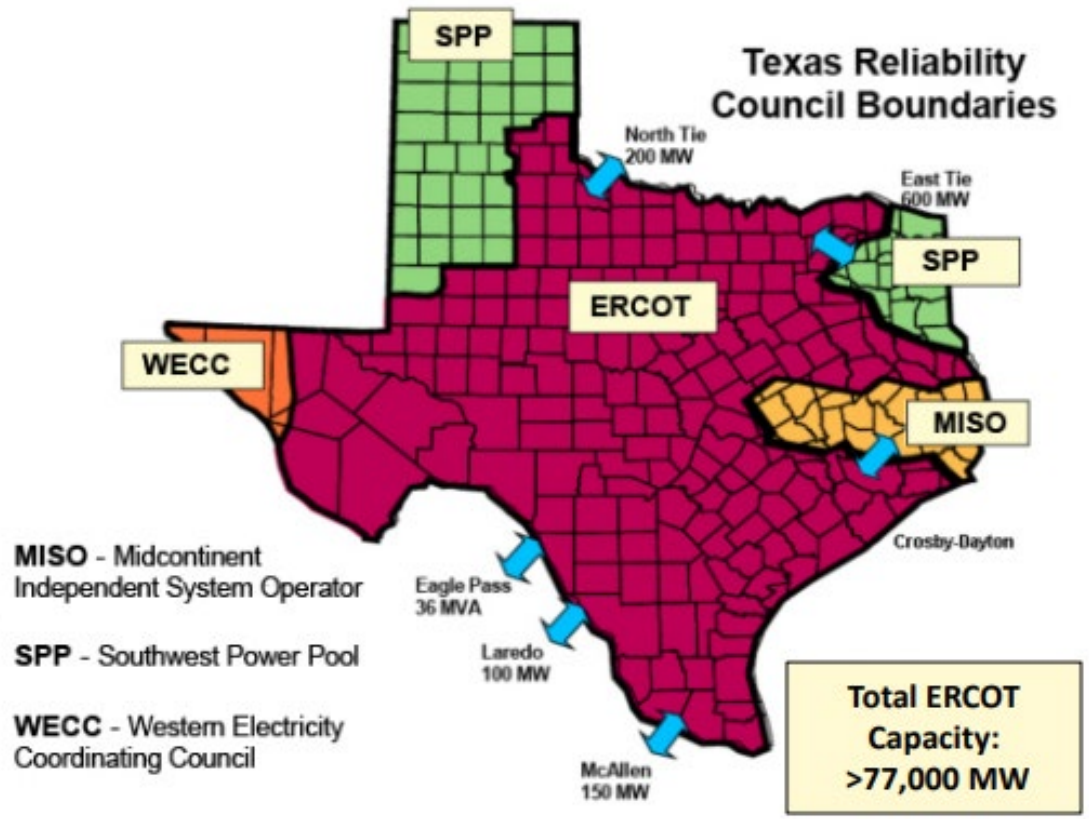
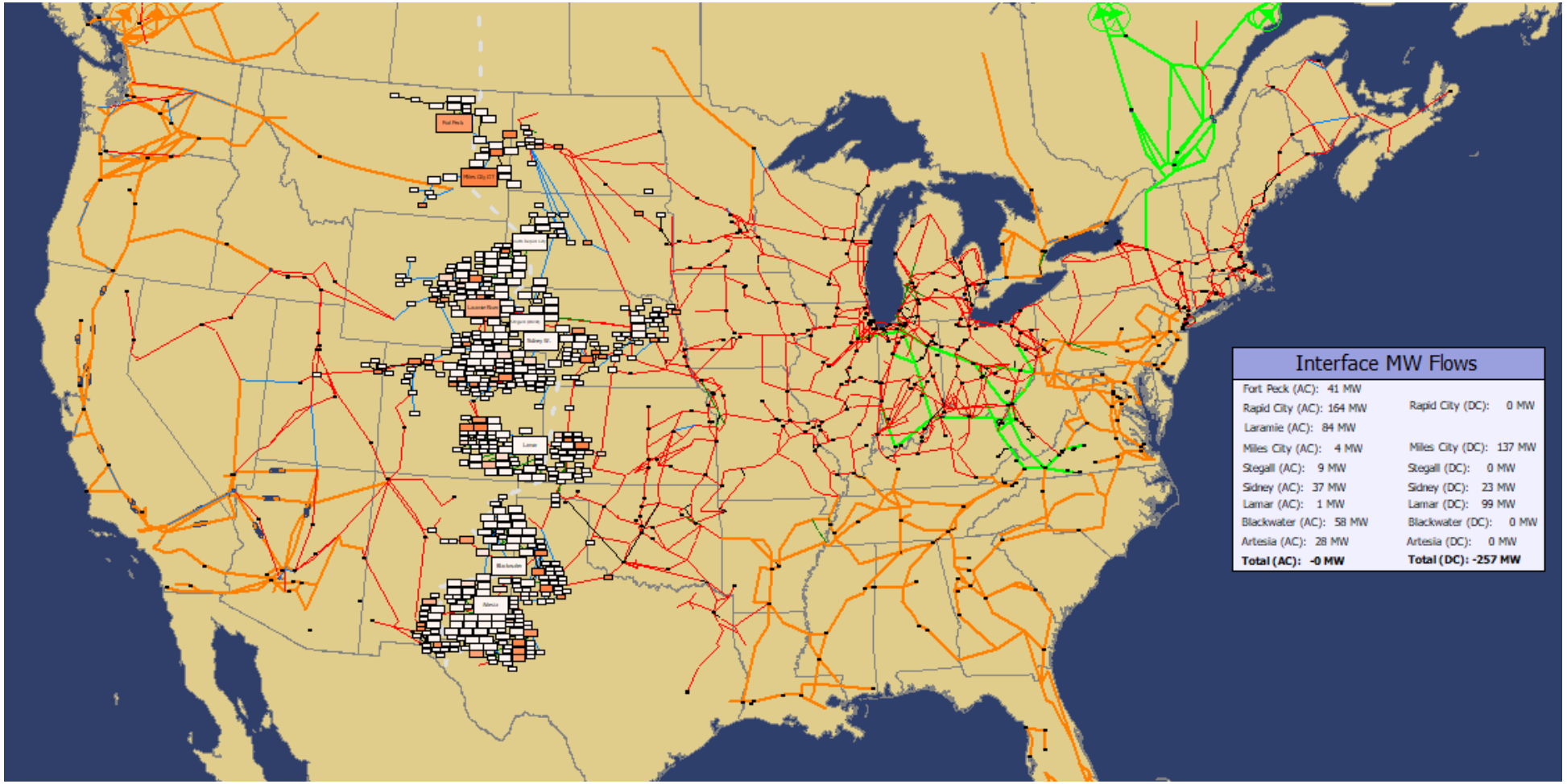


Image Source: aect.net/documents/2017/AECT%20LSB%20012617.pdf

Joining the East and West Grids

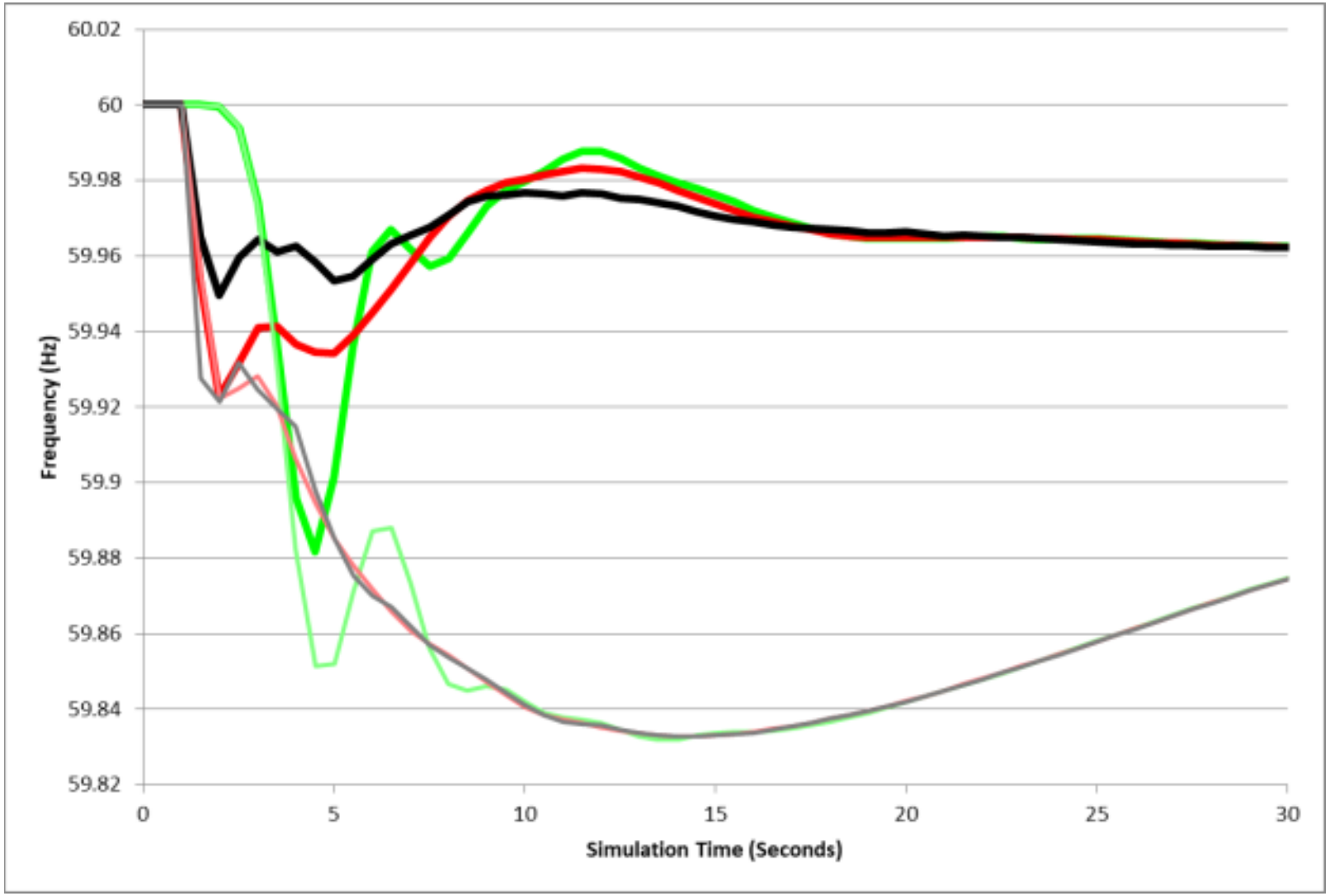
- In 2020 we did a research project for SPP looking at an ac interconnection of the East and West grids
  - This did not include ERCOT, but did include parts of Texas
- There are nine locations where the grids are close and could be tied together
- The study required lots of dynamic simulations using quite detailed full system models (transient stability level, 110,000 buses)
- The result was there are no show stoppers to doing this, and there could be good benefits!
- We have just started (Fall 2022) a follow-up project, looking more at the economic benefits

East-West Combined Grid



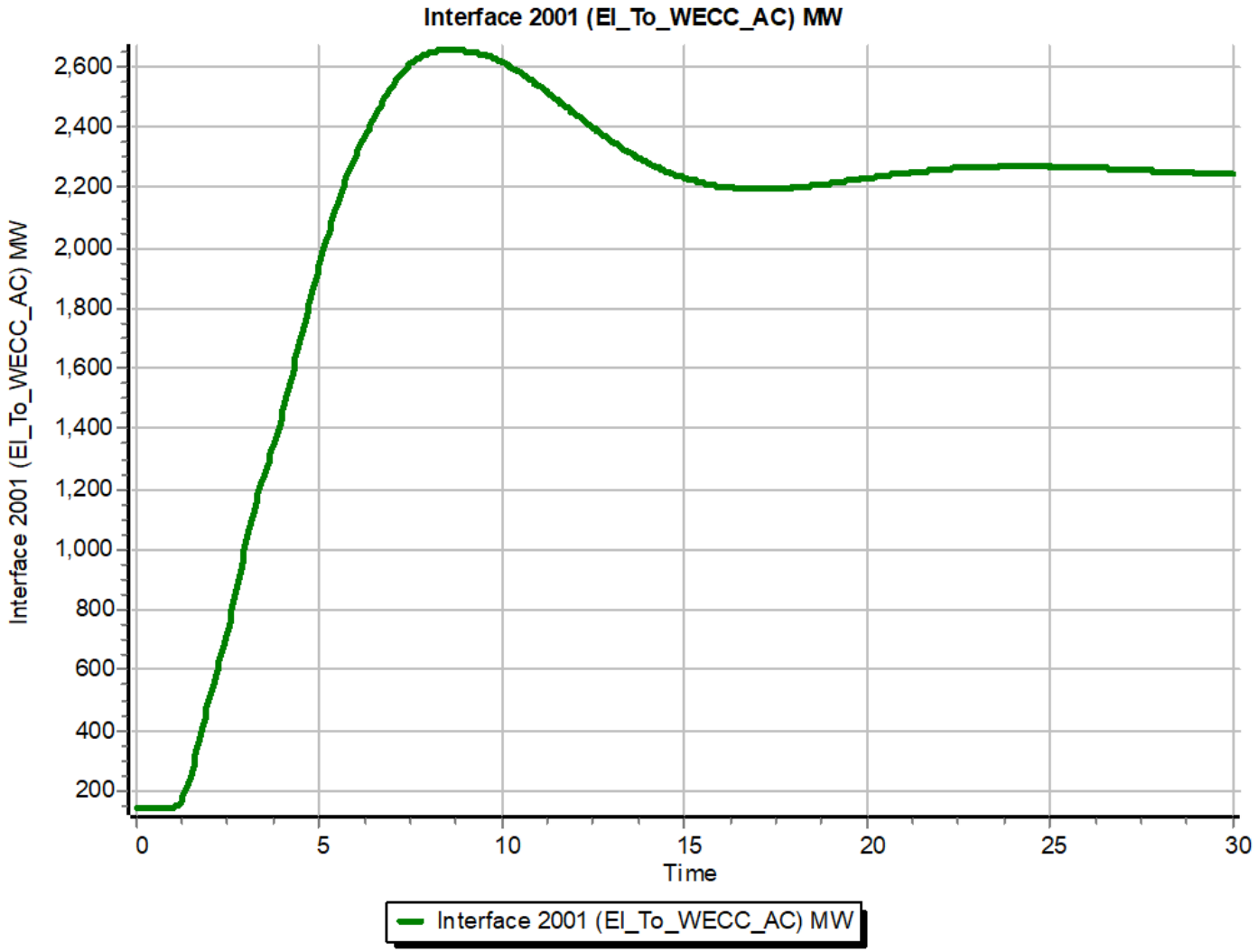
The study included Canada but we did not consider any ac interconnections between the grids in Canada; the grids were connected at nine points from Montana to New Mexico

WECC Frequency Response: With and Without the AC Interconnection



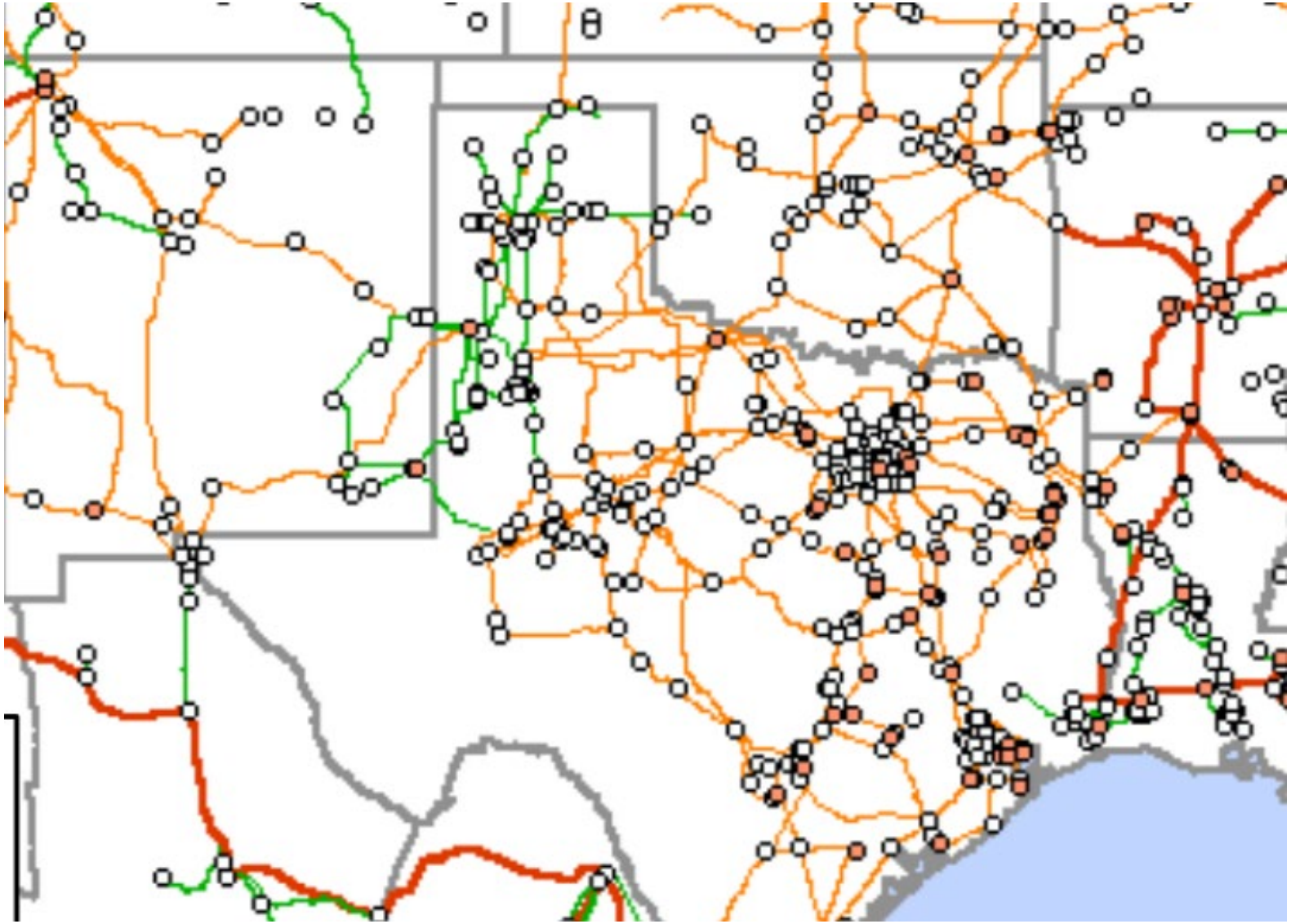
The graph compares the frequency response for three WECC buses for a severe contingency with the interface (thick lines) and without (thin lines)

AC-Tie Interface, Severe Contingency



The large, and seemingly persistent, change in the interface flow required the need for modeling the system's longer term AGC response.

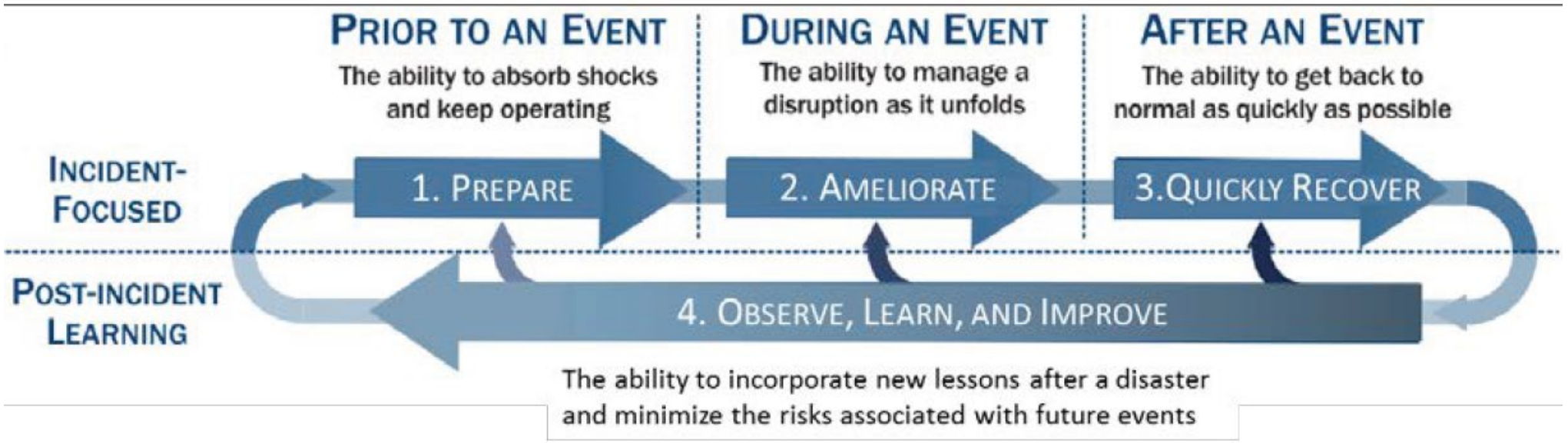
ERCOT-East-West Transmission



Orange is 345 kV,
Red is 500 kV

An ac interconnection would probably be the least expensive approach to greatly increase the ERCOT import/export capability, assuming it did not change the current regulation approach

Back to General Resilience: The Four Stage 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.

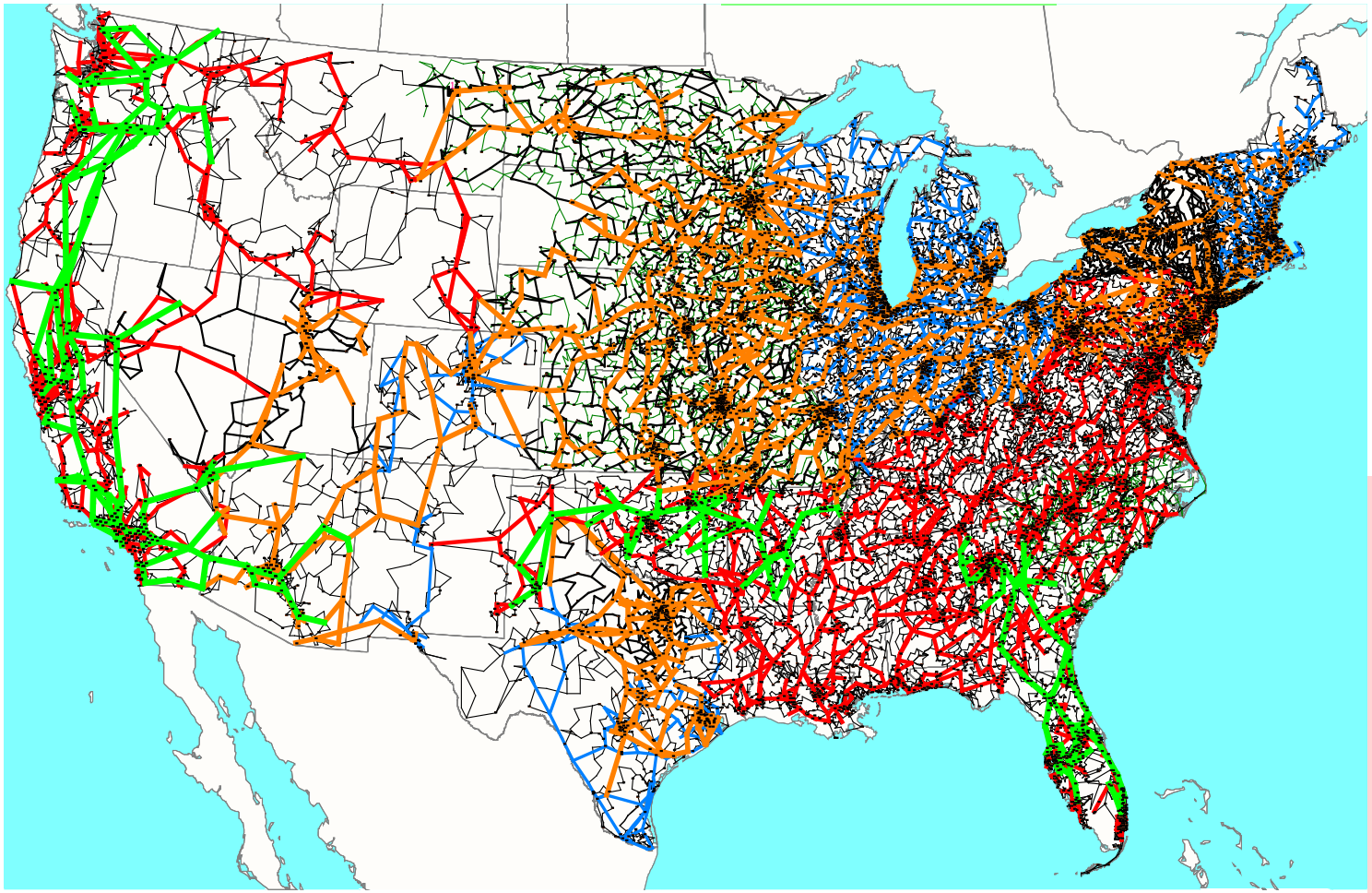
How to Approach HILF Events

- 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

82,000 Bus Synthetic Grid



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

We hope to develop models for other countries and are in the process of adding additional detail; creating realistic synthetic grids is challenging since real grids involve lots of engineering

Resilience and Grid Size

- There is no optimal ac grid size for resiliency
  - Larger grids can share resources, particularly during emergencies, and can provide access to larger power markets
  - But larger grids also open up the risk to cascading outages, potentially causing large scale blacks
  - The world's largest grids are 1) State Grid of China (900 GW), 2) Continental Europe (850 GW), 3) North American Eastern Interconnect (650 GW)
- Probably the most effective approach is to have grids the can flexibly breakup into smaller grids (known as adaptive islanding

General Grid Resilience Comments

- Understanding resilience requires considering how grids will respond to particular disturbances
- Substantially changing the topologies of existing grids is usually not an option
- Simplistic studies of how a grid disturbance could cascade often lead to incorrect conclusions
  - Sequential power flows, sequentially taking out overloaded devices are not particularly helpful
- Full detail models of large-scale actual grids including the protection system usually don't exist and modeling them would requiring knowing the associated remedial action schemes

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 societies become more dependent on electricity, short and small duration blackouts become more concerning, and large-scale, long duration outages can be catastrophic
- There are many couplings between electric grids and other infrastructures such as natural gas, water, cyber, and increasing transportation
- These couples need to be more fully considered in electric grid resiliency modeling and simulation

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 societies worldwide, 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?