

# **ECEN 615**

## **Methods of Electric Power Systems Analysis**

### **Lecture 25: Auctions, Electric Grid Resiliency**

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**TEXAS A&M**  
UNIVERSITY

# Security Constrained OPF

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- Security constrained optimal power flow (SCOPF) is similar to OPF except it also includes contingency constraints
  - Again the goal is to minimize some objective function, usually the current system cost, subject to a variety of equality and inequality constraints
  - This adds significantly more computation, but is required to simulate how the system is actually operated (with N-1 reliability)
- A common solution is to alternate between solving a power flow and contingency analysis, and an LP

# Security Constrained OPF, cont.

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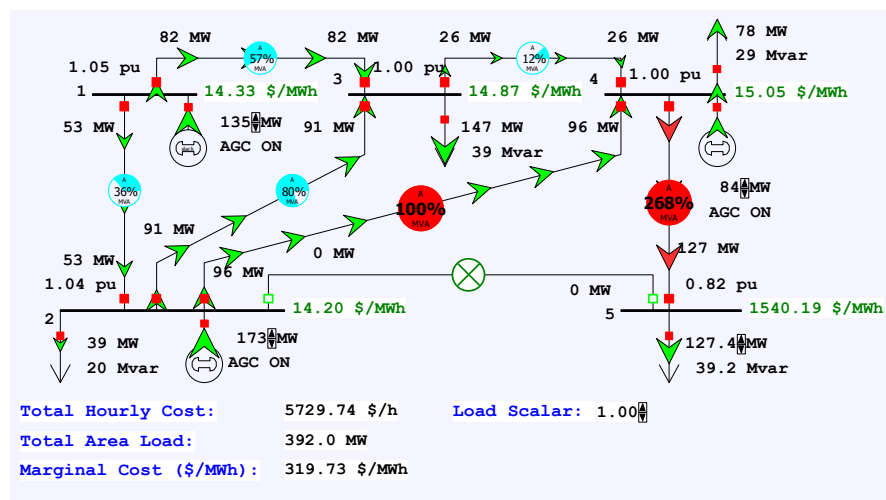


- With the inclusion of contingencies, there needs to be a distinction between what control actions must be done pre-contingent, and which ones can be done post-contingent
  - The advantage of post-contingent control actions is they would only need to be done in the unlikely event the contingency actually occurs
- Pre-contingent control actions are usually done for line overloads, while post-contingent control actions are done for most reactive power control and generator outage re-dispatch

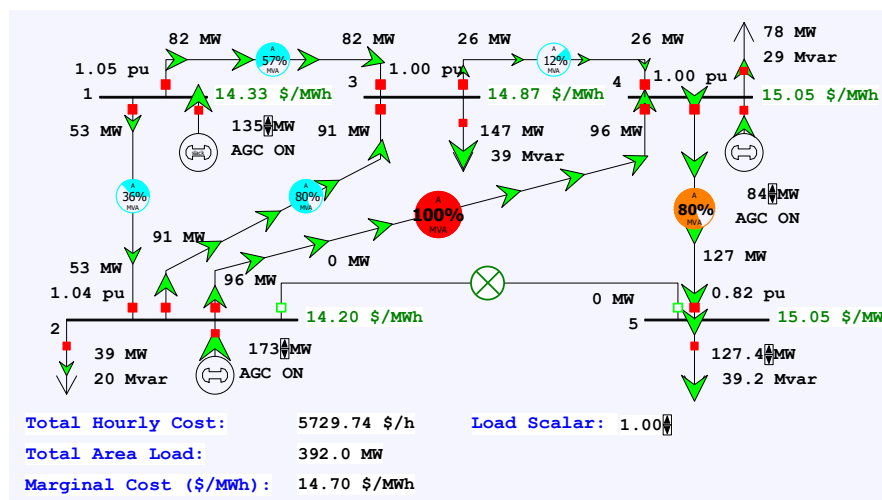
# SCOPF Example



- We'll again consider Example 6\_23, except now it has been enhanced to include contingencies and we've also greatly increased the capacity on the line between buses 4 and 5; named Bus5\_SCOPF\_DC



Original with line 4-5 limit of 60 MW with 2-5 out



Modified with line 4-5 limit of 200 MVA with 2-5 out

# PowerWorld SCOPF Application



Just click the button to solve

Security Constrained Optimal Power Flow Form - Case: Example6\_23

File Case Information **Run** Onlines Tools Options Add Ons Window

Run Full Security Constrained OPF Close ? Help Save As Aux Load Aux

SCOPF Status SCOPF Solved Correctly

Options

- Results
  - Contingency Violations
  - Bus Marginal Price Details
  - Bus Marginal Controls
- LP Solution Details
  - All LP Variables
  - LP Basic Variables
  - LP Basis Matrix

Options

SCOPF Specific Options

Maximum Number of Outer Loop Iterations 1

☒ Consider Binding Contingent Violations from Last SCOPF Solution

☒ Initialize SCOPF with Previously Binding Constraints

☒ Set Solution as Contingency Analysis Reference Case

Maximum Number of Contingency Violations Allow Per Element 12

Basecase Solution Method

☒ Solve base case using the power flow

☐ Solve base case using optimal power flow

Handling of Contingent Violations Due to Radial Load

☒ Flag violations but do not include them in SCOPF

☐ Completely ignore these violations

☐ Include these violations in the SCOPF

DC SCOPF Options

Storage and Reuse of LODFs (when appropriate)

☒ None (used and disgarded)

☐ Stored in memory only

☐ Stored in memory and case pwb file

Clear Stored Contingency Analysis LODFs

SCOPF Results Summary

Number of Outer Loop Iterations 1

Number of Contingent Violations 1

SCOPF Start Time 11/1/2017 7:55:50 AM

SCOPF End Time 11/1/2017 7:55:50 AM

Total Solution Time (Seconds) 0.136

Total LP Iterations 24

Final Cost Function (\$/Hr) 6301.94

Contingency Analysis Input

Number of Active Contingencies: 7 View Contingency Analysis Form

Contingency Analysis Results

Solving contingency L\_000003Three-000004FourC1

Applied:

OPEN Line Three\_138.0 (3) TO Four\_138.0 (4) CKT 1 | CHECK | Oper

Contingency L\_000003Three-000004FourC1 successfully solved.

Solving contingency L\_000004Four-000005FiveC1

Applied:

OPEN Line Four\_138.0 (4) TO Five\_138.0 (5) CKT 1 | CHECK | Oper

Contingency L\_000004Four-000005FiveC1 successfully solved.

Contingency Analysis finished at November 01, 2017 07:55:50

Number of times to redo contingency analysis

# Auctions

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- In its simplest form, an auction is a mechanism of allocating scarce goods based upon competition
  - a seller wishes to obtain as much money as possible, and a buyer wants to pay as little as necessary.
- An auction is usually considered efficient if resources accrue to those who value them most highly
- Auctions can be either one-sided with a single monopolist seller/buyer or a double auction with multiple parties in each category
  - bid to buy, offer to sell
- Most people's experience is with one-side auctions with one seller and multiple buyers

# Auctions, cont.

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- Electricity markets can be one-sided, with the ISO functioning as a monopolist buyer, while multiple generating companies make offers to sell their generation, or two-sided with load participation
- Auctions provide mechanisms for participants to reveal their true costs while satisfying their desires to buy low and/or sell high.
- Auctions differ on the price participants receive and the information they see along the way

# Types of Single-Sided Auctions with Multiple Buyers, One Seller

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- Simultaneous auctions
  - English (ascending price to buy)
  - Dutch (descending price to buy)
- Sealed-bid auctions (all participants submit offers simultaneously)
  - First price sealed bid (pay highest price if one, discriminatory prices if multiple)
  - Vickrey (uniform second price) (pay the second highest price if one, all pay highest losing price if many); this approach gives people incentive to bid their true value



# Uniform Price Auctions: Multiple Sellers, One Buyer

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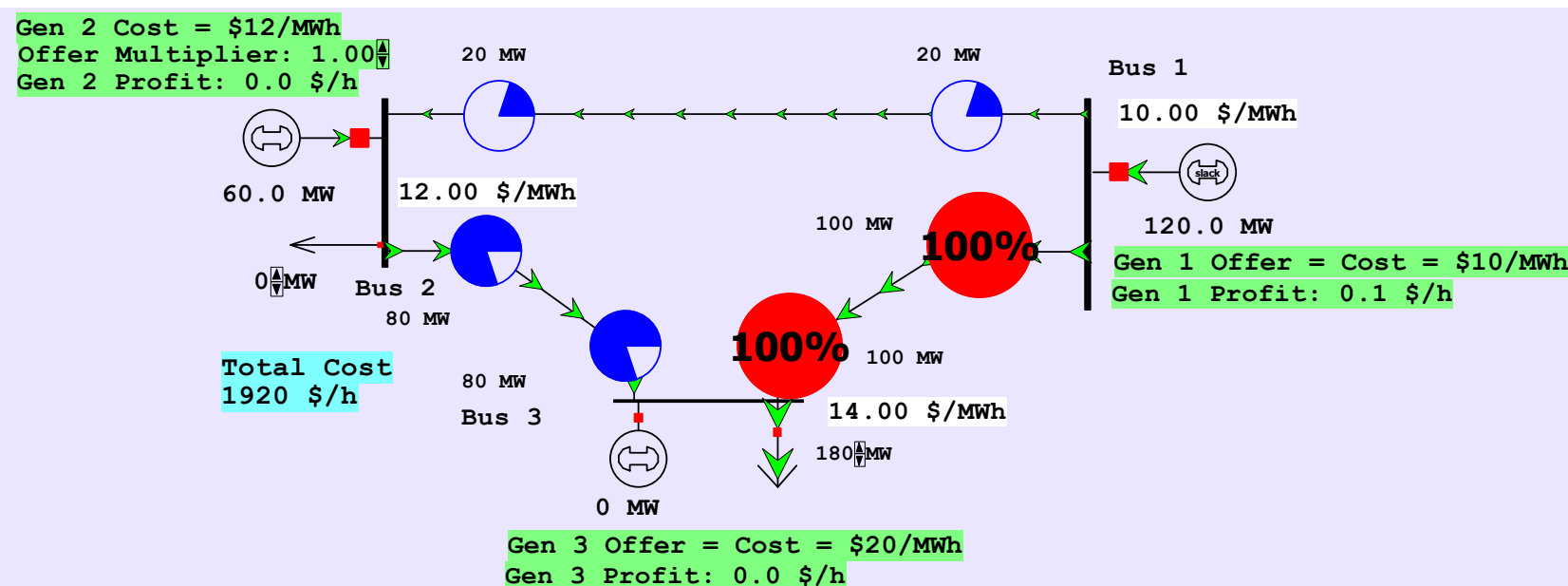


- Uniform price auctions are sealed offer auctions in which sellers make simultaneous decisions (done when submitting offers).
- Generators are paid the last accepted offer
- Provides incentive to offer at marginal cost since higher values cause offers to be rejected
  - reigning price should match marginal cost
- Price caps are needed to prevent prices from rising up to infinity during shortages
- Some generators offering above their marginal costs are needed to cover their fixed costs

# What to Offer Example



- Below example shows 3 generator case, in which the bus 2 generator can vary its offer to maximize profit



Note, this example makes the unrealistic assumption that the other generators do not vary their offers in response

# Horizontal Market Power

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- One issue is whether a particular group of generators has market power
- Market power is the antithesis of competition
  - It is the ability of a particular group of sellers to maintain prices above competitive levels, usually by withholding supply
- The extreme case is a single supplier of a product (i.e., a monopoly)
- In the short run what a monopolistic producer can charge depends upon the price elasticity of the demand
- Sometimes market power can result in decreased prices in the long-term by quickening the entry of new players or new innovation

# Market Power and Scarcity Rents

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- A generator owner exercises market power when it is unwilling to make energy available at a price that is equal to that unit's variable cost of production, even though there is currently unloaded generation capacity (i.e., there is no scarcity).
- Scarcity rents occur when the level of electric demand is such that there is little, if any, unused capacity
- Scarcity rents are used to recover fixed costs

# High-Impact, Low-Frequency Events



- Growing concern to consider what the NERC calls High-Impact, Low-Frequency Events (HILFs); others call them black sky days
  - Large-scale, potentially long duration bl
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) HEMPs
- The next several slides will consider some challenges in this area including some coverage of Winter Storm Uri

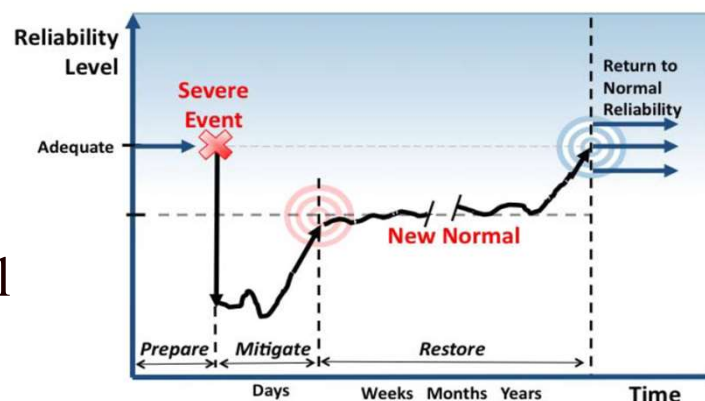


Image Source: NERC, 2012

# Reliability and Resiliency

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- 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

# What is Grid Resilience?

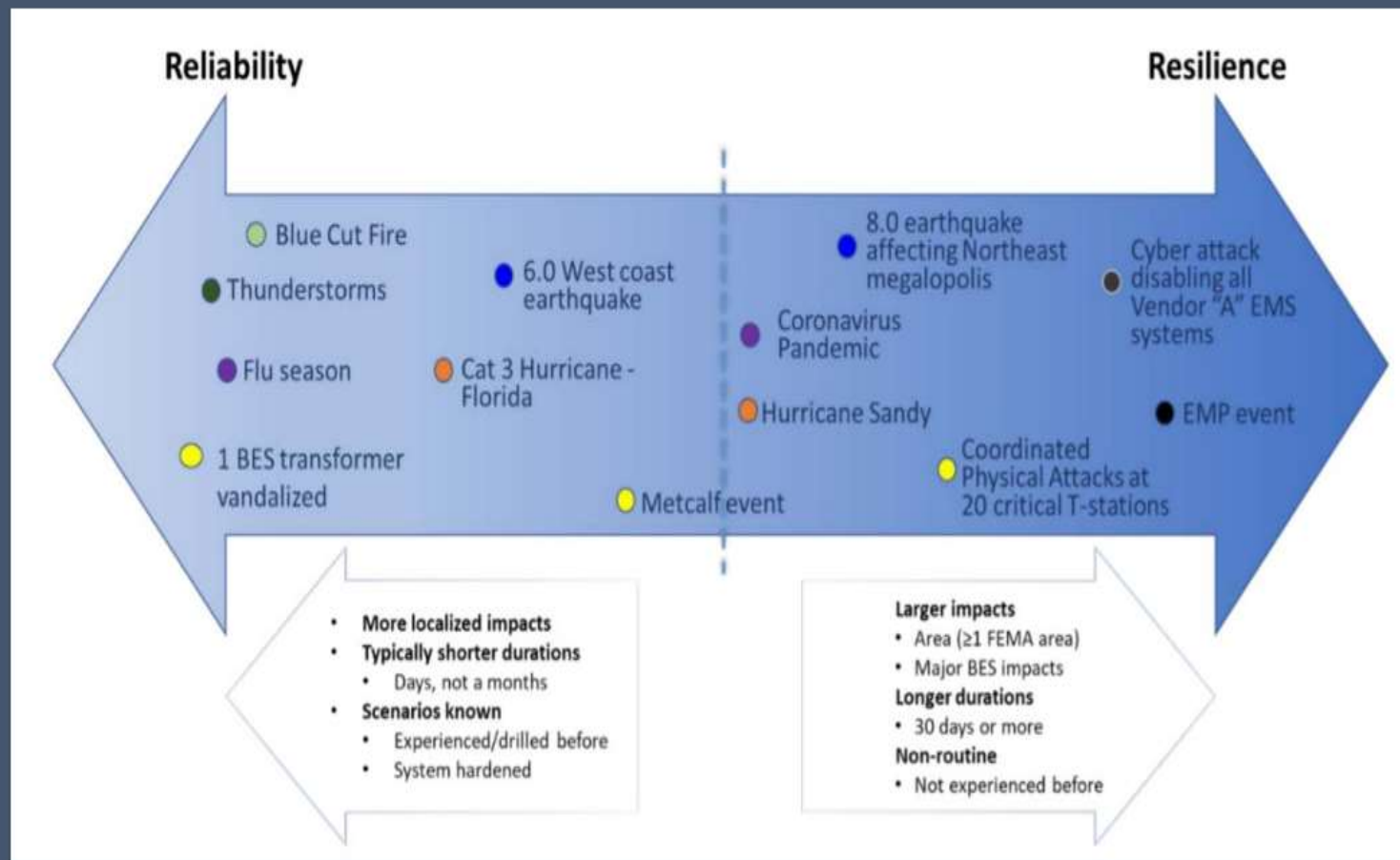
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- Merriam Webster Dictionary (resilience in general)
  - “An ability to recover from or adjust easily to misfortune or change”
- EPRI & North American Transmission Forum (NATF)
  - The ability of the system and its components (... equipment and human ...) 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 53<sup>rd</sup> North American Power Symposium keynote address by Dan Smith of Lower Colorado River Authority, Nov/2021

# Reliability – Resilience Continuum



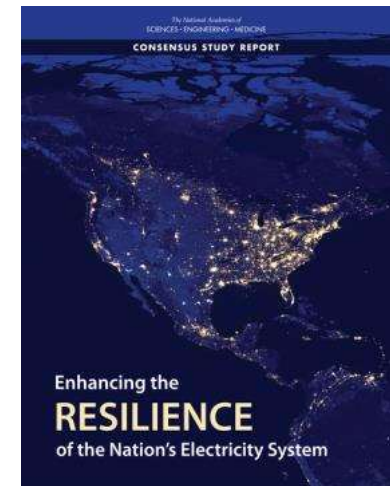
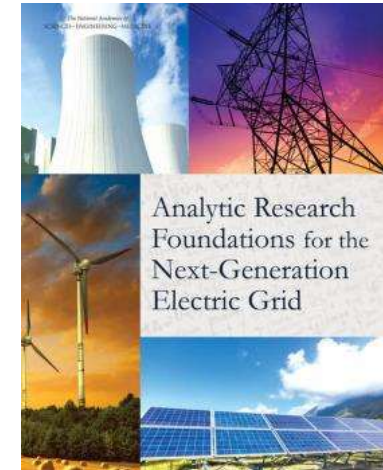
Credit: NATF TRMM Users Guide

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



# Several Recent Reports on Resiliency

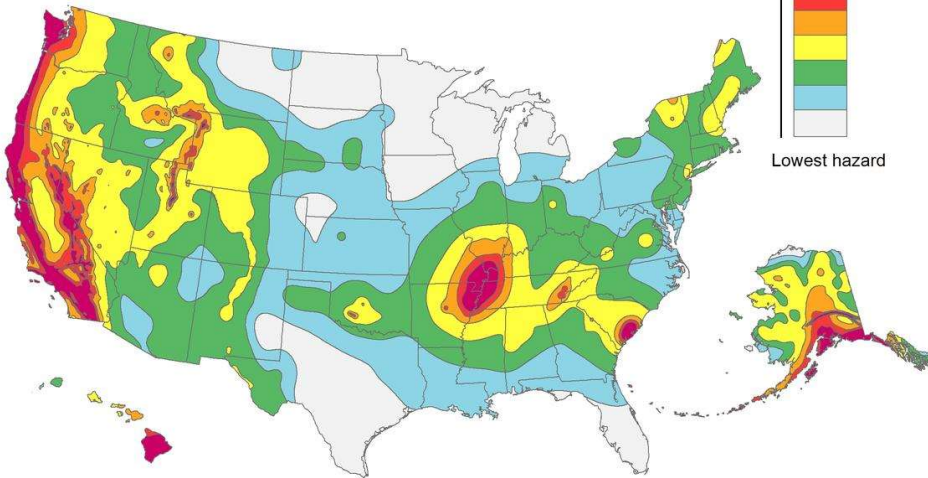
- *Analytic Research Foundations for the Next-Generation Electric Grid*, 2016
  - Make everything as simple as possible but not simpler [maybe from Einstein]
- *Enhancing the Resilience of the Nation's Electricity System*, 2017
- US Department of Energy Transmission Innovation Symposium, May 2021
  -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



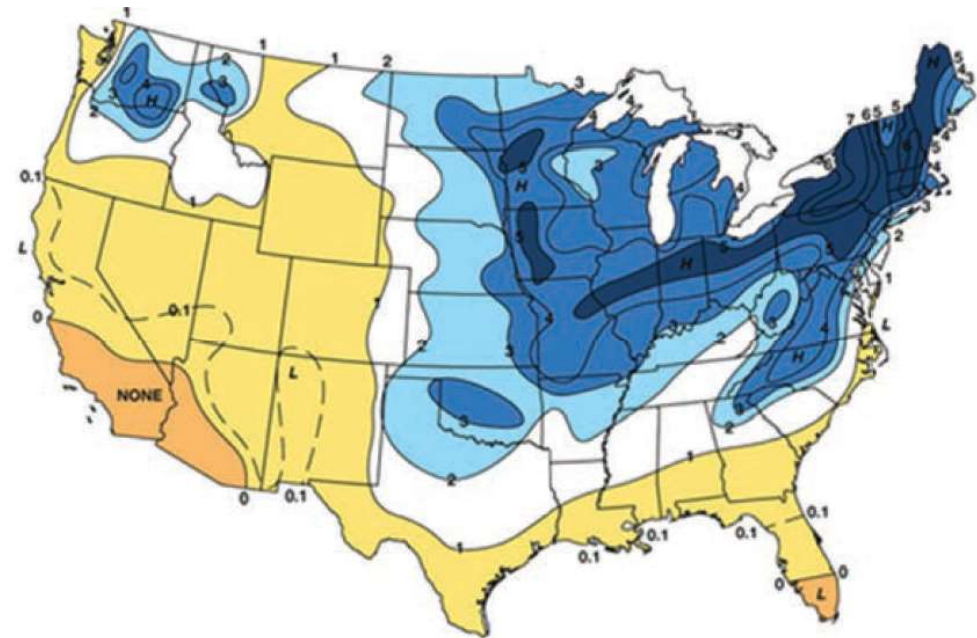
# Resilient to What?

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

## Earthquake Risk

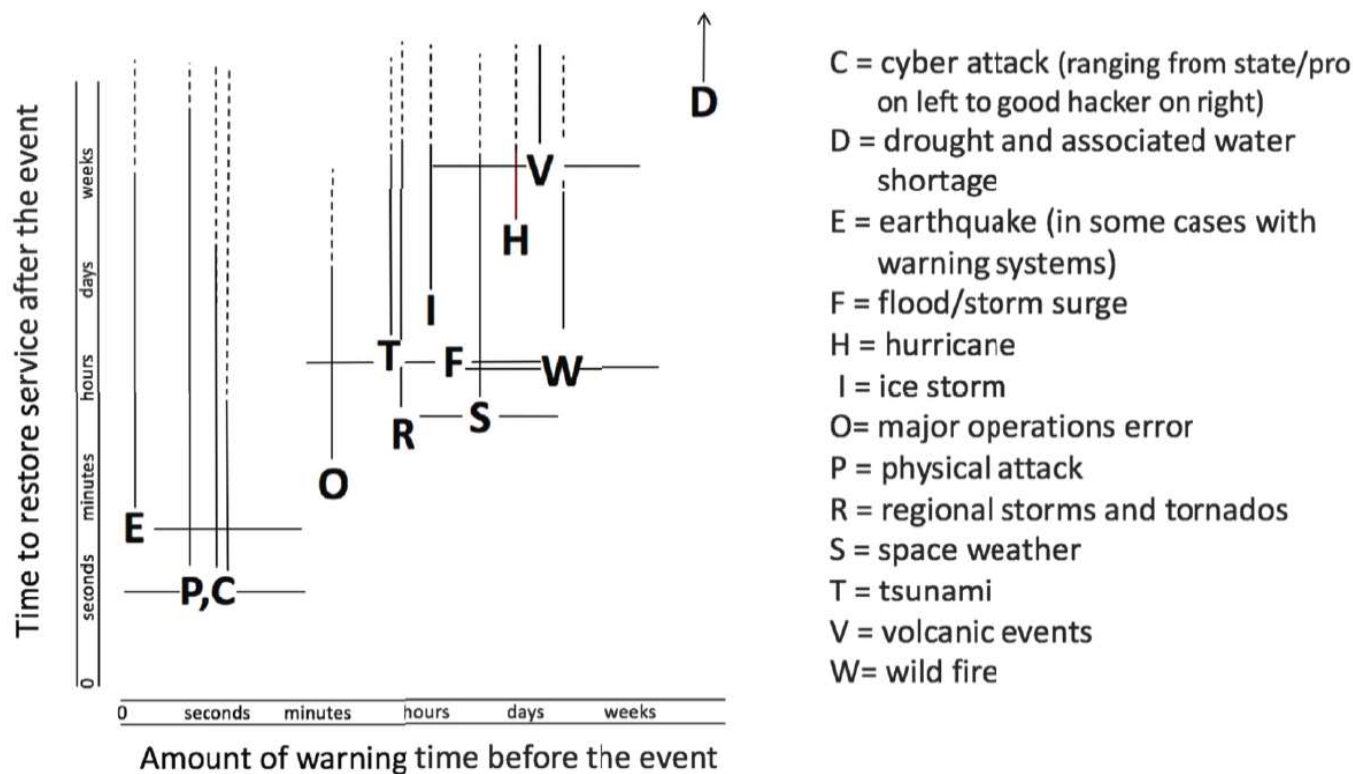


## Freezing Rain Risk



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

# Some Electric Grid Risks



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

**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

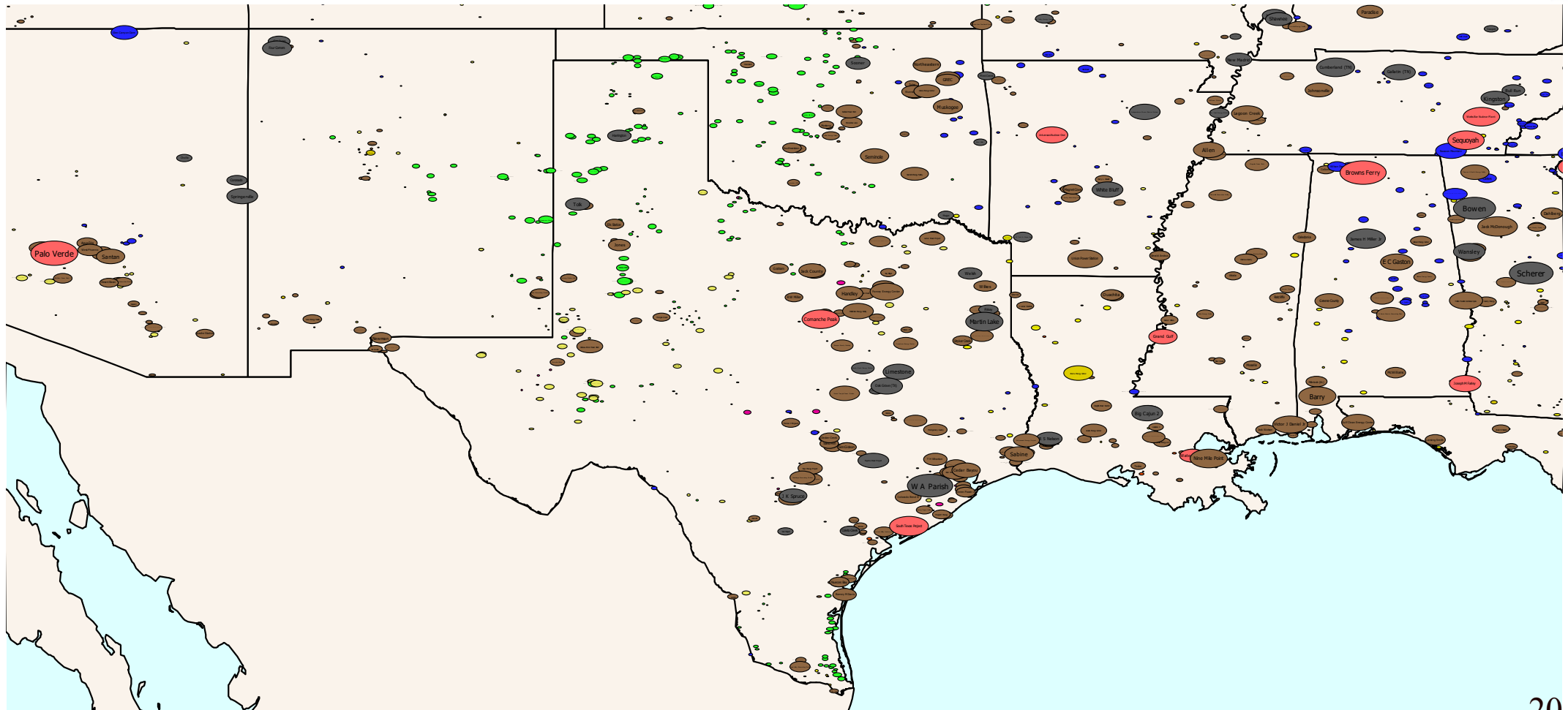
Source: *Enhancing the Resilience of the Nation's Electricity System*, 2017

# 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



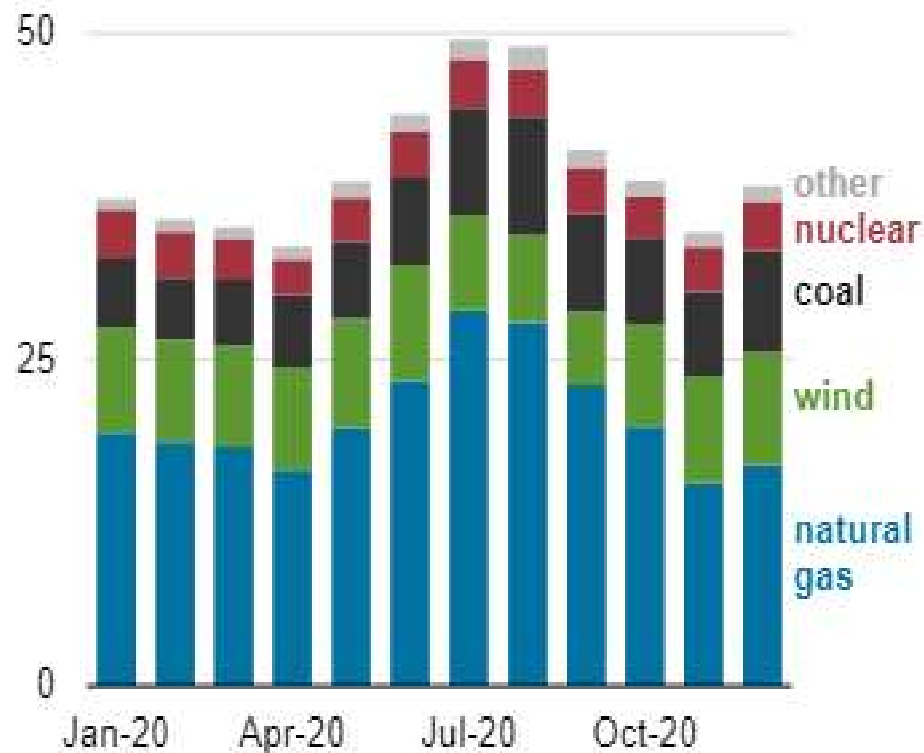
# Zoomed View of Generation Sources, 2021



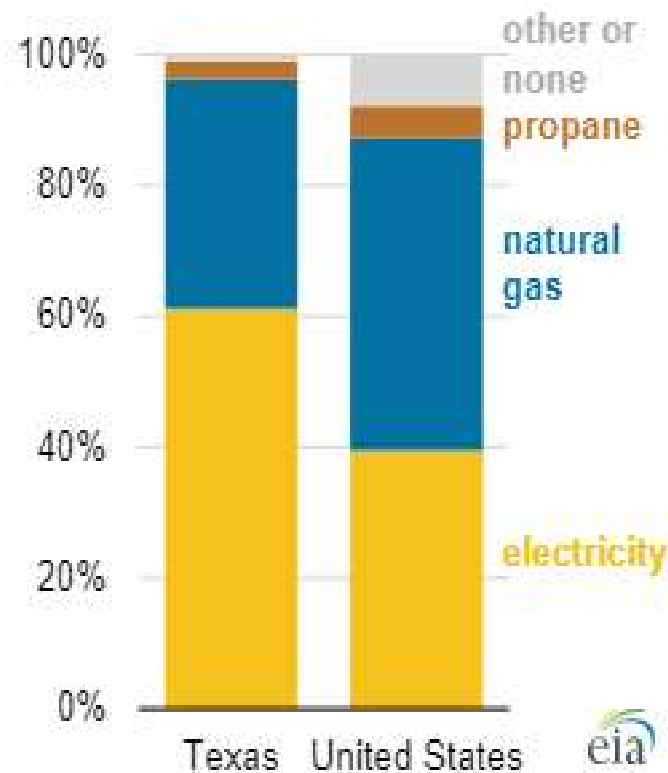


# Texas Generation and Home Heating Sources

Texas monthly electricity generation by source  
(Jan 2020–Dec 2020)  
million megawatthours

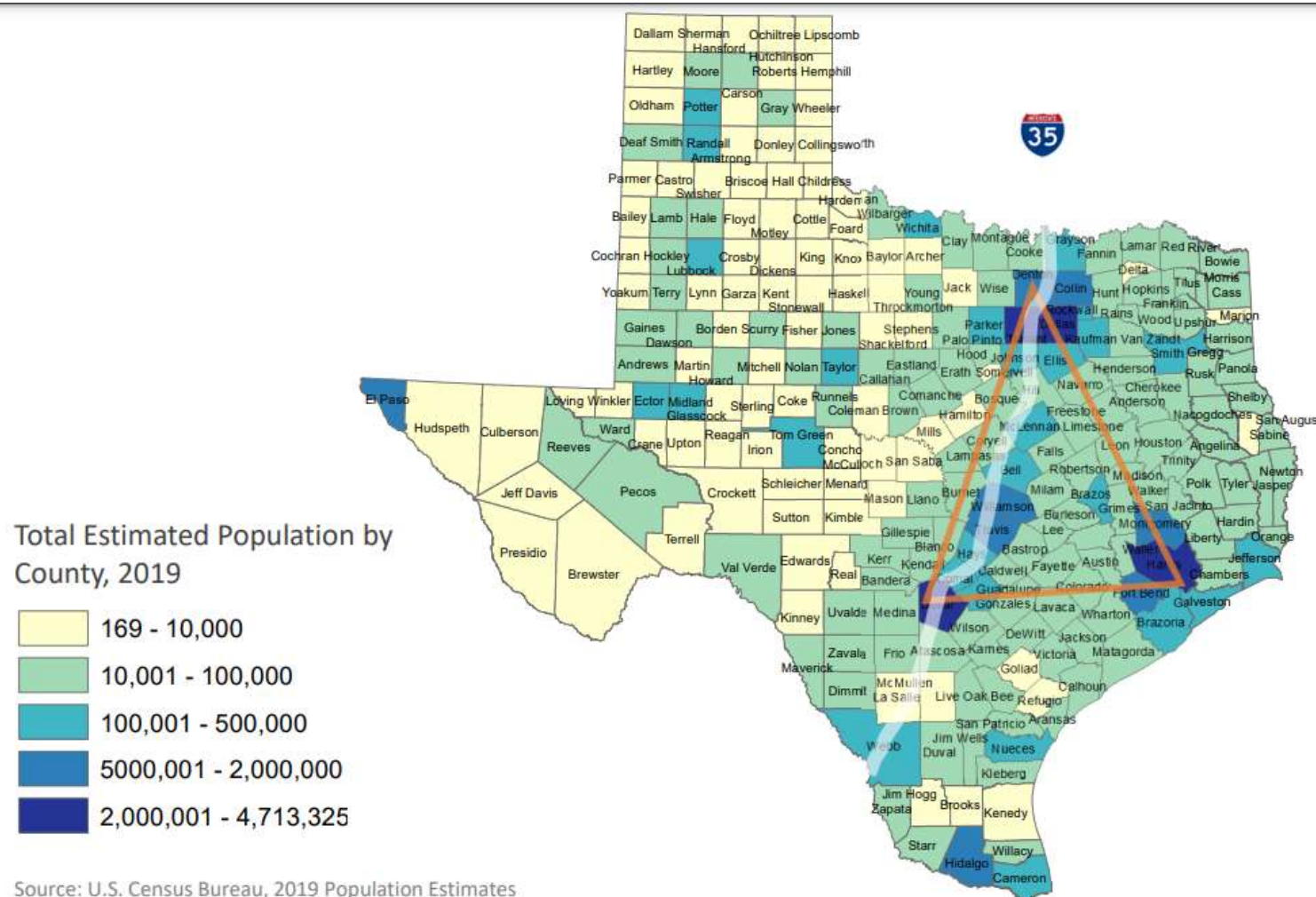


Primary home heating source (2019)  
percentage of total



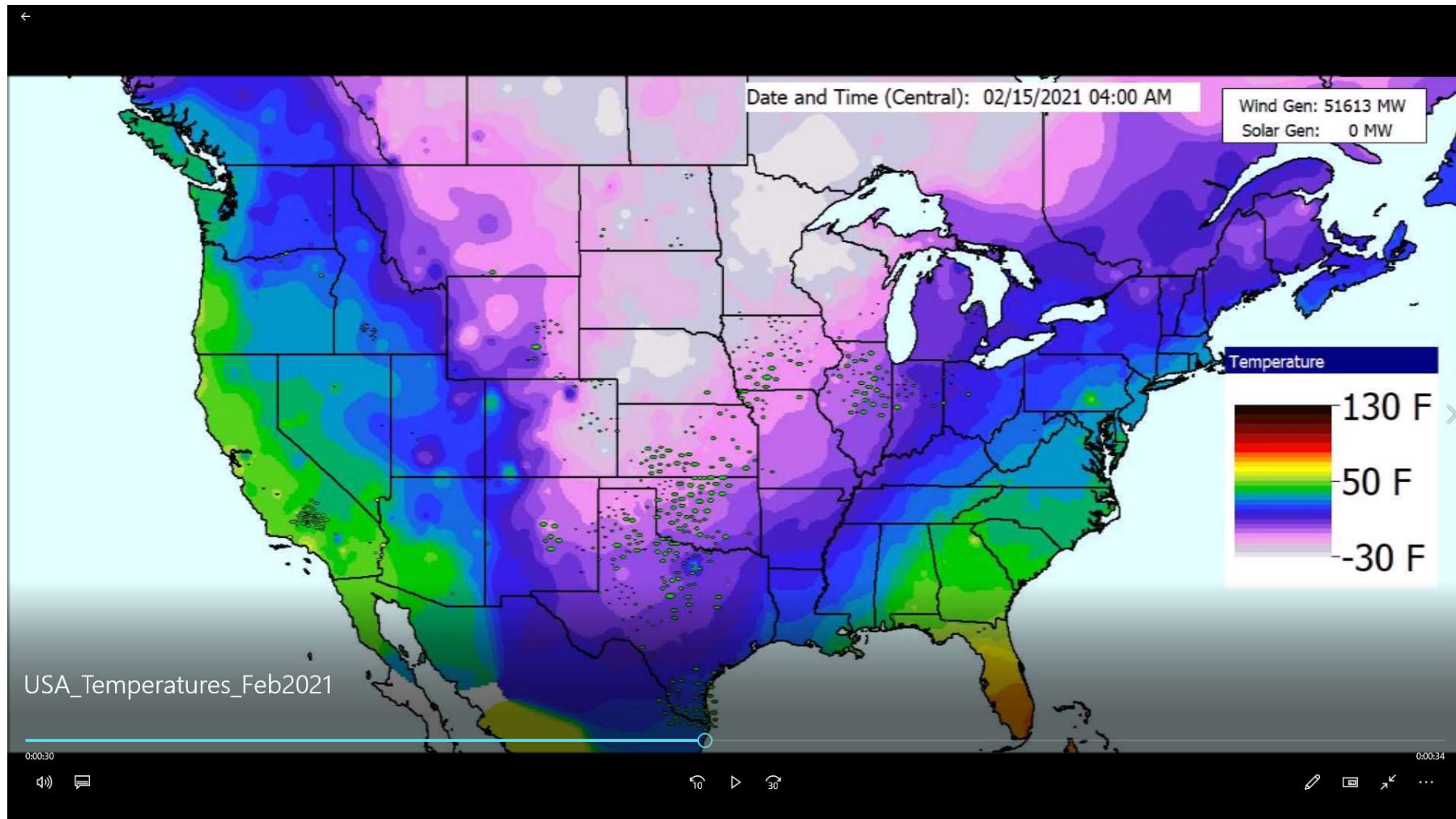
Texas population is growing, increasing 16% from 25.1 million in 2010 to 29.2 million on 2020

# Texas Population Density



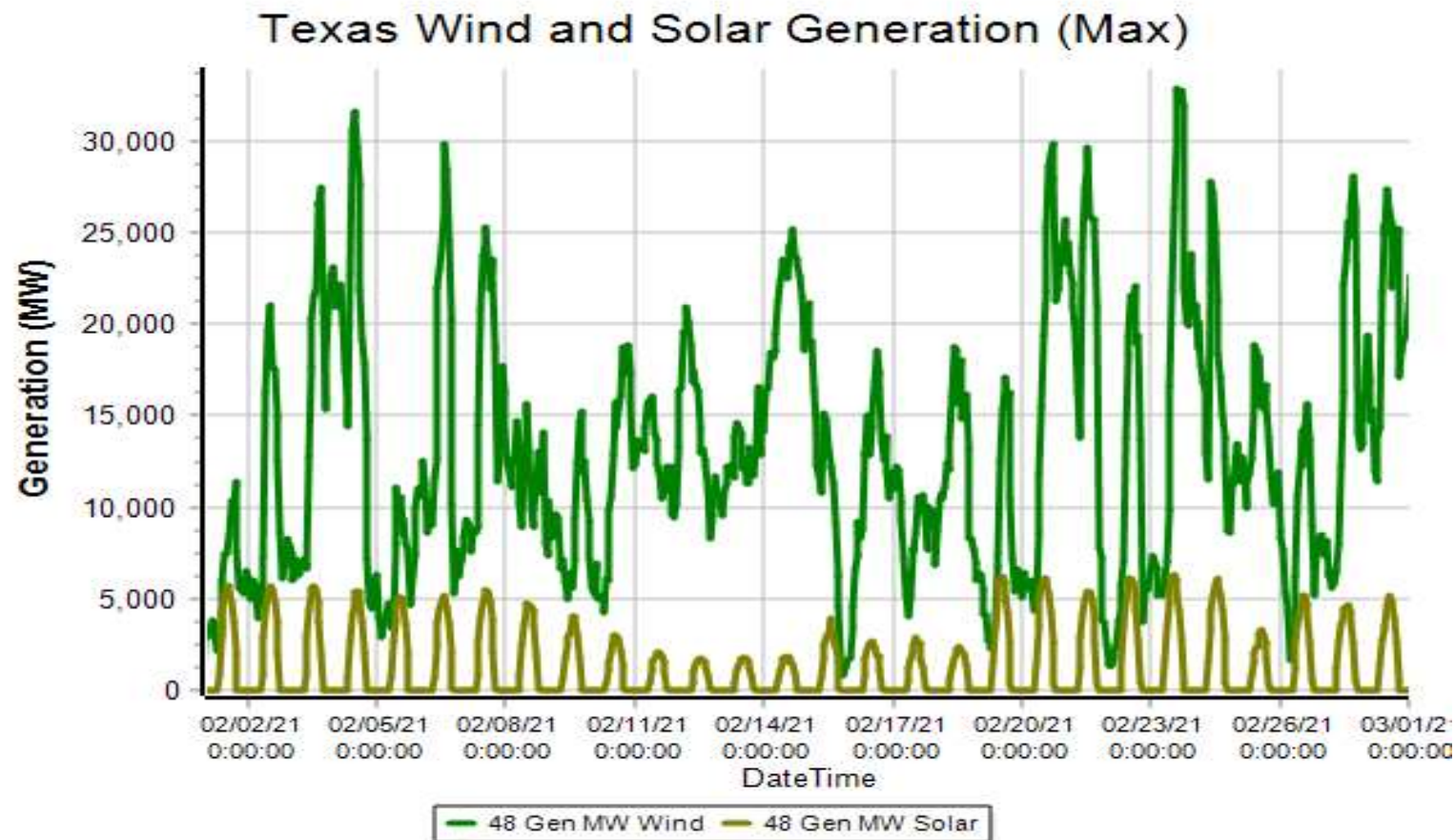
85% of population is along or east of the I35 corridor (DFW to Waco to Austin to San Antonio to Laredo)

# Visualization of Temperatures, Feb 11 to 18, 2021



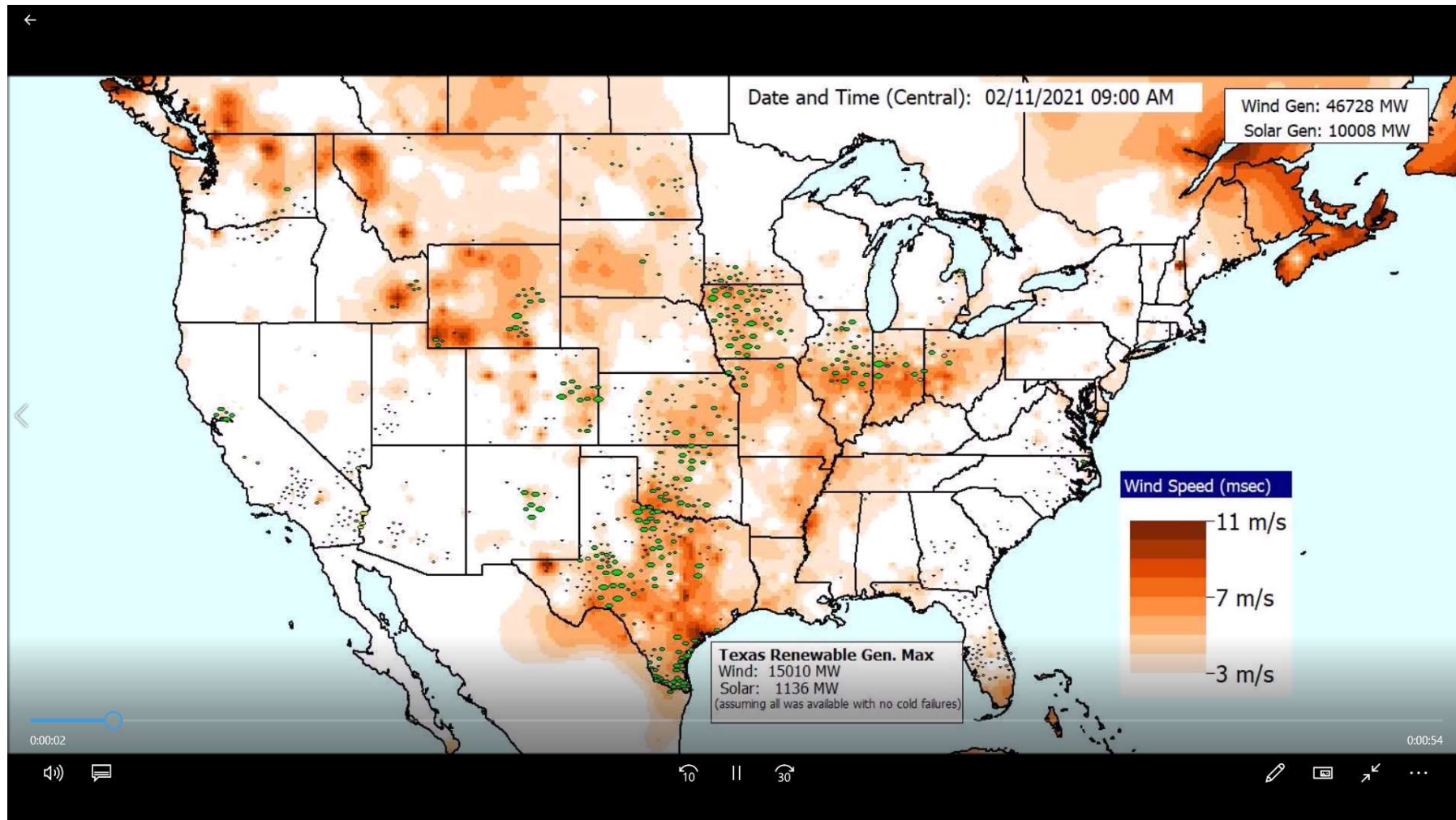


# Texas Wind and Solar Max Gen Based on Weather



This does not account for cold weather failures

# Visualization of Wind Speed, Feb 11 to 18, 2021



# ERCOT Generation Feb 11-18, 2021

Power generation in Texas by fuel source

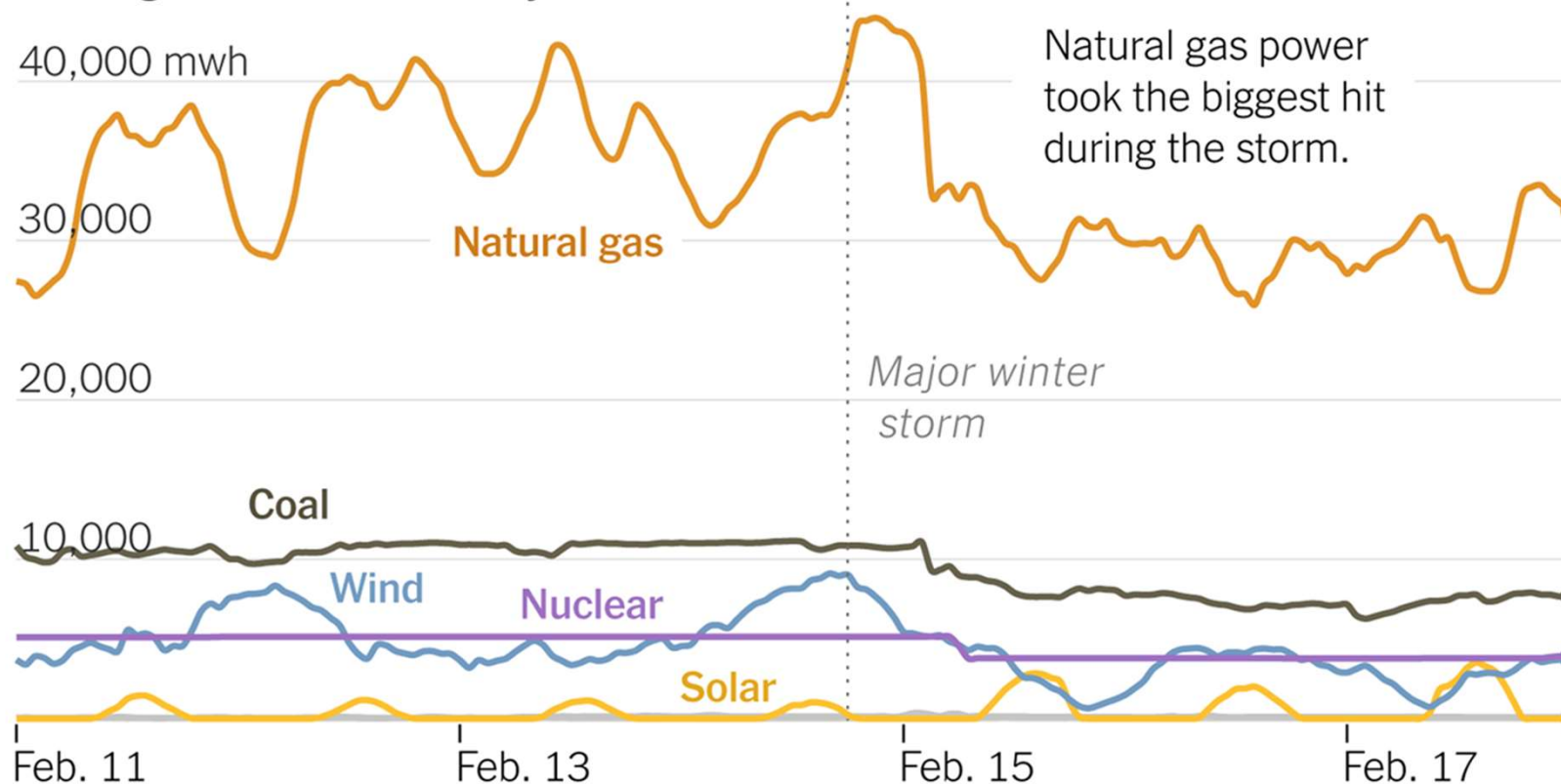
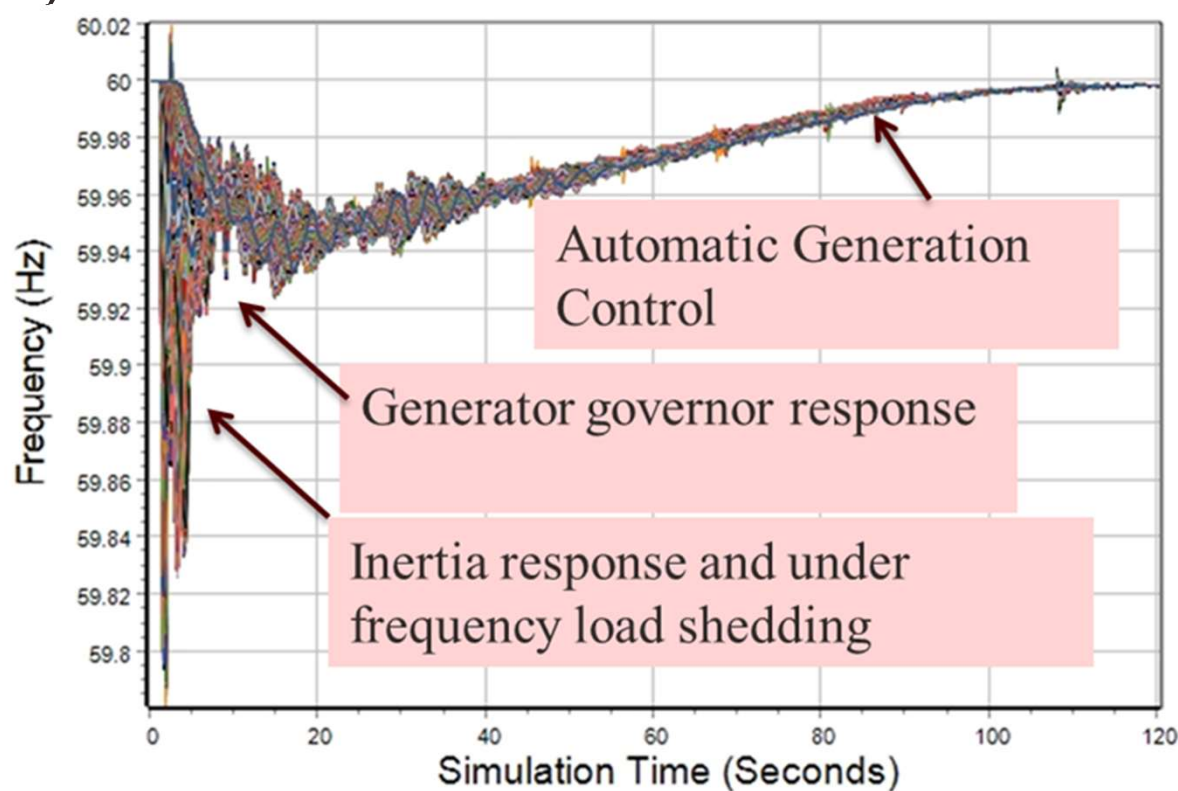


Image source: New York Times, Feb 23, 2021

# 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

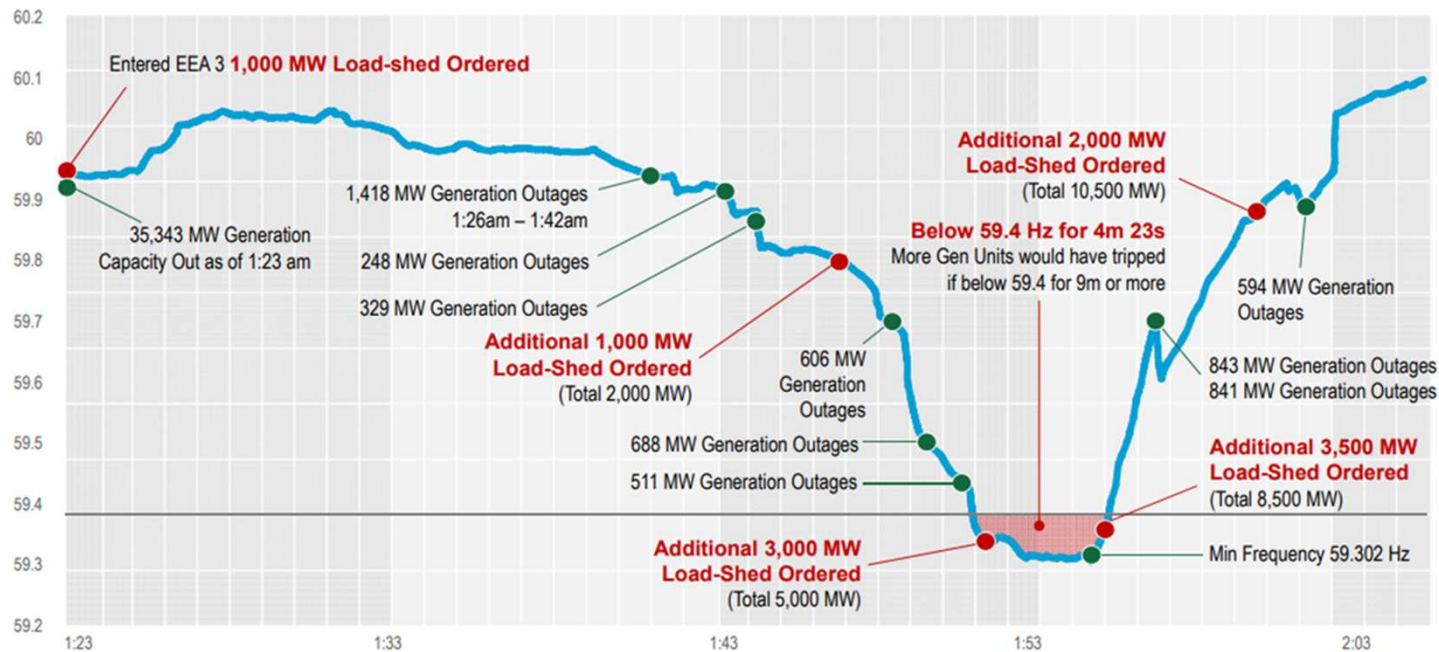


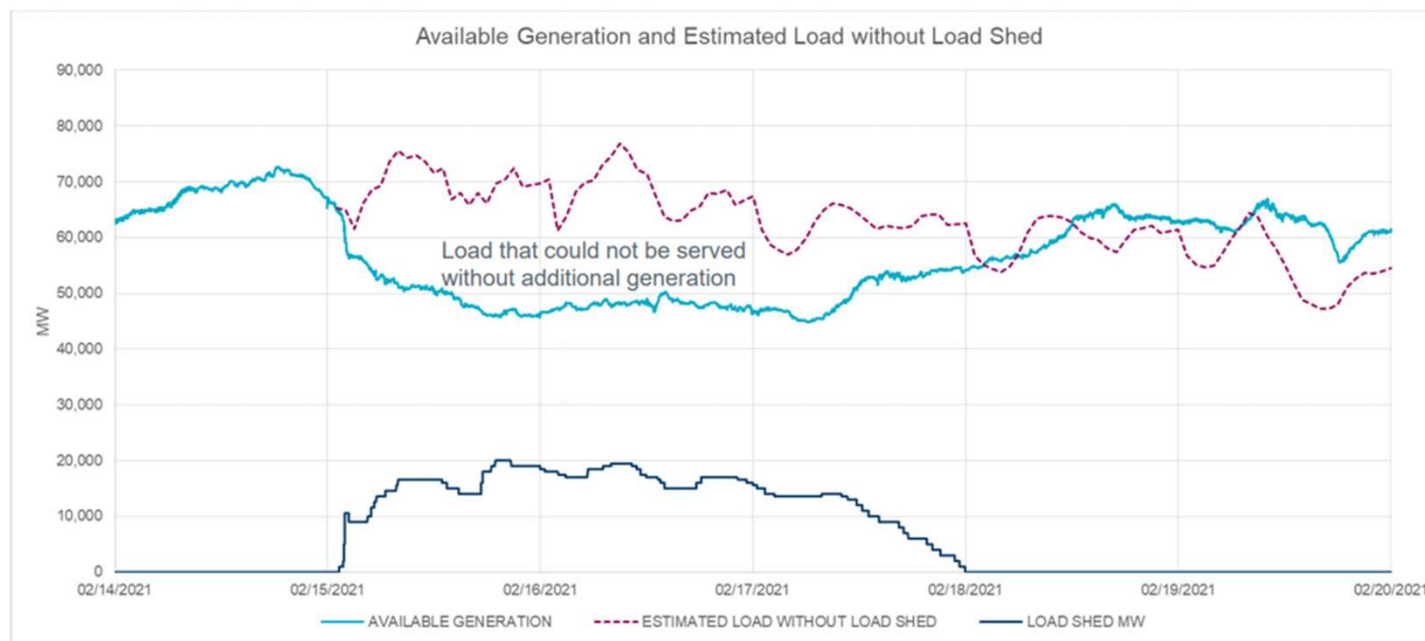
Image source: ERCOT  
Presentation by Bill  
Magness, February 25, 2021

# ERCOT Load Shed and Rotating Blackouts



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

## Available Generation and Estimated Load Without Load Shed

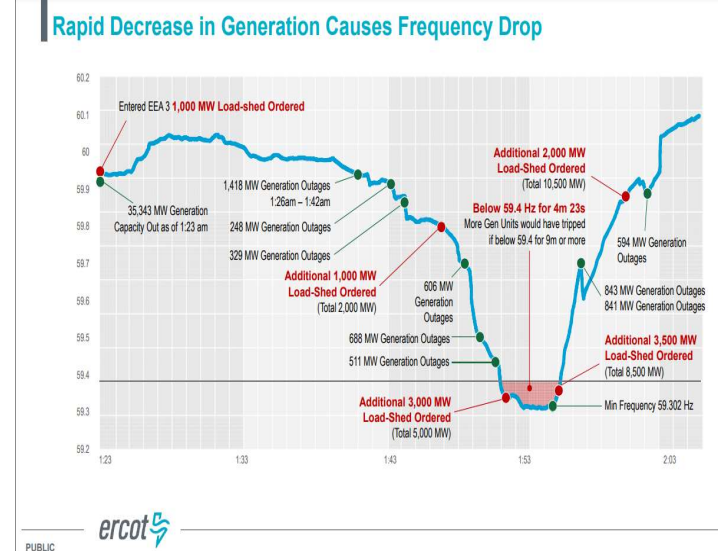


At the time the ERCOT peak load had been 74.8 GW (summer); winter peak of 69.2 GW was set on 2/14/21 (previous winter peak was 65.9 GW). A new peak of 80 GW was set on 7/20/22.

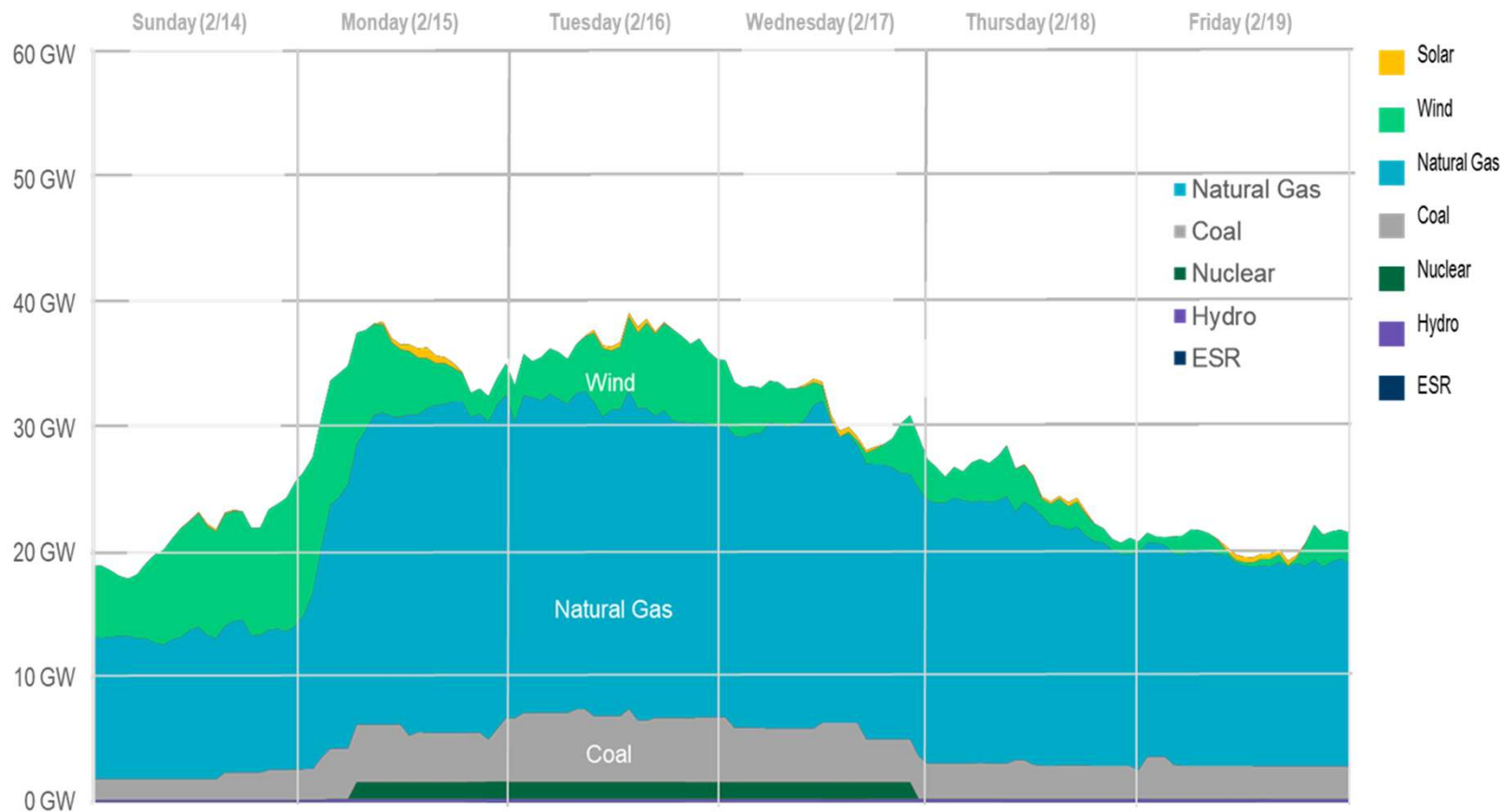
Available Generation shown is the total HSL of Online Resources, including Quick Starts in OFFQS. The total uses the current MW for Resources in Start-up, Shut-Down, and ONTEST.

# 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?



Version Date: 4/22/2021

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

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- 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

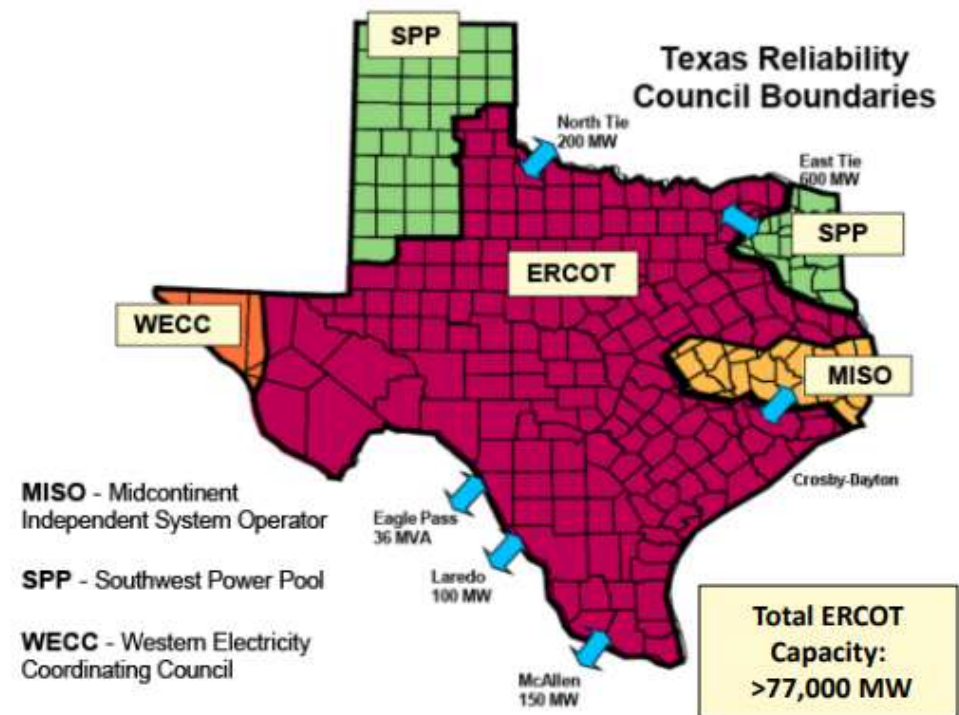


Image Source: [aect.net/documents/2017/AECT%20LSB%20012617.pdf](http://aect.net/documents/2017/AECT%20LSB%20012617.pdf)

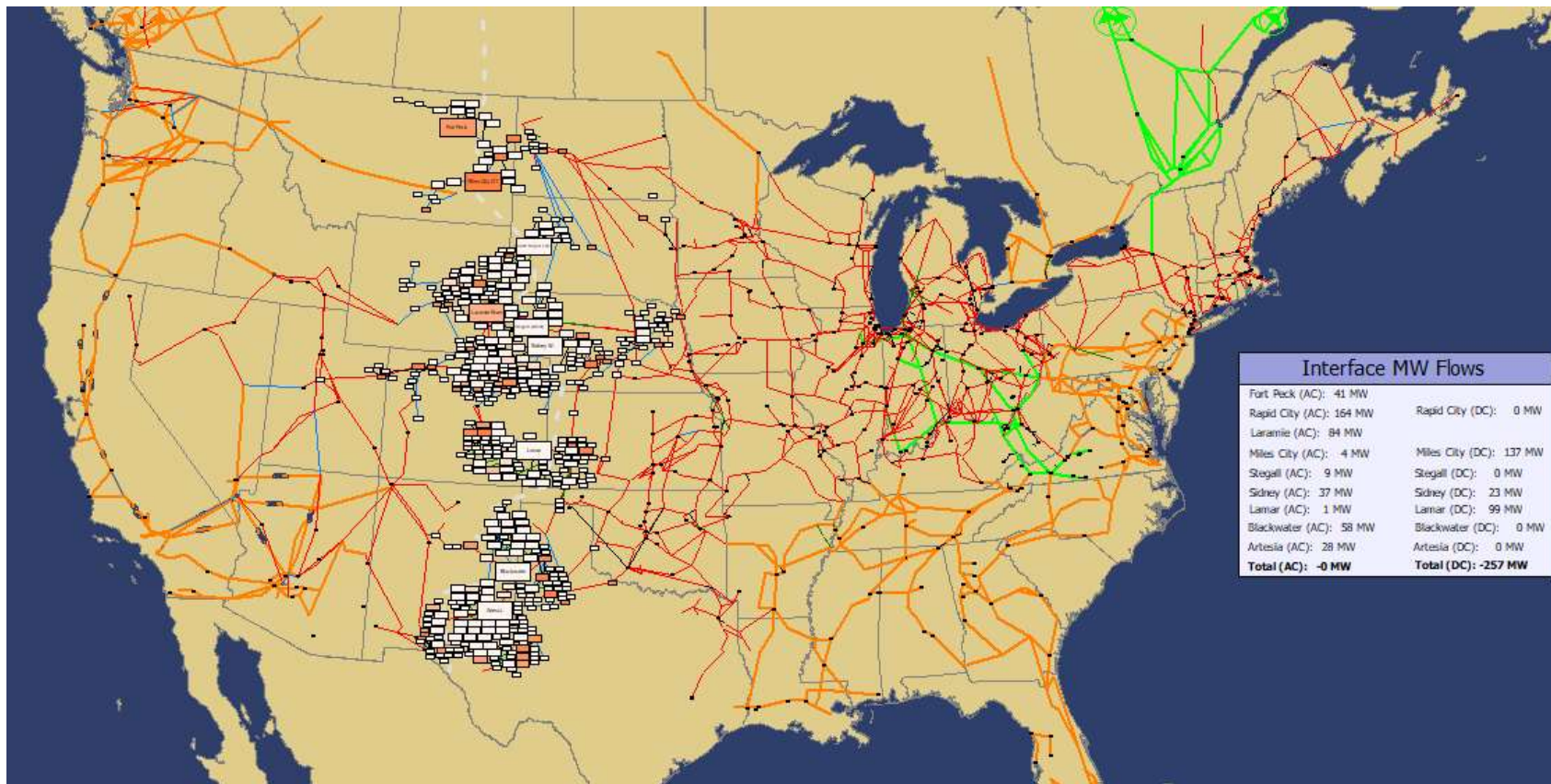
# Joining the East and West Grids

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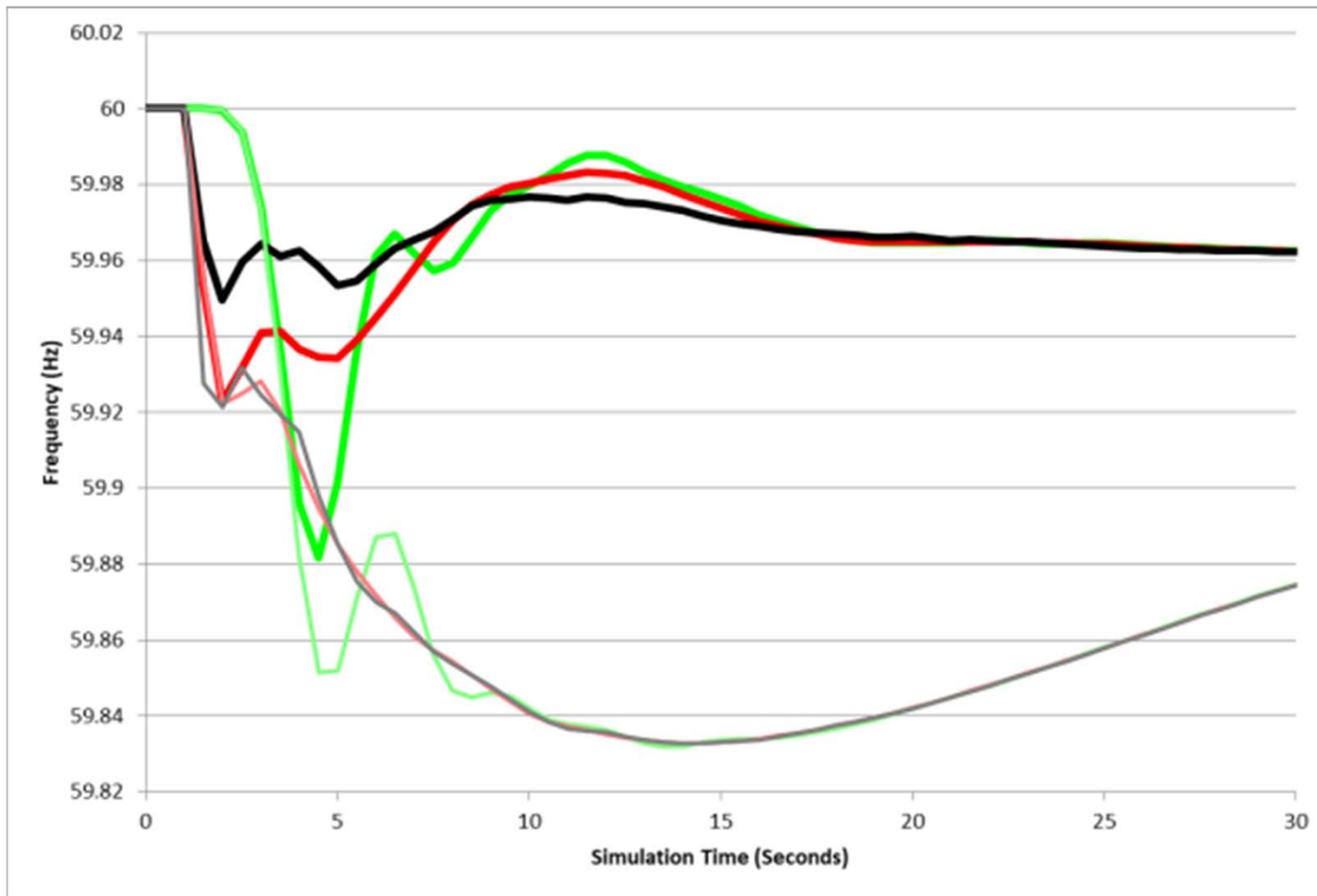
- In 2020 we did a research project for SPP looking at an ac interconnection of the East and West grids
  - This did not include ERCOT, but did include parts of Texas
- There are nine locations where the grids are close and could be tied together
- The study required lots of dynamic simulations using 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



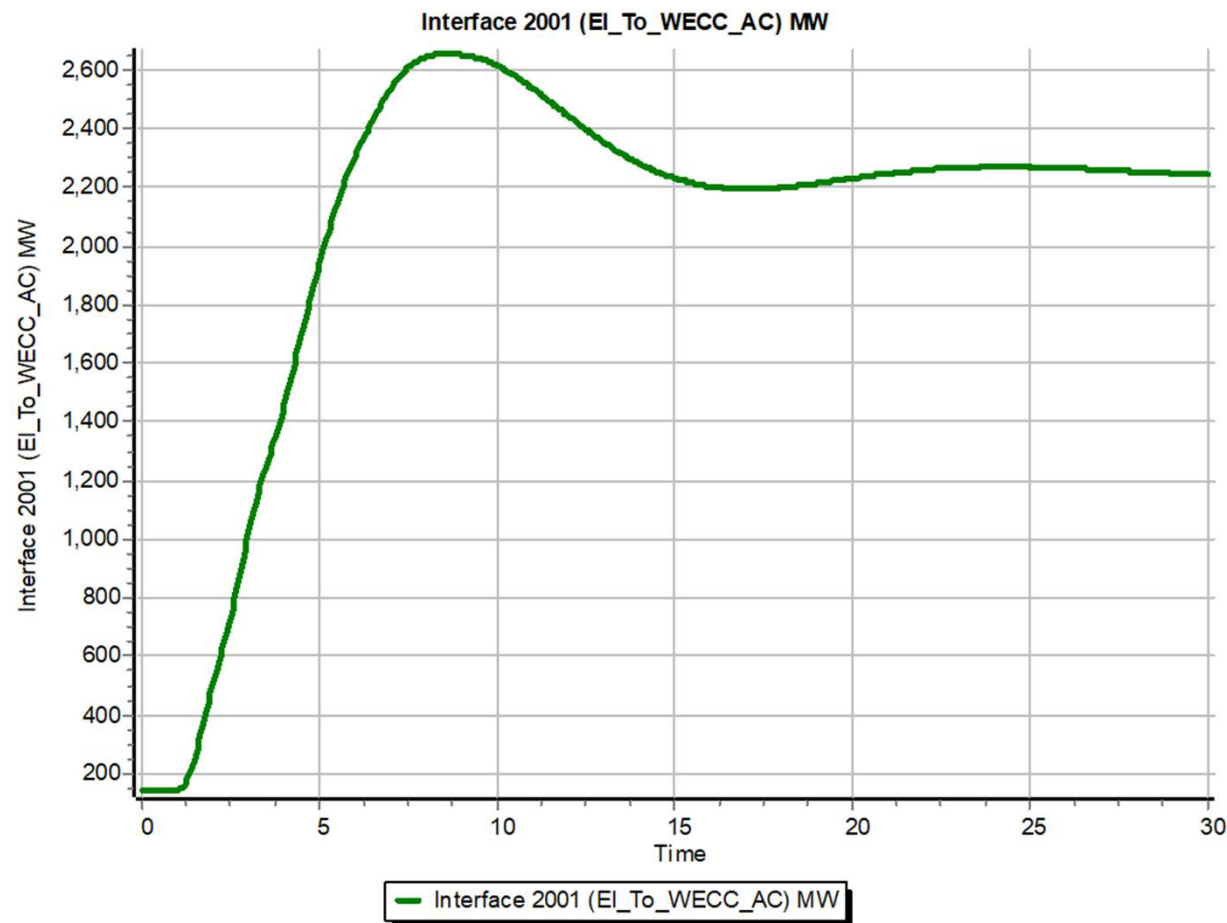
The study included Canada but we did not consider any ac interconnections between the grids in Canada; the grids were connected at nine points from Montana to New Mexico

# 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)

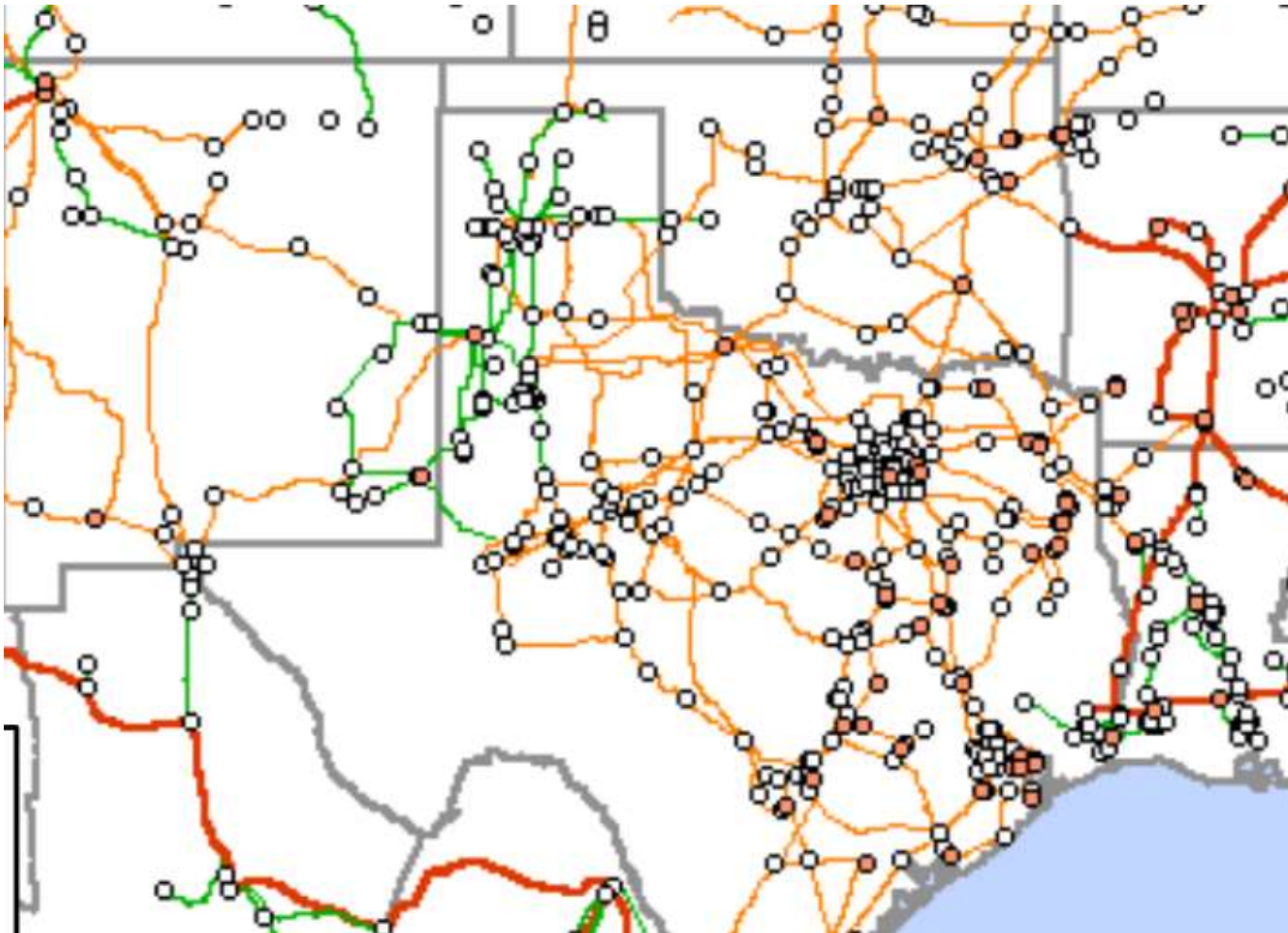
# AC-Tie Interface, Severe Contingency



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



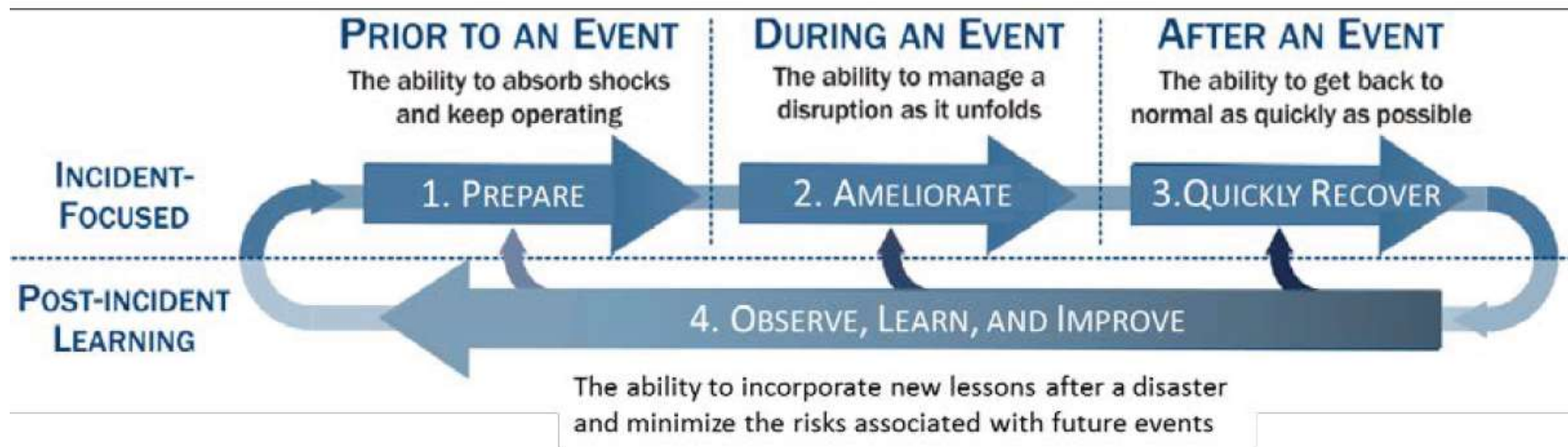
# ERCOT-East-West Transmission



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

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- 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

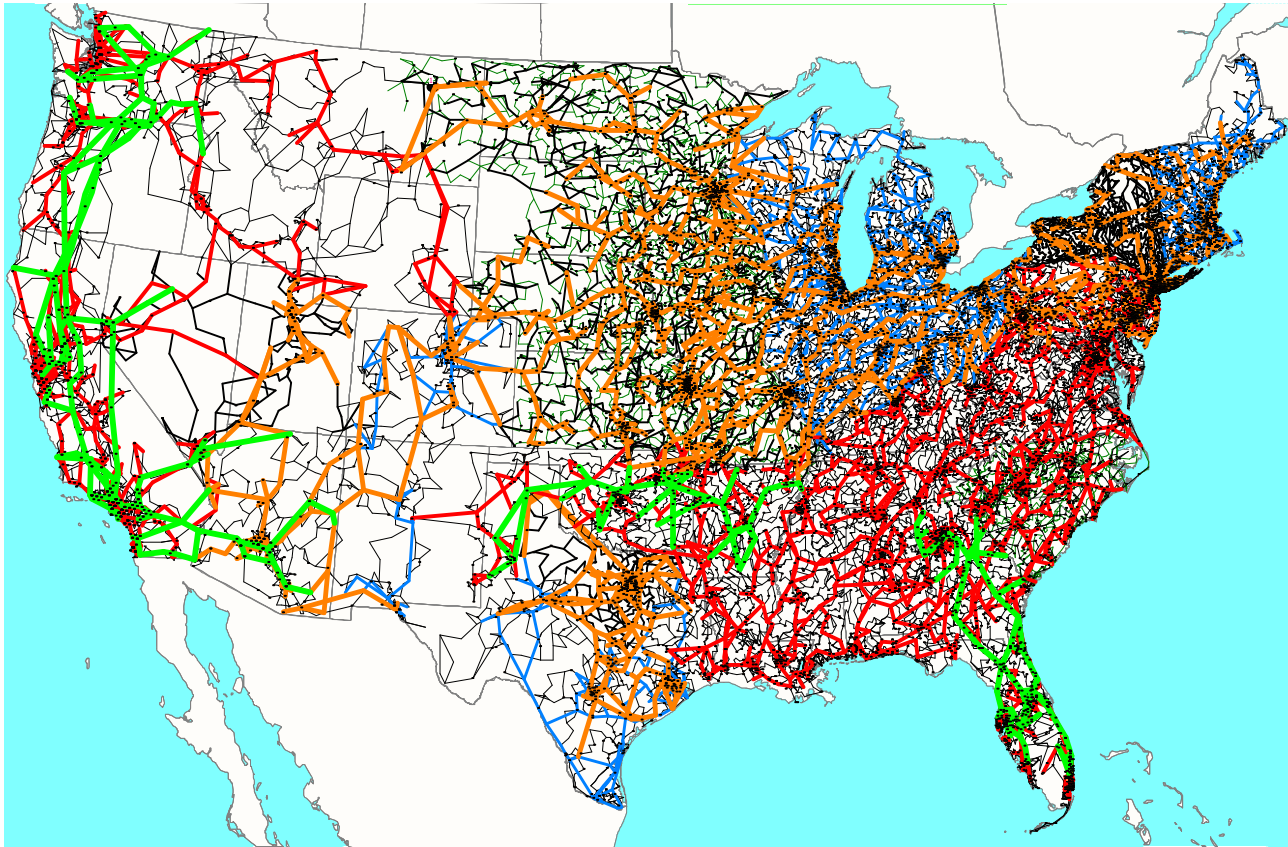
# HILF Two Main Categories

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- 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

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- 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

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- 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 require knowing the associated remedial action schemes

# Resiliency and Renewables

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- 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

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- 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

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- 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”