ECEN 615
Methods of Electric Power Systems Analysis

Lecture 24: Electricity Markets

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Announcements

- Homework 7 does not need to be turned in but should be finished before the second exam
- Exam 2 is on Thursday Dec 1 during class (for the on campus students); it will be comprehensive, but with more emphasis on the material after the first exam
  - It is like the first exam (closed book, closed notes, with calculators allowed) except you can bring in two 8.5 by 11" note sheets (e.g., your one from exam 1 plus a new one)

Variation in Two Bus Solution Regions

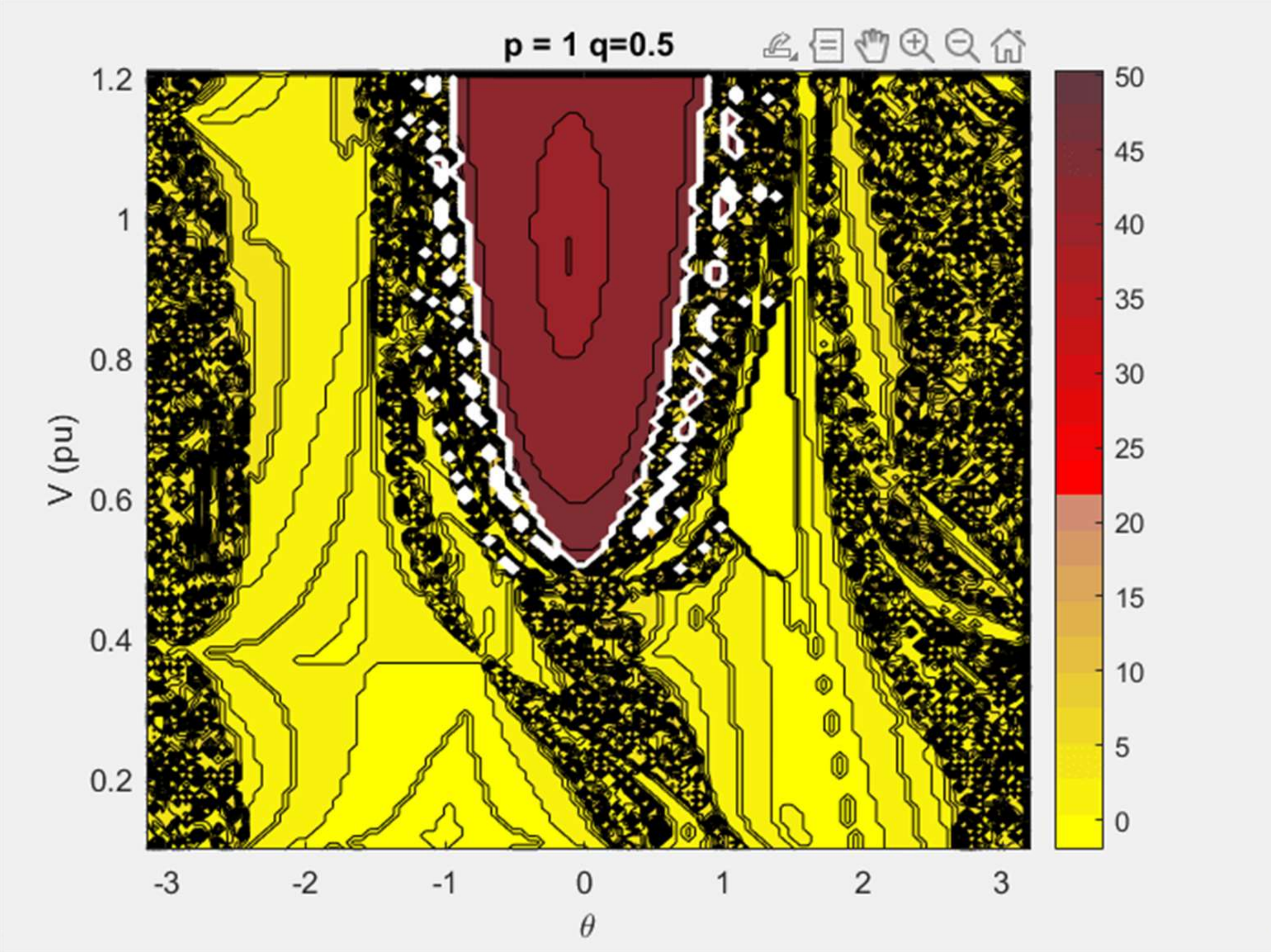


Image provided by Alamera Alquennah

Security Constrained OPF

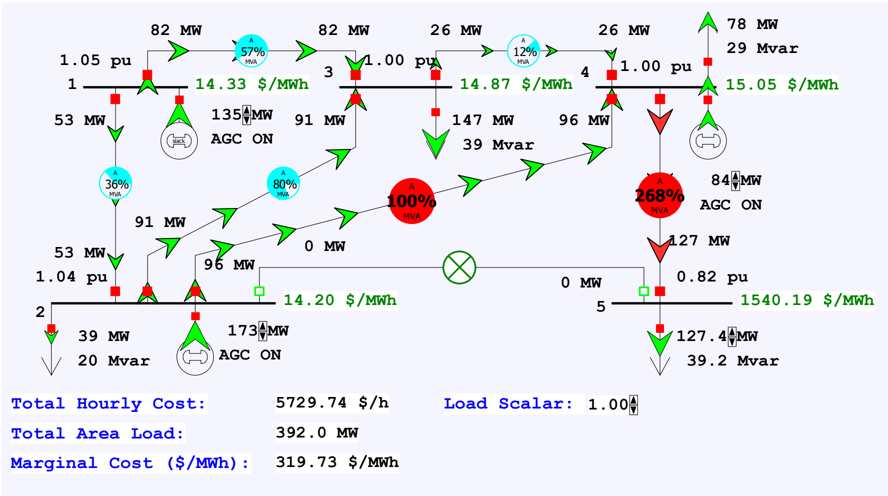
- Security constrained optimal power flow (SCOPF) is similar to OPF except it also includes contingency constraints
  - Again the goal is to minimize some objective function, usually the current system cost, subject to a variety of equality and inequality constraints
  - This adds significantly more 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

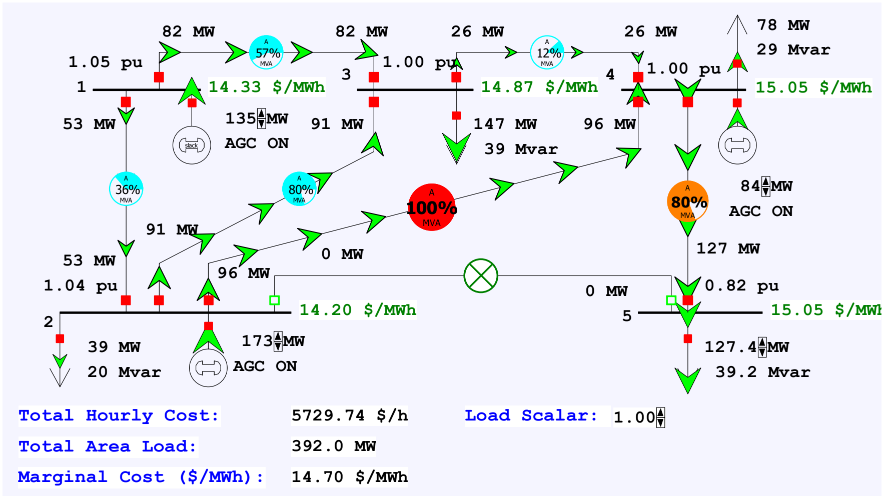
Security Constrained OPF, cont.

- 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





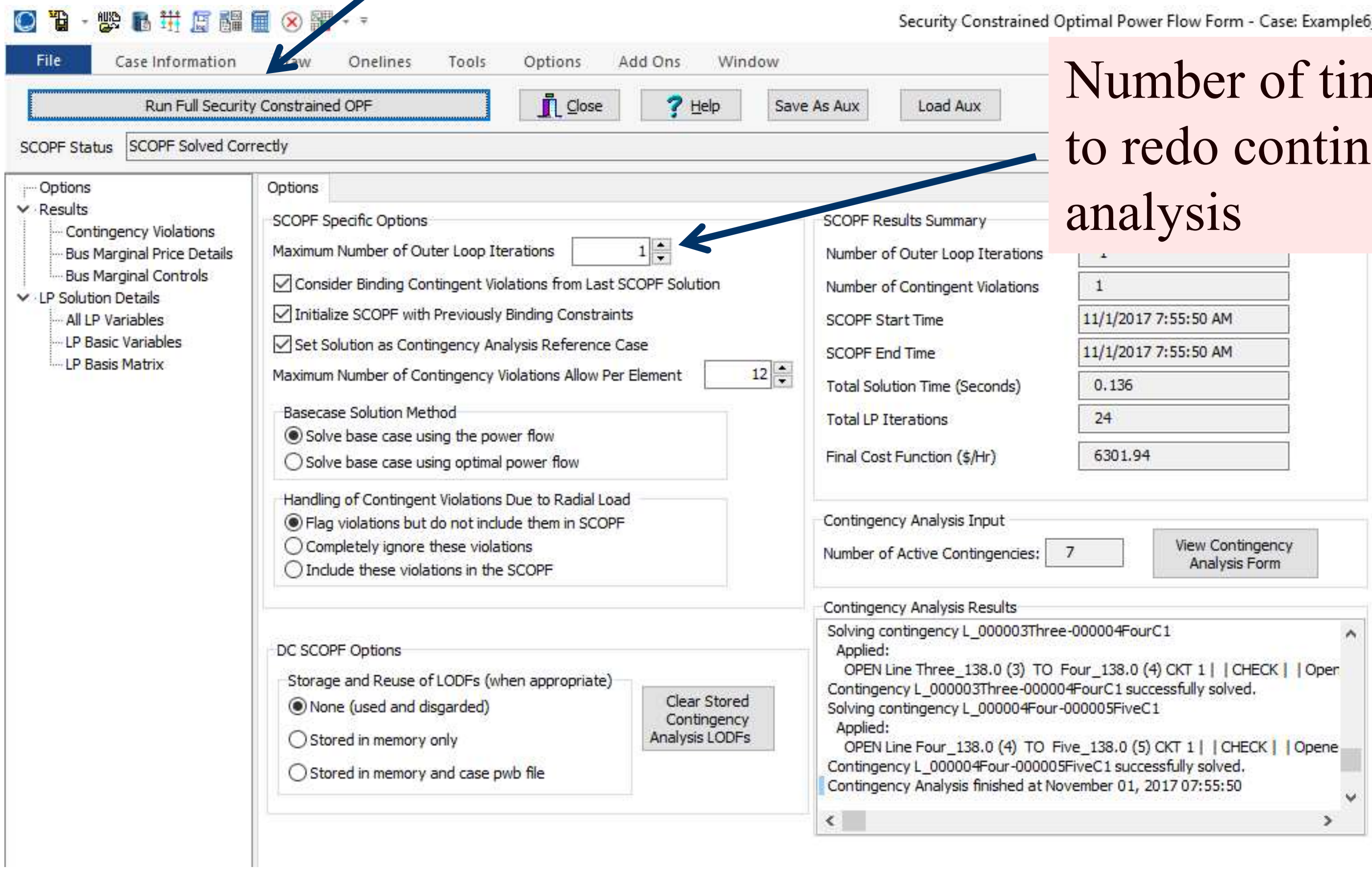
Original with line 4-5 limit of 60 MW with 2-5 out

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

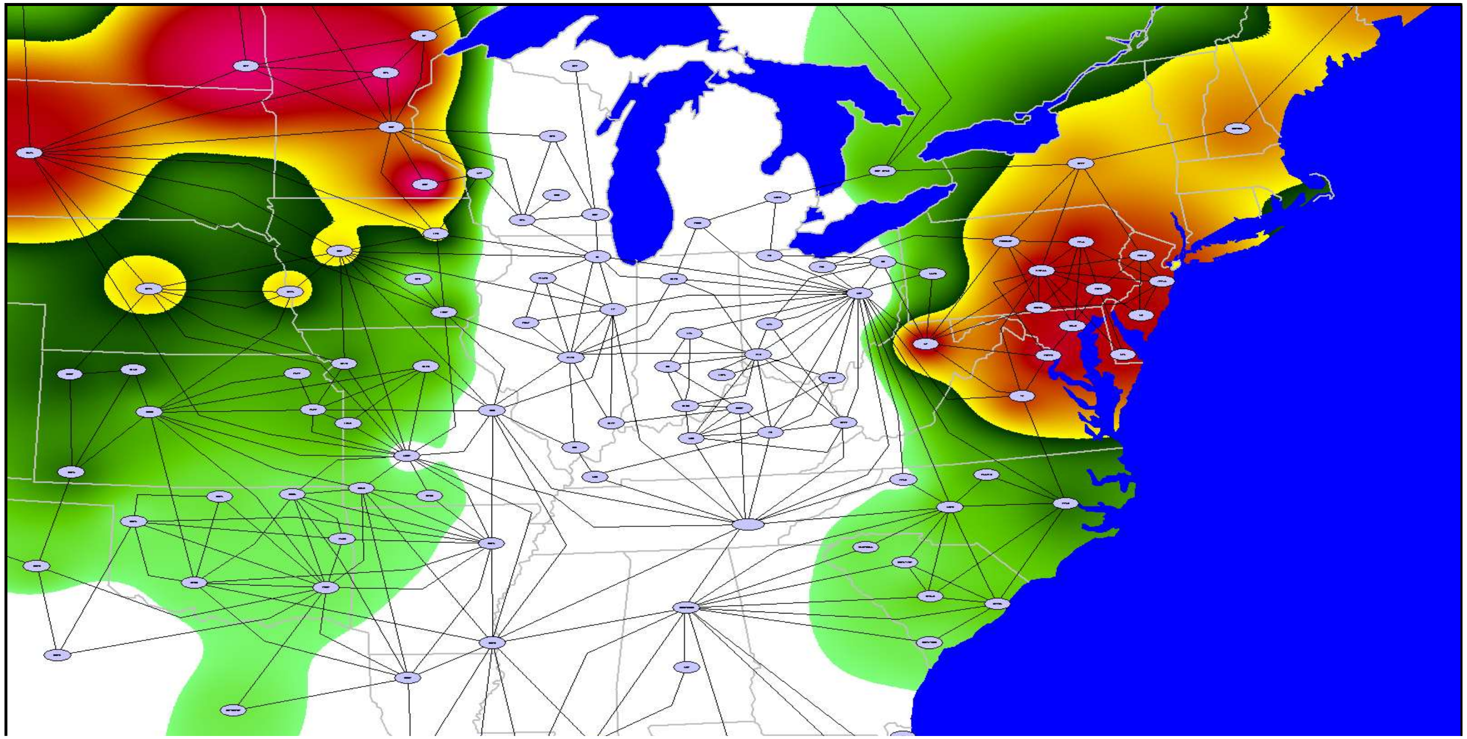
PowerWorld SCOPF Application

Just click the button to solve

Number of times to redo contingency analysis



June 1998 Heat Storm: Two Constraints Caused a Price Spike



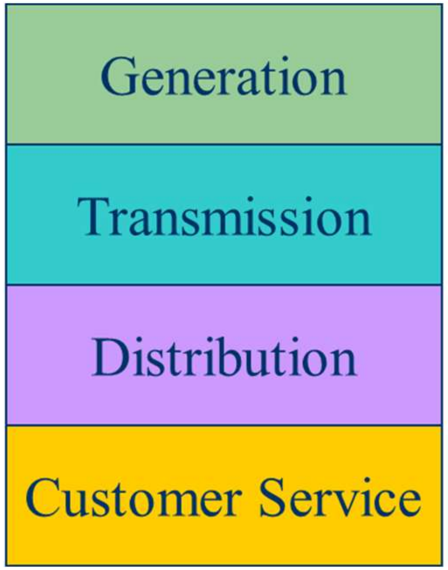
Price of electricity in Central Illinois went to $7500 per MWh!

Since 1998 new transmission has been added to the grid to help alleviate these constraints

Colored areas could NOT sell into Midwest because of constraints on a line in Northern Wisconsin and on a Transformer in Ohio

Electricity Markets History

- For decades electric utilities operated as vertical monopolies, with their rates set by state regulators
- Utilities had an obligation to serve and customers had no choice
  - There was little third party generation
- Major change in US occurred in 1992 with the National Energy Policy Act that mandated utilities provide "nondiscriminatory" access to the high voltage grid
- Goal was to setup true competition in generation



Markets Versus Centralized Planning

- With the vertically integrated utility, a small number of entities (typically utilities) did most of the planning
  - For example, which new generators and/or lines to build
  - Planning was coordinated and governed by regulators
  - Regulators needed to know the utilities actual costs so they could provide them with a fixed rate of return
- With markets the larger number of participants often make individual decisions in reaction to prices
  - For example, whether to build new generation
  - Generator owners in general to not need to reveal their true costs; rather they make offers into the market

Overall Goal

- Goal is to maximize the economic surplus (or total welfare), which is the sum of the consumer surplus and the producer surplus (i.e., their profit)
- Generation owners have to decide their offer prices
- If their price is too high, they are not selected to generate
- At the wholesale level, the consumers often just see a price, though there can be price responsive load bids

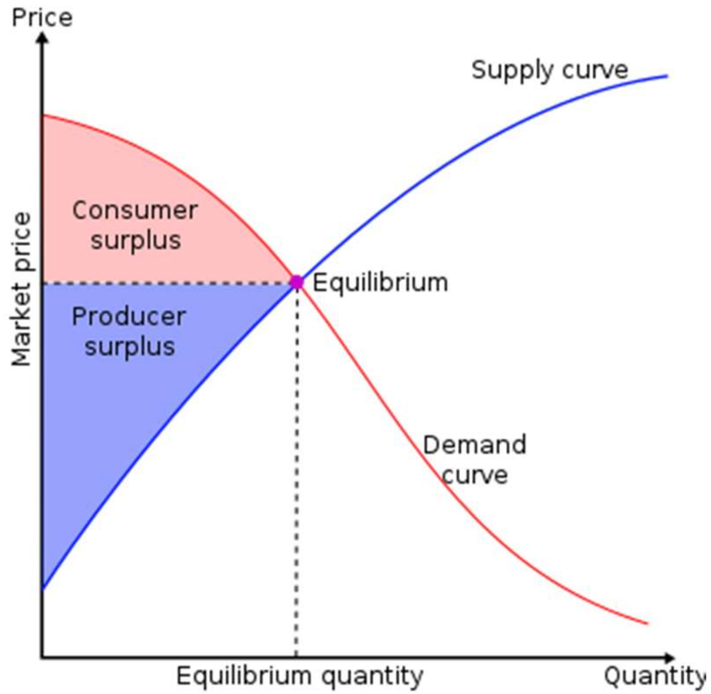
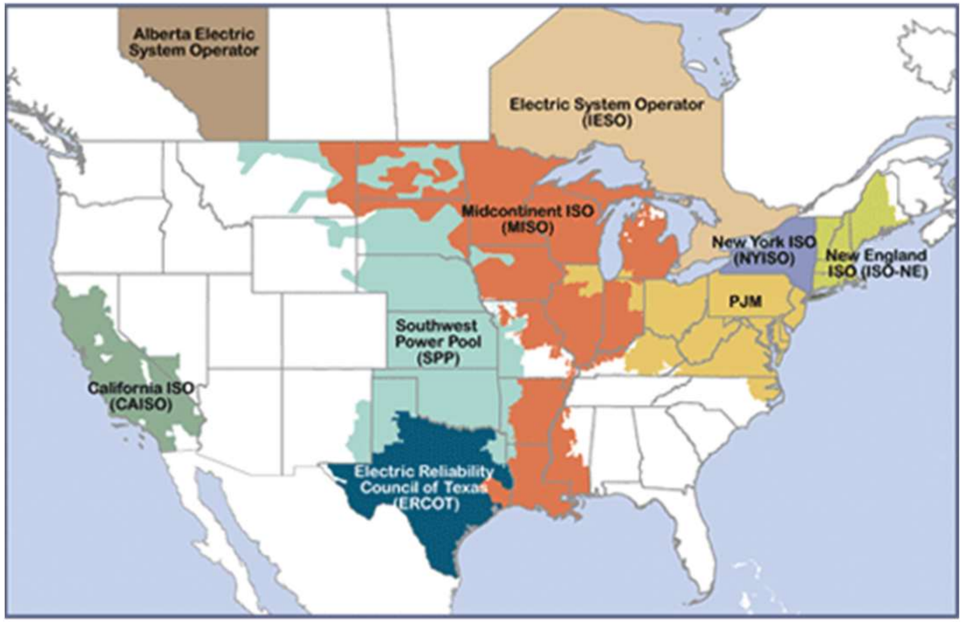


Image Source: en.wikipedia.org/wiki/Economic_surplus#/media/File:Economic-surpluses.svg

Electricity Markets Today in North America

- Starting in about 1995 electricity markets gradually started to develop, both in the US and elsewhere
- In North America more than 60% of the load is supplied via wholesale electricity markets; markets differ but they all have certain common features



  - The terms regional transmission organizations (RTOs) and independent system operators (ISOs) are used (RTOs are more functionality and most are actually RTOs

Image source: www.ferc.gov/industries-data/electric/power-sales-and-markets/rtos-and-isos

Aside: NERC Reliability Coordinators (RCs)

As noted in NERC IRO-001-1, "Reliability Coordinators must have the authority, plans and agreements in place to immediately direct reliability entities within the Reliability Coordinator Areas to re-dispatch generation, reconfigure transmission, or reduce load to mitigate critical conditions to return the system to a reliable state."

Electricity Markets Common Features

- Day ahead market – this is needed because time is required to make decisions about committing generators
  - Generation owners submit offers for how much generation they can supply and at what price; accepted offers are binding
- Real-time energy market – needed because day ahead forecasts are never perfect, and unexpected events can occur
- Co-optimization with other "ancillary services" such as reserves

The source for much of this material "Analytic Research Foundations for the Next-Generation Electric Grid" (Chapter 2), The National Academies Press, 2016 (free download available)

Electricity Markets Common Features

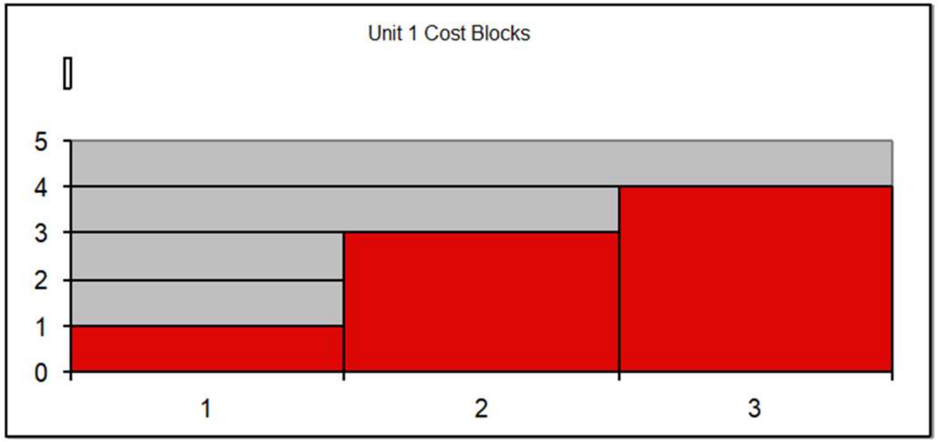
- Pricing is done using locational marginal prices, determined by an SCOPF
  - Most markets include a marginal losses component
- LMP markets are designed to send transparent price signals so people can make short and long-term decisions
  - Generators are free to offer their electricity at whatever price they desire; they do not have to reveal their "true" costs
  - Most of the times markets work as planned (competitive prices)
  - During times of shortages (scarcity) there are limits on LMPs; ERCOT's had been $9000/MWh prior to Uri; now it is $5000/MWh
  - Markets are run by independent system operators (ISOs)

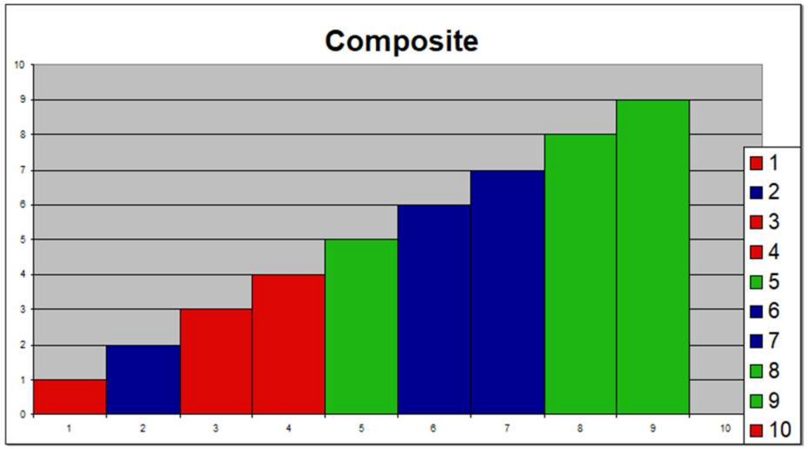
LMP Energy Markets

- In an LMP energy market the generation is paid the LMP at the bus, and the loads pay the LMP at the bus
  - This is done in both the day ahead market and in the real-time market (which makes up the differences between actual and the day ahead)
- The generator surplus (profit) is the difference between the LMP and the actual cost of generation
- Generators that offer too high are not selected to run, and hence make no profit
- A key decision for the generation owners is what values to offer

Generator Offers

- Generator offers are given in piecewise linear curves; that is, a fixed \$/MWh for so much power for a time period
- In the absence of constraints (congestion) the ISO would just select the lowest offers to meet the anticipated load
- Actual dispatch is determined using an SCOPF





General Guidelines

- Generators with high fixed costs and low operating costs (e.g., wind, solar, nuclear) benefit from running many hours
  - Usually they should submit offers close to their marginal costs
  - Wind (and some others) receive a production tax credit (PTC) for their first ten years of operation
    - $23/MWh for systems starting construction before 1/1/2017
    - $18/MWh 2017, $14/MWh in 2018, $10/MWh in 2019
    - It was suppose to end in 2019, but was extended in 12/2019 through 2020 at $15MWh
    - Then it got extended through the end of 2021 at $18/MWh
    - On 8/16/22 President Biden signed the Inflation Reduction Act of 2022 that extended the PTC through at least 2024 and provides 100% for certain projects
  - Generators with low fixed costs and high operating cost can do fine operating fewer hours (at higher prices)

Auctions

- 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.

- 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

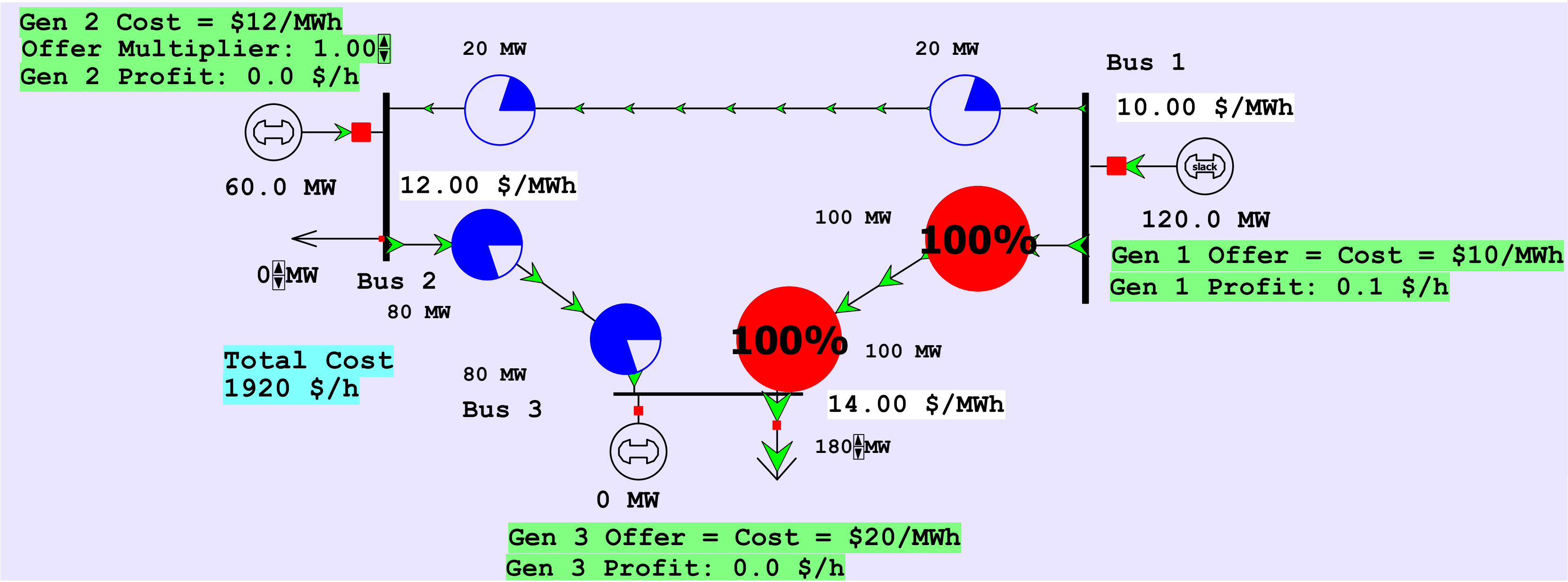
- Simultaneous auctions
  - English (ascending price to buy)
  - Dutch (descending price to buy)
- Sealed-bid auctions (all participants submit offers simultaneously)
  - First price sealed bid (pay highest price if one, discriminatory prices if multiple)
  - Vickrey (uniform second price) (pay the second 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

- 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

- 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

- 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 thought 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 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

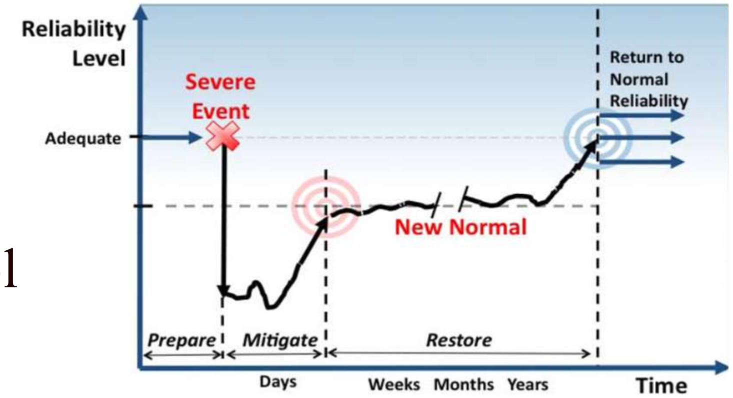


Image Source: NERC, 2012

- The next several slides will consider some challenges in this area including some coverage of Winter Storm Uri

Reliability and Resiliency

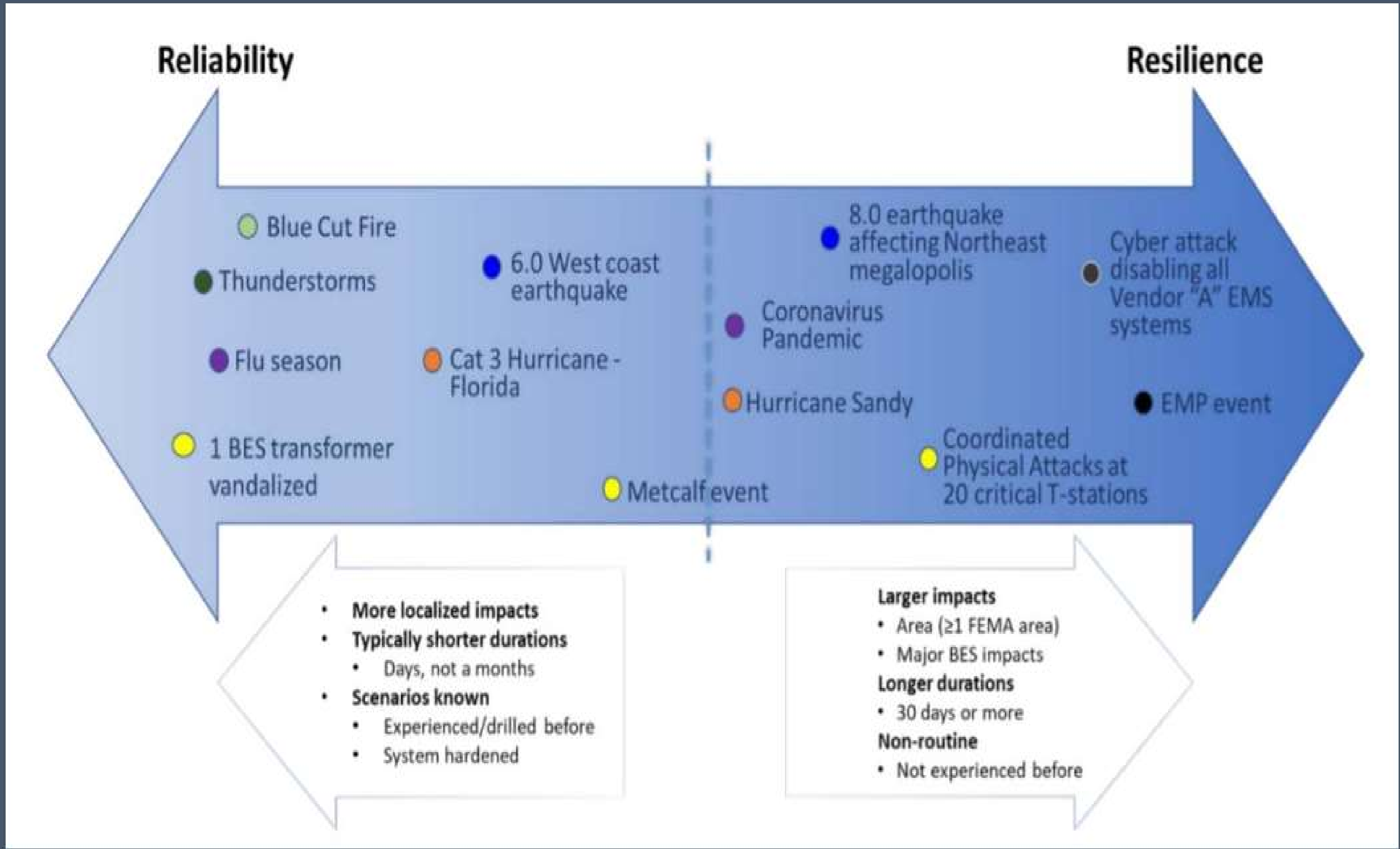
- Keeping the lights on involves designing and operating the electric grid with a goal of simultaneously increasing two related but ultimately different concepts: reliability and resiliency
- Reliability: suitable or fit to be relied on: dependable
  - One of the key benefits of interconnected electric 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

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

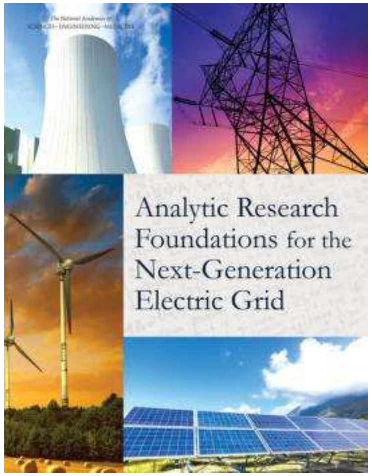


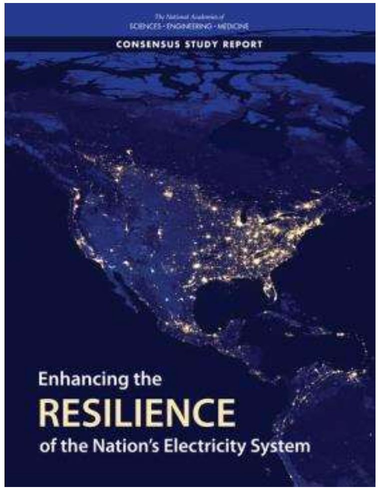
Credit: NATF TRMM Users Guide

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

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

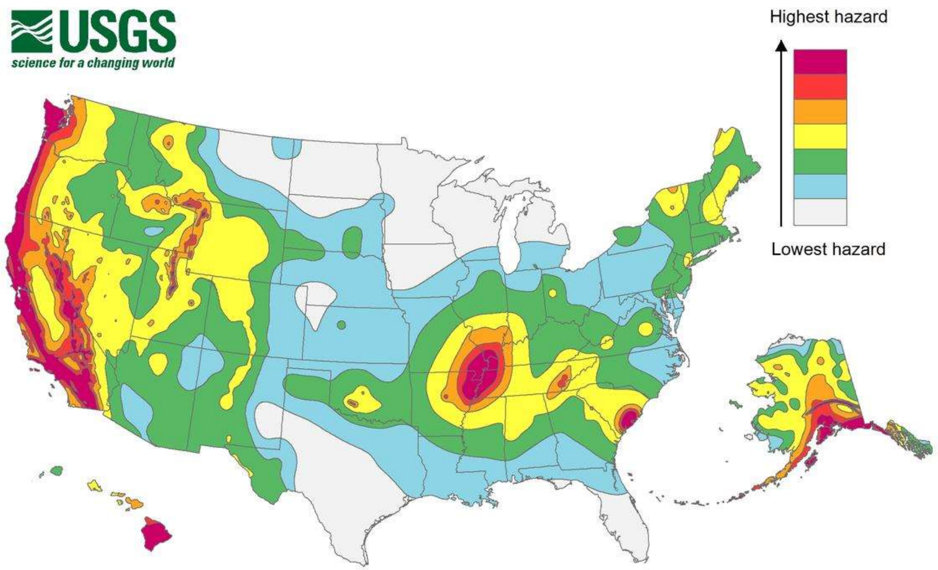




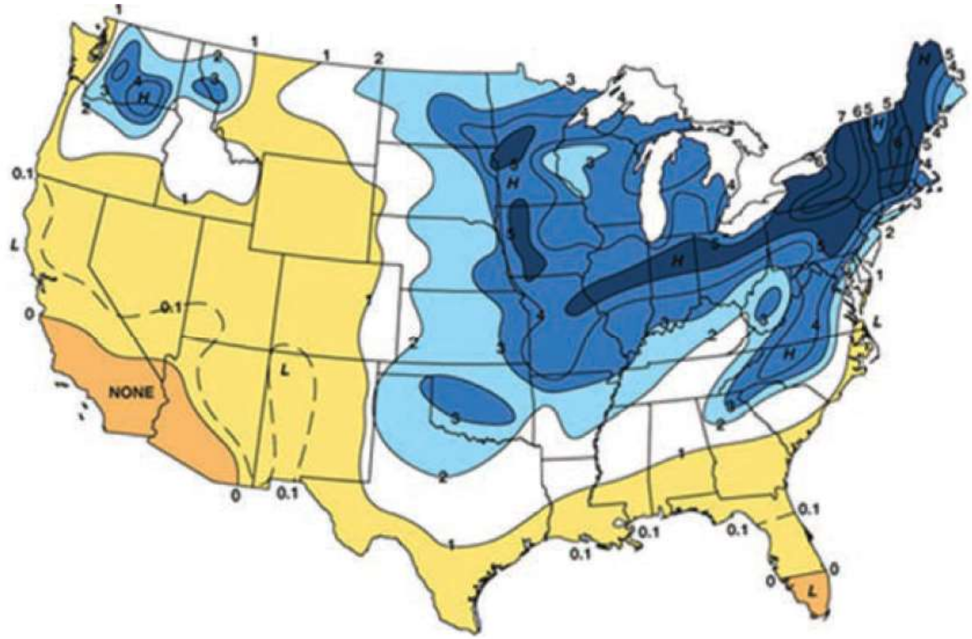
Resilient to What?

- 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

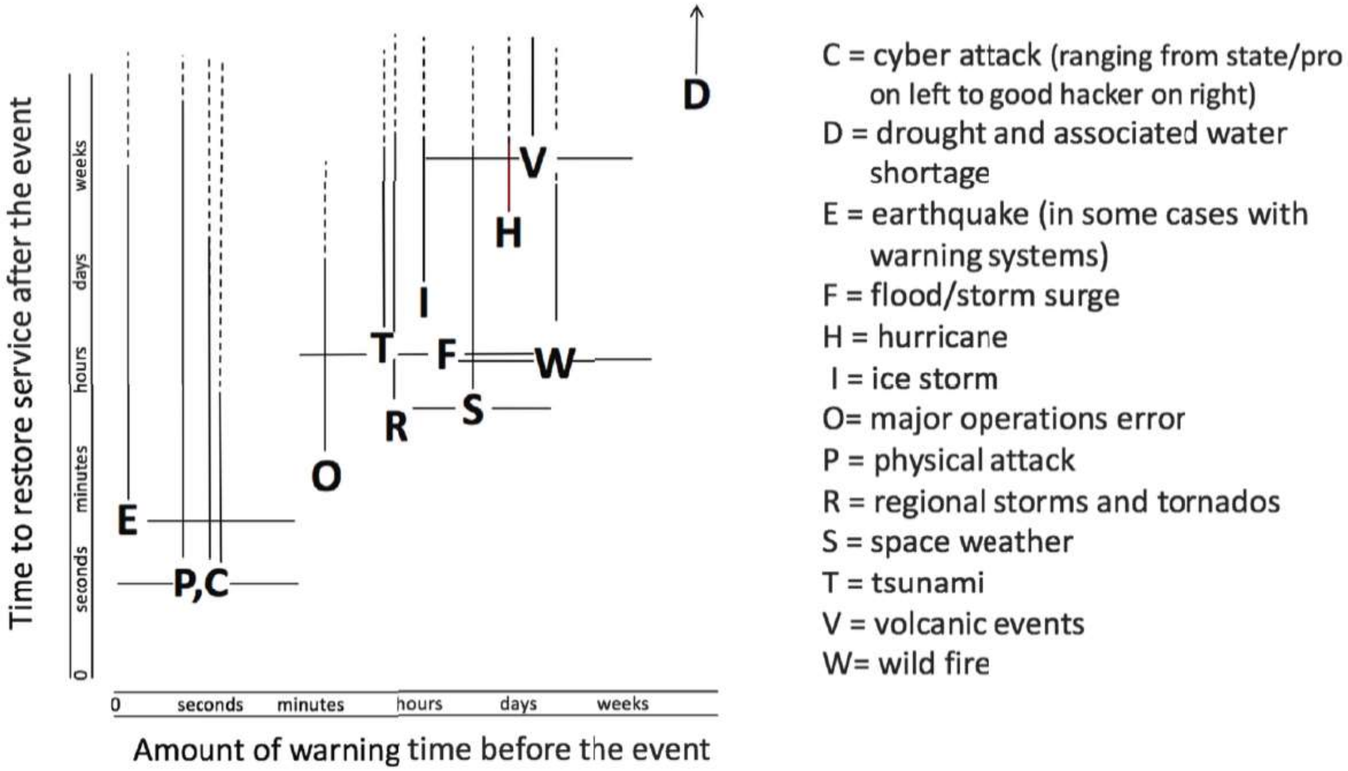


FIGURE 3.1 Mapping of events that can cause disruption of power systems. The horizontal placement provides some indication of how much warning time there may be before the event. The vertical axis provides some indication of how long it may take to recover after the event. Lines provide a representation

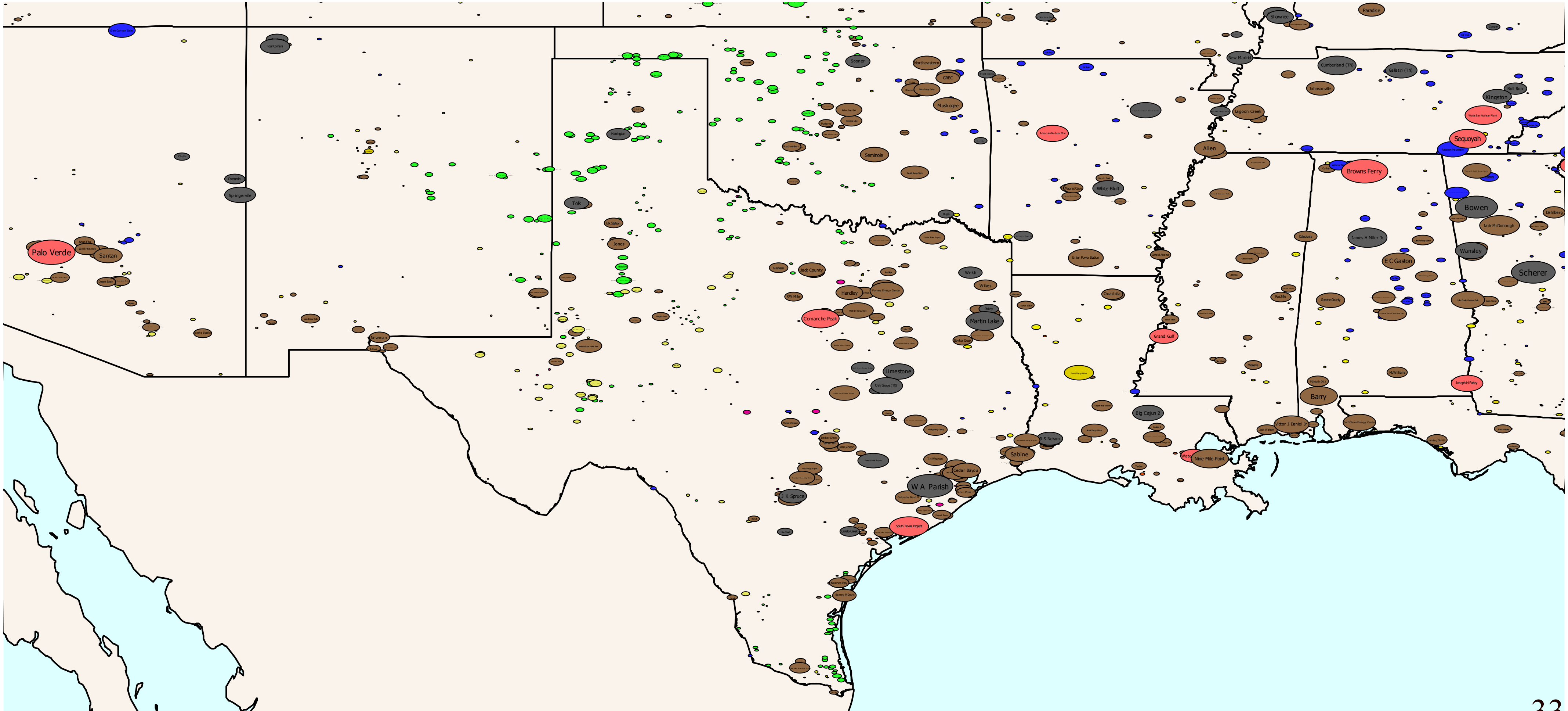
This image does not mention cold weather, though it is discussed in the 2017 report

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

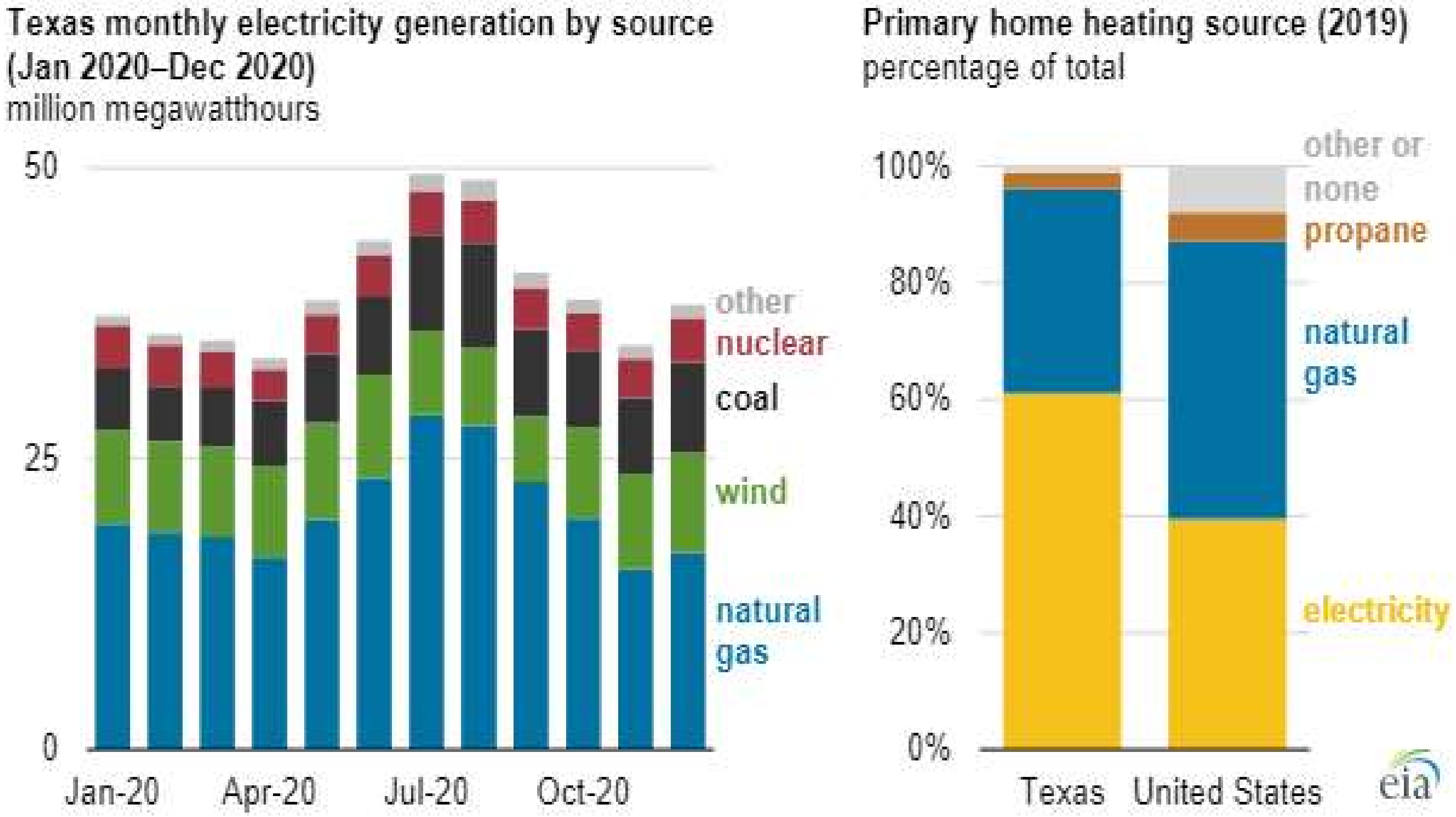
Texas Near Blackout, February 2021

- 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



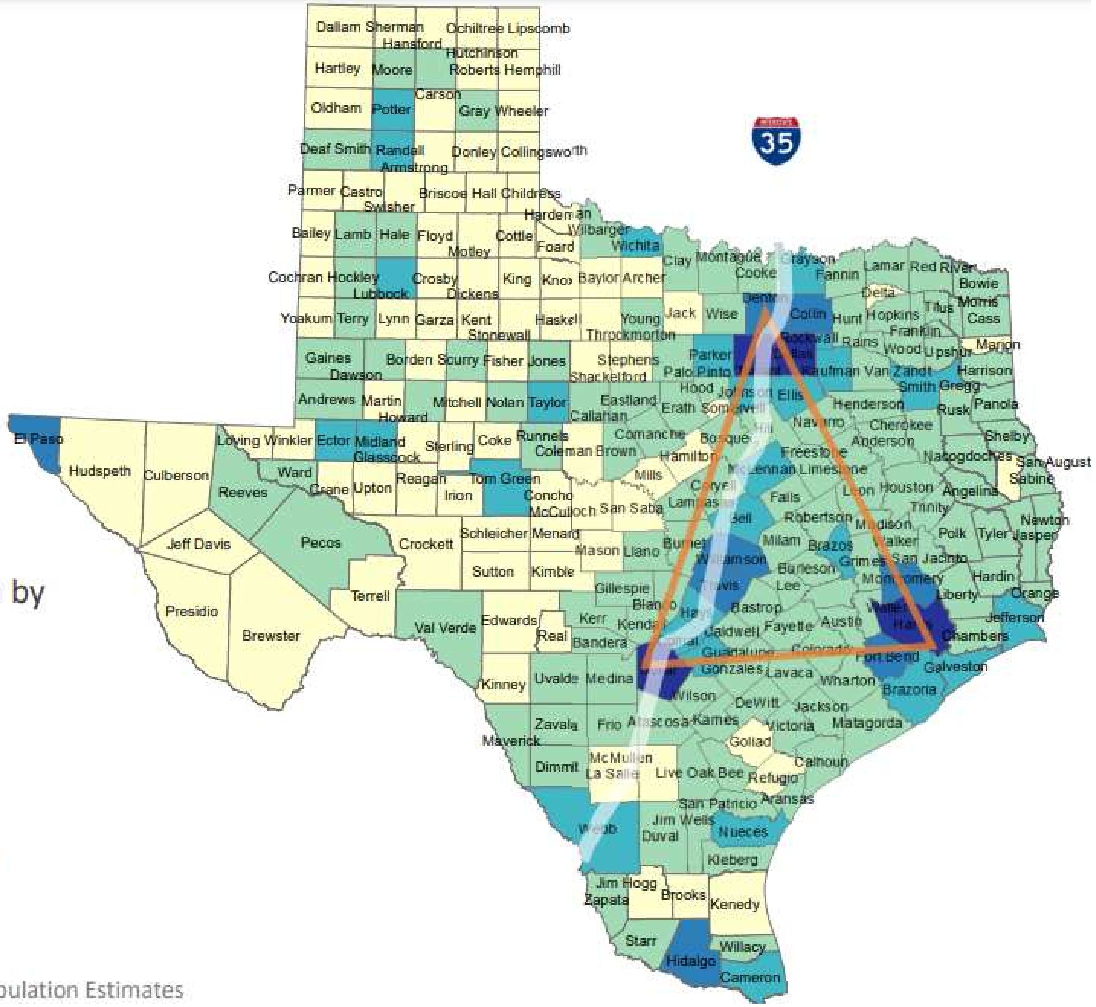
Texas Generation and Home Heating Sources



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



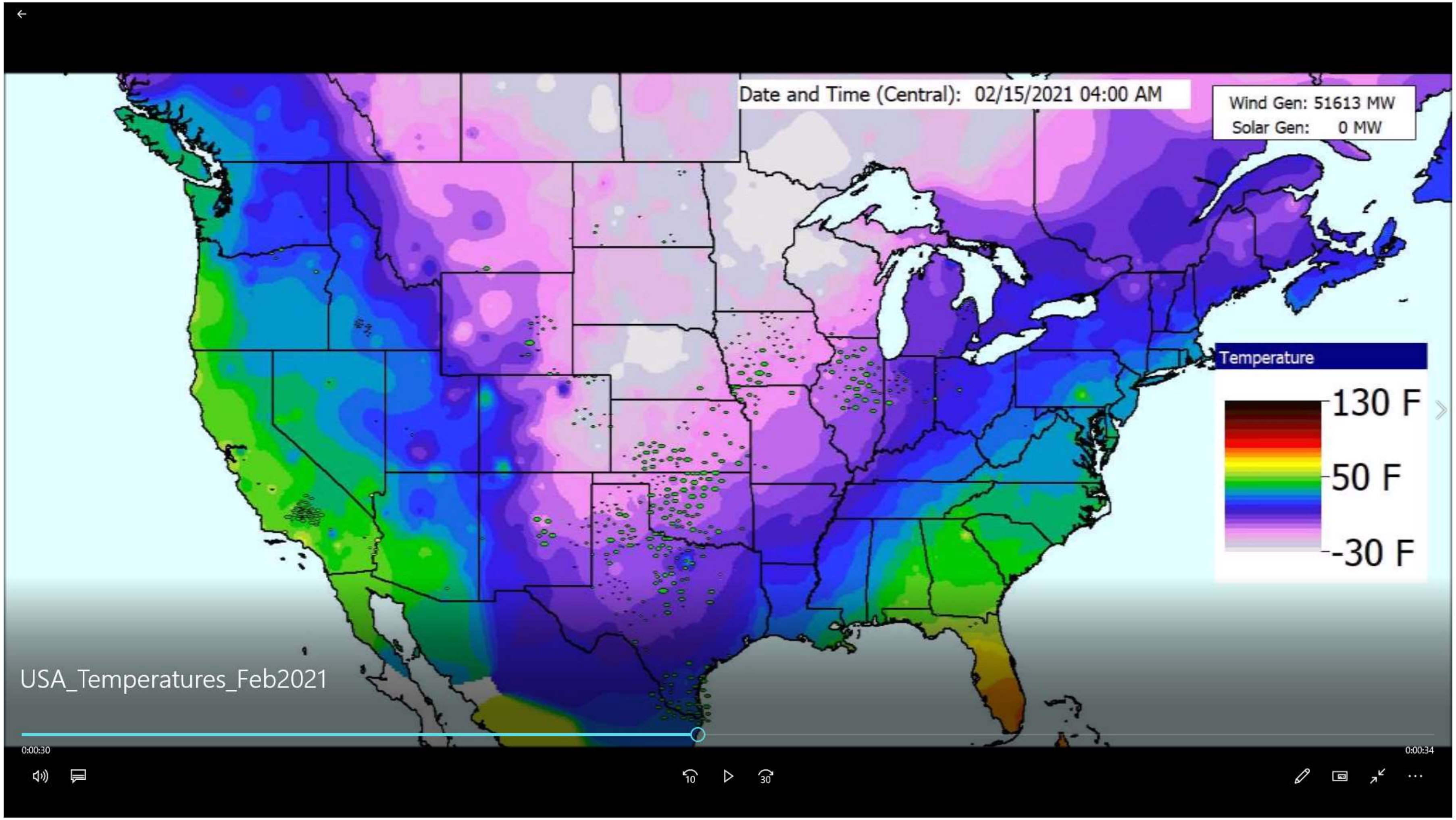
Total Estimated Population by County, 2019

- 169 - 10,000
- 10,001 - 100,000
- 100,001 - 500,000
- 5000,001 - 2,000,000
- 2,000,001 - 4,713,325

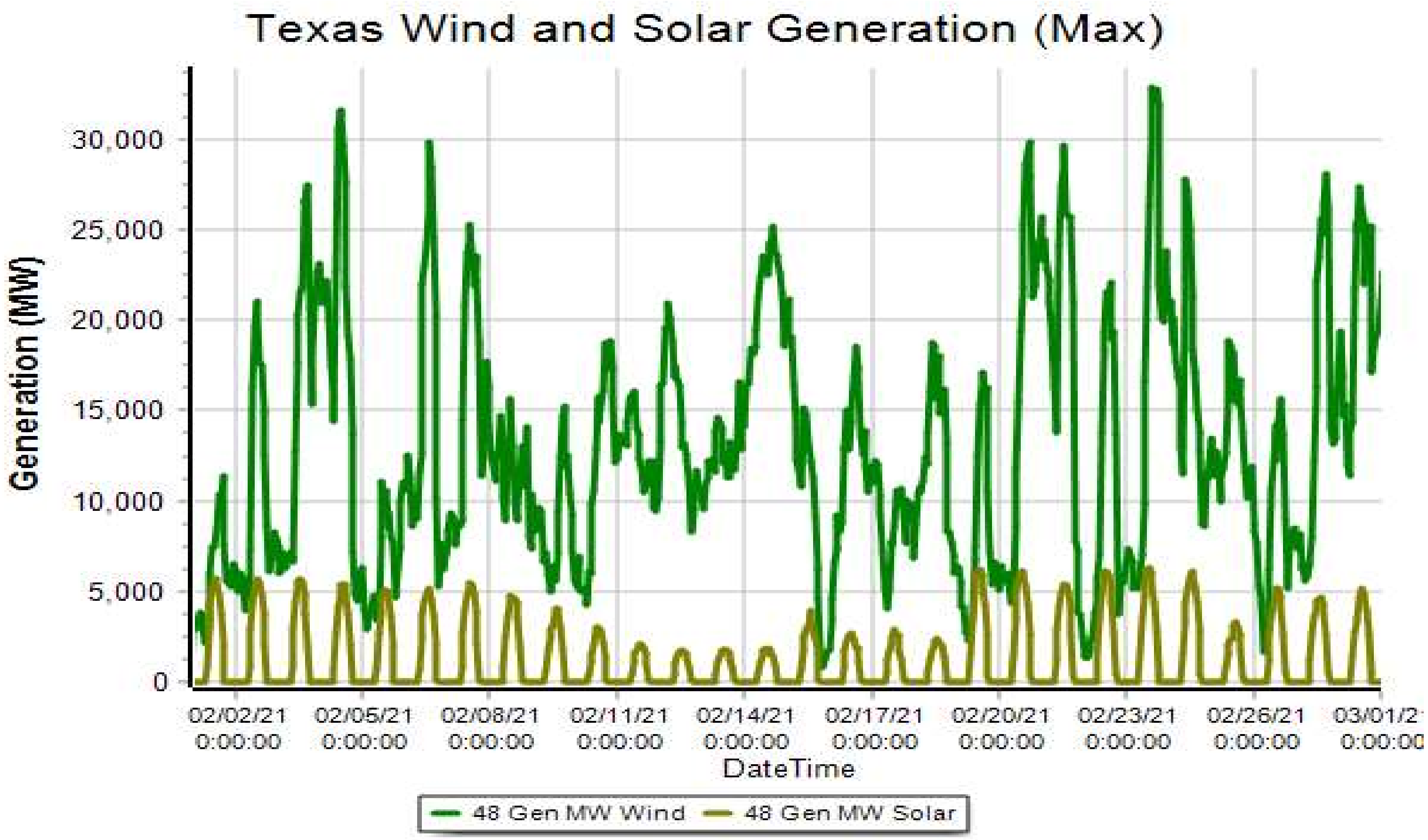
Source: U.S. Census Bureau, 2019 Population Estimates

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

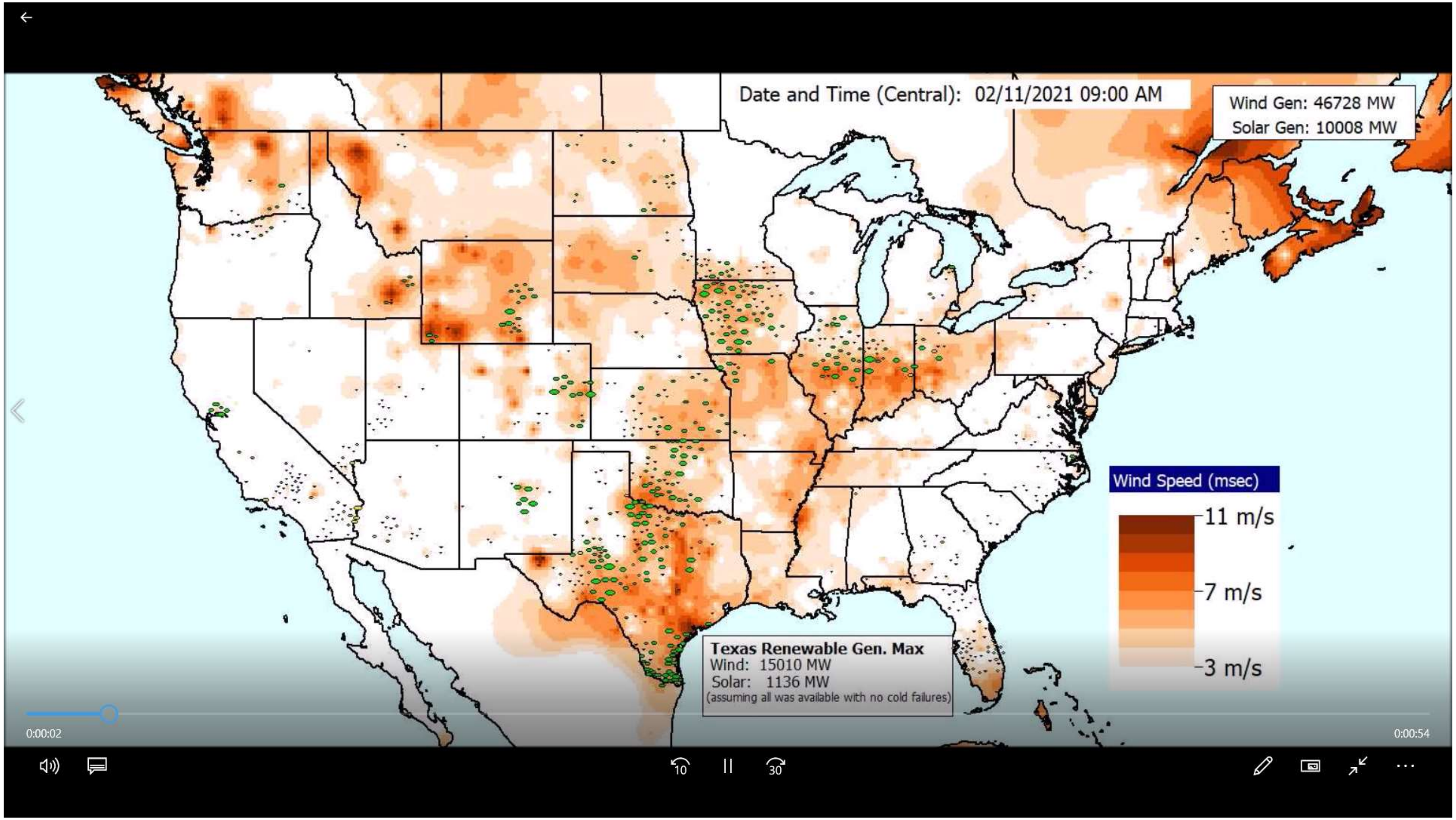


Texas Wind and Solar Max Gen Based on Weather



This does not account for cold weather failures

Visualization of Wind Speed, Feb 11 to 18, 2021



ERCOT Generation Feb 11-18, 2021

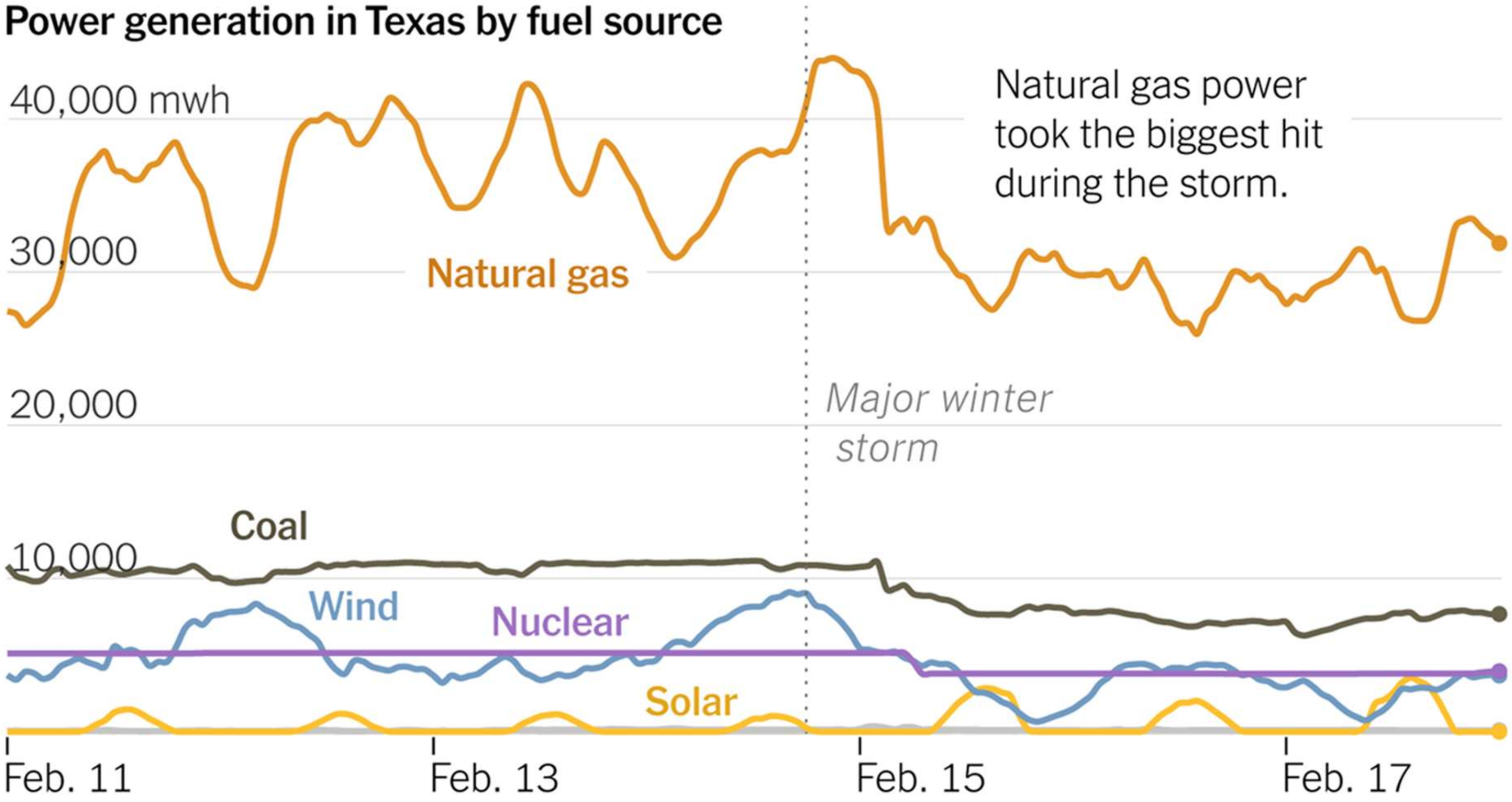
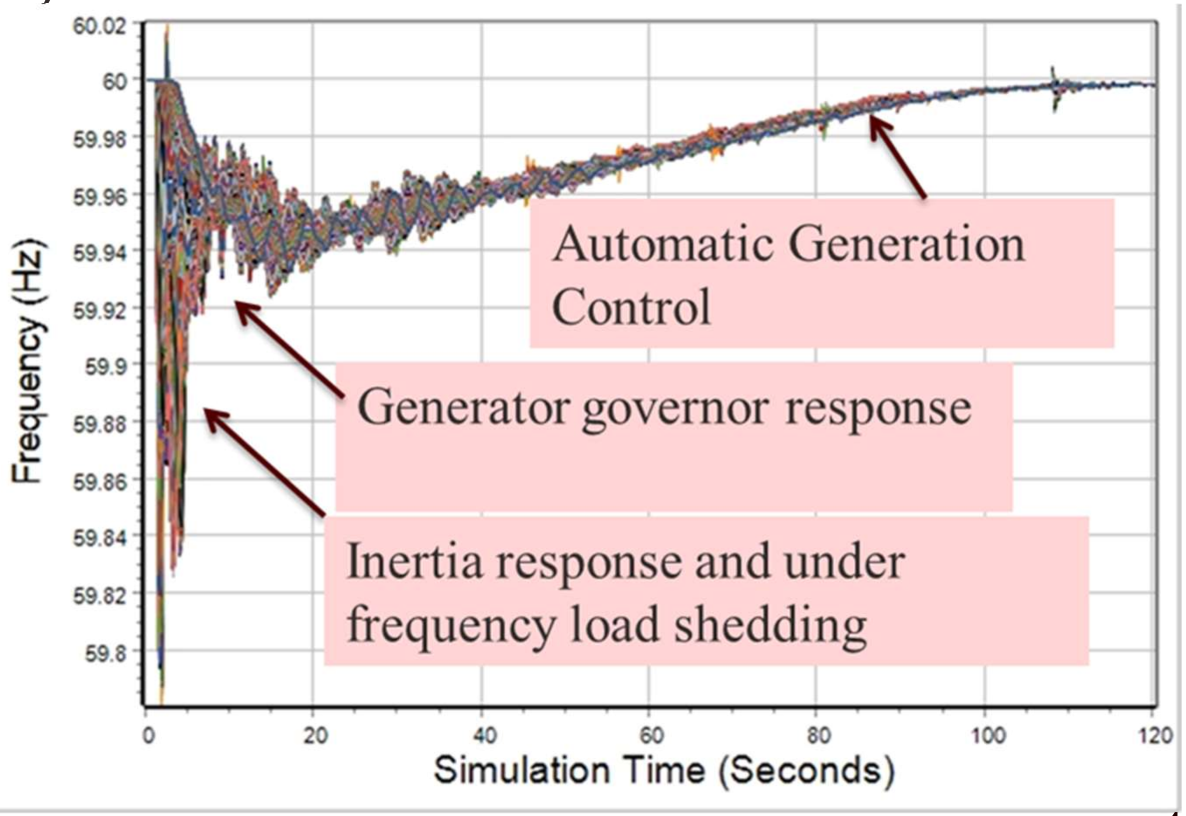


Image source: New York Times, Feb 23, 2021

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

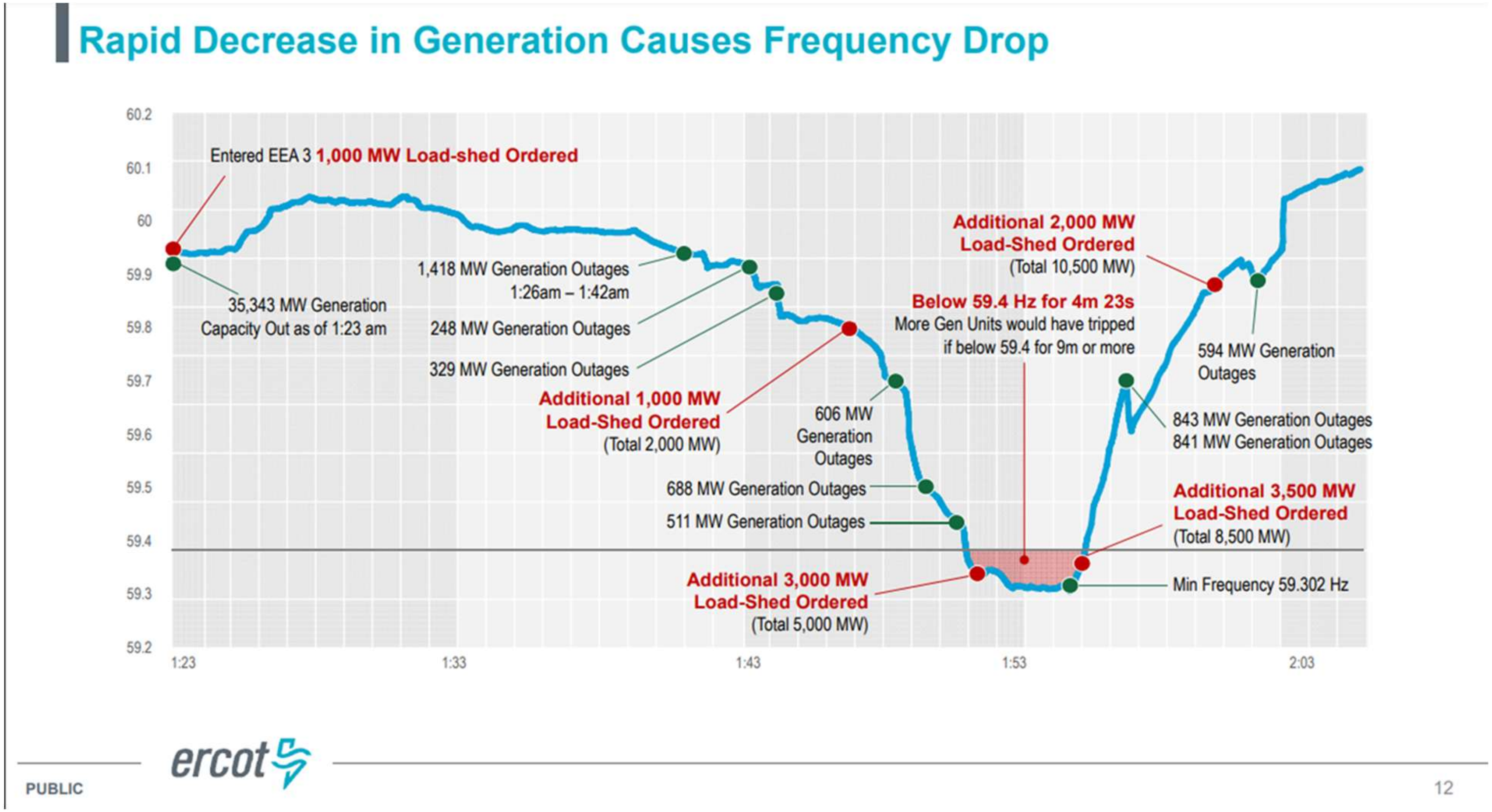
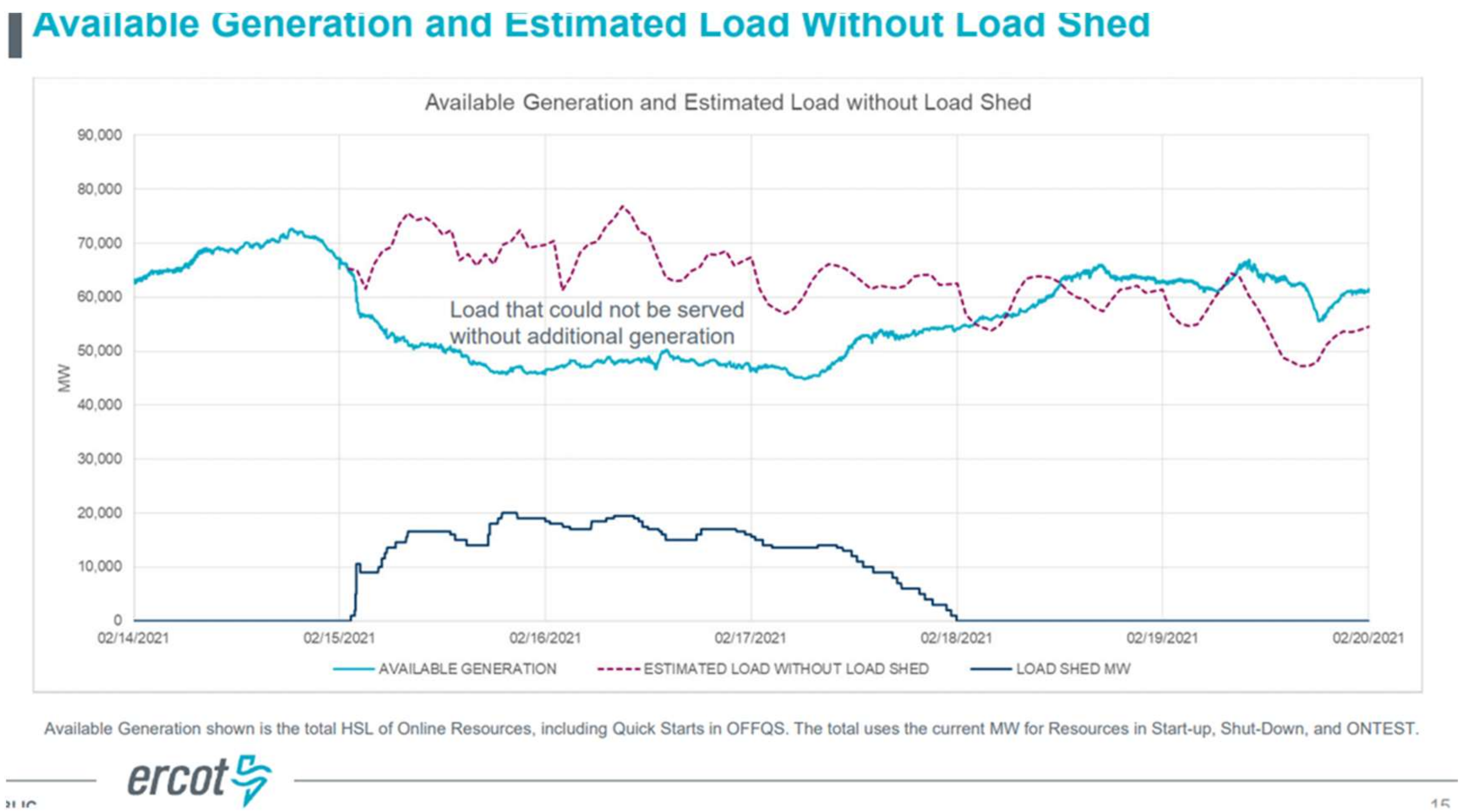


Image source: ERCOT Presentation by Bill Magness, February 25, 2021

ERCOT Load Shed and Rotating Blackouts

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

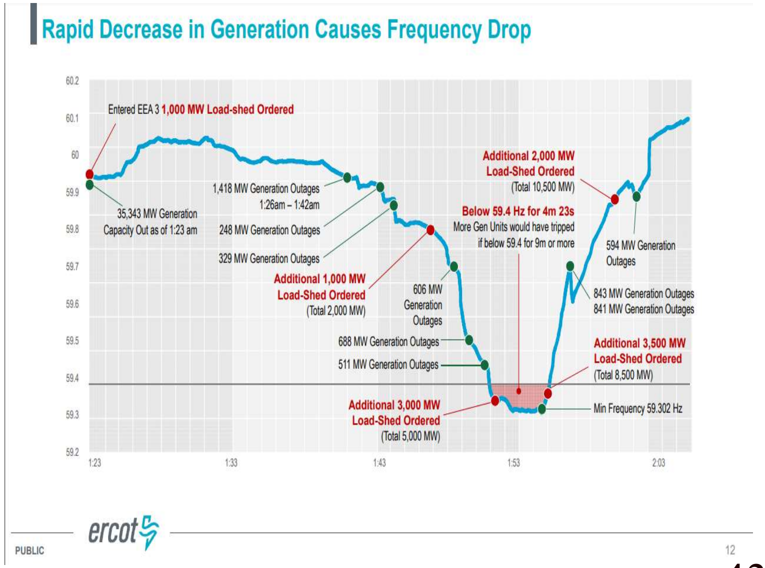


At the time the ERCOT peak load had been 74.8 GW (summer); winter peak of 69.2 GW was set on 2/14/21 (previous winter peak was 65.9 GW). A new peak of 80 GW was set on 7/20/22.

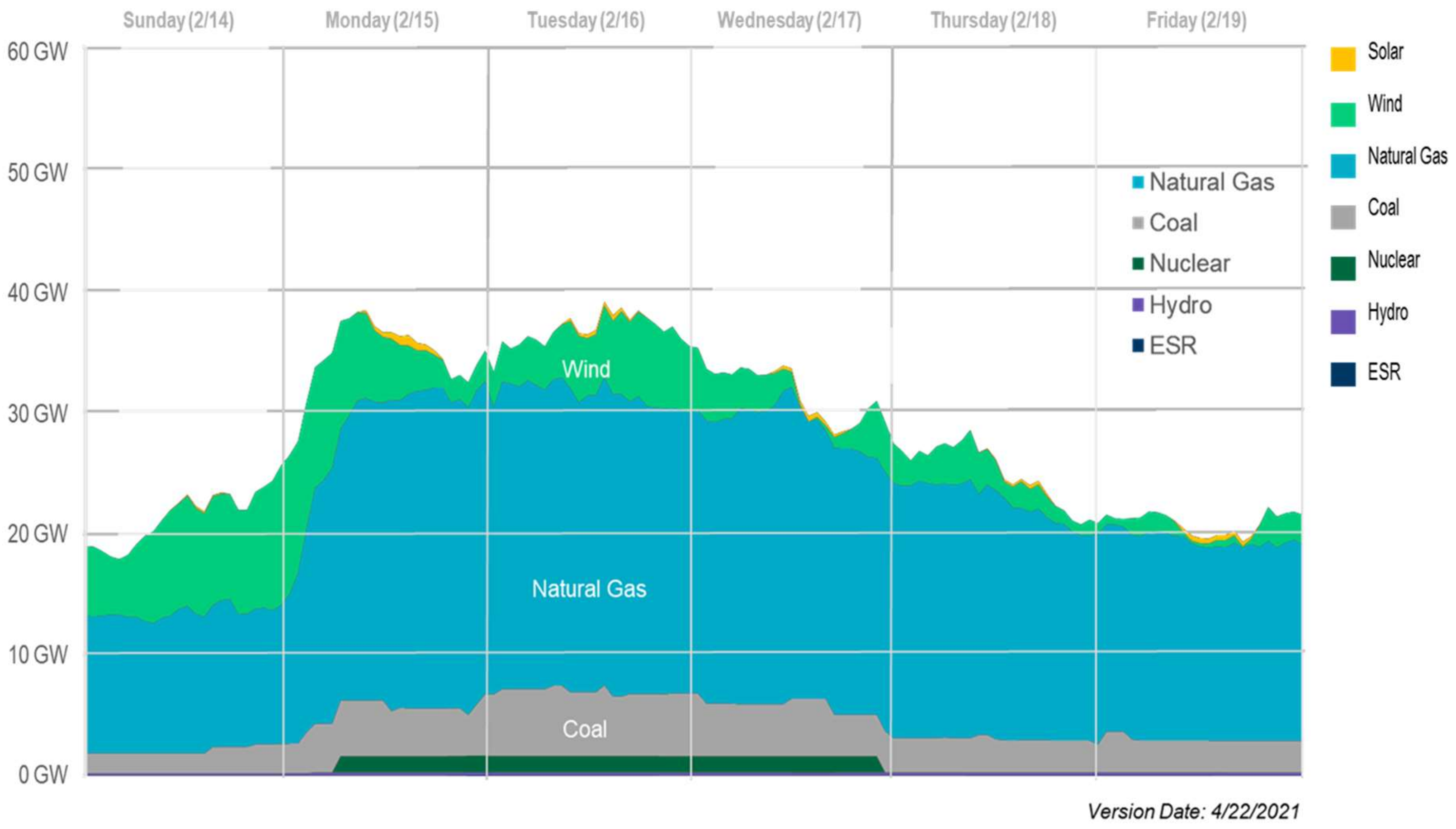
Image source: ERCOT Presentation by Bill Magness, February 25, 2021

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

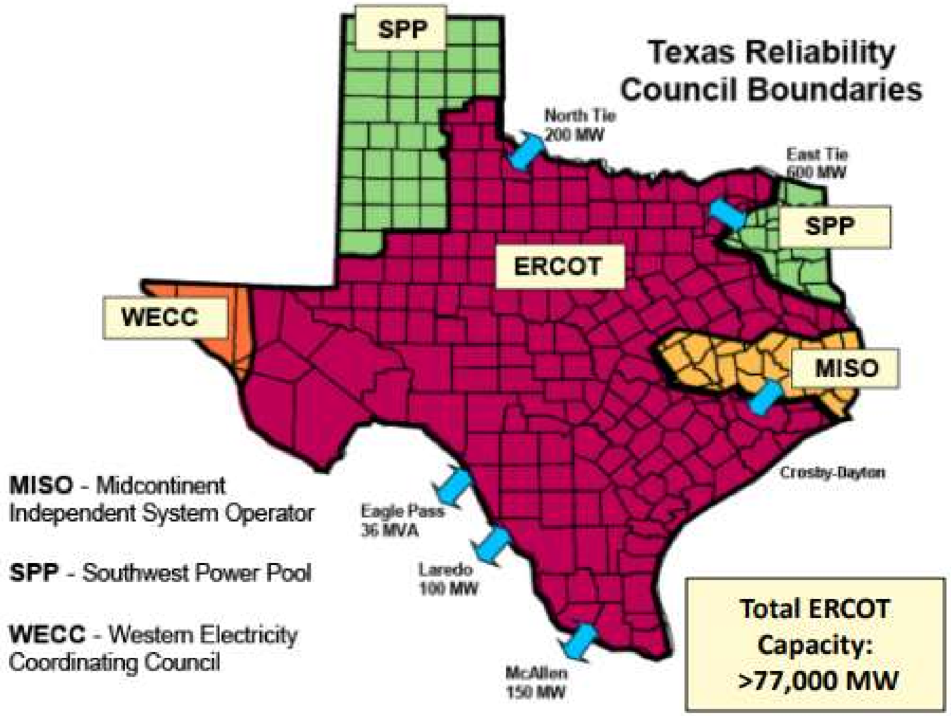
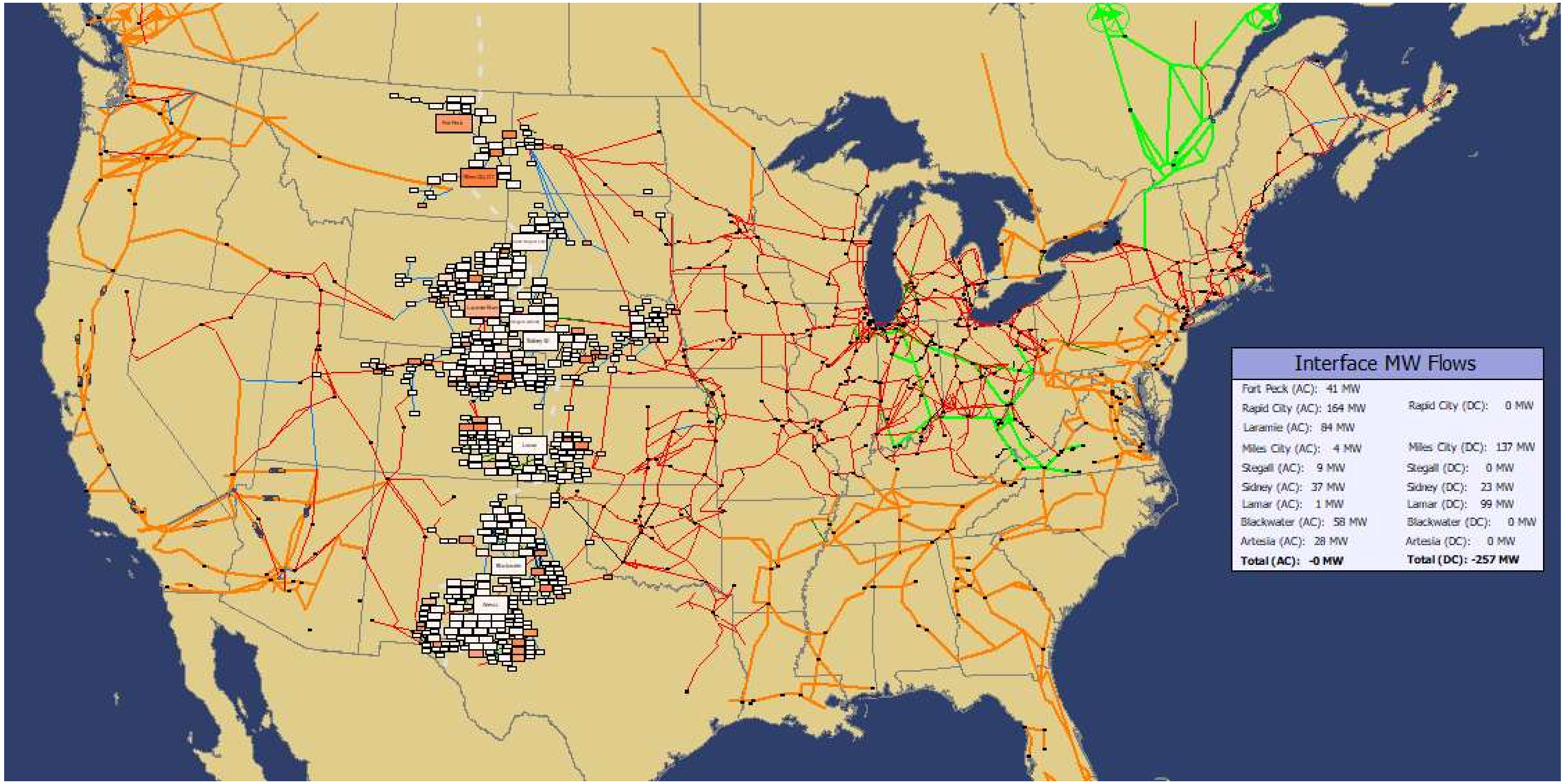


Image Source: aect.net/documents/2017/AECT%20LSB%20012617.pdf

Joining the East and West Grids

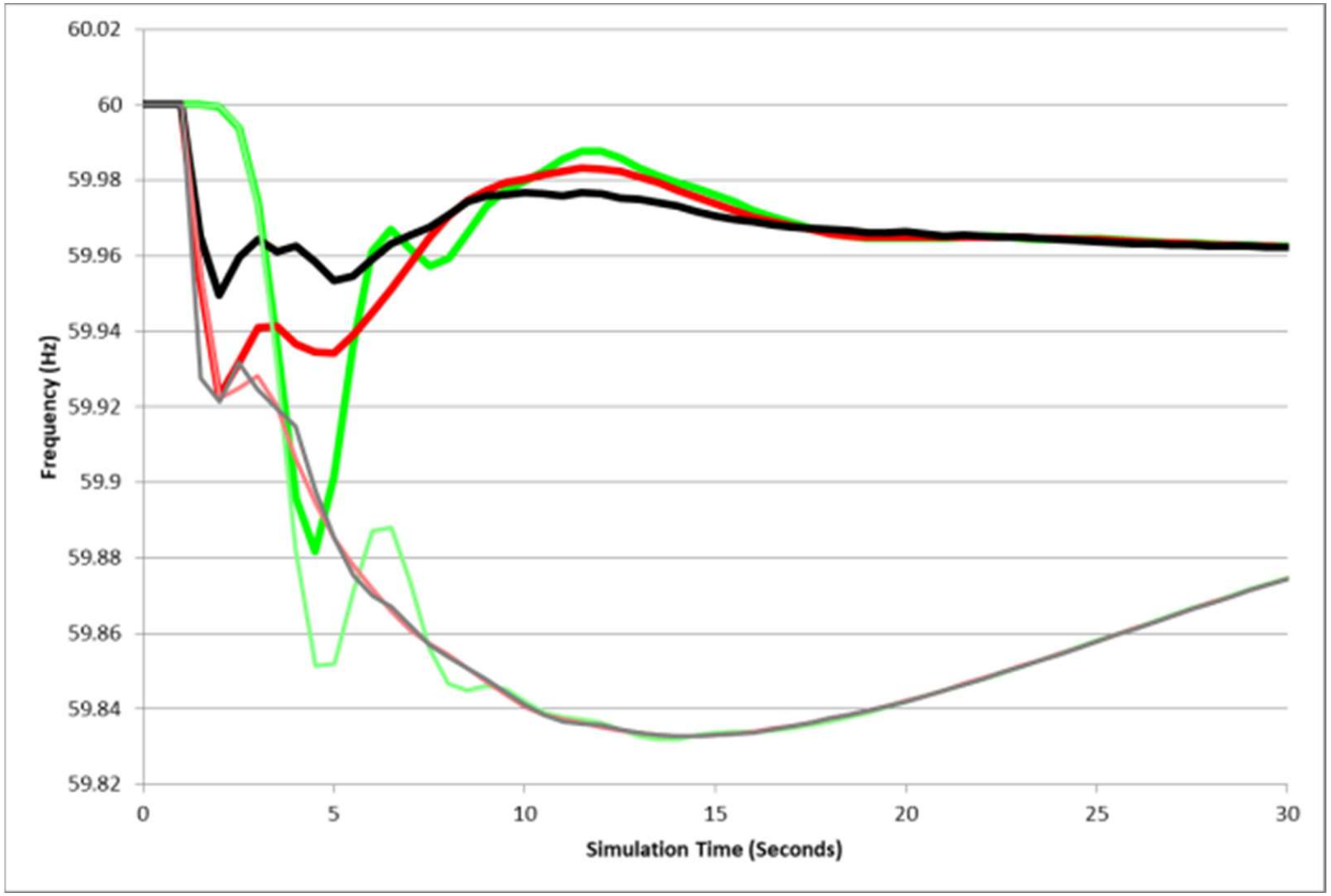
- In 2020 we did a research project for SPP looking at an ac interconnection of the East and West grids
  - This did not include ERCOT, but did include parts of Texas
- There are nine locations where the grids are close and could be tied together
- The study required lots of dynamic simulations using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



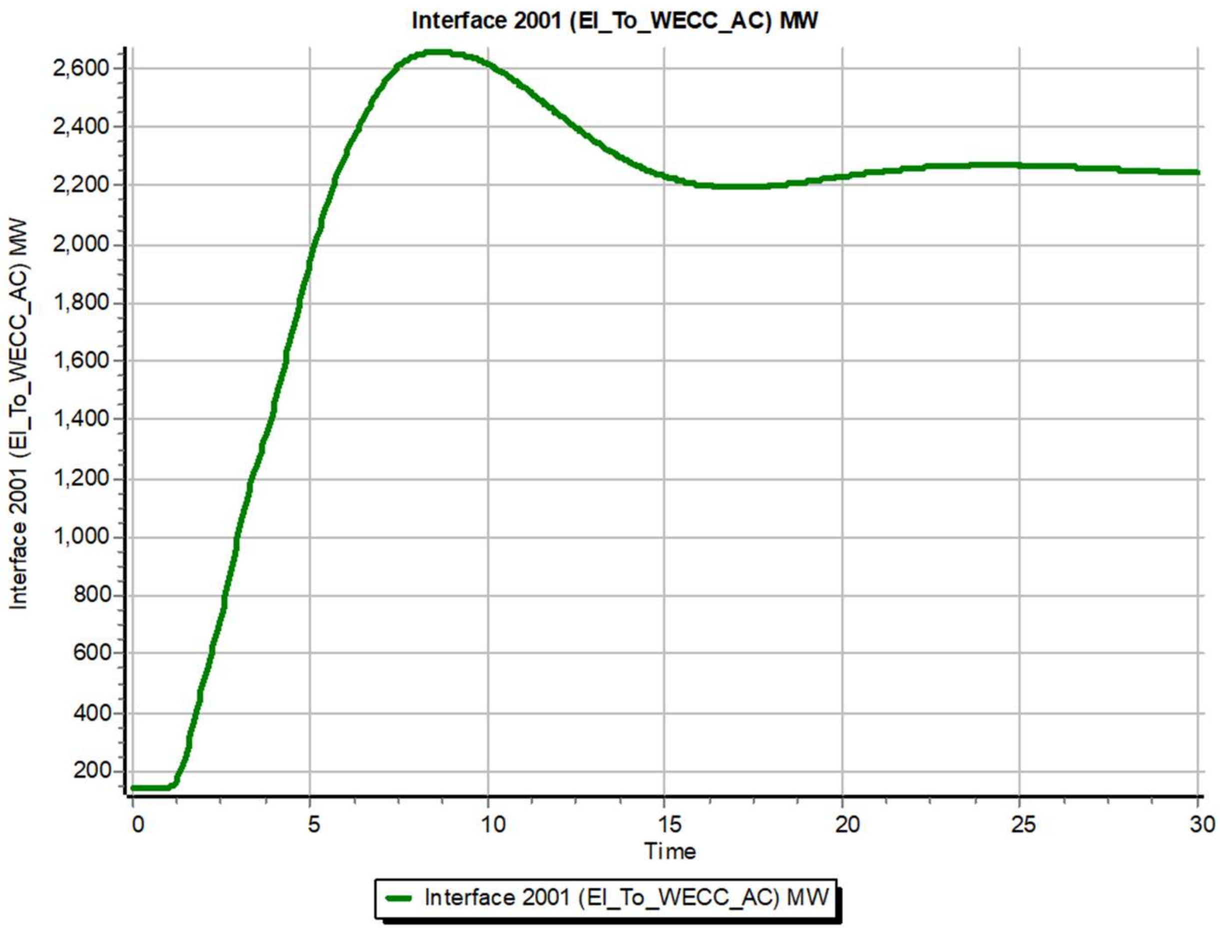
The study included Canada but we did not consider any ac interconnections between the grids in Canada; the grids were connected at nine points from Montana to New Mexico

WECC Frequency Response: With and Without the AC Interconnection



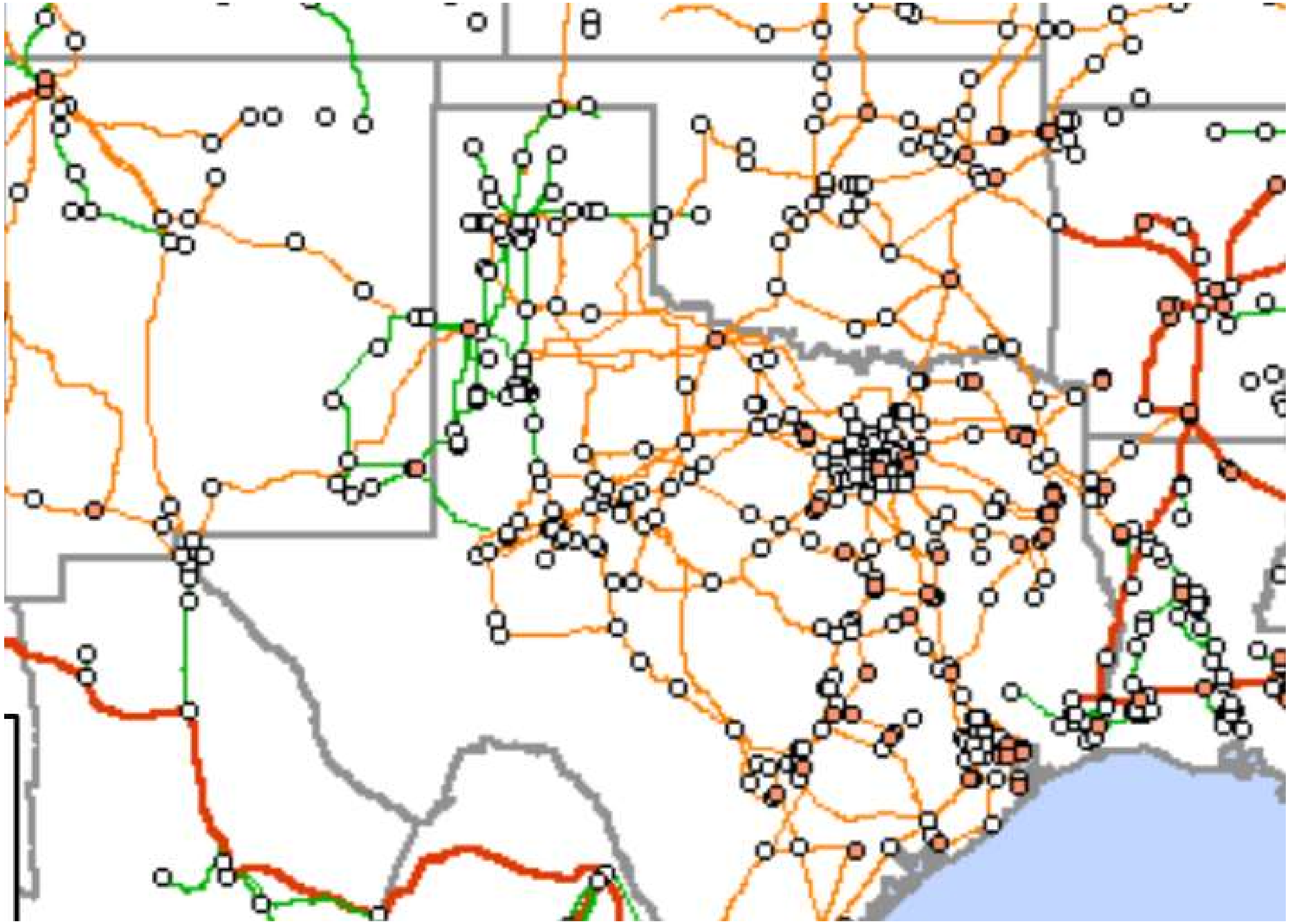
The graph compares the frequency response for three WECC buses for a severe contingency with the interface (thick lines) and without (thin lines)

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.

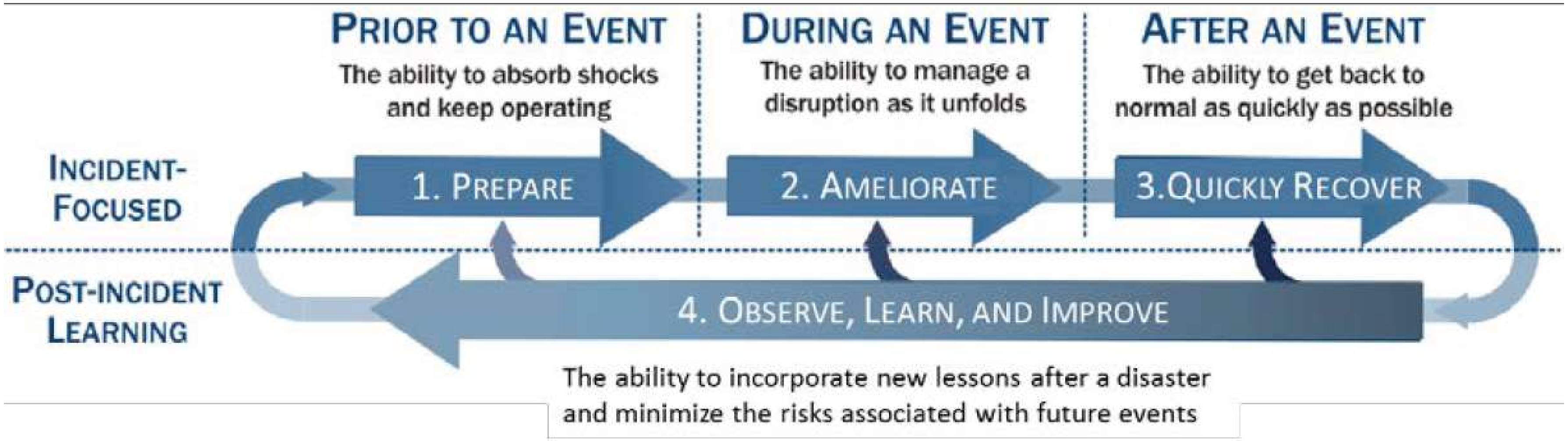
ERCOT-East-West Transmission



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.

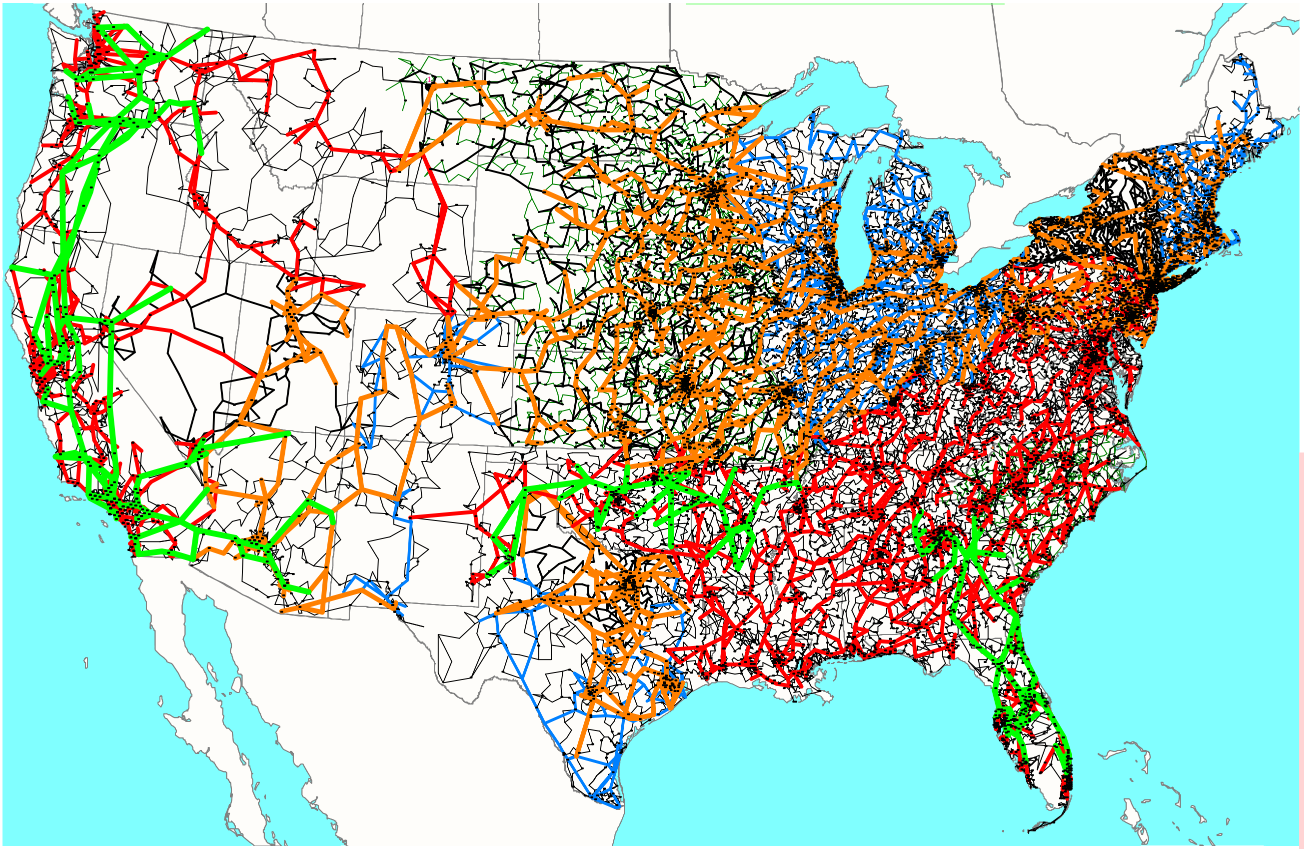
How to Approach HILF Events

- 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”