ERCOT's Experience Integrating High Shares of IBR

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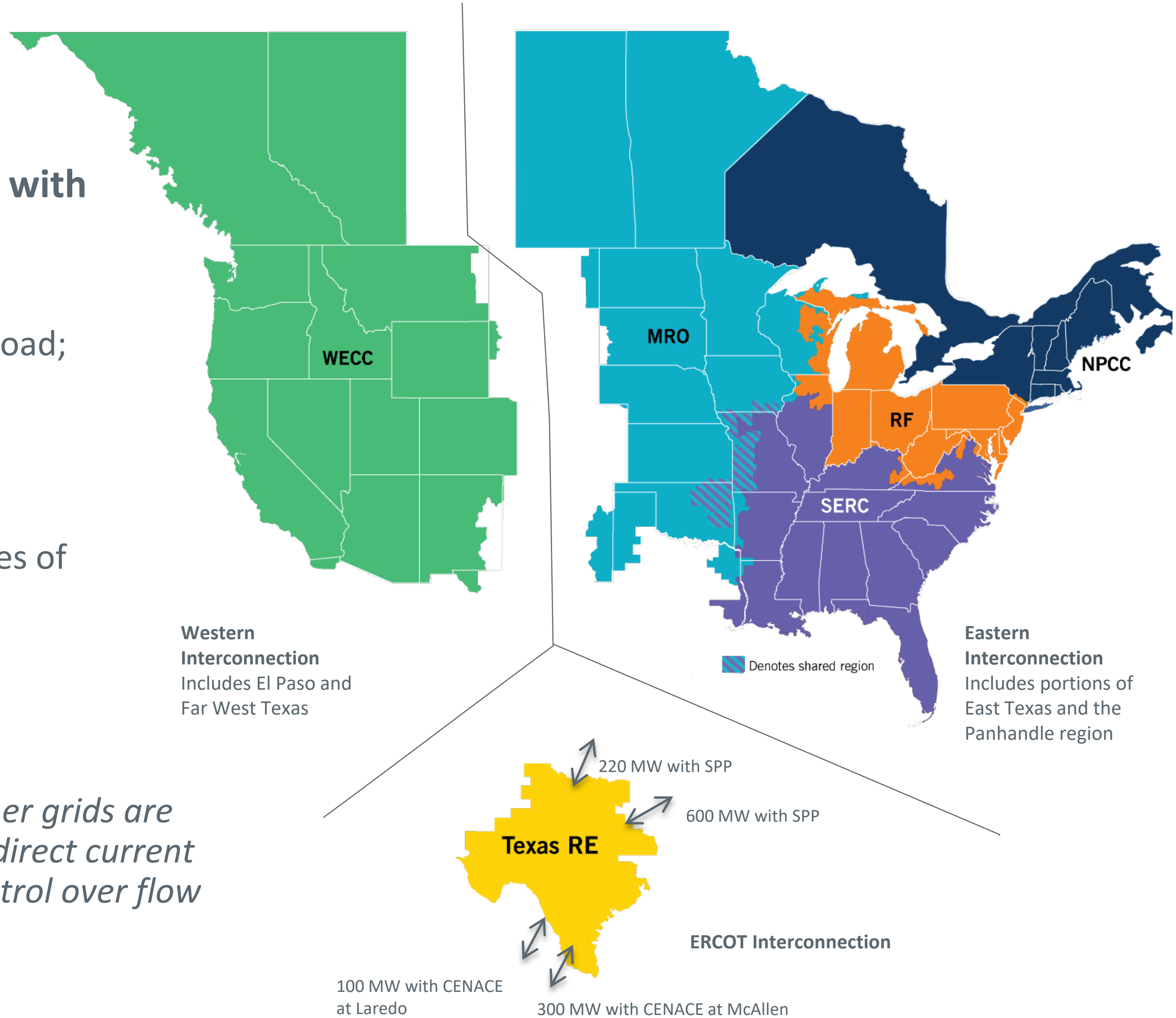
The ERCOT Region

The interconnected electrical system serving most of Texas, with limited external connections

- 90% of Texas electric load; 75% of Texas land
- 74,820 MW peak, Aug. 12, 2019
- More than 46,500 miles of transmission lines
- 650+ generation units (excluding PUNs)

ERCOT connections to other grids are limited to ~1,220 MW of direct current (DC) ties, which allow control over flow of electricity

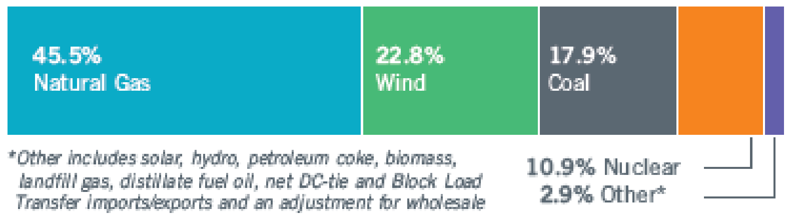


ERCOT Facts

More than
26 million
customers in the ERCOT region

- 1,800+ active market participants that generate, move, buy, sell or use wholesale electricity
- 86,000+ megawatts (MW) of expected capacity for summer 2021 peak demand

2020 Energy Use



*Other includes solar, hydro, petroleum coke, biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load Transfer imports/exports and an adjustment for wholesale storage load

381 billion kilowatt-hours of energy were used in 2020, a nearly 5 percent decrease compared to 2019.

74,820 MW
Record peak demand (Aug. 12, 2019)

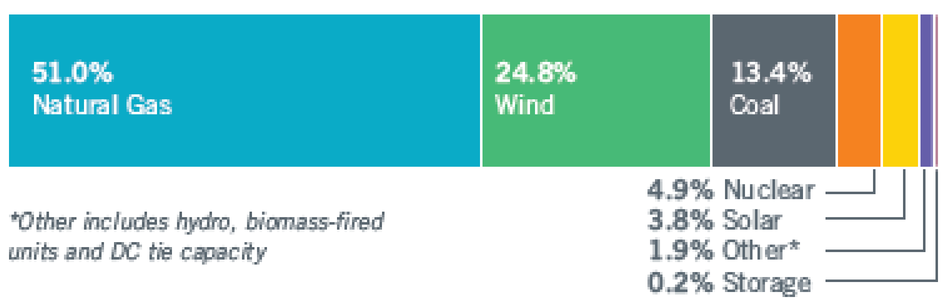
71,930 MW
Weekend peak demand record (Aug. 11, 2019)

1 MW of electricity can power about 200 Texas homes during periods of peak demand.

- 710+ generating units, excluding PUNs
- Transmission projects endorsed in 2020 total $1,071 million
- 46,500+ miles of high-voltage transmission

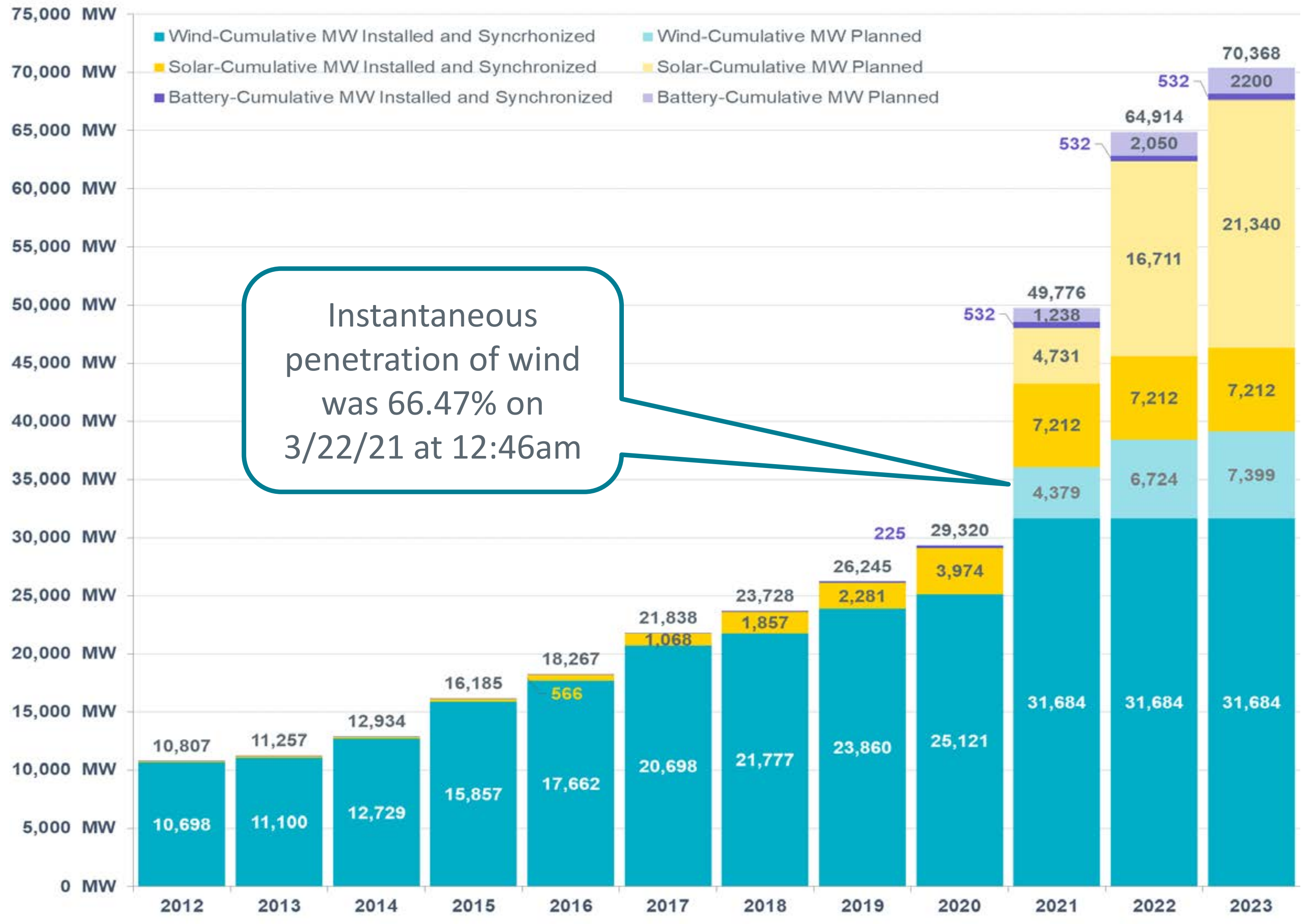
2021 Generating Capacity

Reflects operational installed capacity based on the December 2020 CDR report



Other includes hydro, biomass-fired units and DC tie capacity

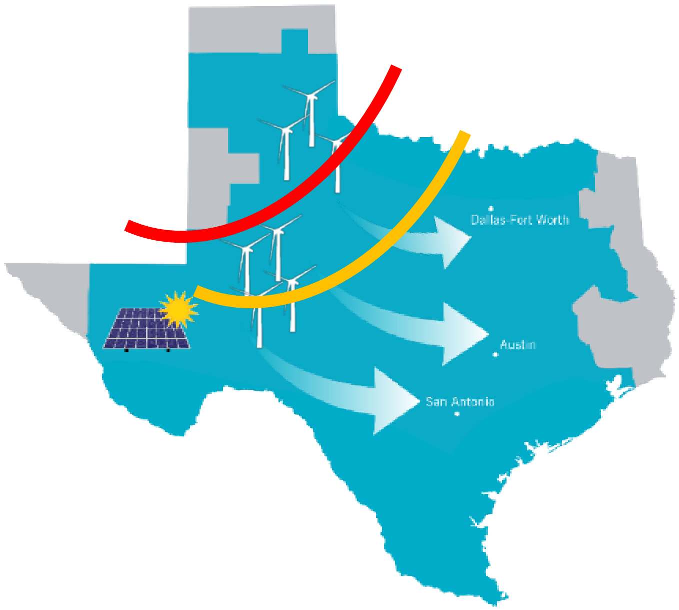
Inverter-Based Resource Capacity – April 2020

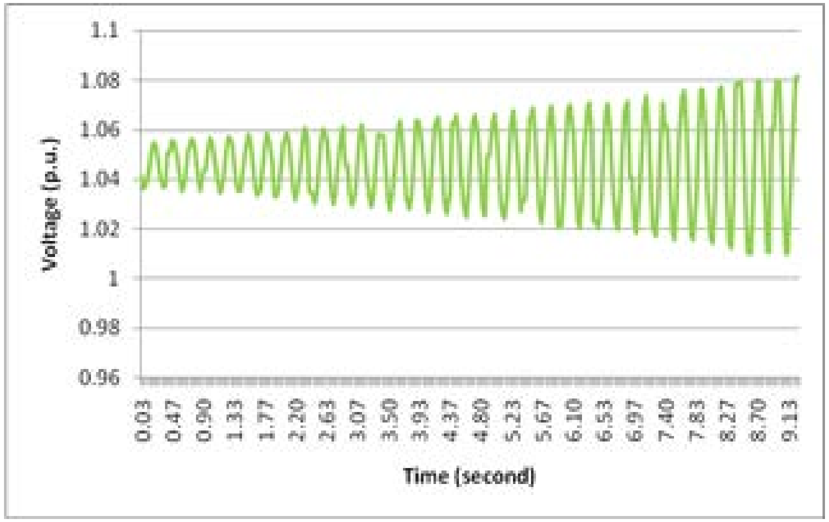


Cumulative MW Planned include projects with signed interconnection agreeements

Renewable Development and Stability Challenges in the Panhandle Region

- As of December 2020, ~4.2 GW operational and ~0.25 GW planned in Panhandle.
- ~ 2.8 GW operational and ~ 2.1 GW planned in the nearby Panhandle area
- Low local load and only a few synchronous generators
- Stability challenges are primary constraints for renewable output
  – Weak Grid: real time monitoring; offline studies
  – Voltage Stability: real time monitoring
  – Dynamic Stability: offline studies; real time is under development

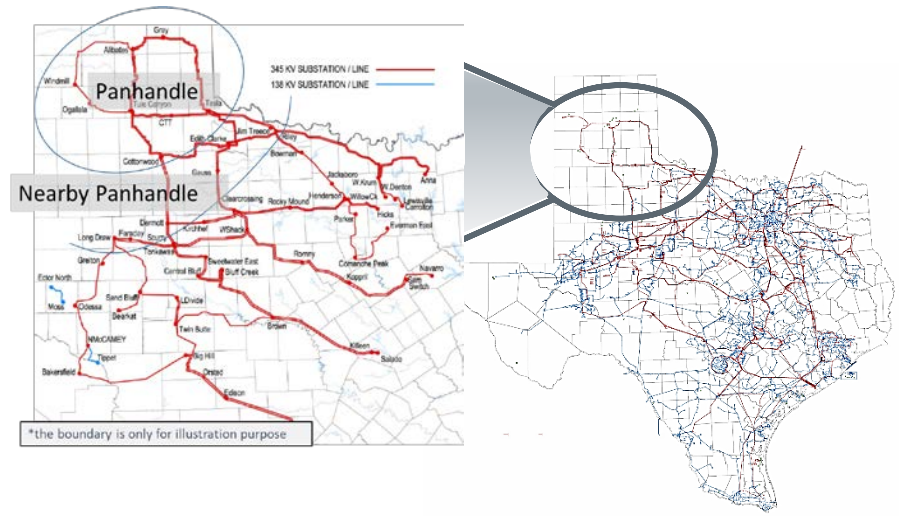




How do you measure system strength?

ERCOT has conducted Panhandle region-wide EMT Studies since 2016 to assess the weak grid conditions and the proper threshold for metrics:

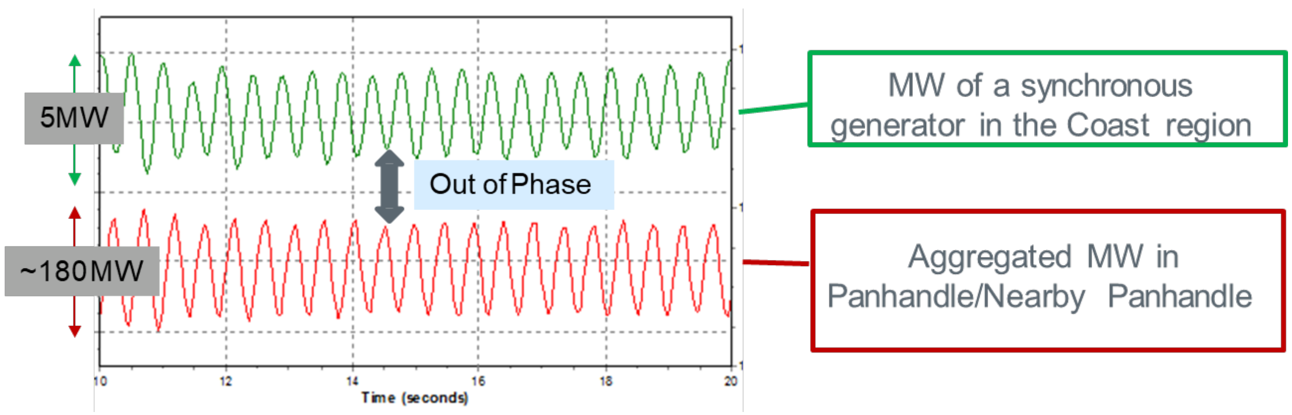
- Issue is complex because of effect of many clustered projects (different owners and OEMs) that are remote, needs to be considered
- Metrics are highly system dependent and need to be verified and regularly reviewed



At the end of May 2021, Lubbock Power&Light municipal utility got connected into ERCOT bringing additional load and medium size synchronous generator in Nearby Panhandle, elevating low short circuit ratio concerns in the area.

Small Signal Stability: Need for Power Oscillation Damping

- Synchronous generators with power system stabilizer (PSS) provide damping to the system oscillation in the range of 0.2-2 Hz.
- Under high renewable output conditions, limited/no synchronous generators in West Texas lead to insufficient damping support needed to maintain stability during and after the disturbances.
- Increasing need of damping support to maintain acceptable dynamic responses with high renewable power transfer.

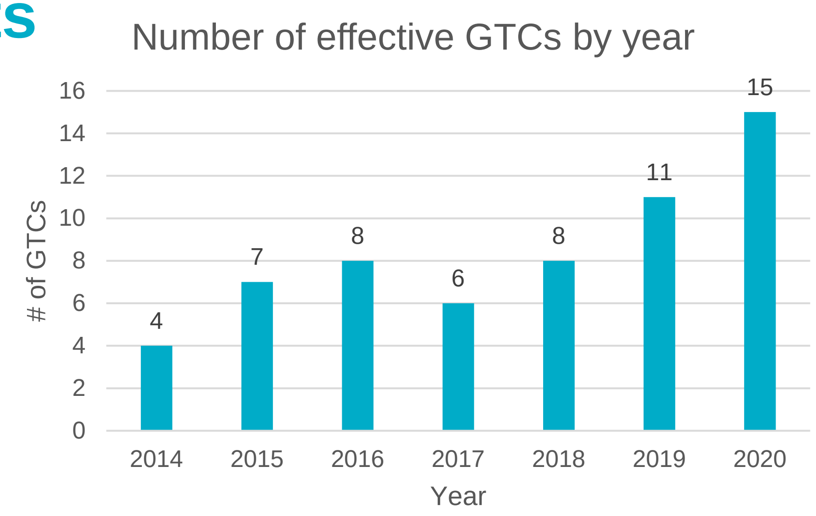


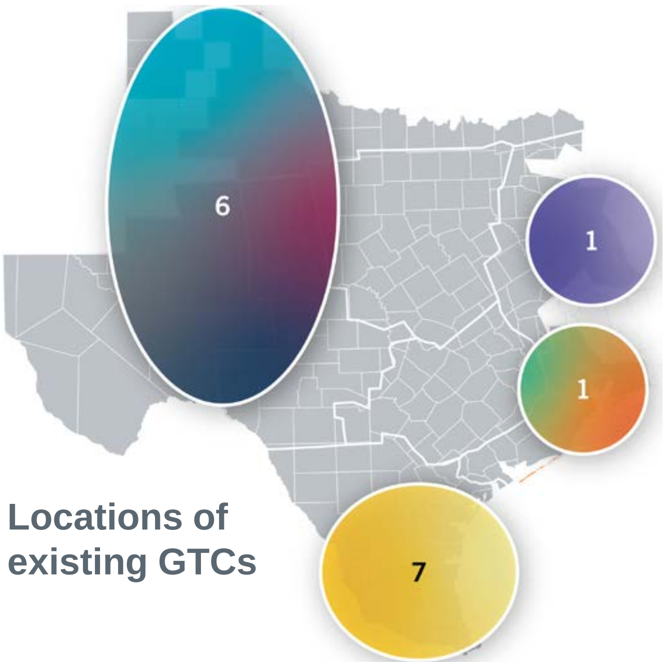
Observed oscillatory responses in the Panhandle dynamic studies. Synchronous condensers identified as primary participants.

Increasing Stability Constraints

- As of April 31, 2021, there were 48 GW of renewable generation (~36 GW wind and ~12 GW solar) planned to be in service by the end of 2021.
- Much of the growth is concentrated in West and South Texas, contributing to stability constraints associated with the long-distance transfer of power to urban load centers.
- These stability constraints can limit power transfers below the physical thermal ratings of the individual transmission lines.

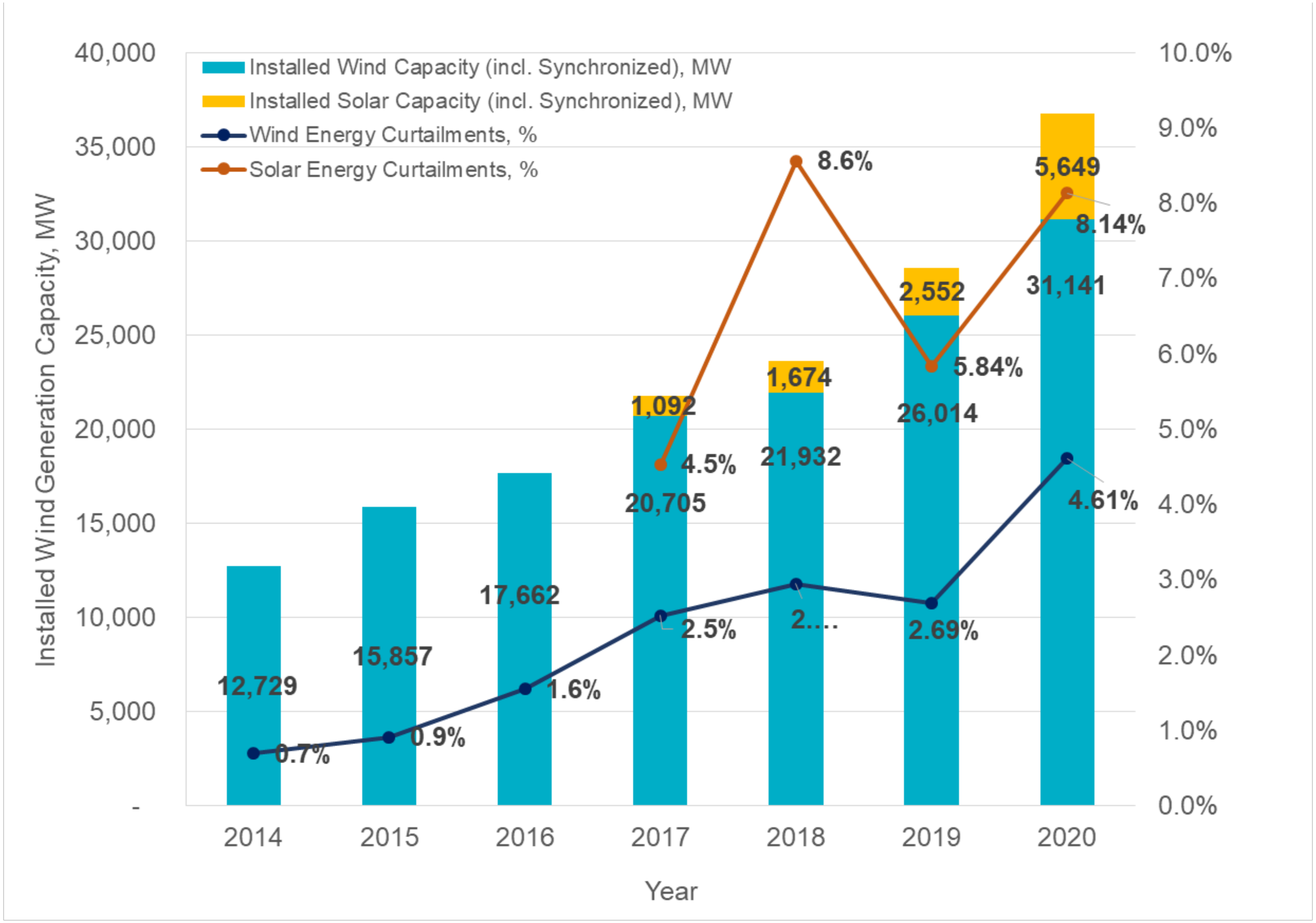
- A Generic Transmission Constraint (GTC) is a tool that ERCOT uses to manage stability limitations in real-time operations.
- ERCOT has seen an increase in stability constraints in recent years, particularly in West Texas and South Texas, which has led to an overall increase in the number of GTCs.
- ERCOT needs better real time tools to identify and manage stability constraints.





Locations of existing GTCs

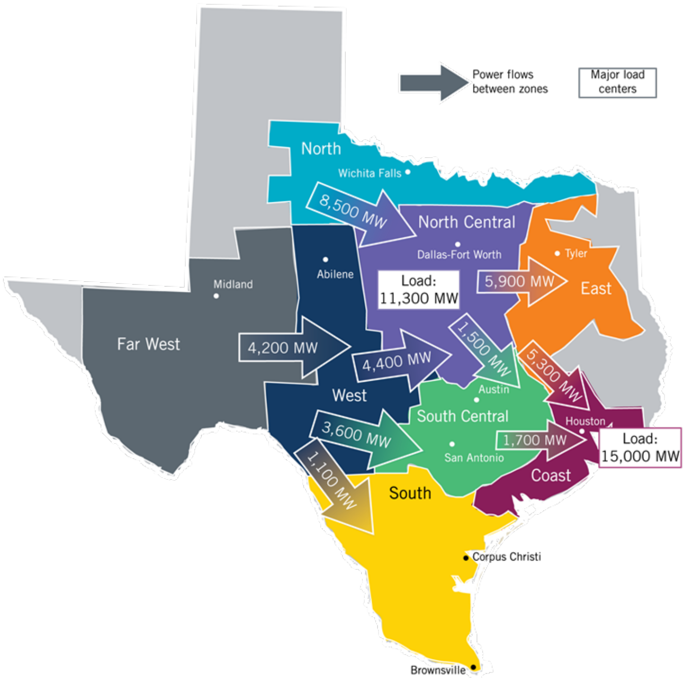
Wind and Solar Curtailments



Curtailment % is calculated based on potential uncurtailed annual energy yield

ERCOT High Penetration Study

- A long term study completed in 2018.
- ~70% Penetration of Inverter-Based Wind and Solar Resources
- Less Synchronous Generators
- Wide-area weak grid issues
- Significant active and reactive power losses
- IBR controls require sufficient system strength for reliable operation or more robust inverter control capability is required, grid forming inverters (?)
- Synchronous condensers are subject to synchronous machine instabilities (inter & intra area oscillations & angular instability)

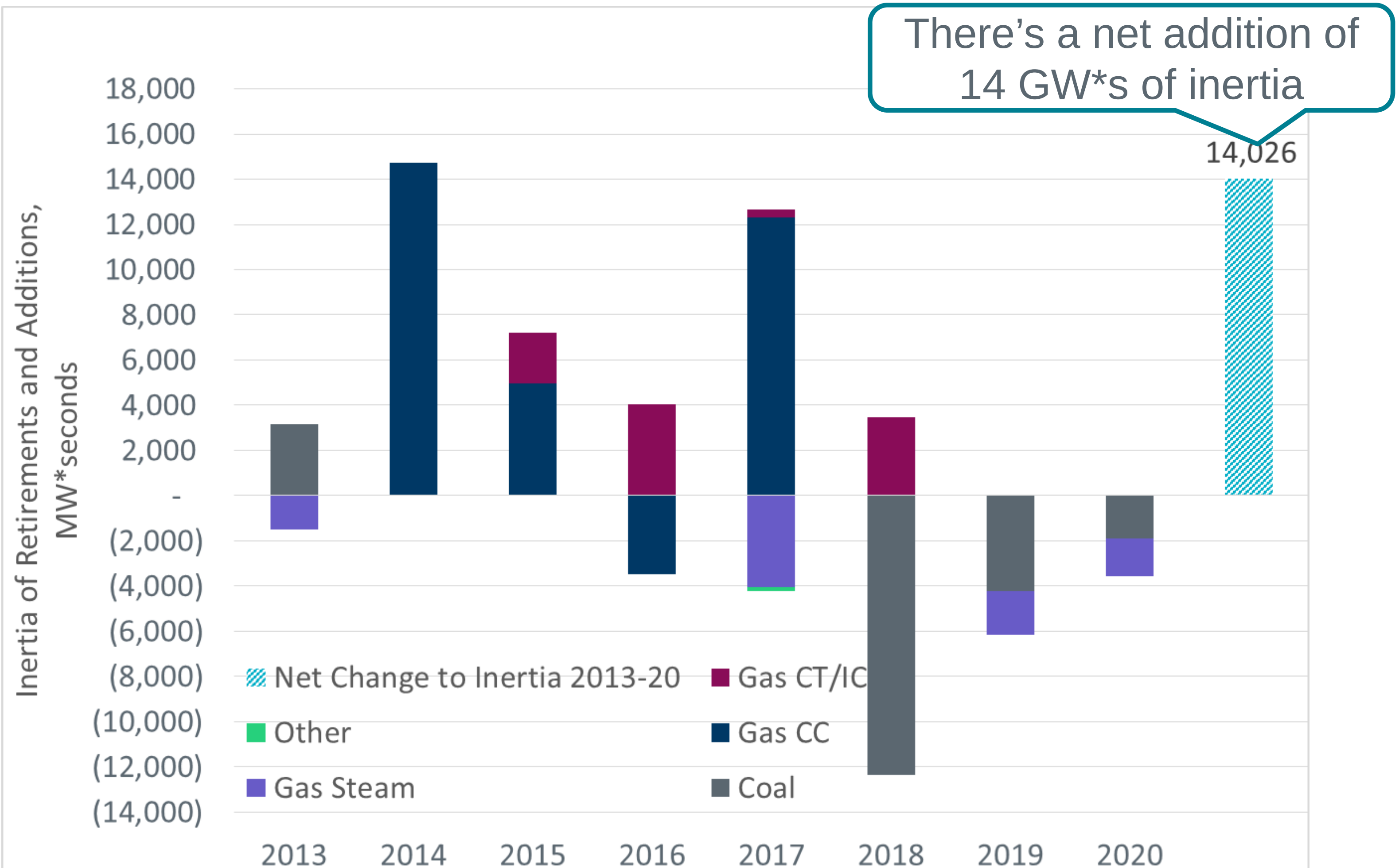


Load:	42.2 GW (includes PUNs)
Solar output:	17 GW (90% dispatch)
Wind output:	11 GW (48% dispatch)
West Texas Exports:	15.5 GW (major 345 kV circuits)
Losses (MW):	6%

http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penertration_of_Renewable_Generatio....pdf

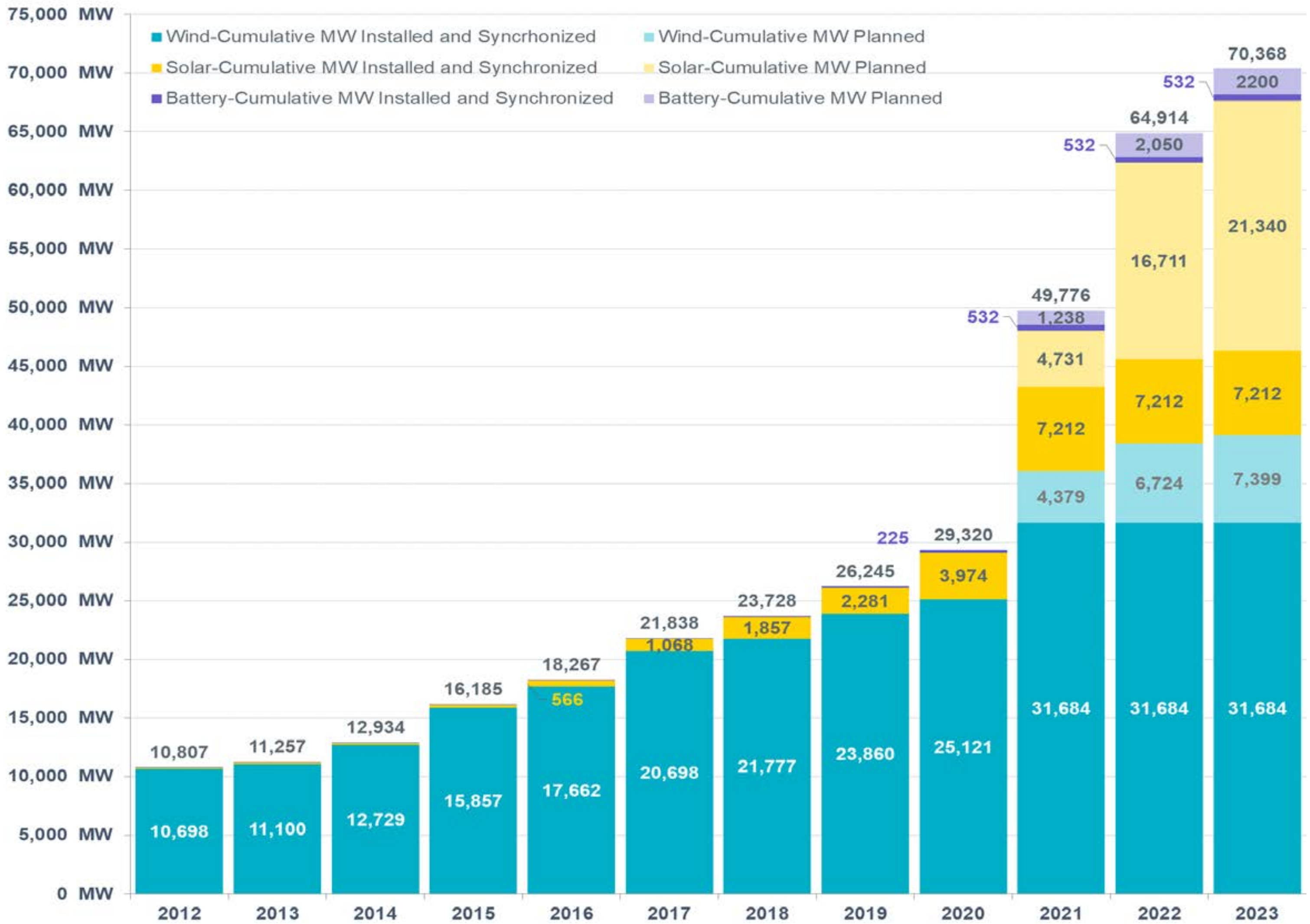
Circular problem

Synchronous Generation Retirements, Mothballing and Additions



~11600 MW of capacity retired or mothballed (primarily coal and gas-steam), and ~9300 MW of capacity was added (primarily CC and CTs) from 2013 through 2020.

ERCOT added about 18 GW of IBRs 2013-2020



Cumulative MW Planned include projects with signed interconnection agreeements

Inertia and Monitoring

- Between 2013-2020, observed average and minimum inertia was relatively constant
- Minimum inertia to date 109 GWs on 3/22/2021, prior to that 128 GW*s was all time lowest;
- Critical inertia determined as 100 GWs;
- Inertia Monitoring and forecasting set up in the control room;
- Frequency Containment Reserve is based on expected inertia conditions and sufficiency monitored in real time;
- Fast Frequency Response Ancillary Service was implemented in March 2020 (full response in 0.25 s, at 59.85 Hz)
- With implementation of FFR critical inertia will reduce to 90 GWs
- Currently, nuclear generation and generation “driven” online by AS requirements brings about sufficient inertia
- As more inverter-based resources seek qualification for AS provision this may change in the future

General Resource Interconnection Process

Interconnection Request
↓
Screening Study (Steady State)
↓
Full Interconnection
↓
Quarterly Stability Assessment
↓
Commissioning

- Full Interconnection
  - Steady State, Dynamic, Short Circuit, and Facility Studies
  - Subsynchronous Resonance (if applicable)
  - Reactive Study
- Quarter Stability Assessment
  - Include existing resources and resources with planned initial Synchronization dates ~3-6 months in the future
- Include high renewable scenarios with the consideration of limited nearby synchronous generators and/or transmission outages

A typical time line for IBR Interconnection: ~24 Months

Interconnection Processes, Modeling, Data Must Evolve

- IBRs are required to provide both dynamic and EMT models
- Resource Entities and Interconnection Entities are responsible for providing models and associated test results and document

Model Quality Tests (dynamic and EMT)	• Includes Voltage Test, Frequency Test, **System Strength Tests** and others
Unit Model Validation (EMT)	• Includes Voltage Test, System Strength, and others
Model Verification	• Provide evidence that model parameters match what is implemented in the field.

Summary: ERCOT Practices and Experience

- Increasing stability and system strength challenges with more IBRs connected to the grid:
  - Complex, time consuming, model and tool adequacy
  - Additional stability challenges (control instability, overvoltage/high voltage collapse)
  - May require tight voltage control (may no longer be a local issue)
  - Identification and management of stability constraints in planning and operations
  - Early communication and coordination is always better
  - Continue to explore ways to reliably operate under weak grid conditions or improve the system strength
- Inertia is less pressing issue, as it does not decline in proportion to additions of IBRs and with new fast frequency control measures in place, critical inertia value can be set lower.

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