ERCOT Renewable Integration

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ETH
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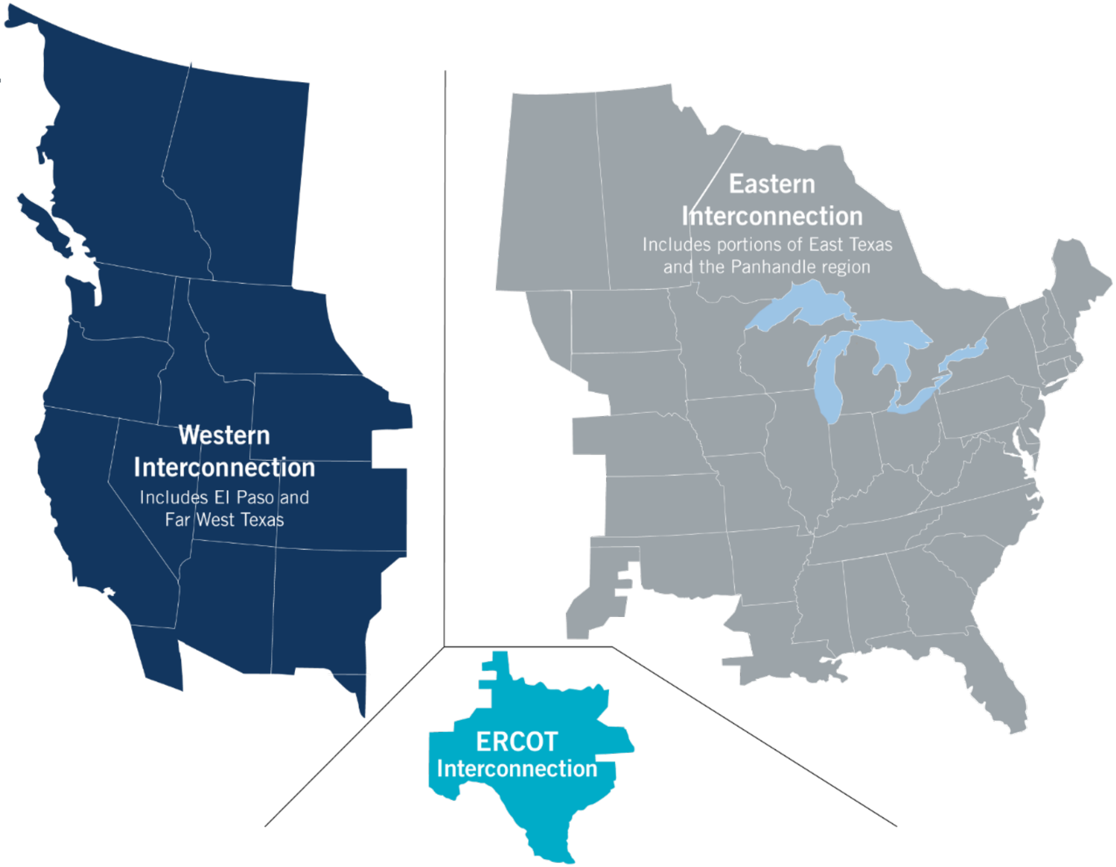
Outline

- ERCOT Overview
- ERCOT Renewable Integration
- Key Takeaways

What is ERCOT?

Independent System Operator (ISO) assigned with four primary responsibilities by the Texas Legislature:

- **System Reliability**
- **Competitive Wholesale Market**
- **Open Access to Transmission**
- **Competitive Retail Market**



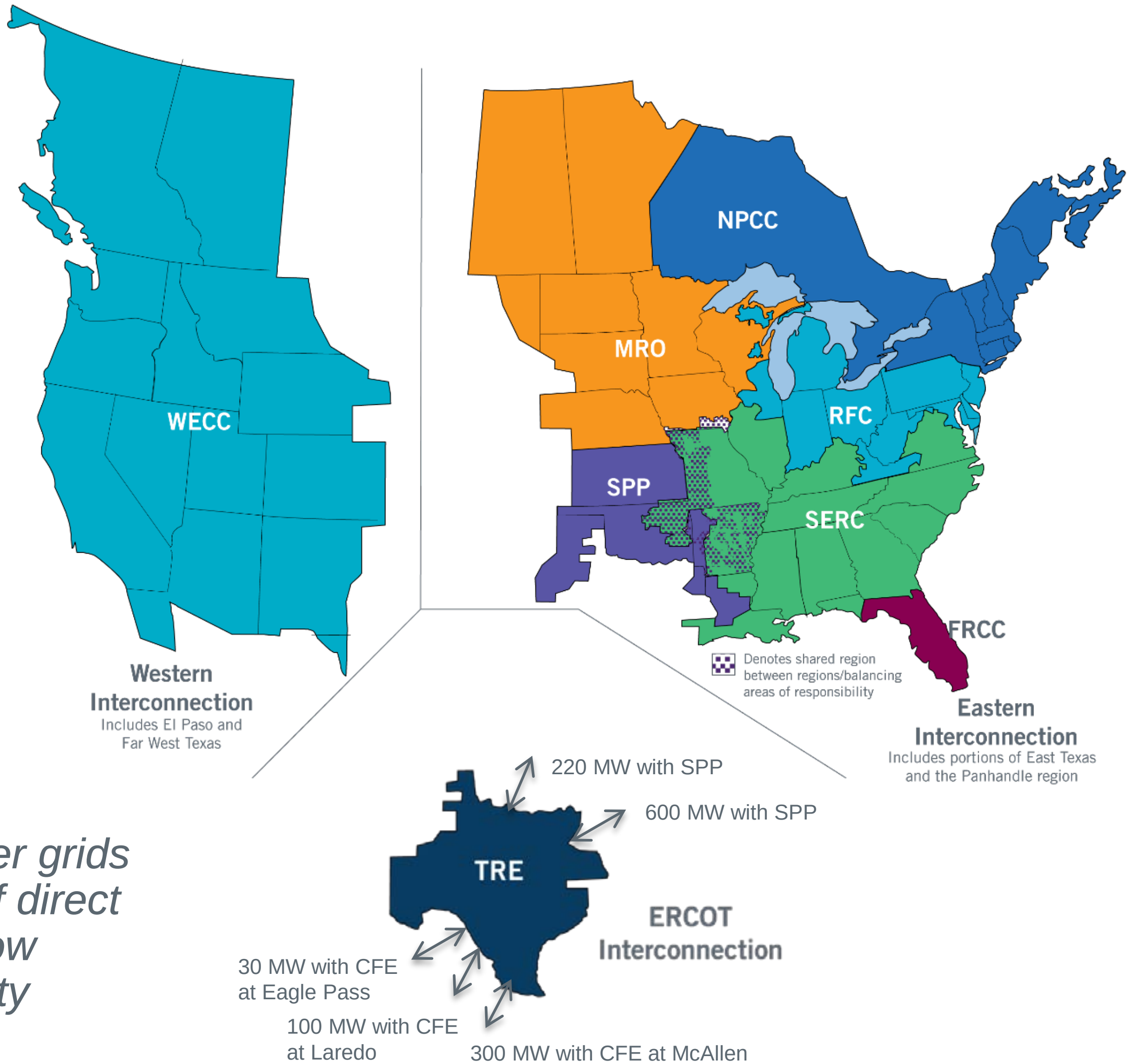
ERCOT is a nonprofit organization and regulated by the Public Utility Commission of Texas, with oversight by the Texas Legislature.

ERCOT is not a market participant and does not own generation or transmission/distribution wires.

The ERCOT Region

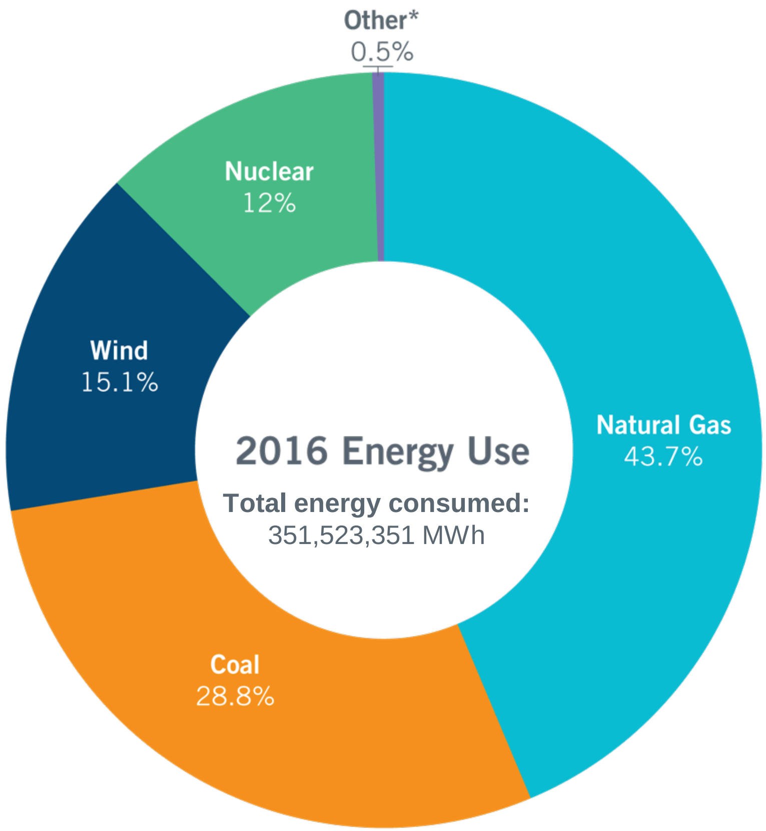
The interconnected electrical system serving most of Texas, with limited external connections

- 90% of Texas electric load; 75% of Texas land
- 71,110 MW peak, August 11, 2016
- More than 46,500 miles of transmission lines
- 570+ generation units

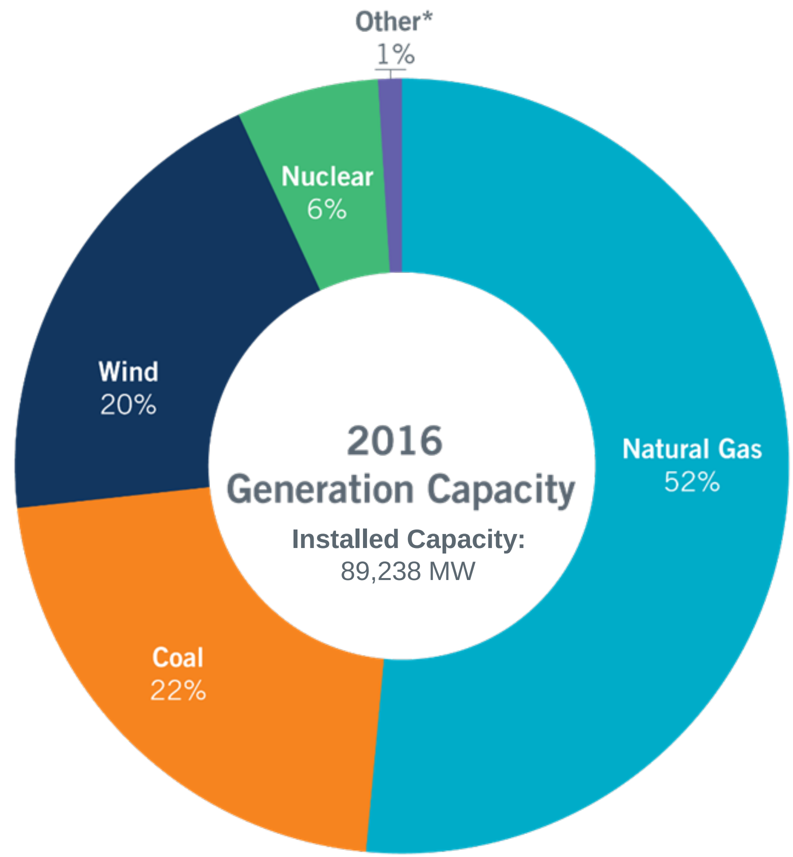


ERCOT connections to other grids are limited to ~1,250 MW of direct current (DC) ties, which allow control over flow of electricity

Energy and Installed Capacity in 2016

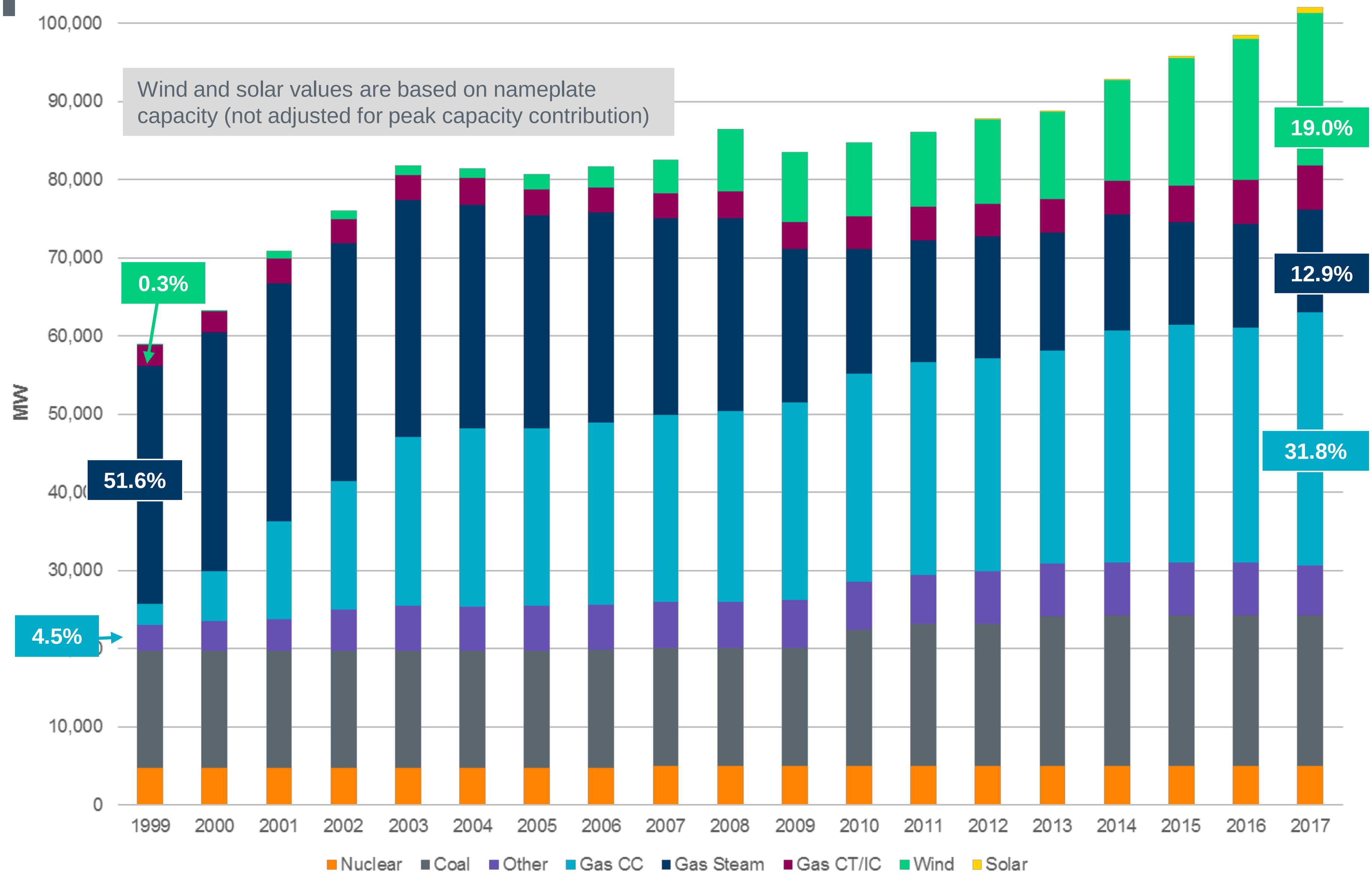


*Includes solar, hydro, petroleum coke, biomass, landfill gas, and DC Ties

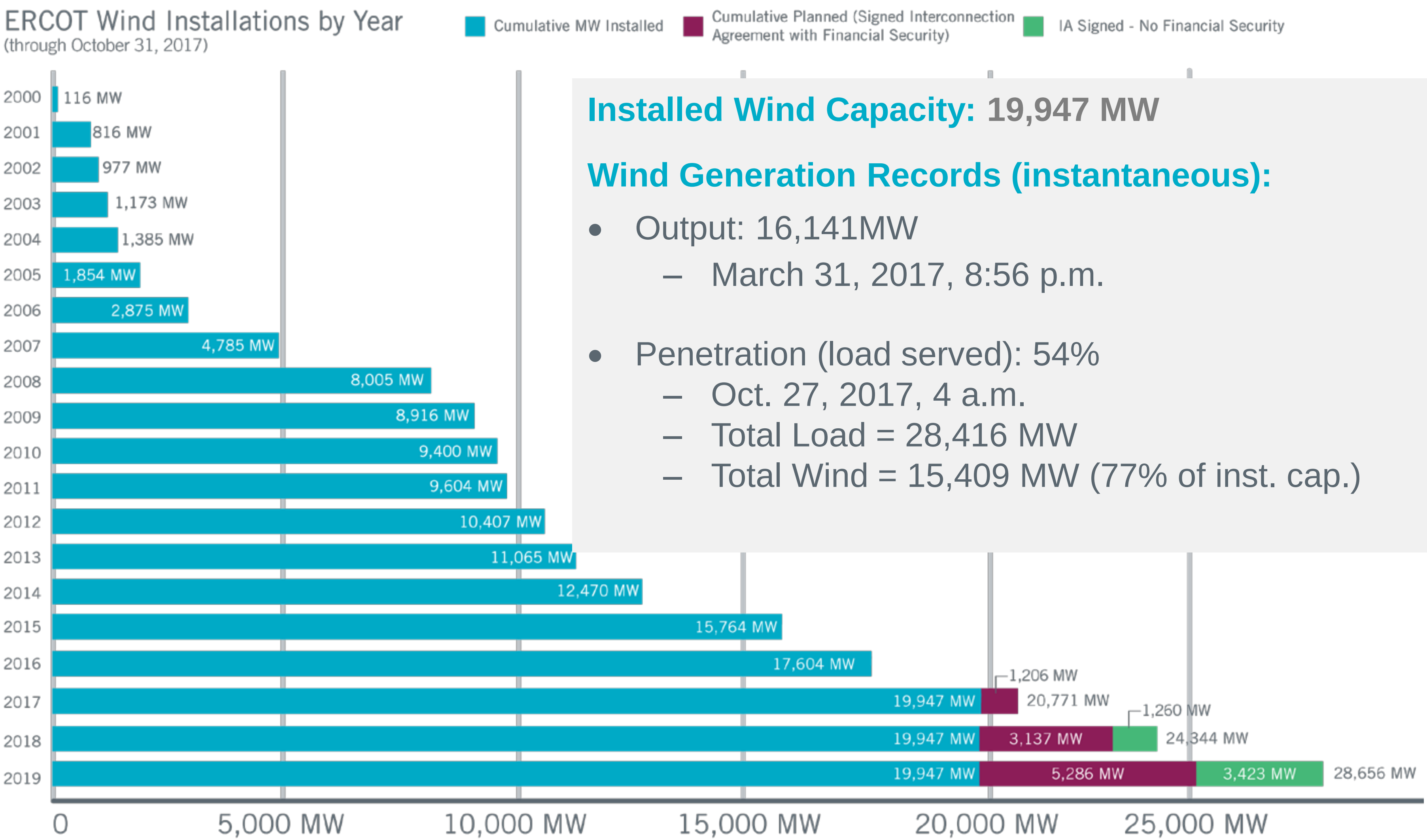


*Includes solar, hydro and biomass

ERCOT Installed Capacity (1999-2017)



Wind Generation Capacity – October 2017

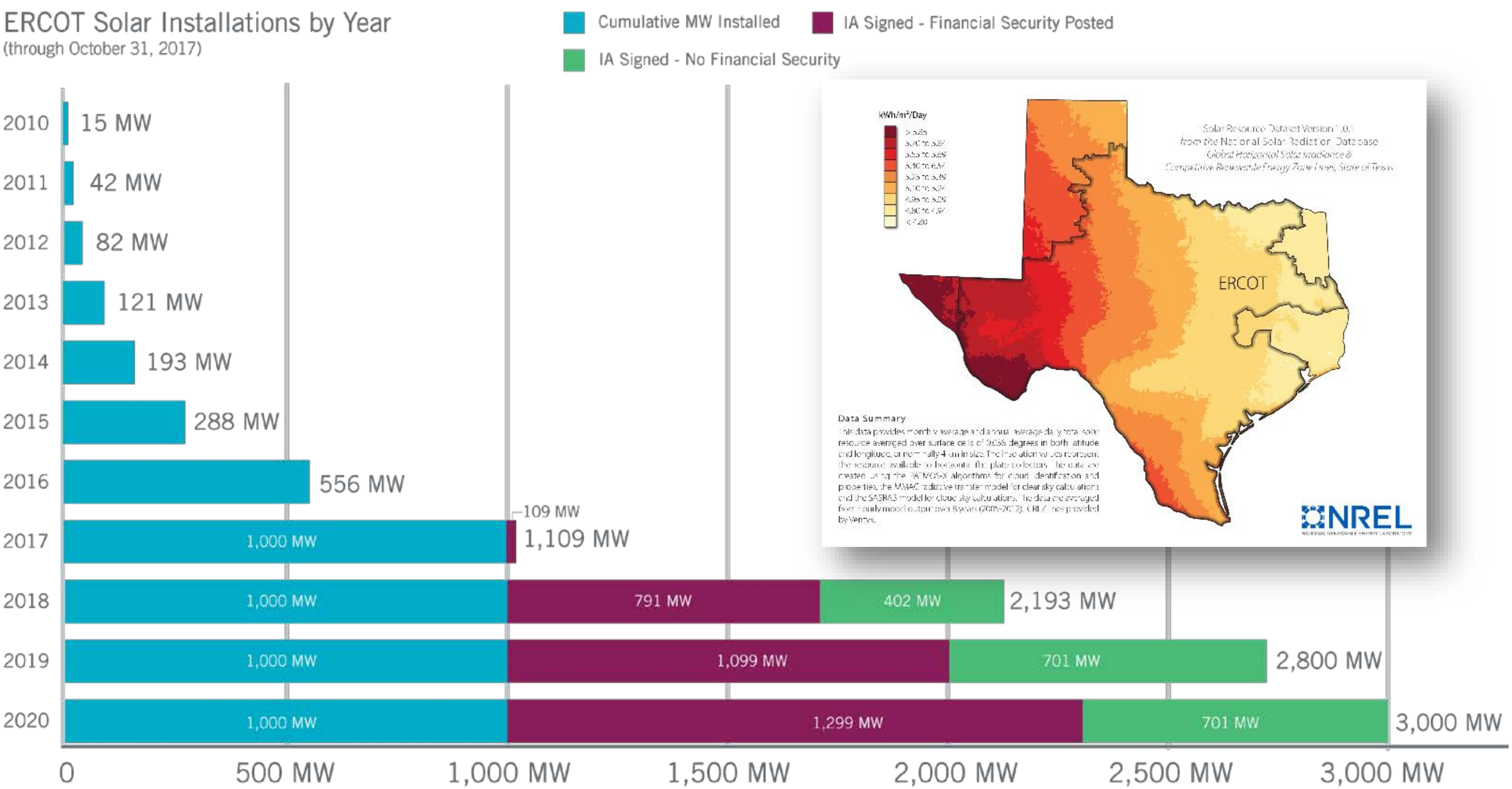


Installed Wind Capacity: 19,947 MW

Wind Generation Records (instantaneous):

- Output: 16,141MW
  - March 31, 2017, 8:56 p.m.
- Penetration (load served): 54%
  - Oct. 27, 2017, 4 a.m.
  - Total Load = 28,416 MW
  - Total Wind = 15,409 MW (77% of inst. cap.)

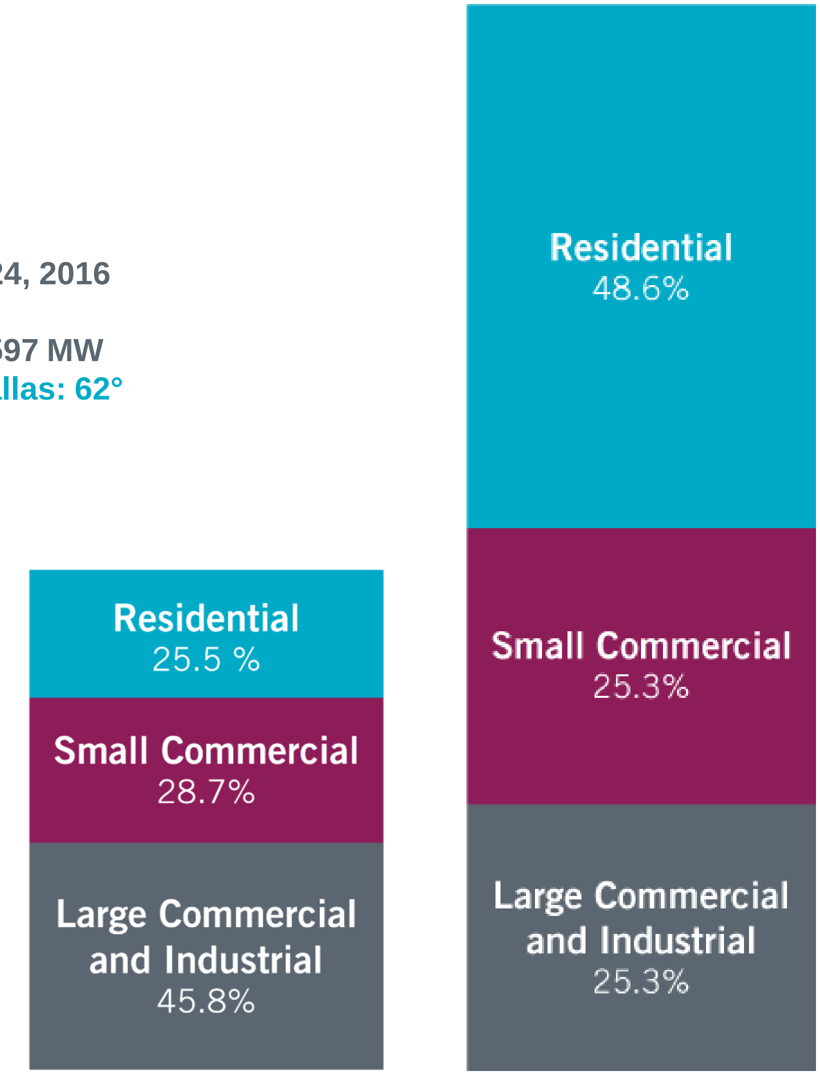
Utility Scale Solar Generation Capacity – October 2017



The data presented here is based upon the latest registration data provided to ERCOT by the resource owners and can change without notice. Any capacity changes will be reflected in current and subsequent years' totals. Scheduling delays will also be reflected in the planned projects as that information is received. This chart reflects planned units in the calendar year of submission rather than installations by peak of year shown.

Weather Impacts on Load by Customer Type

Thursday, March 24, 2016
5:00 PM
ERCOT Load: 33,597 MW
Temperature in Dallas: 62°



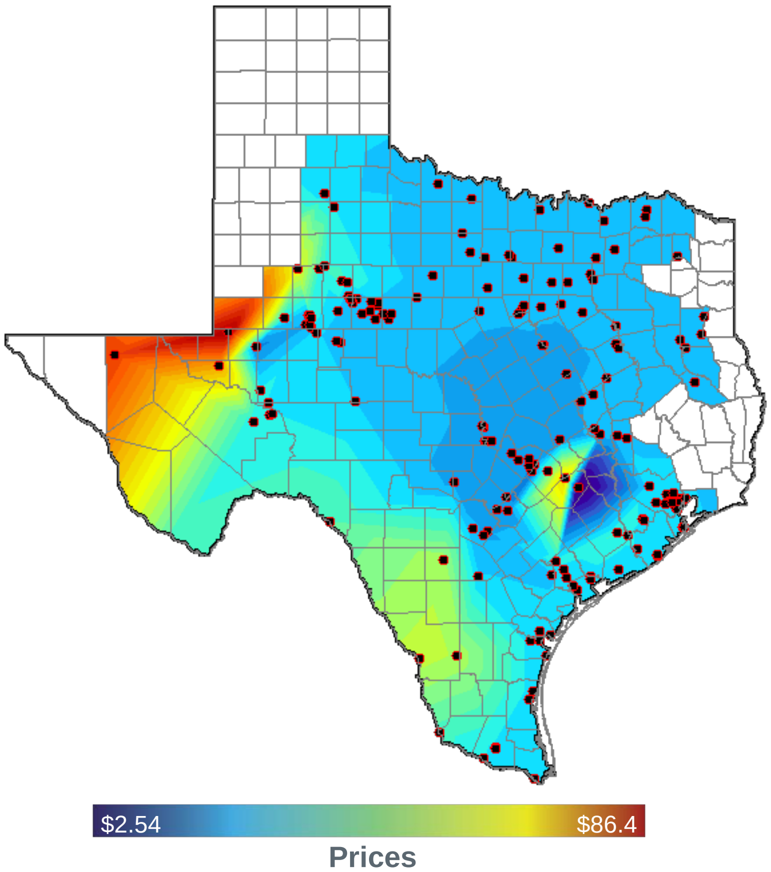
Thursday, Aug. 11, 2016
5:00 PM
ERCOT Load: 71,093 MW
Temperature in Dallas: 106°

>37,000 MW of weather-sensitive load -- 53% of peak

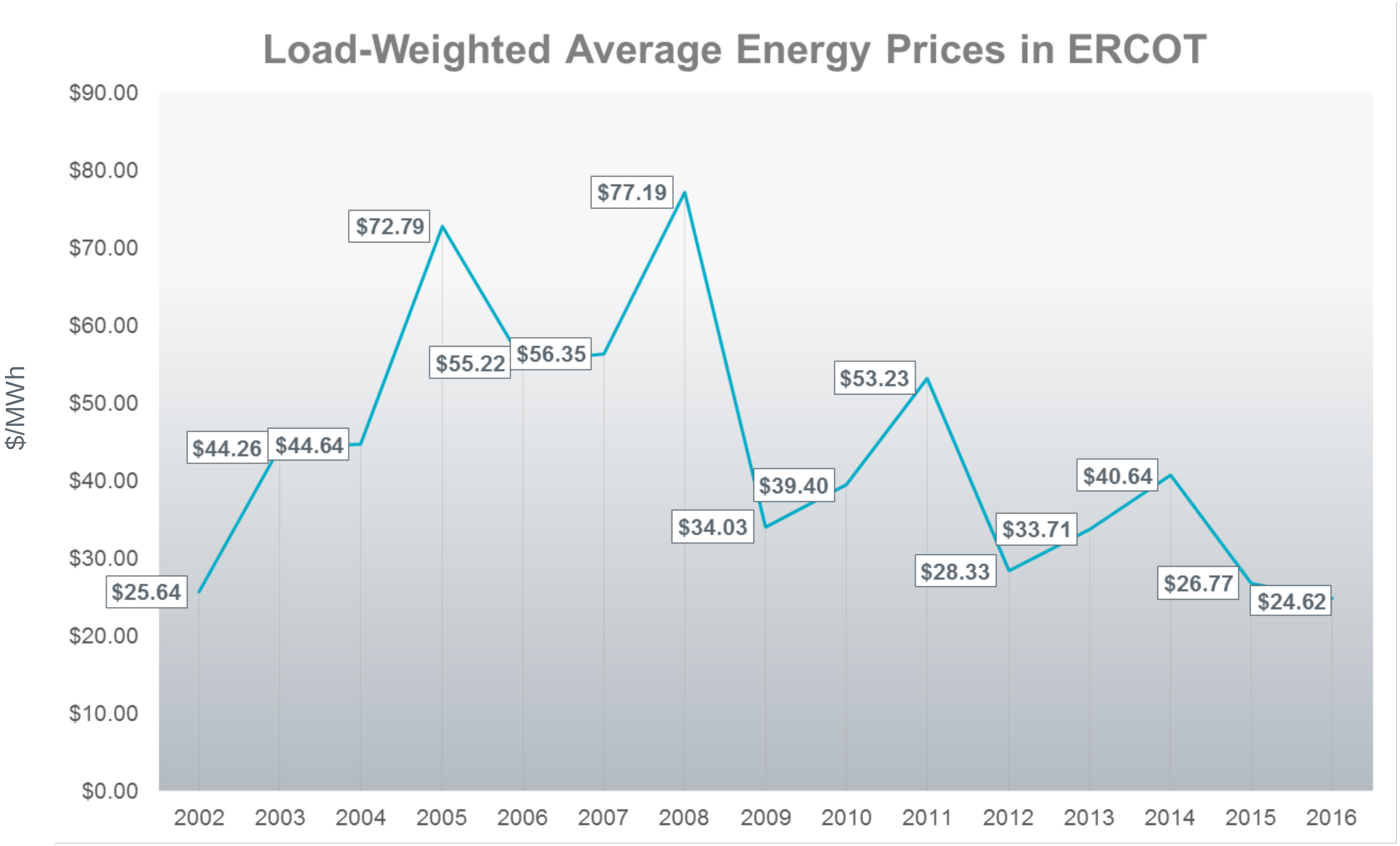
- Customer class breakdown is for competitive choice areas; percentages are extrapolated for municipals and co-ops to achieve region-wide estimate
- Large C&I are IDR Meter Required (>700kW)
- Hourly integrated demand values

Energy Market Construct

- Full retail competition for >75% of demand
- No capacity market; $9000 price cap, with operating reserve scarcity adder
- Generator self-commitment; ERCOT makes residual reliability commitments
- Voluntary Day-Ahead Market; ancillary services procured in DAM, co-optimized with energy
- All generators (including renewables) submit offers for generation output
- Real-Time market clears every five minutes, using generation with the lowest bids to serve the load, subject to unit operational and transmission constraints
- All generators (including renewables) receive output level instructions and locational marginal prices

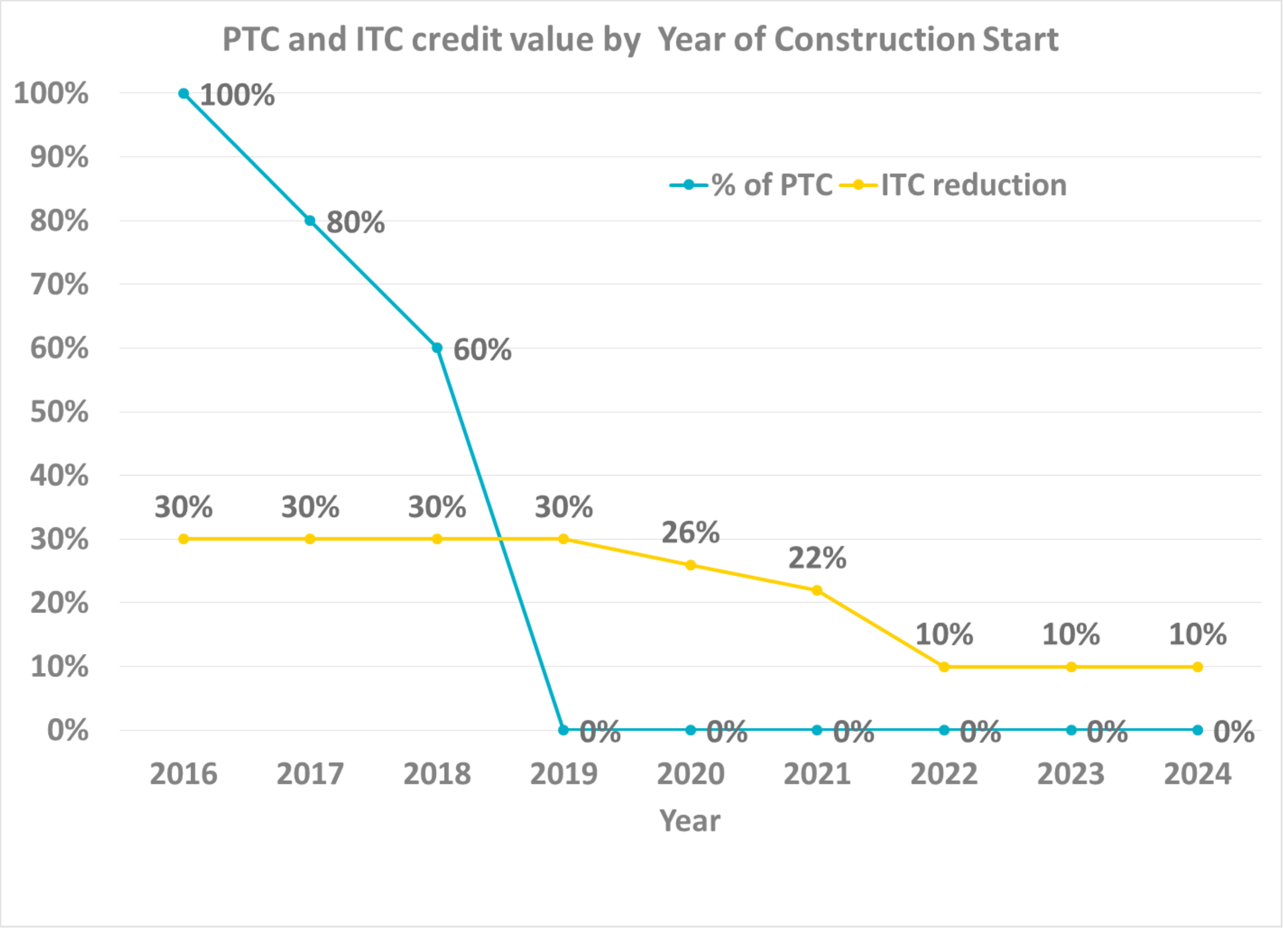


Wholesale Energy Prices at Record Lows



Drivers for RE Development: Federal Tax Credits

- Federal Renewable Electricity Production Tax Credit (PTC)
  - Established in 1992
  - Duration of 10 years after facility is placed in service
- Business Energy Investment Tax Credit (ITC)
  - Established in 2008



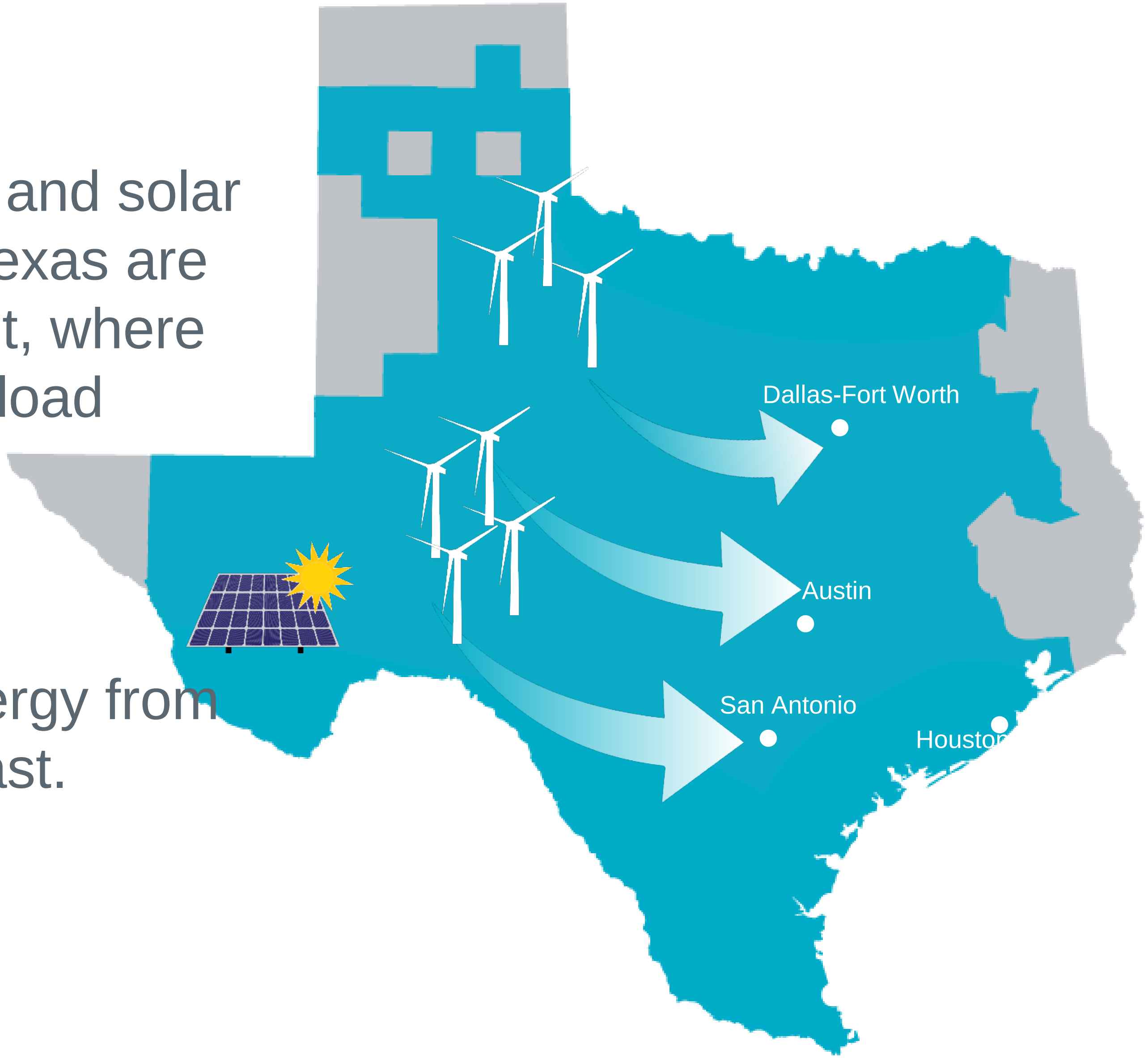
ERCOT Renewables Related Legislation

- Texas Senate Bill 7 (1999)
  - Texas Renewable Portfolio Standard created
  - 2,000 MW net by 2009
    - 2,880 MW including the current 880 MW already online
- Texas Senate Bill 20 (2005)
  - 5,880 MW by Jan. 1, 2015
    - 500 MW must come from non-wind resources
  - 10,000 MW by Jan. 1, 2025
  - Set up process for the PUC to designate Competitive Renewable Energy Zones (CREZs)

Renewable Resources in ERCOT

- The best wind and solar resources in Texas are south and west, where far away from load centers.

- Need to move renewable energy from the West to East.



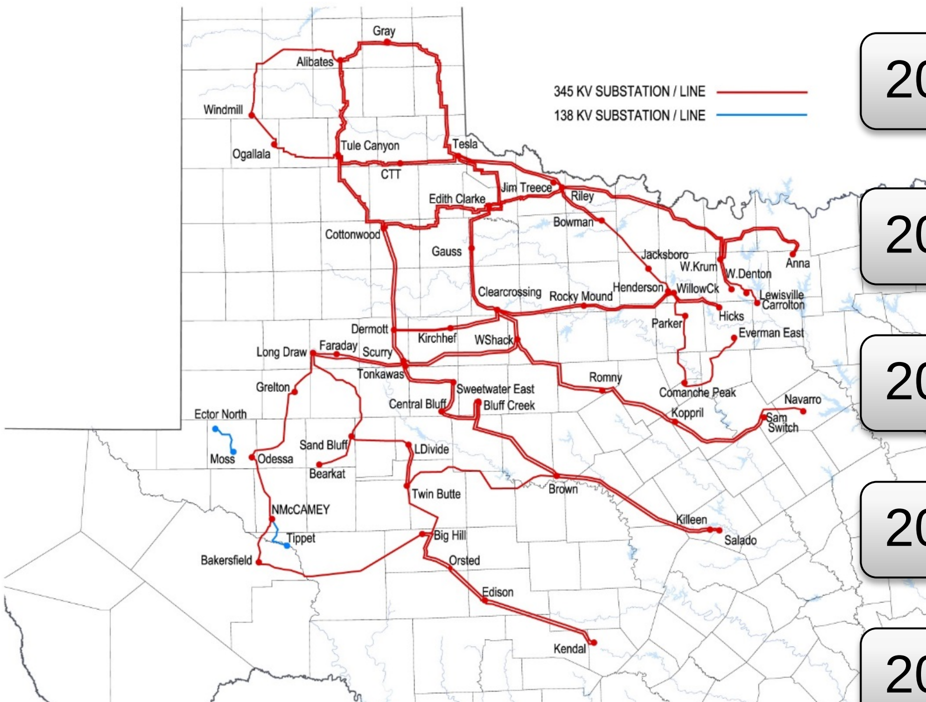
Which came first? (Generation, Transmission)

Transmission is built for generation once the generator is committed to build.

Generators will build once the transmission has been committed to be built.

CREZ Implementation

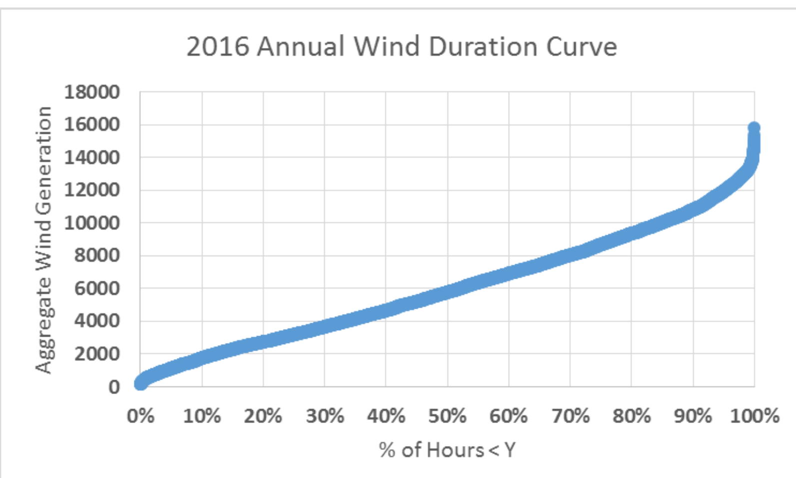
– Accommodate 18.5 GW of wind
– $6.8 Billion
– ~3,600 circuit miles 345 kV transmission

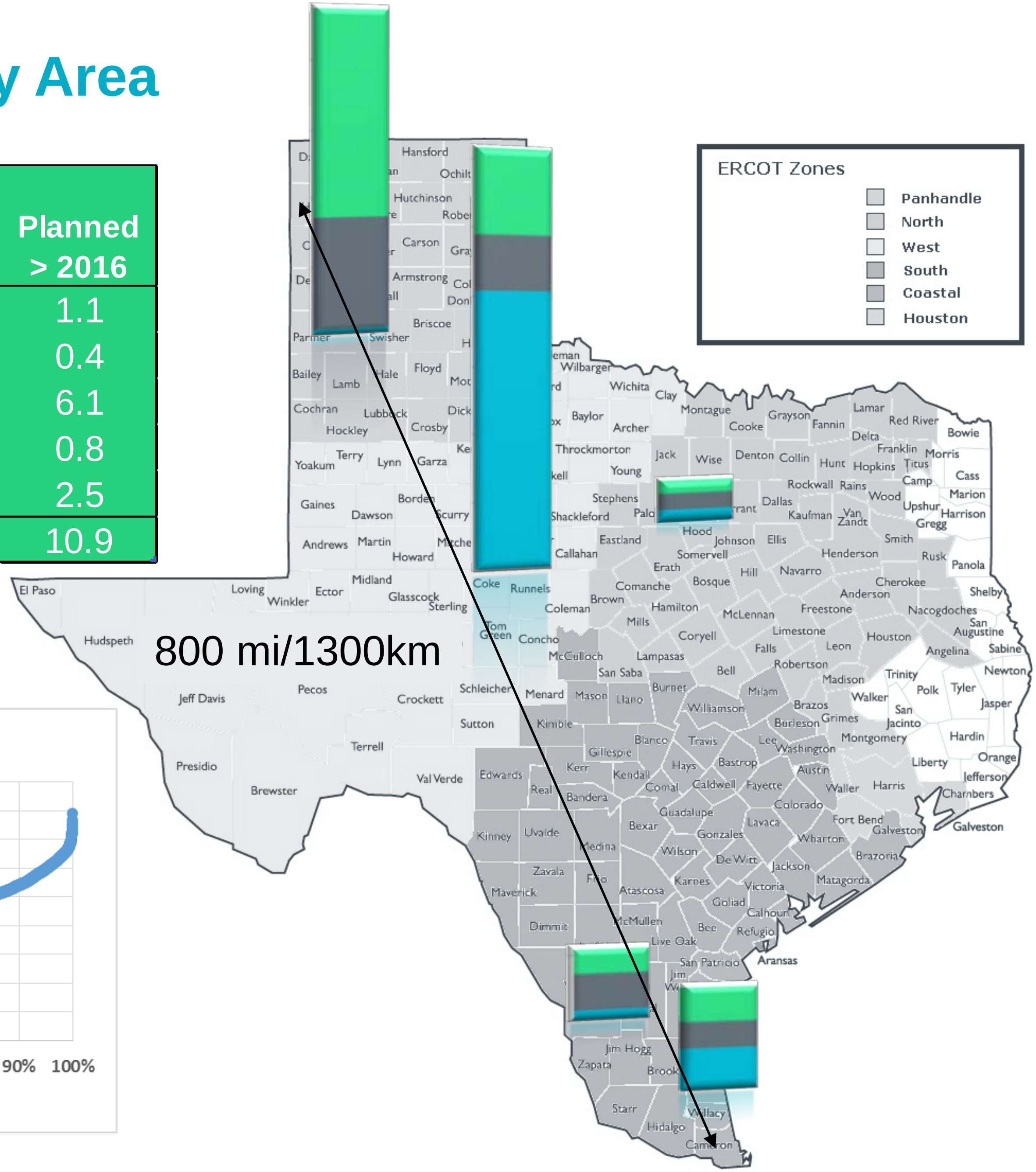


2006	• ERCOT determined best wind resource zones in Texas
2007	• ERCOT conducted CREZ Optimization Transmission Study
2008	• The PUCT selected Transmission Plan to accommodate 18.5 GW wind capacity
2010	• TSPs started the construction • ERCOT conducted reactive study
2013	• CREZ was nearly completed

Wind Installation by Area

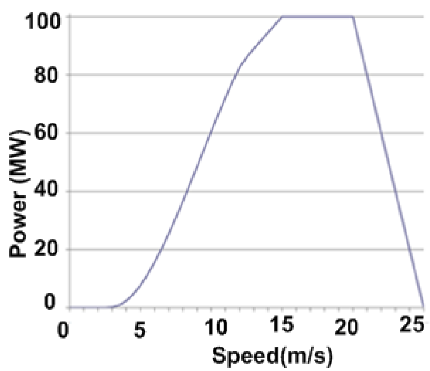
in GW	Existing 2012	Existing 2016	Planned > 2016
COASTAL	1.3	2.0	1.1
NORTH	0.4	0.9	0.4
PANHANDLE	0.2	3.4	6.1
SOUTH	0.3	1.4	0.8
WEST	8.2	9.8	2.5
Total	10.4	17.6	10.9





Variability/ Intermittency Challenge

Variability/ Intermittency	Frequency Response/ Inertia
Voltage Ride-Through	Reactive Support
Stability	Weak Grid



*The steep part of the power curve from 4-12 m/s is where power changes strongly with wind speed.

- Severe changes in wind generation output can be caused by different types of weather events (large wind ramps)
  - Frontal system, trough, dry line, thunderstorms, low-level jets, weakening pressure gradients, strengthening pressure gradients, etc.
- Solar generation output can instantaneously fluctuate with cloud cover
- Texas weather can change rapidly
- Geographic diversity can help

Variability/ Intermittency Solutions

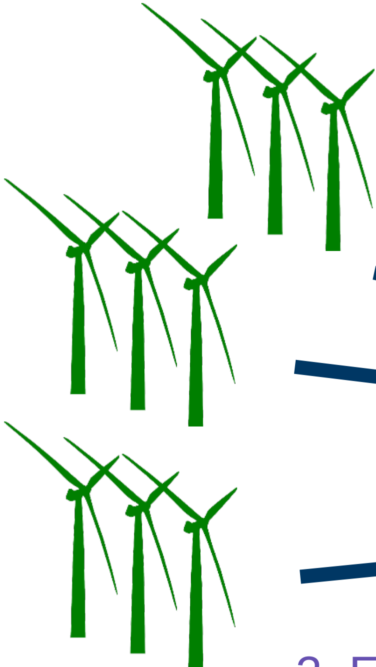
Variability/ Intermittency	Frequency Response/ Inertia
Voltage Ride-Through	Reactive Support
Stability	Weak Grid

1. Wind forecast improvements

2. Ancillary Service products and procurement

3. More frequent generation dispatch
   – ERCOT moved from a 15-minute to a 5-minute dispatch in 2010

ERCOT Wind Generation Forecast



1. Wind plants send site location, status, derate, and telemetered meterologic data to ERCOT

4. ERCOT uses 168-hour forecast to make operational decisions including unit commitment and dispatch

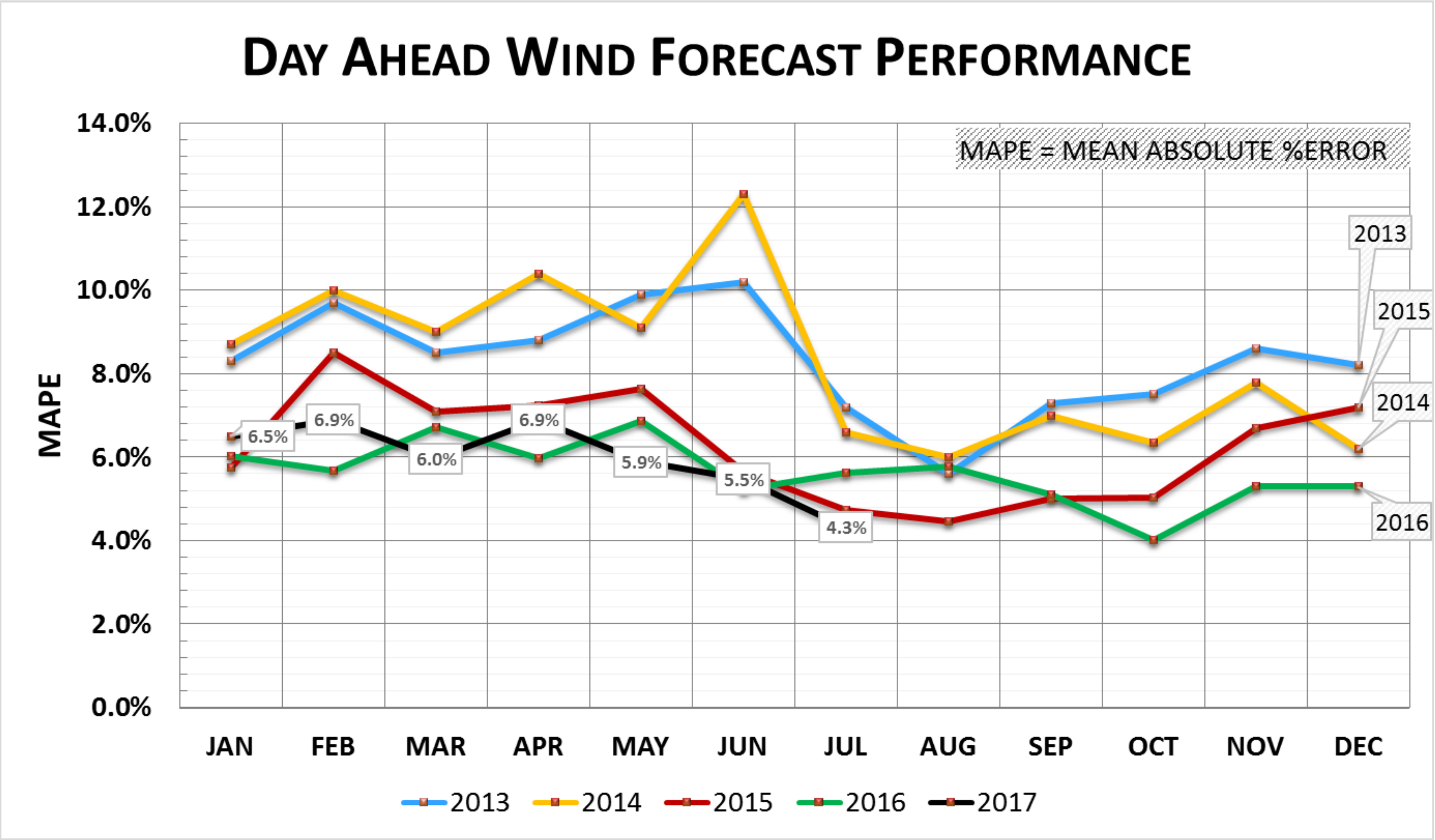
ercot

2. ERCOT sends information from wind plants to AWS Truepower

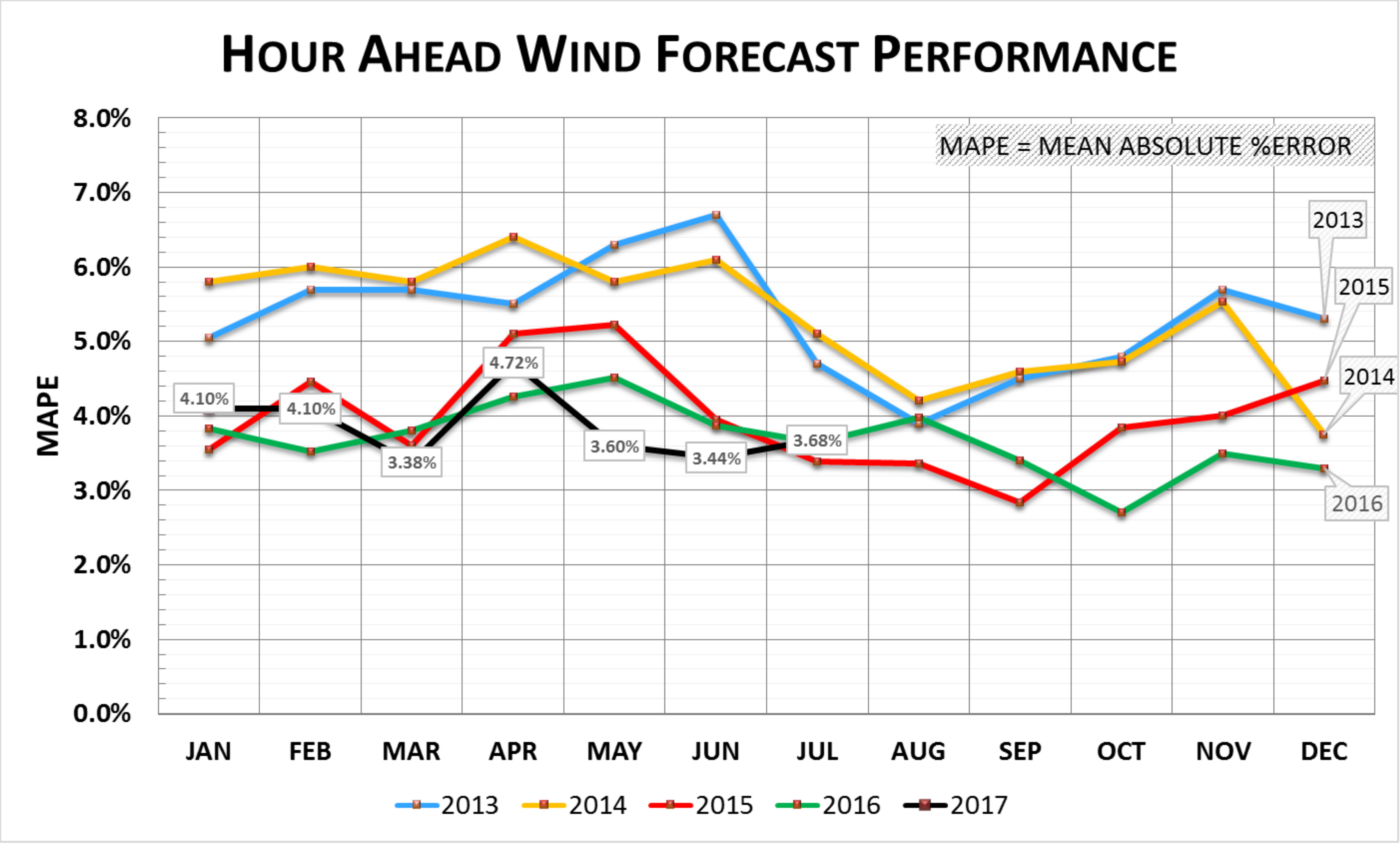
3. AWS Truepower computes and sends ERCOT a rolling 168-hour generation forecast for all wind plants

AWS Truepower

Wind Forecast Performance (Day-Ahead)



Wind Forecast Performance (Hour-Ahead)



Ramp Rate Limitation

- Renewable resources that were installed after 2009 are required to implement controls which limit per minute ramping to **20%** of the unit's nameplate rating.

6.5.7.10 Intermittent Renewable Resource Ramp Rate Limitations

1) Each Intermittent Renewable Resource (IRR) that is part of a Standard Generation Interconnection Agreement (SGIA) signed on or after January 1, 2009 shall limit its ramp rate to **20% per minute of its nameplate rating (MWs)** as registered with ERCOT when responding to or released from an ERCOT deployment.
2) The requirement of paragraph (1) above does not apply during a Force Majeure Event or during intervals in which a decremental deployment instruction coincides with a demonstrated decrease in the available IRR.
3) Each IRR that is part of an SGIA signed on or before December 31, 2008 and that controls power output by means other than turbine stoppage shall limit its ramp rate to 20% per minute of its nameplate rating (MWs) as registered with ERCOT when responding to or released from an ERCOT deployment.

Existing Ancillary Services

Regulation Up

Fast-Responding Regulation Up

Regulation Down

Fast-Responding Regulation Down

Responsive

Non-Spin

Frequency Response/ Inertia Challenge

Variability/ Intermittency

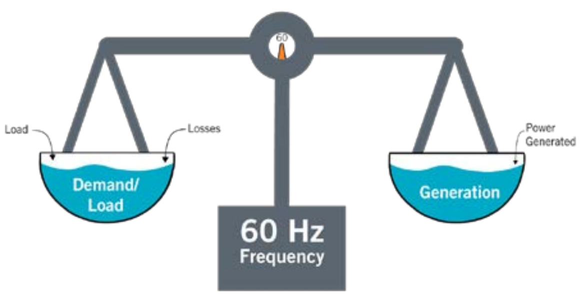
Frequency Response/ Inertia

Voltage Ride-Through

Reactive Support

Stability

Weak Grid



- ERCOT has two ancillary services to maintain frequency at 60 Hz
- Regulation Service manages the minute-to-minute changes in frequency due to net load changes
  - Intermittent generation increases contribute to minute-to-minute variability
- Responsive Reserve Service responds to significant frequency deviations (typically due to unit trips)
  - Non-synchronous generation does not provide system inertia, displace synch generation. Frequency rate of change increases after unit trips.

Frequency Response/ Inertia Solutions

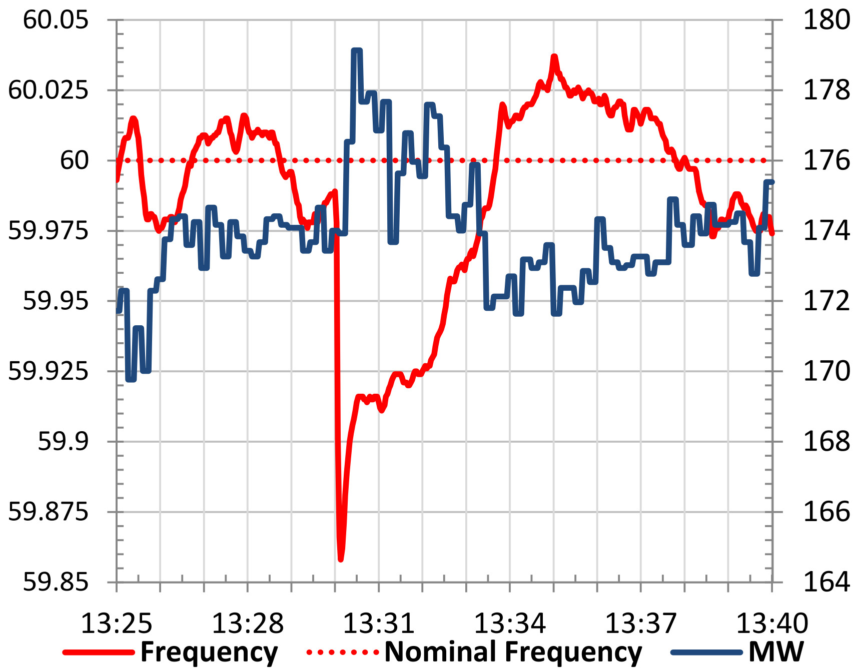
Variability/ Intermittency	**Frequency Response/ Inertia**
Voltage Ride-Through	Reactive Support
Stability	Weak Grid

1. Grid code requirement introduced for intermittent generation to provide frequency response same as all other generators (2012)

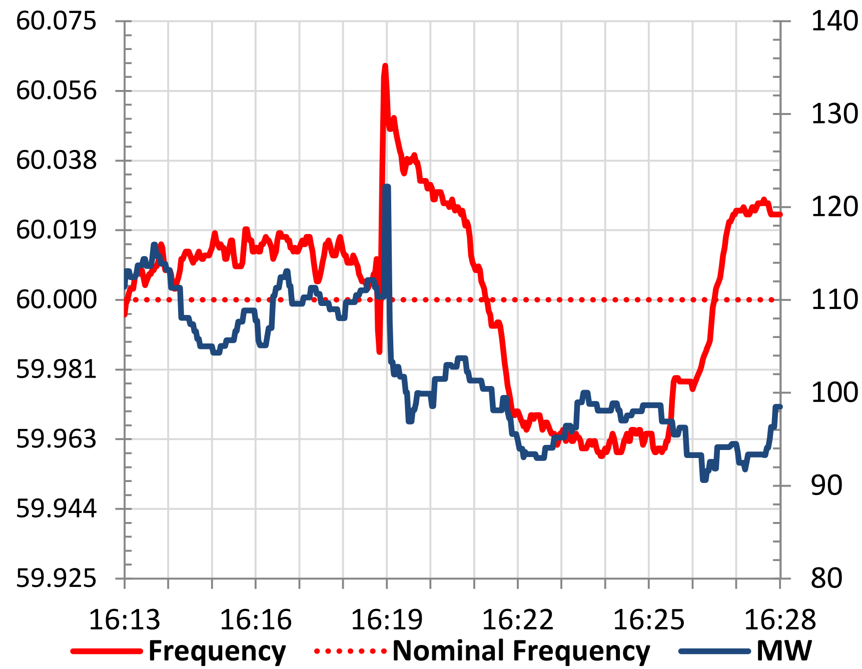
2. Procure more Responsive Reserve Service during periods of low inertia

Frequency Control

- Renewable resources are required to assist in ERCOT's frequency control and provide a "governor-like" response (Primary Frequency Response) to frequency deviations.
  - Implemented regional standard in 2015 which has reduced the Governor Dead-band for most resources including renewables from 36 mHz to 17 mHZ.

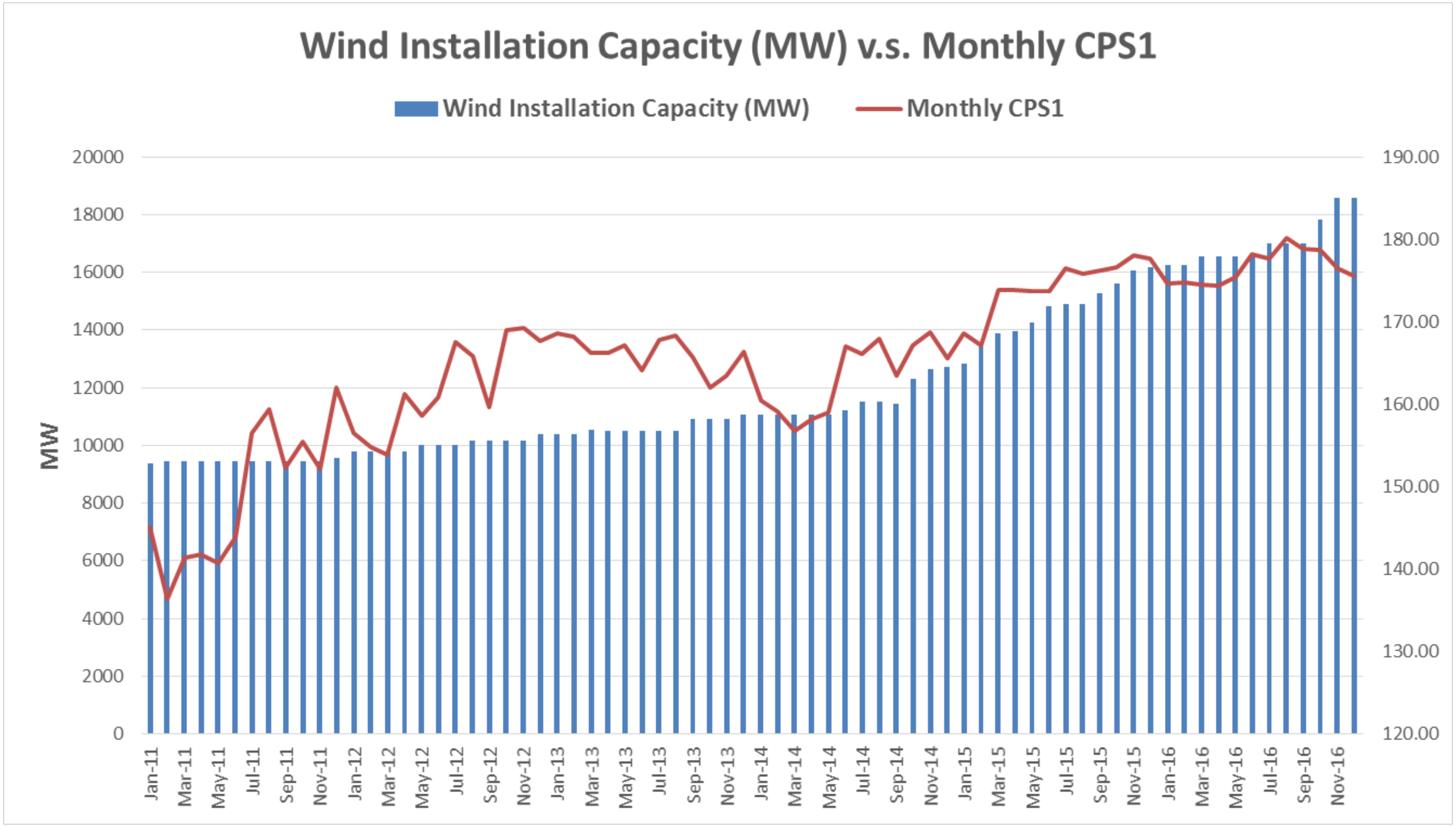


Wind Resource Response to Low Frequency 07/13/2016



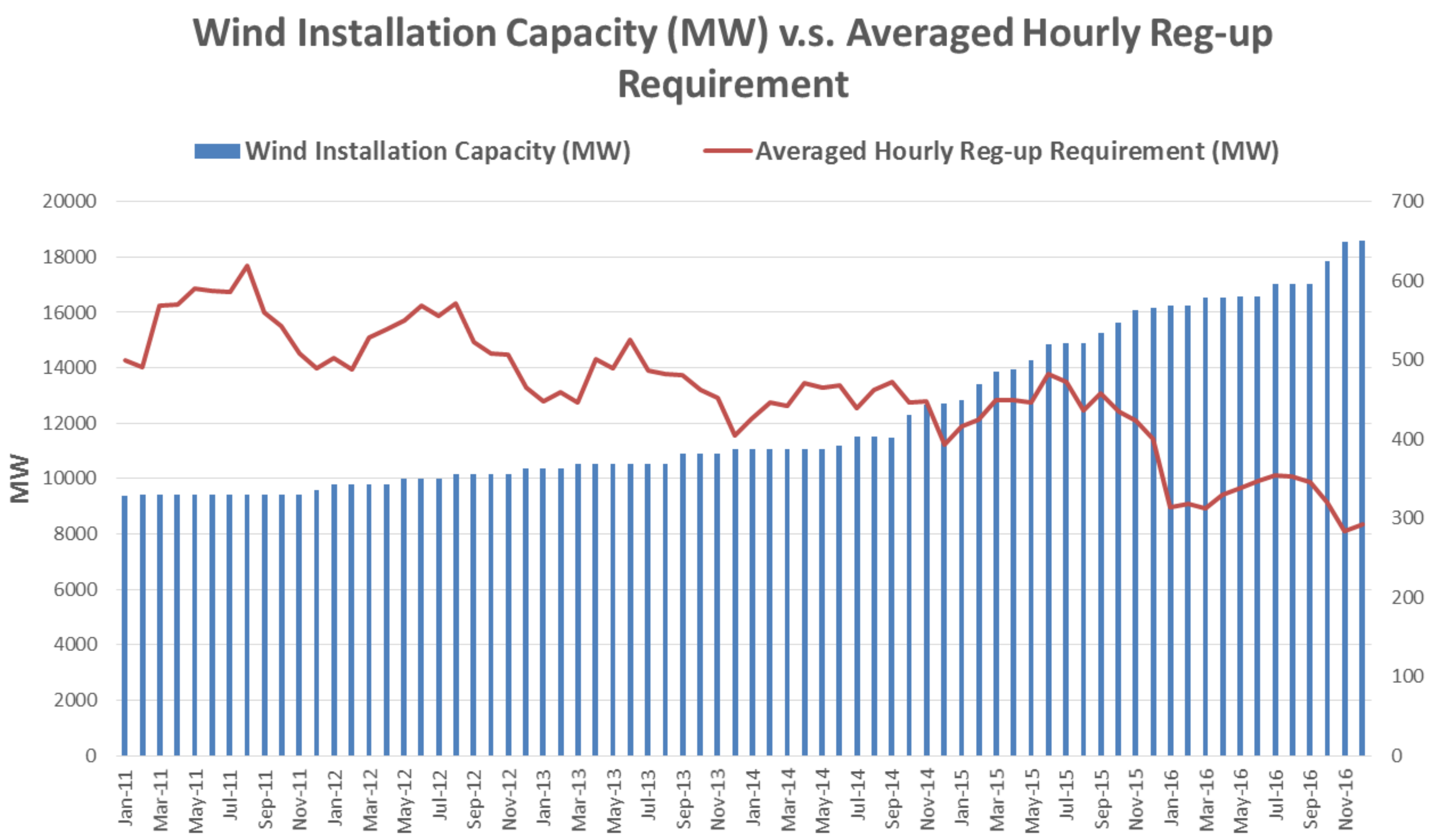
Wind Resource Response to High Frequency 08/25/2015

Trend of Monthly CPS1



CPS1 (Control Performance Standard) is a measure of how tightly an operator controls frequency to nominal

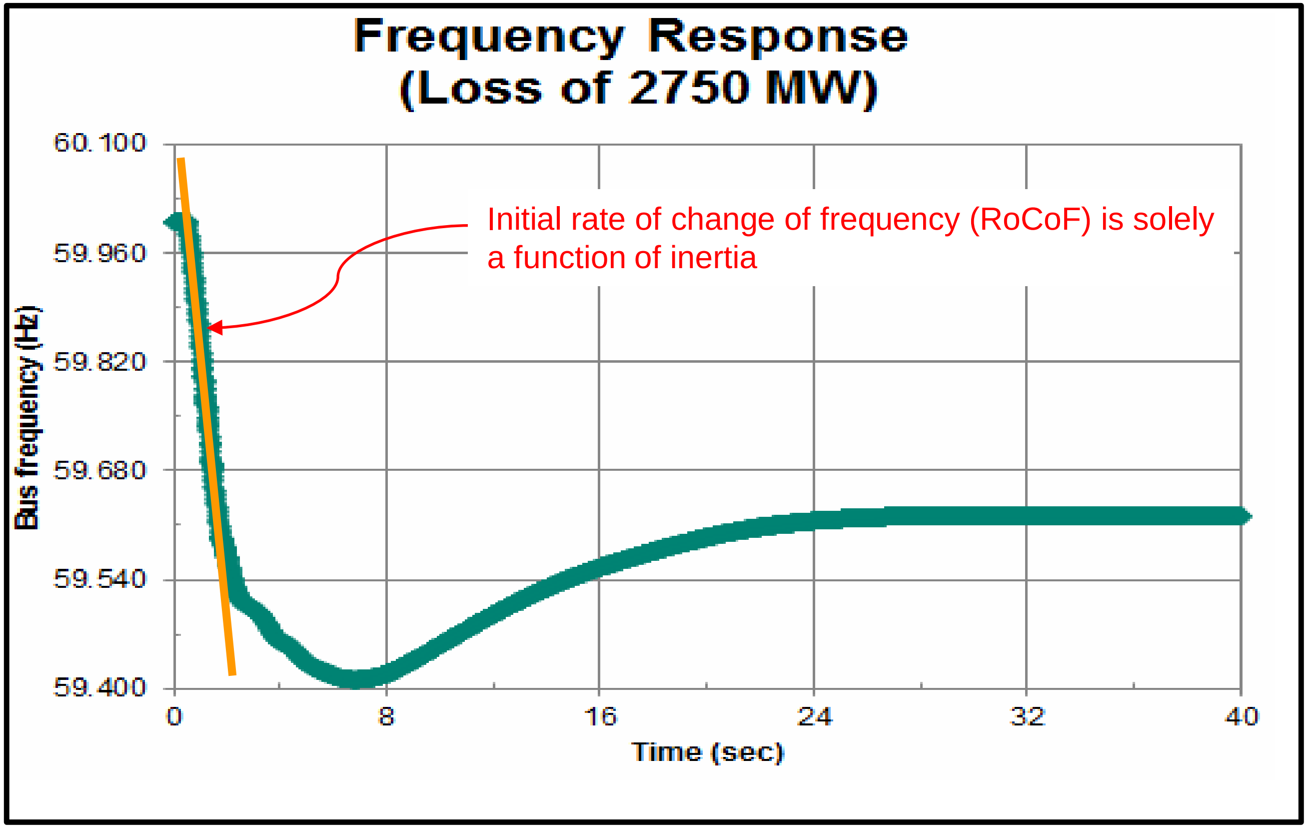
Wind Installed Capacity vs. Regulation-Up Requirement



As more wind has been added Regulation requirements have gone down!

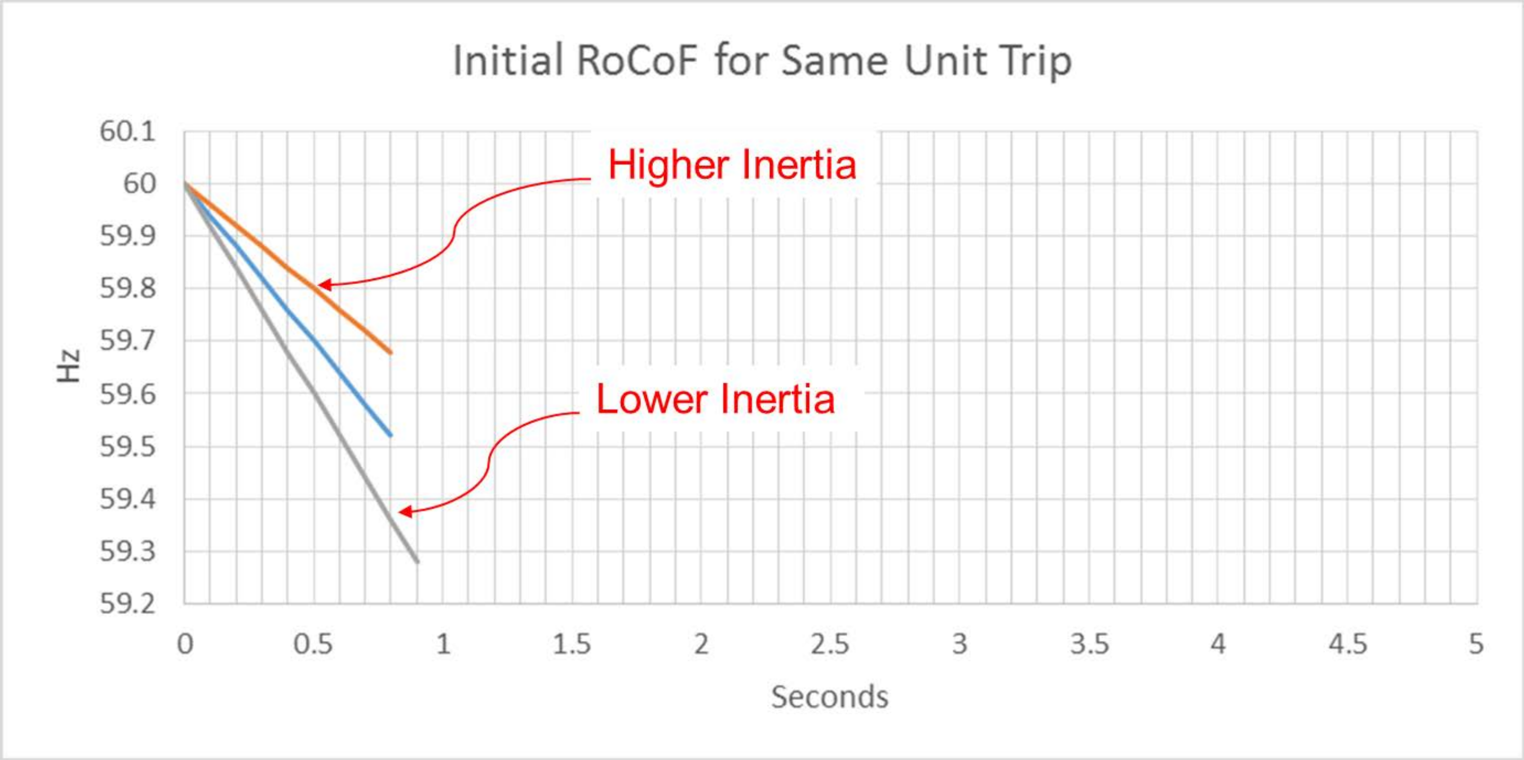
Inertia

- Following a resource trip, the initial rate of change of frequency (prior to any resource response) is solely a function of inertia.
  - Only synchronous machines provide inertia to the system
  - Other resources may provide frequency response



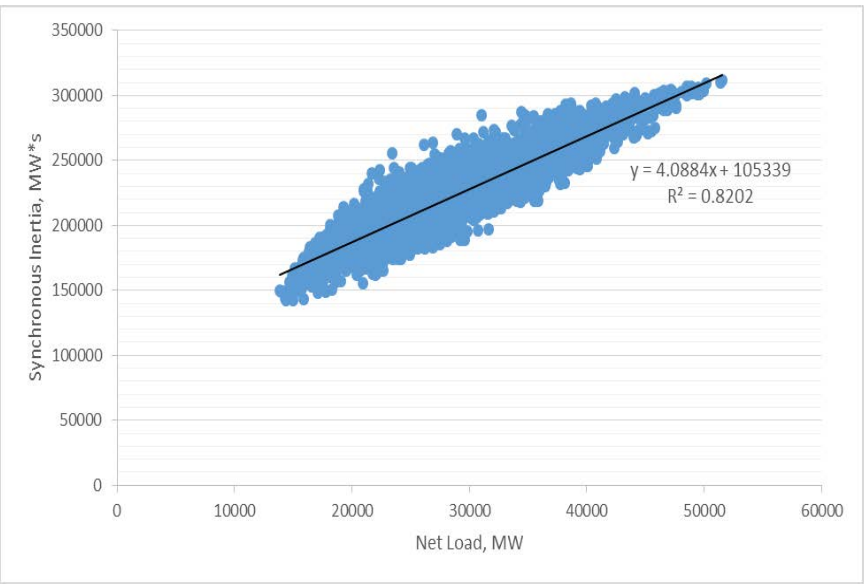
Inertia

- With increasing integration of renewables, there could be periods when total inertia of the system could be low, as less synchronous machines will be dispatched to be online.
  - During such situations it is essential to have adequate frequency response capabilities.

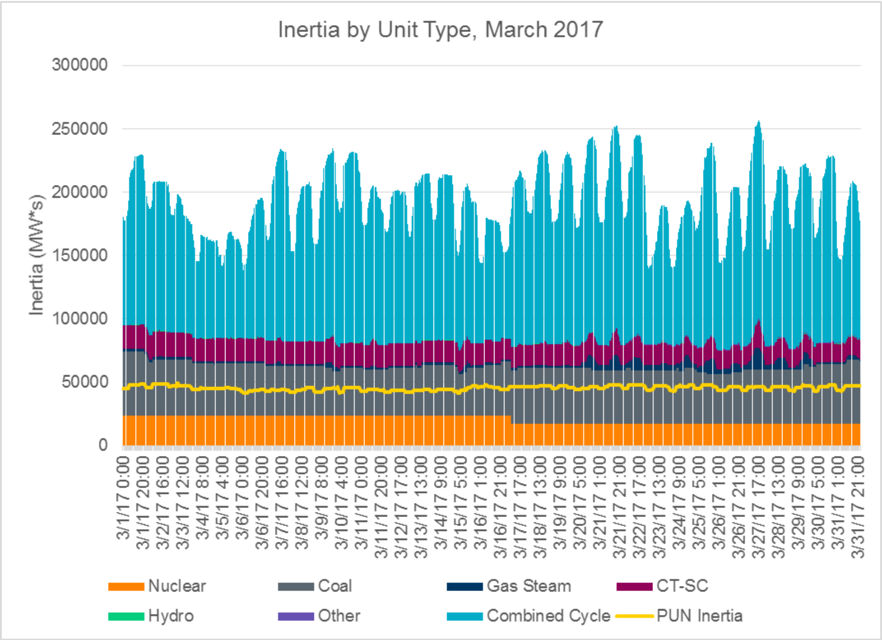


Inertia Patterns in ERCOT

- High in summer
- Low in spring and autumn
- Correlated with net load (net load=load - wind generation)

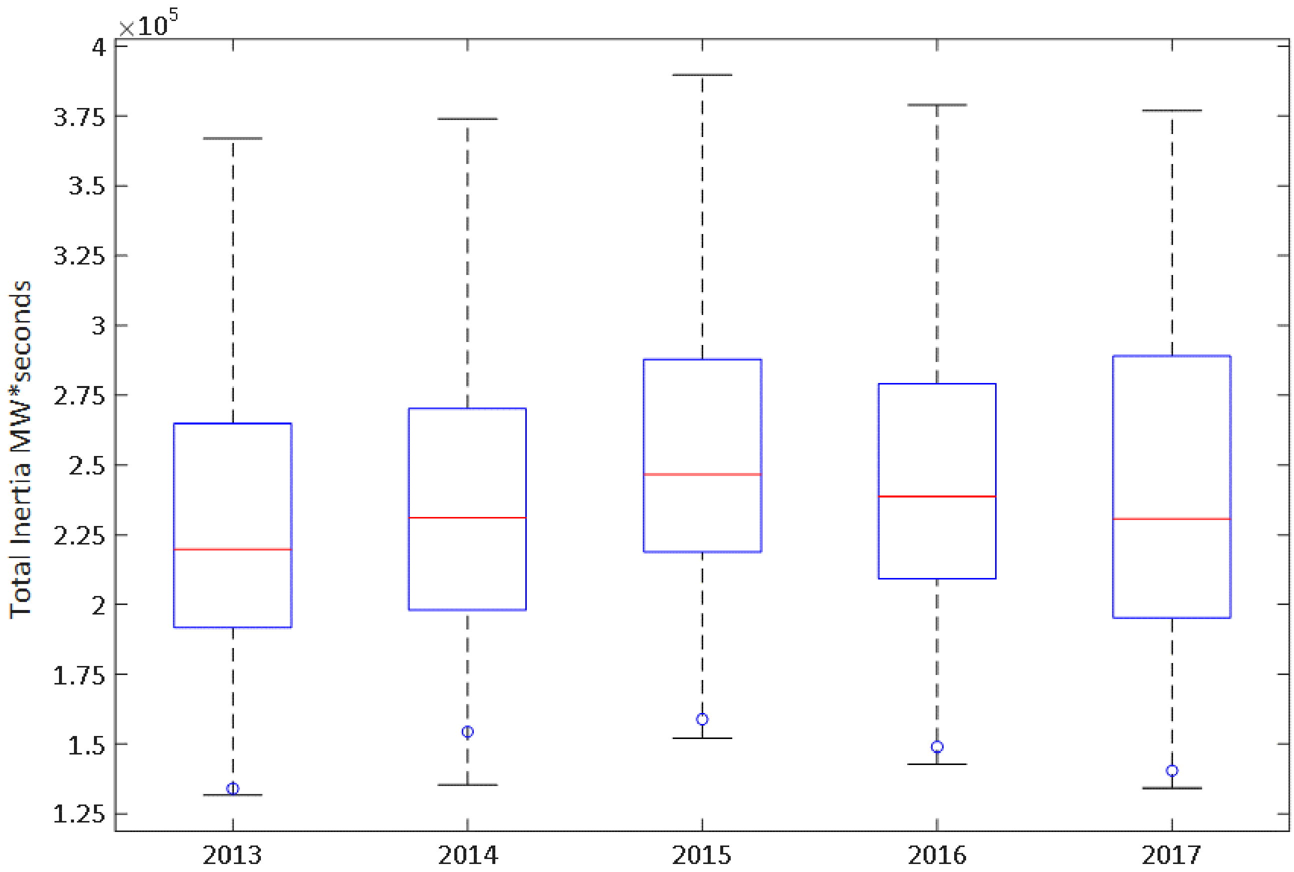


Net load vs Inertia in 2016



Inertia contribution by fuel type in March 2017

Inertia trend in the past years 2013-2017 (Sept.)

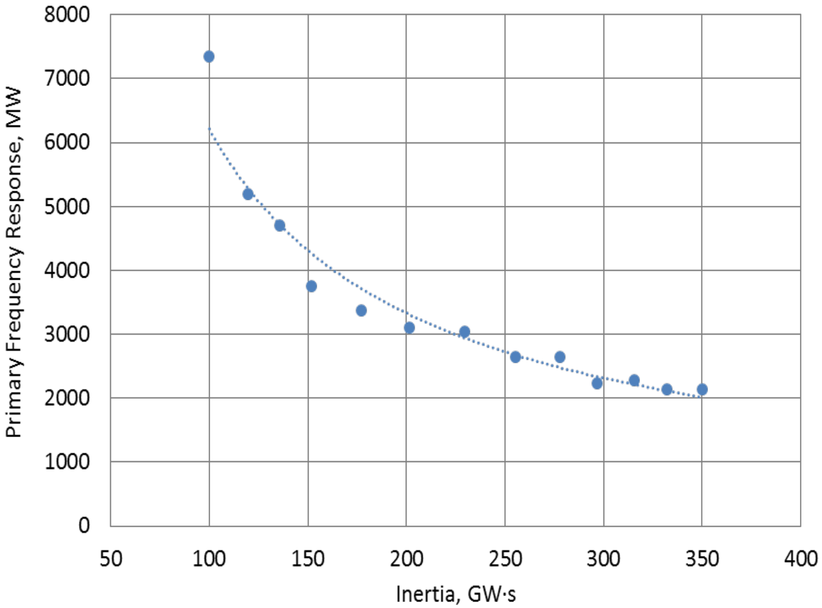


Responsive Reserve Service (RRS)

- ERCOT procures Responsive Reserve Service, which is used during generator trip events for frequency support;
- There are two types of resources currently providing RRS:
  - Generators, deploying RRS though primary frequency response (PFR), i.e. governor response with 5% droop and deadband of ±17 mHz.
  - Load resources, deploying RRS through fast frequency response (FFR), i.e. underfrequency relays automatically disconnecting a load within 0.5 seconds if system frequency drops to 59.7 Hz or lower.
- Load Resource participation is limited to 50% of total RRS.
- Until recently (June 2015) ERCOT was procuring 2800 MW of RRS for every hour in a year.

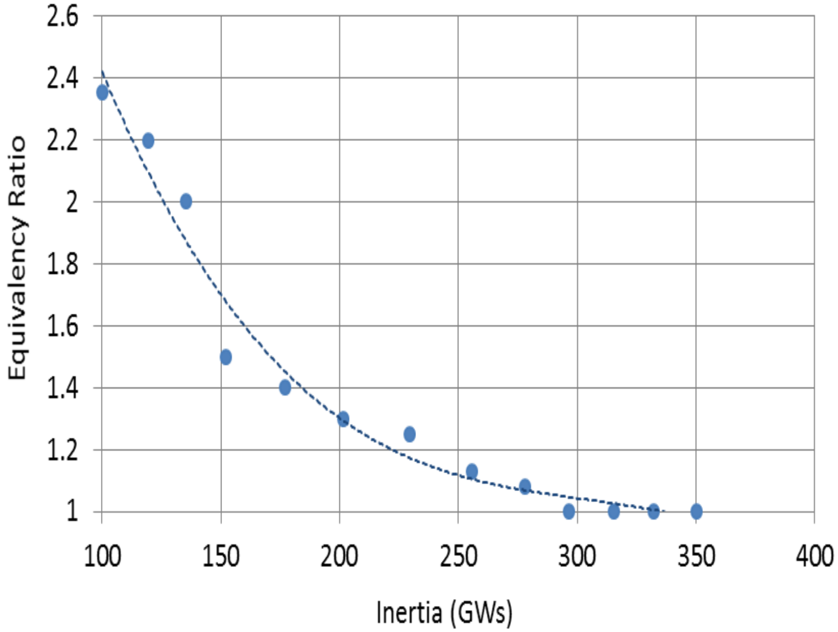
Impacts of Inertia

PFR need as a function of inertia



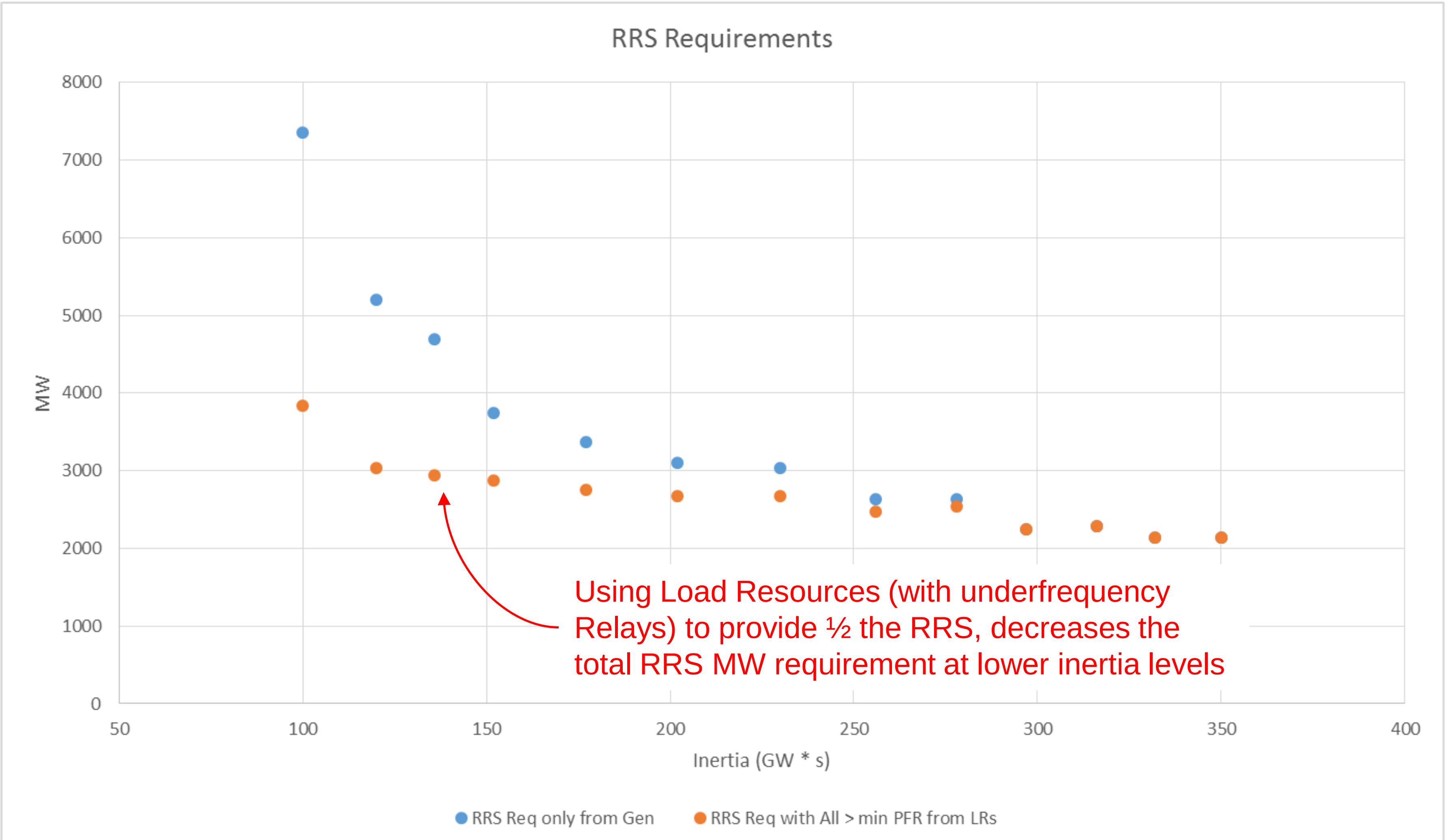
Based on the dynamic studies for 13 inertia cases, tripping two nuclear units (2750 MW) and determining PRF needed to prevent frequency from dropping below 59.4 Hz (0.1 Hz above UFLS)

Equivalency ratio between PFR and FFR resources

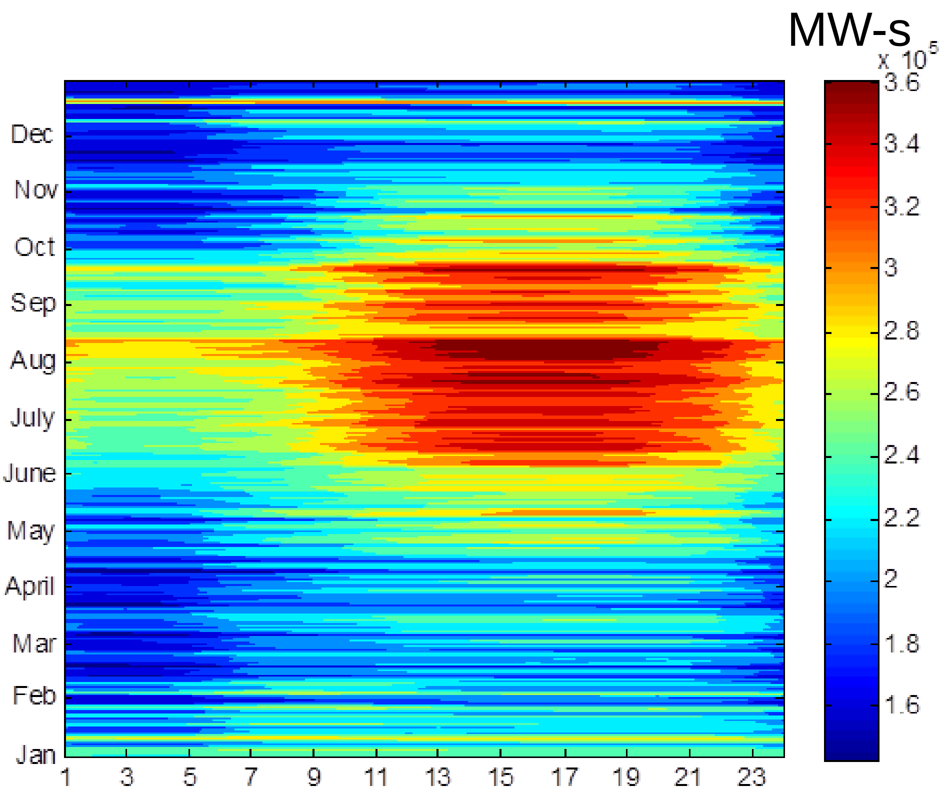


Based on the dynamic studies gradually substituting part of PFR with FFR resources.

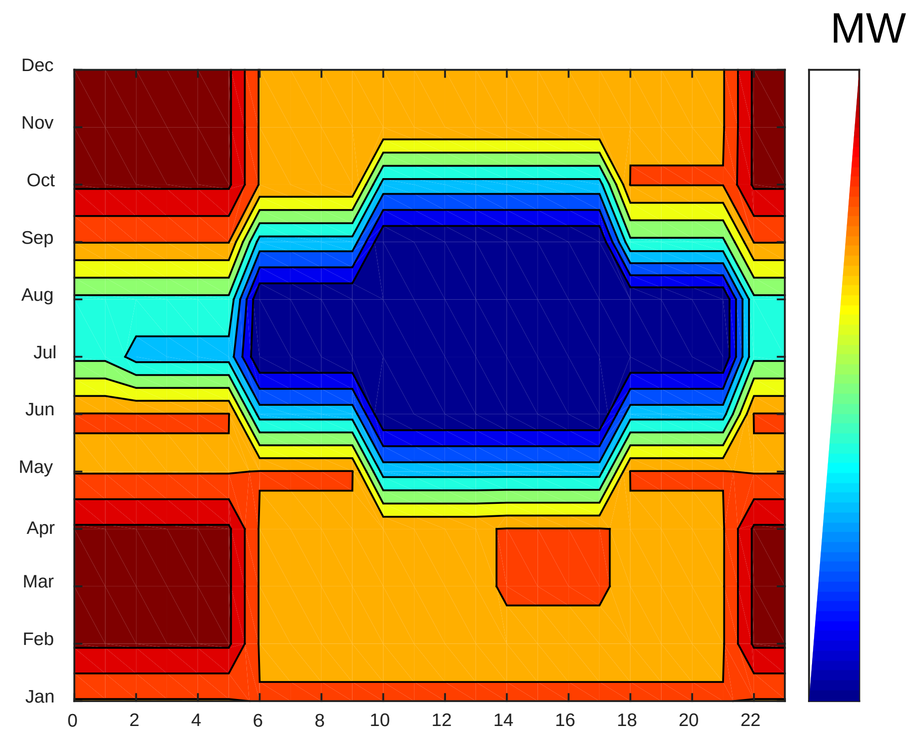
Varying Responsive Reserve Requirement



Inertia Impact on Hourly RRS Requirements

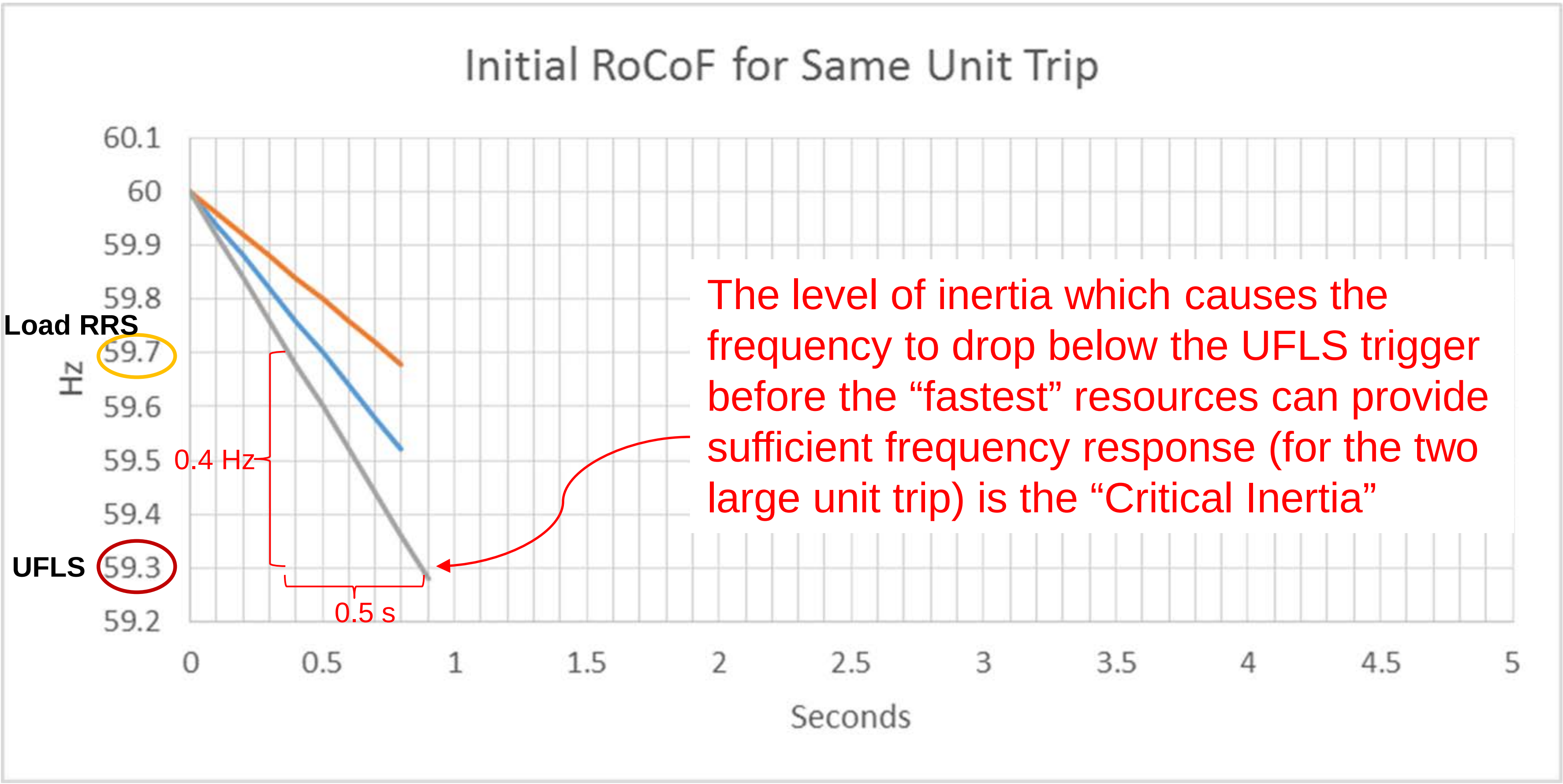


2016 Inertia Heat-Map



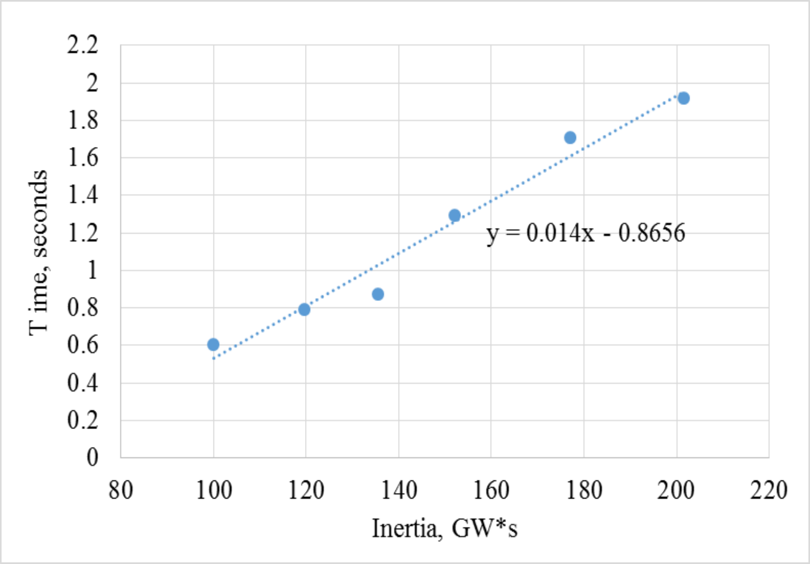
2017 Responsive Reserve Service Requirement

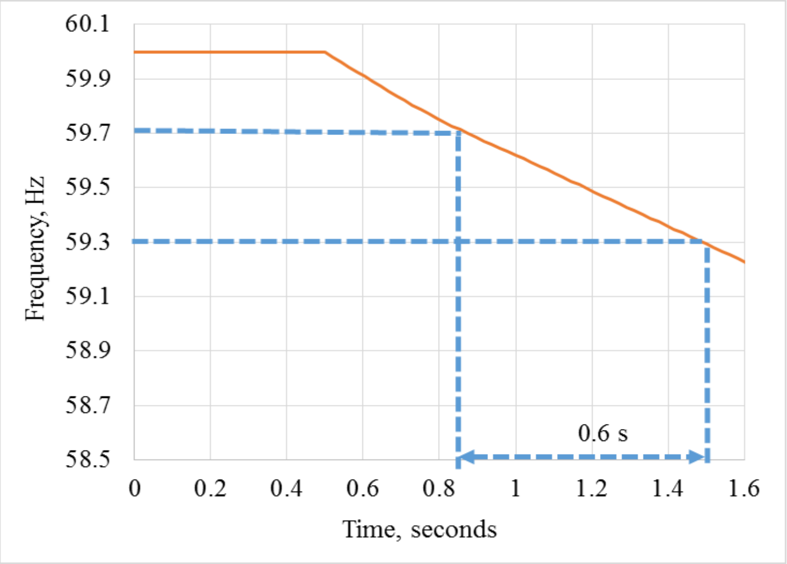
Critical Inertia Concept



Criteria for Determining Critical Inertia in ERCOT

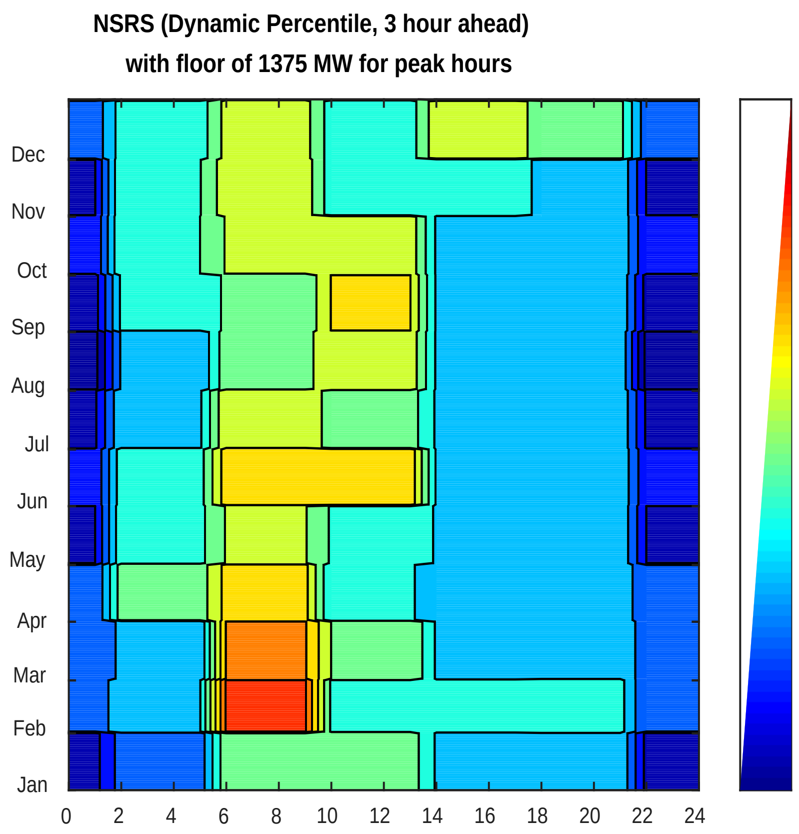
- Critical inertia for ERCOT is the inertia level below which, for a generation loss of 2750 MW, frequency takes less than 0.5 seconds to travel from 59.7 Hz to 59.3 Hz (UFLS).



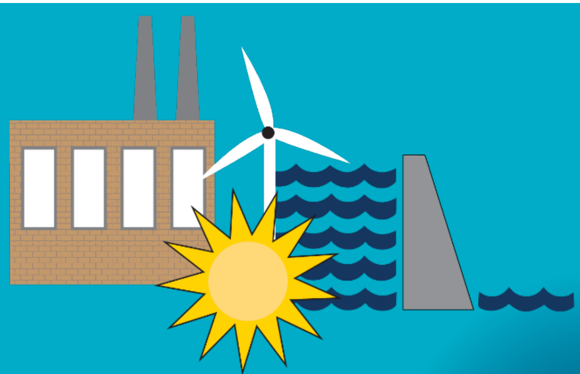


Ancillary Services – Non-Spin

- Used to ensure sufficient capacity is available to cover load/wind forecast errors or replace deployed RRS
  - 30 min deployment required but most provided by 10 min quick start or unloaded on-line generation
  - Must be dispatchable
- Quantity required varies based on historic 3-hour ahead forecast error and risk of large ramps.

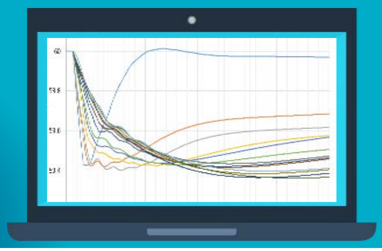


Reliability Risk Desk in the Control Room



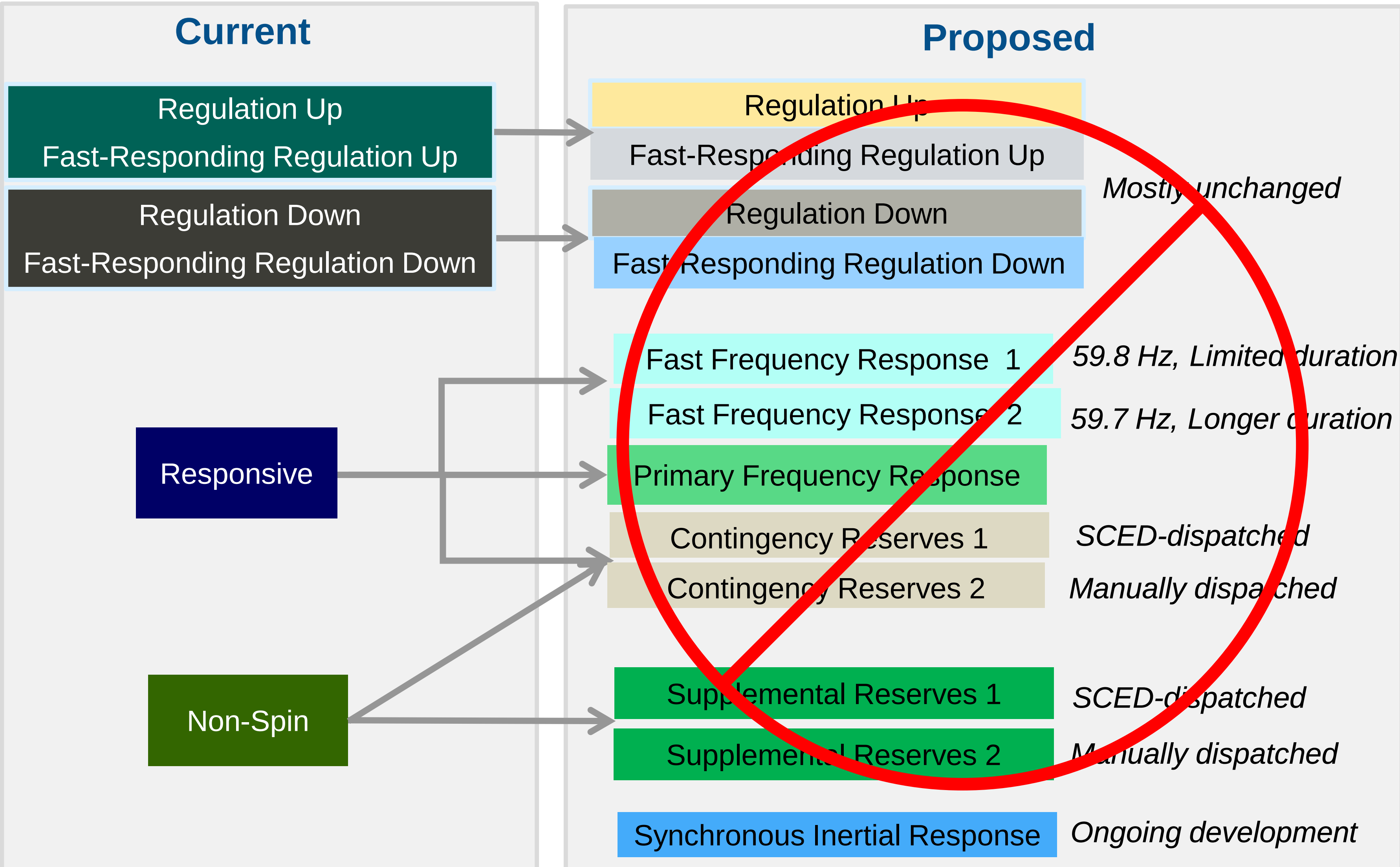
Network model driven real-time inertia calculation

Offline studies for a wide range of inertia conditions to determine critical inertia and reserve requirements



- Monitoring of real-time inertia against critical inertia conditions;
- Forecasting reserve needs based on expected inertia conditions from day ahead to hours ahead
- Monitoring reserve sufficiency

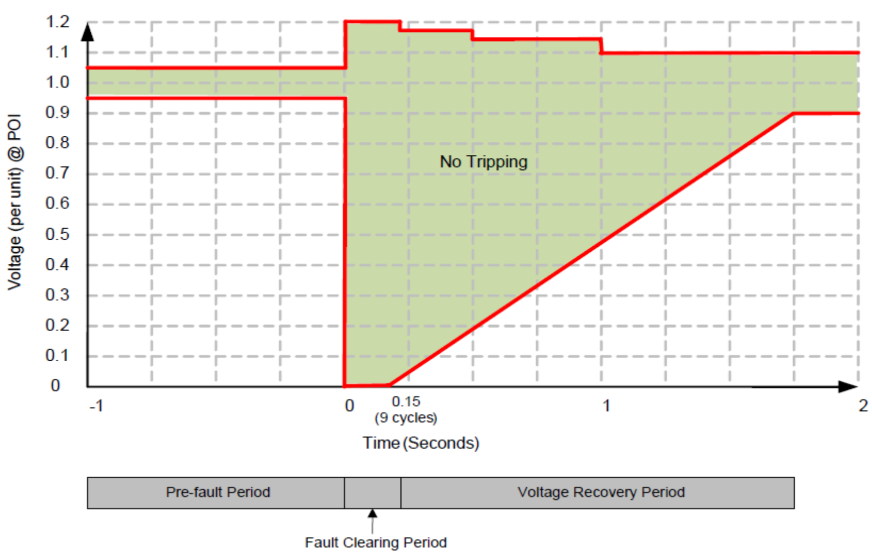
Proposed Future Ancillary Services

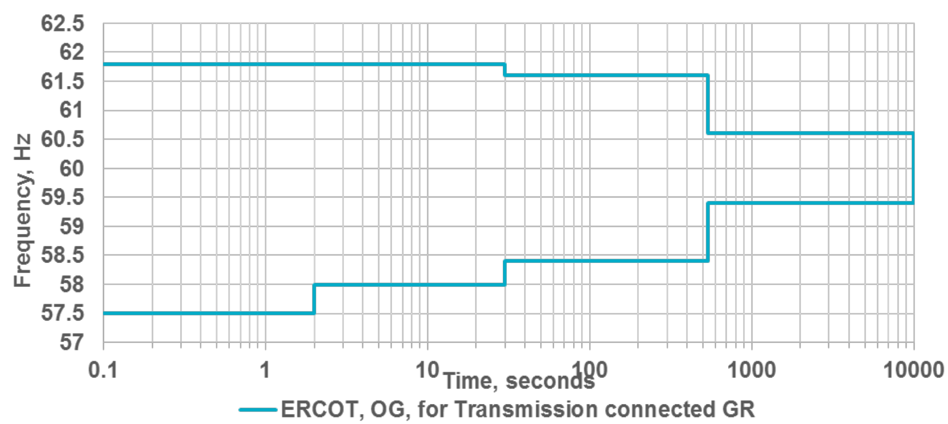


Voltage/Frequency Ride-Through Challenge

Variability/ Intermittency	Frequency Response/ Inertia
Ride-Through Support	Reactive Support
Stability	Weak Grid

- Under low voltage conditions (such as after a fault and line trip) inverter-based generators may trip;
- If a generator trips under low voltage conditions it may exacerbate the problem and cause more wide-spread system issues.





Reactive Support Challenge

Variability/ Intermittency	Frequency Response/ Inertia
Voltage Ride-Through	**Reactive Support**
Stability	Weak Grid

- Generation resources aid in providing voltage support by providing reactive power
- Early wind turbine technology not only did not provide reactive power, but consumed it
- A lack of voltage support could lead to voltage instability

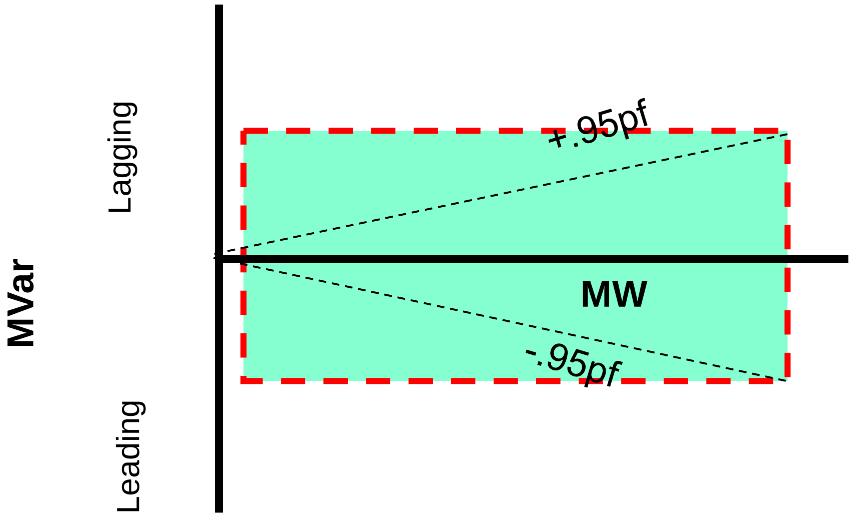
Reactive Support Solution

Variability/ Intermittency	Frequency Response/ Inertia
Voltage Ride-Through	Reactive Support
Stability	Weak Grid

- New wind turbine technology and solar inverters can provide reactive power to support voltage
- ERCOT requires all new generators (since 2004) to provide reactive power

Reactive Support Solution

- ERCOT requires all new generators (since 2004) to provide reactive power
  - 0.95 power factor, leading and lagging (voltage control mode with AVR);
  - Intermittent generation after 2009 must provide the capability anytime output is at least 10% of capacity;
  - Reactive power capability must be dynamic.



Low System Strength

Variability/ Intermittency

Frequency Response/ Inertia

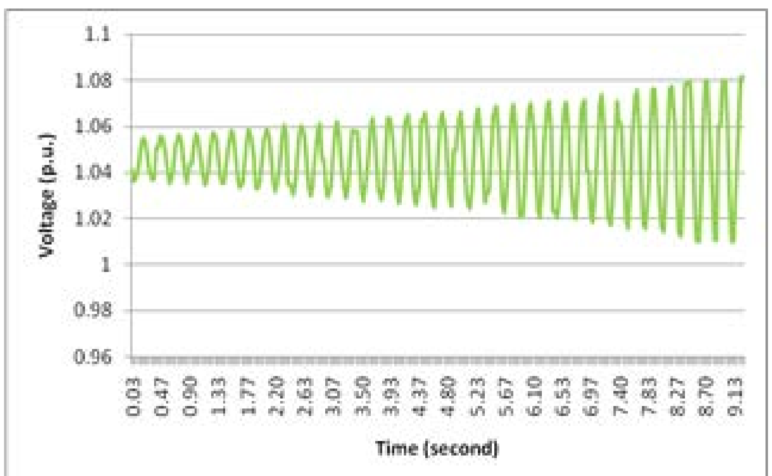
Voltage Ride-Through

Reactive Support

Stability

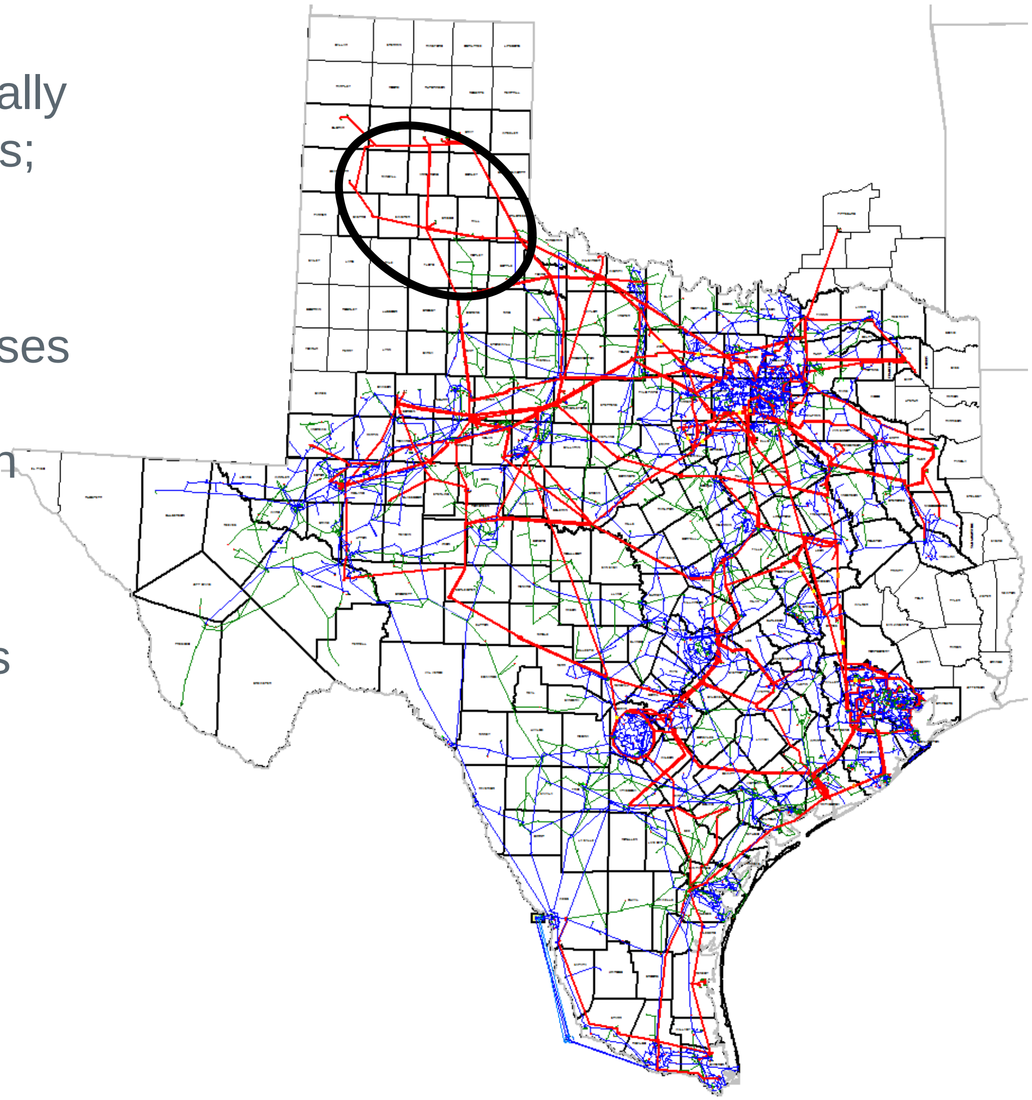
Weak Grid

- Inverter-based generator control systems rely on a “strong” voltage source (synchronous generators);
- As renewables increase on the system, synchronous generators decrease;
- Inverter-based generators can experience weak grid challenges when there are no nearby synchronous sources
- Inverter-based controls are faster responding than synchronous generators, but are more sensitive to voltage variations;



Stability Challenges

- Renewable generation is typically remote from major load centers;
- Transferring power over long distances exponentially increases reactive losses in the transmission system which can lead to voltage instability;
- Voltage stability considerations may limit export from wind generation rich areas.



Low System Strength and Voltage Stability Solutions

- ERCOT introduced the concept of Weighted Short Circuit Ration (WSCR) to characterize system strength of an area rather then individual POI.
- Weighted short circuit ratio of >1.5* was found sufficient for voltage controllers to operate properly and for confidence in positive sequence simulation results
- ERCOT requires all new inverter-based generators to provide PSCAD models
- Monitors WSCR in real time and limits/curtials power production from inverter-based resources to achieve WSCR=1.5
- Additionally there is also voltage stability limit calculated in real time for power transfer from that area

* This result is strictly Panhandle specific, different limit may apply in other low SCR areas

Low System Strength Future Solutions

- Two synchronous condensers will be installed next year (better option to SVC or STATCOM: adds system strength and has dynamic reactive power capability)
- RFP for reactive power coordination tool to identify in Day Ahead and Hour Ahead the best reactive power adjustments needed for the system
- Considering voltage droop implementation, difficult to come up with a requirement due to inaccurate modelling of voltage droop in resource models. Capability is there.
- Follow up evaluation/study for Panhandle WSCR limit, potentially with improved more robust voltage controllers at new plants

Key Takeaways

- System operators must be mindful of variability/intermittency, frequency/ inertia, reactive support, voltage and frequency ride-through, stability, and weak-grid challenges when integrating large amounts of renewable generation;
- Accurate wind and solar generation forecasting is very important;
- Real time awareness tools in the control room are essential for efficient and reliable operation with high levels of renewables;
- Ancillary Services can satisfy essential reliability needs for the system
  - ERCOT uses market-based solutions as much as possible
- Some of the essential reliability requirements need to be implemented through grid codes. Modern renewable generation technology can provide grid support.
  - Grandfathering can be problematic. Most challenges are not bad when there is only a small amount of renewables connected but can quickly evolve into problems with rapid deployment.
- Accurate renewable generation models are critical for power system engineers to ensure reliability

Questions

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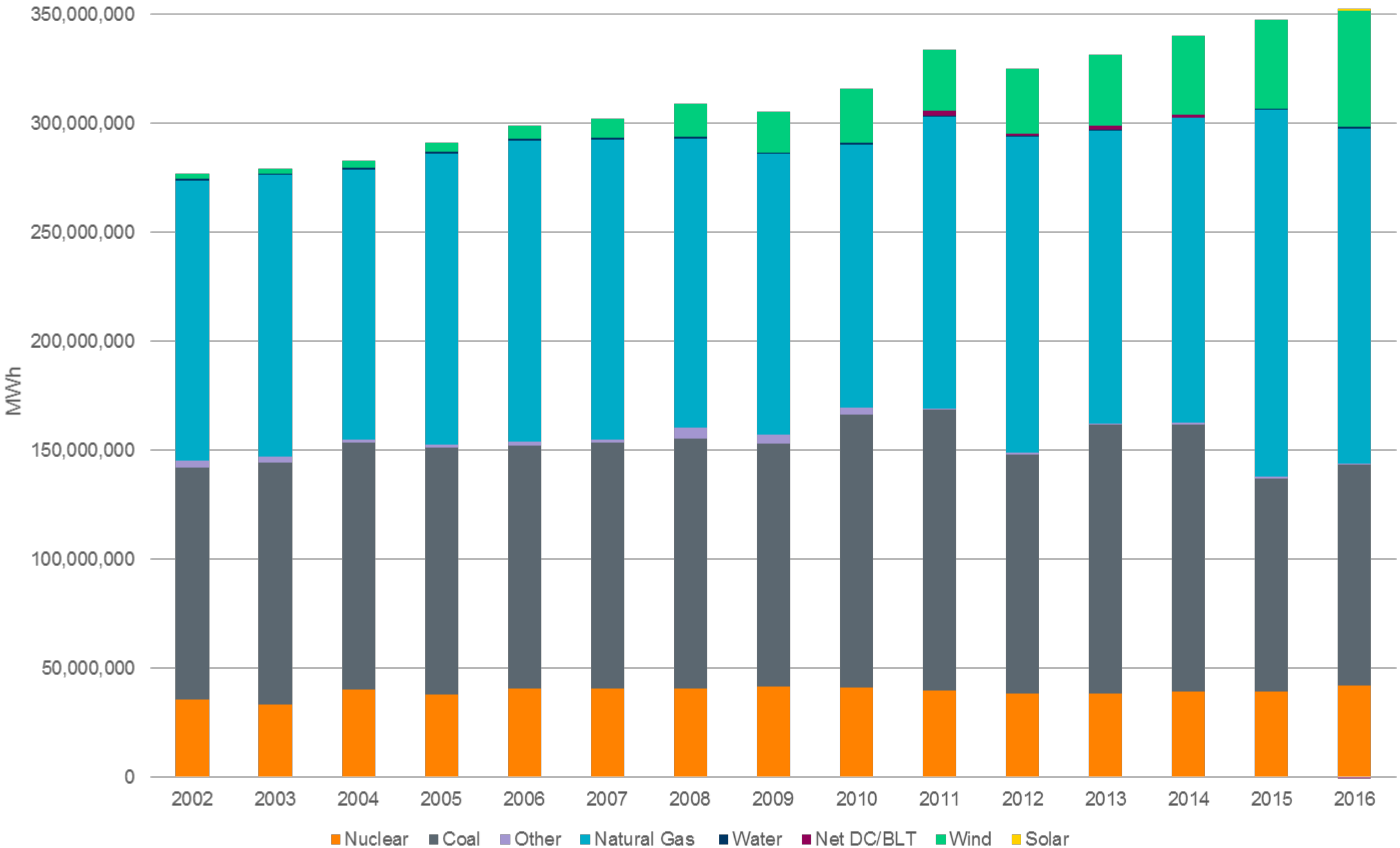
Energy Fuel Mix 2002-2016 (MWh)



*Source: Historical ERCOT Demand and Energy Reports