ERCOT's Experience Integrating High Shares of IBR

Julia Matevosyan
Resource Adequacy
ERCOT

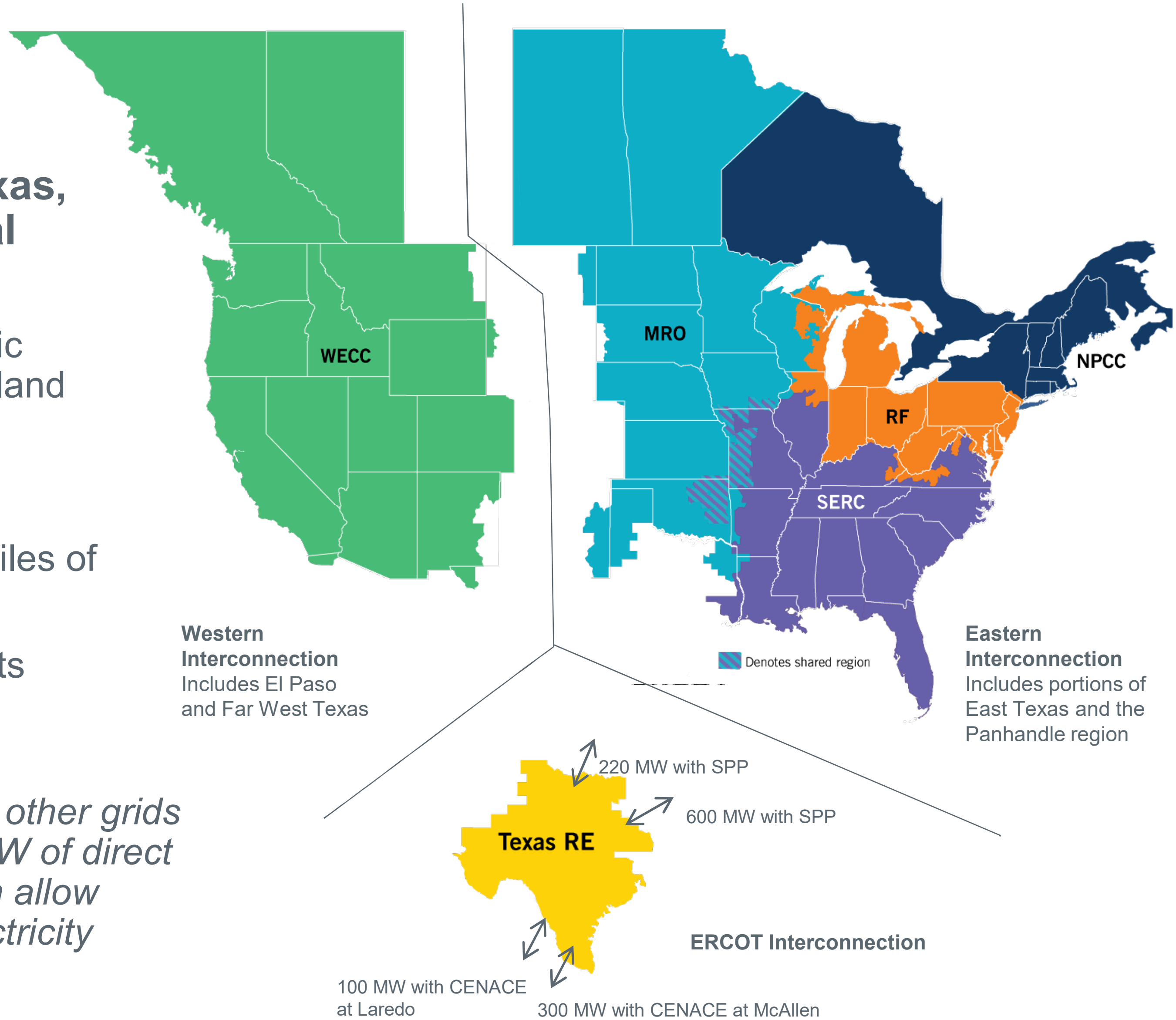
06/16/2021

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
- 710+ 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

exas Load

2

- 1,800+ active m
participants that
move, buy, sell c
wholesale electr
- 86,000+ megaw

2020 Energy Use

*Other includes solar, hydro, petroleum coke, biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load

1

74,820 MW

Record peak demand

71,930 MW

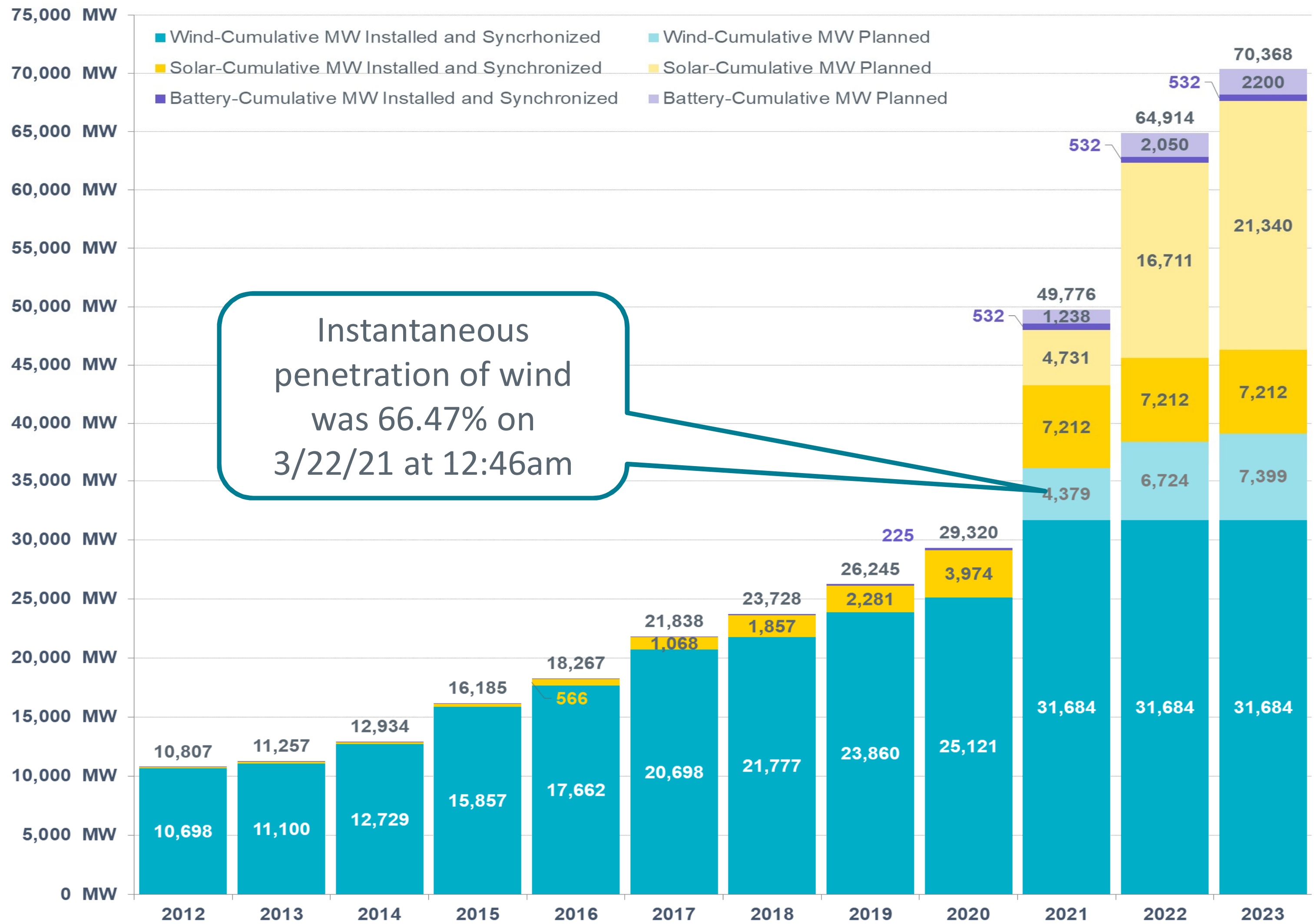
Weekend peak demand record

- 710+ generating
excluding PUNs
- Transmission pro
endorsed in 202
$1,071 million

2021 Generating Capacity

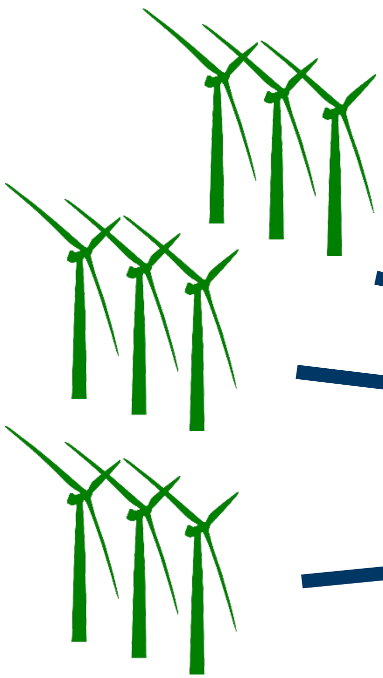
Reflects ope
based on th

Inverter-Based Resource Capacity – April 2020



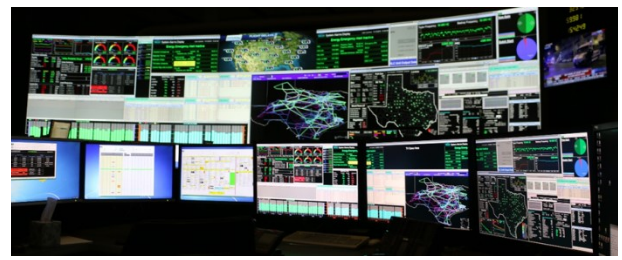
Cumulative MW Planned include projects with signed interconnection agreeements

ERCOT Wind Generation Forecast



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

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



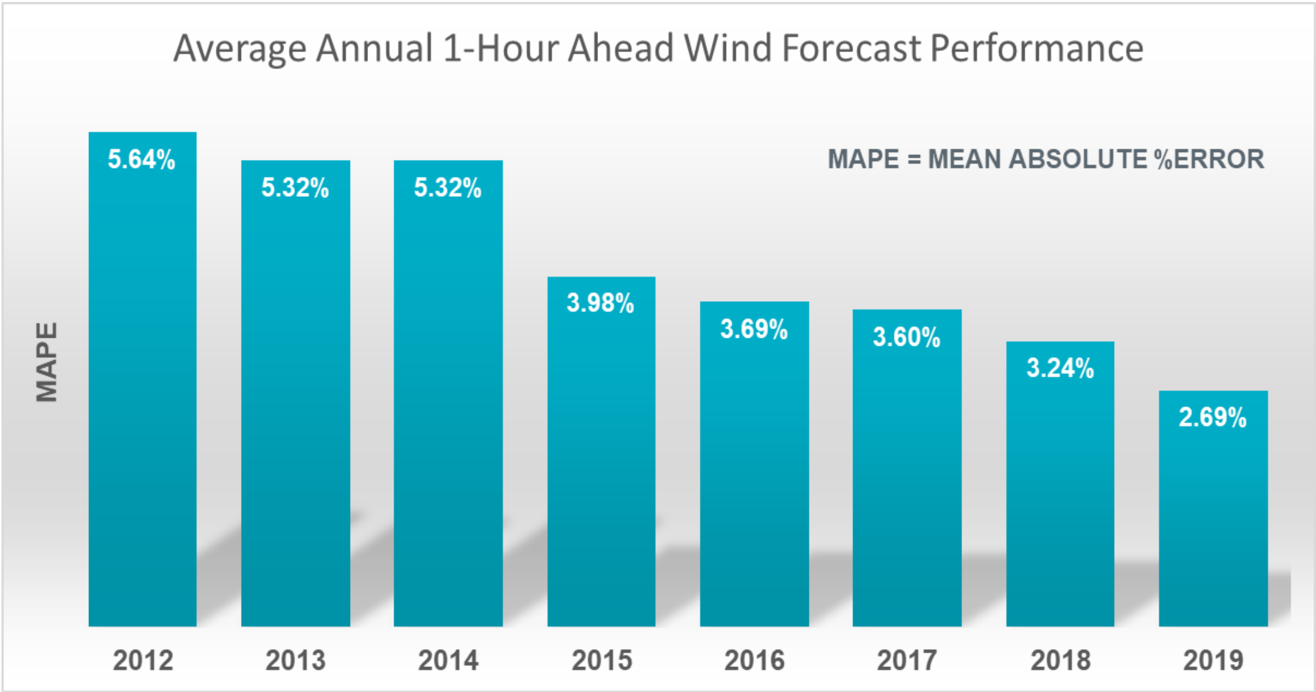
ercot

2. ERCOT sends information from wind plants to the forecast vendor

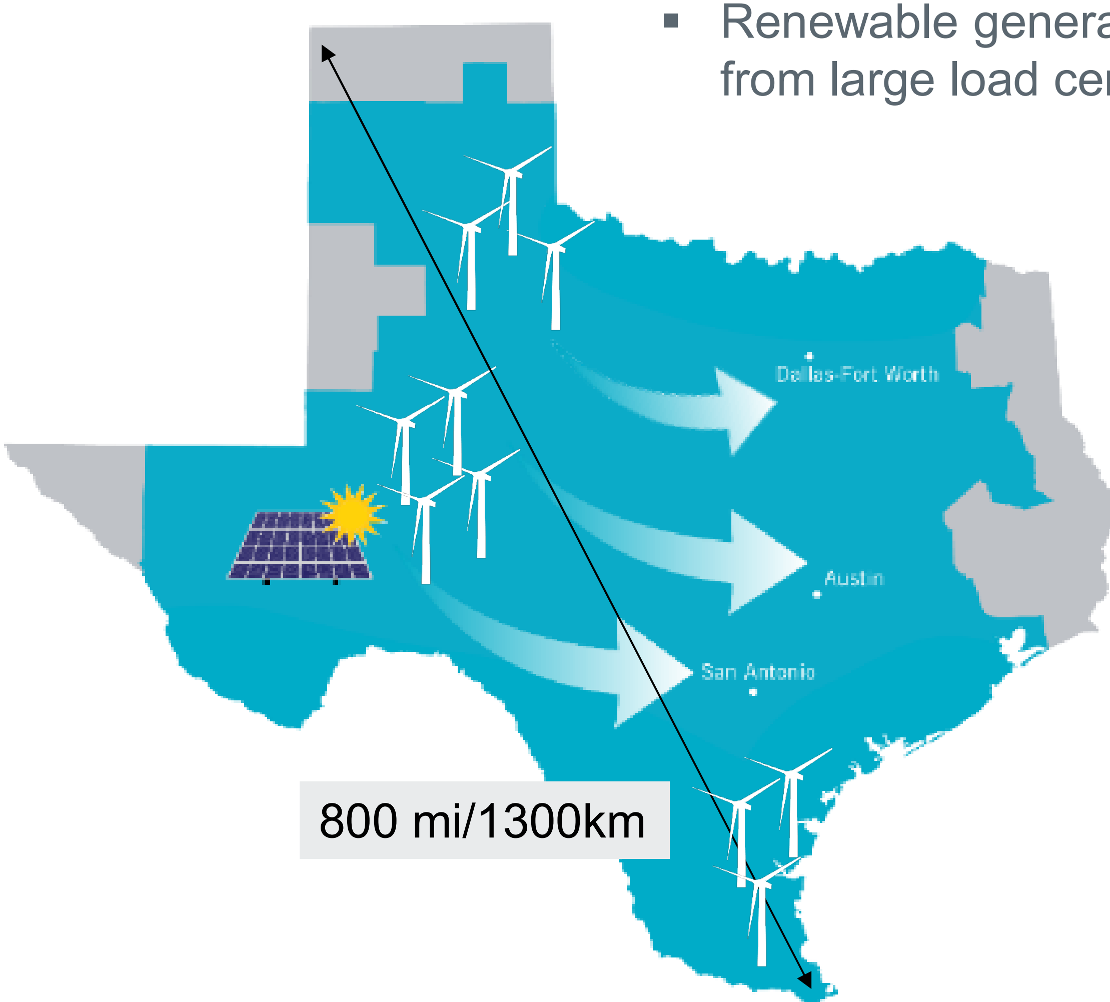
3. Forecast vendor computes and sends ERCOT a rolling 168-hour generation forecast for all wind plants

ercot AWS Truepower

Wind Forecast Performance



Renewable Energy in the ERCOT Region

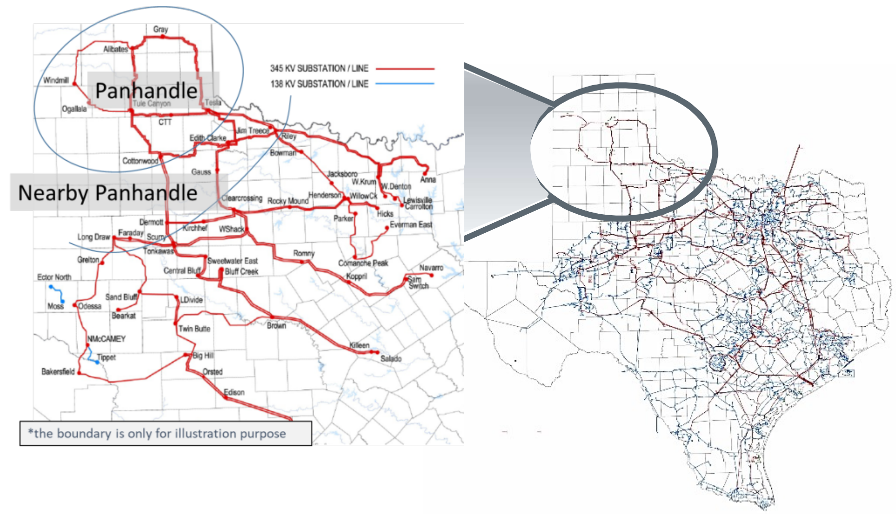


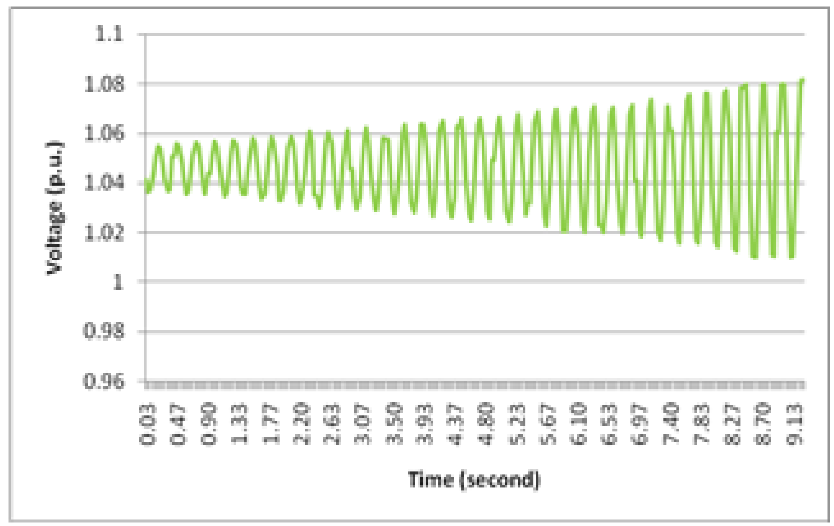
- Renewable generation typically built far from large load centers

Weak Grid and Stability

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 WSCR; offline PSCAD
  - Voltage Stability: real time VSAT
  - Dynamic Stability: offline PSS/e*





*Real time TSAT is currently under development

Weighted Short Circuit Ratio

- 2014 Panhandle study, recognized limitations of a single plant Short Circuit Ratio for characterizing system strength:
  - ignores the interactions between neighboring IBRs in a region
  - may give an overly-optimistic estimation of system strength
- ERCOT proposed the concept of WSCR:
  - recognizes interactions between neighboring IBRs
  - assumes all interacting IBRs are connected at the same bus (!)

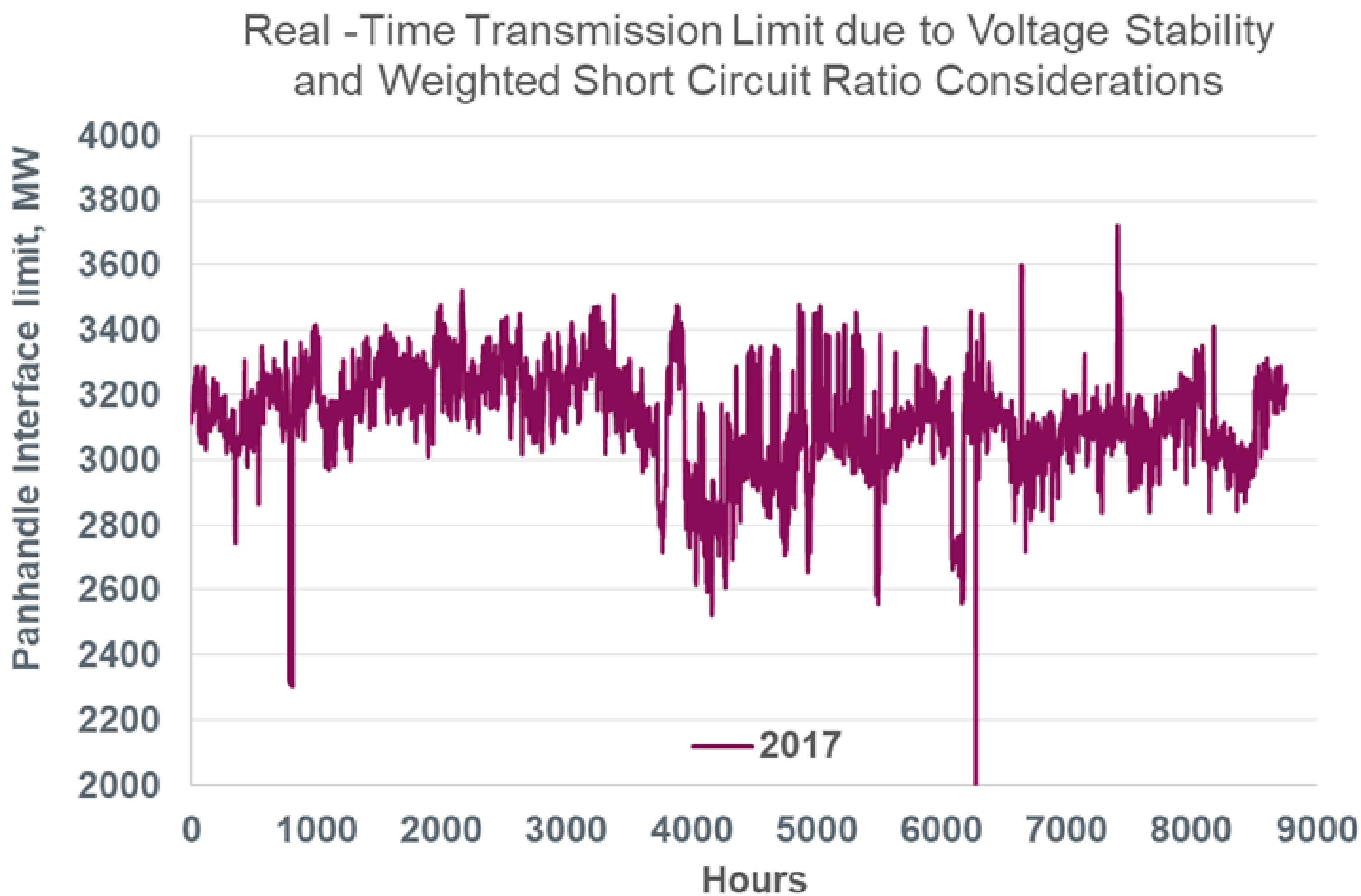
$$WSCR = \frac{\sum_i^N S_{SCMVAi} * P_i}{\left(\sum_i^N P_i\right)^2}$$

- WSCR=1.5 was proposed as the minimum pre-contingency system strength for Panhandle (based on PSS/E study results)

Evaluation of Panhandle Export Limit in Real Time

- Currently, WSCR≥1.5 is maintained in Panhandle by curtailing wind generation, if WSCR is the most limiting constraint
- WSCR calculation is built into real-time VSAT*, from which Panhandle export limit is determined every 10 minutes
  - $WSCR = \frac{\sum_i^N S_{SCMVAi} * P_i}{\left(\sum_i^N P_i\right)^2}$
  - $\sum_i^N P_i$ is total Panhandle generation at the time of evaluation
  - If WSCR <1.5, scale down all P_i proportionally so that WSCR = 1.5 under pre-contingency condition
  - New $\sum_i^N P_i$ determines Panhandle export limit based on WSCR

Real Time Panhandle Export Limit

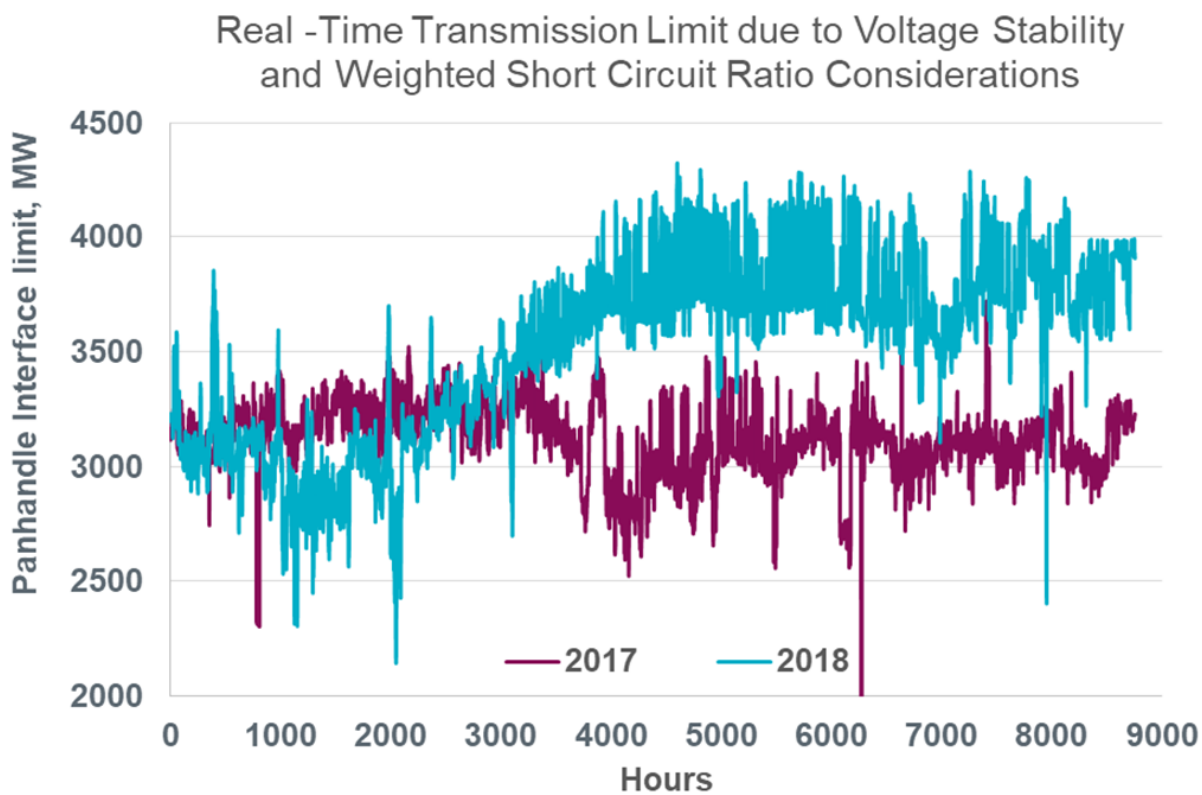


Synchronous Condenser Characteristics

- Two Synchronous Condensers were installed in Panhandle in 2018, each with the following specifications:
  - ~175/-125 MVAR, for +/- 10% voltage variation range
  - ~1600 Amps short circuit capability on the high-voltage side
- Placed in locations that increase WSCR but also improve voltage support and transient response
- High availability design is required since SynCons' outage directly translates into reduction of the maximum power export
  - Redundancy in cooling system aux supply, control and protection systems
  - The wide range of the machine operating voltage
  - Brushless excitation system to reduce maintenance time

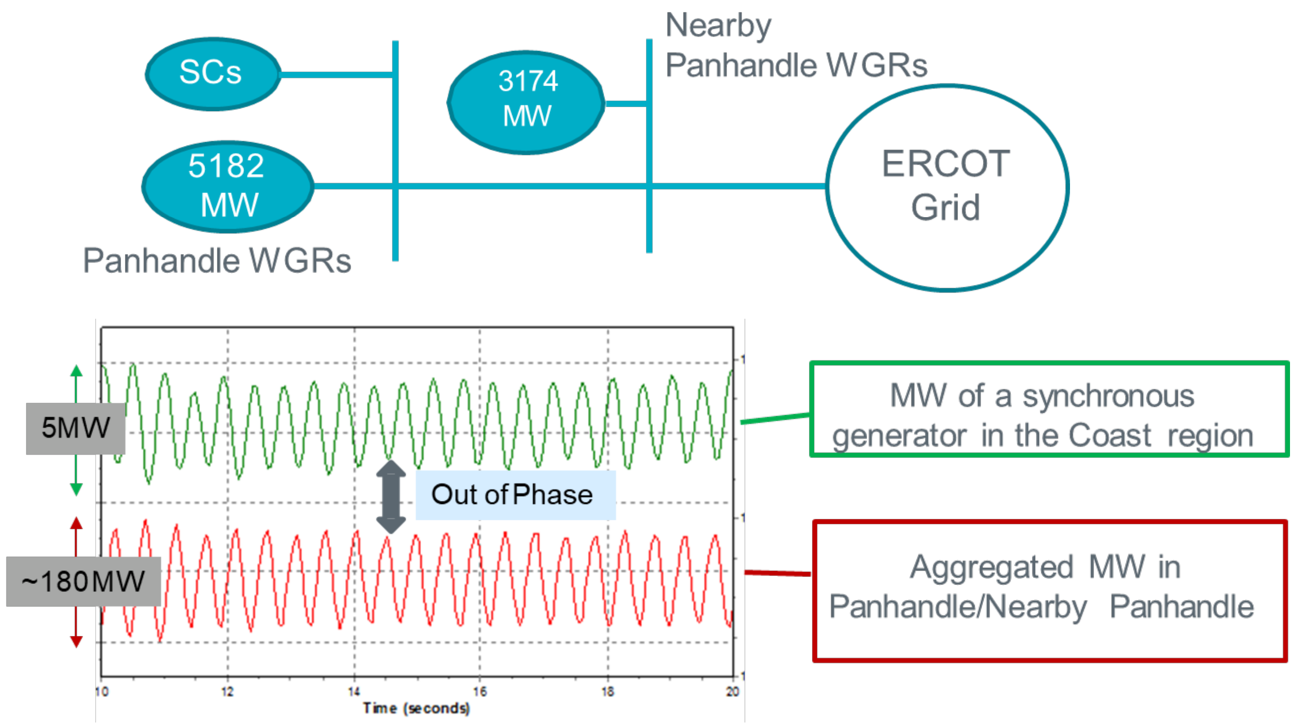
Impact of SynCons on Panhandle Export Limt

- SynCons have enabled increase in Panhandle export limit by ~470 MW
- The benefit may diminish with additional IBRs and topology changes



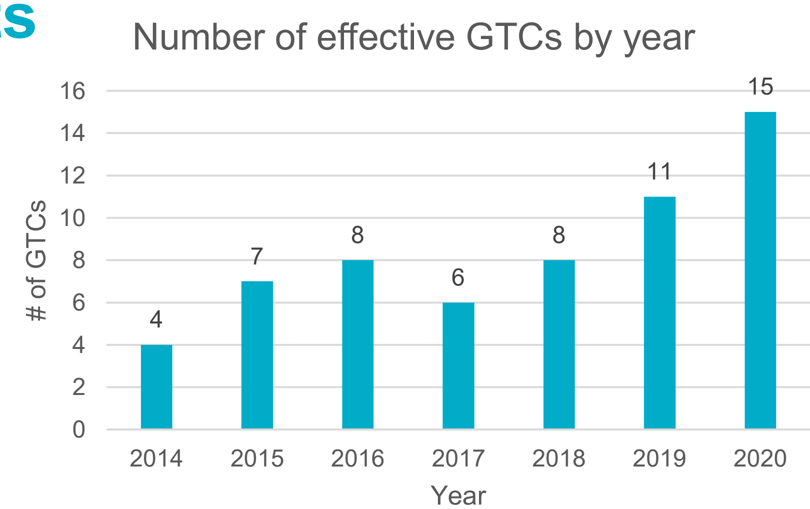
Inter-Area Oscillations Observed with SynCons, Need for Power Oscillation Damping

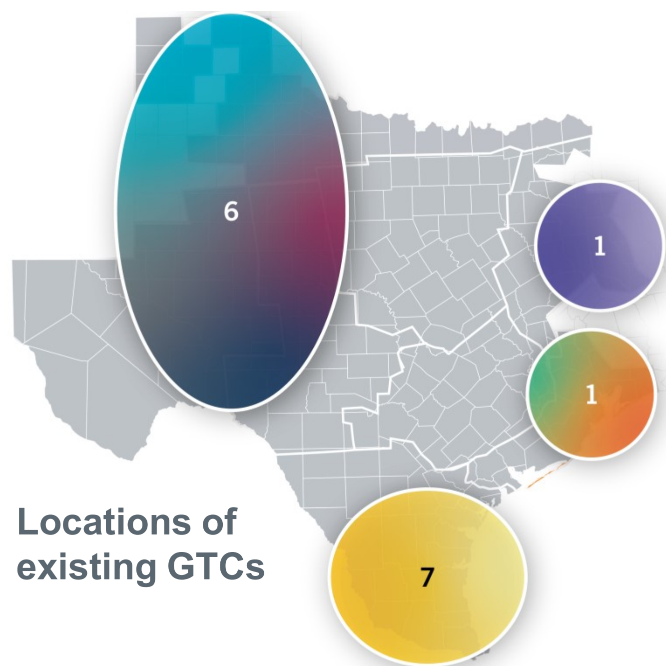
2019 Panhandle dynamic studies identified oscillatory behavior (~1.8 Hz) between SynCons and rest of ERCOT's synchronous generators.



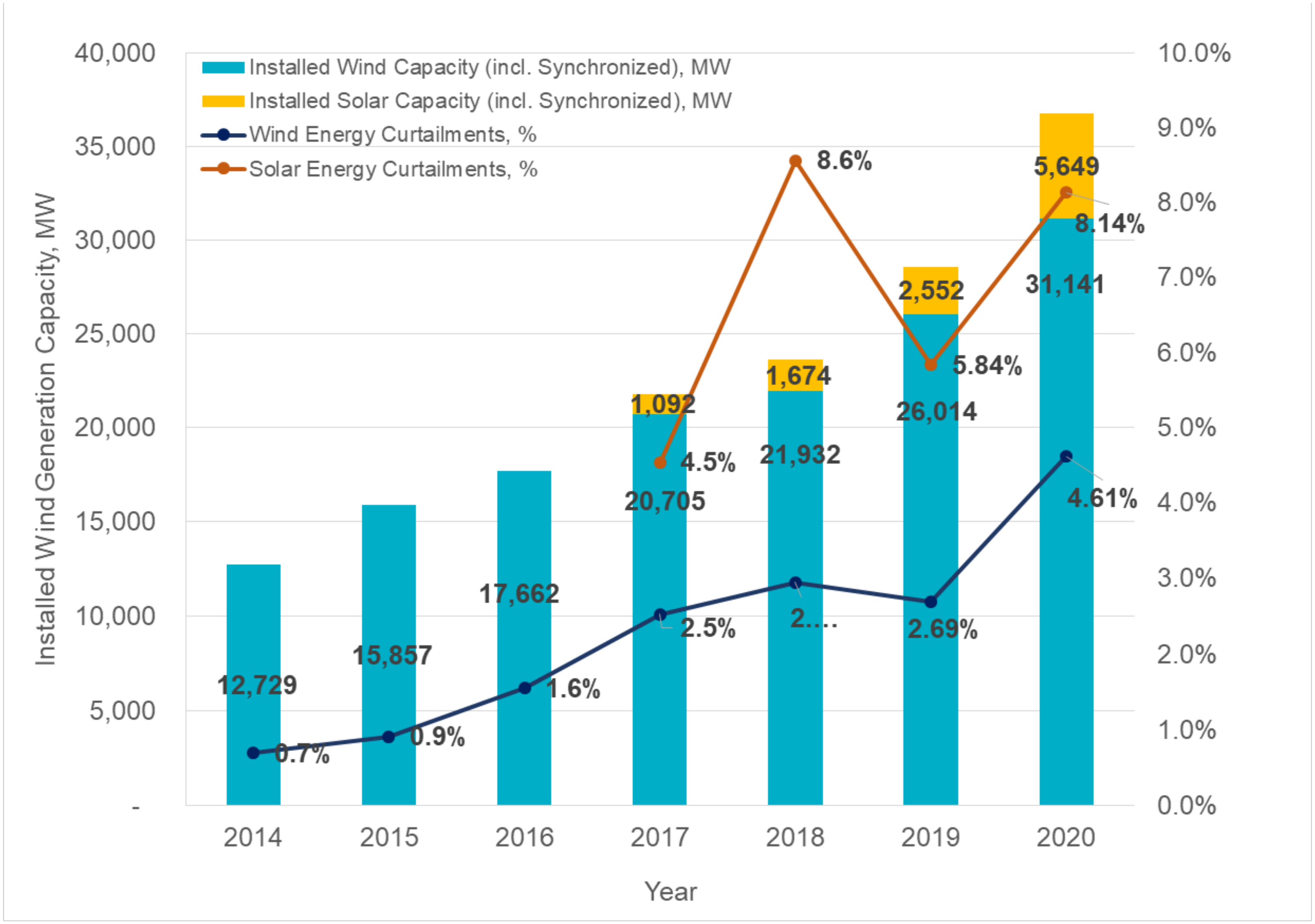
Increasing Stability Constraints

- As of October 31, 2020, there were 48 GW of renewable generation (~35.4 GW wind and ~12.4 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.





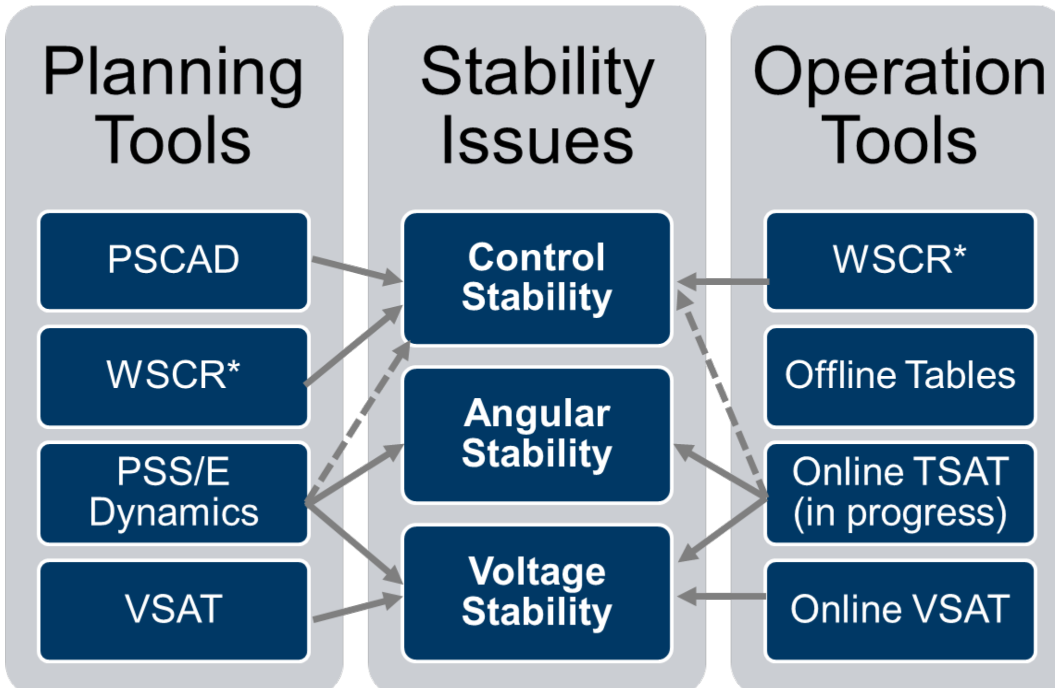
Wind and Solar Curtailments



Curtailment % is calculated based on potential uncurtailed annual energy yield

Stability Assessment and Tools

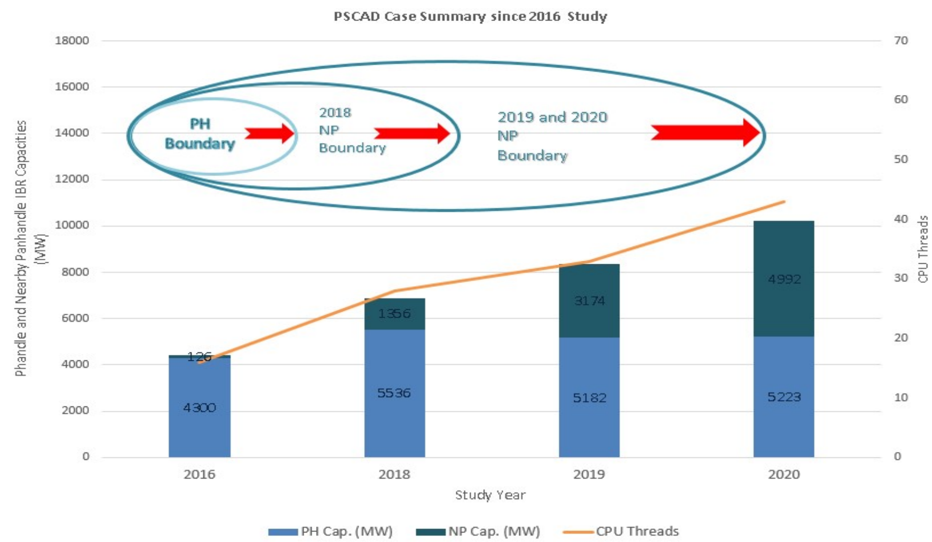
- With more IBRs
  - Increasing stability challenges
  - Require PSCAD studies: complex and time consuming
- Needs and Improvements
  - Model accuracy and usability
  - Tool and simulation efficiency
  - Better communication and coordination

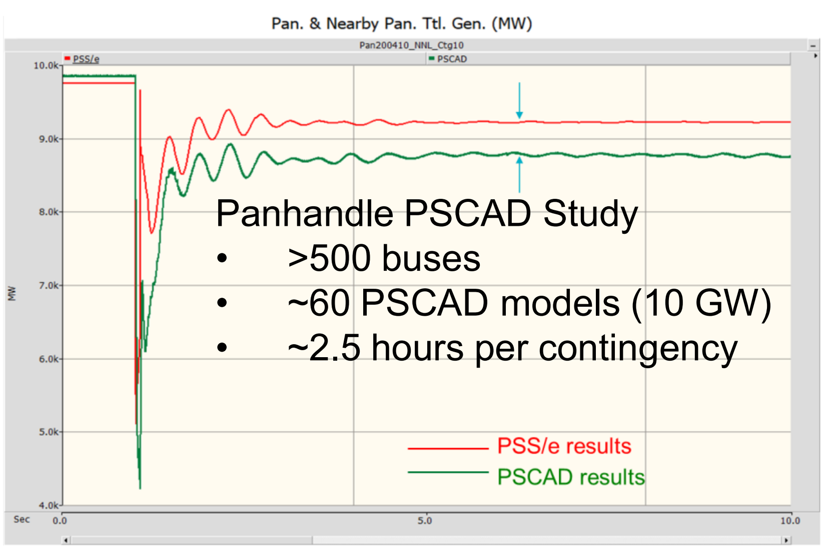


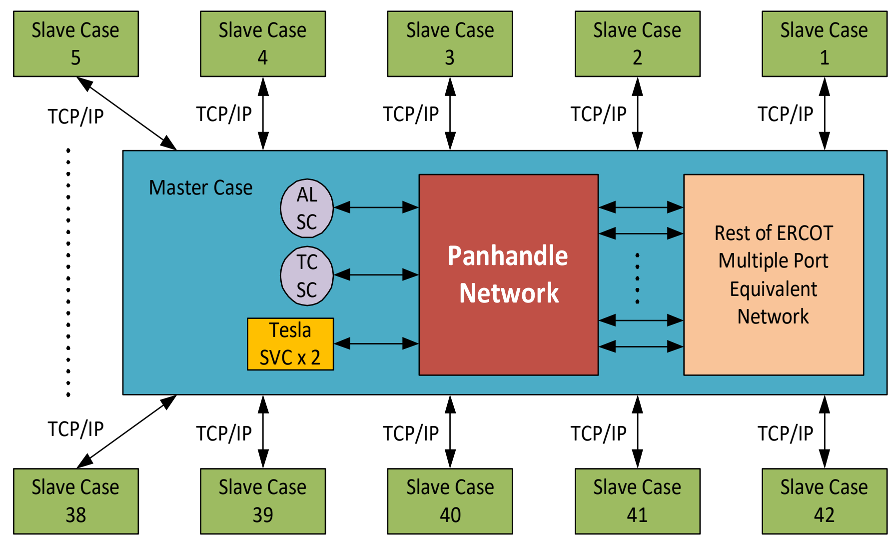
* WSCR (weighted short circuit ratio) is used to identify the system strength of an area with multiple IBRs. Detailed PSCAD studies are required to validate the adequacy of WSCR application and its threshold for weak grid identification.

EMT (PSCAD) Study

- Require regular PSCAD studies
  - To assess the instability that may not be identified in PSS/E
  - To confirm the adequacy of dynamic models and simulation tools
  - To identify the adequacy and threshold of WSCR application







Dynamic Model Requirements

- IBRs are required to provide both dynamic (PSS/e and TSAT, User Defined or Generic) and EMT (PSCAD) models
- Resource Entities and Interconnection Entities are responsible for providing models and associated test results and document

Model Quality Tests (PSS/E and PSCAD)	• Flat Start, Voltage Test (small and large disturbance), Frequency Test (e.g., +/-0.3 Hz), **System Strength Tests** • Phase-angle Jump (PSCAD only)
Unit Model Validation (PSCAD)	• Voltage Test (small and large disturbance), System Strength, Phase-angle Jump, and Subsynchronous Test
Model Verification	• Provide evidence that tunable model parameters match what is implemented in the field. For example: screenshots, nameplate photographs, signed manufacturer commissioning reports, etc.

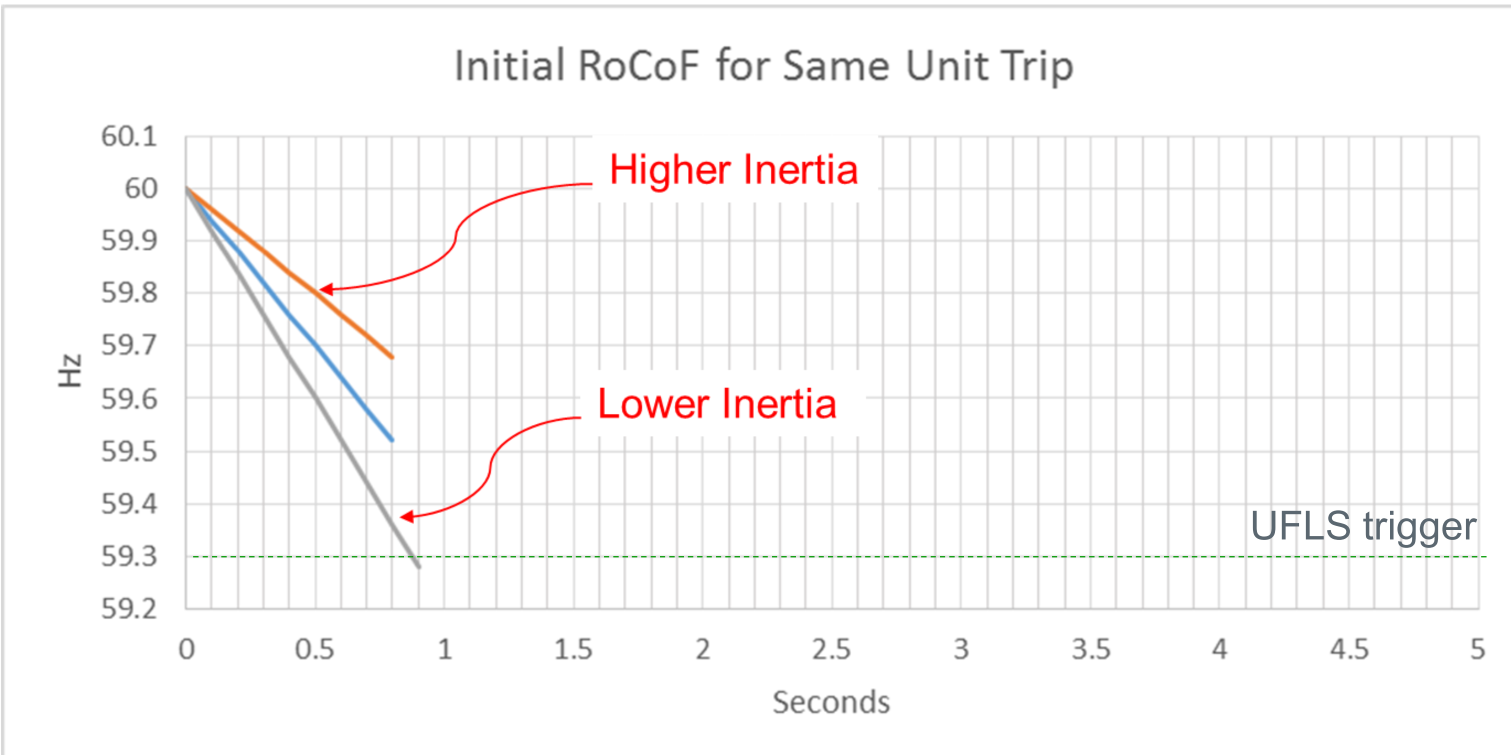
Summary: Weak Grid and Stability

- IBRs are being developed in areas far away from load centers and synchronous generators
- Increasing number of stability constraints
- Simple metrics such as WSCR are not applicable in weak grid areas with load and synchronous generation
- Synchronous Condensers while helping with grid strength may introduce other stability issues
- Limitation of available dynamic tools/models under weak grid conditions
- Large scale EMT studies are time consuming
- Modelling, model validation and keeping models up to date is an ongoing issue
- Need of Voltage/Reactive optimization and dispatch closer to real time. Absence of such tool may lead to optimistic study assumptions compared to real time conditions.

Inertia and Frequency

Effect of Synchronous Inertia on System Frequency

- With increasing integration of inverter-based generation, there could be periods when total inertia of the system could be low since less synchronous machines will be online.



RoCoF – Rate of Change of Frequency, Hz/s

Inertia Calculation

- In 2016, ERCOT implemented a real-time inertia calculation using inertia parameters of each individual synchronous generator and its status (on/off) telemetry (updated every 4 seconds).

$$M_{sys} = \sum_{i \in I} H_i \cdot MVA_i$$

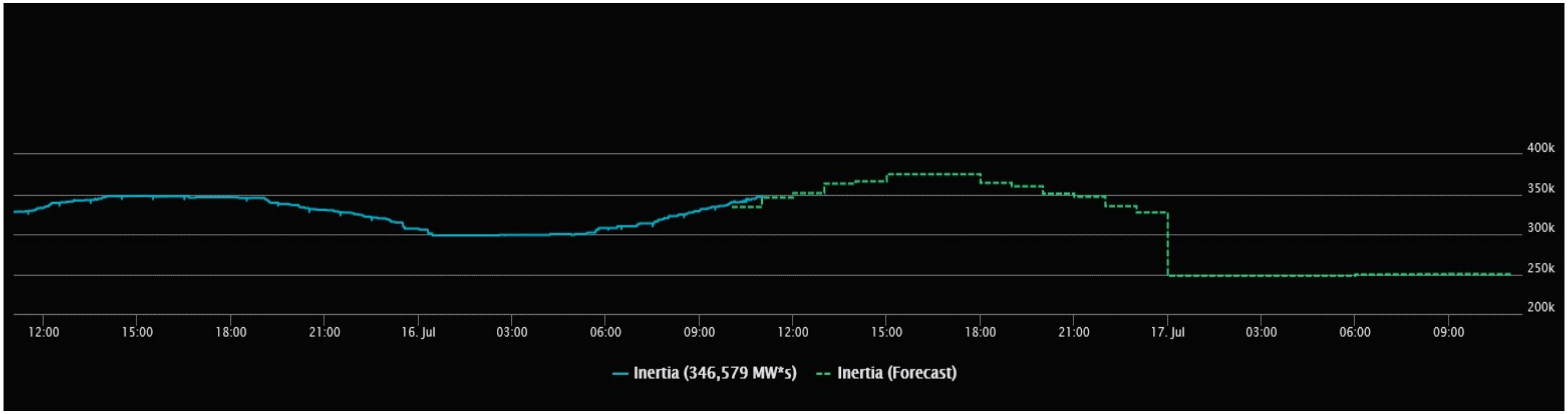
where I is the set of online synchronous generators or condensers,

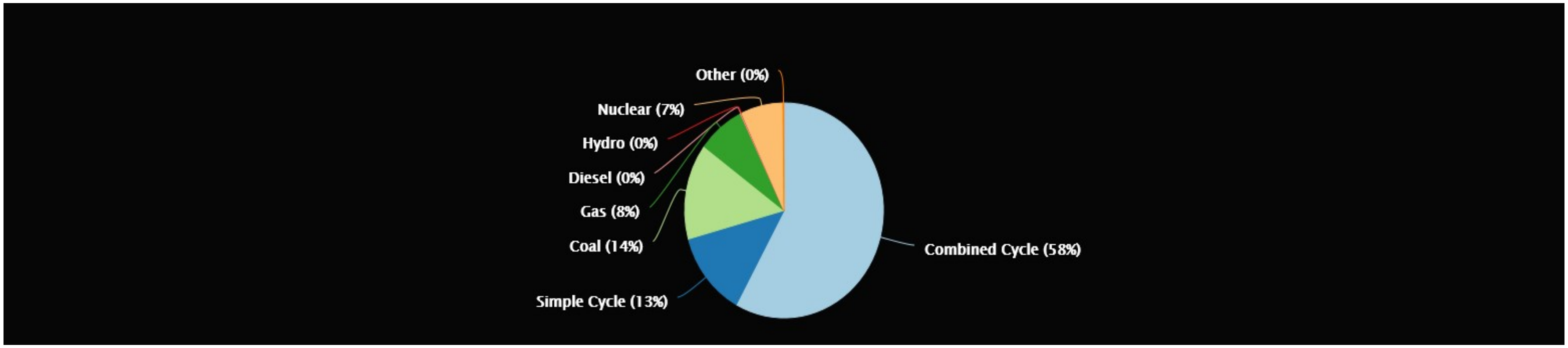
MVA_i is MVA base of on-line synchronous generator or synchronous condenser i, and

H_i is inertia constant for on-line generator or synchronous condenser i in a system (in seconds on machine MVA_i)

- Motor load also provides inertial contribution but we cannot track it

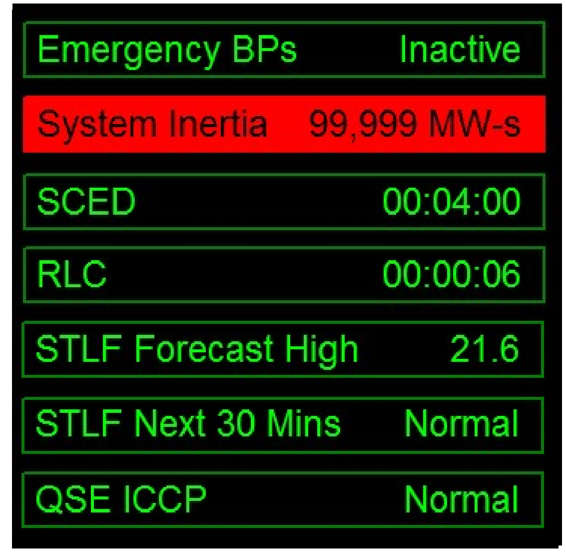
Inertia Monitoring in Real-Time and Forecasting





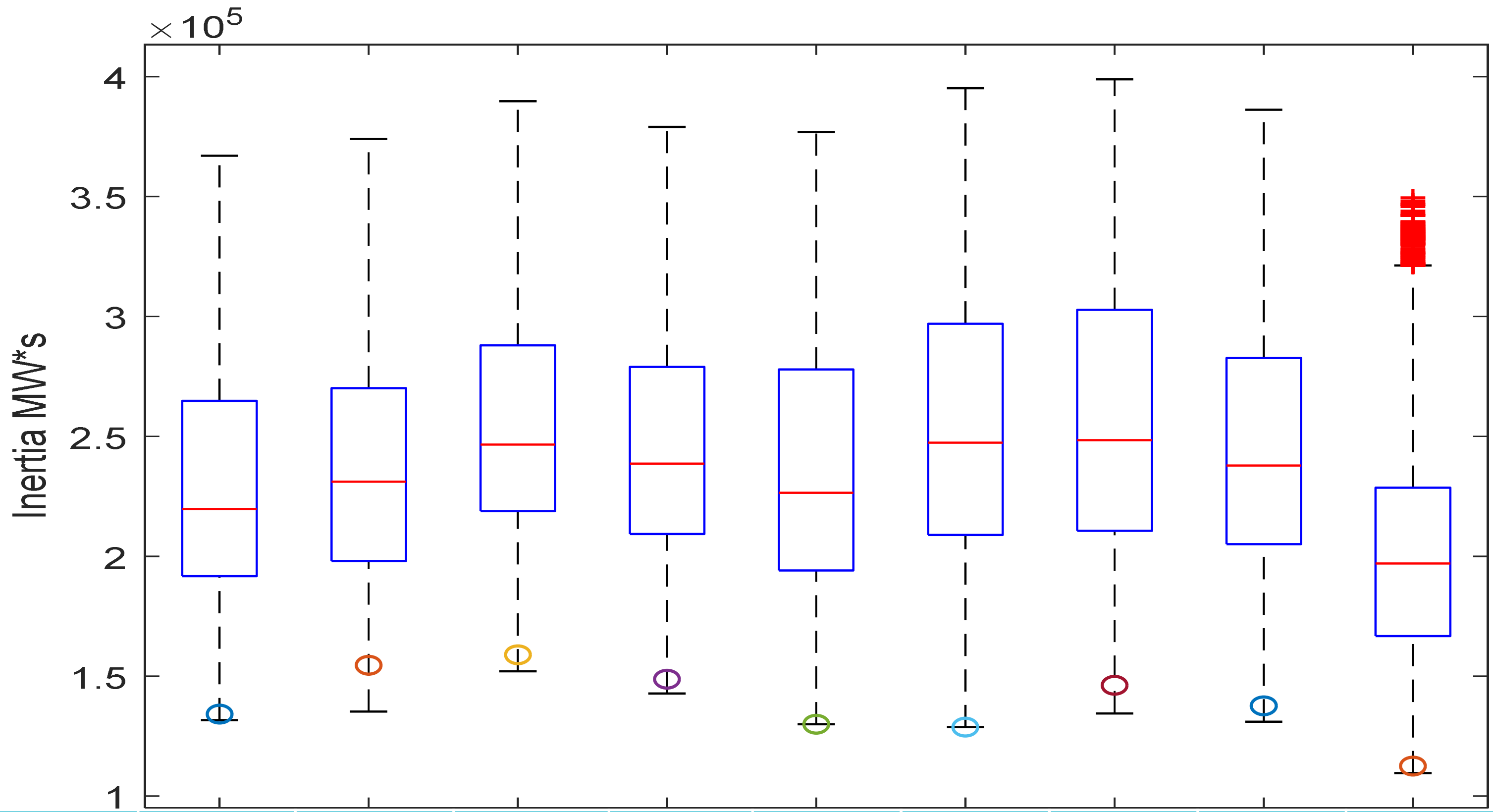
Maintaining Critical Inertia

- Critical Inertia is the minimum level of system inertia at or below which a system cannot be operated reliably <u>with existing frequency control practices.</u>
- **Criteria:** Simultaneous trip of two largest generating units (2,805 MW) should not cause involuntary under frequency load shedding (UFLS).
- Based on existing frequency control mechanisms, Critical Inertia for ERCOT is around 100 GWs.
- Visual alarms are raised when inertia gets close to critical.



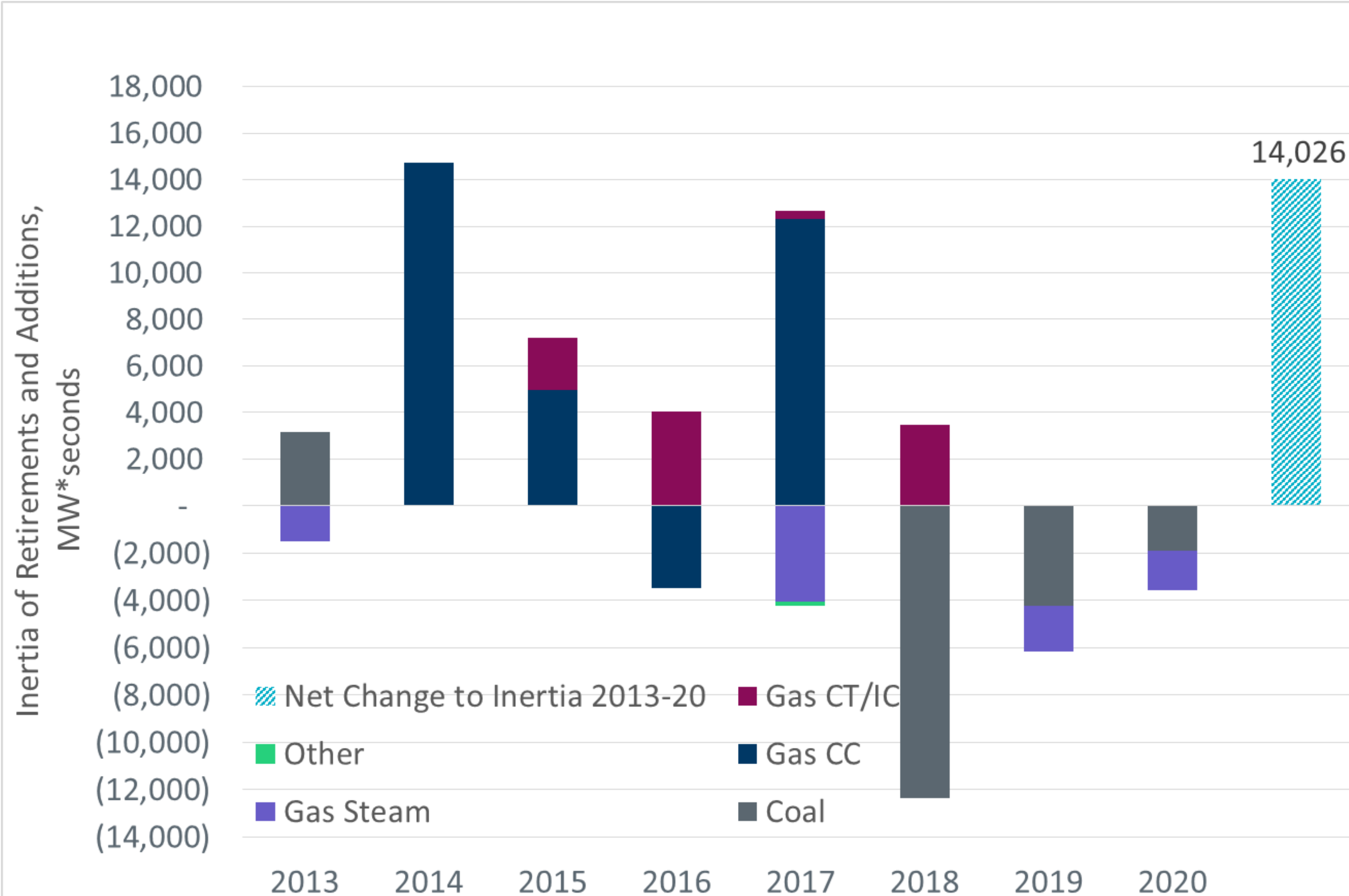
- 120 GWs >= Inertia Normal
- 120 GWs > Inertia >= 110 GWs Yellow
- 110 GWs > Inertia >= 100 GWs Orange
- 100 GWs < Inertia Red

ERCOT Inertia 2013-2020



Date and Time	2013 3/10 3:00 AM	2014 3/30 3:00 AM	2015 11/25 2:00 AM	2016 4/10 2:00 AM	2017 10/27 4:00 AM	2018 11/03 3:30 AM	2019 3/27 1:00 AM	2020 05/01 2:00 AM	2021 03/22 00:00 AM
Min synch. Inertia (GW*s)	132	135	152	143	130	128.8	134.5	131.1	109
System load at minimum synch. Inertia (MW)	24,726	24,540	27,190	27,831	28,425	28,397	29,883	30,679	32,599
Non-synch. Gen. in % of System Load	31	34	42	47	54	53	50	57	65

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's Ancillary Services, At Glance

New Framework, NPRR 863

Regulation Up
157 to 687 MW

Regulation Up
157 to 687 MW

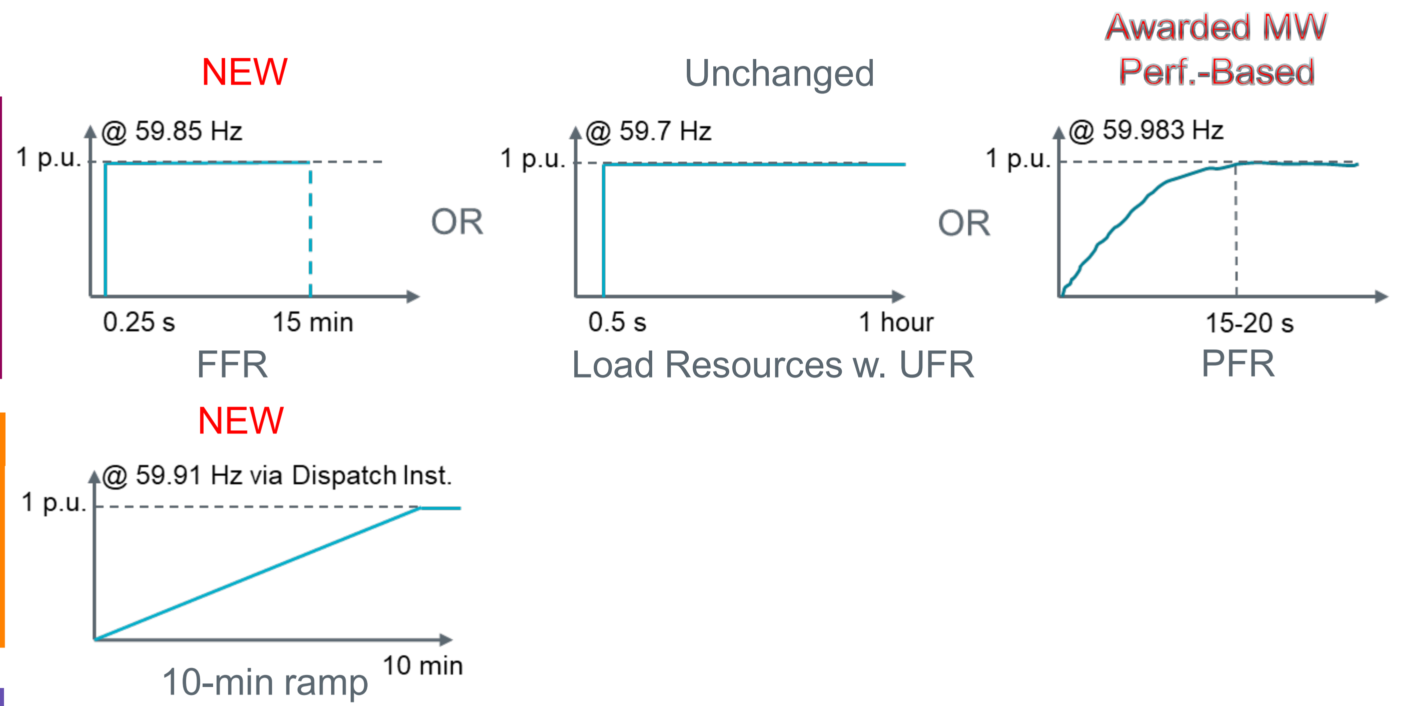
Responsive Reserve Service (RRS)
- Fast Frequency Response (FFR)
- Load Resources on UFR
- Primary Frequency Response (PFR)

2,300 to 3,200 MW

ERCOT Contingency Reserve Service (ECRS)
- 10 minute ramp
- Load Resources may or may not be on UFR

508 to 1,644 MW

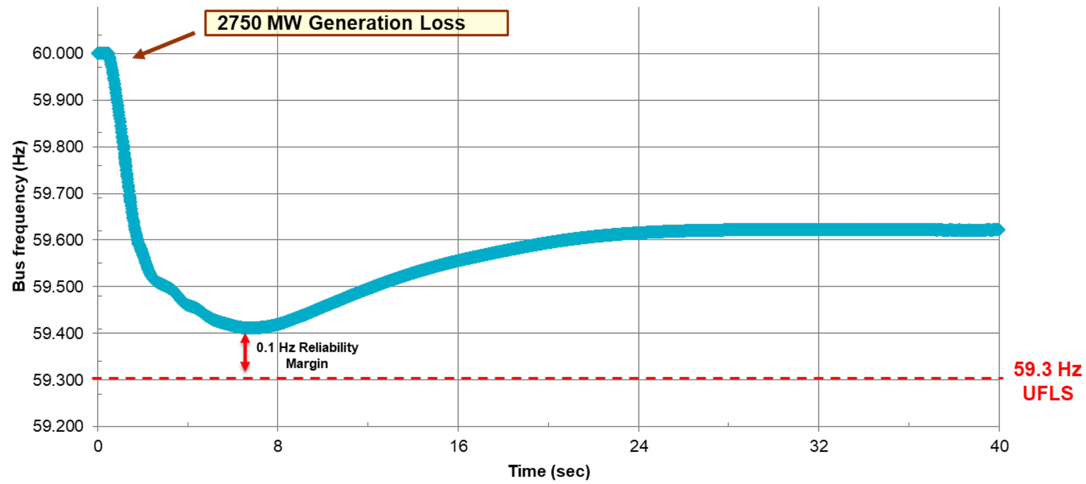
Non-Spin
0 to 1,180 MW



Overall A/S: 3,807 to 5,958 MW*

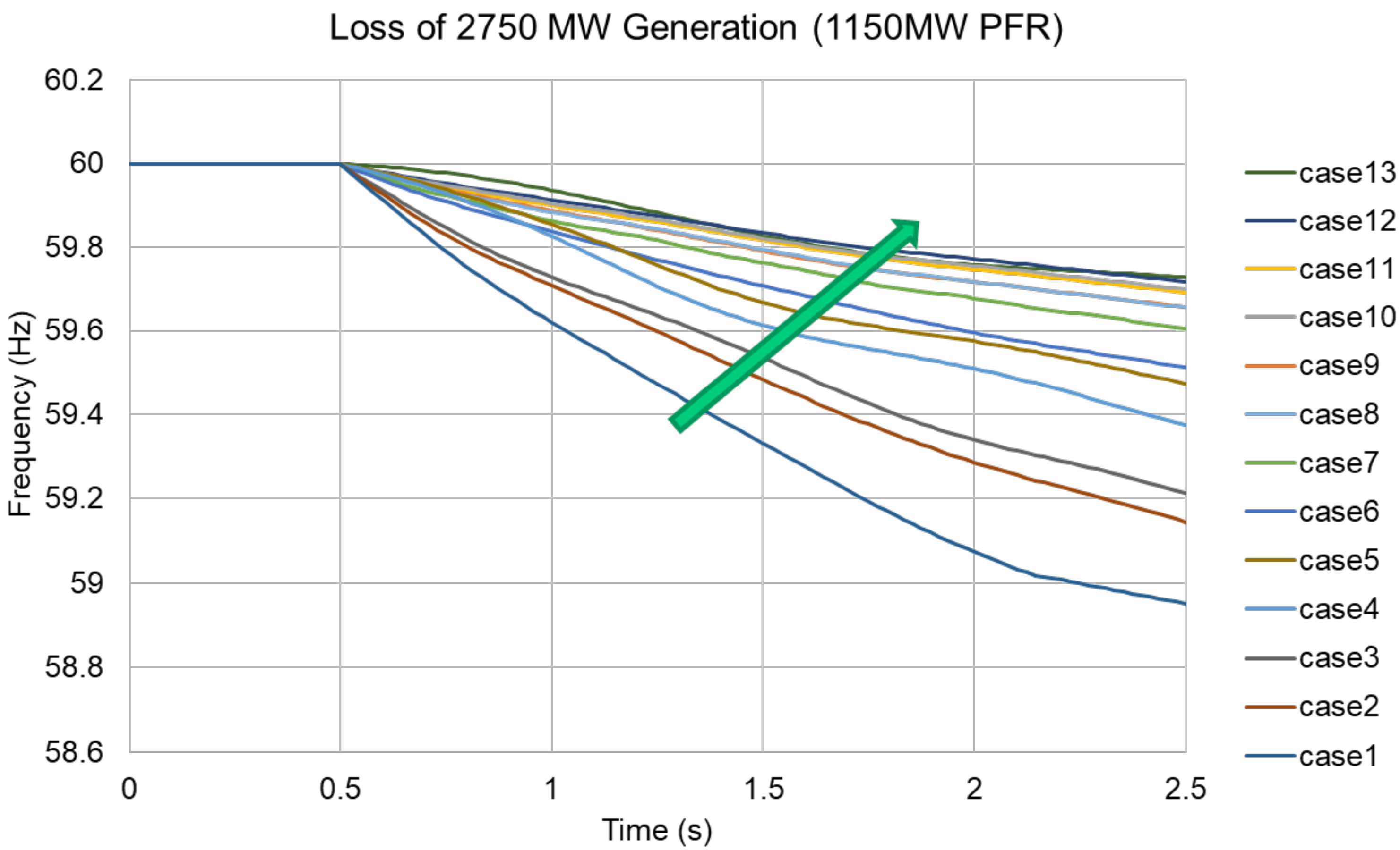
FFR implemented on 3/1/2020 and ECRS will be implemented in 01/2022

Quantifying Frequency Containment Reserve



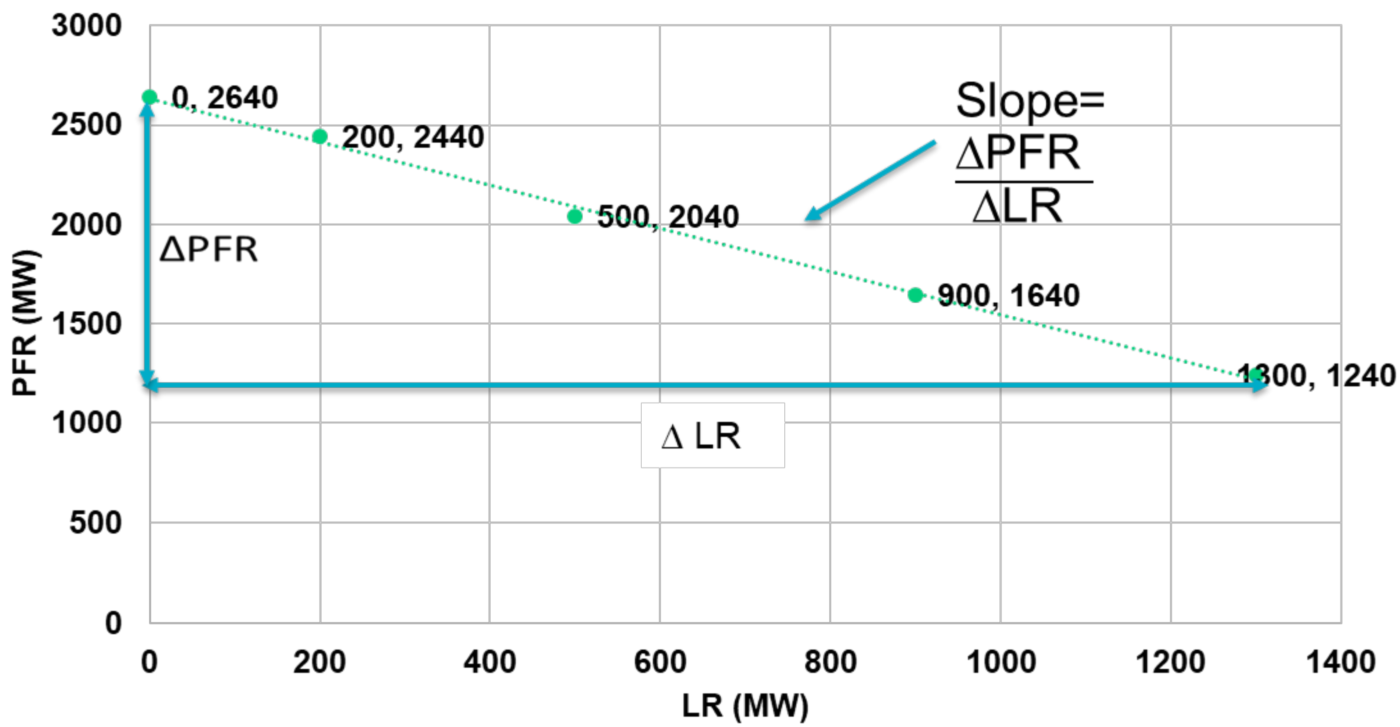
- After a generator trip, to arrest system frequency above involuntary underfrequency load shedding trigger (UFLS), frequency containment reserves are used
- In ERCOT Responsive Reserve Service (RRS) is procured to provide frequency containment
- RRS can be provided by generators through governor response (also called PFR) or
- Load Resources with underfrequency relays, through 0.5 second step response at 59.7 Hz
- ERCOT used to procure 2800 MW of frequency containment reserve for all hours
- Studies shown that during lower inertia times, due to higher RoCoF after generation trip this amount is not sufficient

Impact of Inertia on System Frequency



	Inertia (GW.s)
case13	376
case12	358.5
case11	340
case10	324
case9	307
case8	290
case7	260
case6	224.3
case5	190
case4	184.3
case3	153.6
case2	140
case1	108

Equivalency Ratio between PFR and Load Resources

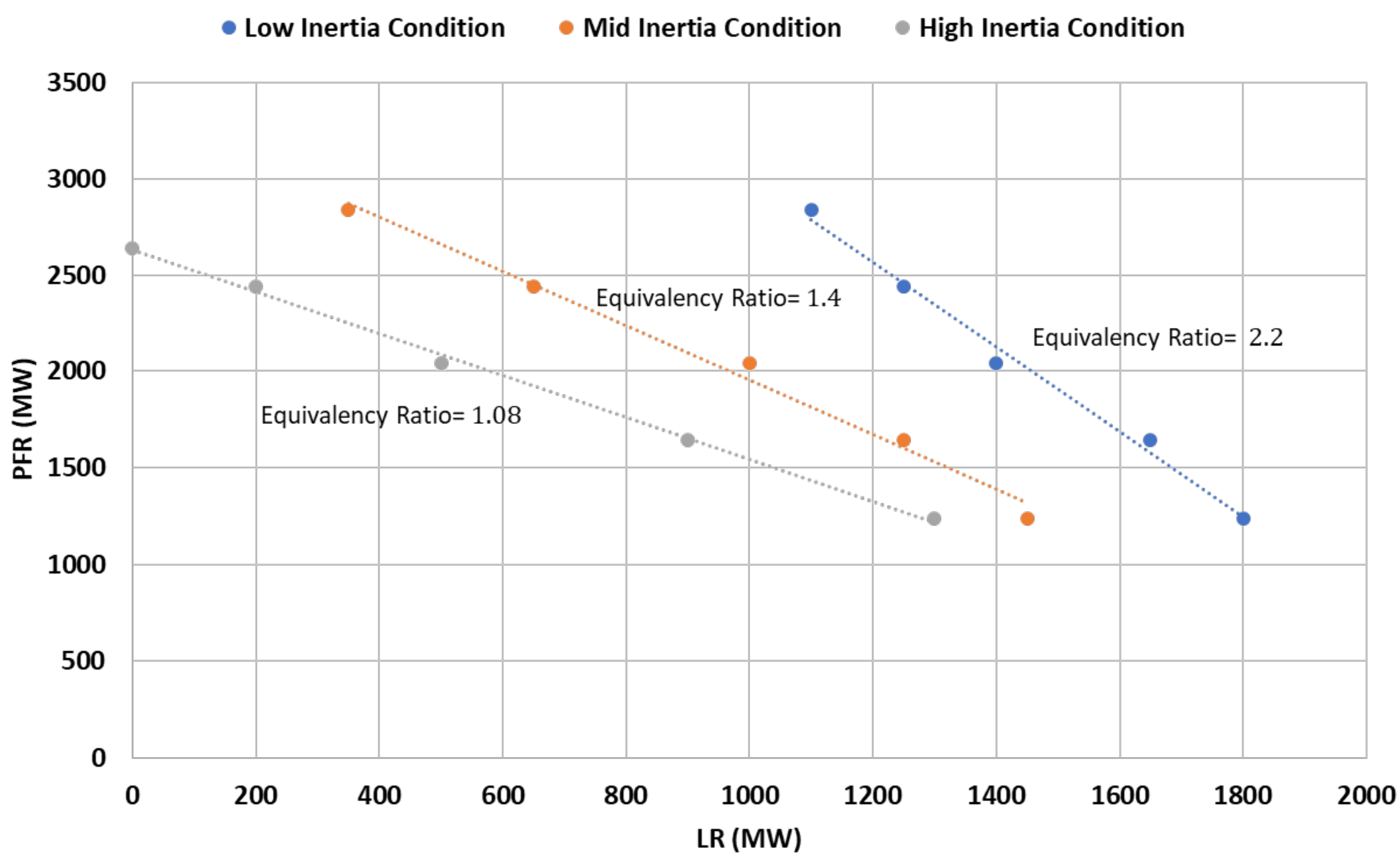


PFR/LR Equivalency Ratio= - Slope= $-\frac{\Delta PFR}{\Delta LR}$

Interpretation: To replace 1MW of LR, $-\frac{\Delta PFR}{\Delta LR}$ MW of PFR is needed

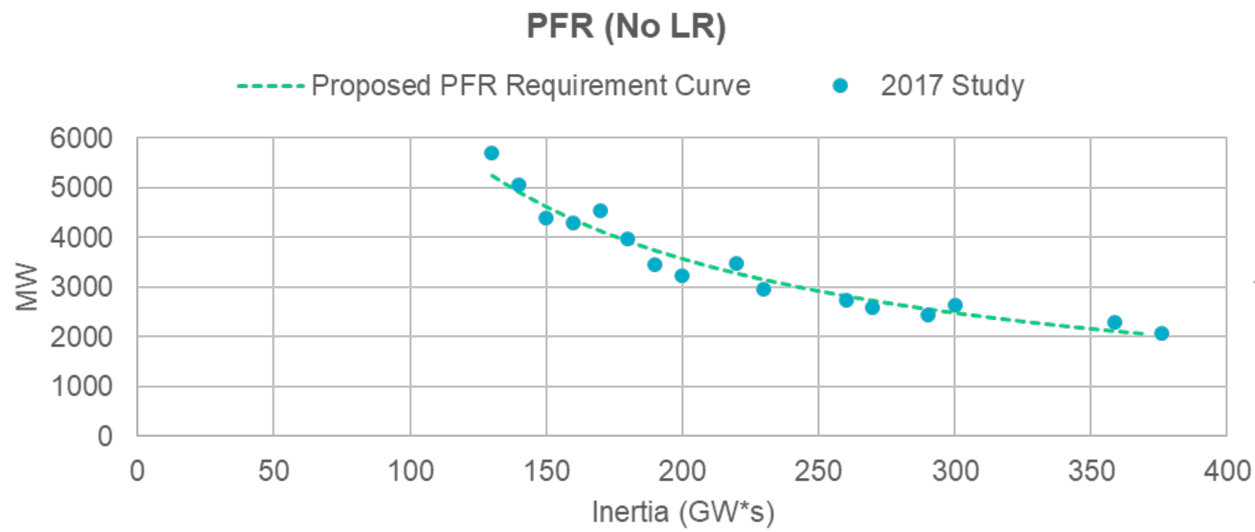
(1MW FFR = $-\frac{\Delta PFR}{\Delta LR}$ MW PFR)

Equivalency Ratio at Different Inertia Conditions

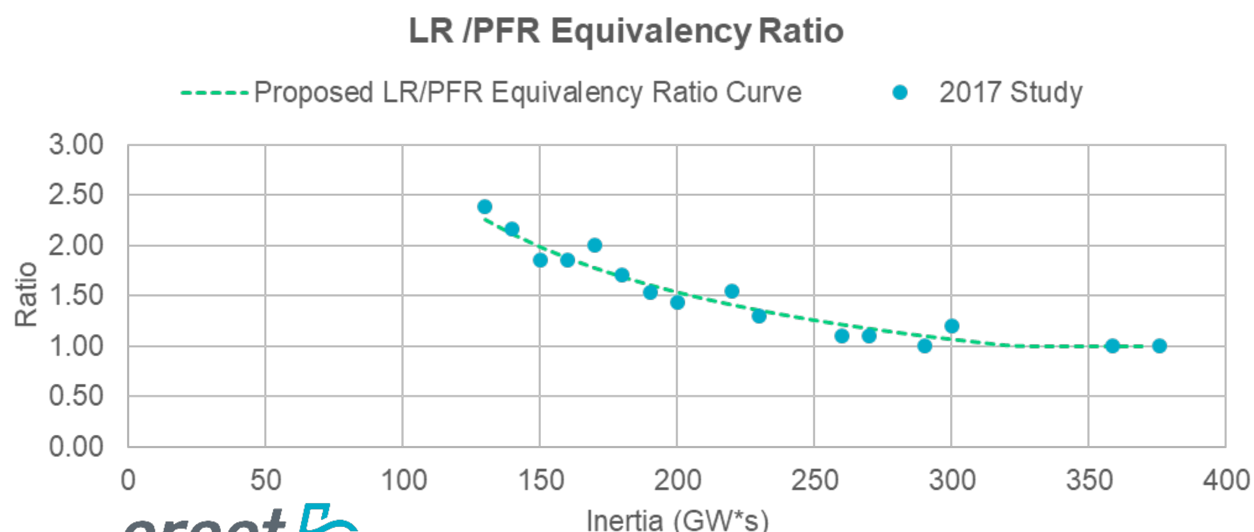


Source: Weifeng Li, ERCOT

RRS Requirements



$$PFR(No\ LR) = 399275 \times Inertia^{-0.890}$$

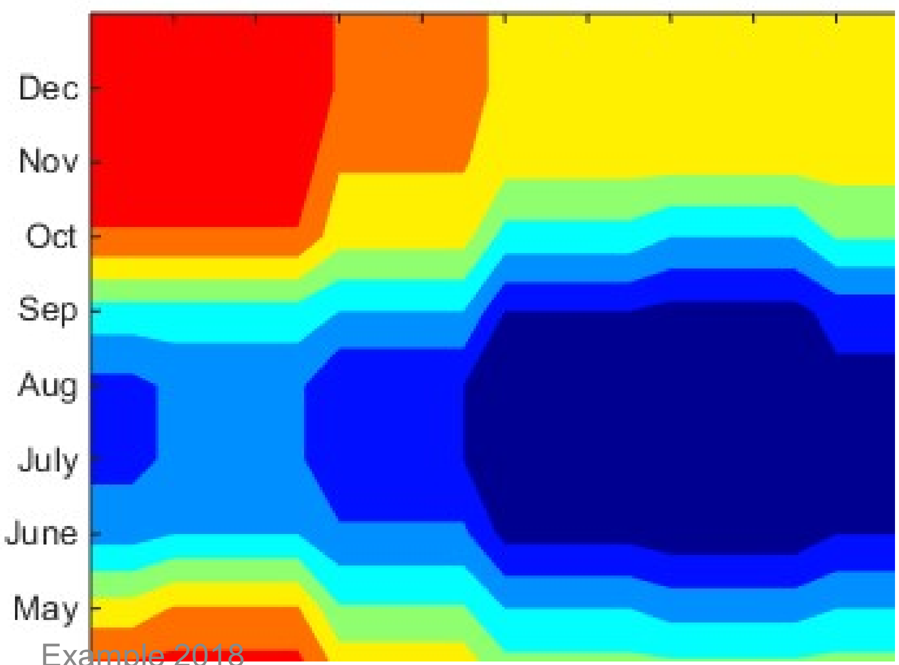


$$LR/PFR = 173.28 \times Inertia^{-0.892}$$

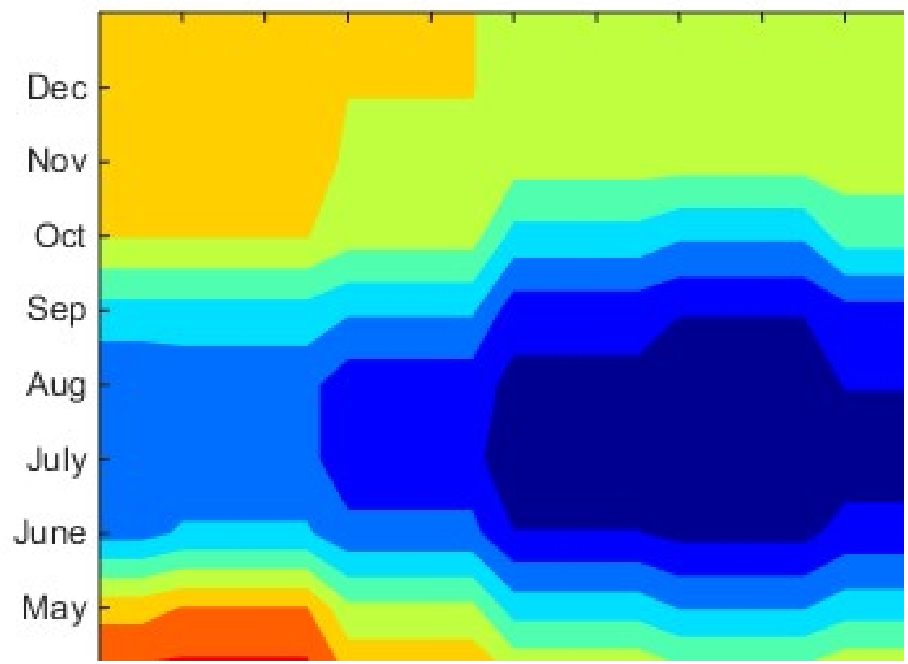
RRS Monthly Requirements

- RRS requirements are determined before the operating year, for the whole year.
- ERCOT determines actual RRS needs based on expected inertia conditions in the day ahead and closer to real time, and monitors RRS sufficiency.
- If RRS is insufficient, ERCOT can rely on other available frequency-responsive capacity or procure additional RRS.

Equivalency Ratio

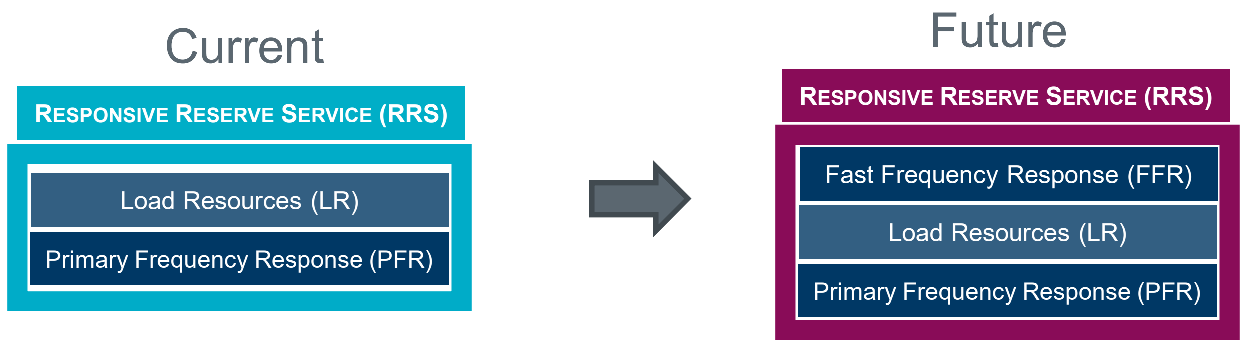


Total RRS Requirement



Example 2018

Fast Frequency Response (FFR)



Load Resource (LR):

- Delivered within 30 cycles (0.5 seconds)
- Triggered at 59.7 Hz by under frequency relay
- Sustain until recalled. Once recalled, restore within 3 hours

Fast Frequency Response (FFR):

- Delivered within 15 cycles (0.25 seconds)
- Triggered at 59.85Hz
- Sustain for up to 15 mins. Once recalled, restore within 15 mins

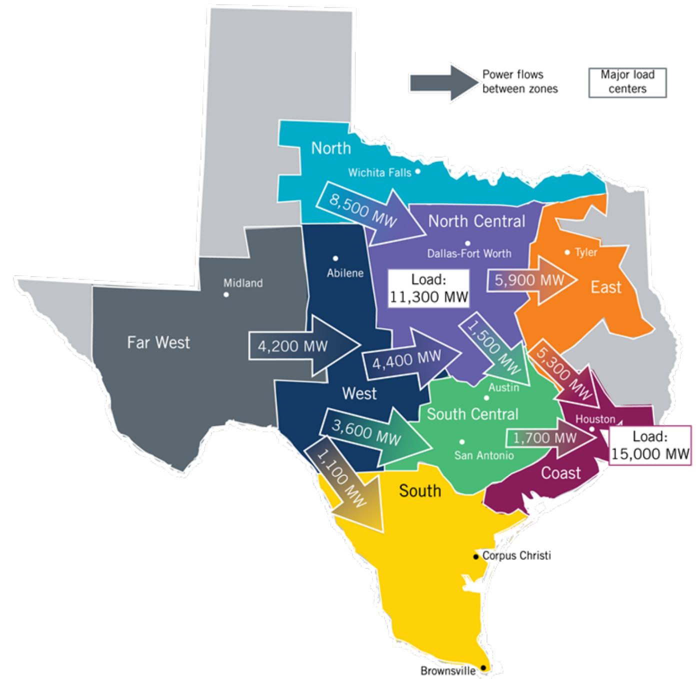
Summary: Inertia and Frequency Containment

- 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

Few other things to mention...

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 issue
- 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 (?)
- Synchronous condensers are subject to synchronous machine instabilities (inter & intra area oscillations & angular instability)

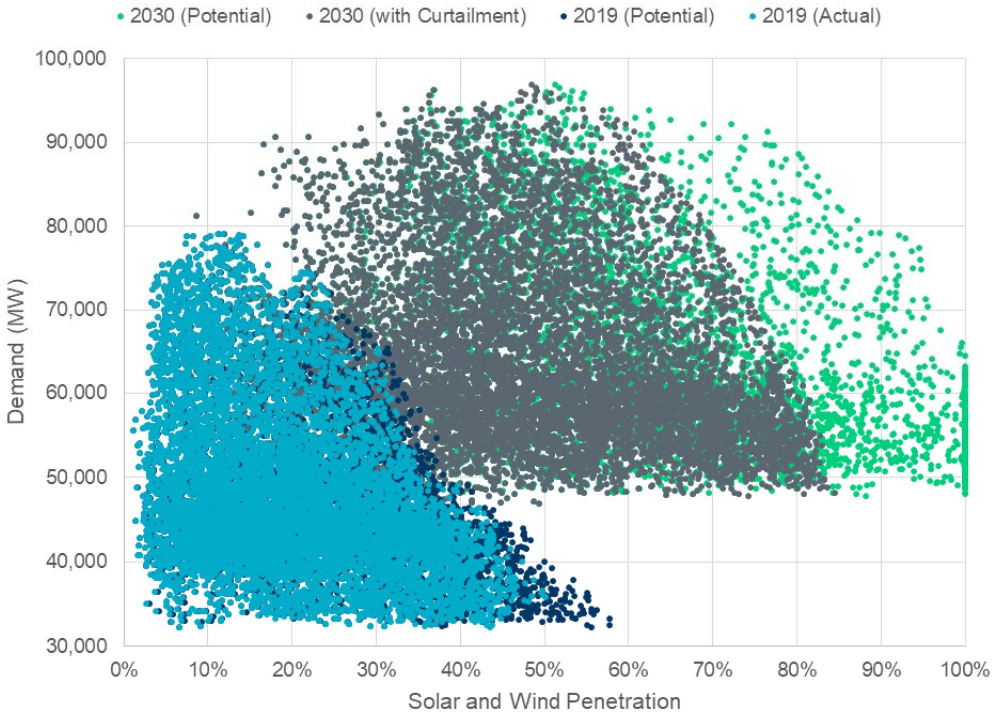


Load:	42.2 GW (includes PUNs)
Solar output:	17 GW (90% dispatch)
Wind output:	11 GW (48% dispatch)
West Texas Exports:	15.5 GW (major 345 kV circuits)
Losses (MW):	6%

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

2020 Long Term System Assessment

LTSA Modeled Solar and Wind Penetration for Every Hour of 2030 Compared to 2019 Historic



Renewable penetration is defined as the percentage of total demand at any given time that is being served by solar and wind generation. The "potential" penetration is based on the available wind and solar irradiance while the "actual" and "with curtailment" values include transmission constraints and other reliability limitations.

- Historically, the most stressed system conditions – from both resource scarcity and transmission security standpoints – have been during summer afternoons. In all five scenarios studied, stressed system conditions were observed at other times of the day and on days throughout the year due to the changed resource mix.

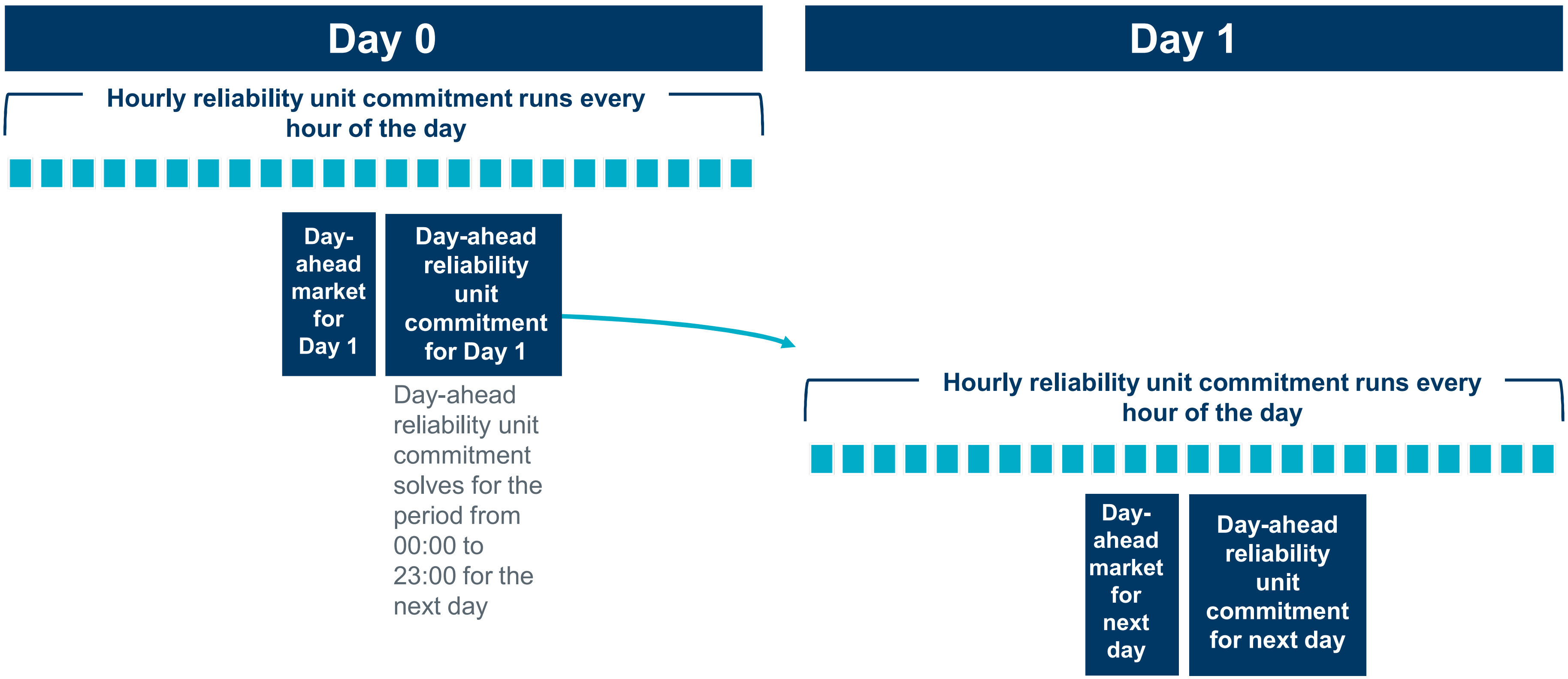
Circular problem

References

- Use of Generic Transmission Constraints in ERCOT, 2020
  http://www.ercot.com/content/wcm/lists/197392/The_Use_of_GTCs_in_ERCOT_July_2020.pdf
- Report on Existing and Potential Constraints and Needs, 2020
  http://www.ercot.com/content/wcm/key_documents_lists/89026/2020_Report_on_Existing_and_Potential_Electric_System_Constraints_and_Needs.pdf
- Panhandle studies:
  - http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf , 2014
  - http://www.ercot.org/content/news/presentations/2016/Panhandle%20System%20Strength%20Study%20Feb%2023%202016%20(Public).pdf , 2016
  - http://www.ercot.com/content/wcm/lists/144927/Panhandle_and_South_Texas_Stability_and_System_Strength_Assessment_March....pdf, 2018
  - http://www.ercot.com/content/wcm/lists/197392/2019_PanhandleStudy_public_V1_final.pdf, 2019,
  - http://www.ercot.com/content/wcm/lists/197392/2020_PanhandleStudy_public_final__004_.pdf, 2020
- Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid, 2018
  http://www.ercot.com/content/wcm/lists/144927/Dynamic_Stability_Assessment_of_High_Penetration_of_Renewable_Generation_in_the_ERCOT_Grid.pdf
- West Texas Stability Assessment, 2020
  http://www.ercot.com/content/wcm/lists/197392/2020_West_Texas_Export_report_final.pdf

Appendix

Market Processes



Operational Studies and Situational Awareness Tools