A photograph of a multi-lane highway covered in snow. Several cars are driving on the road. In the background, there are various signs, including a speed limit sign for 65, a sign for Rayford Rd and Sawdust Rd, and several commercial signs for businesses like 'WOW! SELECTION NO WAY! PRICES', 'Cody', and 'Voss Law Center'. A large black sign with a diamond symbol and the text 'HOV 2+ ONLY 2 OR MORE PERSONS PER VEHICLE' is visible on the right side of the road. The overall scene is hazy and wintry.

# Lessons from the 2021 Texas Electricity Crisis

Peter Cramton

12 May 2021

Peter Cramton is Professor of Economics at the University of Cologne and the University of Maryland (emeritus since 2018). He was vice chair and an independent director of the ERCOT board before resigning on February 24, 2021. He is grateful to his research team: Emmanuele Bobbio, David Malec, and Pat Sujarittanonta.

Many interconnected systems

Weather

People

Electricity

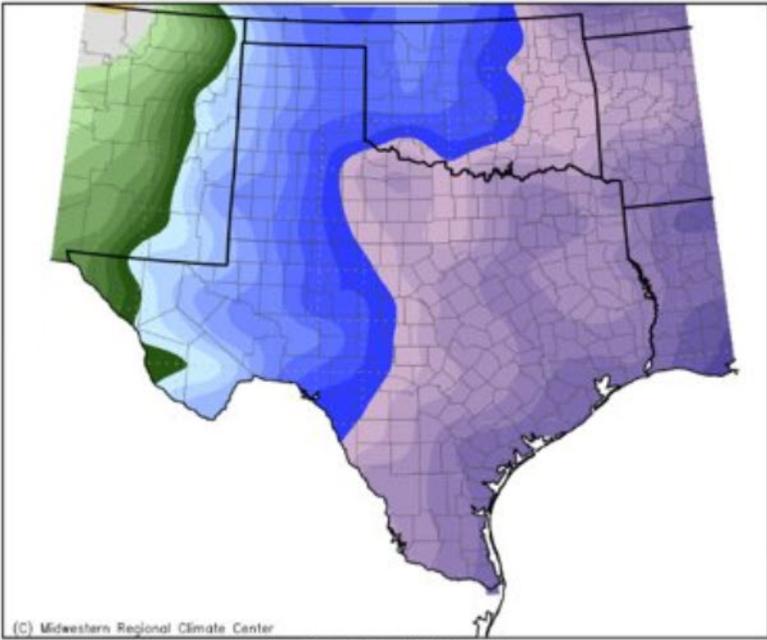
Water

Gas

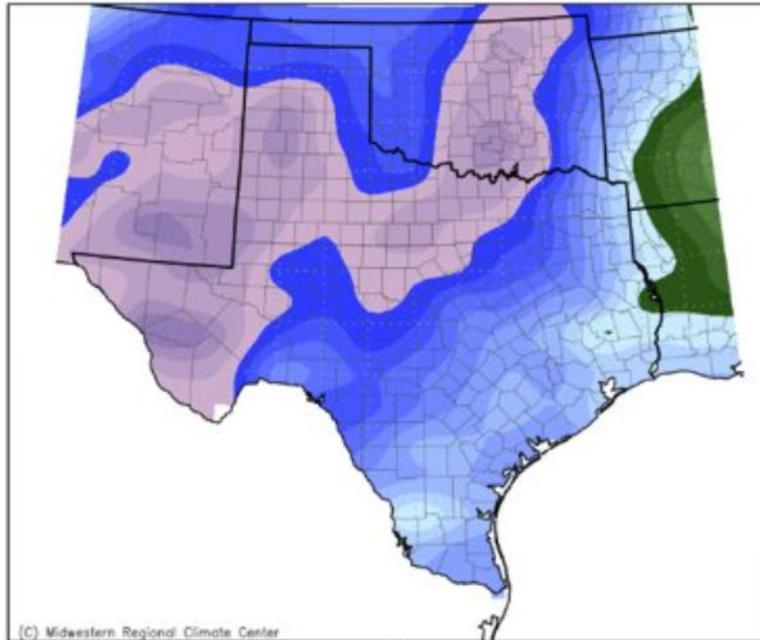
# Historical Comparison with Past Arctic Outbreaks, 7-day Temperature Anomalies

Temperature departures from normal for the 7-days centered on the coldest day for Dec. 1989, Feb. 2011, and Feb. 2021 outbreaks. Feb. 12-18, 2021 had the most significant extended period of below normal temperatures compared to these prior outbreaks. (Midwest Regional Climate Center online plotter does not go below -25F departure)

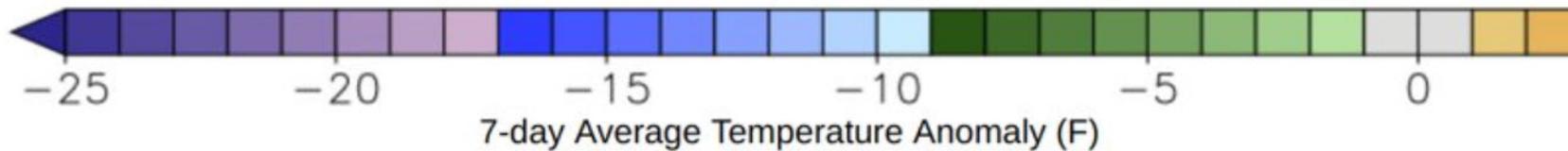
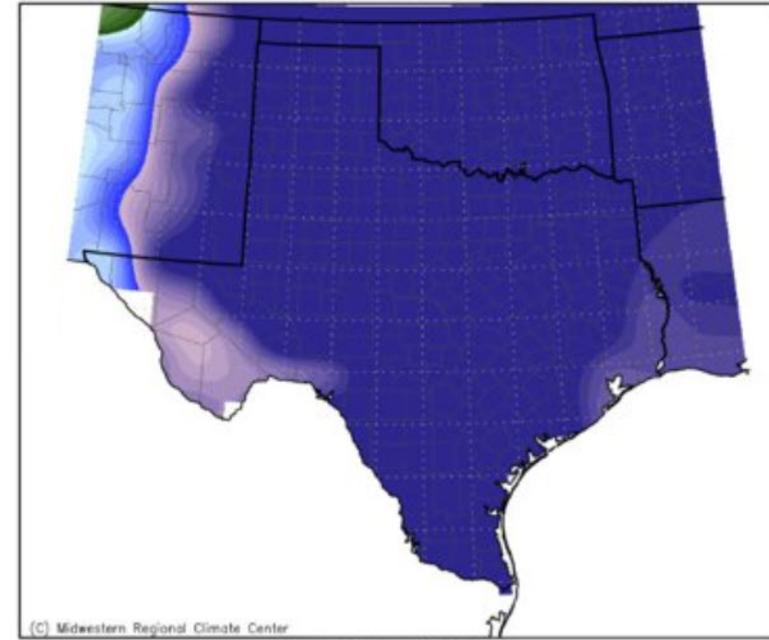
Average Temperature (°F): Departure from Mean  
December 19, 1989 to December 25, 1989



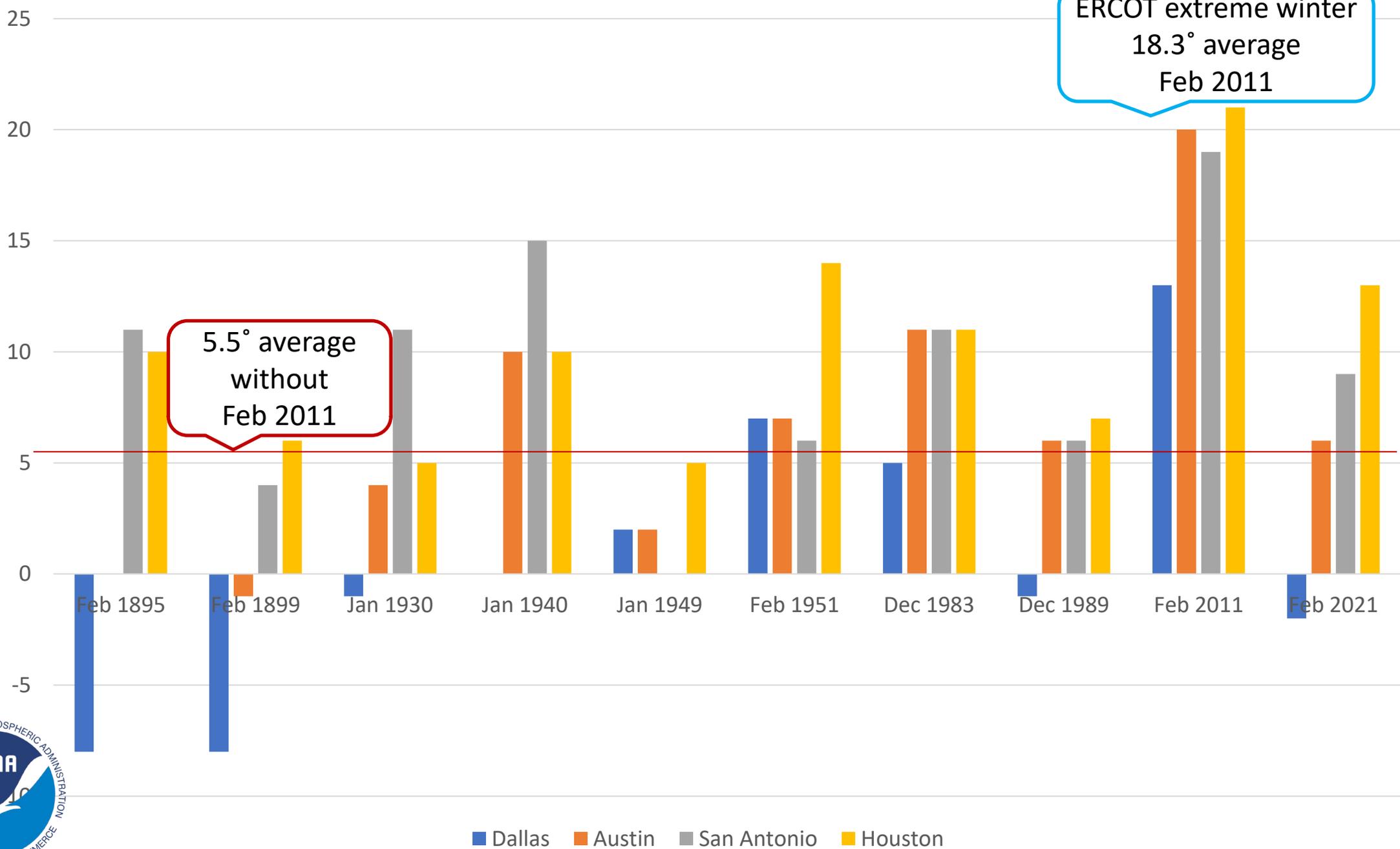
Average Temperature (°F): Departure from Mean  
January 31, 2011 to February 6, 2011



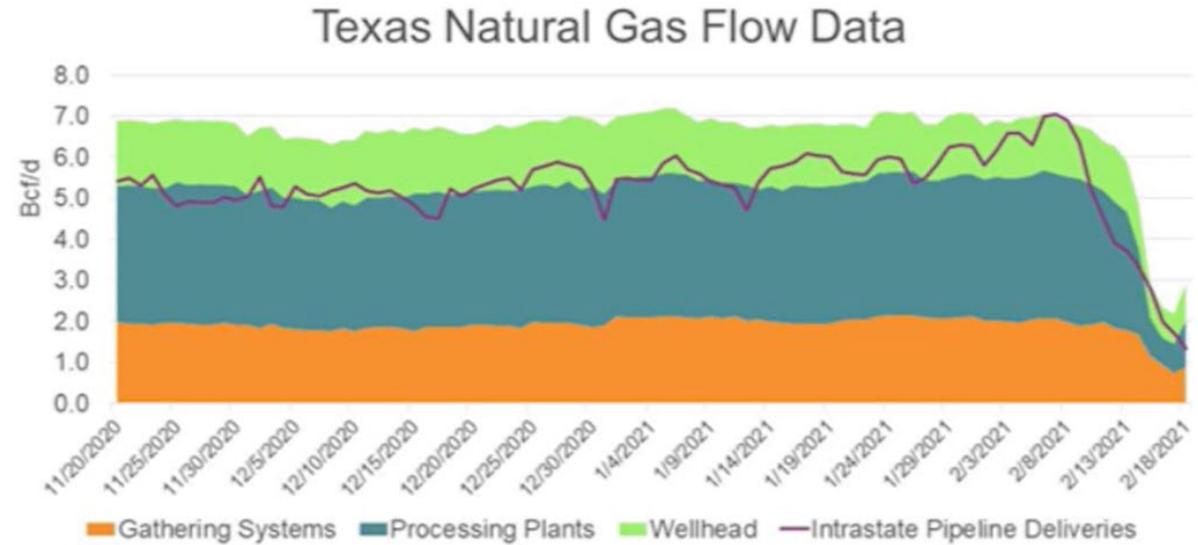
Average Temperature (°F): Departure from Mean  
February 12, 2021 to February 18, 2021



# Coldest temperatures during Texas cold snaps, Fahrenheit



Natural gas flow drops sharply on Friday, 12 Feb, *well before* electricity outages on Monday, 15 Feb



Source | Enverus

### Fri. 12 Feb. 2021

Over the week natural gas pipeline flow data shows a significant drop. Spot gas prices soars on Friday to over \$150/MMBtu at HSC (some locations topped out at \$999 for other locations according to NGI).

### Sat. 13 Feb. 2021 08:43

ERCOT Physical Responsive Capability (PRC), which is a measure of online capacity that is available to respond quickly to disturbances, falls below 3 GW for the first time during the weekend.

### Sat. 13 Feb. 2021 04:02

ERCOT notes the first major thermal generator failure at 04:02. Frequency declines to 59.238 Hz, while load was at 55,391 MW.

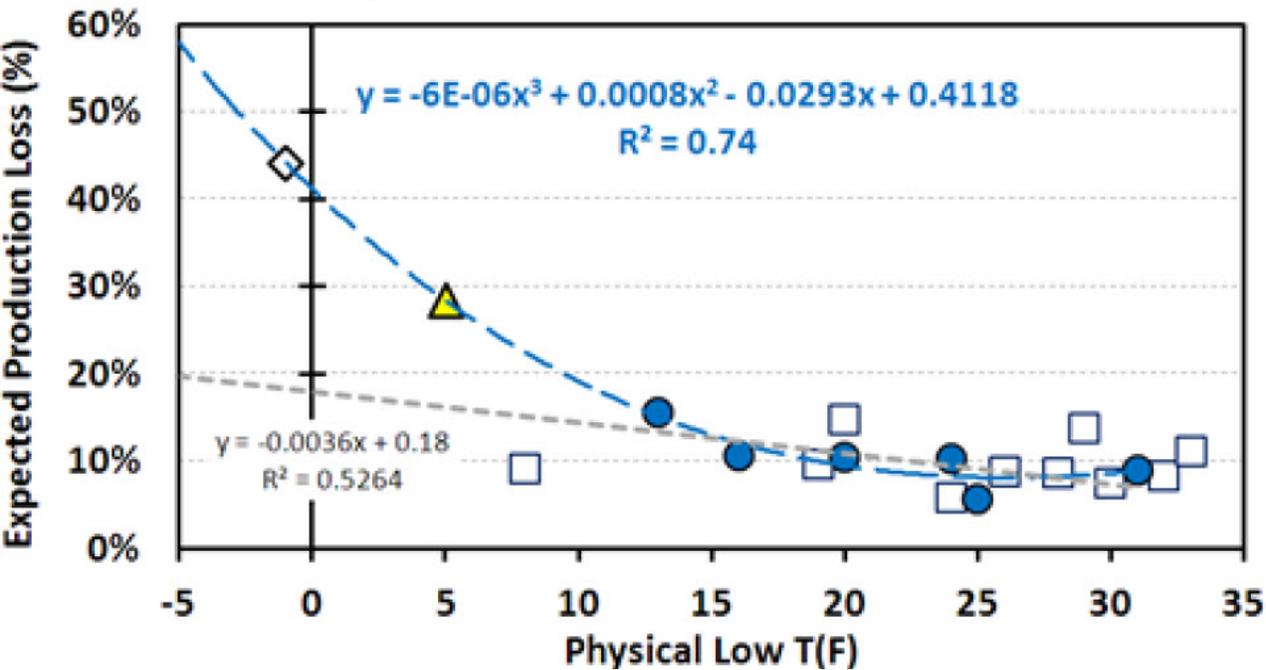
### Sun. 14 Feb. 2021

ERCOT issued a Watch for a projected reserve capacity shortage with no market solution available for HE 17:00-21:00, which causes a high risk for an EEA event.

Source: Enverus, [18 Feb 2021](#).

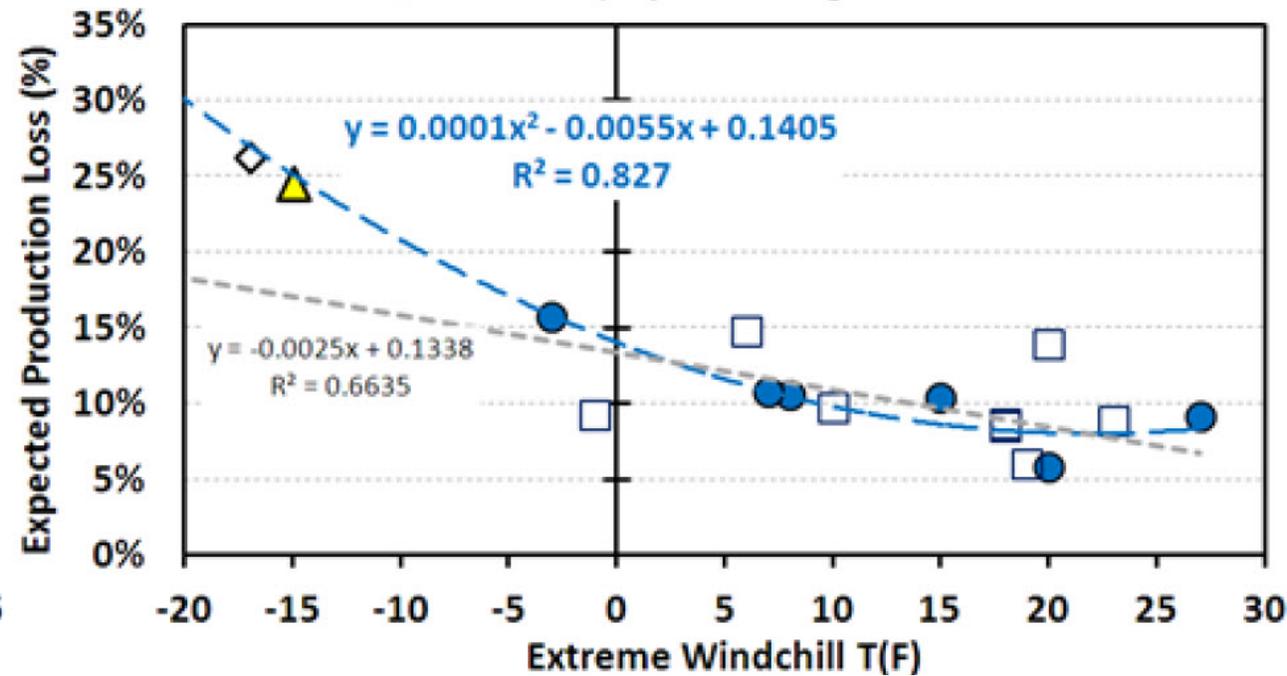
### Barnett Shale Gas Production Loss: Freezing Temperature

- Events not Captured in ERCOT Database, 1994-2009
- Events Captured in ERCOT Database (Deliverable 1), 2002-2011
- ▲ Dec 19-29, 1983 Event projected along loss curve
- ◇ Dec 11-28, 1989 Event projected along loss curve



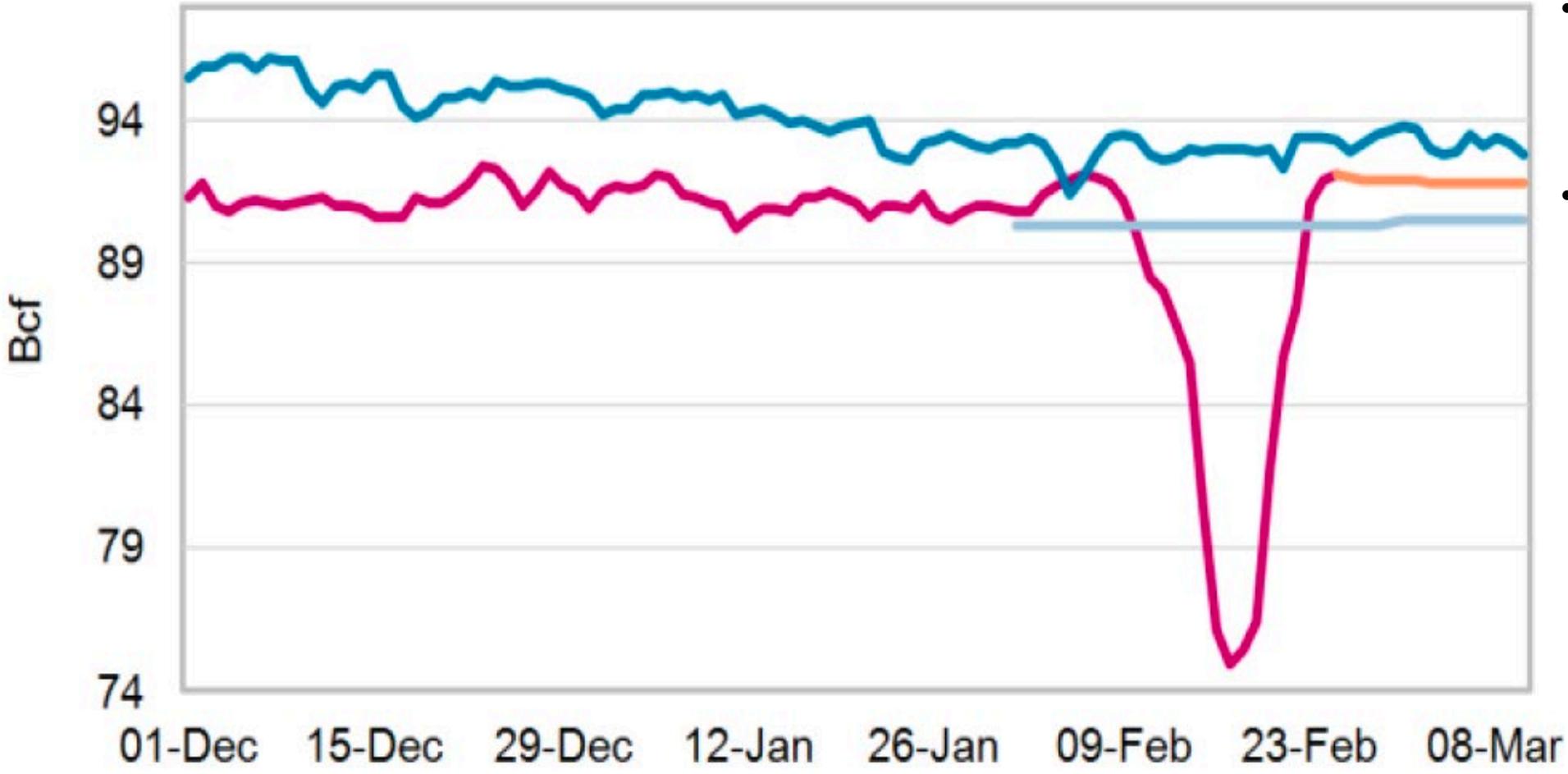
### Barnett Shale Gas Production Loss: Wind Chill

- Events not Captured in ERCOT Database, 1994-2009
- Events Captured in ERCOT Database (Deliverable 1), 2002-2011
- ▲ Dec 19-29, 1983 Event projected along loss curve
- ◇ Dec 11-28, 1989 Event projected along loss curve



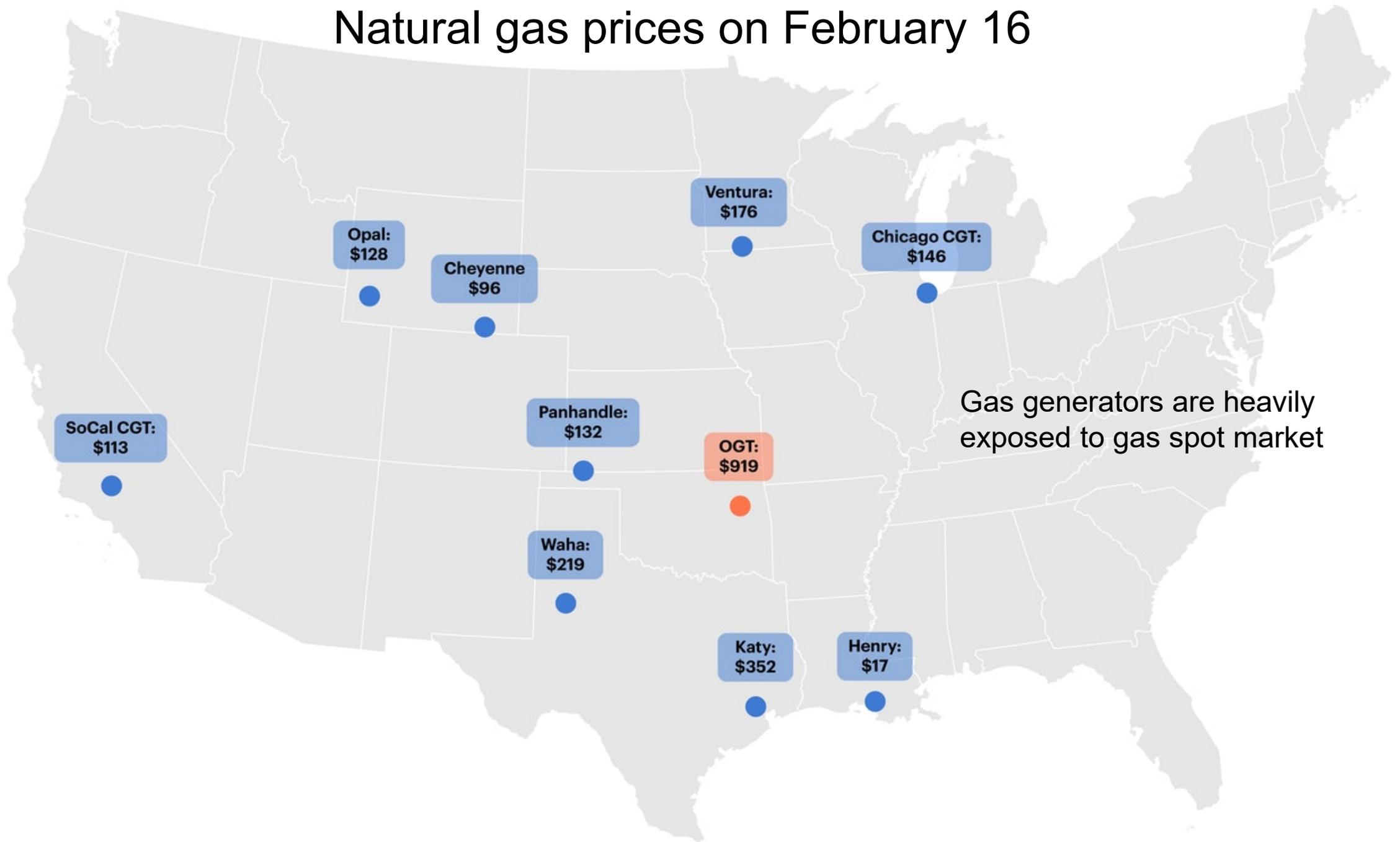
# TOTAL U.S. DRY GAS PRODUCTION

— 2021 — 2020 — 14 Day Forecast — Monthly Avg Outlook



- US natural gas production drops 21%
- TX natural gas production drops 45%

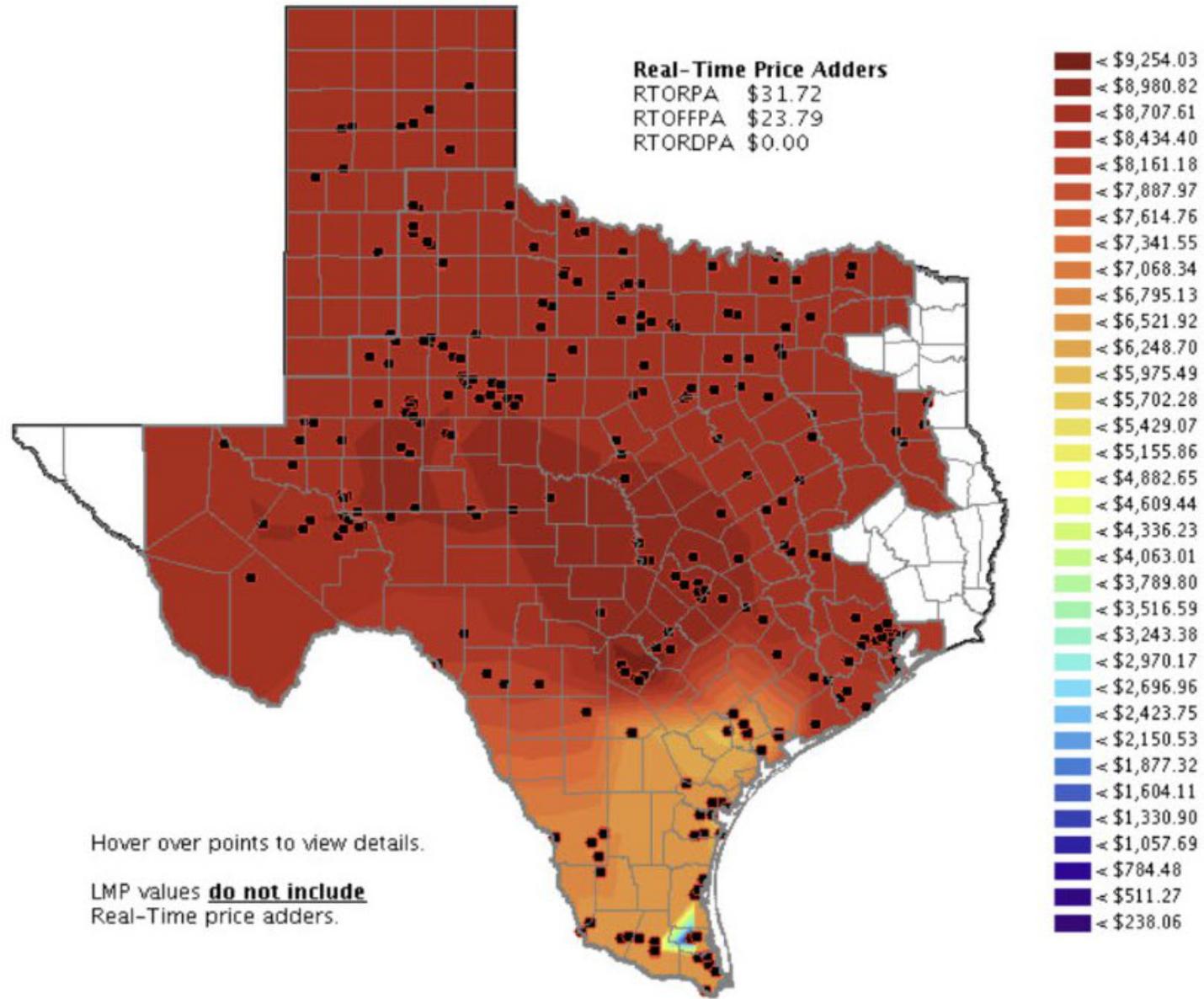
# Natural gas prices on February 16



Gas generators are heavily exposed to gas spot market

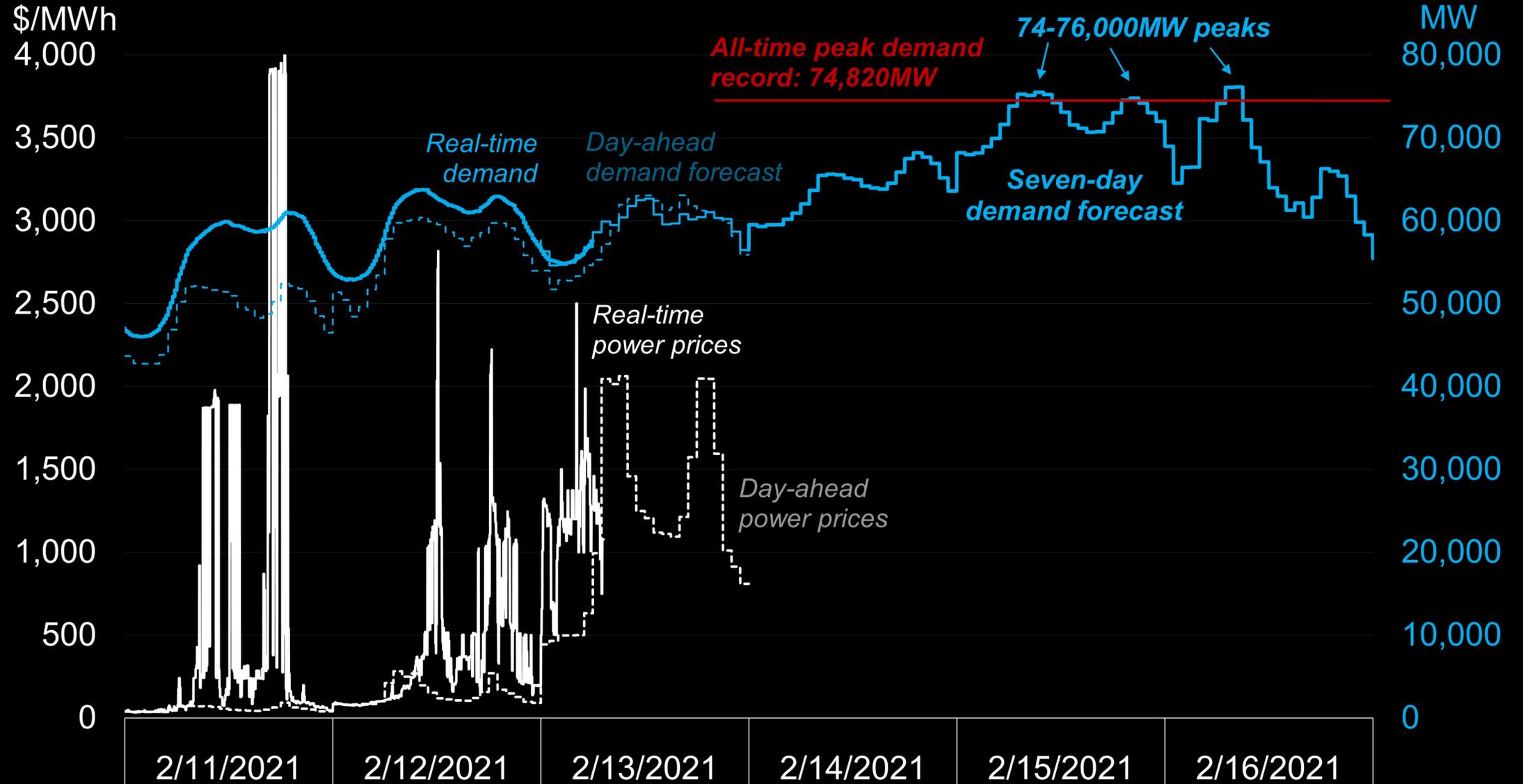
Last Updated: Feb 13, 2021 09:10

Download KML: [Contours and Points](#) / [Points Only](#) / [TX Counties](#) / [ERCOT Region](#)



# Extreme Cold Could Push Texas Electricity Demand to All-time Highs

ERCOT load and power prices



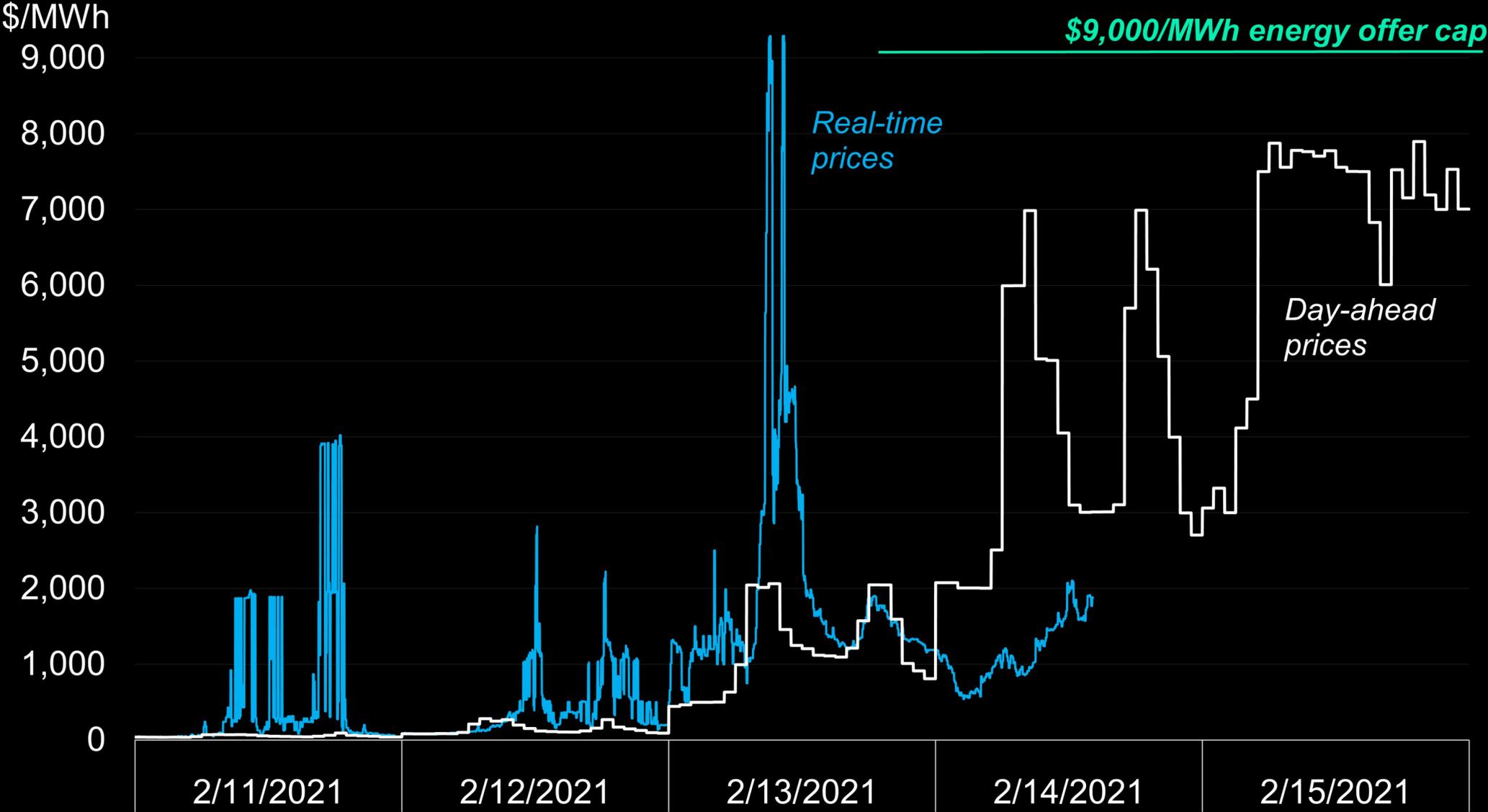
Source: ERCOT

Note: As of February 13, 8am EST

Source: Brian Bartholomew

# Extreme Cold Pushes Texas Power Prices to Record Highs

ERCOT North Hub real-time and day-ahead energy prices



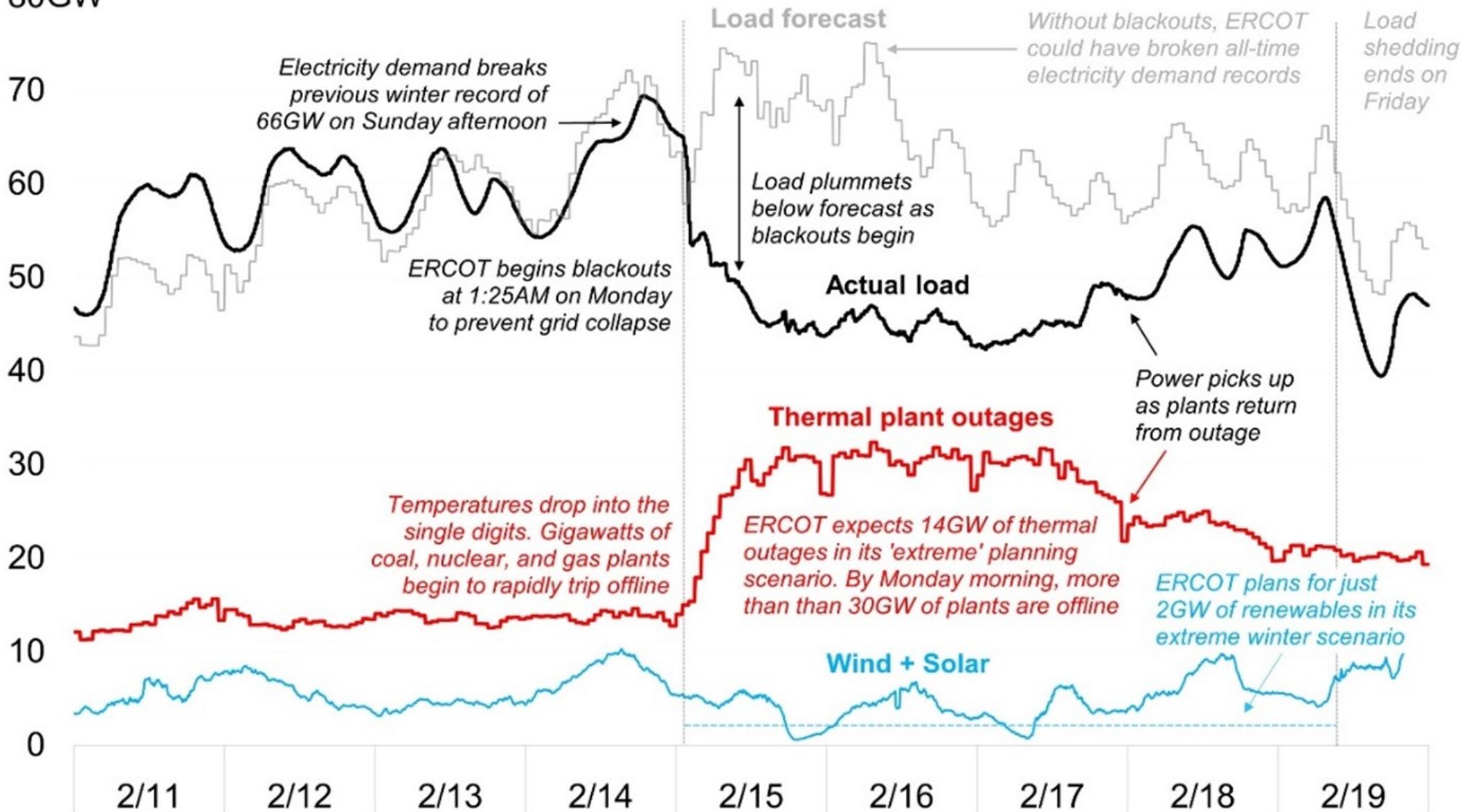
Source: ERCOT

Source: Brian Bartholomew

# Extreme Weather, Extreme Outages Pushed Texas into Blackouts

ERCOT electric load, load forecasts, thermal plant outages, and renewables

80GW

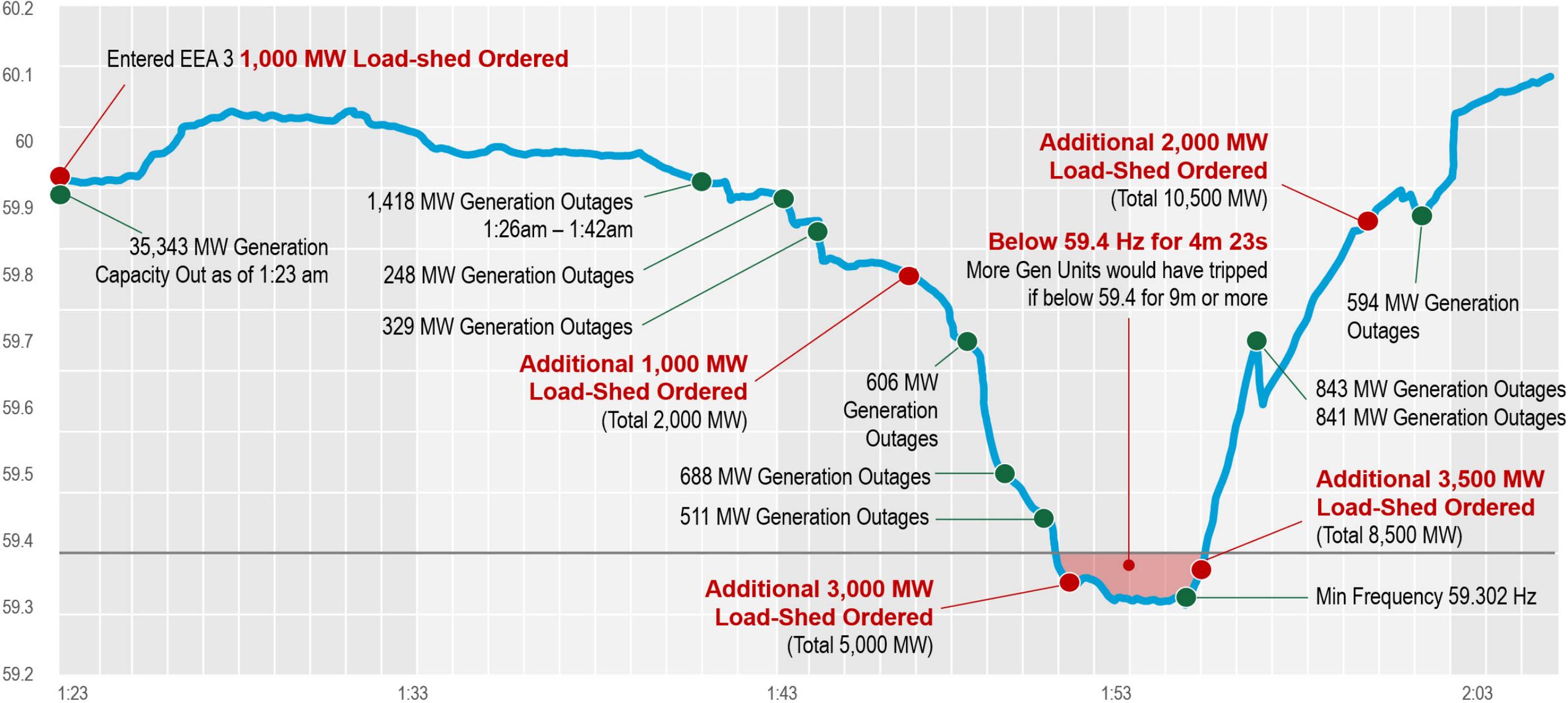


Data source: ERCOT

Note: 'Thermal plant outages' is non-renewable generator outages reported by ERCOT

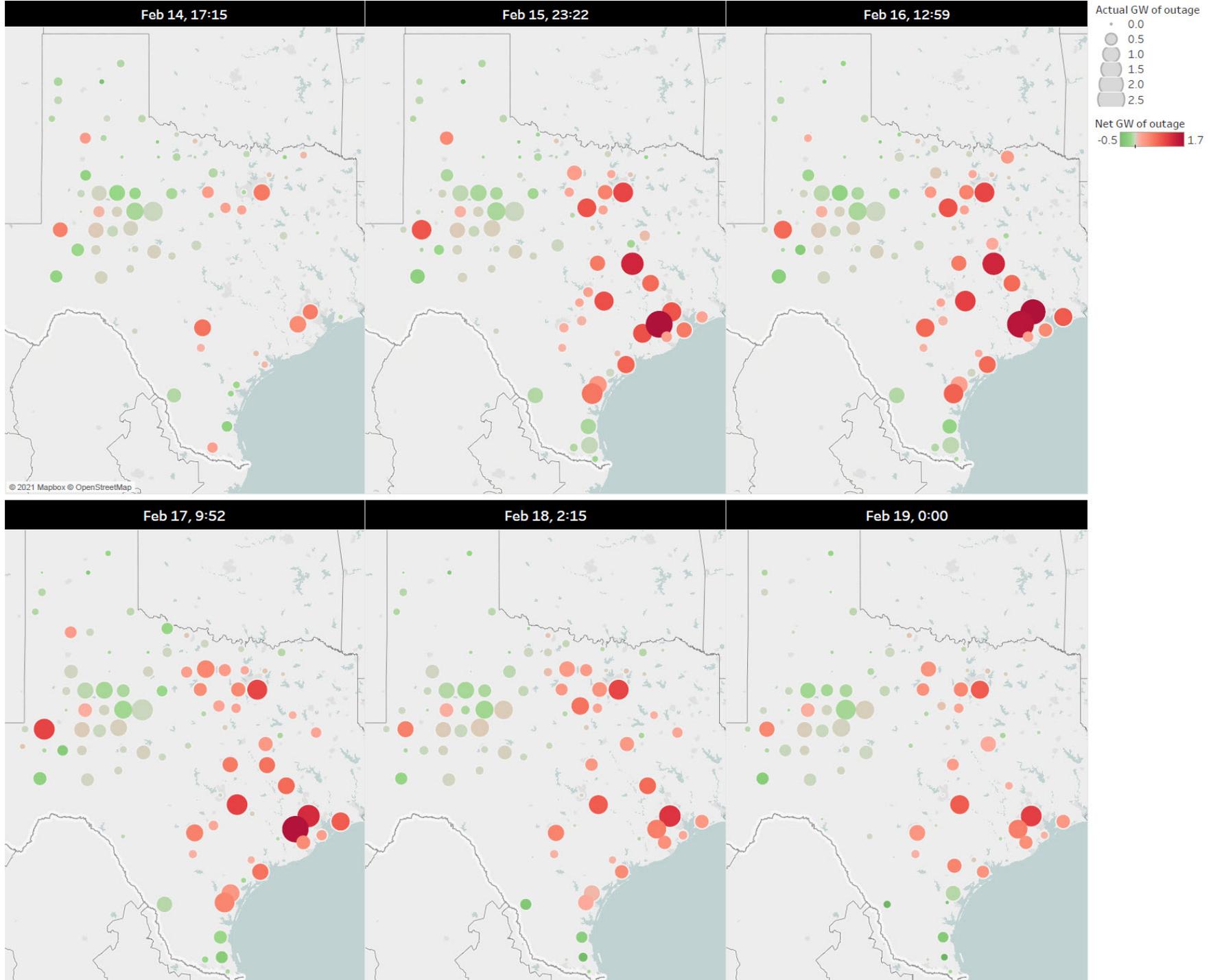
Source: Brian Bartholomew

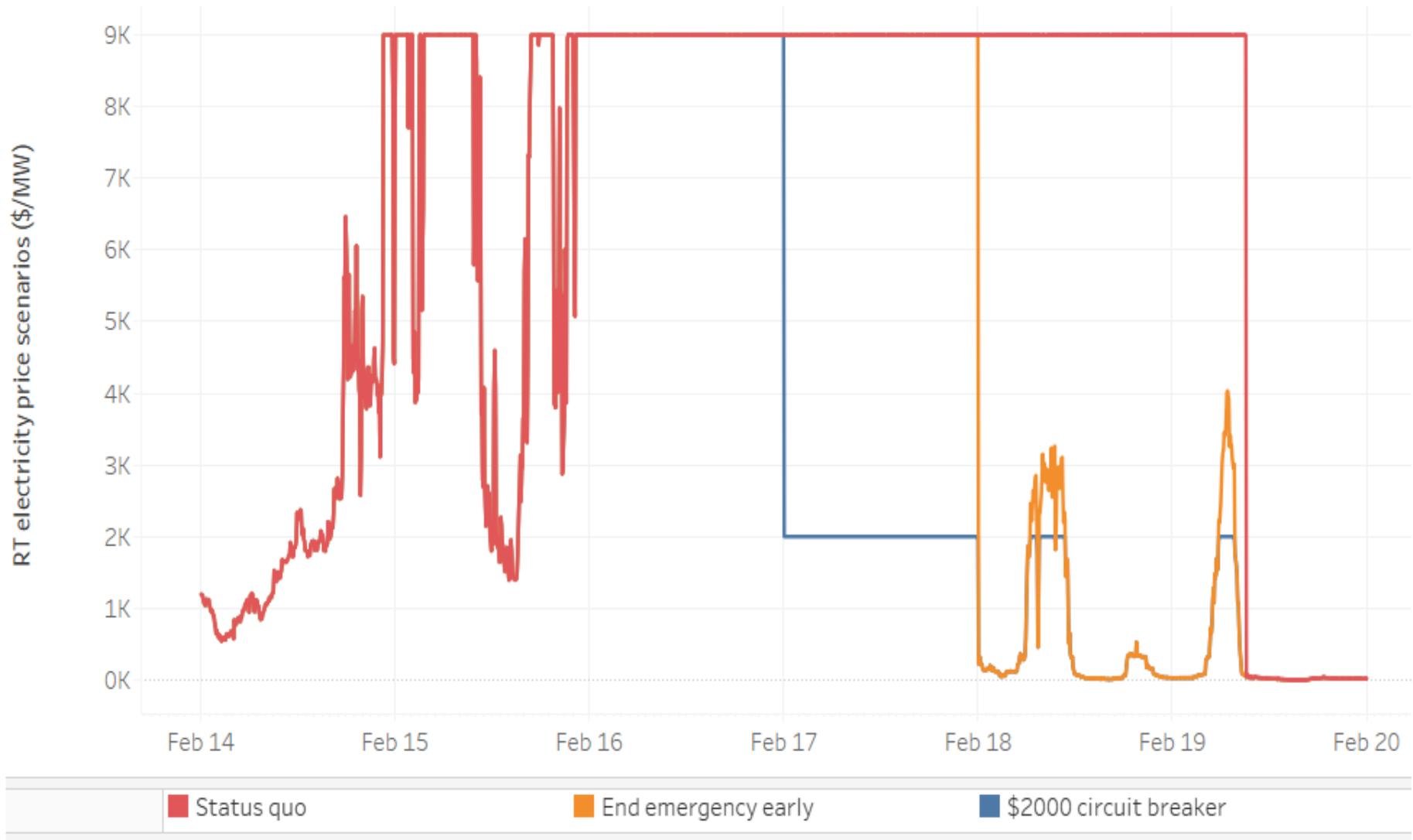
# ERCOT control room 1 am, Monday, February 15

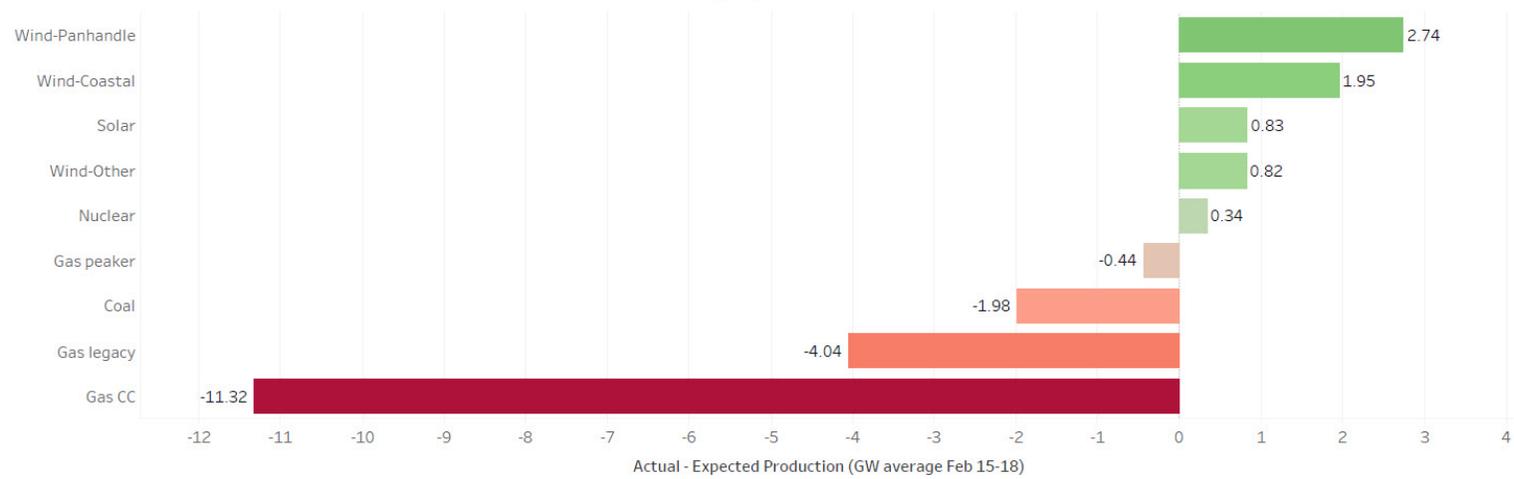
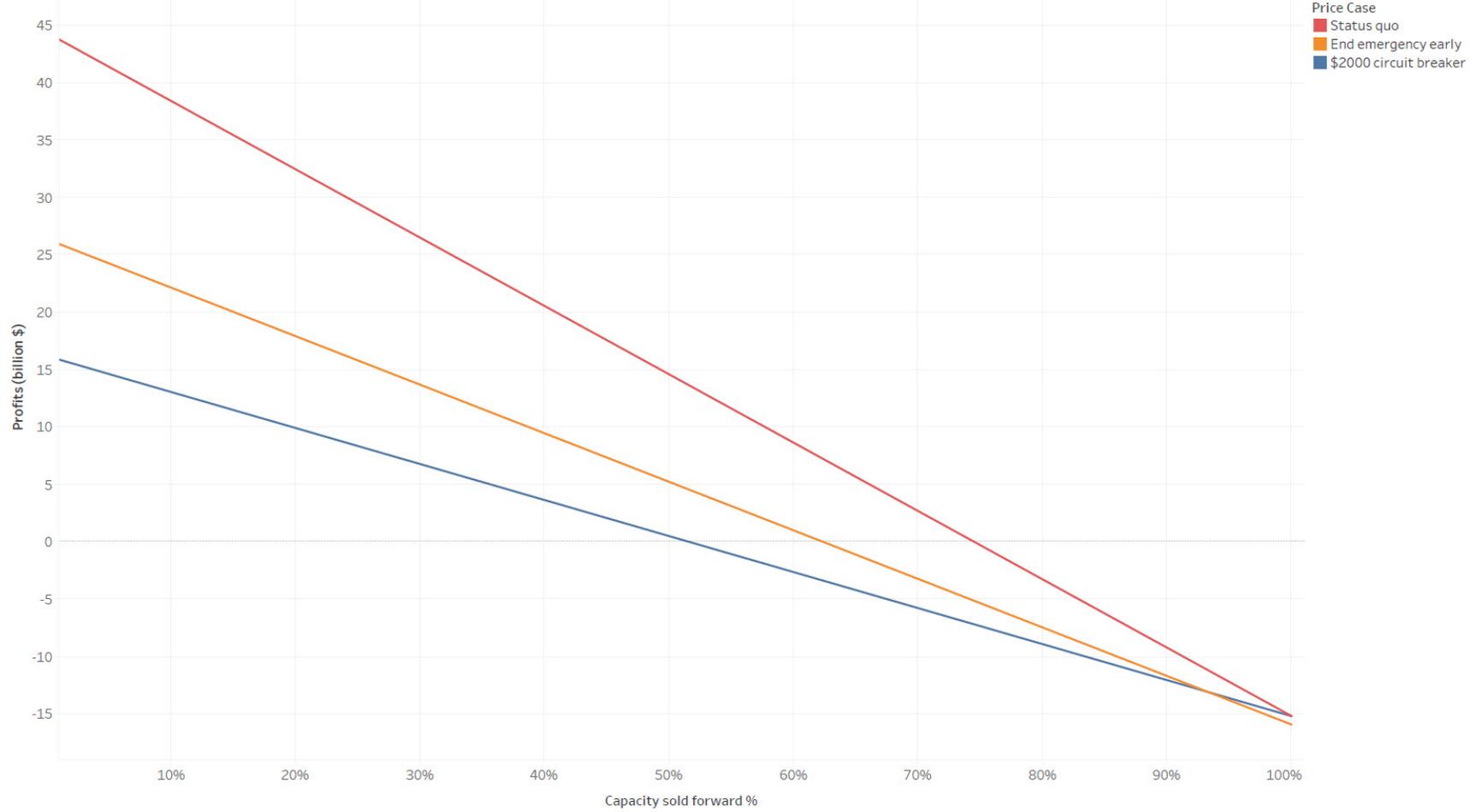


# Thermal outages

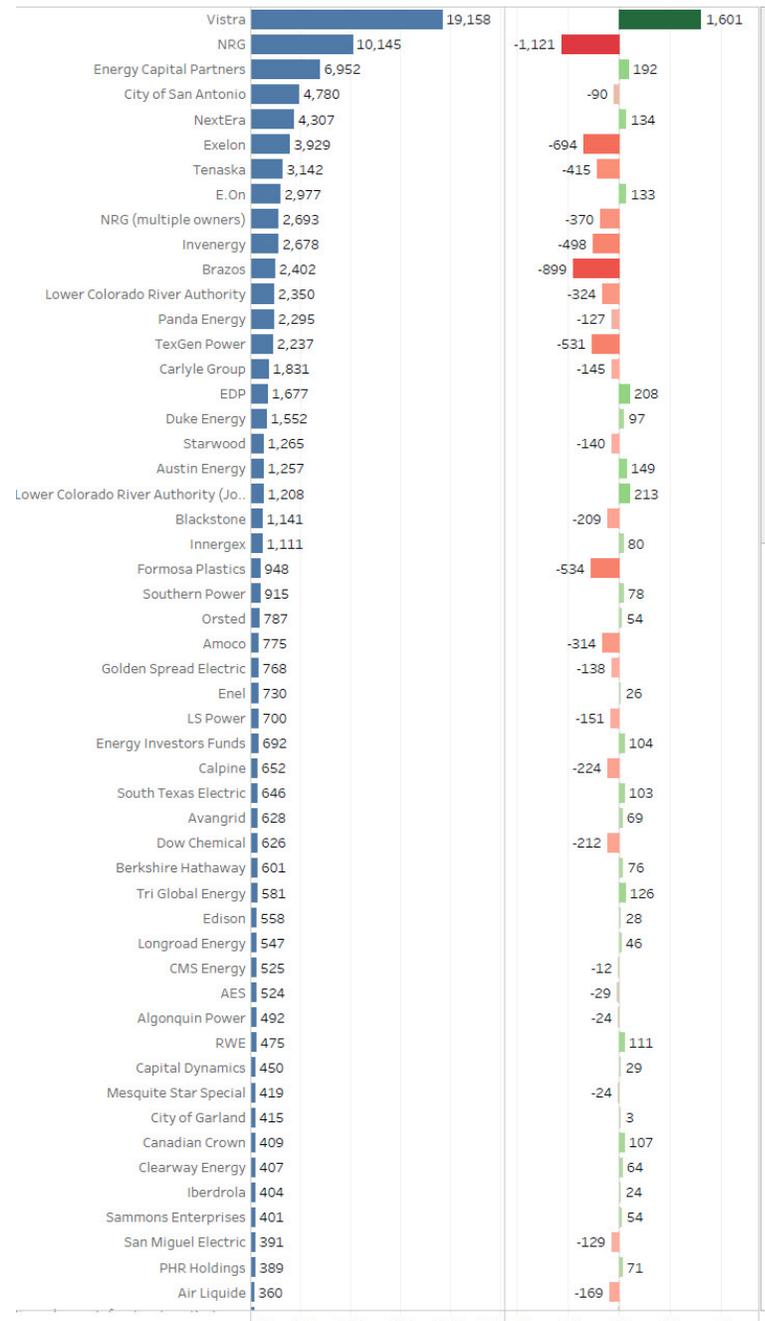




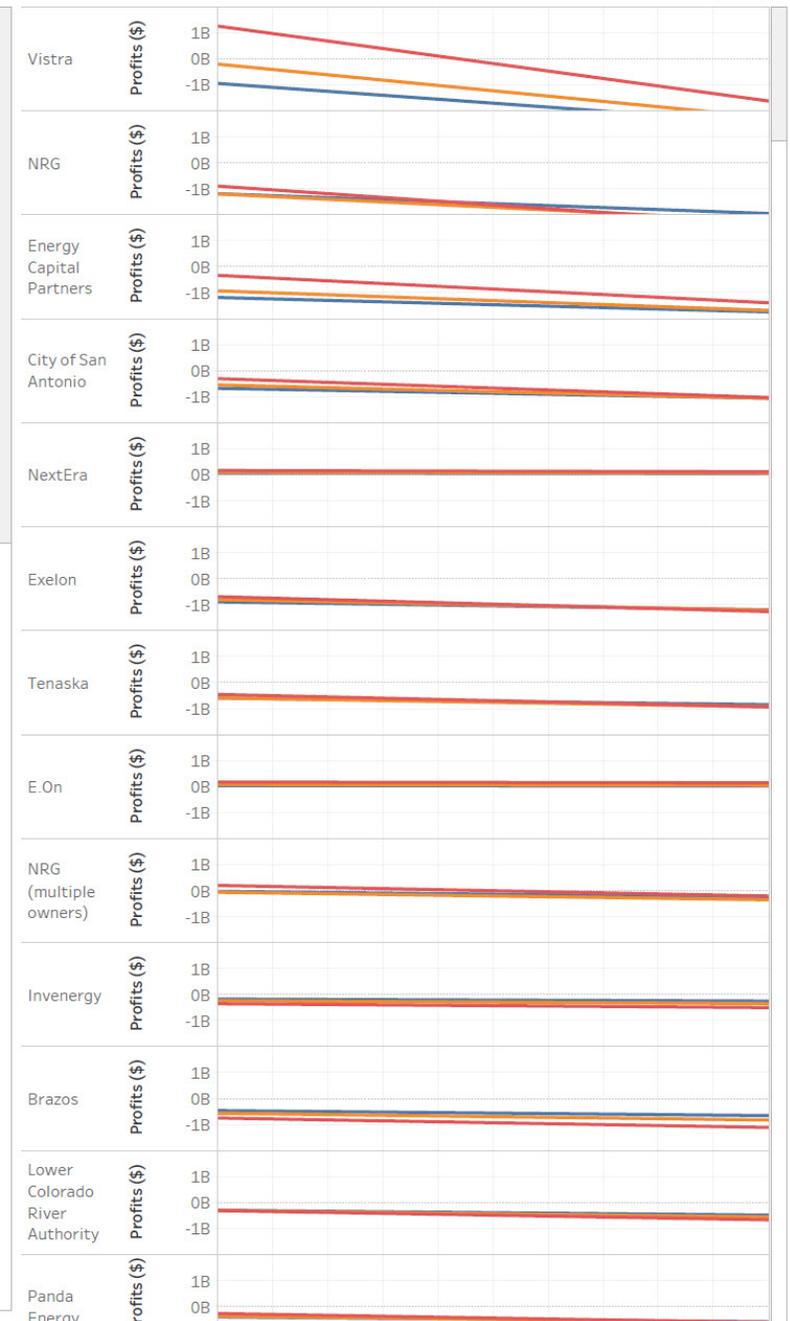




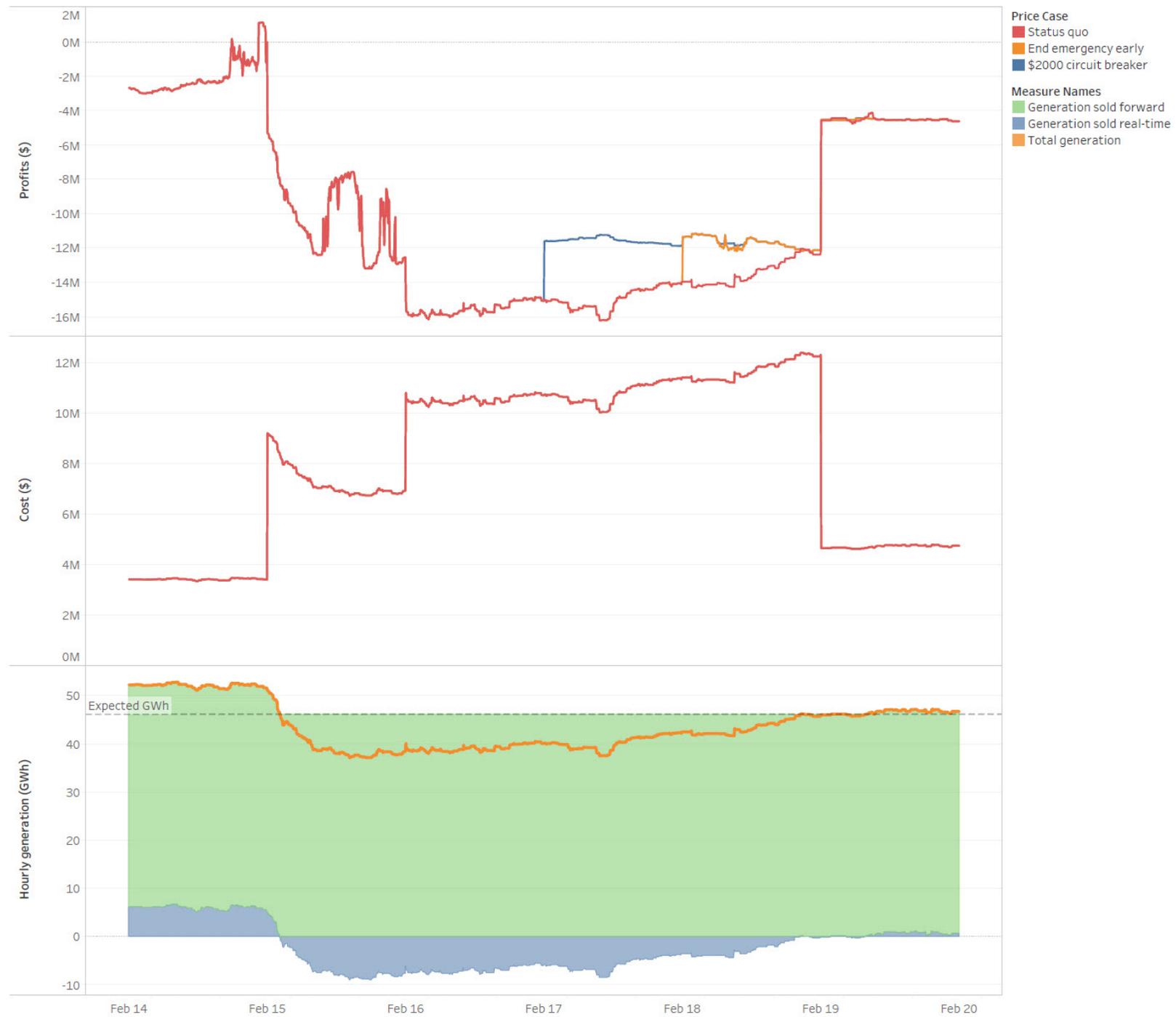
Performance by owner



Repricing (owner)

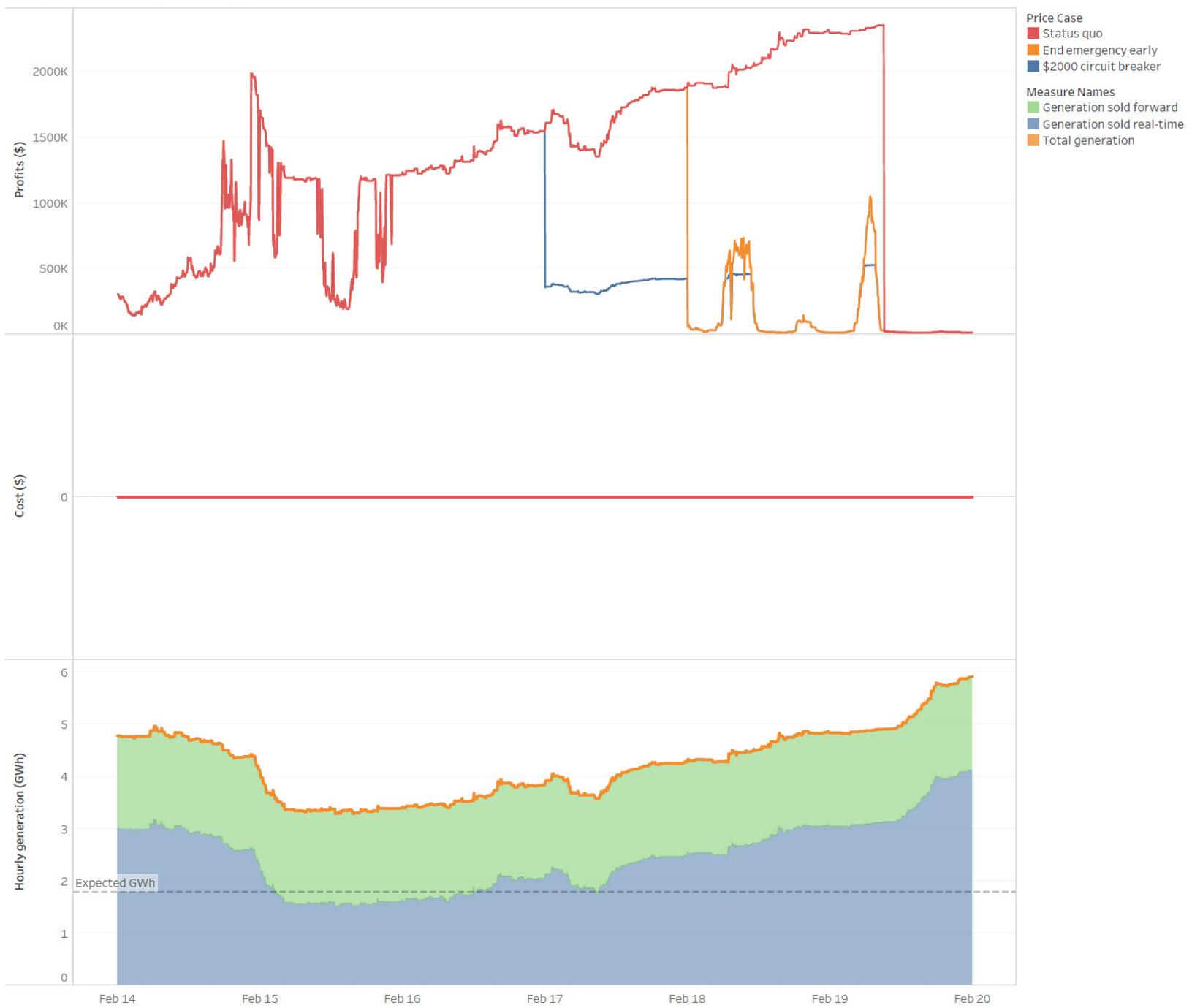


Analysis over time by technology: Gas CC, Gas legacy, Gas peaker

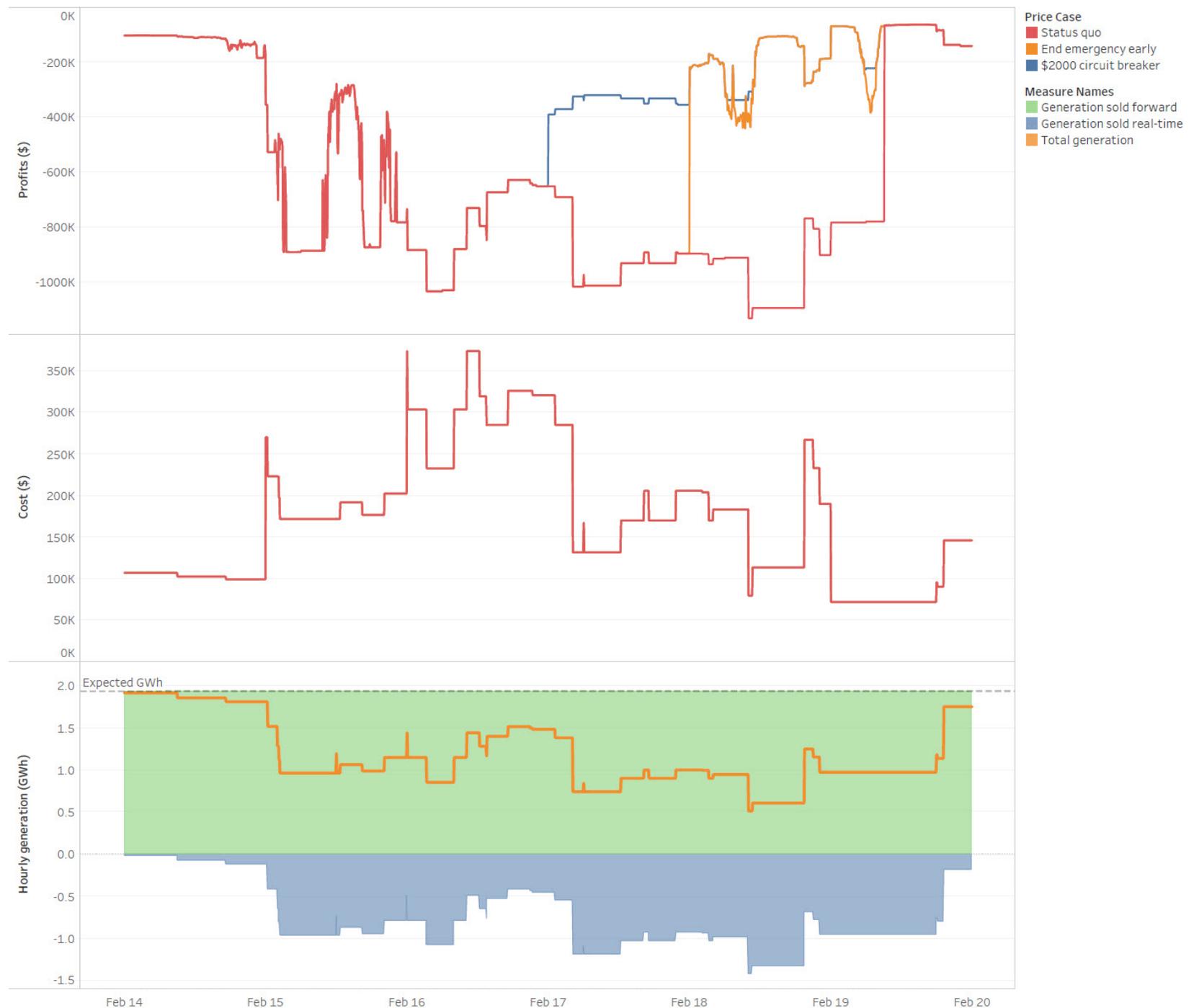


# W i n d   a n d   s o l a r

Analysis over time by technology



Analysis over time by owner: Brazos





# Possible Legislative Changes

- ERCOT Board members must live in Texas
  - Independent expertise → political appointees
- Winterization requirements
  - Penalties
  - Funded?
  - Natural gas facilities too?
- Securitization
  - Natural gas utilities / electric co-ops / broader
- Assign reserve costs to renewable generators
- Weather alert / improved communications
- Dispatchable generation requirement

## Improve communications

Governor and regulator

System operator

Public

Generators

Distribution  
companies

Retail  
service  
providers

Customers

It is likely that many Texans will lose power because of the storm, some for multiple days. The number of Texans who must experience a long outage in freezing temperatures depends on your actions. I ask and plead with all Texans who have power: *Please put your sweaters and coats on and turn the thermostat down to 55° F or lower.* Each kilowatt-hour you conserve enables more Texans to have power. Let's stand together and defeat this storm.

# Improve critical infrastructures essential for a resilient grid

- Reform the natural gas market to assure a reliable supply of gas in sub-zero temperatures
- Use standards and grants to promote energy efficiency in new and existing homes

# Enhance oversight of ERCOT as the electric industry undergoes rapid innovation

- Retain the core elements of the existing governance structure
- Improve oversight to be more responsive to rapid innovation



Electricity market design matters

# Improve ERCOT market rules and systems to embrace the future

- Improve forecasting
- Improve the analysis of resilience and reliability
- Encourage price-responsive demand
- Integrate battery storage
- Accommodate distributed generation
- Add a winter circuit breaker
- Avoid repricing, especially of forward markets
- Facilitate liquid and efficient trade of forward energy
- Add a forward-energy market for simple, transparent, and efficient trade up to 48 months ahead
- Consider a 24-hour iterative settlement that is more flexible and efficient than the day-ahead market
- Improve the real-time market with a 30-minute rolling look ahead

# First fix your spot market

- Financial day ahead market for scheduling
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to constraints
  - Allow simple expression of unit characteristics and economics (3-part bids for fossil)
  - Allow virtual bids and offers to arbitrage between day ahead and real time markets
  - Automatically mitigate market power if it appears due to local constraints
- Physical real time market for dispatch and settlement
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to constraints
  - Automatically mitigate market power if it appears due to local constraints

*Result: Day-ahead and real-time prices that induce efficient behavior!*

# Is reliability a public good?

- Absent demand response, yes.
- But an effective market encourages demand response with
  - Demand curves for reserves that reflect the value of avoiding shortage (\$9000 shortage price)
  - Rate plans that let the consumer see and feel the real-time price on the margin (it is fine if most consumers select a flat rate plan!)
  - Emergency demand response that pays customers to reduce in emergency
    - ERCOT has 2 GW
    - Pay-for-performance is key (e.g ERCOT Aug 2019 vs CA Aug 2020)

*Result: reliability is no longer a problem (and is not a public good)*

# Capacity market: Buy enough in advance

- Buy: capacity is bought on behalf of load
  - Capacity = energy and reserves during shortage [vs anytime]
  - Capacity is a derivative of the real time market = *pay for performance* [vs exceptions, missing money]
- Enough:
  - Capacity demand curve to guarantee physical capability [vs vertical]
  - Capacity value = ability to provide energy during shortage [vs nameplate, EFORd]
- In advance:
  - Three years ahead for price formation [vs spot]

# Learning to ride a bike: does a capacity market help or hurt?

\$125



\$55





# Forward energy market

- Simple, transparent, and efficient trade up to 48-months ahead
- Single foundational product: monthly forward energy
  - At system hub (or various load zones)
  - Type of day: weekday or weekend
  - Hour of day
  - Months ahead
- About  $2 \times 24 \times 48 = 2304$  products
- Preferences: Each participant submits a piecewise linear demand curves for one or more linear combination of products (shifting from current position to a new target position) in quantity flows expressing the rate at which you move from new position based on prices



# Flow Trading

Eric Budish, Peter Cramton, Pete Kyle,  
Mina Lee, and David Malec

# Key elements

Periodic clearing

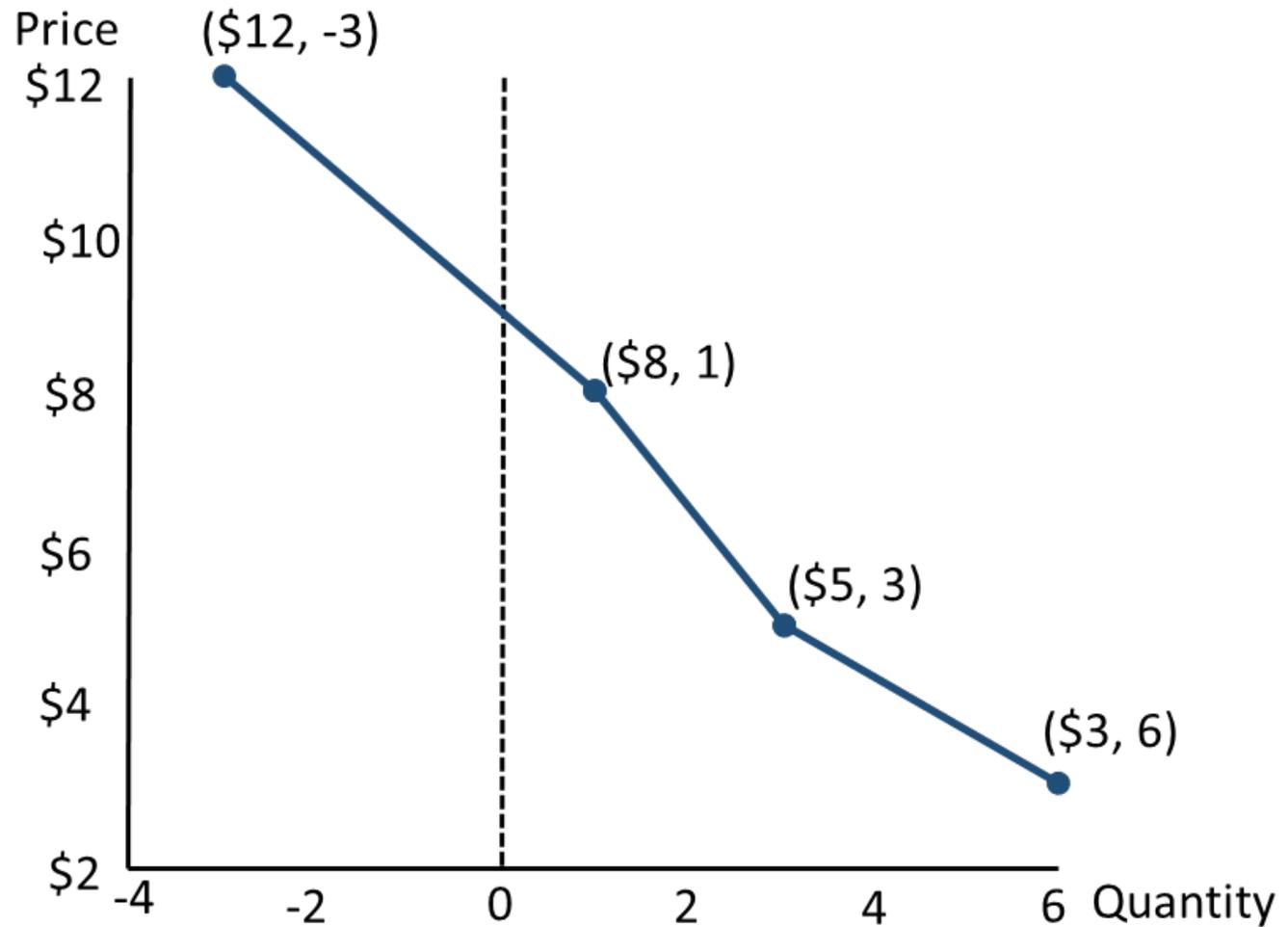
Sophisticated expression of preferences

Optimization of gains from trade

Improved outcome discovery, transparency, trust, and privacy

*“At \$1,730.22 I want to buy 10.1234 shares of Amazon per minute.”*

Preference  
expression:  
Piecewise-  
linear demand  
in flows



# Features of market outcome

---

Competitive equilibrium quantities and prices exist and are unique when it matters (positive quantity traded and not perfect substitutes)

---

Outcome maximizes as-bid social welfare s.t. constraints

---

Incentives for truthful bidding are good (and excellent for most liquid products)

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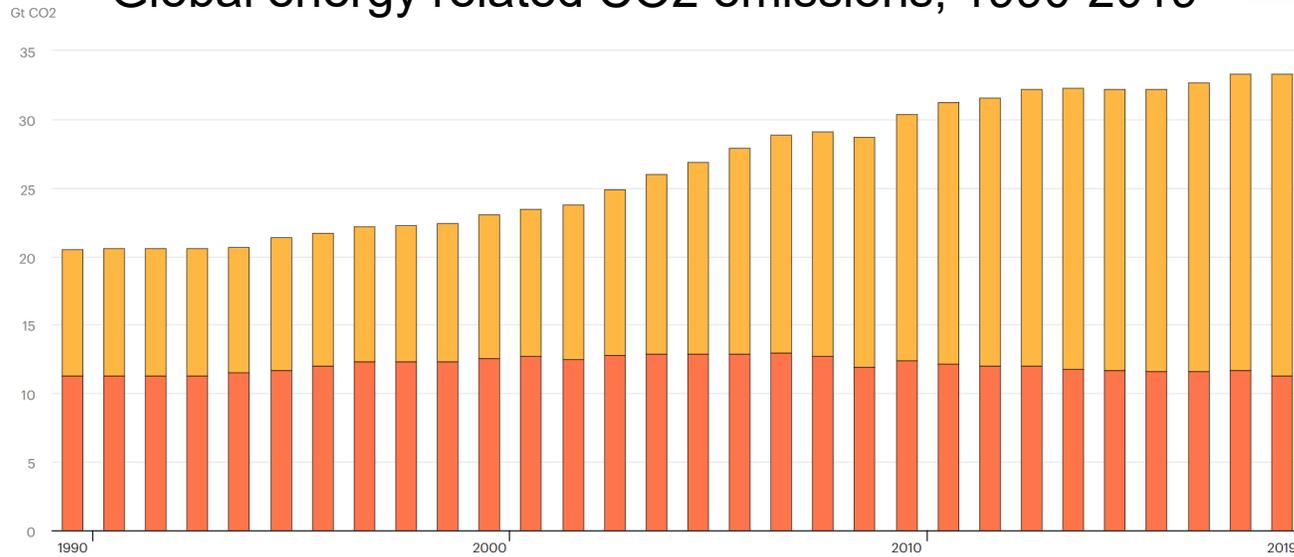
Outcome is as-bid envy free  
(given prices, everyone gets their favorite bundle)

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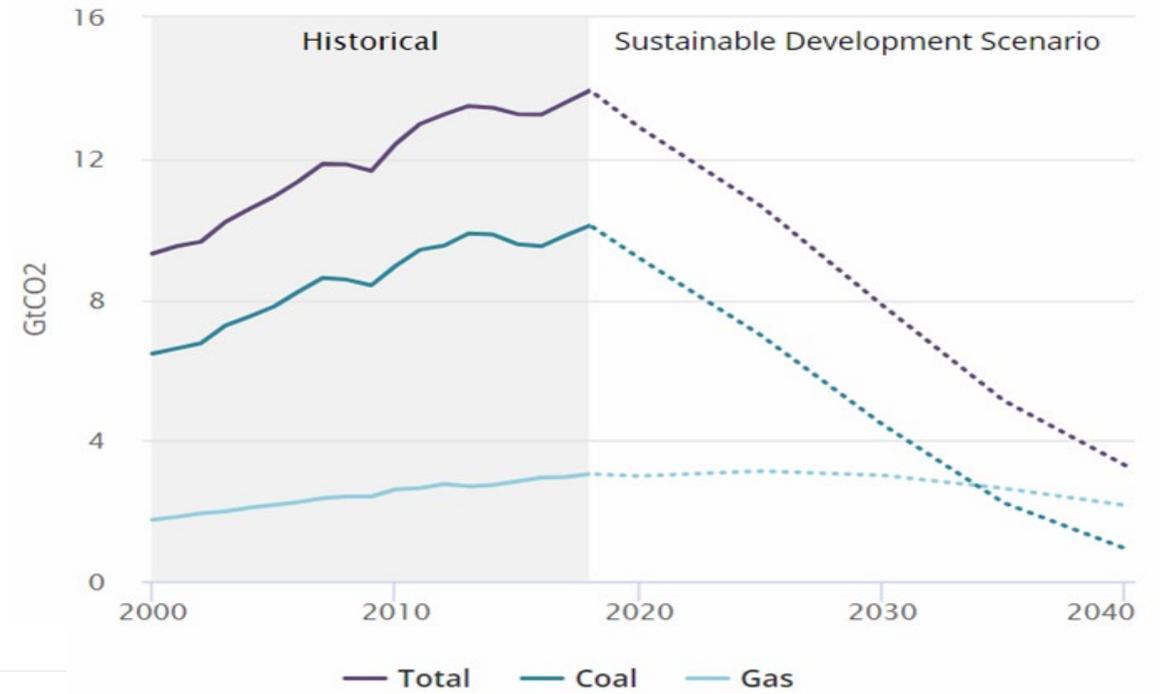
Scales to large number of products and participants

# Climate policy matters

Global energy related CO2 emissions, 1990-2019

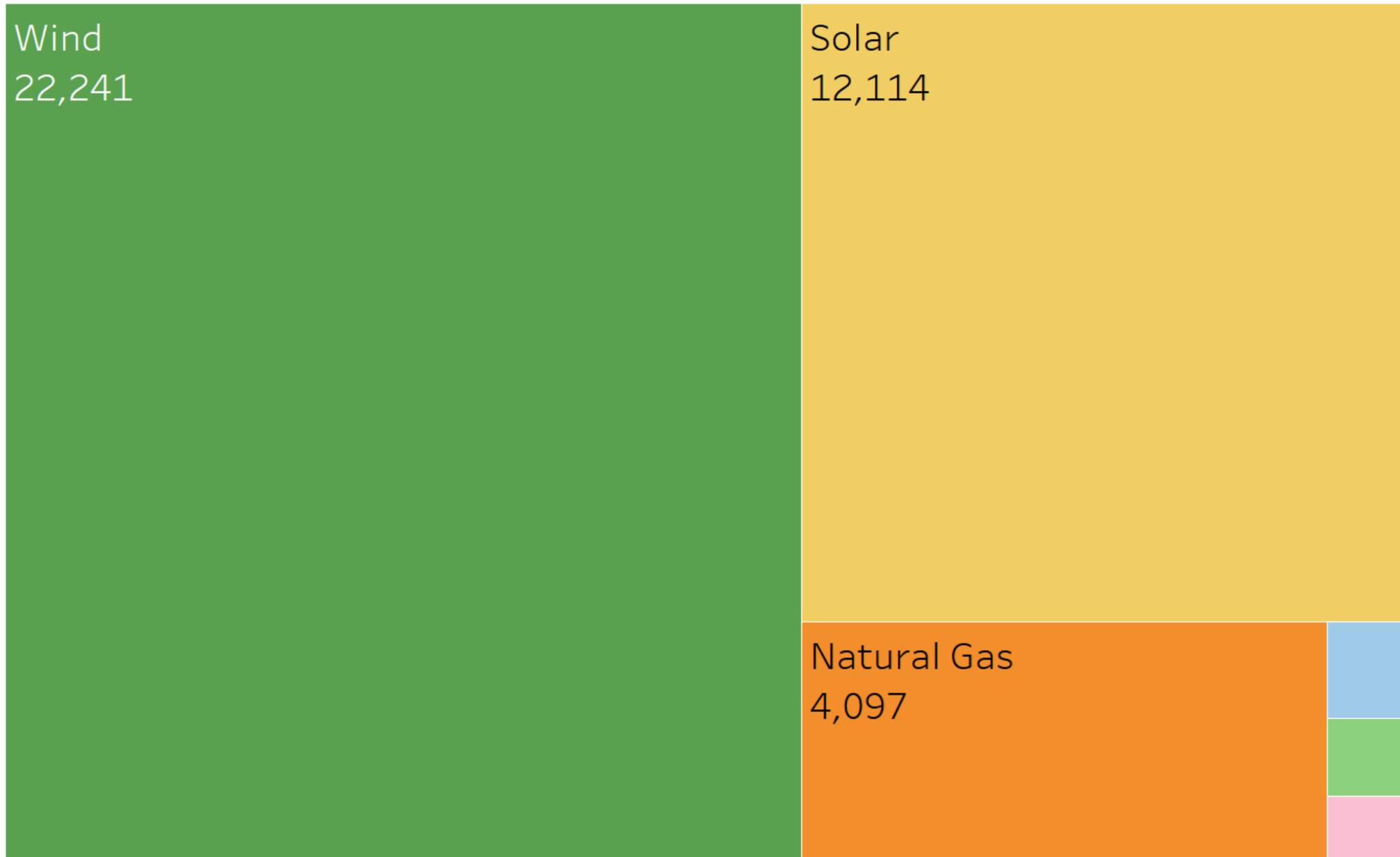


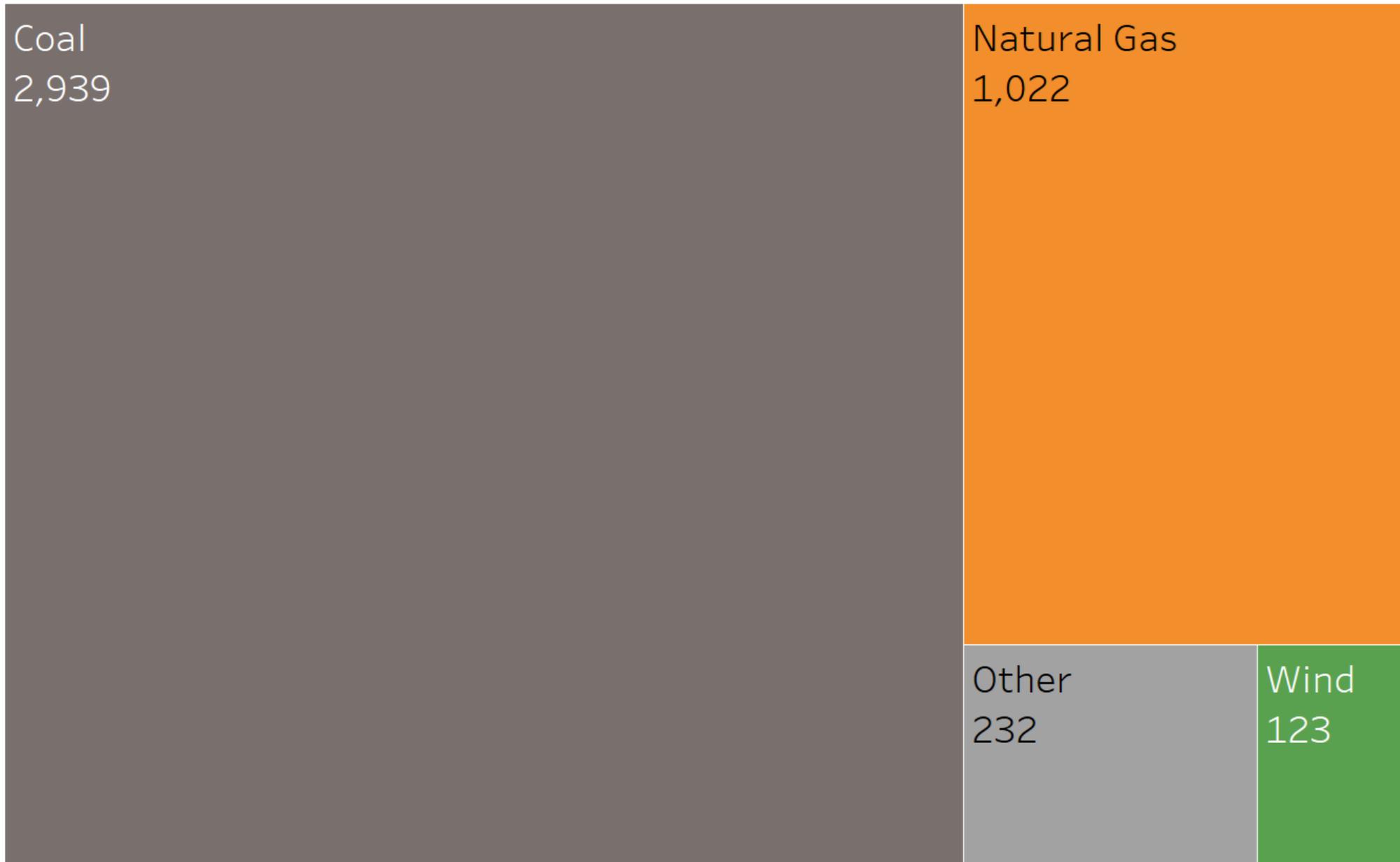
Power sector CO2 emissions



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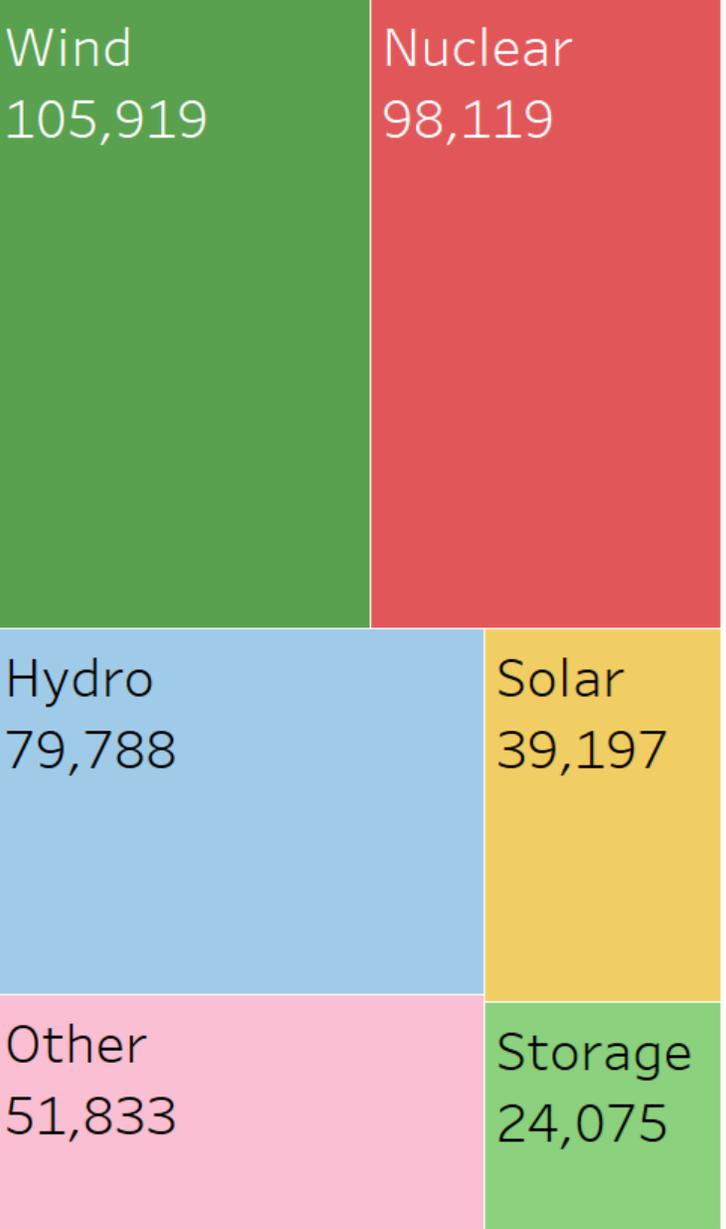
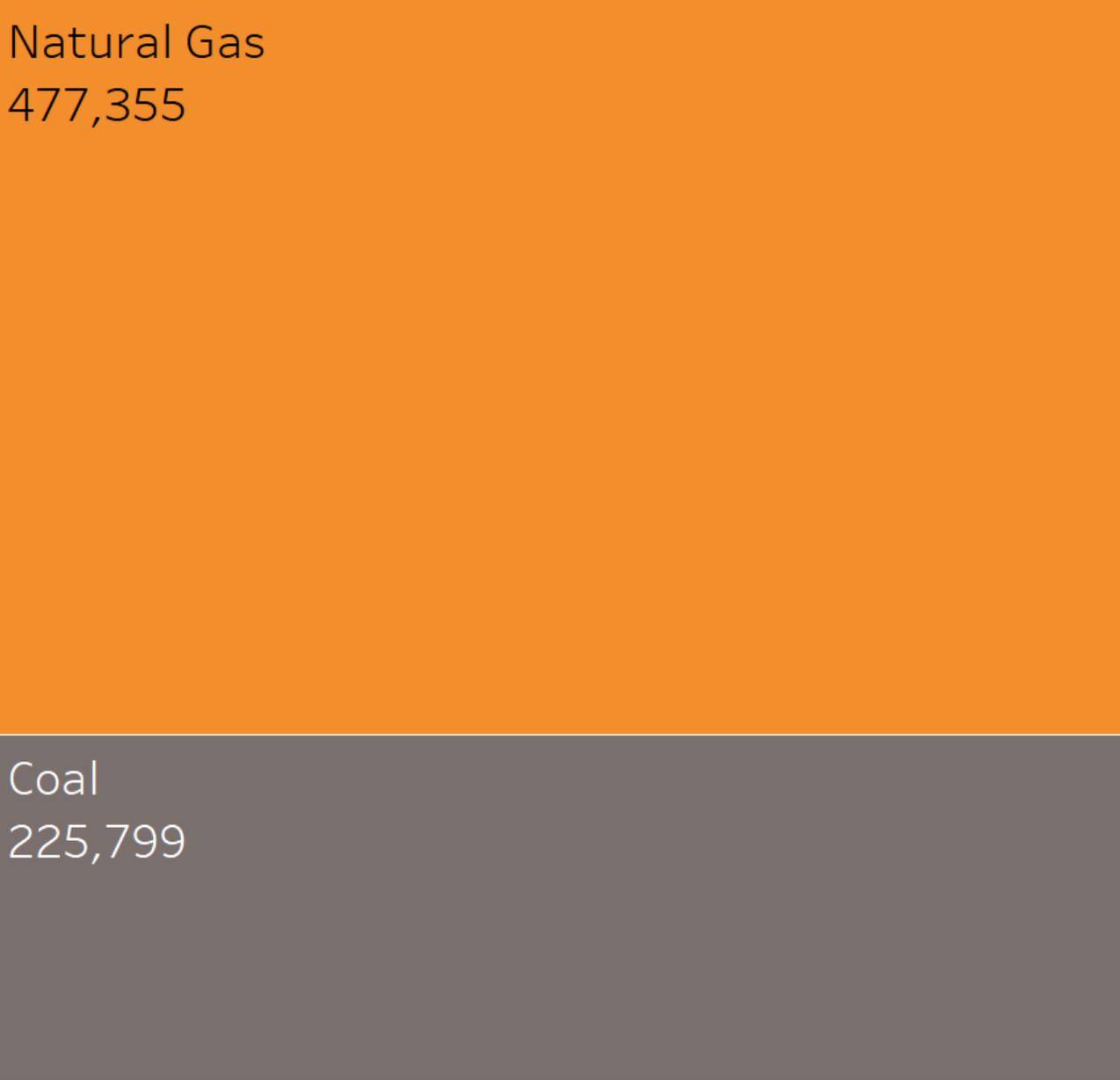
Last updated Tuesday, May 28, 2019





# Summer Capacity MW, EIA, Mar 2020

## United States



Category	Value
Mar 2020 Total	1,102,084 MW
Planned	39,034
Retiring	4,316
Change	43,350 (3.9%)

# Electricity Markets in Transition

A forty-year model of entry and exit

Peter Cramton, Emmanuele Bobbio,  
David Malec and Pat Sujarittanonta

10 February 2021

We are grateful to PJM Interconnection for funding and expert help. Funding also from Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2126/1– 390838866 and by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program under grant agreement No 741409.

# Multi decade analysis of energy transition

## Goal:

- Understand drivers of energy transition
  - Policy (market design, climate policy, ...), technology, input prices, consumer behavior

## Approach:

- Market dynamics driven by private investment decisions (entry-exit)
- Investors are sophisticated (rational, forward looking)
- Profits and performance from detailed model of energy market
- Train econometric model on synthetic data from energy model to obtain global approximation

# Storage



Batteries are fundamentally different

Marginal cost (benefit) is opportunity cost (benefit)

Opportunity cost depends on price expectations and capabilities

Approach

Day ahead: directly model battery characteristics and schedule optimally

Real time: optimally dispatch based on linear program

# Price responsive demand

Portion of load is traditional

Portion of load is price responsive

Constant elasticity (a 1% increase in price, decreases quantity by 0.1%)

Demand curve for price responsive demand explicitly modeled





Distributed energy resources: solar + battery

# Federal action to improve the resilience of critical infrastructures

- Use standards and grants to foster energy efficiency
- Strengthen the ties between the major interconnections in the United States

