Carnegie Mellon University

Electric and Gas Reliability: Insights from Actual Data

March 31, 2021

University of California at San Diego

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What I'll cover today

1. Available data on natural gas and electric reliability
2. What we've learned about reliability of gas pipelines and gas-fueled electric generators
3. What we've learned about the reliability of all electric power generators and

    a bit about what happened in Texas last month

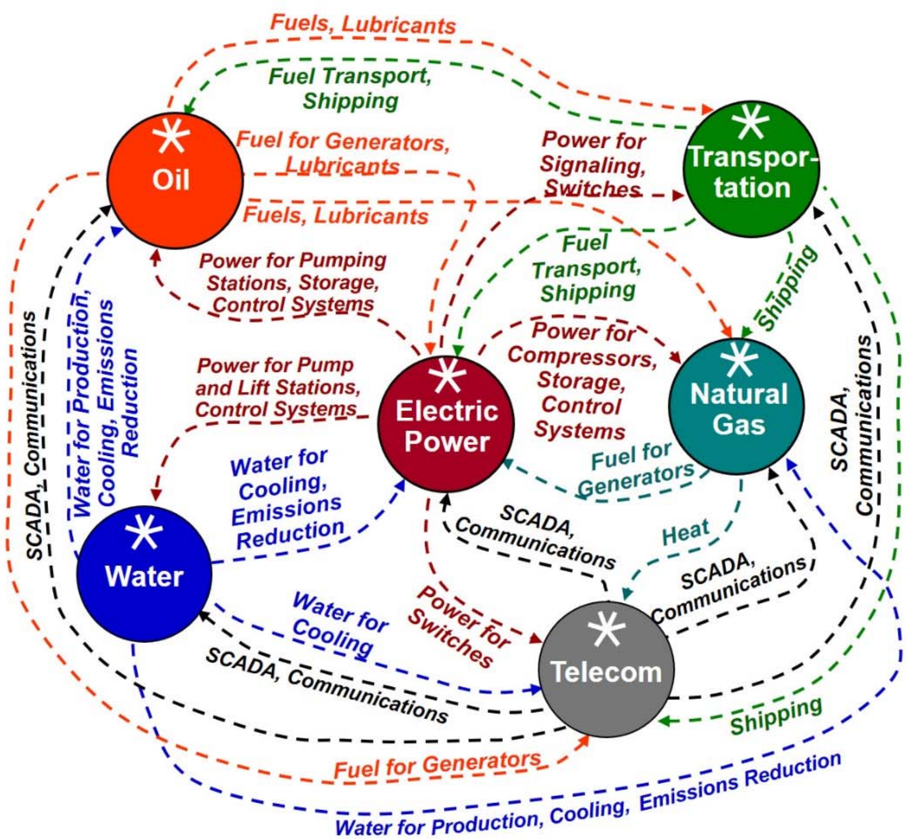
    how the power grid could better procure reliability resources

4. Final brief remarks about dependence of gas pipelines on electricity

Our reliability research began with a workshop 20 years ago

Examples of Infrastructure Interdependencies

Terry Kelly, OSTP

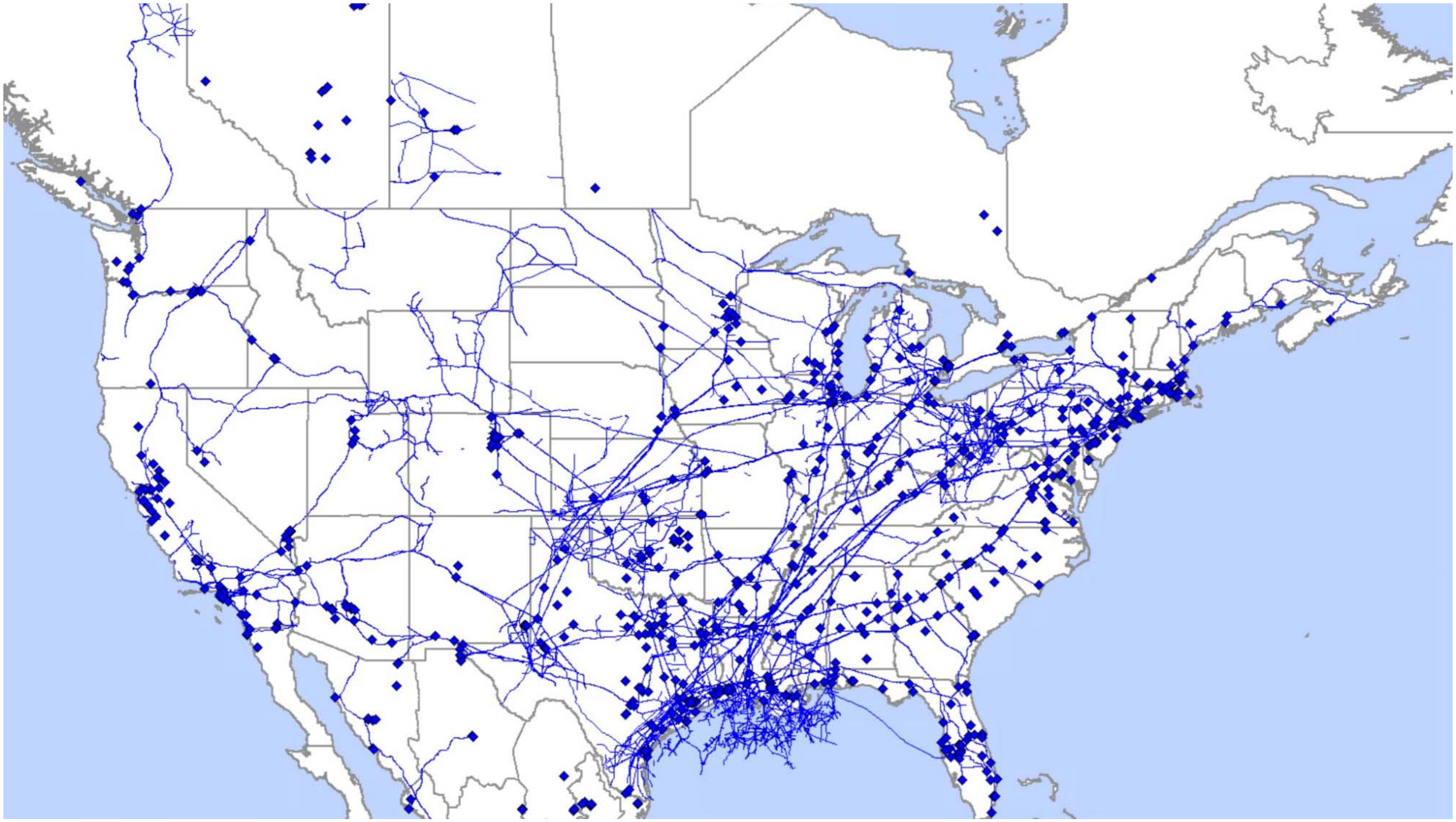


Available gas grid data

Operating natural gas pipelines 12" and larger

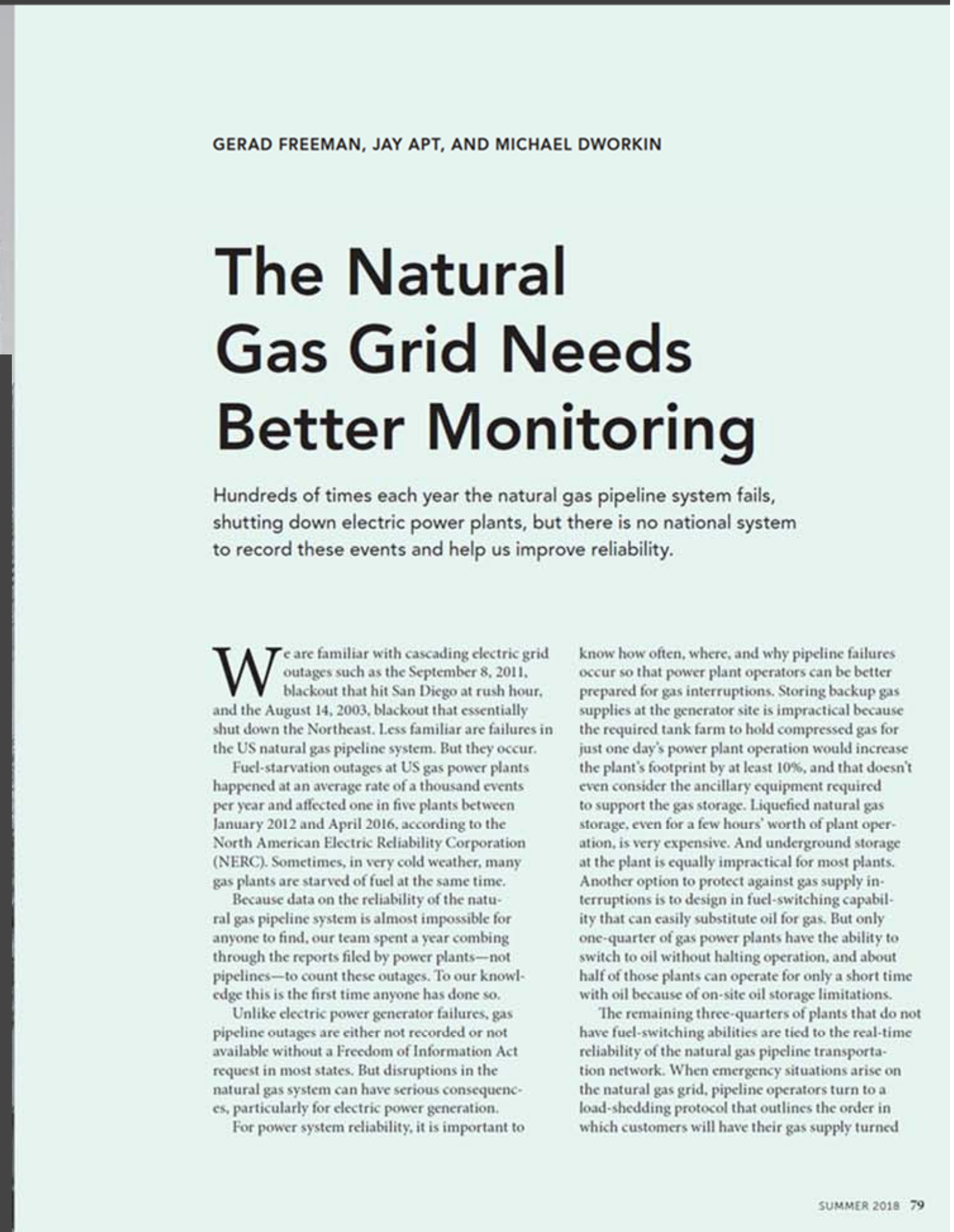
Source: ABB Velocity Suite

Operating natural gas electric generation units 100 MW and larger



Source: ABB Velocity Suite

Spoiler alert



GERAD FREEMAN, JAY APT, AND MICHAEL DWORKIN

The Natural Gas Grid Needs Better Monitoring

Hundreds of times each year the natural gas pipeline system fails, shutting down electric power plants, but there is no national system to record these events and help us improve reliability.

We are familiar with cascading electric grid outages such as the September 8, 2011, blackout that hit San Diego at rush hour, and the August 14, 2003, blackout that essentially shut down the Northeast. Less familiar are failures in the US natural gas pipeline system. But they occur.

Fuel-starvation outages at US gas power plants happened at an average rate of a thousand events per year and affected one in five plants between January 2012 and April 2016, according to the North American Electric Reliability Corporation (NERC). Sometimes, in very cold weather, many gas plants are starved of fuel at the same time.

Because data on the reliability of the natural gas pipeline system is almost impossible for anyone to find, our team spent a year combing through the reports filed by power plants—not pipelines—to count these outages. To our knowledge this is the first time anyone has done so.

Unlike electric power generator failures, gas pipeline outages are either not recorded or not available without a Freedom of Information Act request in most states. But disruptions in the natural gas system can have serious consequences, particularly for electric power generation.

For power system reliability, it is important to know how often, where, and why pipeline failures occur so that power plant operators can be better prepared for gas interruptions. Storing backup gas supplies at the generator site is impractical because the required tank farm to hold compressed gas for just one day's power plant operation would increase the plant's footprint by at least 10%, and that doesn't even consider the ancillary equipment required to support the gas storage. Liquefied natural gas storage, even for a few hours' worth of plant operation, is very expensive. And underground storage at the plant is equally impractical for most plants. Another option to protect against gas supply interruptions is to design in fuel-switching capability that can easily substitute oil for gas. But only one-quarter of gas power plants have the ability to switch to oil without halting operation, and about half of those plants can operate for only a short time with oil because of on-site oil storage limitations.

The remaining three-quarters of plants that do not have fuel-switching abilities are tied to the real-time reliability of the natural gas pipeline transportation network. When emergency situations arise on the natural gas grid, pipeline operators turn to a load-shedding protocol that outlines the order in which customers will have their gas supply turned

Freeman, G. M., Apt, J., & Dworkin, M., (2018). The gas grid needs better monitoring. Issues in Sci. & Tech., 34 (4), 79-84.

What data are out there for public assessments on the gas side? Federal Energy Regulatory Commission (FERC) Forms

- 18 CFR § 284.262 → FERC Form 588
- "Emergency transaction" reports from pipeline operators
    - Emergency transaction – "an actual or expected shortage of gas supply [that forces] an interstate pipeline company, intrastate pipeline, local distribution company, or [pipeline that is not under FERC jurisdiction due to stipulations in the Natural Gas Act] to curtail deliveries of gas or provide less than the projected level of service to any customer."
- Should capture both complete and partial gas outages (system pressure reductions)
- No longer collected, but no loss

- 18 CFR § 2.55(b)(4) → Reports of Service Interruptions and Force Majeure
    - Serious interruptions on interstate pipelines

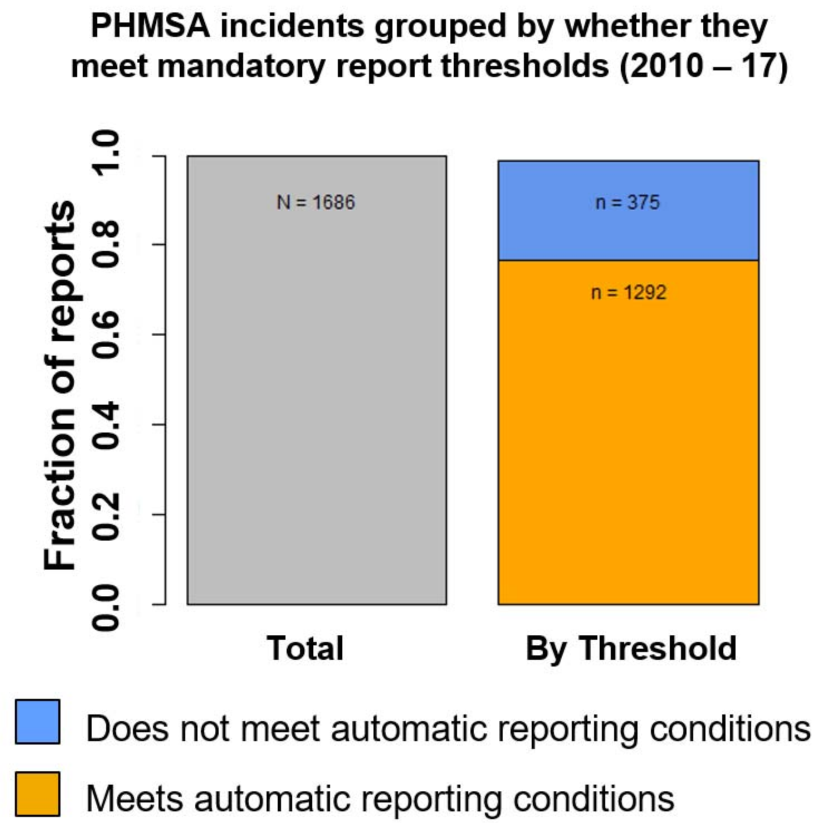
What data are out there for public assessments of gas?
Pipeline and Hazardous Materials Safety Administration (PHMSA)

- 49 CFR § 191.3: Reports of events that result in **both** a release of gas or hazardous liquid from the pipeline **and at least one** of the following:

1. “A death, or personal injury necessitating in-patient hospitalization;
2. Estimated property damage of $50,000 or more . . . excluding the cost of gas lost or;
3. Unintentional estimated gas loss of three million cubic feet or more.”

   This is far too large. A 200 MW NGCC consumes roughly 1 million ft^3 per hour

- Or any event that is “significant in the judgment of the operator, even though it did not meet the [previous] criteria . . . of this definition”

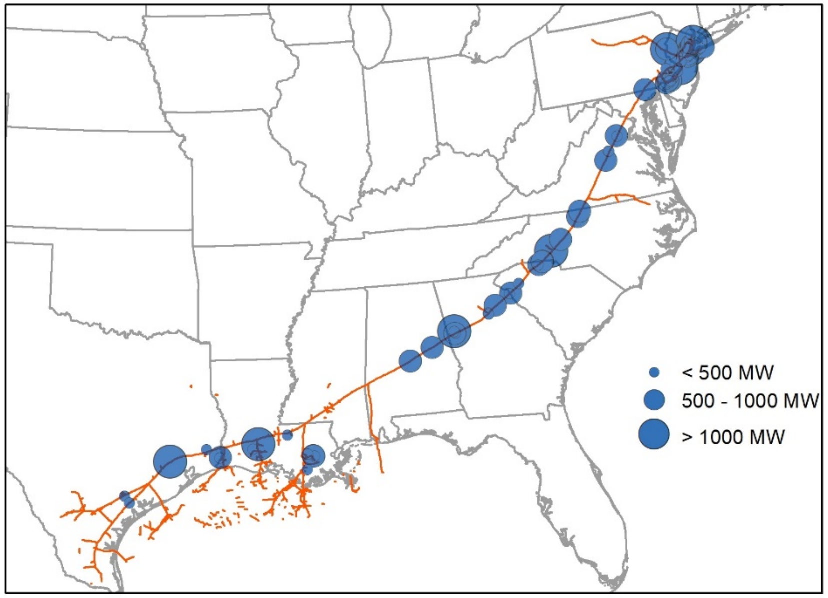


Source: PHMSA Natural Gas Distribution, Gathering, and Transmission Accident and Incident Database

What data are out there for public assessments of gas?
Pipeline Critical Notices

- Pipeline companies post critical notices on their information portal websites.
- Case study: Transcontinental Pipeline
  - Looking at Operational Flow Orders (OFOs) – imbalance between inflows and outflows on the pipeline.
  - 35 OFOs were issued between 8/2014 and 8/2017. 6 had coinciding power plant failures.
  - 292 power plant failure events occurred during these 6 OFOs.
  - **14 events at 4 power plants representing 900 MW of capacity failed while holding firm fuel contracts on Transco at the time.**

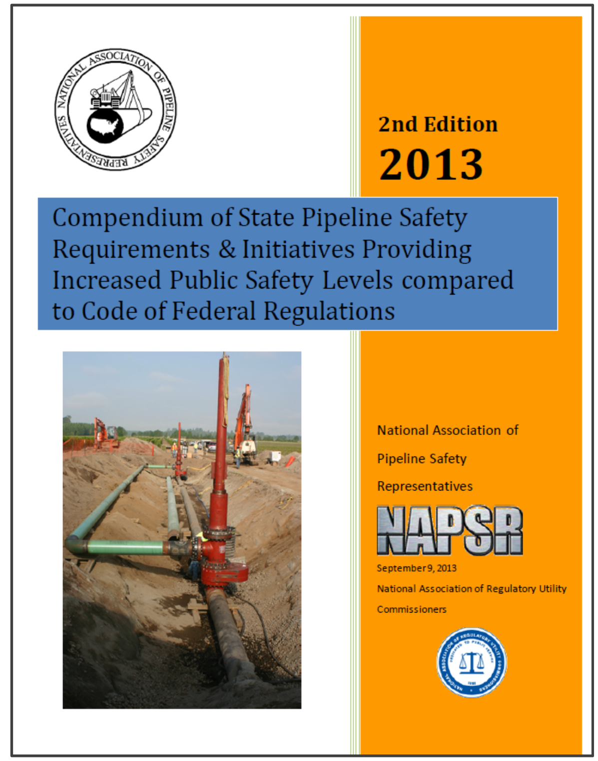
Gas Power Plants on Transcontinental Pipeline



Sources: NERC-GADS 2012-2015, Williams Transcontinental Pipeline Information Portal, 2015 EIA Form 860, EIA Shapefiles

What data are out there for public assessments of gas?
State Public Utility Commission (PUC) Reports

- Gas service interruptions are often within the purview of the State PUCs, but mandatory reporting thresholds vary
- 2013 National Association of Pipeline Safety Representatives (NAPSR) Compendium
    - 20 states require reports of outages affecting a specific number of customers, specific duration, or gas delivery pressure issues.
        - *WY: all service interruptions*
        - *PA: lesser of 2,500 customers and 5% of total customers*
        - *FL: lesser of 500 customers and 10% of total customers*
        - *WA: > 25 customers*
        - *Only NH, RI, and WA report system pressure issues*



Thresholds for mandatory reporting of service interruptions on the gas side vary greatly by state

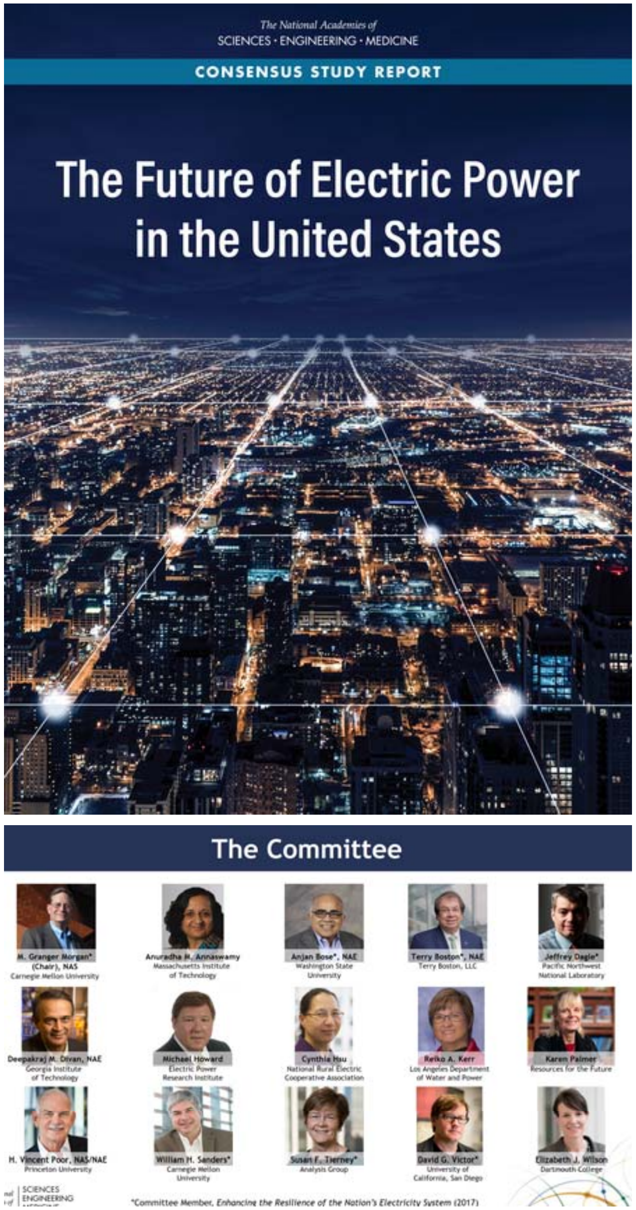
What data are out there for public assessments of generators?

GADS – Generating Availability Data System

- Generator-level database recording anything affecting ability of a generator to produce electricity
- NERC GADS (2012-present):
  - 8,500 generators (~85% of capacity in North America)
  - ≥20 MW mandatory reporting threshold for conventional generators; no wind or solar
- PJM GADS (1995-present):
  - 1,850 generators (~95% of capacity serving PJM)
  - All conventional generators participating in PJM markets; no wind or solar

What else do we need for a public assessment?

- Consistent reporting standards for pipeline events that would trigger a GADS report and level the regulatory playing field.
- A pipeline failure event that causes an:
  - Unanticipated reduction in ability to serve customers of the pipeline by 25,000 standard cubic feet per hour (scf/h) should be reported by pipelines with firm contracts to fuel plants of nameplate 20 MW or more
  - 900 scf/h should be reported by pipelines with firm contracts to fuel plants of nameplate 20 MW or less
- These data should be collected by a central reliability agency, like NERC, and made available for third-party reliability assessments.



Recommendation 3.2: Congress should build off of the example it set in the electric power system when it established in the Energy Policy Act of 2005 an Electric Reliability Organization with responsibility to set and enforce reliability standards for the electric industry, and authorize FERC to designate a central entity to establish standards for and otherwise oversee the reliability of the nation's natural gas delivery system. Congress should also authorize FERC to require greater transparency and reporting of conditions occurring on the natural gas delivery system to allow for better situational awareness as to the operational circumstances needed to help support electric-system reliability.

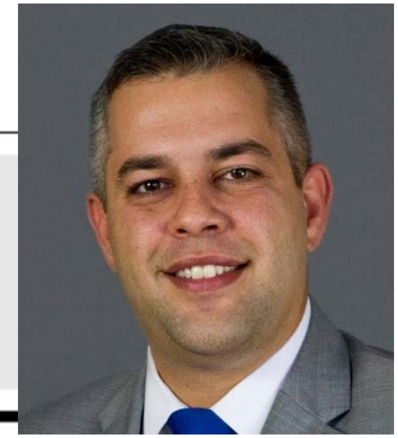
Despite the gas data limitations,
we can learn quite a lot

Energy Policy 147 (2020) 111805

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol



What causes natural gas fuel shortages at U.S. power plants?

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ARTICLE INFO

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Correlated failures
Fuel assurance
Fuel security
Generating availability data system
Pipeline failures
Pipeline curtailment

ABSTRACT

Using 2012–2018 power plant failure data from the North American Electric Reliability Corporation, we examine how many fuel shortage failures at gas power plants were caused by physical interruptions of gas flow as opposed to operational procedures on the pipeline network, such as gas curtailment priority. We find that physical disruptions of the pipeline network account for no more than 5% of the MWh lost to fuel shortages over the six years we examined. Gas shortages at generators have caused correlated failures of power plants with both firm and non-firm fuel arrangements. Unsurprisingly, plants using the spot market or interruptible pipeline contracts for their fuel were somewhat more likely to experience fuel shortages than those with firm contracts. We identify regions of the Midwest and Mid-Atlantic where power plants with non-firm fuel arrangements may have avoided fuel shortage outages if they had obtained firm pipeline contracts. The volume of gas needed by power plants to fuel the lost MWh in those regions was only a small fraction of the total volume delivered to potentially non-essential commercial and industrial pipeline customers in those regions and modest prices there at the times when power plants failed indicate gas was available.

Results

1. Gas shortages caused correlated failures of plants using both firm and spot gas pipeline contracts (“non-firm”) for their fuel supplies.
2. Physical disruptions of the pipeline network accounted for no more than 5% of the MWh lost to fuel shortages.
3. Unsurprisingly, plants with non-firm fuel contracts were more likely to experience fuel shortages than those with firm contracts.
4. But firm contract plants also were cut off.
5. Non-firm plants in parts of the Midwest and Mid-Atlantic may have avoided fuel shortage outages if they held firm contracts.

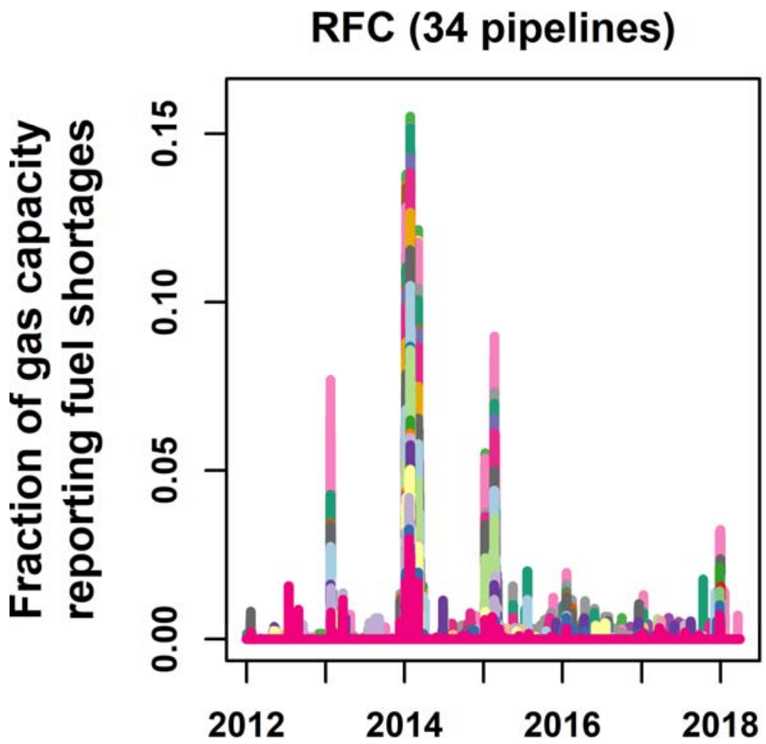
Data mapping power plants to pipelines

1. **NERC Generating Availability Data System** (GADS)
   Sample: 1/2012 – 3/2018 (6 years)
   - 6,505 events at 328 natural gas plants
   - Only unscheduled fuel shortage or fuel conservation causes (9130, 9131, 9134)

2. **Generator characteristic data** (EIA-860)
   - To group events by pipeline

3. **Fuel receipt and contract status data** (EIA-923)
   - To group events by contract type

4. **Pipeline scheduling and pricing data** (EIA-857, ABB Velocity Suite)
   - To examine capacity and spot market gas availability on pipelines



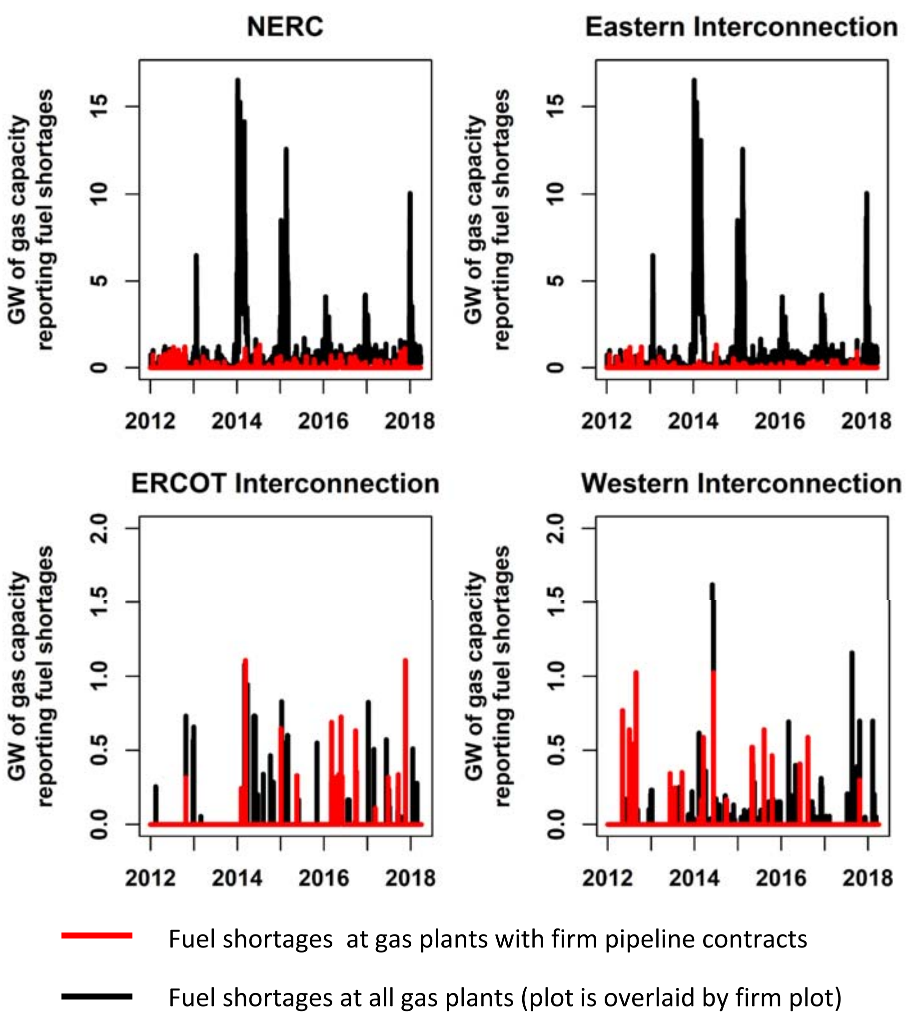
Time series plot of gas plant fuel shortage and conservation interruption failure magnitude as a fraction of nameplate capacity in RFC, indicating the pipeline fueling the plant. Each color represents an individual pipeline system.

Pipeline failures explain very few fuel shortage failures

Transmission pipeline *force majeure* events explain only a maximum* of 9% of unscheduled fuel shortage events (5% of MWh lost).

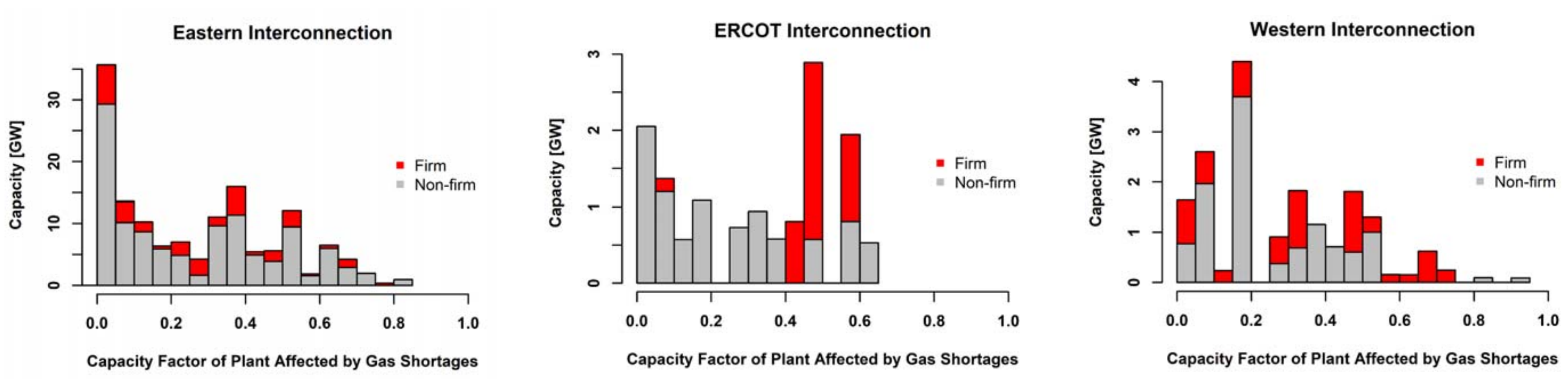
*This upper bound is constructed by considering *force majure* events that occurred anywhere along the pipeline

Gas plants were affected by fuel shortages regardless of their pipeline contract statuses



- During some hours, firm contract plants made up all fuel shortages (a firm contract is not a cure-all)
- In some regions, the peaks in the gas fuel shortage time series were at times made up mostly of capacity on firm pipeline contracts

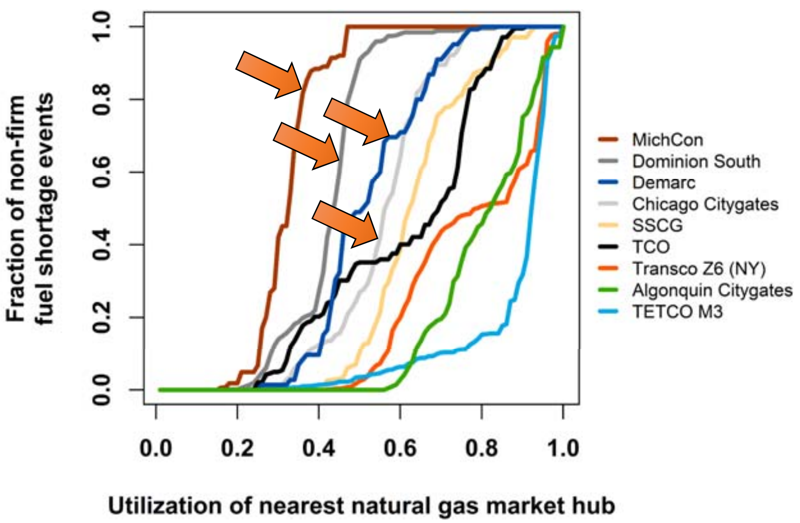
Peaker, shoulder and sometimes baseload plants in each pipeline contract grouping were all affected by gas shortages in just the 6-year study period.



Notes: Bars are weighted by gas-fired power plants' maximum nameplate capacity over the study period. Capacity factors were constructed from EIA-923 data over the study period. Plots show initial grouping of plants by contract using majority of quantity of gas consumed over the study period. "Affected" means that the plant reported one or more fuel shortage failures of any magnitude over the study period.

There was available pipeline capacity during fuel shortage events in many places

- 60% of all MWh lost to fuel shortages occurred at plants near four hubs: MichCon, Dominion South, Demarc, and Chicago Citygates
- These hubs were under-utilized (flowing gas at <60% demonstrated peak) during the majority of days with fuel shortages at nearby power plants using non-firm pipeline contracts.
- So, there was space to move gas through the hub but, was there gas supply to be had?

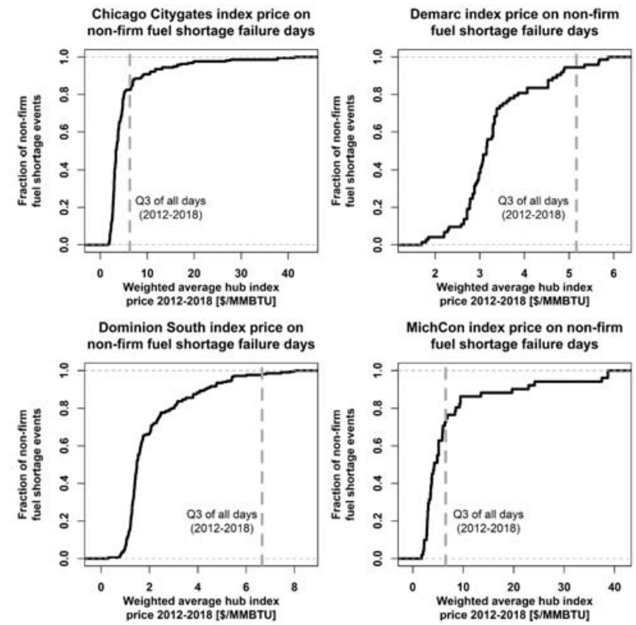


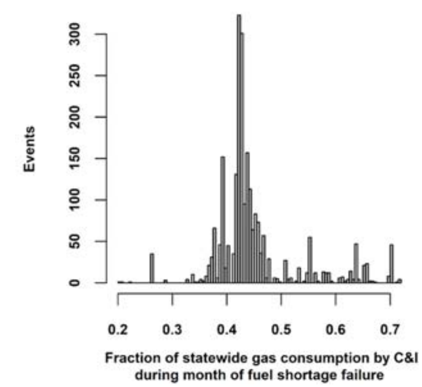
Was there gas to be had?

1. Was there both gas commodity and transportation available on the hub spot market?
    - We see modest gas hub prices** at Chicago, Demarc, and Dominion South during days with fuel shortages at non-firm plants

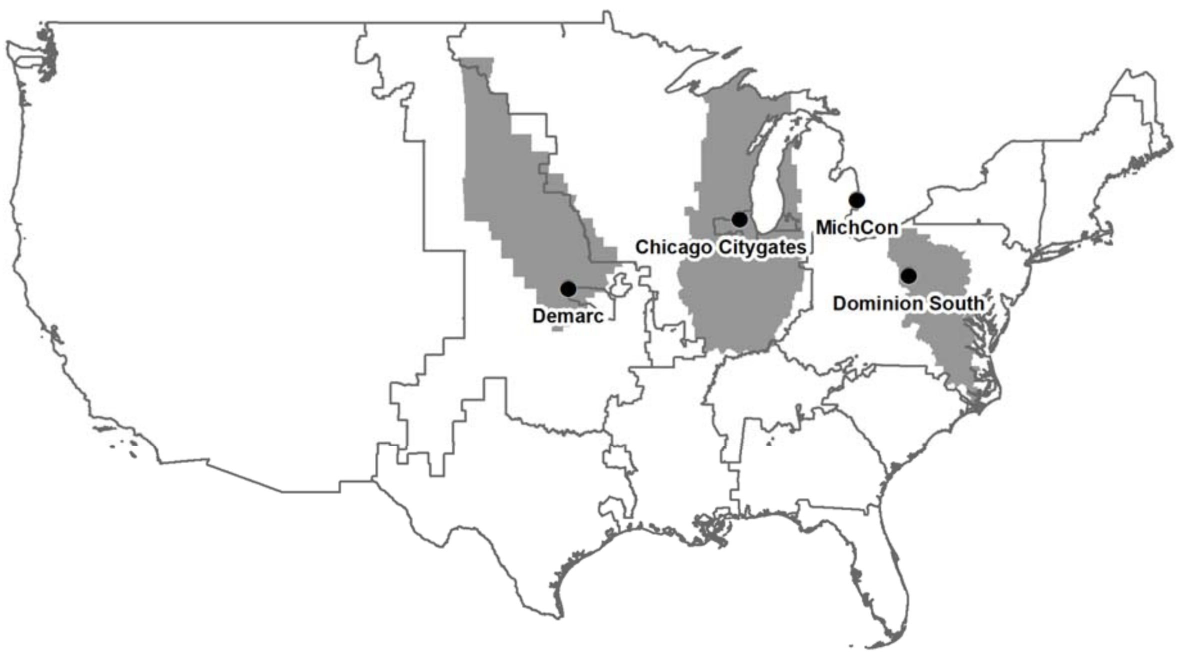
2. Could we have diverted gas from other customers?
    - Between 0.1-9% of statewide gas delivered to C&I could have supplied all of the MWh lost to fuel shortages

**Hub spot price < third quartile price of overall study period distribution for >80% of non-firm events



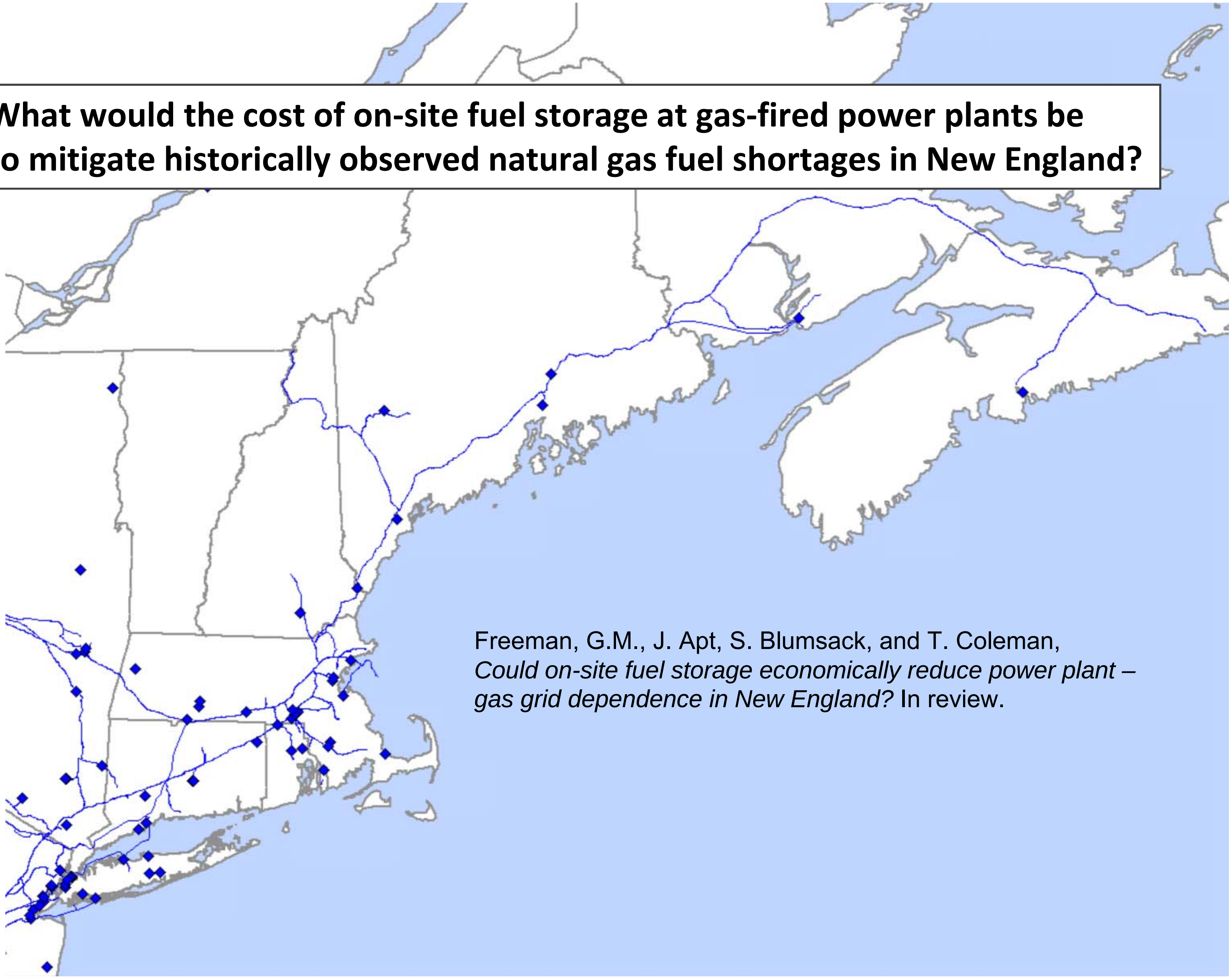


Where were the areas with underutilized hubs and modest spot prices?



Note: MichCon displayed here for informational purposes only.

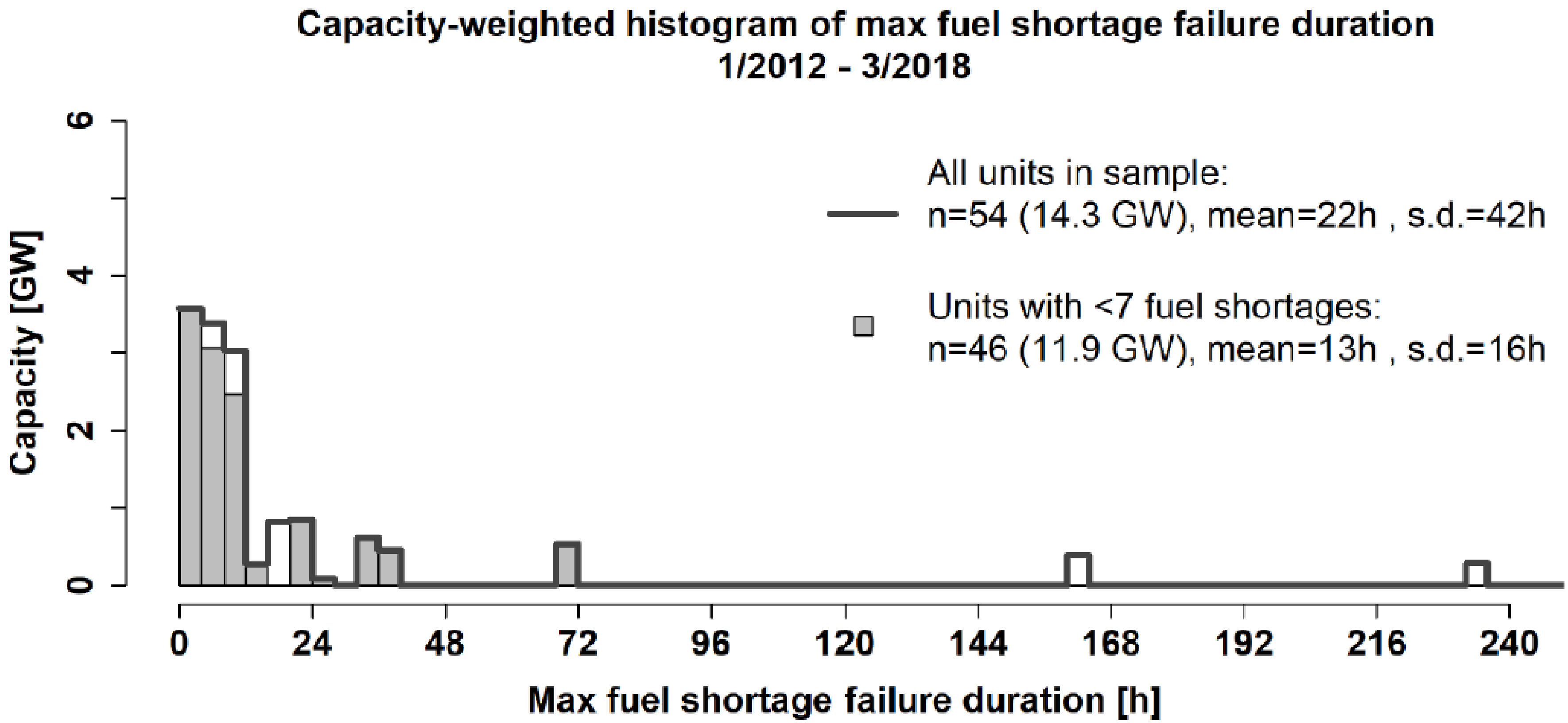
What would the cost of on-site fuel storage at gas-fired power plants be to mitigate historically observed natural gas fuel shortages in New England?



Freeman, G.M., J. Apt, S. Blumsack, and T. Coleman, *Could on-site fuel storage economically reduce power plant – gas grid dependence in New England?* In review.

Source: ABB Velocity Suite

How long are the observed New England gas outages?



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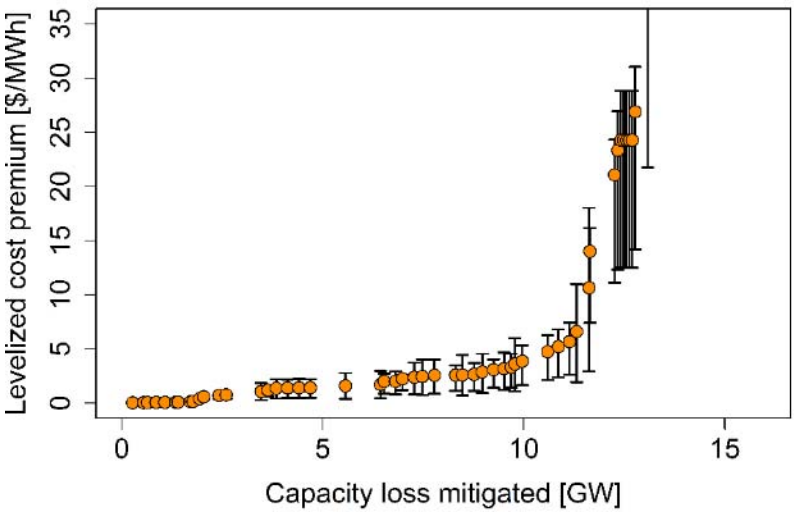
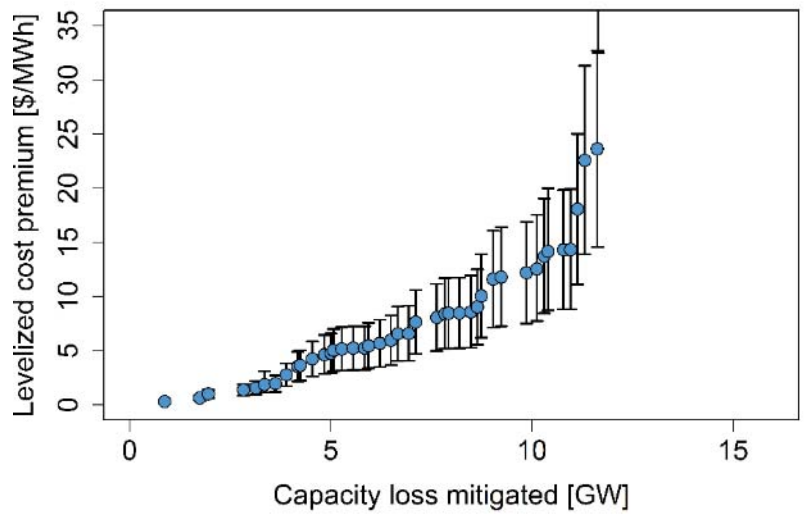
Freeman, G.M., J. Apt, S. Blumsack, and T. Coleman, Could on-site fuel storage economically reduce power plant – gas grid dependence in New England?. In review.

Supply curve for gas/oil dual fuel and on-site CNG storage

Gas/oil dual fuel



On-site CNG storage



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Electric power generator reliability

Carnegie Mellon University

Six years ago, we began a project with NERC that uses a generator-by-generator record of outages, partial outages, and failures to start

GADS: “Generating Availability Data System”

- 8,500 generating units in all 8 NERC regions
- Covers 85% of installed capacity in the U.S. and Canada
- 4 year study period (2012-2015) for our initial work
- 2012- March 2018 for our work on natural gas interruptions you just saw

In parallel, we worked with PJM, analyzing the same sort of data covering 23 years

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Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Resource adequacy risks to the bulk power system in North America

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Applied Energy 253 (2019) 113513

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A time-dependent model of generator failures and recoveries captures correlated events and quantifies temperature dependence

Sinnott Murphy[a], Fallaw Sowell[b], Jay Apt[a,b,*]

Unscheduled outages (U)
Start Failures (SF)
Derates (D)

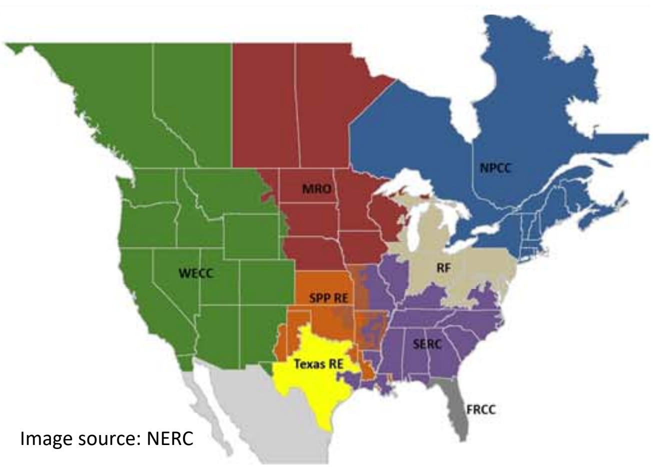


Image source: NERC

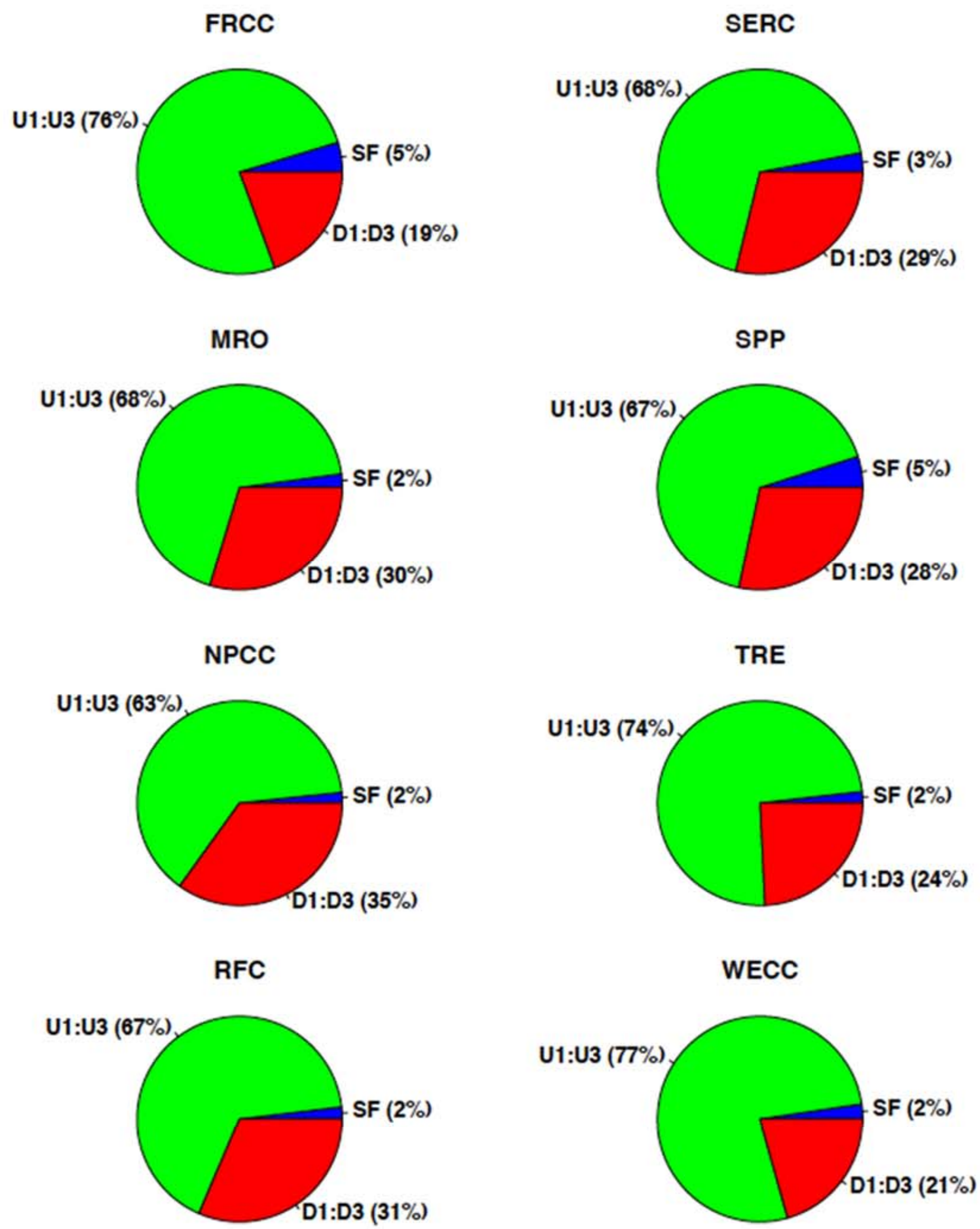


Figure A.3: Proportion of unscheduled unavailable capacity (MWh) by event type category.

Generator outage duration

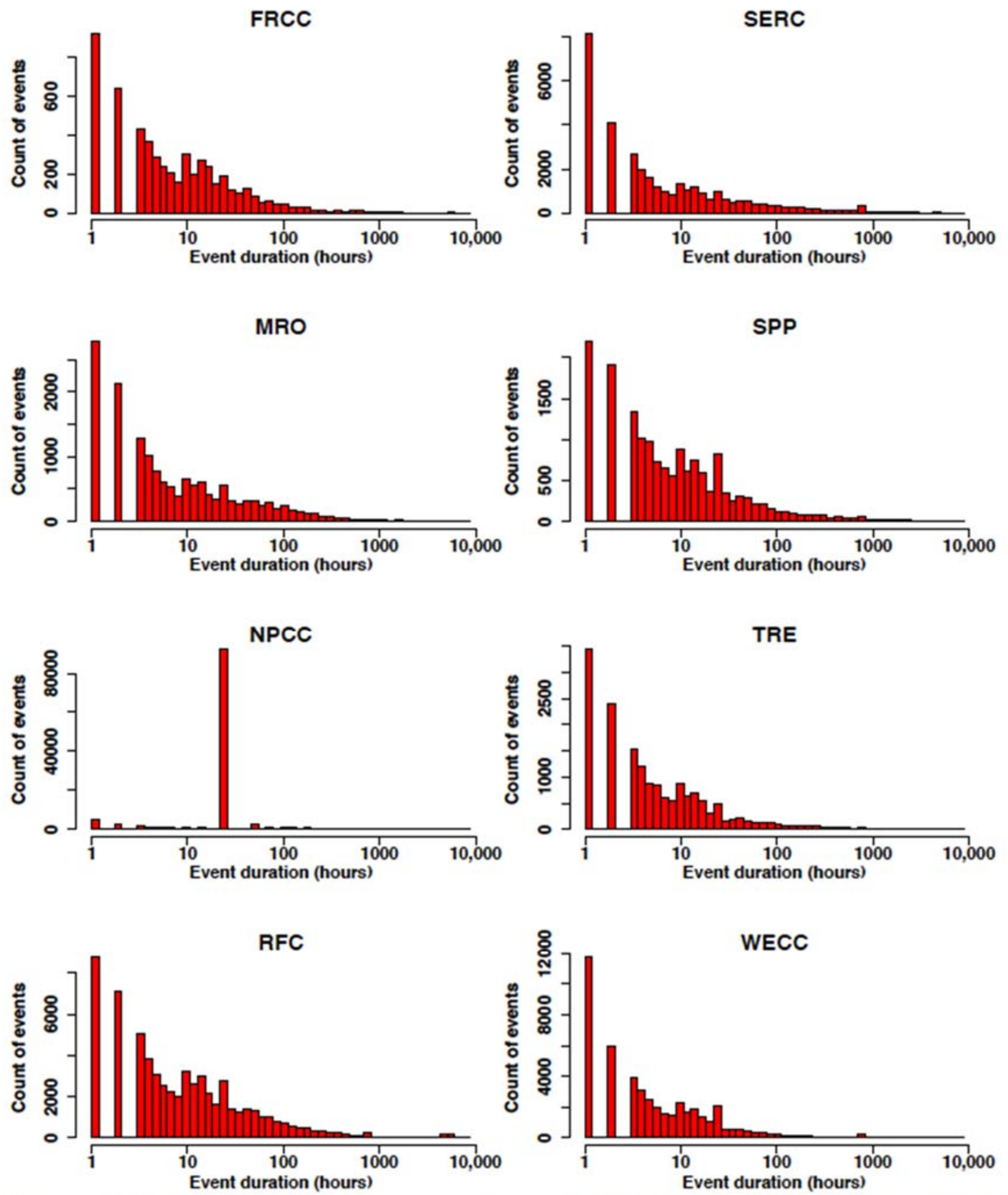


Figure A.8: Histogram of event durations for unscheduled deratings. Full study period. Note the log scale.

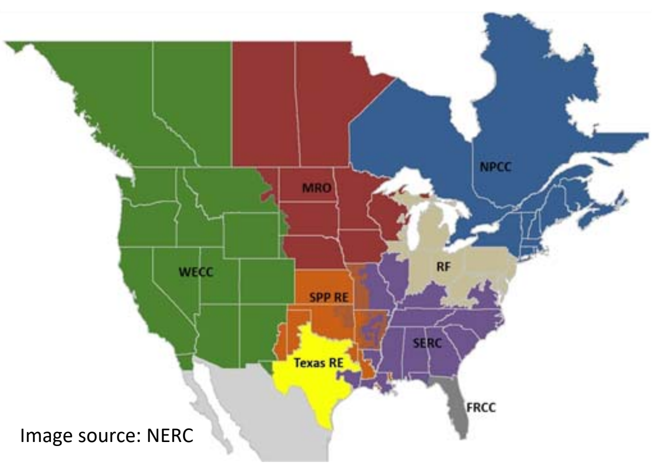
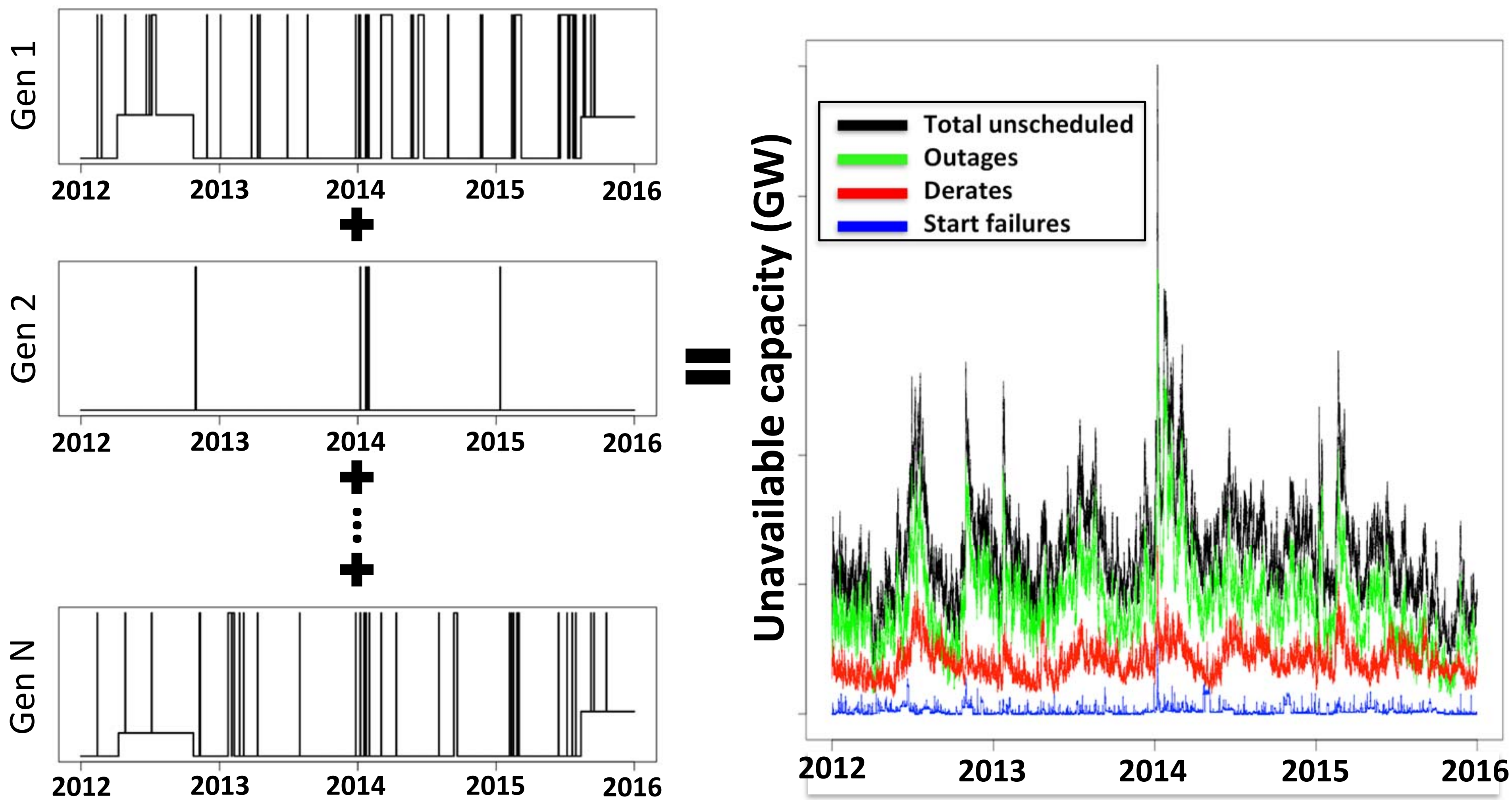
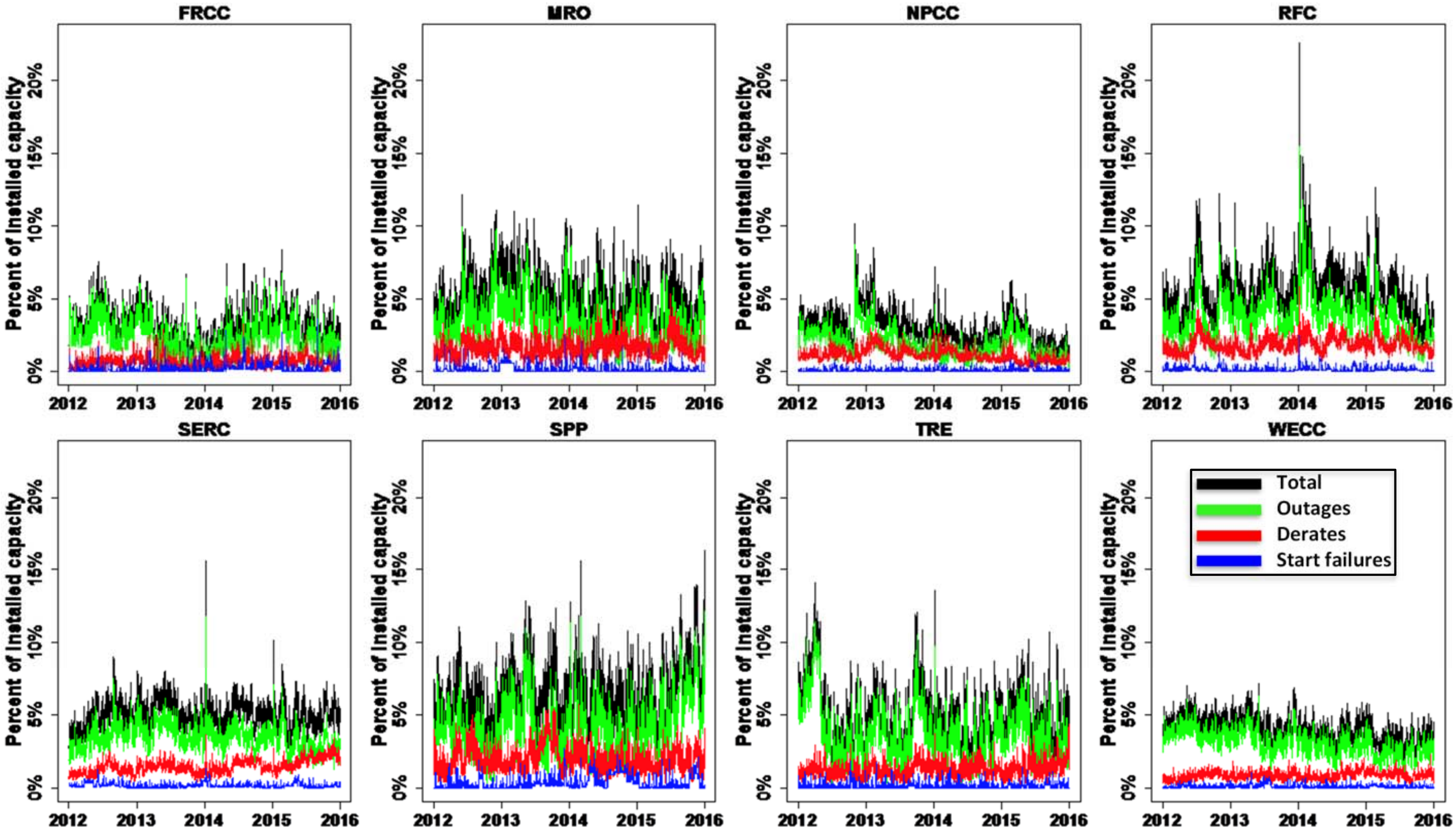


Image source: NERC

Aggregating generator time series



Time series of unscheduled unavailable capacity for each region

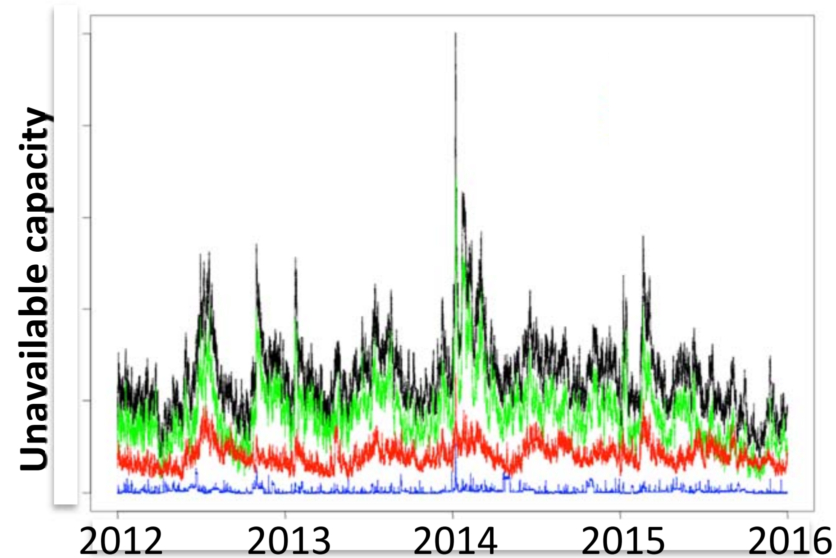


If generator failures are time-dependent, what affects them?

Gaver et al. (1964): environmental conditions can elevate failure probabilities

January 7, 2014 (Polar Vortex): 22% of PJM's total capacity was unavailable

PJM (2014): relationship between cold weather and outages



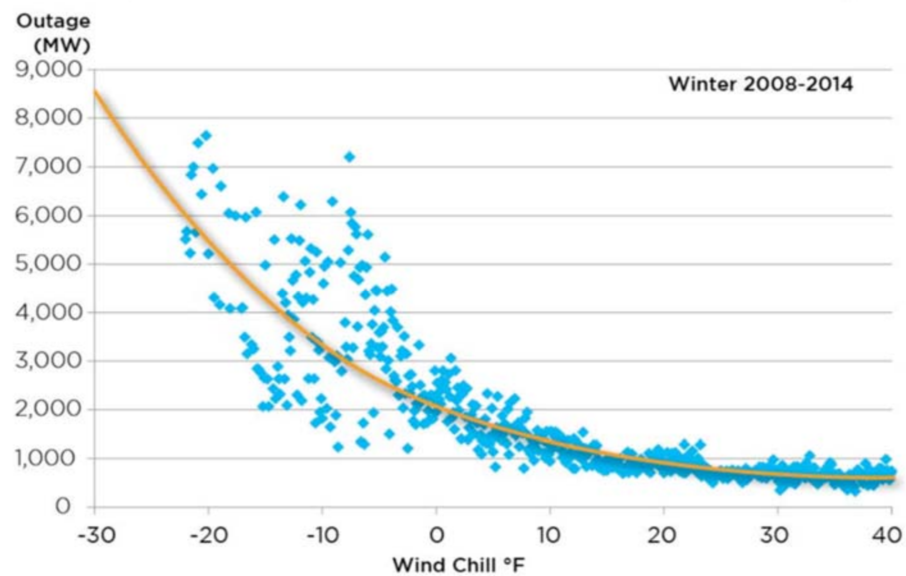
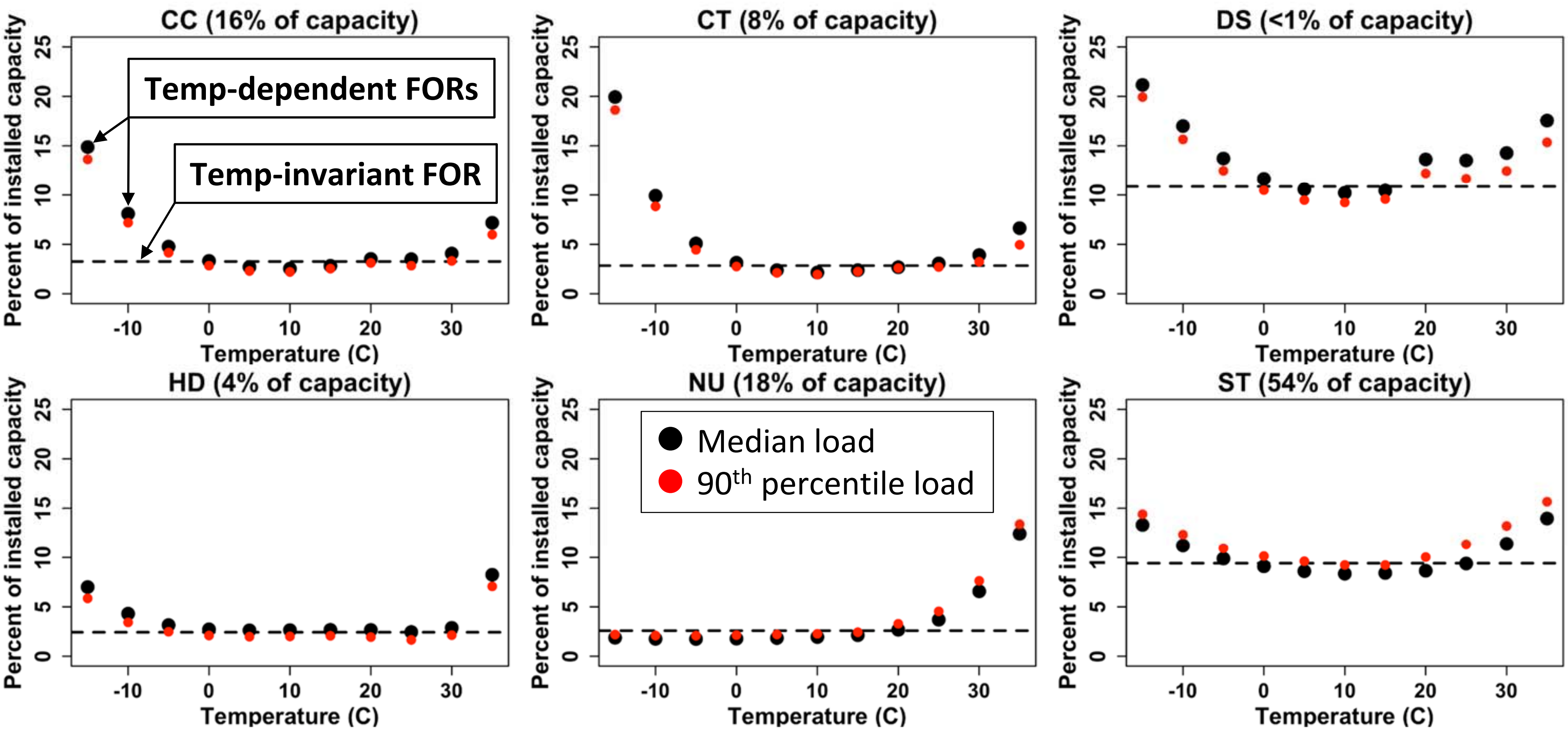


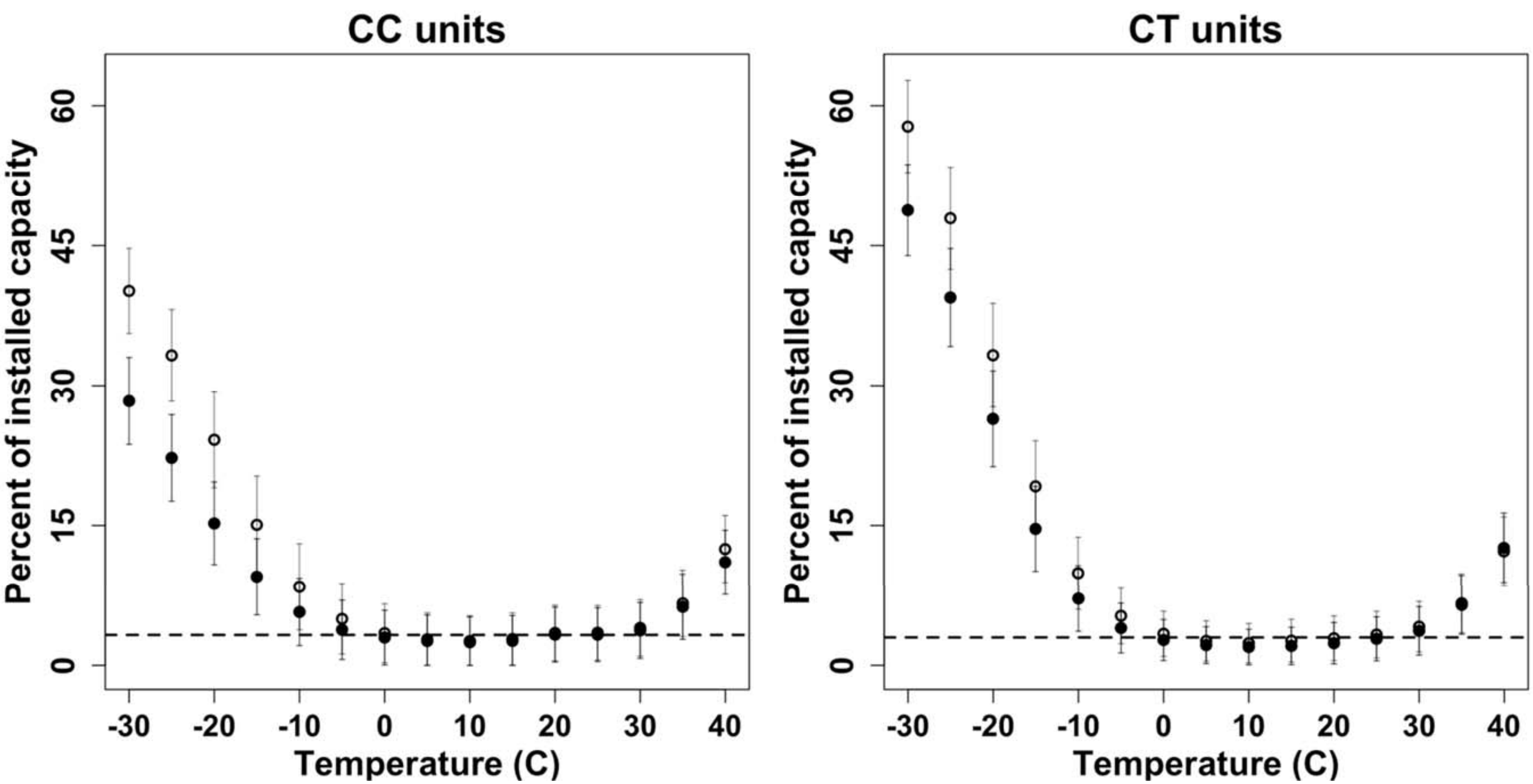
Figure 6, PJM 2014

We modeled the relationship between temperature and unavailable capacity



Unit type key:
CC: combined cycle gas
CT: simple cycle gas
DS: diesel
HD: hydroelectric
NU: nuclear
ST: steam turbine (coal)

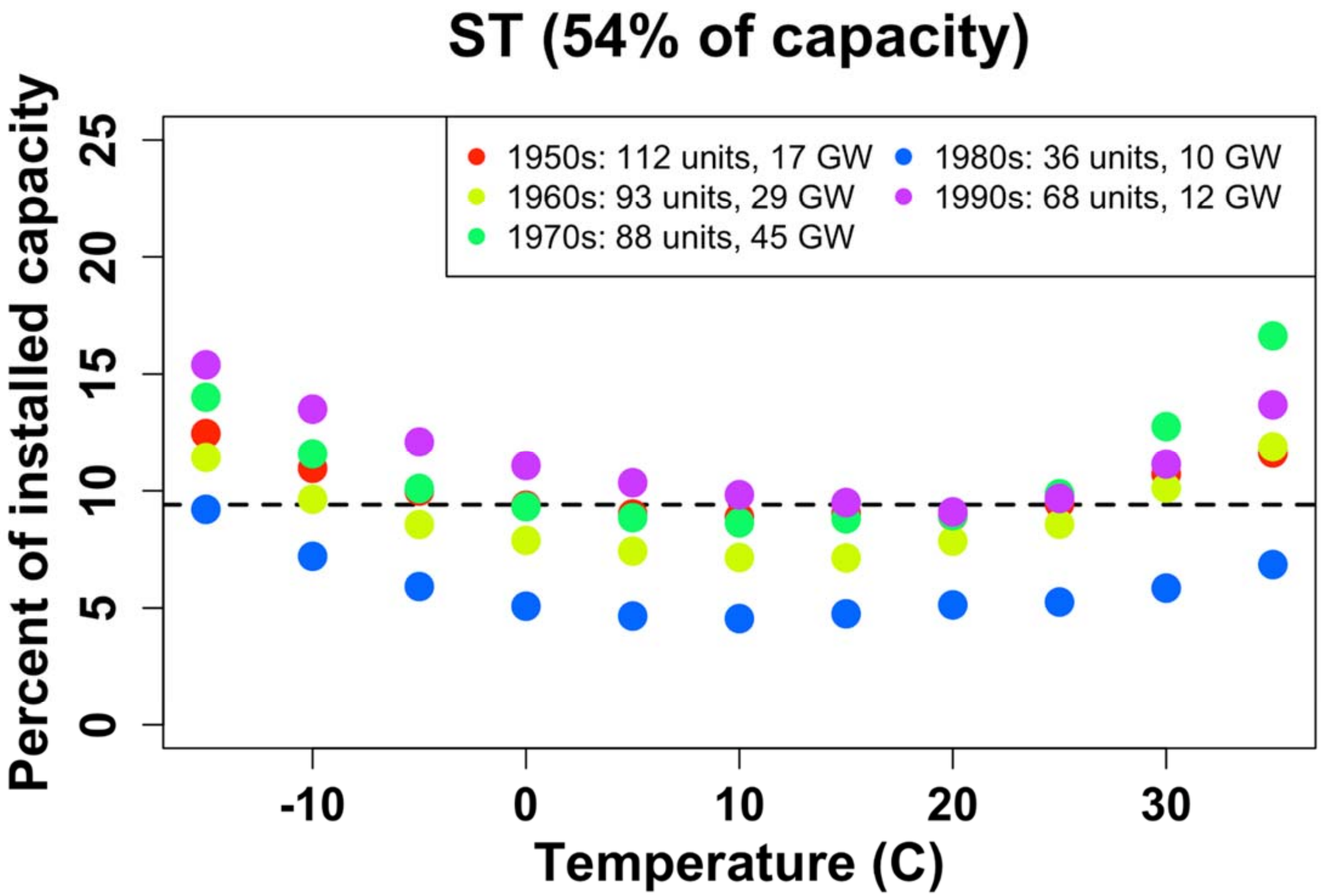
Temperature dependence still present for gas generators when ignoring fuel events



Key:

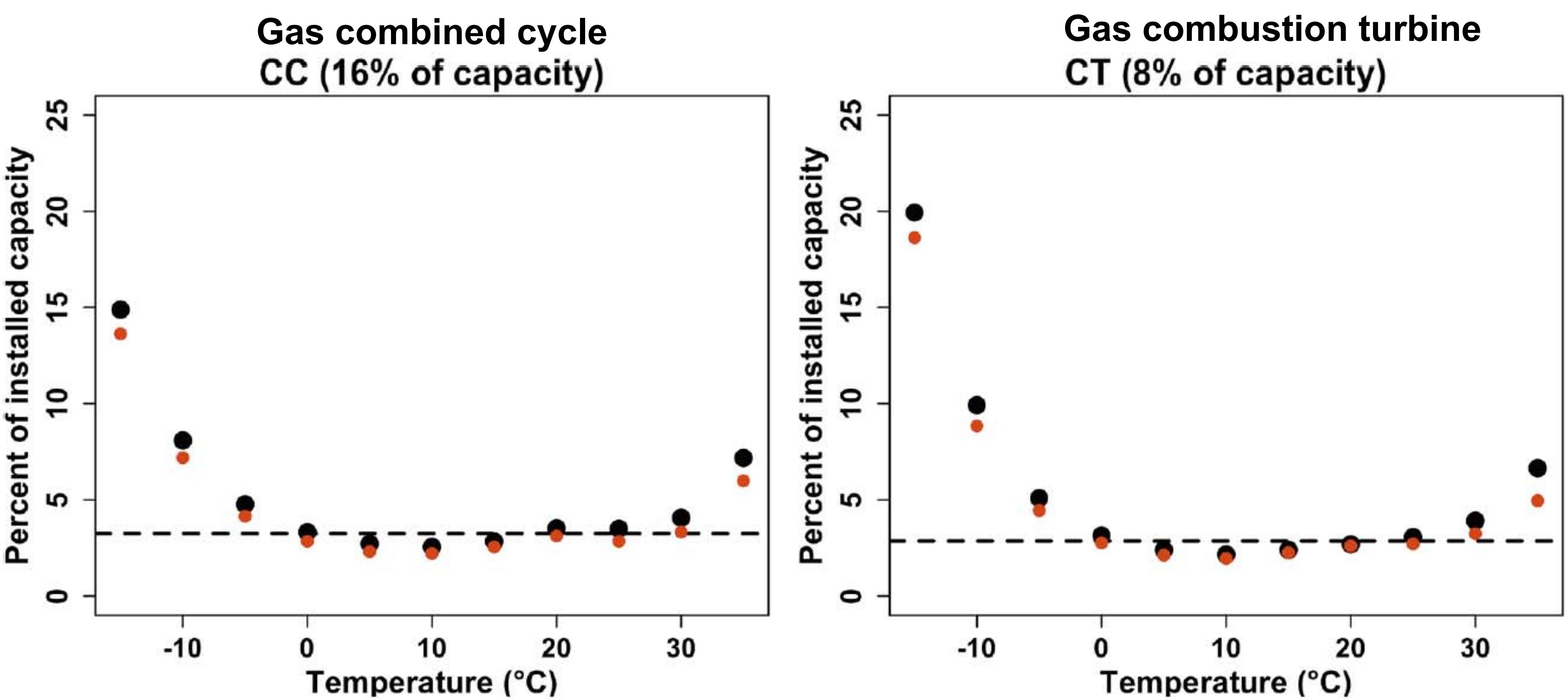
- o Open circles: including all unscheduled events
- • Solid circles: excluding fuel unavailability events

Consistent temperature dependence for coal generators when segmenting by generator age

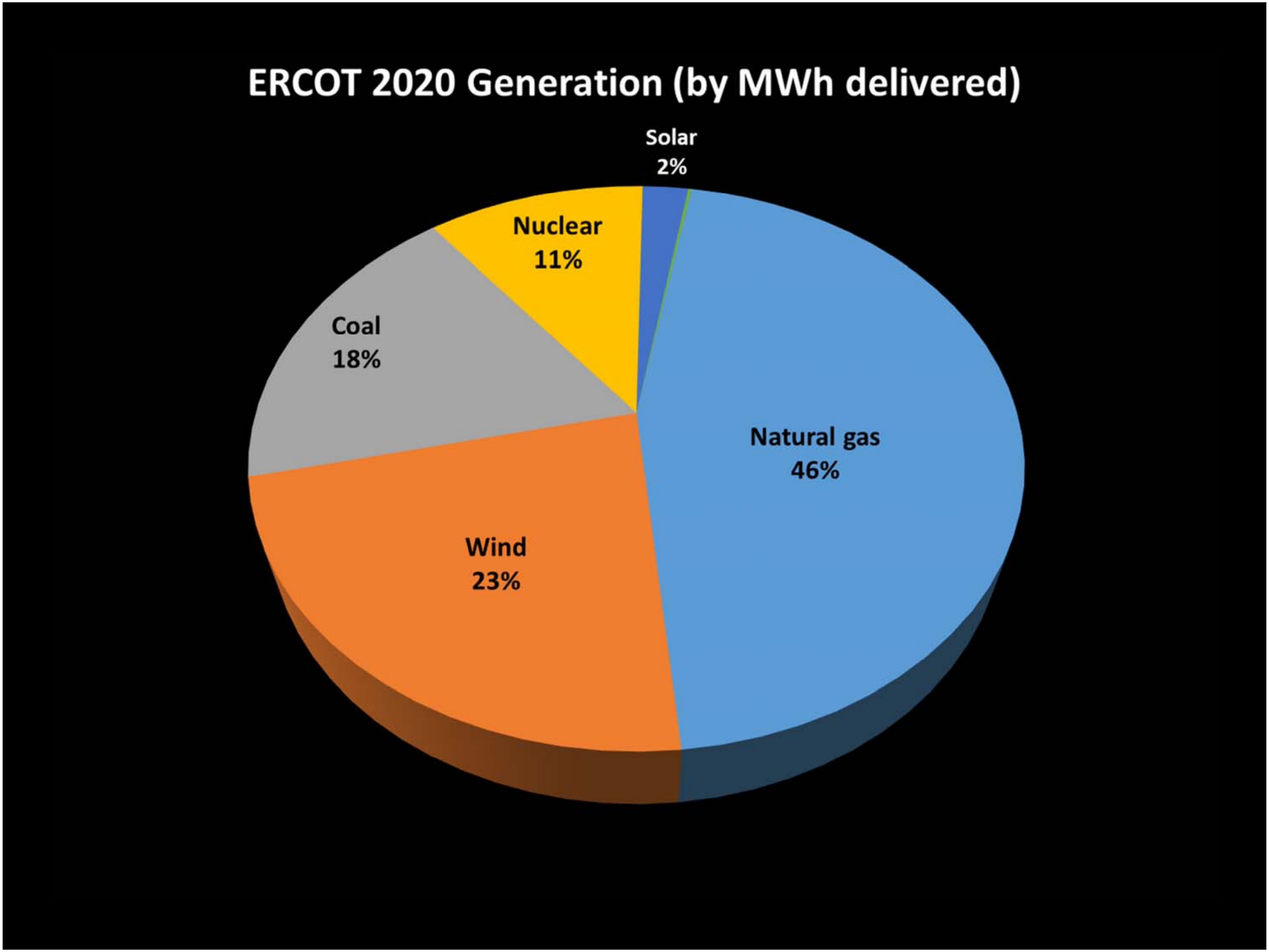


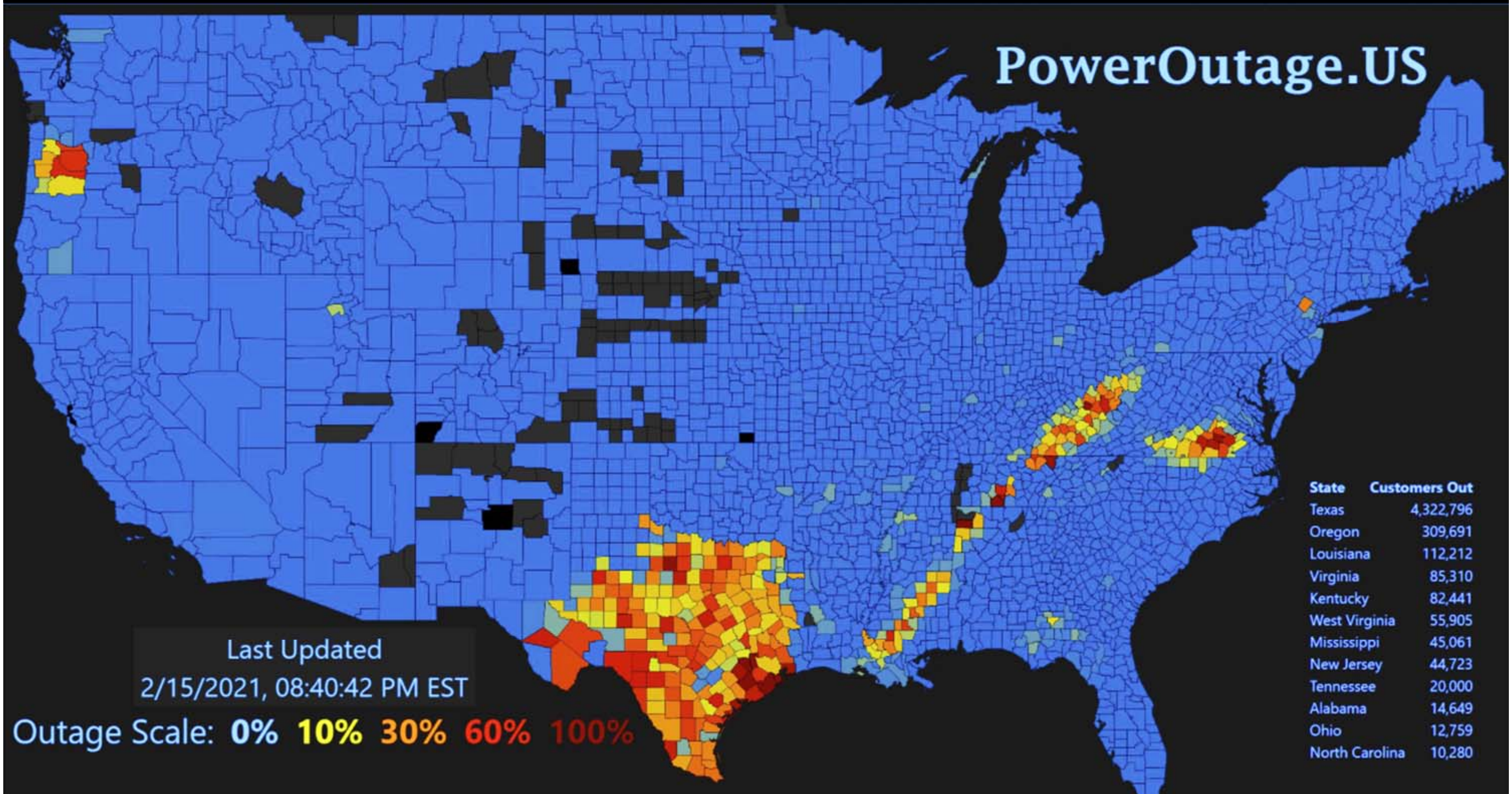
To summarize:

- Correlated failures of NERC electric power generators occurred in 2012–2015.
- Correlated failures happen in most NERC regions even when major storms are removed.
- Correlated outages should be considered in defining resource adequacy requirements.



Which brings us to
Texas


ERCOT 2020 Generation (by MWh delivered)
Solar
2%
Nuclear
11%
Coal
18%
Natural gas
46%
Wind
23%



PowerOutage.US
State Customers Out
Texas 4,322,796
Oregon 309,691
Louisiana 112,212
Virginia 85,310
Kentucky 82,441
West Virginia 55,905
Mississippi 45,061
New Jersey 44,723
Tennessee 20,000
Alabama 14,649
Ohio 12,759
North Carolina 10,280
Last Updated
2/15/2021, 08:40:42 PM EST
Outage Scale: 0% 10% 30% 60% 100%

Generation that failed 2/15-18/2021

(ERCOT has 107 GW. A large nuclear plant is approx. 1 GW)

https://www.entergynewsroom.com/article/entergy-texas-storm-update-2-15-21-5-p-m/

https://www.powermag.com/wp-content/uploads/2014/10/PWR_1014_SR_OM_WinterGas_Fig3.jpg

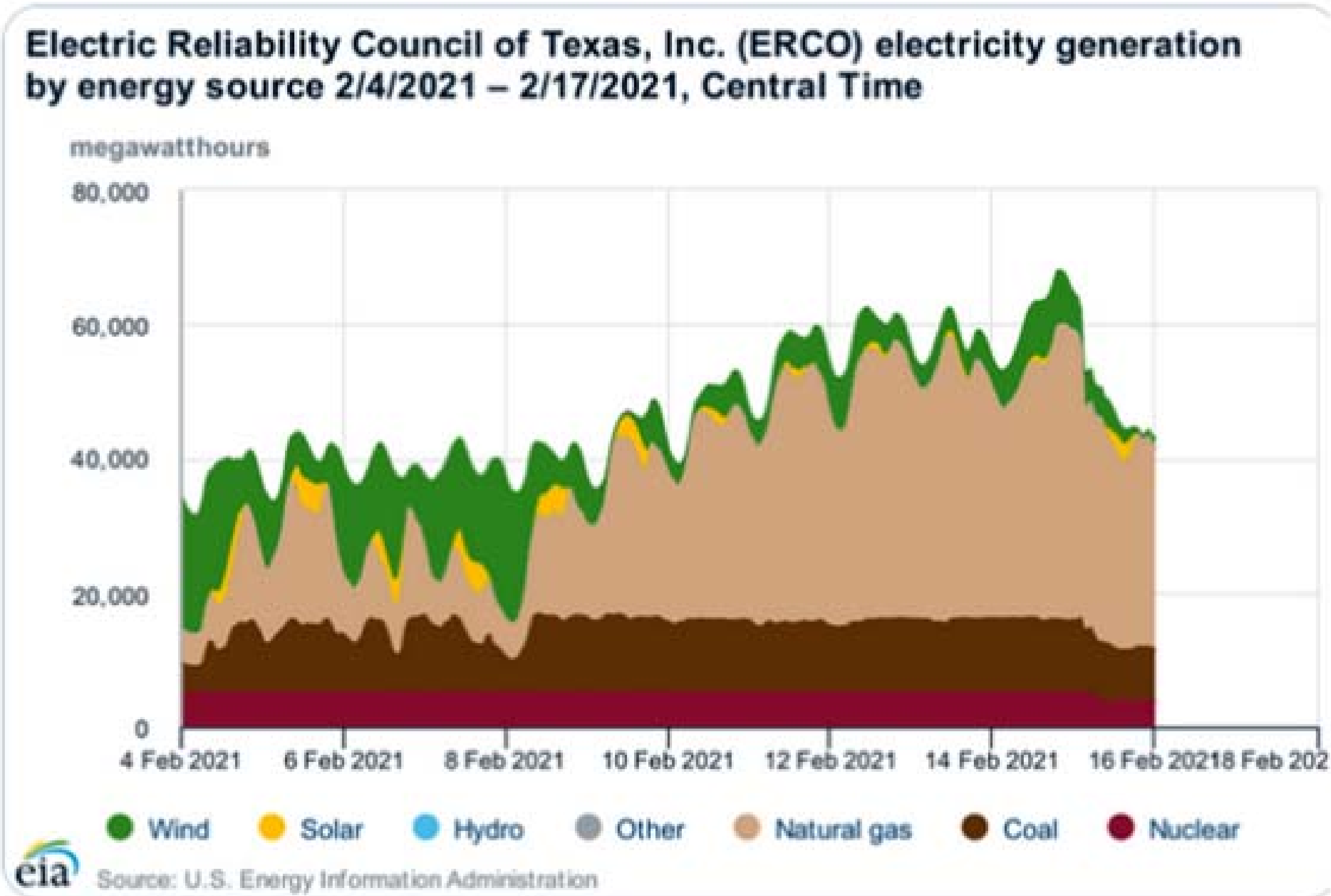
15 GW of natural gas

4 GW of coal

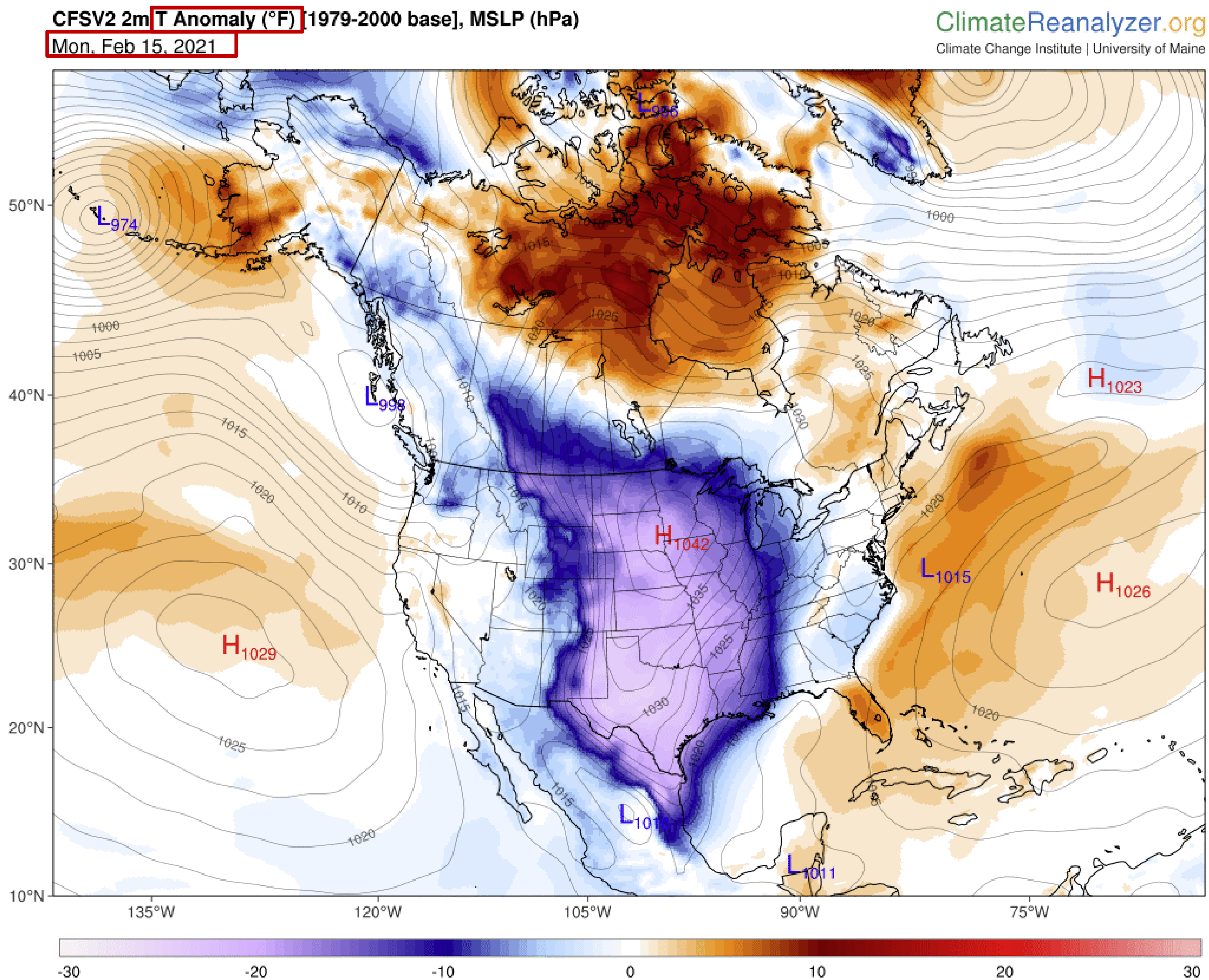
3 GW of wind

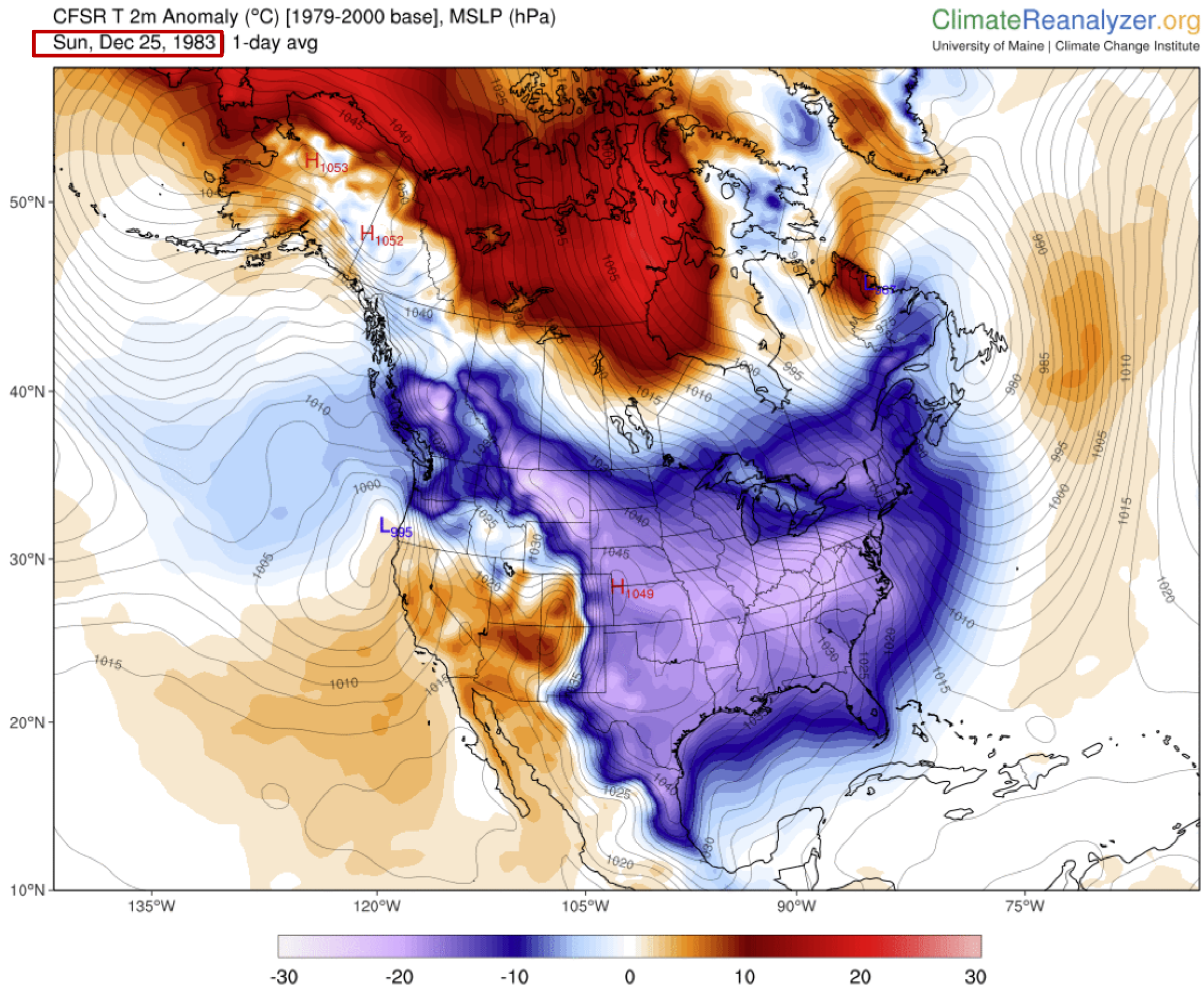
1 GW of nuclear

1 GW of solar



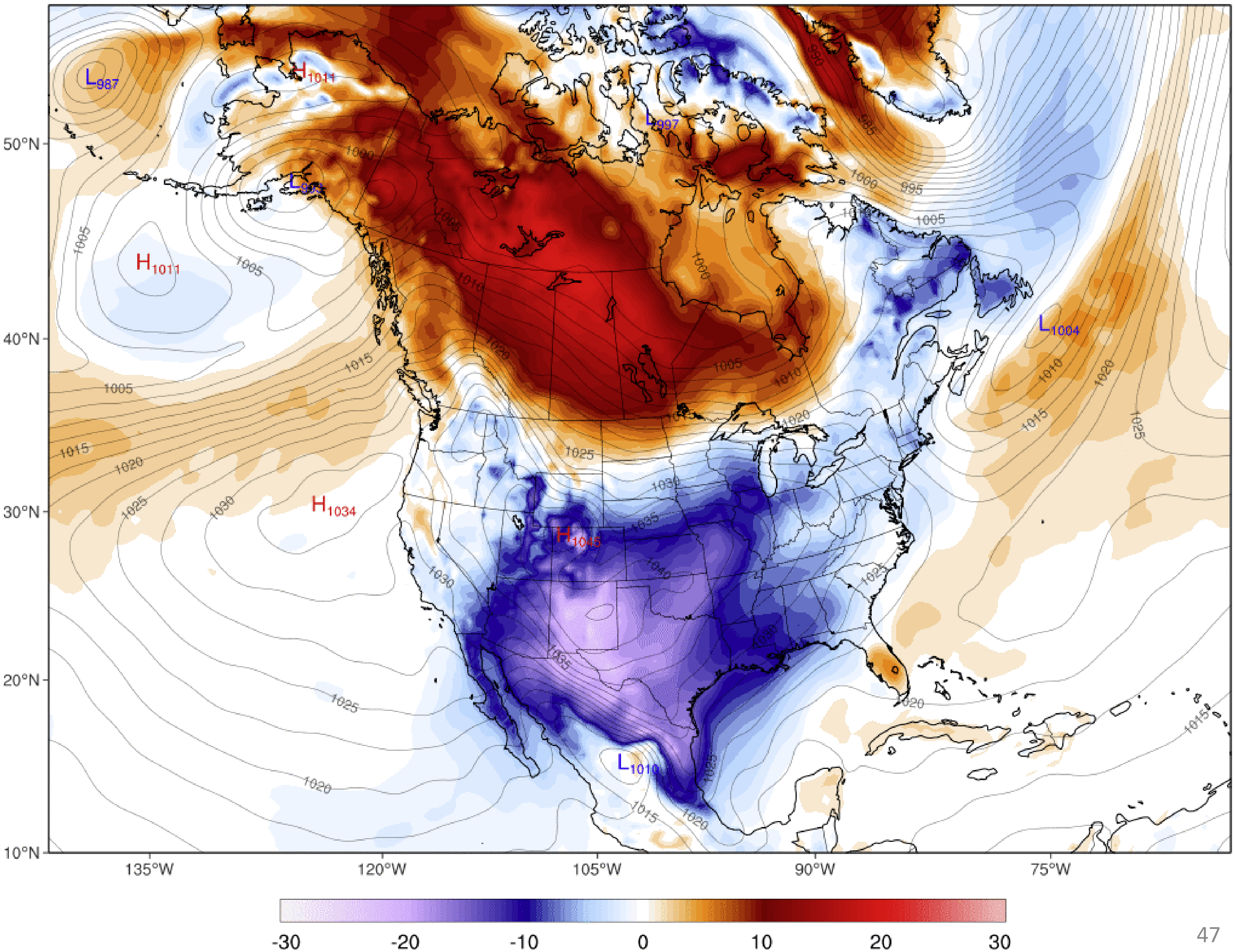
12:42 PM · Feb 17, 2021 · Twitter Web App


CFSV2 2m T Anomaly (°F) [1979-2000 base], MSLP (hPa)
Mon, Feb 15, 2021
ClimateReanalyzer.org
Climate Change Institute | University of Maine
L974
L998
H1042
H1023
L1015
H1026
H1029
L1011
50°N
40°N
30°N
20°N
10°N
135°W
120°W
105°W
90°W
75°W
-30
-20
-10
0
10
20
30


CFSR T 2m Anomaly (°C) [1979-2000 base], MSLP (hPa)
Sun, Dec 25, 1983 1-day avg
ClimateReanalyzer.org
University of Maine | Climate Change Institute
H1053
H1052
H1049
L995
50°N
40°N
30°N
20°N
10°N
135°W
120°W
105°W
90°W
75°W
-30
-20
-10
0
10
20
30

CFSR T 2m Anomaly (°C) [1979-2000 base], MSLP (hPa)
Thu, Feb 03, 2011 | 1-day avg

ClimateReanalyzer.org
University of Maine | Climate Change Institute



Expected Unserved Energy and Reserve Margin Implications of Various Reliability Standards

January 28, 2015

PREPARED FOR

ERCOT

Electric Reliability Council of Texas

PREPARED BY

Nick Wintermantel
Kevin Carden
Astrape Consulting

ASTRAPÉ CONSULTING
innovation in electric system planning

Methodology and Input Summary

Since most reliability events are high impact, low probability events, a large number of scenarios must be considered to account for uncertainties in weather, load forecasts, and unit performance. The study used a probabilistic approach to model the uncertainty of weather, economic growth, unit availability, and transmission availability with neighboring regions for emergency tie assistance. Utilizing the Strategic Energy Risk Valuation Model (SERVM)[2], 5,500 hourly simulations were performed for 2016 at each reserve margin level to calculate physical reliability metrics for ERCOT. The 5,500 yearly simulations consisted of 11 historical weather years[3], simulated with 5 load forecast error multipliers and 100 Monte Carlo unit outage draws.[4] Each weather year was given equal probability except for 2011 which was given a 1% probability based on National Oceanic and Atmospheric Administration historical weather data. Each load forecast error multiplier was given a distinct probability of occurrence based on a review of historical economic growth uncertainty. Each Monte Carlo unit outage draw was given equal probability. For each iteration simulated, SERVM records the number of events, hours, and magnitude of all firm load shed events. A loss-of-load event in SERVM is defined as one or more consecutive hours of load shed. SERVM dispatches resources to meet load, regulation, spin, and non-spin requirements. For this assessment, it was assumed that load would be shed to maintain 500 MW of regulation and 600 MW of spinning reserve across the ERCOT region.

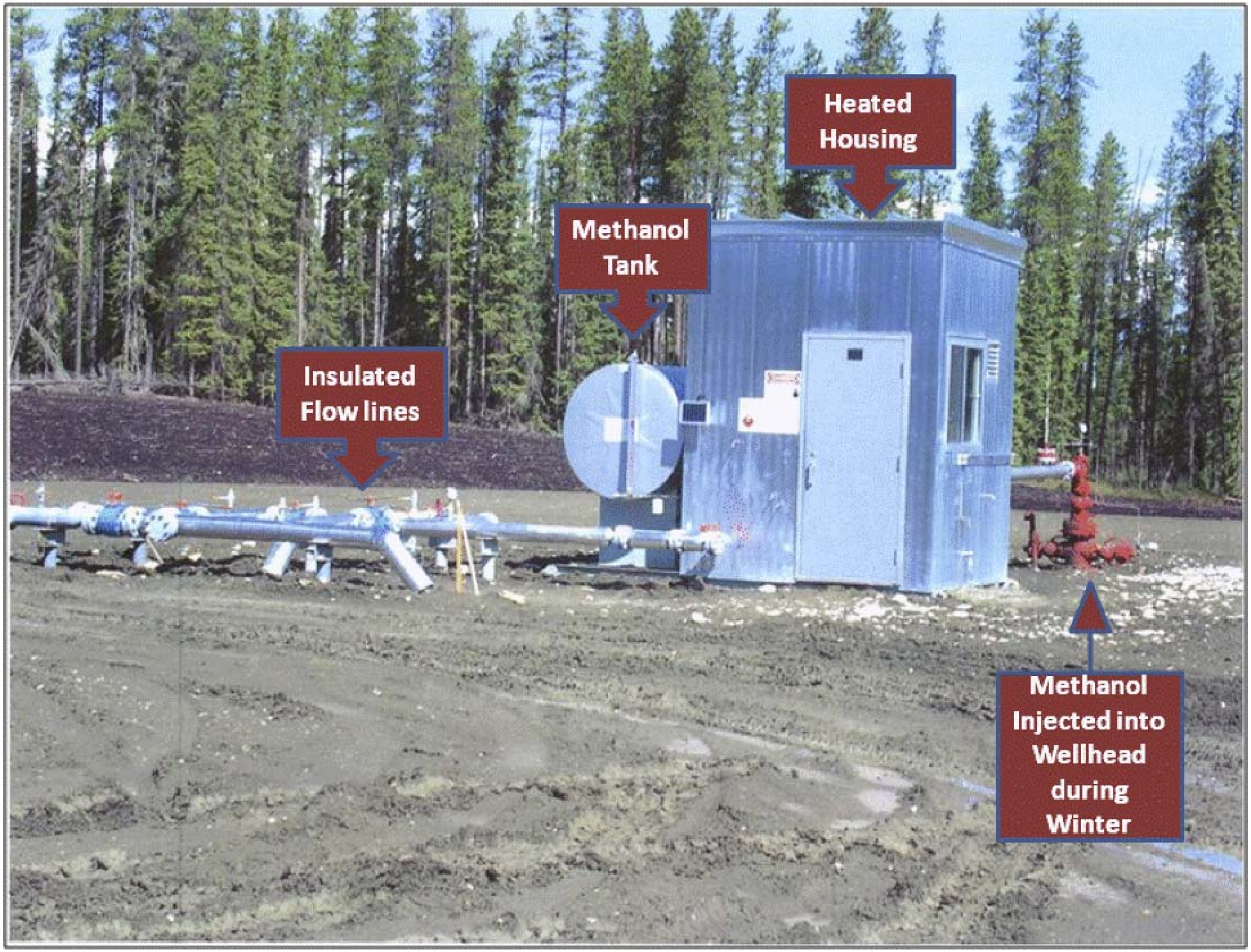
Astrape's latest ERCOT analysis, released 1/15/2021, does not consider temperature in estimating generator failures.

Table A1-4. Forced Outage Rates by Asset Class and Fleet Average

Unit Type	Equivalent Forced Outage Rate *(%)*	Mean Time to Fail *(hours)*	Mean Time to Repair *(hours)*
Gas Combined Cycle	3.7	1,312	32
Gas Combustion Turbine	8.3	967	74
Gas Steam	14.0	687	58
Coal	5.9	833	39
Nuclear	0.2	16,467	330
Fleet Weighted Average	**5.9**		

Sources and Notes: Parameter distributions based on two years (2018-2019) of unit-specific GADS data and asset class average outage rates from ERCOT.


COOPERATIVE
CAES
COMPRESSED AIR ENERGY STORAGE
PLANT

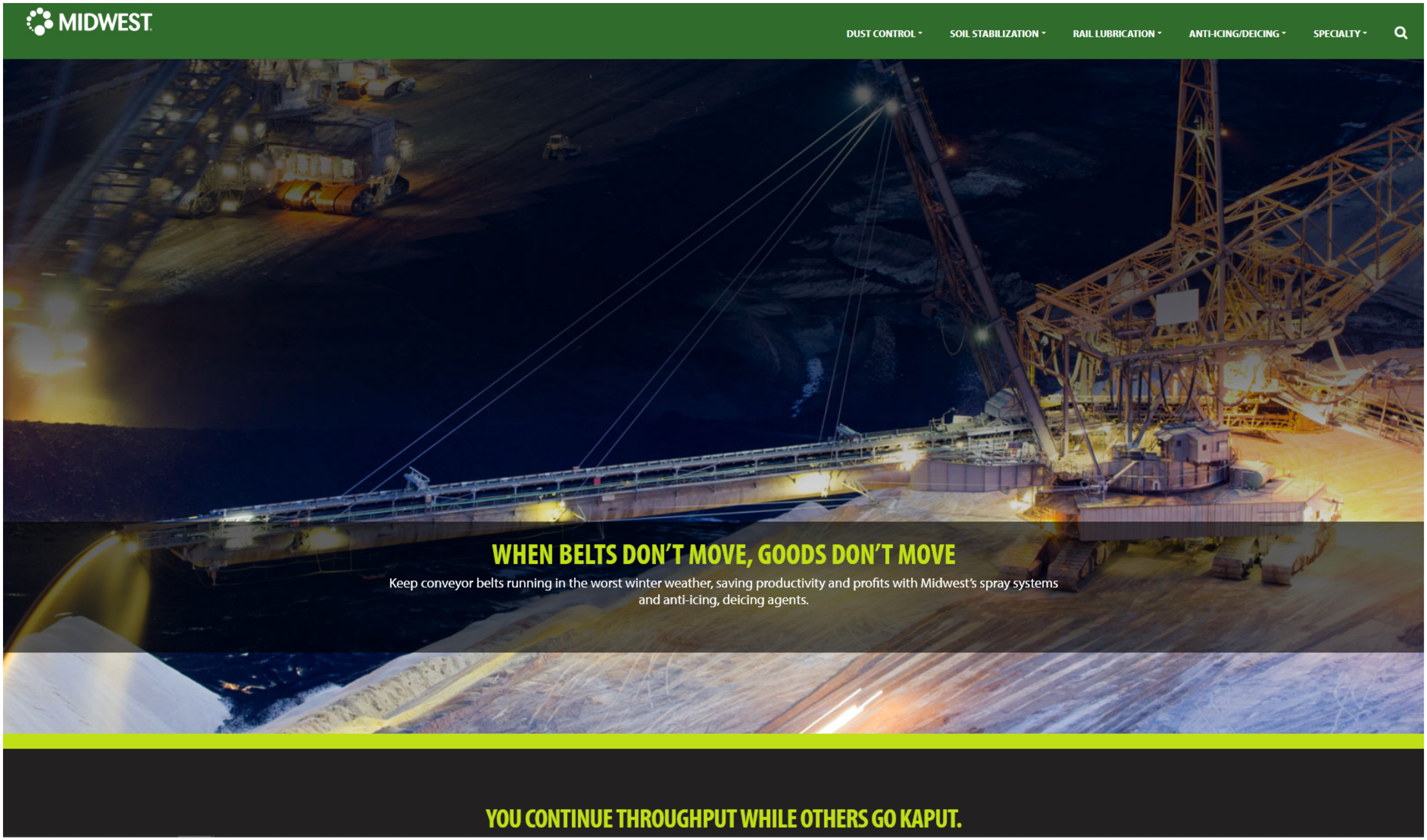


Heated Housing
Methanol Tank
Insulated Flow lines
Methanol Injected into Wellhead during Winter

Figure 13 - Typical wellhead in Warm Climate. (GTI) No methanol or other injection equipment for freeze mitigation. Flow line is elevated without insulation of other protection from cold weather. Tank battery and other production equipment are not protected from cold weather. (Ref. 4)

Gas Well Winterization Expenses				
Cold Weather Protection Equipment	**Description**	**Cost Per Well - Excludes Duplicate Applications**	**Source**	
Capital Cost				
Winterized Production Unit - Net Cost for Winterization	Production unit winterized by internal piping and insulation.	$23,000	Sivals Engineering, Odessa, Tx., Ref 20	
Methanol Injection Pump	High Pressure Pump to Inject Methanol	$1,648	ZKO Oilfield Industries, Ref. 11	
Timberline solar powered methanol pump w/solar panels		$2,800	Timberline Manufacturing, Ref. 22	
Chemical Pump to Supply Chemical Inhibitors	Chemical Inhibitor Pump for Corrosion Protection	$1,350	ZKO Oilfield Industries Ref. 11	
Vent Gas Bottle to Supply Heater	System to Collect Vent Gas from Injection Pumps to Supply Heaters	$675	ZKO Oilfield Industries Ref. 11	
Methanol Tank	Stores Methanol	$1,000	estimate	
Methanol Injection Tubing - High Pressure - $5/Ft - 100 Ft	Methanol Transfer	$500	Drillspot .com	
Flow Line Insulation - $3/Ft - 100 Ft	Insulate Flow Line	$300	Drillspot .com	
Flow Line Heat Tape - $4/Ft - 100 Ft	Provide Heat to Flow Line	$400	Drillspot .com	
Fiberglass Hut for Enlcosing Production Equipment	Weather Protection	$500	JW Williams Co. Casper, Wyoming, Ref. 21	
Catalytic Heater for Location Housing	Heating for Hut	$500	ZKO Oilfield Industries Ref. 11	
Installation Cost - 2 men for 3 days at $50 per hour.	Labor	$2,400	JW Williams Co. Casper, Wyoming, Ref. 21	
Operating Expense for Methanol Injection				
Methanol costs are $4.00 per gallon. Assume 10 gallons per day for 5 months. Methanol cost = 5 months * 30 days/mo.*10 gal/day * $4/gallon = $6000	Methanol Cost	$6,000	Timberline Manufacturing, Ref. 22	
Maintenance - Per Month - $200 @ 5 months		$1,000		
Total - Cost per Year		$7,000		

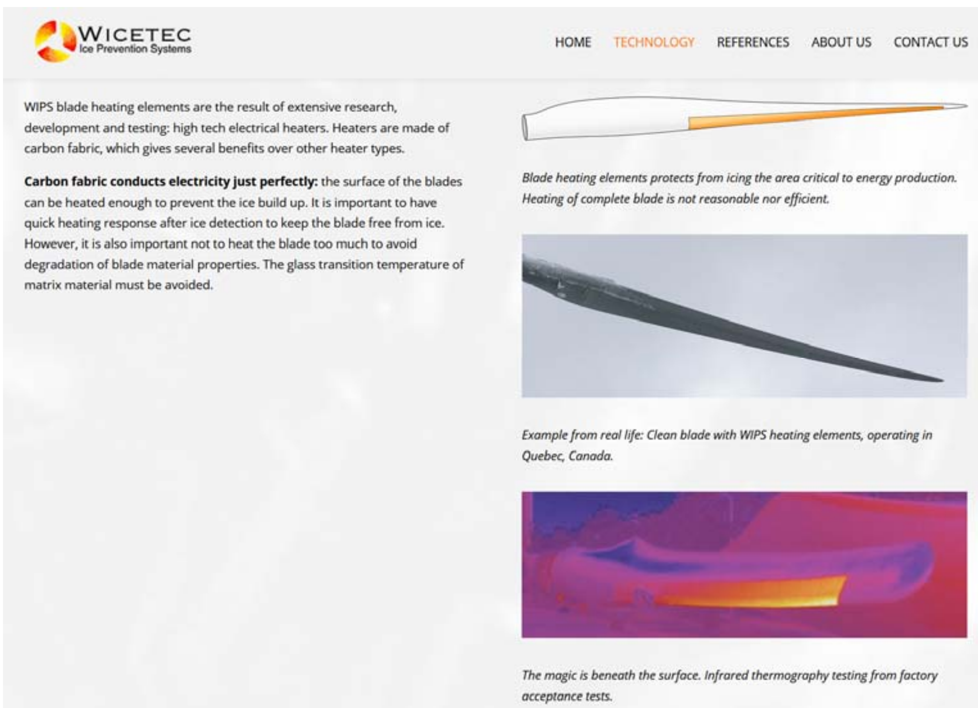
Deicing for coal conveyor belts



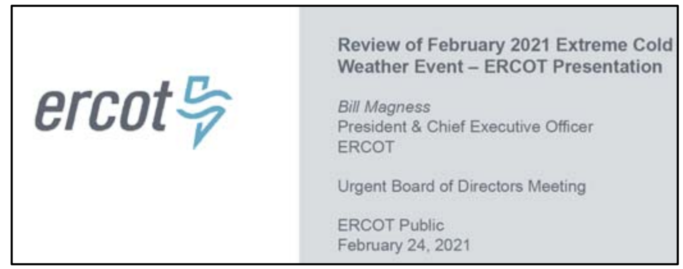
https://midwestind.com/anti-icing-and-deicing/conveyor-belt-deicer/

Wind turbines

- Not only blades (can buy heated blades)
- Gearboxes
- Cold-temperature packages are available
- But Canada was surprised a few years ago



Generation owners and operators are not required to implement any minimum weatherization standard or perform an exhaustive review of cold weather vulnerability. No entity, including the PUC or ERCOT, has rules to enforce compliance with weatherization plans or enforce minimum weatherization standards.



Evidently, the prospect of $9,000/MWh for electricity or $200/mmcf natural gas was not enough to induce winterization in either system.

What this temperature-dependence means for procuring reserves

Applied Energy 262 (2020) 114424

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Resource adequacy implications of temperature-dependent electric generator availability

Sinnott Murphy[a], Luke Lavin[a], Jay Apt[a,b,*]

[a] Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA
[b] Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA, USA

Energy Policy 147 (2020) 111857

Contents lists available at ScienceDirect

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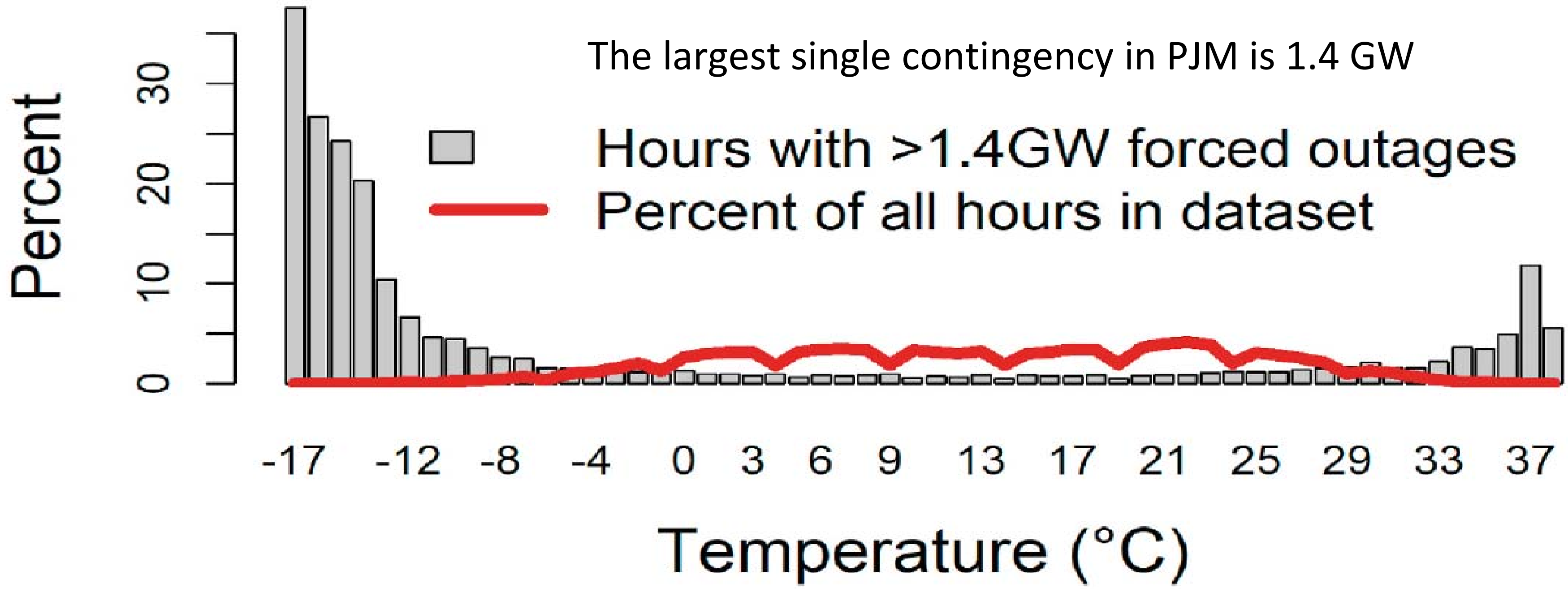
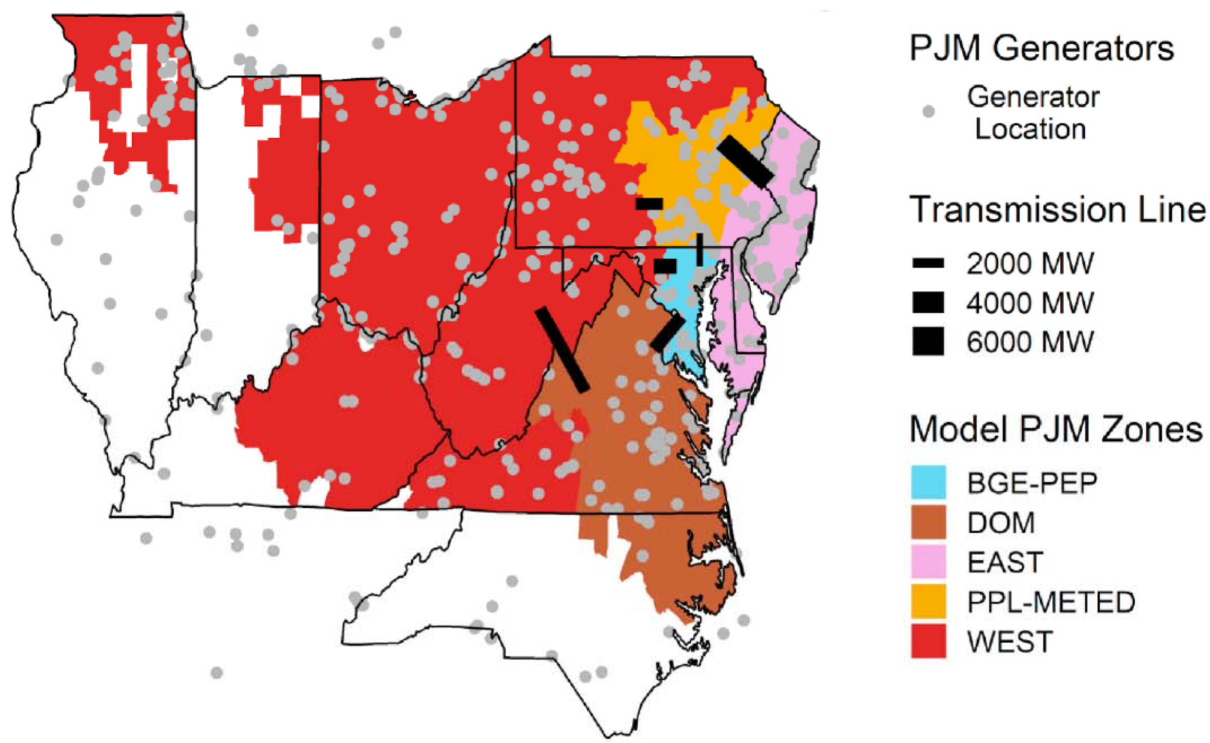
Dynamic operating reserve procurement improves scarcity pricing in PJM

Luke Lavin[a,*], Sinnott Murphy[a,1], Brian Sergi[a,1], Jay Apt[a,b]

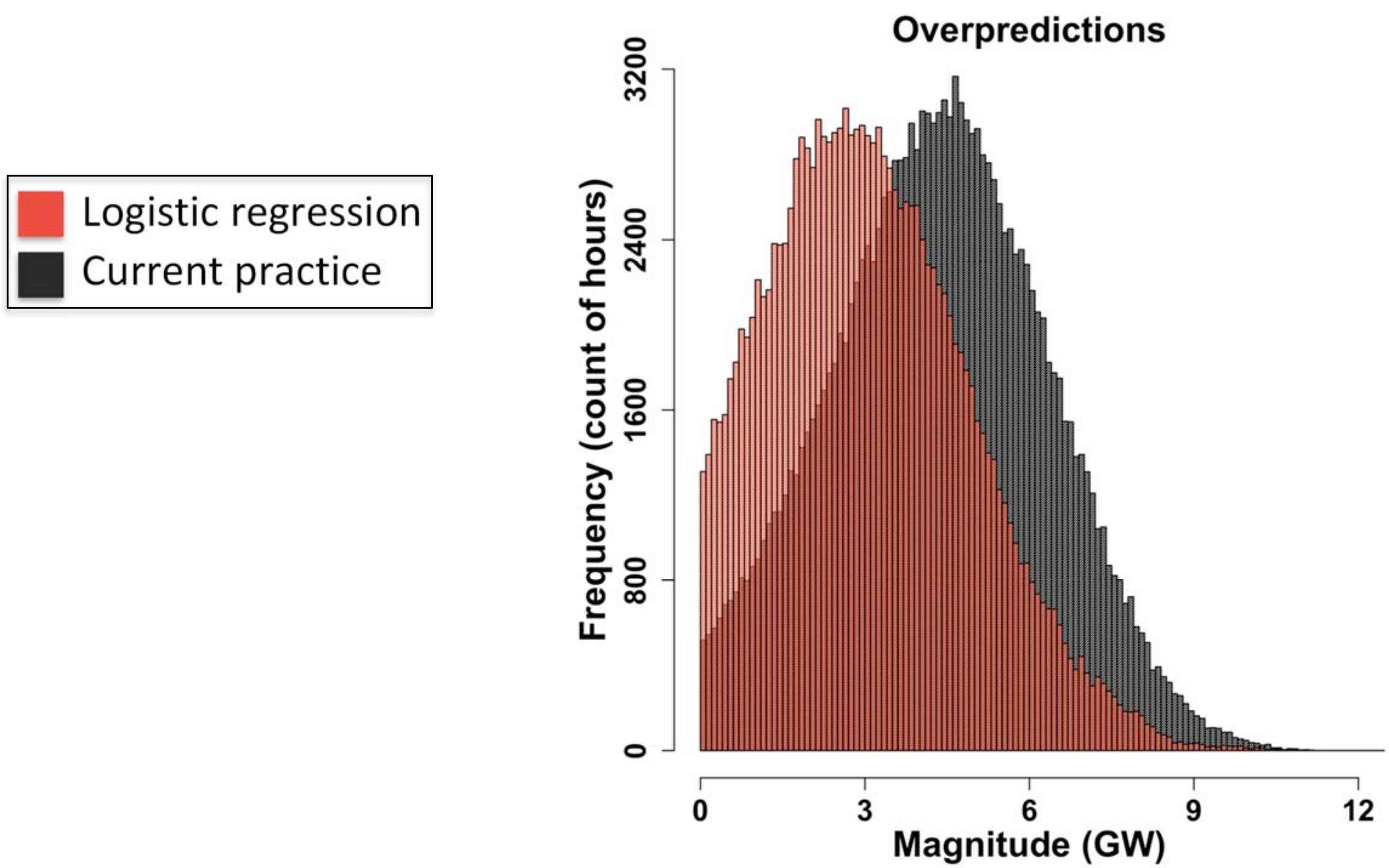
[a] Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA
[b] Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA, USA


The largest single contingency in PJM is 1.4 GW
Hours with >1.4GW forced outages
Percent of all hours in dataset
Percent
0
10
20
30
-17
-12
-8
-4
0
3
6
9
13
17
21
25
29
33
37
Temperature (°C)


PJM Generators
Generator Location
Transmission Line
2000 MW
4000 MW
6000 MW
Model PJM Zones
BGE-PEP
DOM
EAST
PPL-METED
WEST

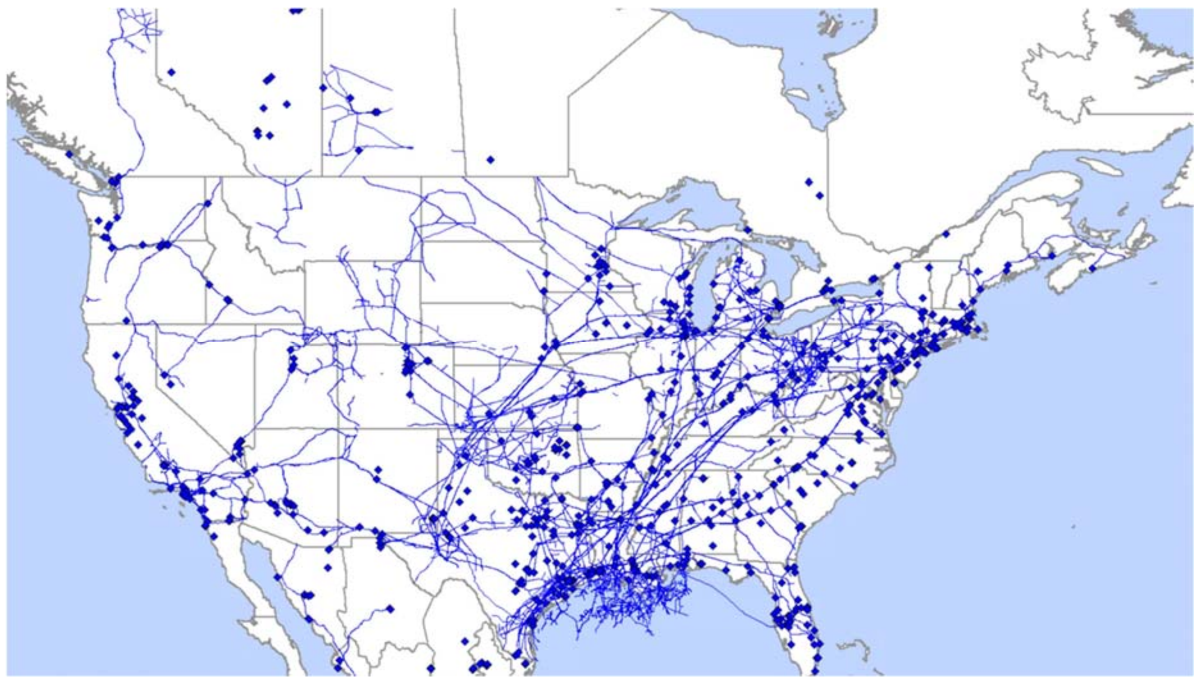
Is it possible to procure less reserves without increasing resource adequacy risk?

More accurate quantification of generator loss-of-load probabilities leads to a more accurate operating reserve valuation, increasing social welfare by $17.1 million in a cold weather week.

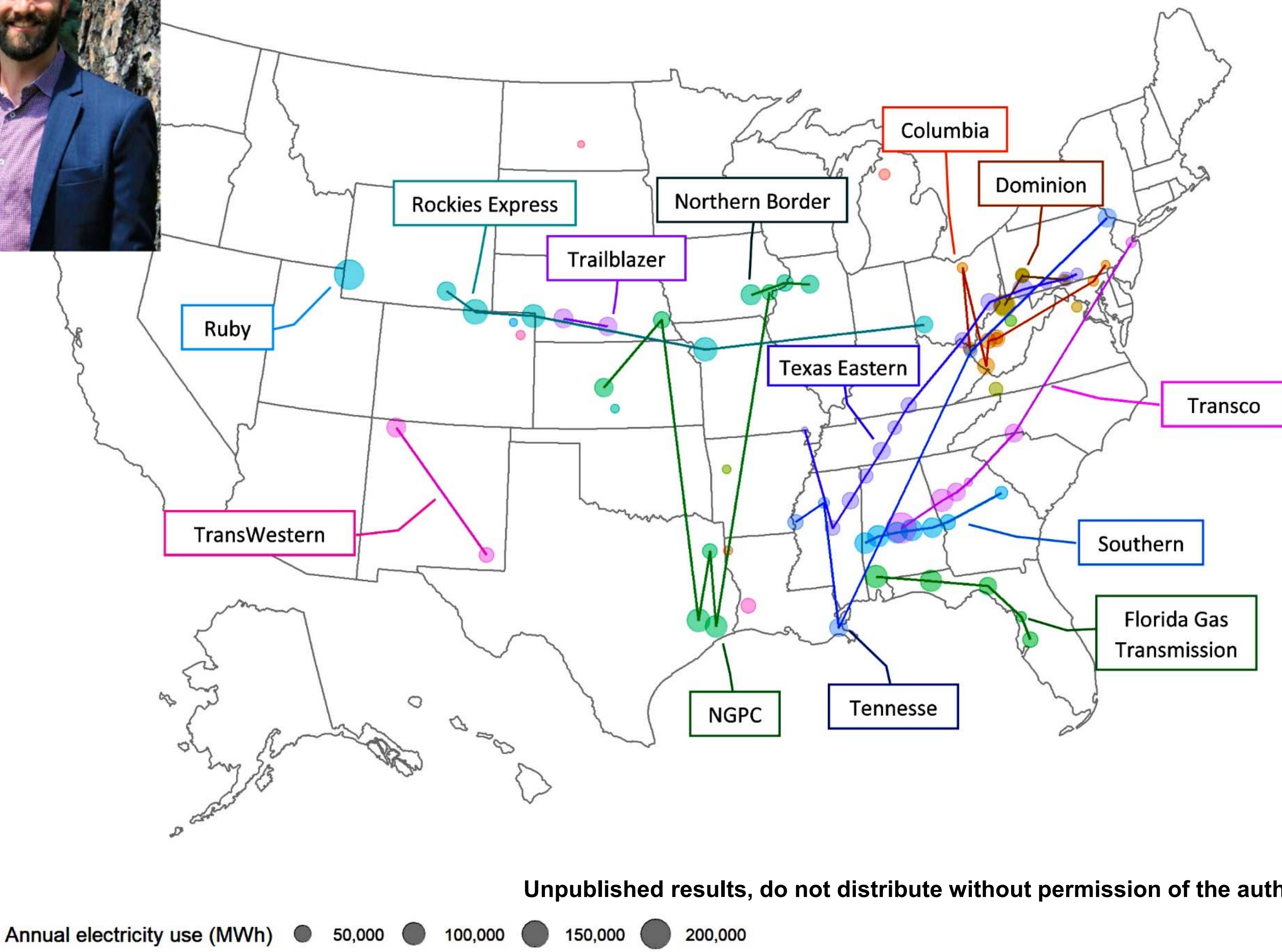


Finally, there is clearly a dependence of electric generation on natural gas…

…What about the reverse?



Large electrically driven natural gas compressor stations



Unpublished results, do not distribute without permission of the author

Note: Compressor stations with annual average hourly electricity demand >500 kW are included. Due to available data, some large electrically driven compressor stations with low capacity factors but necessary to meet peak gas demand may not be included. Lines connect stations from same system together from west to east, and does not necessarily represent the pipeline path.

Carnegie Mellon University

Thank you!

Jay Apt
apt@cmu.edu
www.cmu.edu/electricity

Scan the QR code below for my full contact information