Electric Power Generator Reliability and Natural Gas Reliability

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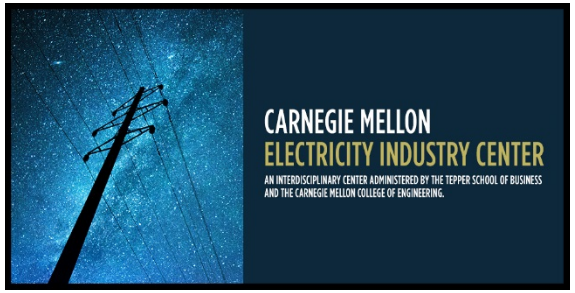
Carnegie Mellon University

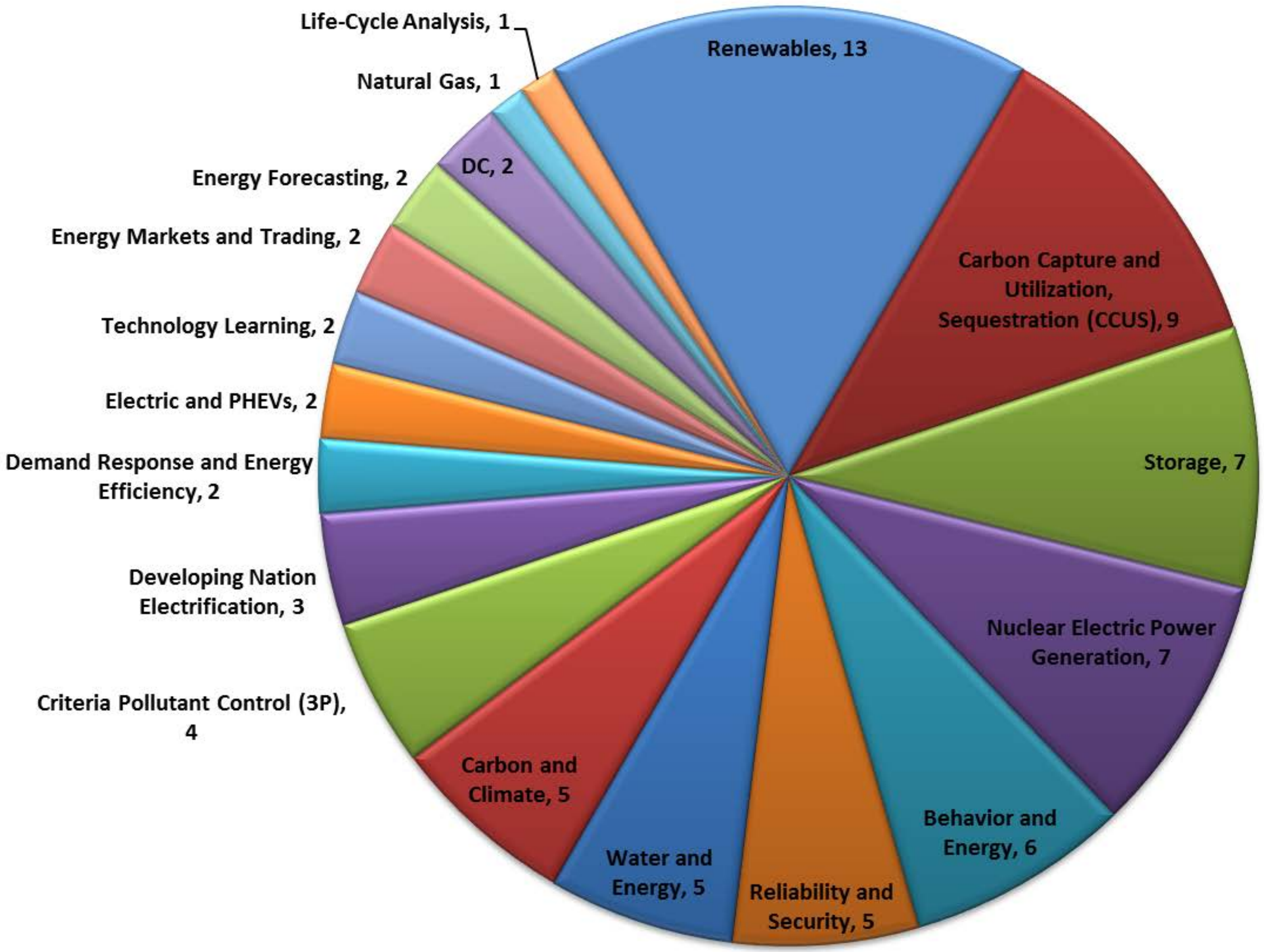
May, 2019

Carnegie Mellon Electricity Industry Center

- We are in our 19th year.
- Created jointly by the A.P. Sloan Foundation and EPRI after a 16-university competition.
- Close research partnerships with industry.
- We define ‘Electricity Industry’ broadly to include the companies that supply the equipment, the organizations that build and operate the grid, the agencies that shape and regulate the system, and the customers who use the power.
- Support: 30% from federal & state government, 30% from foundations, 40% from industry.
- 33 faculty, 26 Ph.D. students.



CEIC Papers Published or Submitted in 2017 and 2018 through August



Our work on reliability and security

Began with a workshop in 2001 on resilience, just before the 9/11 attacks

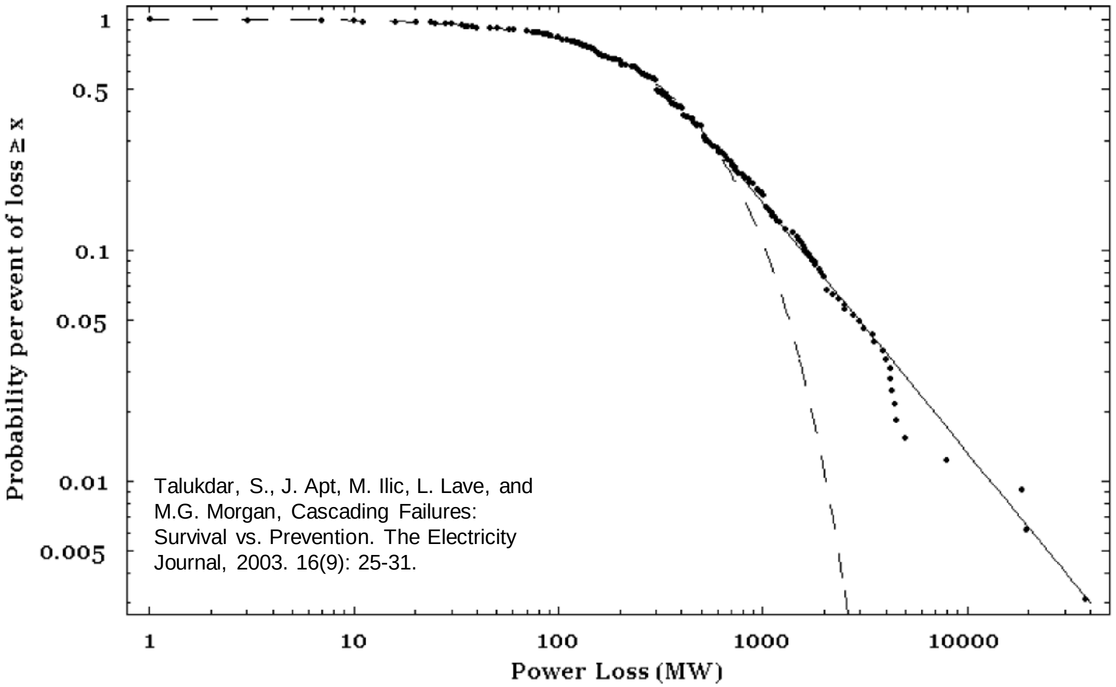


Figure 1: Cumulative Probability of Transmission- and Generation-Related Failures (Points are data as compiled by NERC for the period 1984–2000. The dashed line is an exponential (Weibull) distribution fit to the failures below 800 MW loss. The solid line is a power law fit to the NERC data over 500 MW loss.)

Energy Policy 37 (2009) 5249–5259

Contents lists available at ScienceDirect

Energy Policy

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

Large blackouts in North America: Historical trends and policy implications

Paul Hines [a,*], Jay Apt [b], Sarosh Talukdar [c]

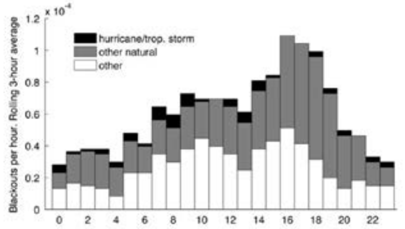
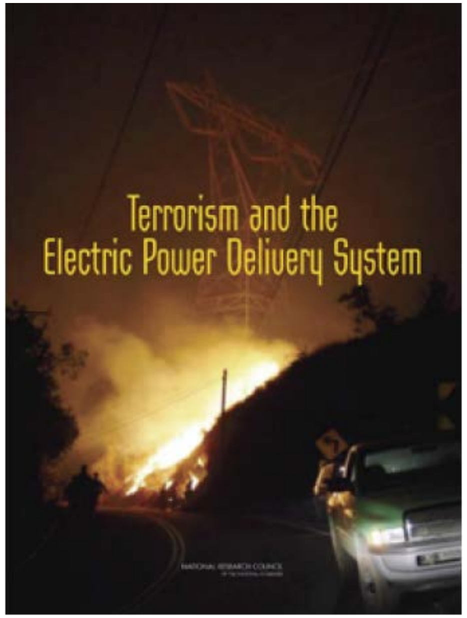
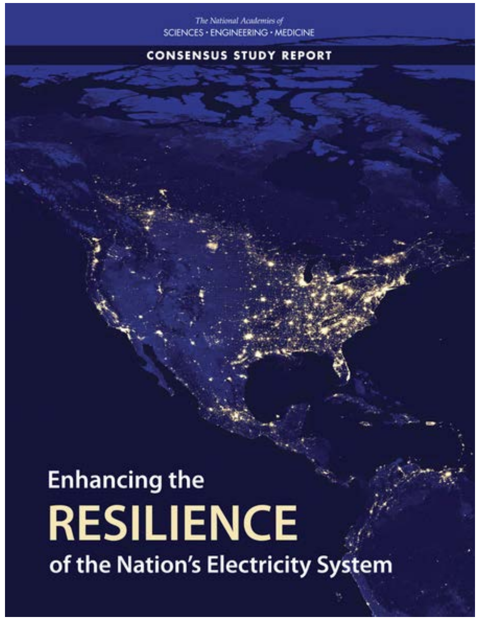


Fig. 5. Blackout frequency as a function of time-of-day. The vertical axis shows the average number of events per hour, using 3-h (centered) rolling averages to smooth out some of the noise in the data.





Four 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 later work on natural gas interruptions

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

We will discuss 4 things today

1. Generation reserves are computed based on the assumption that generators fail independently of each other. NERC data show that, even over 4 years, many generators fail simultaneously (correlated failures).
2. The 23 years of PJM data is long enough to rigorously quantify the temperature dependence of the forced outage rate for each type of generator.
3. Using these data, we compute how much reserve generation is needed to meet mandated reliability requirements in PJM, given that correlated failures occur.
4. Since natural gas generation has increased from 9% to 35% market share in the past 30 years, we take a careful look at why gas plants fail at low temperatures, and a preliminary look at what mitigation may be feasible.

This sort of work has an 85 year history

- “Service Reliability Measured by Probabilities of Outage”, S.A. Smith, Jr., Electrical World, Vol. 103, March 10, 1934, pp. 371-374.
- “The use of theory of probability to determine spare capacity”, P.E. Benner, General Electric Review, Vol. 37, No. 7, 1934, pp. 345-348.

History of the

Application of the Probability Methods (APM)

and

Reliability, Risk and Probability Methods (RRPA)

Subcommittees

Prepared by members of the RRPA Subcommittee

August 2015

Work on IEEE 762 began in 1968, 44 years before mandatory NERC GADS reporting!

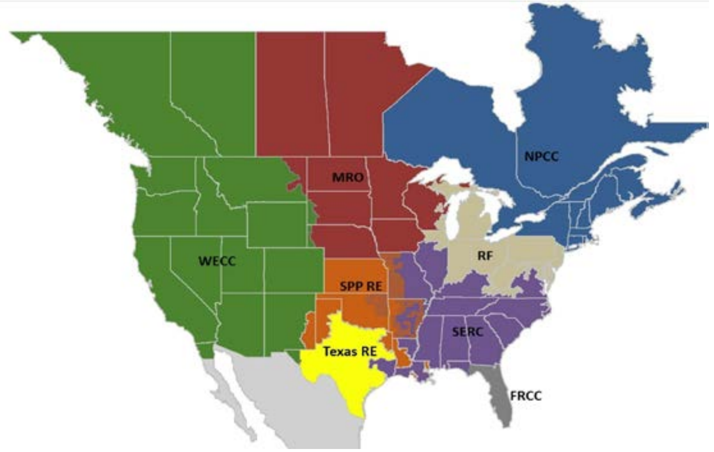
What is new is the availability of detailed data on generator-by-generator failures

Unfortunately, the natural gas system has not evolved to the point where such data are available for pipelines. But we’ve used GADS and EIA data to find some quite interesting results for the gas system’s effect on power generators.

Introduction to the Generating Availability Data System (GADS)

Sinnott Murphy

- Generator-level database recording anything affecting ability of a generator to produce electricity
  - We focus on "unscheduled" events, not out-of-the-money (RS) or scheduled maintenance
- 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



Carnegie Mellon

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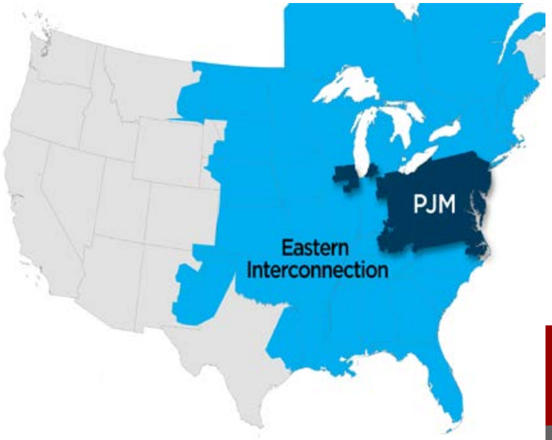
- NERC GADS (2012-present):
  - 8,500 generators (~85% of capacity in North America)
  - ≥20 MW mandatory reporting threshold for conventional generators; no wind or solar
- PJM GADS (1995-present):
  - 1,850 generators (~95% of capacity serving PJM)
  - All conventional generators participating in PJM markets; no wind or solar



1. Examination of resource adequacy modeling assumptions

Research questions:

1. Do correlated failures exist?
2. Is generator availability seasonal?

Data: NERC GADS (2012-2015)

Methods:

1. Block subsampling
2. Autocorrelation functions

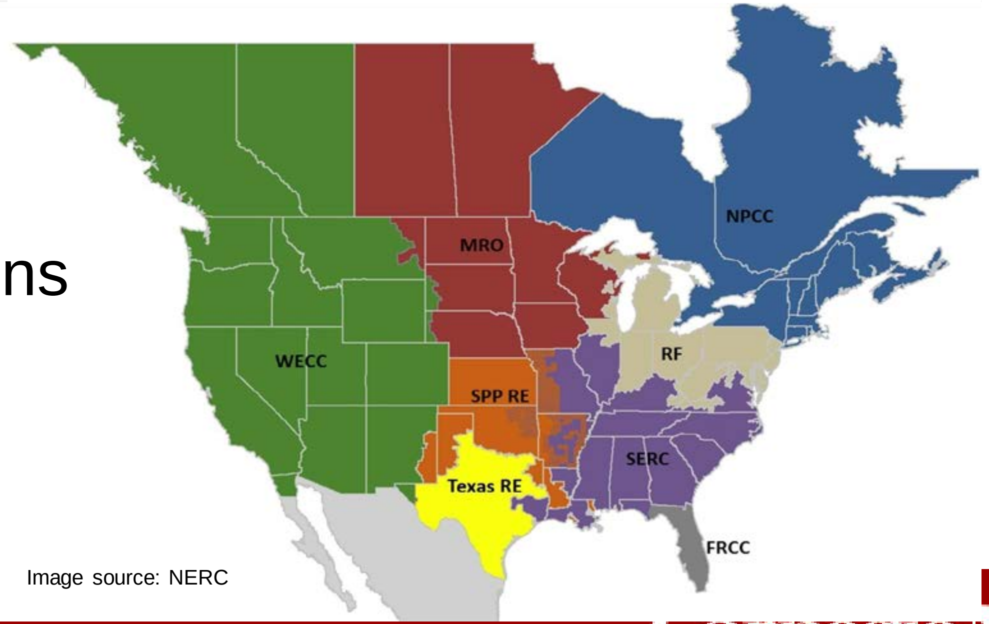


Image source: NERC

Applied Energy 212 (2018) 1360–1376

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

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

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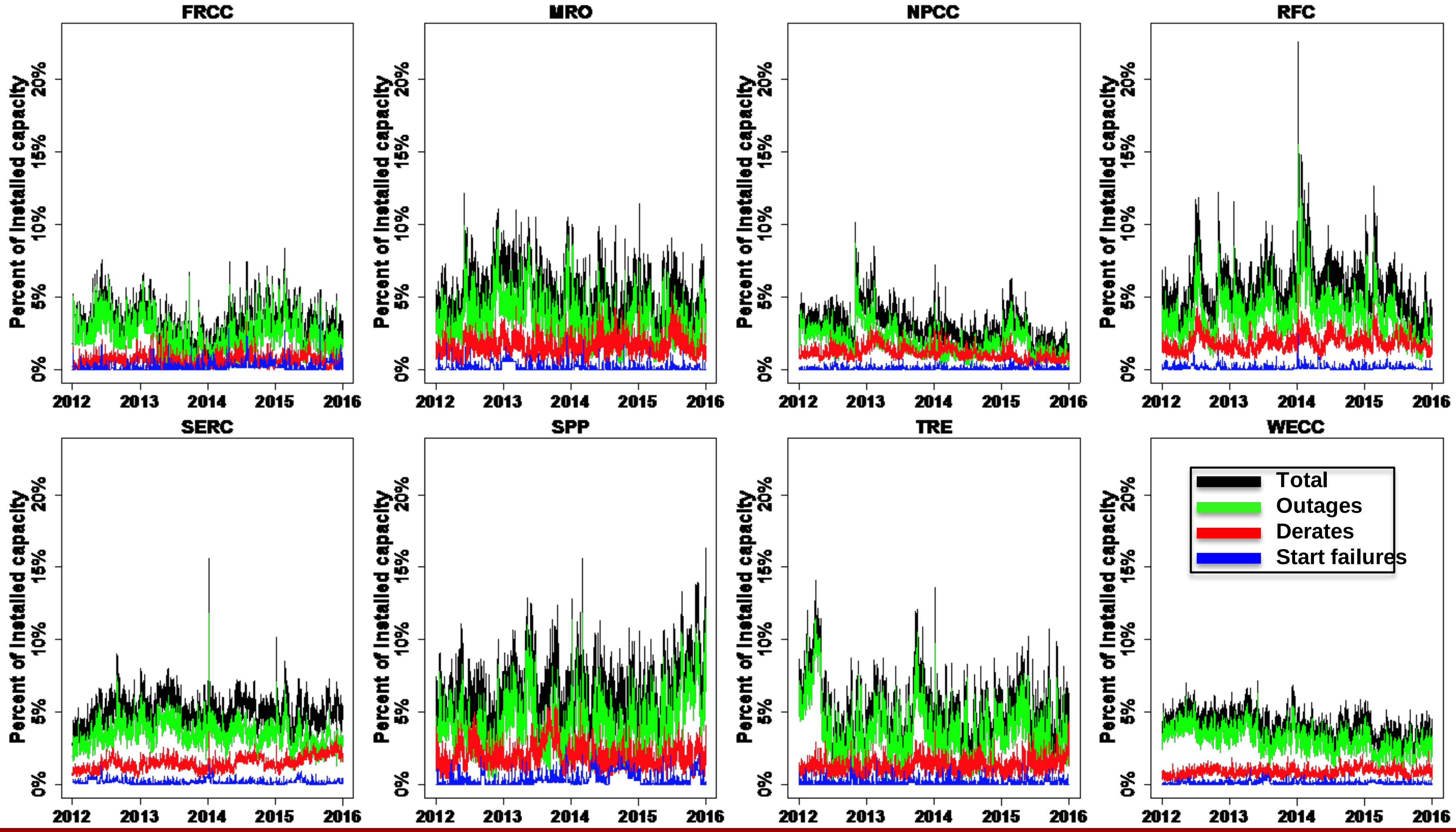
[c] *North American Electric Reliability Corporation, 3353 Peachtree Road Suite 600, Atlanta, GA 30326, USA*

HIGHLIGHTS

- 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.

Time series of unscheduled unavailable capacity for each region



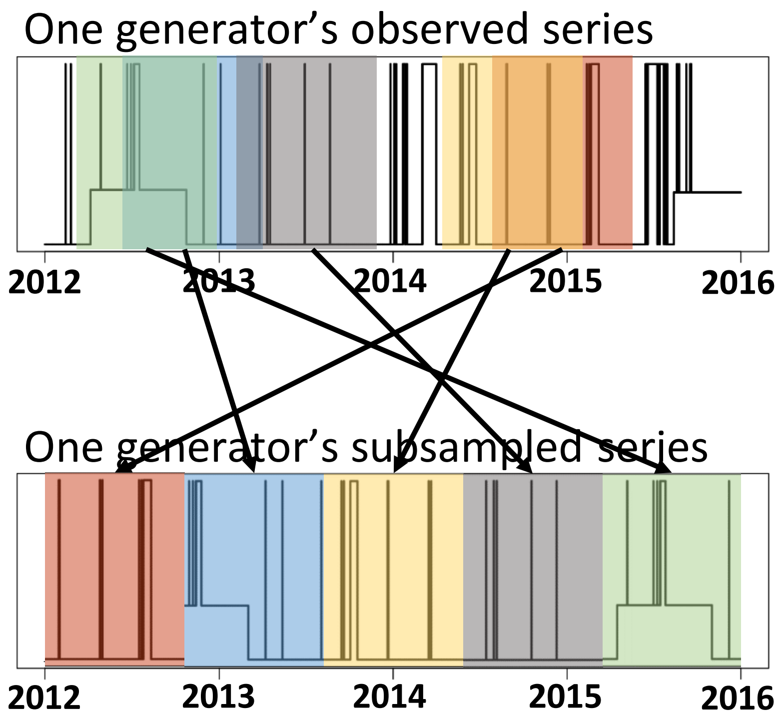
Use block subsampling to test the RAM assumptions (in simple terms, randomly sample the time series for each generator, to destroy any correlations among generators)

Repeat many times

Block subsampling:

1. Subsample "blocks" of observations from each generator's time series
2. Sum over generators to obtain one system-level time series

Block subsampling allows us to create a counterfactual universe where the RAM assumptions hold by design



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Block subsampling:

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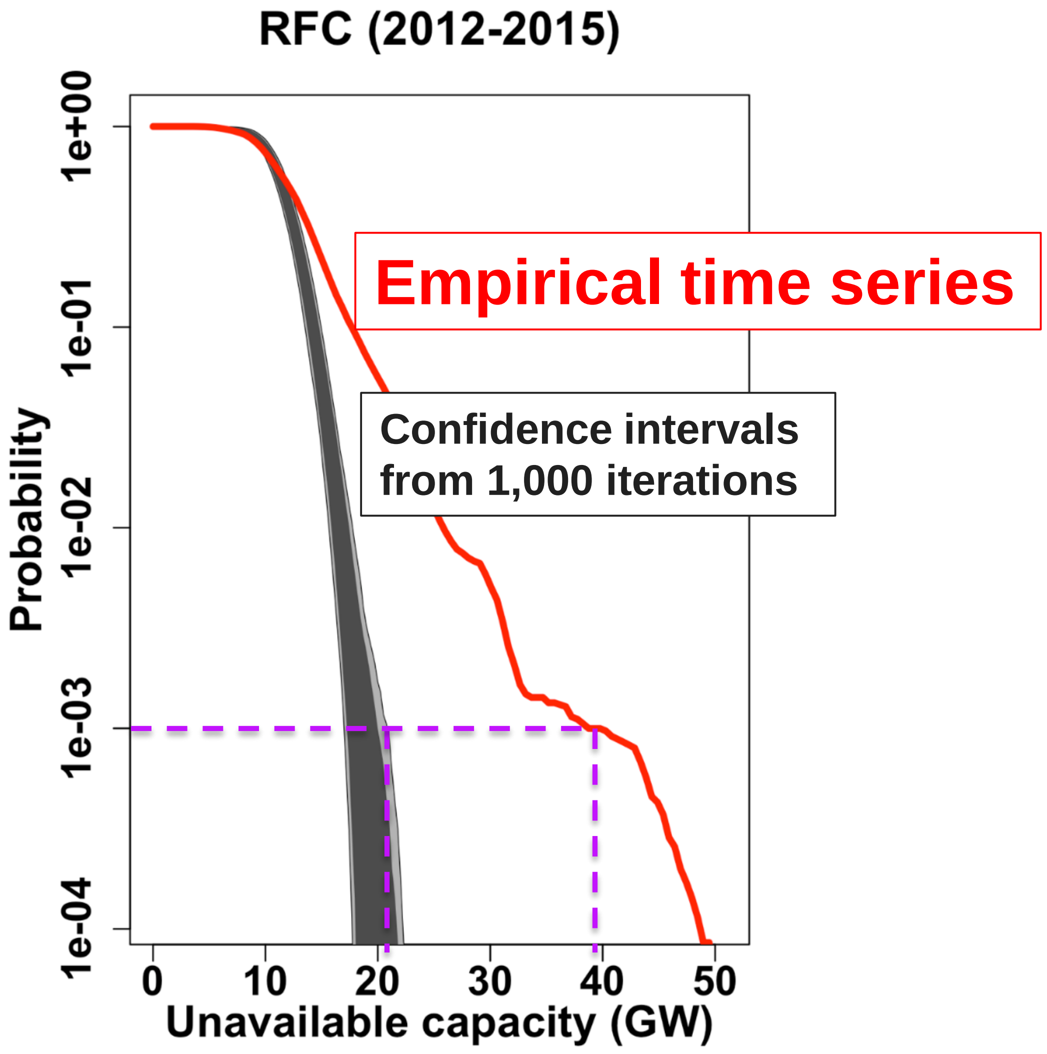
Block subsampling allows us to create a counterfactual universe where the independent failure assumption holds by design



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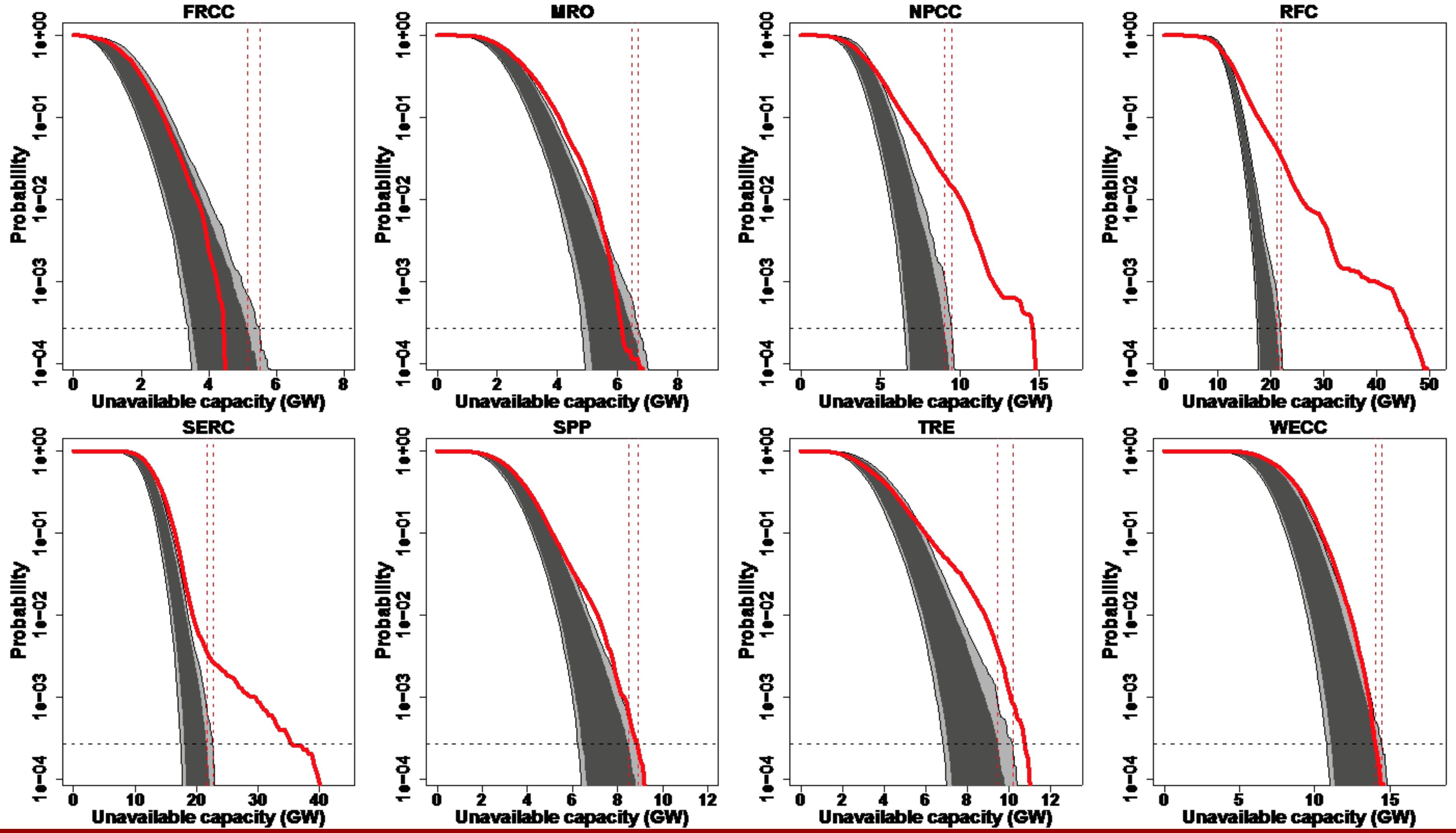
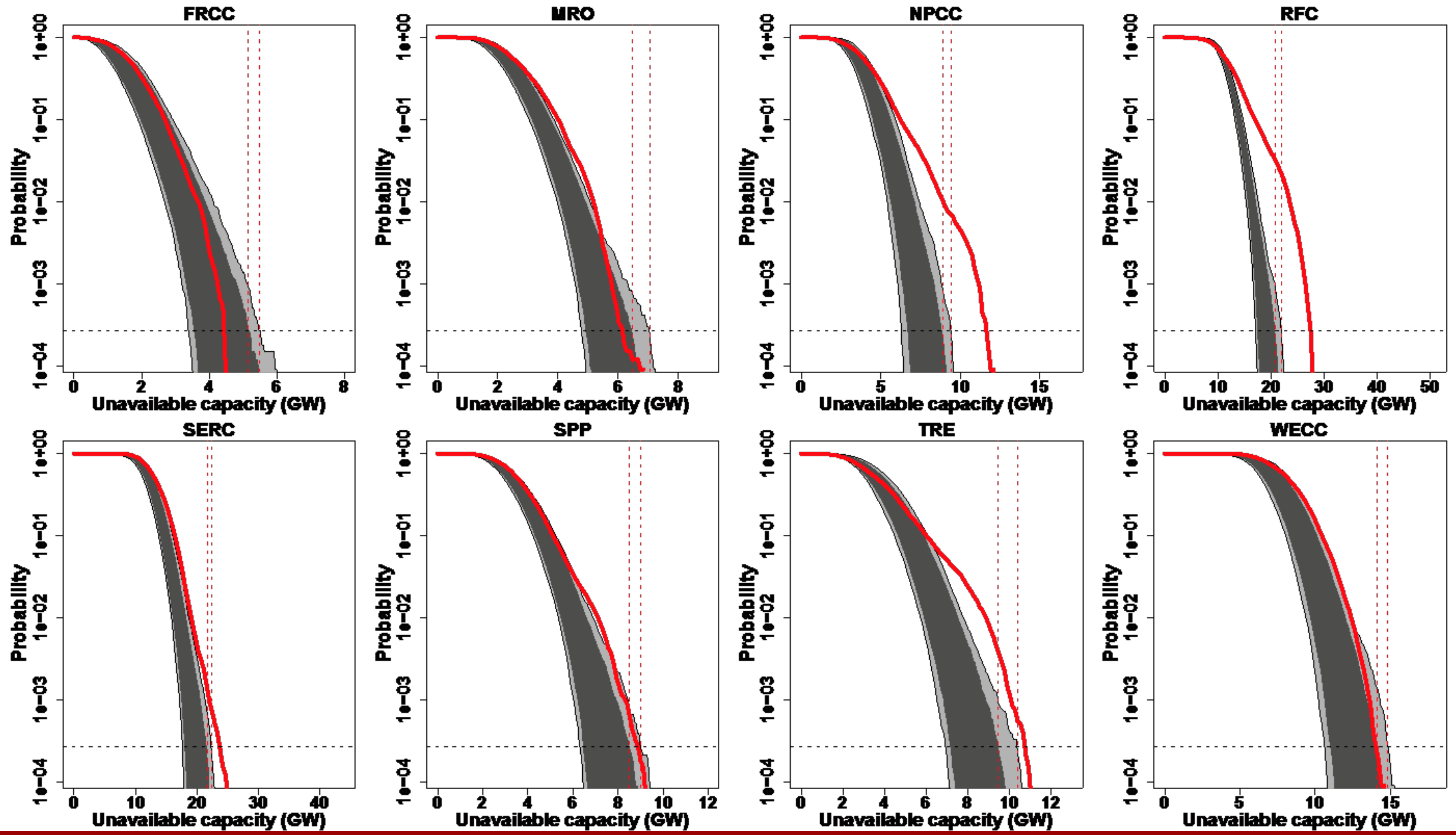
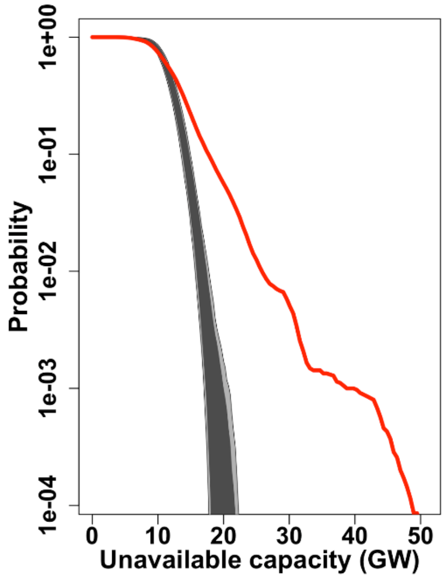


Repeat when excluding 2014 Polar Vortex and Hurricane Sandy



Summary so far

- Correlated generator failures exist in most NERC regions, even with just four years of data



2. Modeling correlated generator failures and recoveries

Research questions: Can we model the correlated failures to improve prediction of system-level failure dynamics?

Data: PJM GADS (1995-2018)

Methods:

1. Logistic regression
2. Monte Carlo simulation

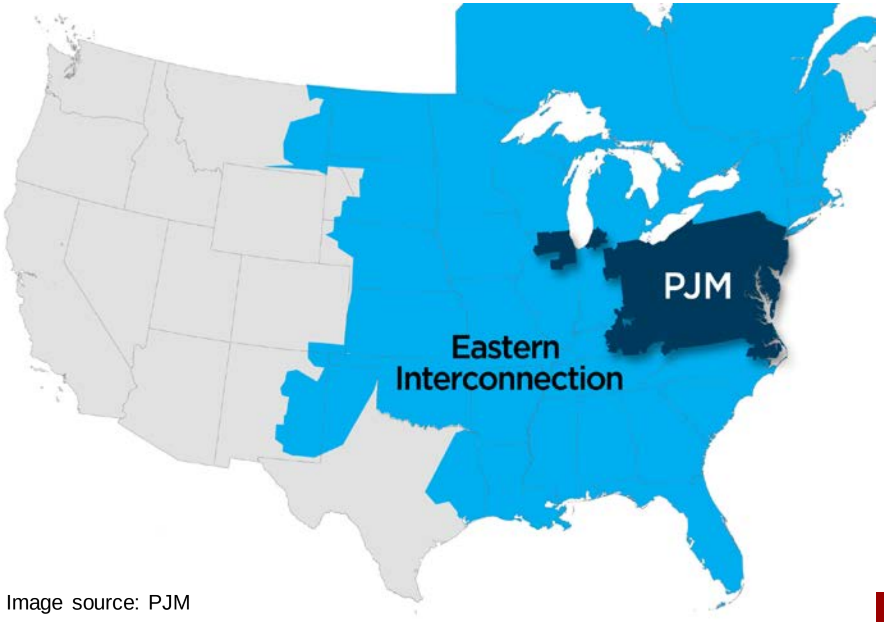


Image source: PJM

Carnegie Mellon Electricity Industry Center Working Paper CEIC-18-02 *www.cmu.edu/electricity*

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

Sinnott Murphy[1], Fallaw Sowell[2] and Jay Apt[1,2*]

[1]Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA.

[2]Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA, USA.

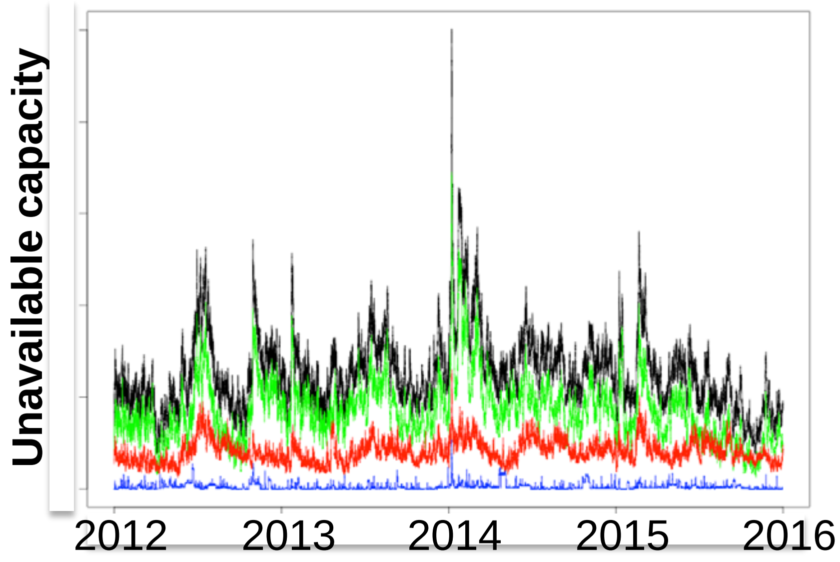
Revised and resubmitted after review at *Applied Energy*
(Working paper available on the CEIC website)

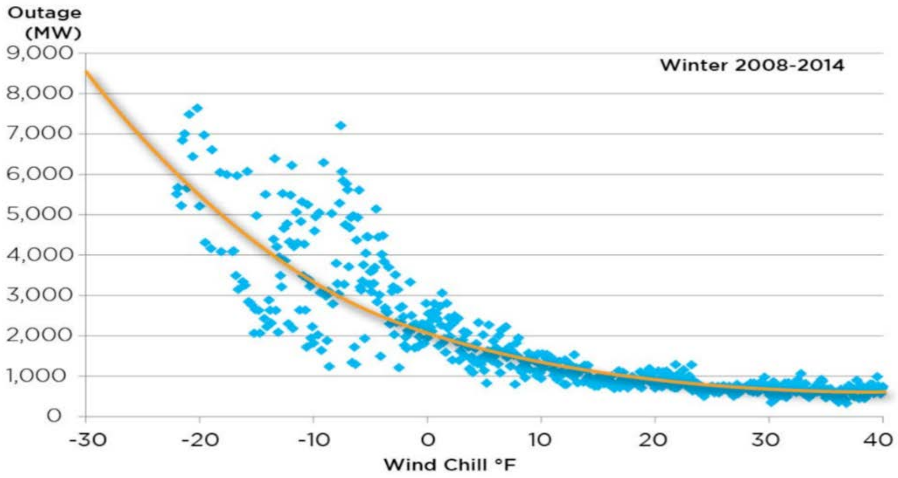
If generator transition probabilities are not constant, what affects them?

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

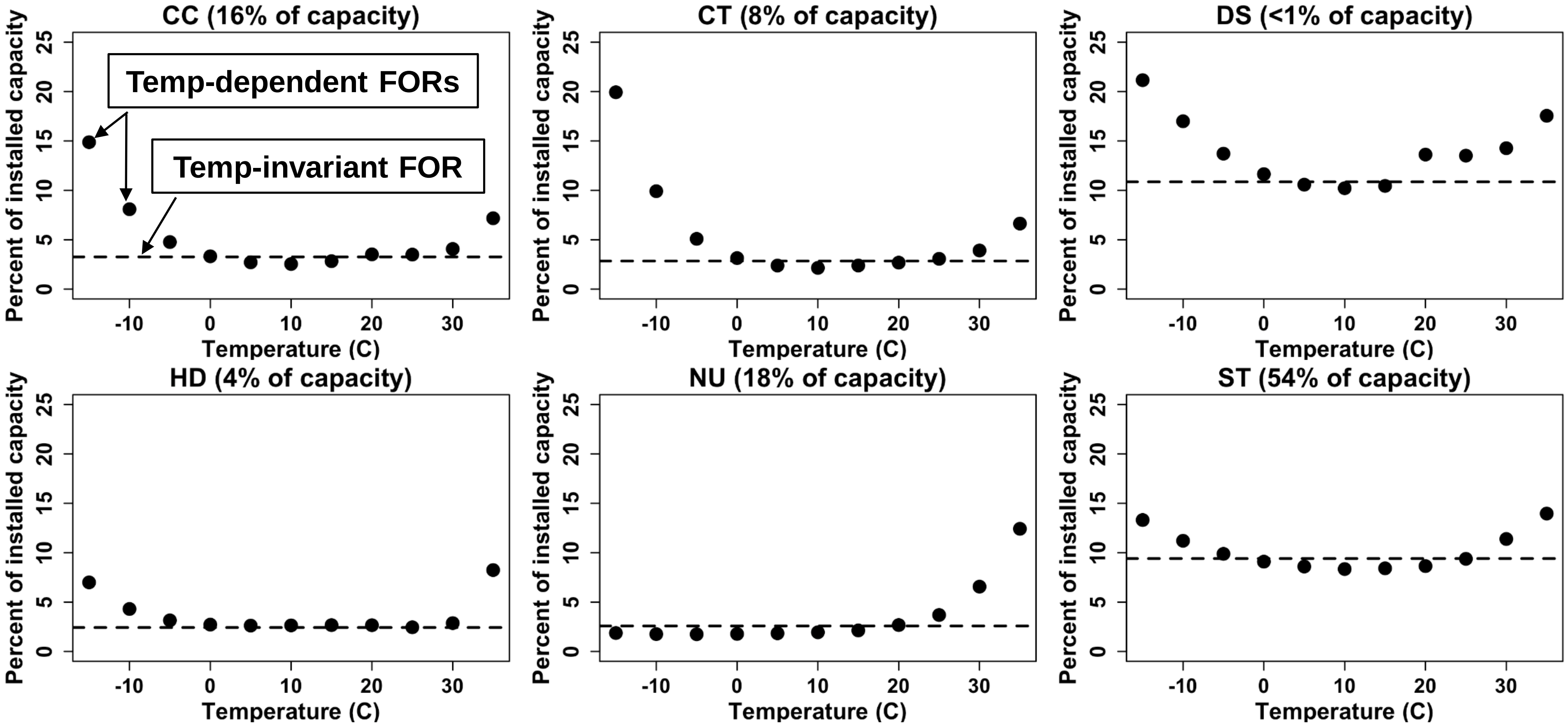
January 7, 2014 (Polar Vortex): 22% of PJM's total capacity was unavailable

PJM (2014): relationship between cold weather and outages





Modeled relationship between temperature and unavailable capacity

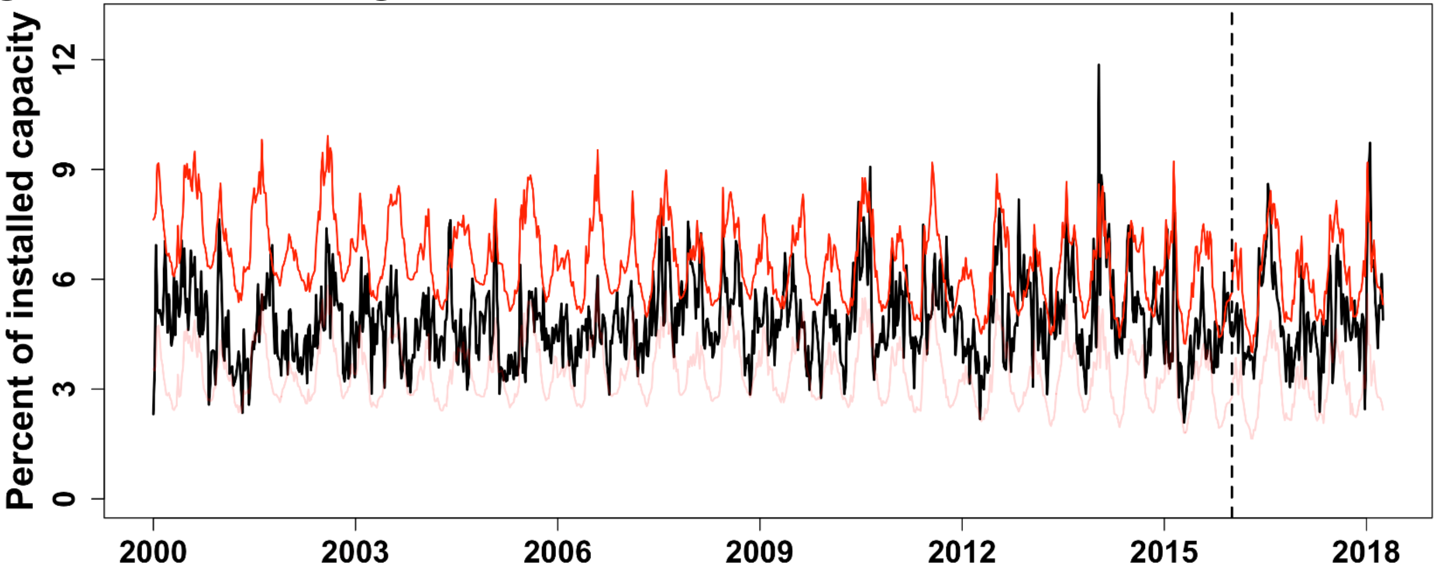


Unit type key:

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

Summary so far

- Correlated generator failures exist in most NERC regions, even with just four years of data.
- 23 years of data in PJM shows many correlated failures are explained by extreme temperatures.
- Incorporating temp-dependent correlated failures does a good job predicting forced outages in PJM.



3. Incorporating temperature dependence into resource adequacy

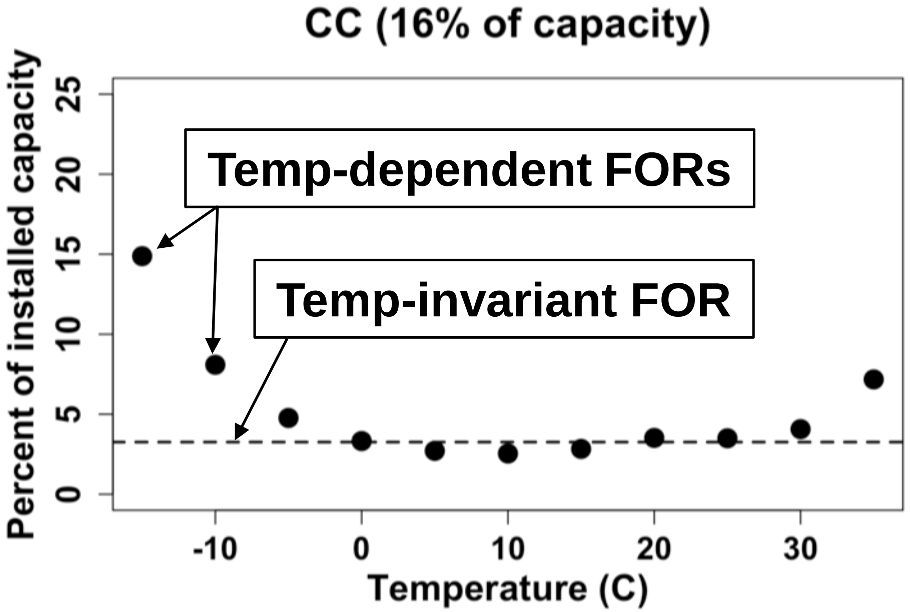
Luke Lavin

Research question:

1. Does temperature dependence represent resource adequacy risk for PJM?

Data: Forced outage rates calculated from PJM GADS

Methods: Modify open-source resource adequacy model to allow temperature-dependent forced outage rates



Overview of resource adequacy modeling (RAM) in PJM

- RAM determines how much capacity is required to meet the forecast peak load of a power system
- Overview of the "supply" side of the equation in PJM:
  1. Obtain five years of performance history for each generator in the power system via GADS
  2. Use to calculate temperature-invariant forced outage rate for each generator (defines probability distribution)

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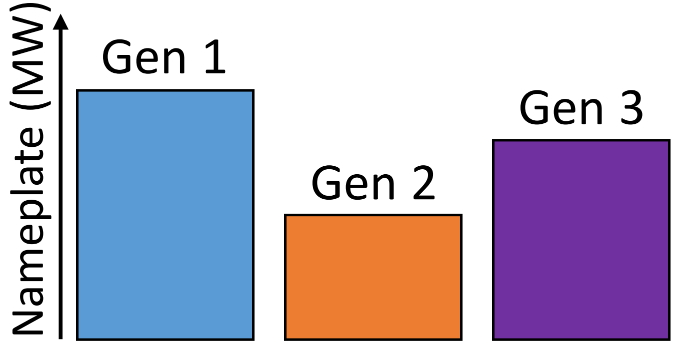
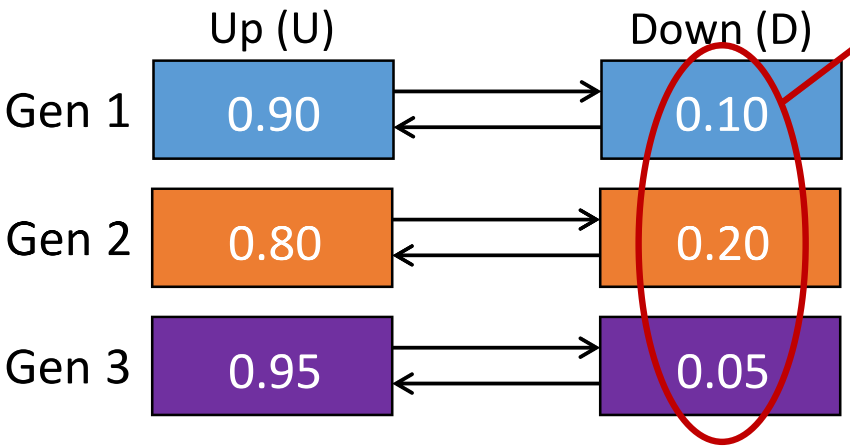
  2. Use to calculate temperature-invariant forced outage rate for each generator (defines probability distribution)
  3. Combine generator distributions to obtain system distribution

Reminder – this approach assumes:
1. Generator failures independent
2. Constant generator availability

Simple example



Generators are treated as independent two-state homogeneous Markov models



Forced outage rate (FOR):
The fraction of the time the generator was unavailable due to an unscheduled event

Generator	FOR	Nameplate
Gen 1	0.10	100
Gen 2	0.20	50
Gen 3	0.05	80

System state (G1-G2-G3)	Probability of state	Available capacity
U-U-U	.9*.8*.95	100+50+80
U-U-D	.9*.8*.05	100+50+0
U-D-U	.9*.2*.95	100+0+80
U-D-D	.9*.2*.05	100+0+0
D-U-U	.1*.8*.95	0+50+80
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D-D-D	.1*.2*.05	0+0+0

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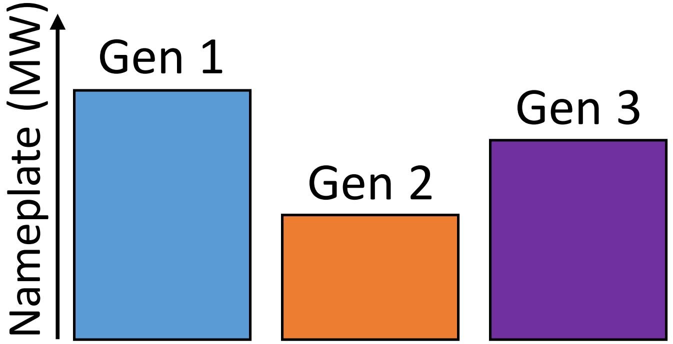

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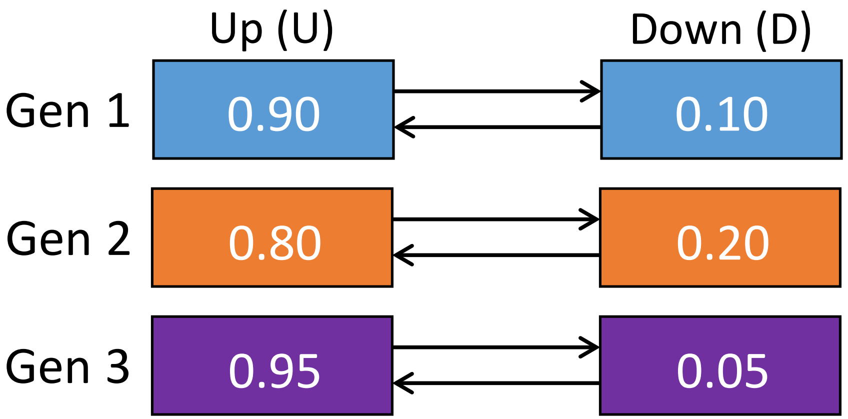

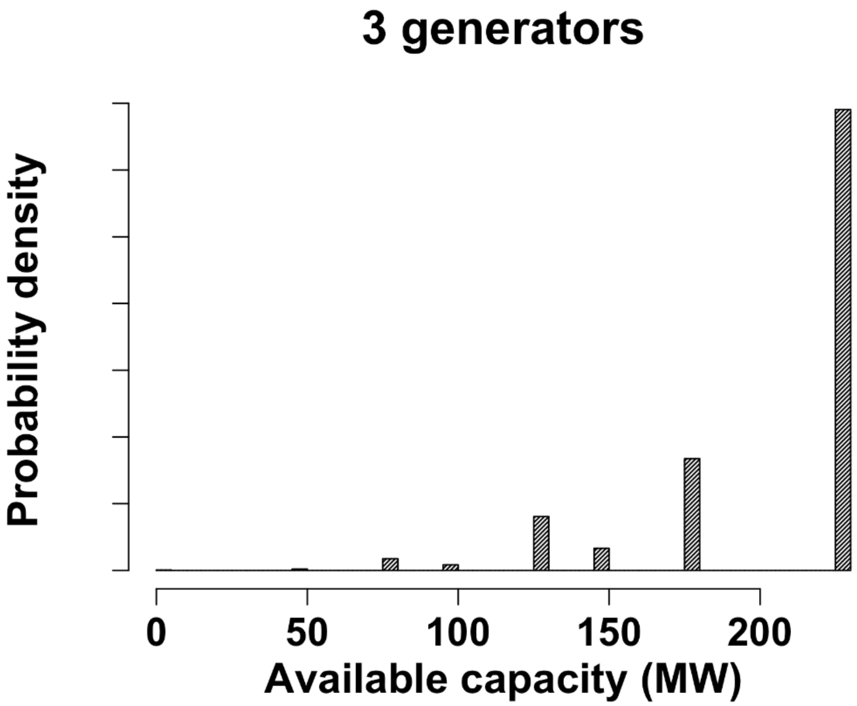

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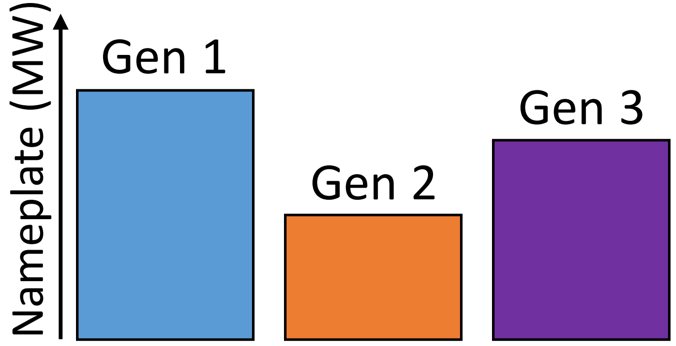

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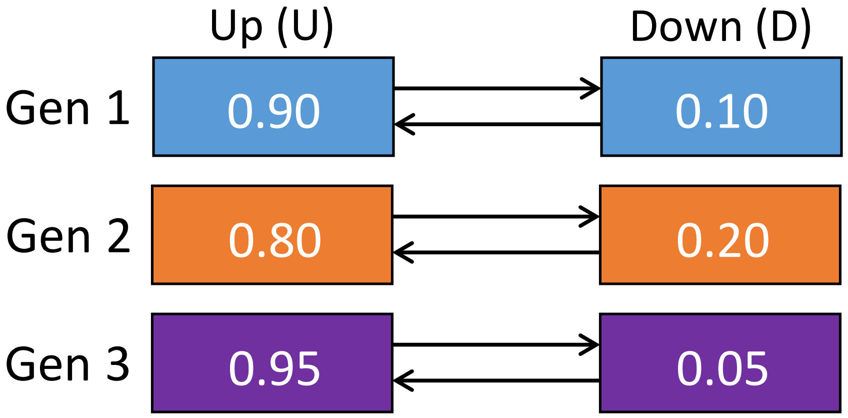

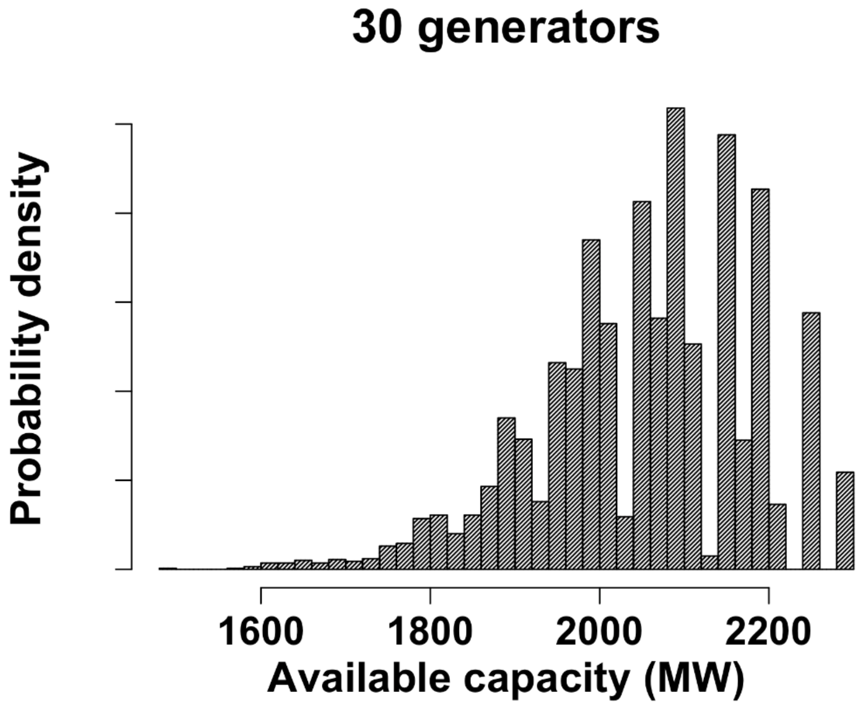

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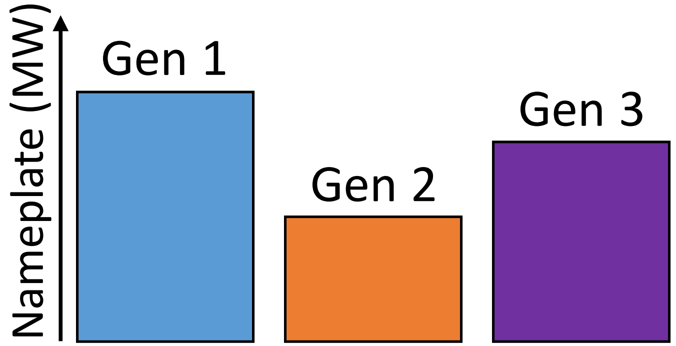

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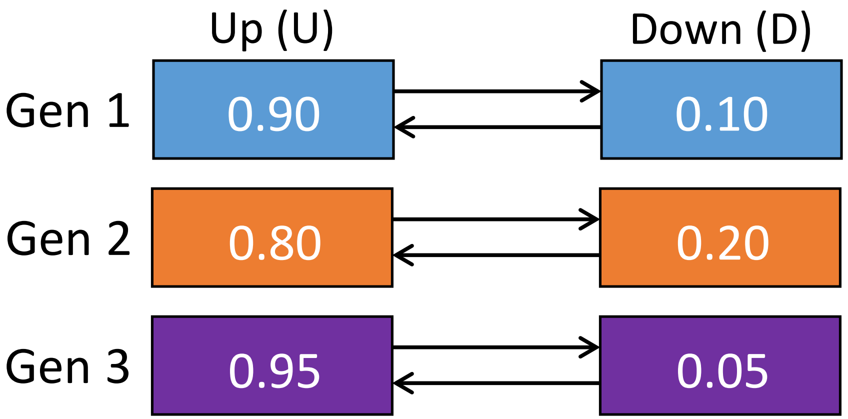
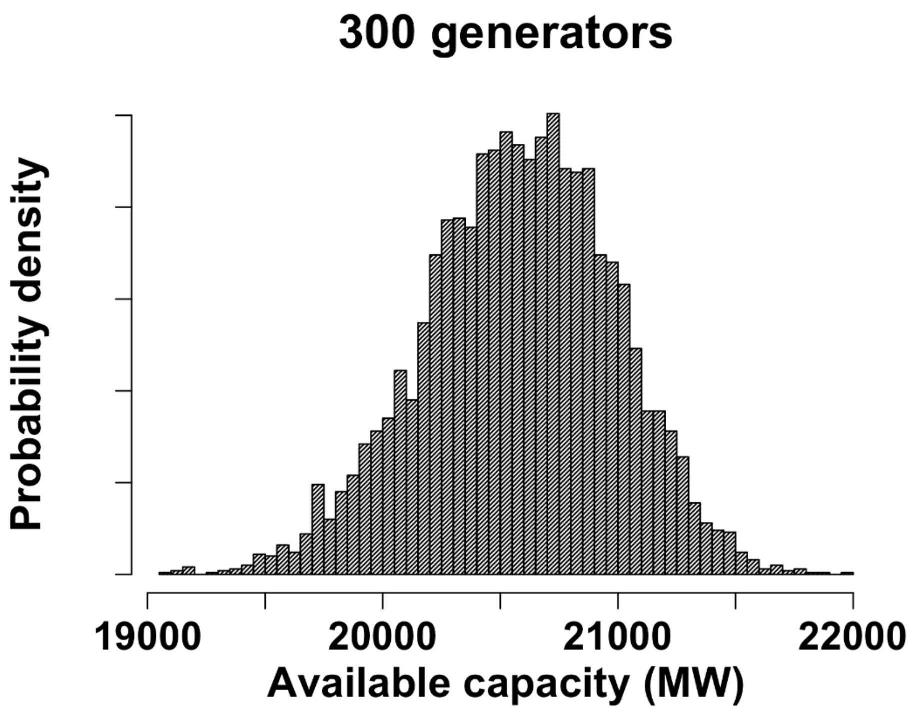
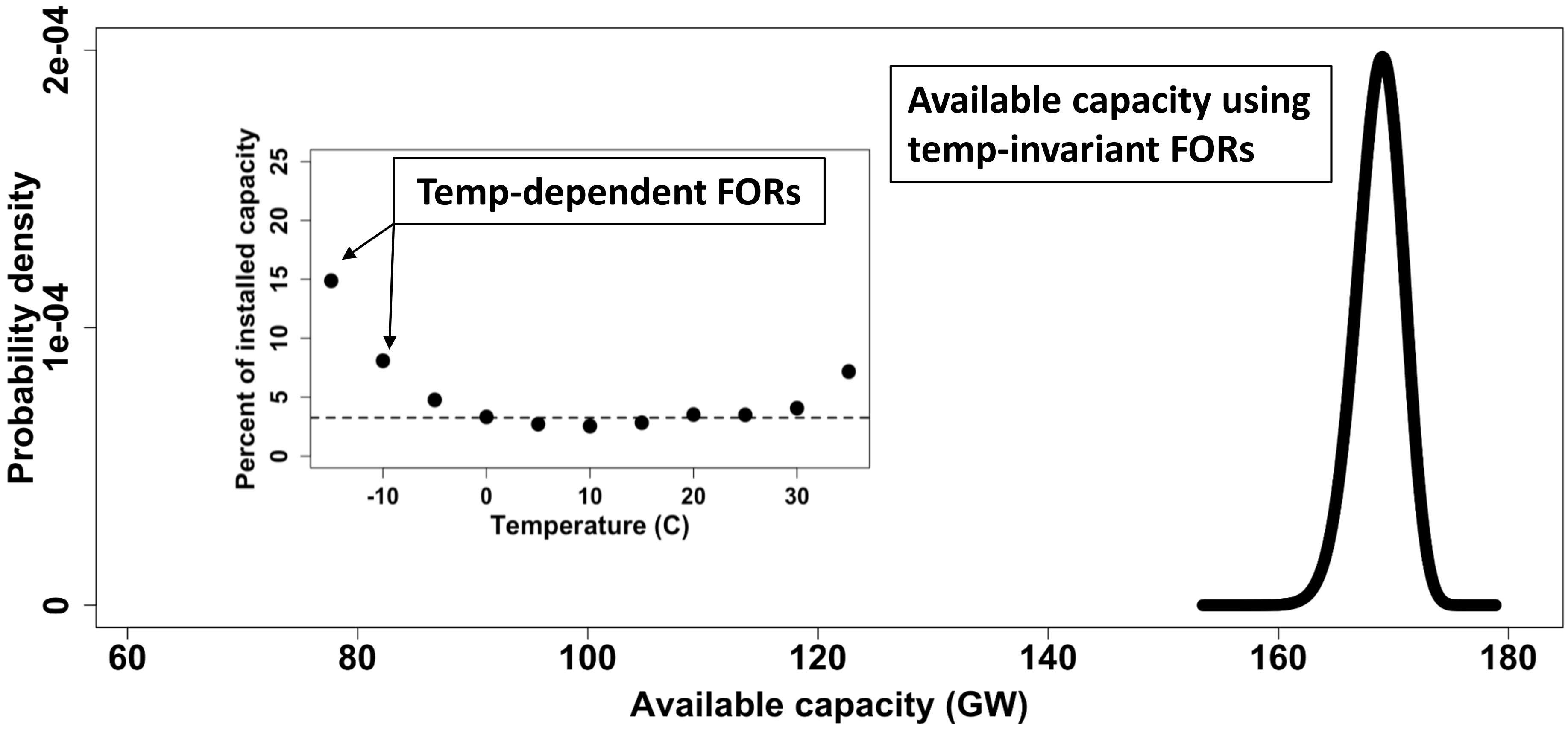
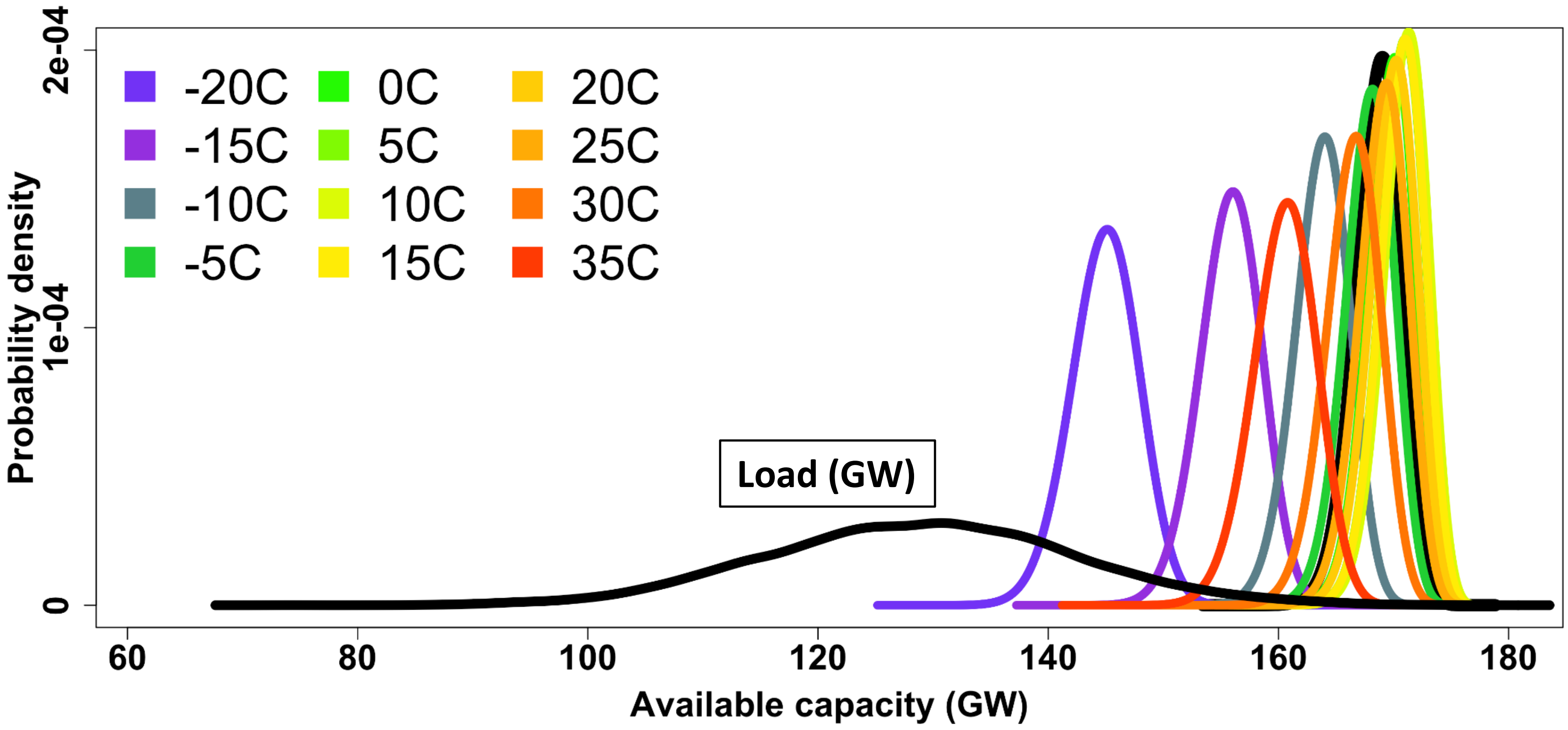




Effect of temperature-dependent forced outage rates for PJM

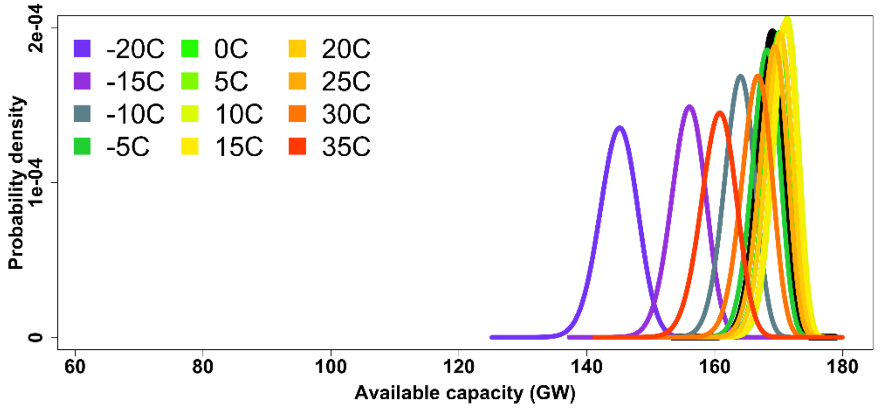


Effect of temperature-dependent forced outage rates for PJM



Introduction to the RECAP model

- A planning model built by Energy+Environmental Economics (E3) in collaboration with CAISO
  - Long-term; no unit commitment or economic dispatch
- Very similar to PJM's tool: RECAP computes capacity requirements for achieving a user-selected reliability target
- We modify RECAP to allow transition probabilities to depend on temperature



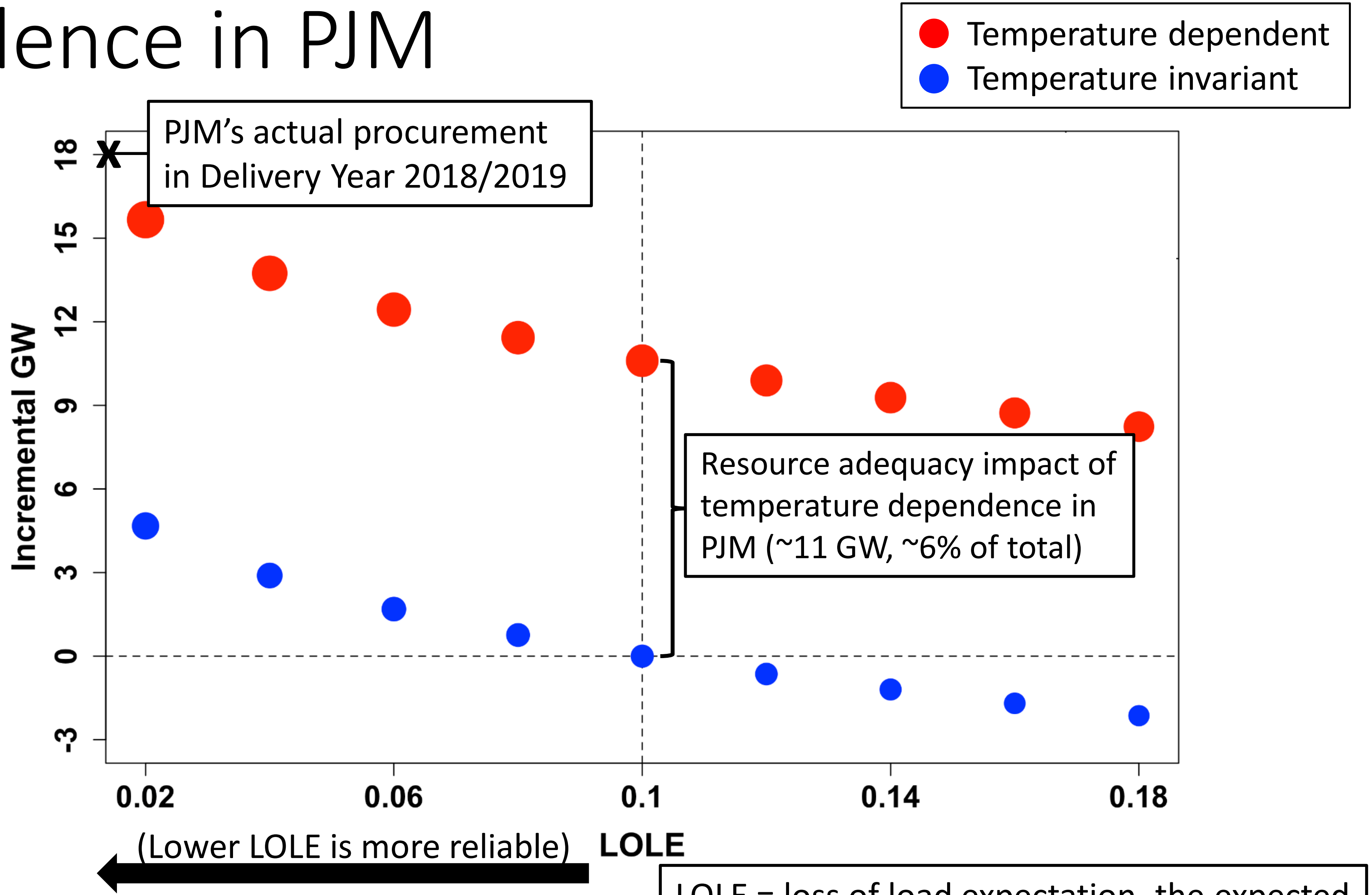
RECAP parameterization

Included	Not included
Conventional generation	Zonal disaggregation
Wind + solar generation	Emergency imports
Scheduled outages	
Summer ambient deratings	
Load forecast	

Reasonably well calibrated:

- PJM: 16.2% reserve margin needed to achieve the reliability target for delivery year 2018/2019
- RECAP: 15.9% reserve margin needed

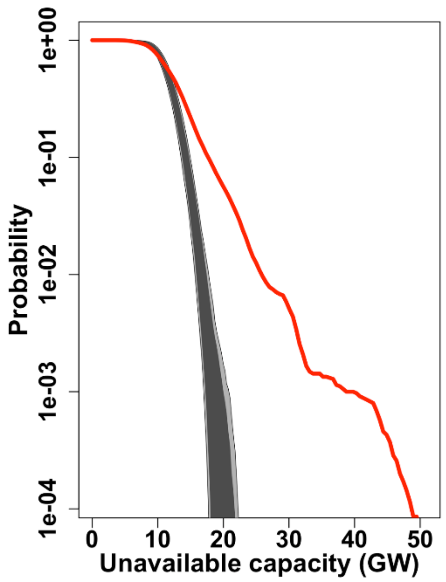
Resource adequacy risk from temperature dependence in PJM



LOLE = loss of load expectation, the expected number of loss-of-load events per year

Summary of generator results

- Correlated generator failures exist in most NERC regions, even with just four years of data



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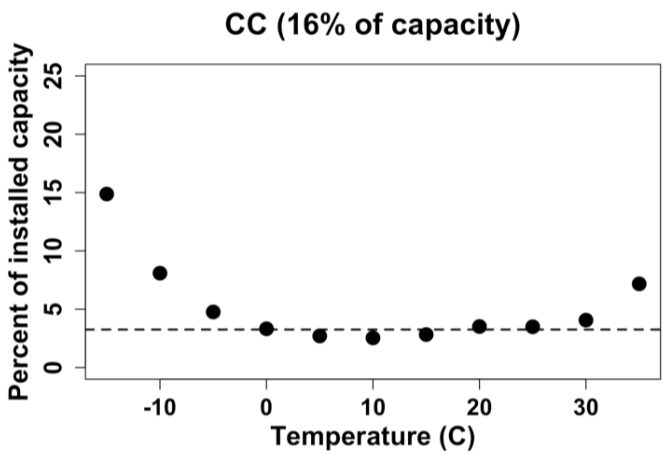
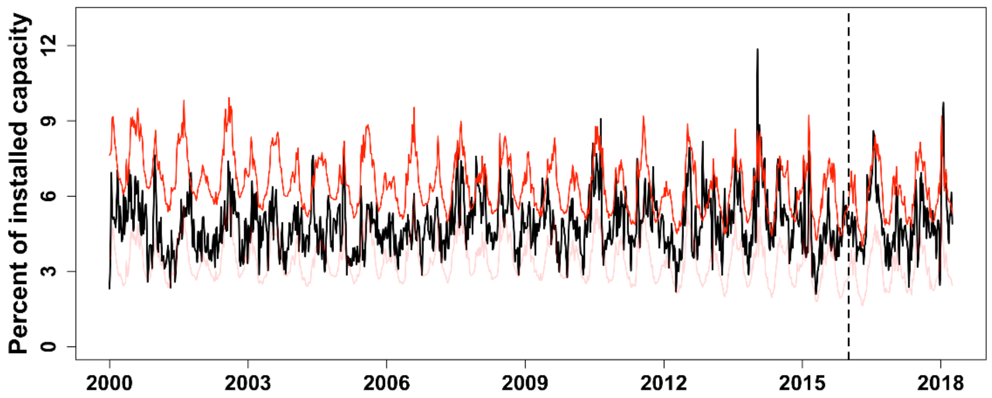




- Temperature dependence has substantial resource adequacy modeling implications

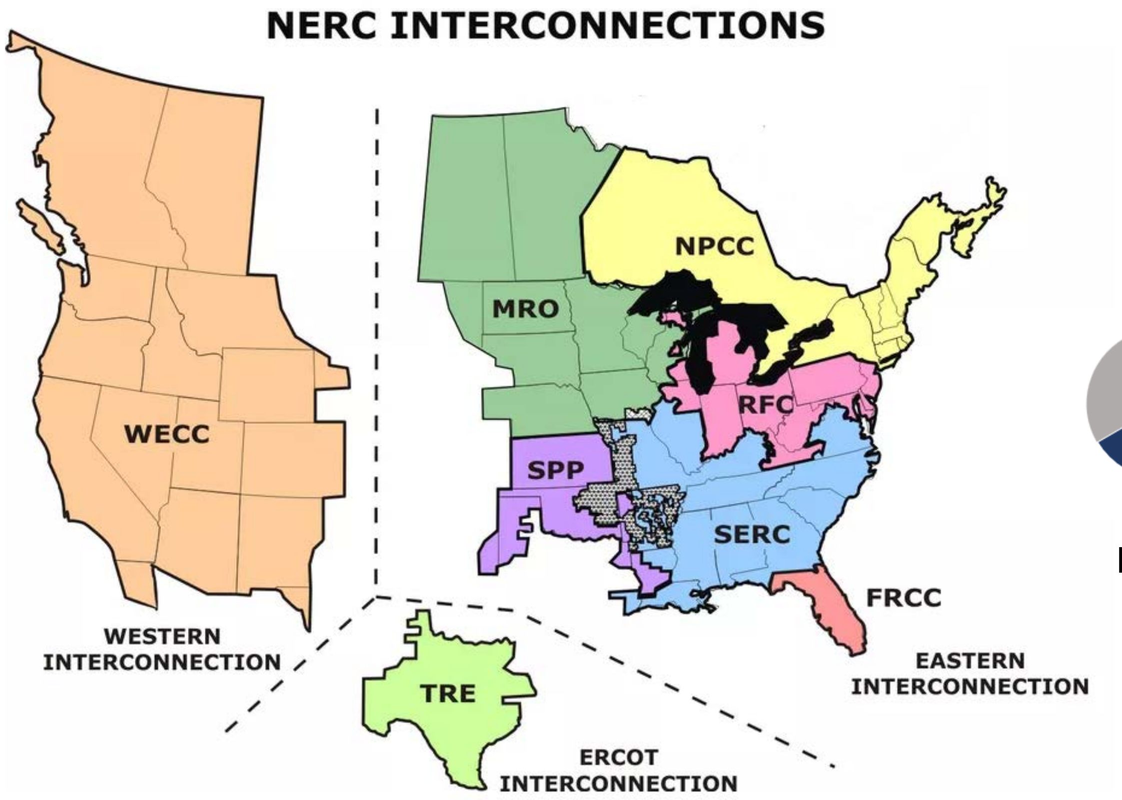
Pipeline failure reporting isn't nearly as good as generator failure reporting

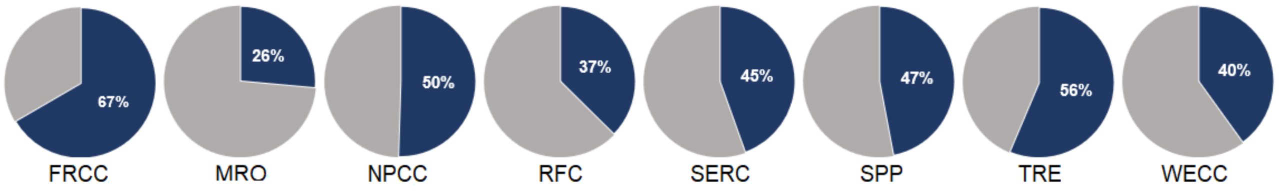
Gerad Freeman

- NERC's 2013 Special Reliability Report Phase II identified a lack of "compiled statistical data on gas system outages" that would be like GADS.
- FERC: interstate pipelines; PHMSA: safety; State PUCs: intrastate
- No central reliability organization.
- FERC Form 588 (emergency transaction report) has essentially no data on pipeline failures.
- PHMSA reporting threshold: death, hospitalization, $50,000 property damage, gas loss of ≥3 million cubic feet, or "significant in the judgement of the operator". Many events, including Aliso Canyon, are missing.
- While Maine requires reports of gas interruptions to power plants of >30 minutes, other states' reporting requirements are generally loose.

See: Gerad Freeman, Jay Apt, and Michael Dworkin. "The Natural Gas Grid Needs Better Monitoring." Issues in Science and Technology 34, no. 4 (Summer 2018).

4. A closer look at gas – electric interdependence





Fraction of U.S. nameplate capacity fueled primarily by natural gas (2017)

Data sources: EIA-860 2017; NERC

GADS and EIA data allow us to analyze electric-gas dependence

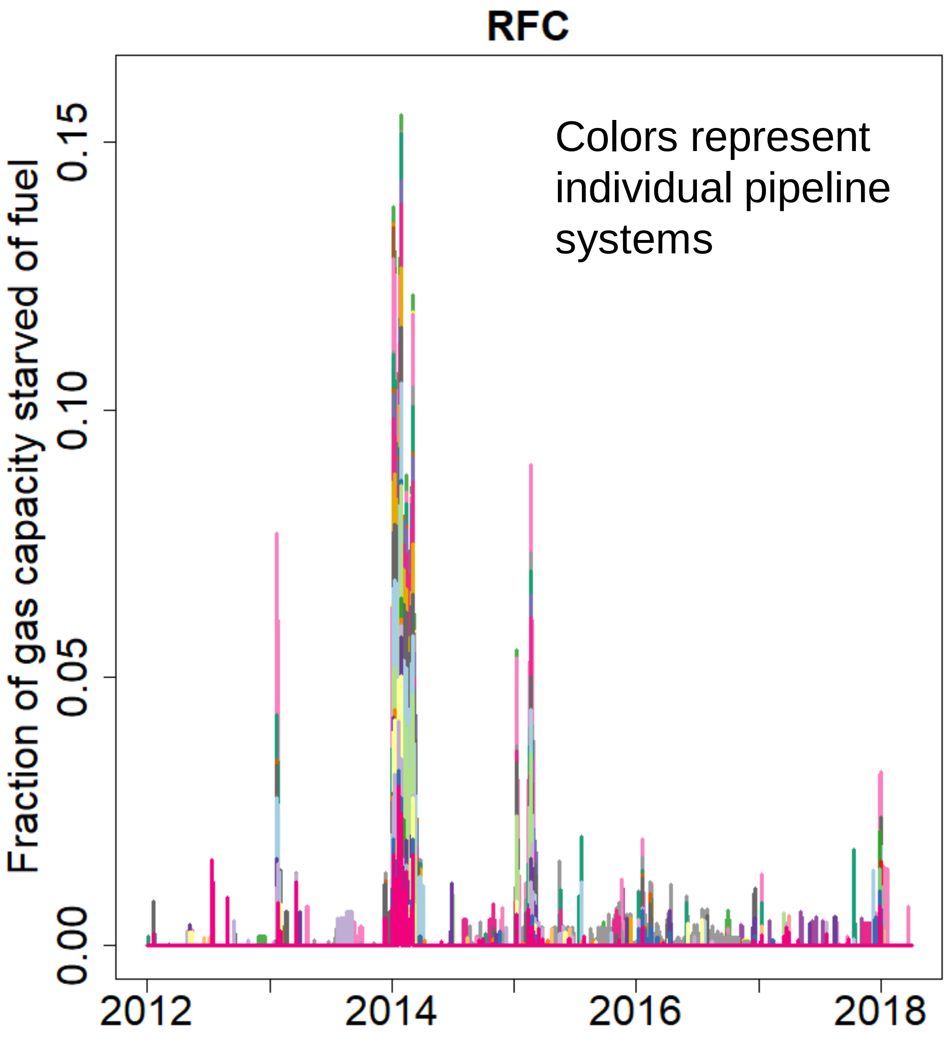
1. **Primary:** NERC Generating Availability Data System (GADS)
   Sample: 1/2012 – 3/2018 (6 years)
   – 6,505 events at 328 natural gas plants
   – Only unscheduled fuel starvation causes (9130, 9131, 9134)

   Secondary: PJM eGADS
   Sample: 3/2002 – 4/2018 (16 years)
   – 3,048 events at 133 natural gas plants

2. **Generator characteristic data**
   – To group events by pipeline

3. **Fuel receipt and contract status data**
   – To group events by contact type

4. **Pipeline scheduling data**
   – To examine high-demand periods

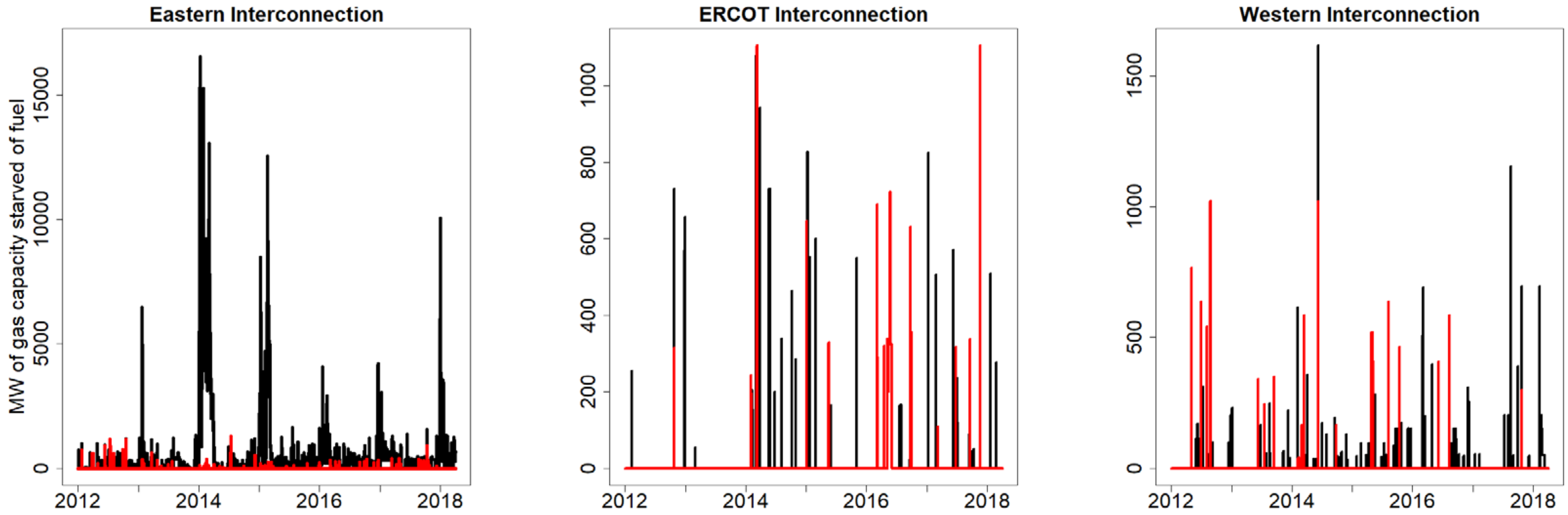


Carnegie Mellon

Correlated, fuel starvation failures at gas plants knocked out generators <u>with both firm and non-firm fuel contracts</u>

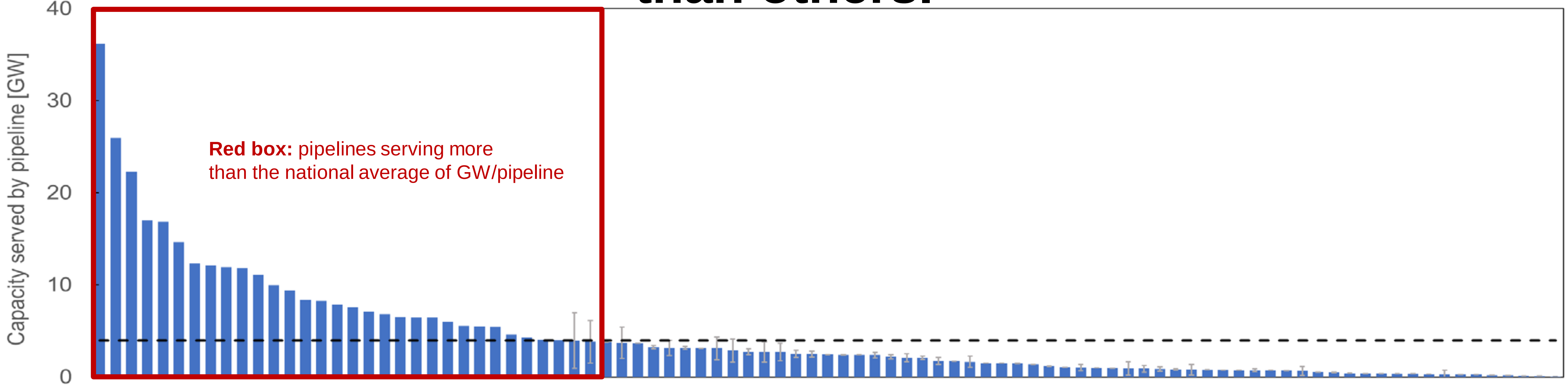
Black: all fuel-starved gas plants

Red: firm contracts, fuel-starved



In the Eastern Interconnection, correlated fuel shortages (GADS 9130, 9131,9134) didn't take down only multiple generators, they affected multiple plants all six years.

More capacity was starved of fuel on some pipelines than others.



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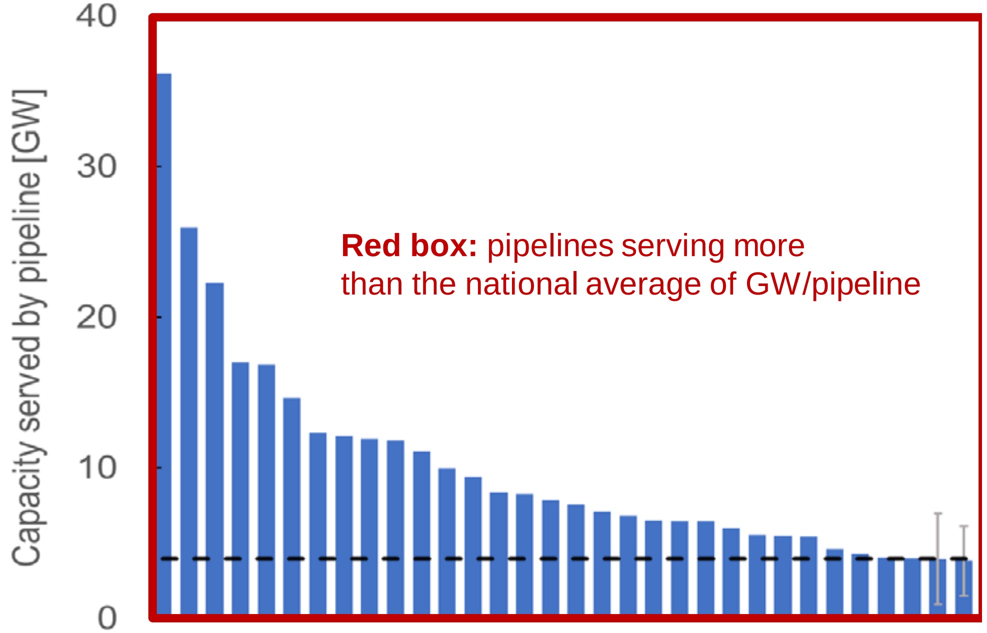
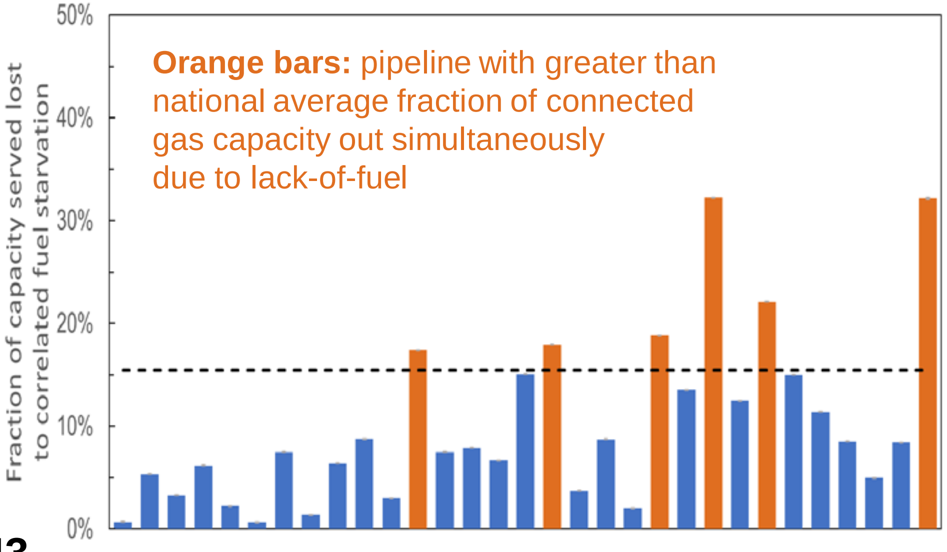
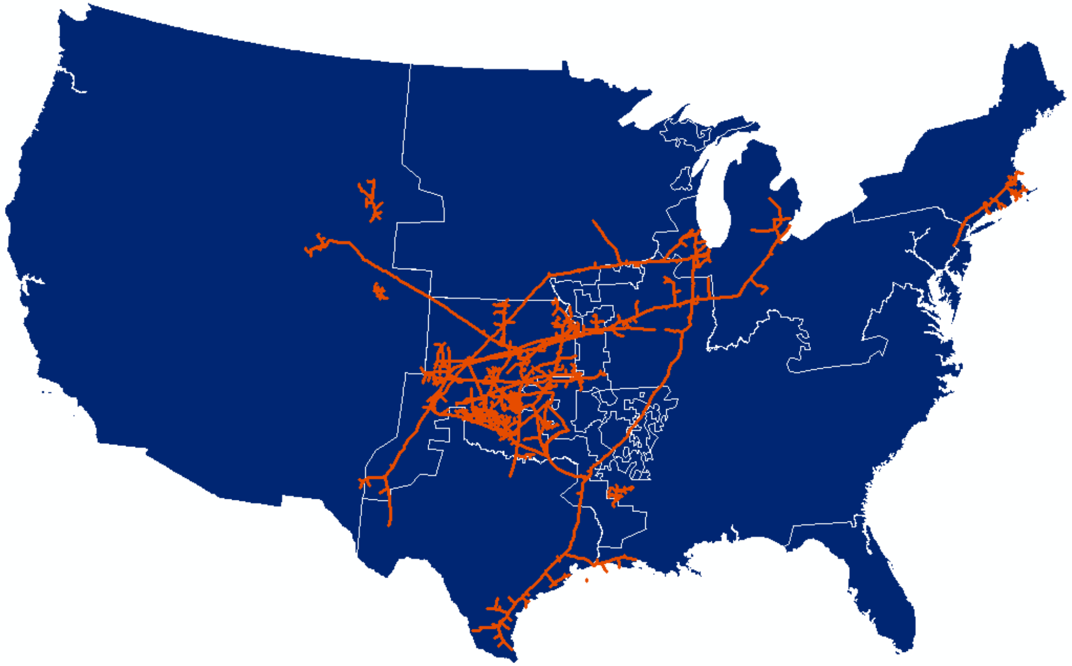




Those pipelines were critical, supply corridor pipelines for Chicago, Detroit, New England and the West.



Data sources: NERC-GADS; EIA-860 2017; EIA Interactive state maps shapefiles

Pipeline failures did not explain the majority of fuel shortage failures

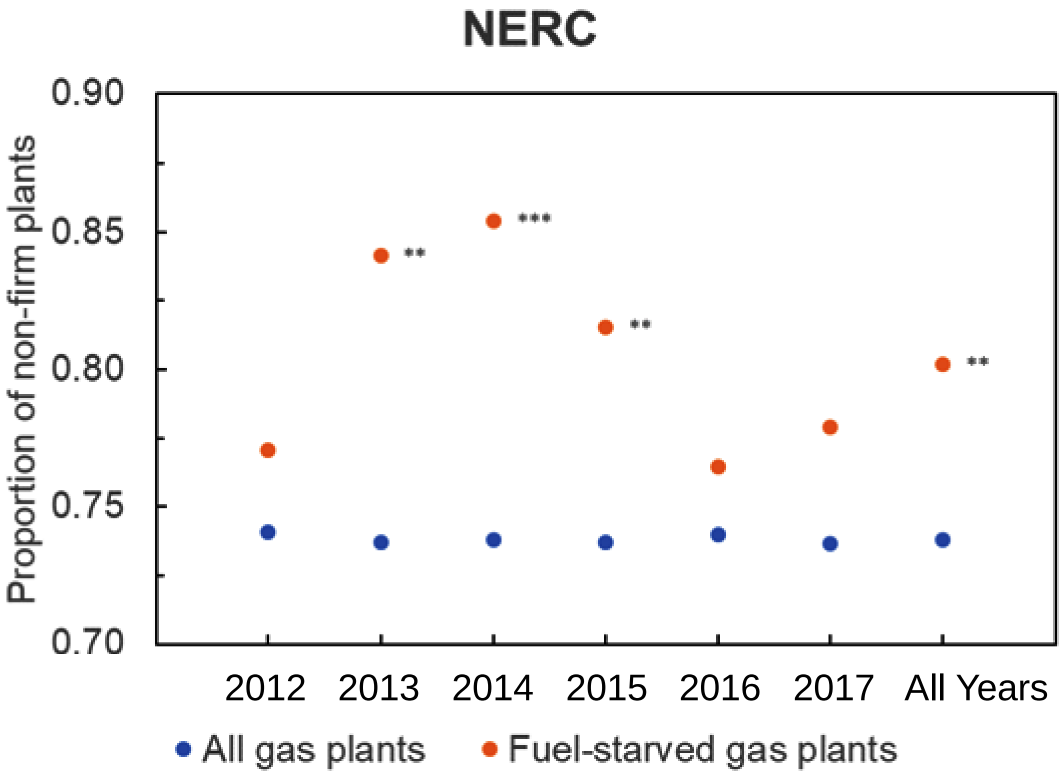
- Pipeline and Hazardous Materials Safety Administration pipeline incidents explained only ~200 of the 6,200 fuel starvation failures between 2012-2017.

- But, PHMSA reporting isn't adequate for these types of reliability studies.*

- Transmission pipeline force majeure events explain only a maximum of <u>9% of unscheduled fuel shortage events</u>.

*See: Gerad Freeman, Jay Apt, and Michael Dworkin. "The Natural Gas Grid Needs Better Monitoring." Issues in Science and Technology 34, no. 4 (Summer 2018).

Gas plants with non-firm fuel procurement strategies are, as expected, over-represented in fuel starvation data



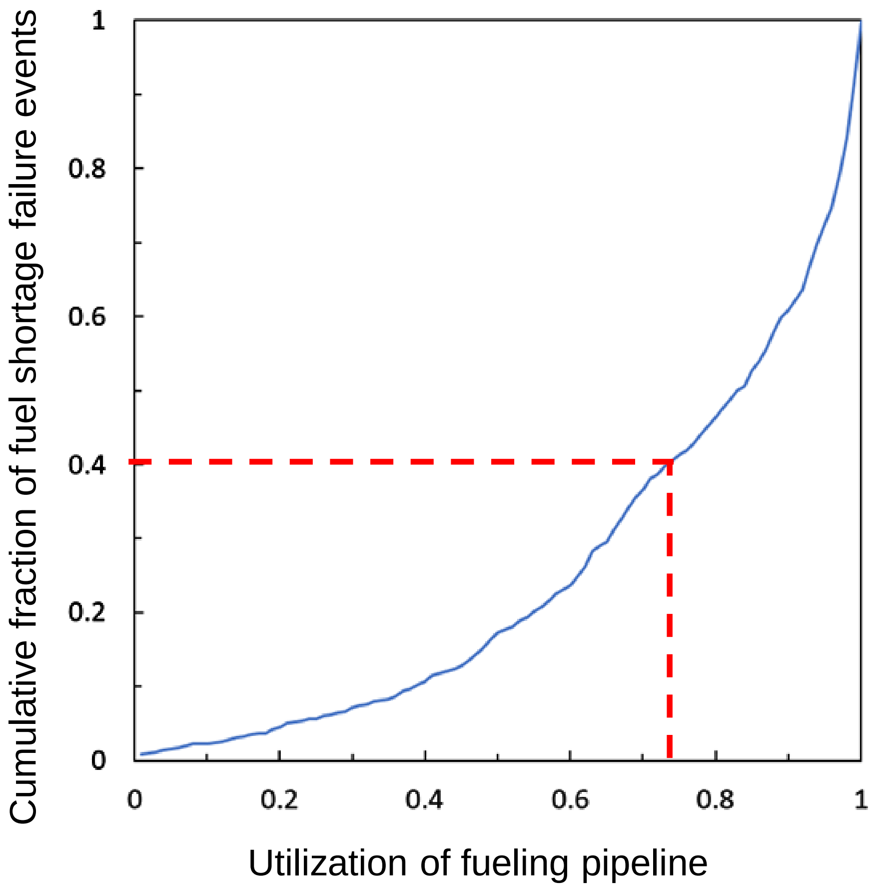
Note: One-sample proportion test result significance:
** : α = 0.05 *** : α = 0.01

Capacity was available on pipelines in PJM during many fuel starvation events

2. Case Study: longer time resolution PJM database (3/2002 – 4/2018)

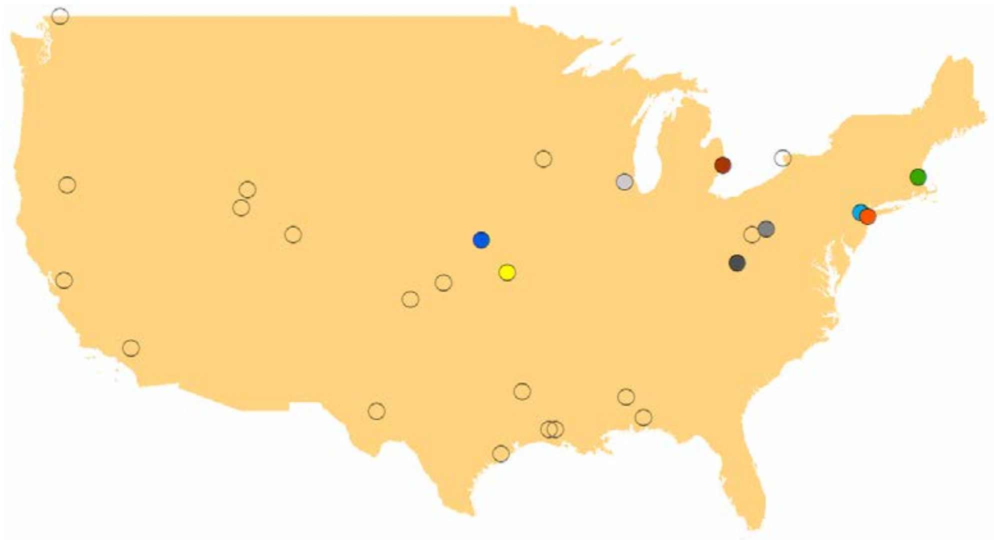
- We take a close look at the utilization of pipelines fueling the fuel-starved power plants

- We find that when ~40% of fuel shortage events began, fueling pipelines were operating well below their demonstrated peaks.



Could plants in RFC and MRO be “firmed up”?

- Back to the NERC sample.
- We group plants by the nearest natural gas trading hub



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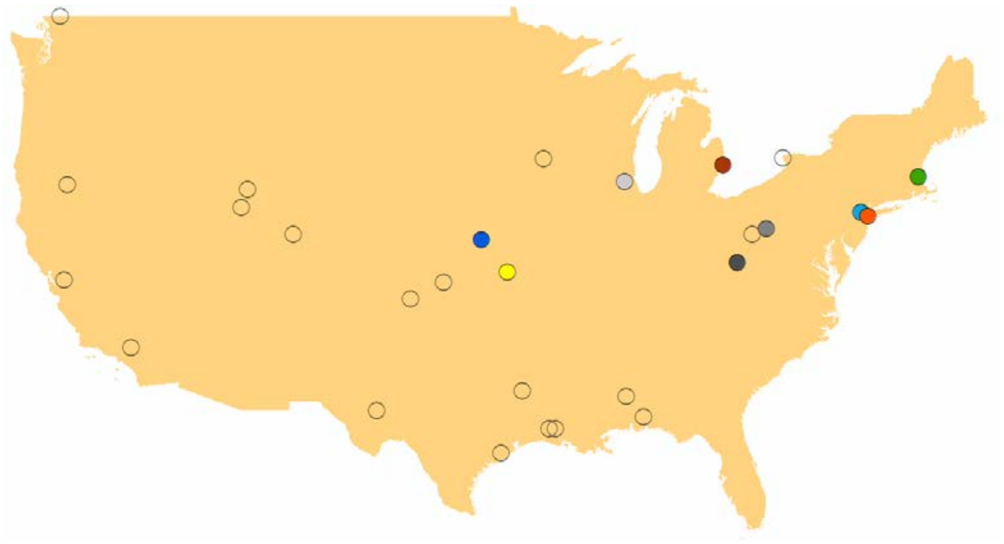
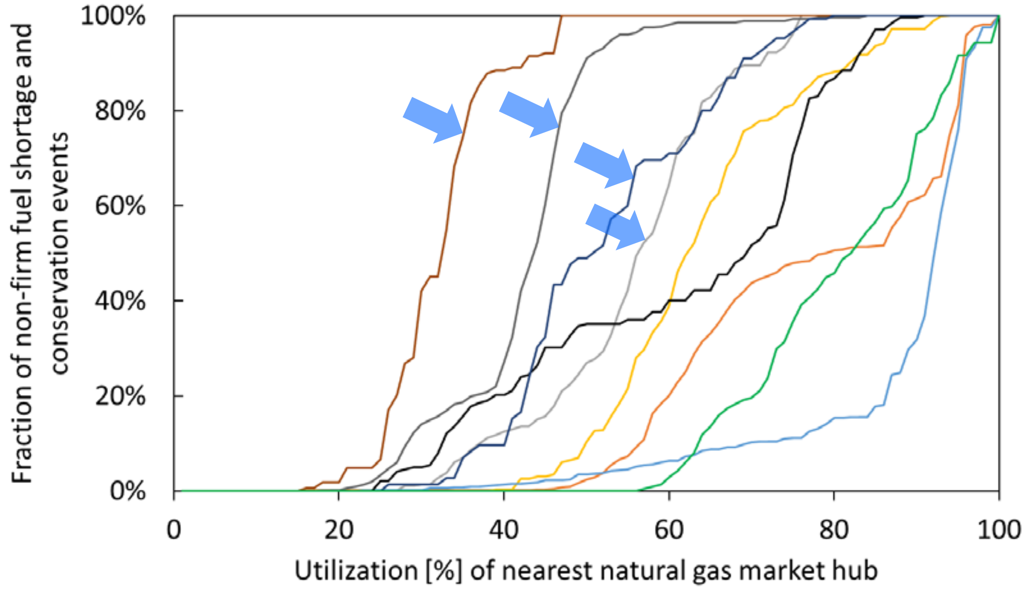
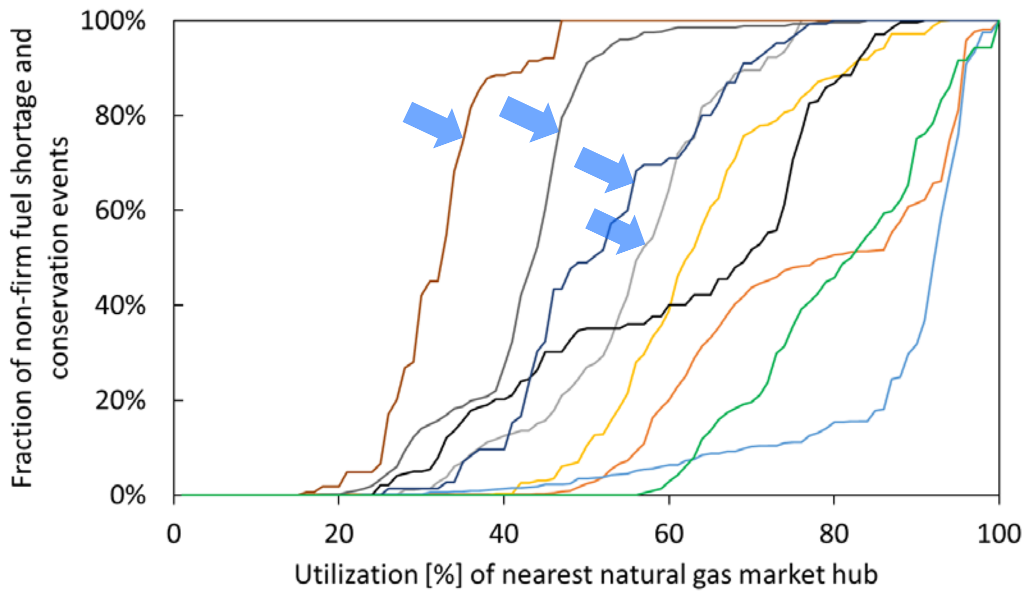




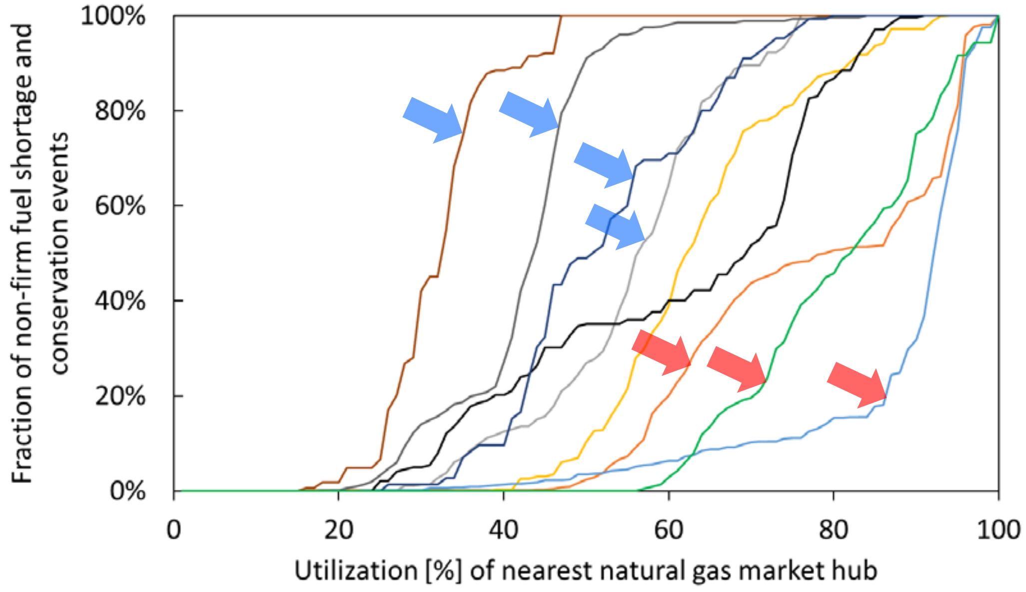
Could plants in RFC and MRO be "firmed up"?

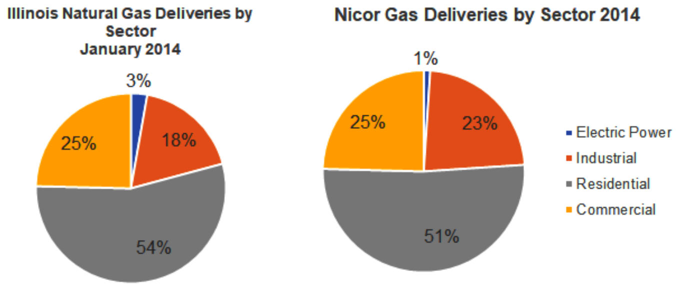
- Back to the NERC sample.
- We group plants by the nearest natural gas trading hub
- Pipeline capacity was available in MRO and RFC (blue) at the nearest major gas trading hub when fuel starvation events occurred.



Could plants in RFC and MRO be "firmed up"?

- Back to the NERC sample.
- We group plants by the nearest natural gas trading hub
- Pipeline capacity was available in MRO and RFC (blue) at the nearest major gas trading hub when fuel starvation events occurred.
- Pipeline capacity was not available in the red area.
- Only sparse public data exist downstream of city gates, so we cannot tell if power plants could out-prioritize C&I customers, or if the gas is going to residents. The utilities have the data.





Summary of findings on interdependence

- Correlated, fuel starvation failures at gas plants knocked out generators with both firm and non-firm fuel contracts
- Critical supply corridor pipelines for major urban areas starved larger fractions of their connected capacity than the national average.
- Pipeline failures did not explain the majority of fuel shortage failures, out-prioritization drove these failures.
- Data downstream of city gates are needed to tell if some plants in RFC and MRO could be “firmed up”. Plants in eastern New York and New England might use dual fuel.

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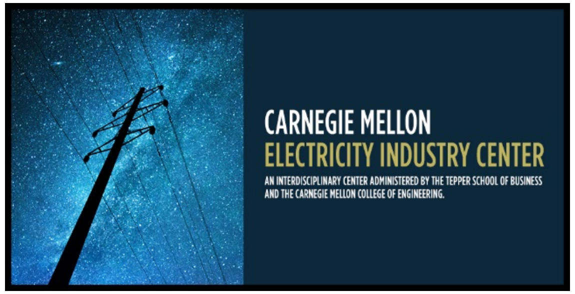

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