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.
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
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 1987 and April 2006, 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. Liquidified 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...
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
  o 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 § 255(b)(4) → Reports of Service Interruptions and Force Majeure
  o 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 ft³ 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”

![PHMSA incidents grouped by whether they meet mandatory report thresholds (2010 – 17)](image)

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.

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

Gerard M. Freeman, Jay Apt, John Moura

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 majeure* 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?

How long are the observed New England gas outages?

Capacity-weighted histogram of max fuel shortage failure duration
1/2012 - 3/2018

All units in sample:
- $n=54$ (14.3 GW), mean=22h, s.d.=42h

Units with <7 fuel shortages:
- $n=46$ (11.9 GW), mean=13h, s.d.=16h

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

Unpublished results, do not distribute without permission of the authors

Electric power generator reliability
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
Resource adequacy risks to the bulk power system in North America

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

Sinnott Murphy\textsuperscript{a}, Fallaw Sowell\textsuperscript{b}, Jay Apt\textsuperscript{a,b,*}
Unscheduled outages (U)
Start Failures (SF)
Derates (D)

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.
Aggregating generator time series

Unavailable capacity (GW)

- Total unscheduled
- Outages
- Derates
- Start failures


Unscheduled Outages Derates Start failures
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
We modeled the relationship between temperature and unavailable capacity.

Unit type key:
- CC: combined cycle gas
- CT: simple cycle gas
- HD: hydroelectric
- DS: diesel
- NU: nuclear
- ST: steam turbine (coal)
Temperature dependence still present for gas generators when ignoring fuel events

**Key:**
- Open circles: including all unscheduled events
- Solid circles: excluding fuel unavailability events
Consistent temperature dependence for coal generators when segmenting by generator age

**ST (54% of capacity)**

- **1950s**: 112 units, 17 GW
- **1980s**: 36 units, 10 GW
- **1960s**: 93 units, 29 GW
- **1990s**: 68 units, 12 GW
- **1970s**: 88 units, 45 GW
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
Generation that failed 2/15-18/2021
(ERCOT has 107 GW. A large nuclear plant is approx. 1 GW)

15 GW of natural gas
4 GW of coal
3 GW of wind
1 GW of nuclear
1 GW of solar


Expected Unserved Energy and Reserve Margin Implications of Various Reliability Standards

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, 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.
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** |
| 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 | Drillsite.com |
| Flow Line Insulation - $3/ft - 100 Ft | Insulate Flow Line | $300 | Drillsite.com |
| Flow Line Heat Tape - $4/ft - 100 Ft | Provide Heat to Flow Line | $400 | Drillsite.com |
| Fiberglass Hut for Enclosing 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

WHEN BELTS DON’T MOVE, GOODS DON’T MOVE
Keep conveyor belts running in the worst winter weather, saving productivity and profits with Midwest’s spray systems and anti-icing, deicing agents.

YOU CONTINUE THROUGHPUT WHILE OTHERS GO KAPUT.

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
Resource adequacy implications of temperature-dependent electric generator availability

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Dynamic operating reserve procurement improves scarcity pricing in PJM

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The largest single contingency in PJM is 1.4 GW.
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

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Annual electricity use (MWh)

- 50,000
- 100,000
- 150,000
- 200,000

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.
Thank you!

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Scan the QR code below for my full contact information