

Simulation and Analysis of Resilient Power Systems in PJM

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SUMMARY

Electricity is a public necessity and is critical to the health and welfare of the nation. Keeping power available whenever and wherever it is needed is the number one priority of PJM Interconnection and other grid operators. Grid operators around the world find themselves contending with new challenges, including a rapidly changing resource mix, stressed fuel delivery systems, extreme weather, cyberattacks and physical security threats. These emerging challenges have introduced a heightened focus on ensuring a resilient system to deliver electricity to consumers.

From a grid operator's perspective, there are many dimensions of resilience that span system operations, planning, and markets, as well as increasingly interdependent external systems that impact the grid. As the resource mix evolves, one component of resilience – fuel security – has become an increased area of focus. Fuel security focuses on the fuel supply chain vulnerabilities inherent to a power system with increased dependence on just-in-time fuel delivery infrastructure.

A major challenge, however, is developing a way to simulate and analyse the resilience of the power grid under a series of extreme but plausible events. This paper discusses the design and development of a simulation methodology using the PLEXOS power system simulation tool to analyse fuel security risk events. Key fuel security risk elements included in the simulation methodology were the availability of natural gas based on contractual arrangements, natural gas pipeline disruptions, and fuel inventory modelling. Descriptions of the novel modelling approaches developed to simulate each of these elements are described in detail.

Using the simulation methodology, PJM studied 324 different scenarios that could occur during an extended period of cold weather, varying elements such as customer demand, interruptible natural gas availability, pipeline disruptions, replenishment frequency of onsite fuel, generator forced outage rates, and potential future retirements of nuclear and coal generation.

KEYWORDS

Energy Security, Fuel Security, Interdependent Infrastructure, Modelling, Resilience

1. INTRODUCTION

The energy industry in the PJM region is in the midst of dramatic change. Over the last decade, as shale gas hydraulic fracturing has become widespread, new gas-fired generation has continued to increase. Other new technologies such as renewable generation, demand response and distributed energy resources have also increased dramatically. During this time, coal has been retiring at a quicker pace, and the prospect for the retirement of nuclear generation has also continued to rise. Presently, natural gas generation makes up 65% of the capacity in the PJM interconnection queue, followed by solar at 25% and wind at 7% [1]. The changing resource mix requires that PJM evolve to ensure that reliability and resilience are maintained into the future.

Resilience can be defined as how grid operators manage the risk of high-impact disruptions, which can happen simultaneously and persist for a period of time. Grid operators must prepare for, be capable of operating through and be able to recover as quickly as possible from these events, no matter the cause. From PJM's point of view, there are many dimensions of resilience that span system operations, planning, markets and interdependent infrastructures of the grid. As the generation in PJM becomes increasingly dependent on natural gas, one component of resilience – fuel security – has become an increased area of focus. Fuel security focuses on the vulnerabilities inherent to a power system with increased dependence on just-in-time fuel delivery.

Until now, few studies have developed a comprehensive framework for how to simulate and analyse the resilience of a power grid to such a series of high-impact low probability, but plausible, events. This paper discusses the design and development a novel simulation methodology to analyse the impacts of such events on the PJM system using Energy Exemplar's PLEXOS® Integrated Energy Model (PLEXOS) power system simulation tool. PLEXOS is a production cost model that performs both a security constrained unit commitment and economic dispatch over a given time horizon. The software provides the needed flexibility to accurately simulate the complexities of PJM's system while developing custom constraints to simulate on-site fuel depletion and replenishment, and varying natural gas availability based on pipeline disruptions and firm or non-firm gas transportation.

Key fuel security risk elements included in the simulation methodology were interruptible natural gas availability, natural gas pipeline disruptions, and fuel inventory modelling. Section II of this paper provides a detailed description of the modelling approaches developed to simulate each element. Section III describes a case study of the modelling approach described in Section II analysing the PJM system during an extended period of cold weather. Section IV presents the results of the case study and Section V discusses the results. Finally, conclusions and next steps are examined in Section VI.

2. METHODOLOGY

A number of input assumptions and scenarios were developed to evaluate the resilience of PJM's system to events related to fuel security. This section discusses the methodology used for developing these fuel security risk scenarios, and how they were modelled in PLEXOS.

Development of Assumptions & Scenarios

Defining the scope of a resilience-focused analysis is inherently challenging because of the nature of the risks and events being assessed. Fuel security risks to the grid are varied, multi-dimensional and range from fairly frequent events such as a winter cold snap to highly unpredictable events like a pipeline disruption. The probabilities of such events are also not easily assessed. The approach used for developing assumptions and scenarios was to define reasonable book-ends for analysis ranging from typical to extreme.

The first key assumption was narrowing the scope of risks being analysed by focusing on the winter season. This analysis focused on cold weather events because risks to PJM generation's ability to

procure adequate fuel to serve load is most prominent during the winter months. This is primarily because during the winter the needs of commercial and residential heating customers are competing with natural gas-fired and dual-fuel generators (which generate more than 30 percent of the megawatt-hours of energy produced in PJM) for natural gas, oil, pipeline transportation and oil deliveries.

In addition, the development of assumptions included a substantial outreach effort to industries that have interdependencies with grid operations to assess fuel supply chain risk. Industry groups that were engaged included: generation owners; natural gas pipelines; fuel marketers; companies responsible for trucking, barge, and rail systems; and industry groups for coal, natural gas, nuclear, renewables and demand response. This outreach collected information about fuel inventories risks of disruption to fuel delivery systems and the potential downstream impacts on dependent power generation.

Fuel Security Risk Modelling Elements

The analysis focused on detailed simulations of three elements of fuel security risk: availability of natural gas based on contractual arrangements, physical natural gas pipeline disruptions and the availability of onsite fuel.

Natural Gas Availability

Surveys and outreach with generation owners were used to identify natural gas generators that are solely reliant on natural gas for operation and that indicated that they do not have a firm natural gas transportation contract. In the simulation model in PLEXOS, individual natural gas unit availability based on this contractual information was used as an input for each scenario. Conservative and optimistic assumptions about the availability of natural gas units with non-firm gas were also formulated for the different scenarios. Most of the year, many of these generators with non-firm gas are able to secure gas supply from the secondary market by working with various suppliers, even during times of high natural gas system demand.¹ PJM has seen the availability of firm gas transportation services through the secondary market, even during conditions of extreme cold. Data from the North American Electric Reliability Corporation (NERC) Generating Availability Data System (GADS) over the past 5 years was analysed to determine historic outage rates resulting from an interruption or curtailment of non-firm gas.

Natural Gas Pipeline Disruptions

To stress the system, interstate pipeline disruption events were modelled in the simulations. The location of each pipeline disruption was selected based on several characteristics: generation facility clusters, levels of generating capacity within those clusters, PJM's overall reliance on a particular pipeline and the configuration and design of the pipeline segment feeding the generation resources. The downstream impacts and duration of the disruption scenarios were developed based on the history of events on the pipeline system and through consultation with the Natural Gas Council and major interstate pipelines.²

In each scenario, the input availability for generators impacted by each pipeline disruption was based on different combinations of disruption locations and severity: partial (medium impact) or full (high impact) disruptions of supply due to each event at each selected pipeline location. This practice was intended to simulate reduced capacity on the constrained portion of the interstate pipeline in the PJM region. Natural gas fuel delivery characteristics such as the limited availability of interruptible capacity during cold weather were also taken into consideration. All generating units with firm transportation were assumed to be available under all temperature conditions and only impacted within

¹ The secondary market consists of a large pool of natural gas marketers and suppliers that have a portfolio of various natural gas transportation and supply assets that they can offer to the market. Generators will often rely on these marketers to deliver gas to them, most often on a firm basis.

² The Natural Gas Council includes five organizations: American Gas Association, American Petroleum Institute, Independent Petroleum Association of America, Interstate Natural Gas Association of America, and The Natural Gas Supply Association.

a pipeline disruption scenario. All dual-fuel units were assumed to be operating on backup fuel during a pipeline disruption.

Fuel Inventory Modelling

Onsite fuel capacities vary from site to site within the PJM footprint. PJM currently collects data about these capacities through surveys and performed an evaluation of the survey responses to develop a total storage capacity for each unit or site. Survey data was also used to identify which oil tanks are dedicated to a single generator and which oil tanks are connected to multiple generators. In order to determine the appropriate starting inventory level, the results from a survey question about each unit's winter starting inventory target for onsite fuel as a percentage of total available storage capacity were used. Fuel delivery methods, refuelling processes and potential logistical issues also vary across the PJM footprint. From the survey data and industry outreach, a sensitivity range for inventory refuelling rates was determined based on the fuel delivery method and maximum inventory level. The inventory-to-generator relationships, inventory capacities (BTU), starting inventory (BTU) and assumed refuelling rates (BTU per day) were input into the model so that the generator fuel inventories could be dynamically depleted and replenished in the simulations as the generators consumed their onsite fuel.

Indicators for System Stress

In order to evaluate system performance during each simulated scenario, several indicators were used to determine if pre-emergency or emergency procedures would have been triggered. The indicators were based on operational procedures described in [2]. The indicators are listed below in order of increasing severity:

- Normal Operations: no emergency procedures triggered
- Demand Response Deployed: pre-emergency action, demand response resources deployed in the simulation
- Reserve Shortage Emergency Warning: an operational reserve shortage is triggered when 10-minute synchronized reserves are less than the largest generator in PJM. Depending on system conditions, a reserve shortage will trigger additional emergency procedures such as voltage reduction warnings and manual load shed warnings.
- Voltage Reduction Emergency Action: voltage reduction action enables load reductions by reducing voltages at the distribution level. PJM estimates a 1-2% load reduction resulting from a 5% load reduction in transmission zones capable of performing a voltage reduction.
- Load Shed Emergency Action: manual load shed action enables zonal or system-wide load shed. This is the last step of all emergency procedure actions.

Using these indicators, the impact of each fuel security risk could be determined in each simulation scenario.

3. CASE STUDY

Using the simulation methodology discussed in Section II, 324 different scenarios were studied that could occur during an extended period of cold weather, varying elements such as customer demand, interruptible natural gas availability, pipeline disruptions, replenishment frequency of onsite fuel, generator forced outage rates, and potential future retirements of nuclear and coal generation [3]. The scenarios were simulated in PLEXOS using hourly security constrained unit commitment and economic dispatch simulations over a 14 day time horizon consistent with current PJM market practices and dispatch mechanisms.

A summary of all the assumptions and sensitivities used in the analysis is shown in Table 1.

Table 1: Modelled Assumptions Summary

Modelled Assumptions		
Study Year	Weather Scenario	
2023/2024	14 days	
Load		
Peak Load	Typical: 50/50 – 1 in 2 years; (134,976 MW peak)	Extreme: 95/5 – 1 in 20 years; (147,721 MW peak)
Load Profile	Typical: 2011/2012 winter	Extreme: 2017/2018 winter
Dispatch		
Dispatch	Typical: Economic	Extreme: Economic; sensitivities to demonstrate impact of Maximum Emergency procedure [2]
Retirements		
Announced: Generation retirements announced by Oct. 1, 2018, and new generation in the PJM interconnection queue and slated to be in operation by 2023	Escalated 1: Generation retirements of 32,216 MW by 2023, with 16,788 MW of capacity added to meet the installed reserve margin requirement (15.8%)	Escalated 2: Generation retirements of 15,618 MW by 2023 with no capacity replacement
Escalated 1 Replacement Capacity Approach		
<ul style="list-style-type: none"> • Replacement resources reflective of PJM interconnection queue and commercial probability • Replacement combined cycle natural gas resources modelled as firm supply and transport • Replacement combustion turbine natural gas resources modelled as dual-fuel with interruptible gas 		
Natural Gas		
Non-Firm Gas Availability	Typical and Extreme: 62.5% and 0%	
Pipeline Disruptions: Four discrete disruption locations, one in each scenario	Medium Impact: Days 1–5: 50%–100% disruption; days 6–14: 100% output (0% derate)	High Impact: Days 1–5: 100% disruption; days 6–14: 20% derate
Fuel Oil		
Initial Oil Inventory Level	85%	
Oil Refuelling (>100 MW site)	Moderate: 40 trucks daily refuelling rate, capped at maximum tank capacity	Limited: 10 trucks daily refuelling rate, capped at maximum tank capacity
Oil Refuelling (<100 MW site)	Moderate: 10 trucks daily refuelling rate, capped at maximum tank capacity	Limited: 0 trucks daily refuelling rate, capped at maximum tank capacity
Expected Forced Outage Rates		
5-Year Average: Historic 5-year average, discounting gas and oil fuel supply outages	Modelled: Regression model of expected outage rates, discounting gas and oil fuel supply outages	
Transmission Modelling		
Announced Retirements: Transmission constraints that are greater than or equal to 230 kV	Escalated Retirements: Individual transmission constraints were not modelled; transfers into eastern PJM were limited based on CETO with a 15% transfer margin adder	
Scheduled Interchange	Total interchange with neighbouring systems limited to +/- 2,700 MW	
Demand Response	7,092 MW modelled locationally based on MW cleared by zone and nodal modelling	
Renewable Modelling	2017/2018 cold snap profile	
Distributed Energy Resources and Energy Efficiency	Accounted for in the load forecast	
Fuel Prices	2023/2024 futures prices adjusted by historic volatility	

4. RESULTS

The simulation results for each of the 324 different scenarios simulated are shown below. Figure 1 shows the results of the announced retirement scenarios with both typical and extreme winter loads and Figure 2 shows the results of the escalated retirement scenarios with both typical and extreme winter loads [3]. A description of each of the actions shown in Figure 1 and Figure 2 is described in Section II.

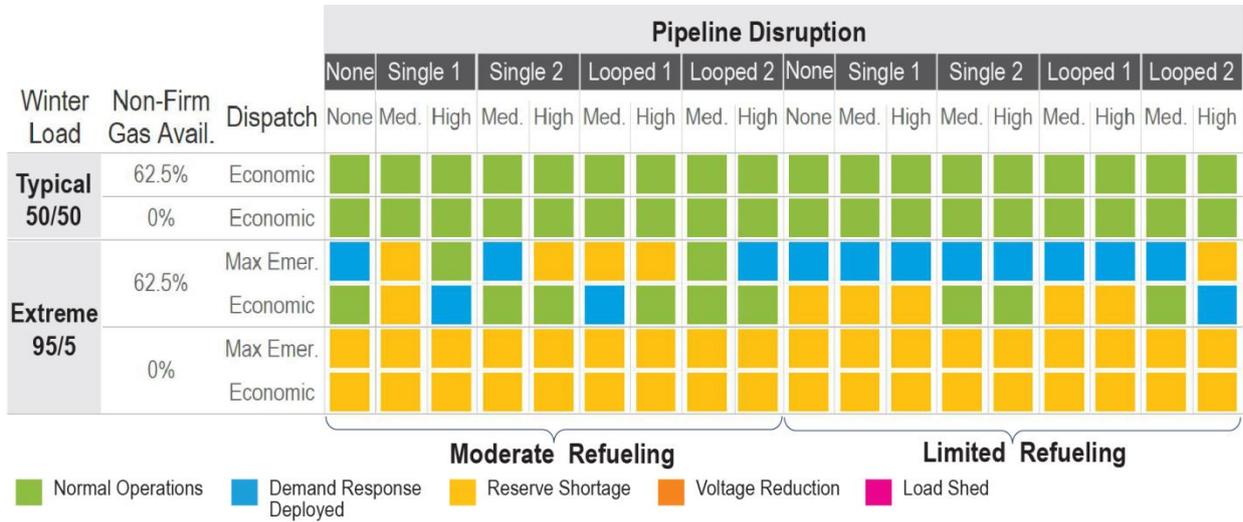


Figure 1: Announced retirements, typical and extreme winter load scenario results

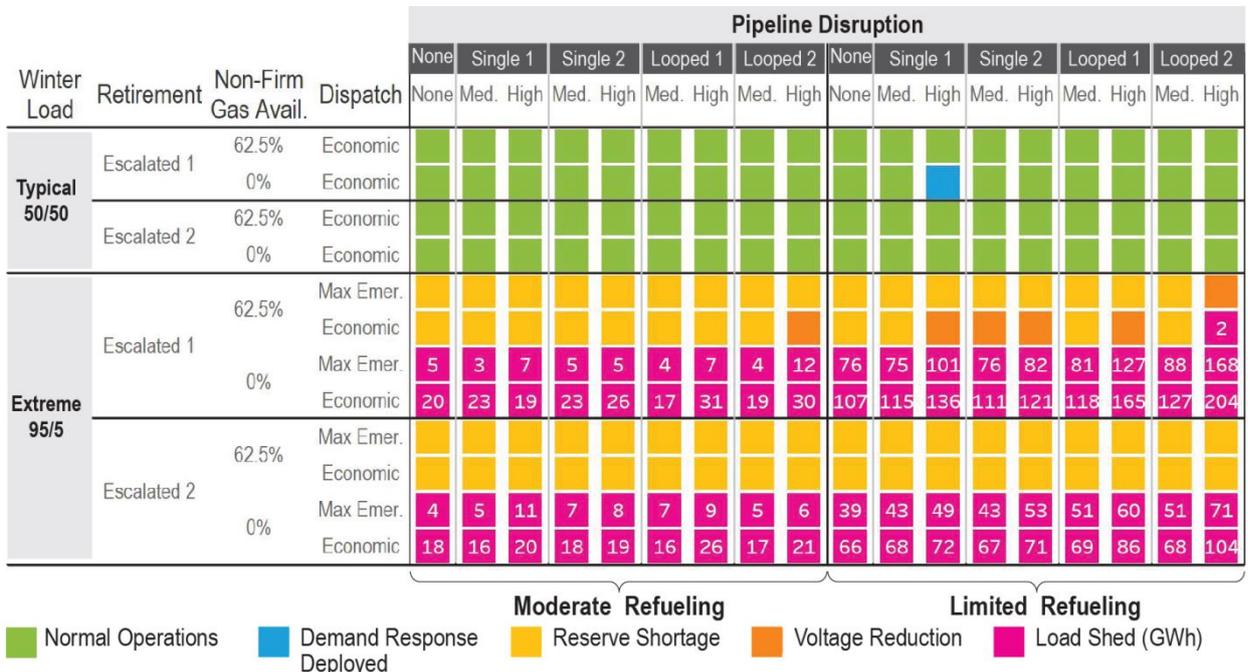


Figure 2: Escalated retirements, typical and extreme winter load (with GWh of load shed) scenario results

As shown in Figure 1, when including only announced retirements as of Oct. 1, 2018, no pre-emergency or emergency actions were triggered on the system in any of the 36 typical winter load scenarios. This was true even when simulating a high-impact pipeline disruption with limited oil refuelling and no non-firm gas availability. In the 72 extreme winter load scenarios including only announced retirements, 11 observed normal operations, 14 deployed demand response and 47 experienced operational reserve shortages.

As shown in Figure 2, when the number of retirements was escalated and paired with typical winter load, only 1 of the scenarios triggered any pre-emergency actions by deploying demand response, but no emergency actions were triggered. However, in the scenarios where the escalated retirements were combined with extreme winter load, 144 of the scenarios triggered pre-emergency and emergency actions. Of these 144 scenarios, manual load shed was observed in 73. The majority of the load shed volume was observed during the peak load hours across the 14-day period.

5. DISCUSSION

In particular, the key variables that had the most impact on the results were:

- The level of retirements and replacements
- The availability of non-firm gas transportation service
- The ability to replenish oil supplies
- The location, magnitude and duration of pipeline disruptions
- Pipeline configurations.

The sensitivity of the results to key input assumptions was identified by adjusting several input variables. For example, in one scenario, total load shed hours decreased from 83 hours to 22 hours when the refuelling variable changed from limited to moderate. For the same scenario, when the availability of non-firm gas was changed from 0 MW to 10,000 MW, the need for load shed was completely eliminated and only voltage reduction was triggered. Finally, in that scenario when Maximum Emergency Operating Procedures were used instead of Economic Dispatch, operational reserves shortages were still triggered, but the need to shed load was eliminated. The high sensitivity of the results to the key input assumptions highlights the importance of accurately modelling and simulating the impacts of such events on the system in order to appropriately manage system risks.

6. CONCLUSIONS

Although it is intuitive that a lack of fuel leads to an inability to produce electricity, this project was the first for PJM to quantitatively simulate plant-level fuel capacities and their aggregate impact on energy production during extreme weather events.

While the case study described in Section III modelled onsite fuel oil inventories that were replenished by truck deliveries, the methodology described in Section II for modelling fuel inventories could be expanded to other fuel types and delivery methods to evaluate system performance under resilience events of different severity and duration. For example, a longer timescale disruption of a large barge or rail fuel delivery system could be simulated to determine their impacts on individual unit inventories, and downstream impacts on the grid.

Similarly, the natural gas availability and pipeline disruption methodologies described in Section II could be applied more broadly in future work. Although the natural gas pipeline disruptions were simulated discretely, the methodology could be used to simulate impacts of coordinated cyber or physical threats impacting multiple pipeline segments. Additional variability could also be applied to the natural gas availability due to contractual arrangements.

As described in Section II and Section III, the simulation methodology is deterministic. The intent of the simulation methodology was to develop a way to study the resiliency of operations during fuel security risk scenarios, not to determine the probabilities of such scenarios occurring. Although each individual input assumption used in the case study was developed using rigorous data collection and outreach, some of the resultant scenarios have never been coincidentally observed in PJM, or have occurred at the severity studied. Future work could include a stochastic approach to the scenario

development within the simulation methodology to attempt to capture the probability of coincident issues.

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