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Light Water Reactors Sustainability Program

Position Paper Evaluating and Prioritizing Nuclear Energy Market Attributes

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Summary

This position paper provides the results of a short turn-around study focused on ensuring electrical grid resilience via adequate baseload (nuclear) representation. This includes:

- Literature review
- Report holistically evaluating grid reliability and resilience (INL/EXT-18-45010)
- Report proposing a framework to quantify the value of inertia from nuclear power plants (INL/EXT-18-45018)
- Multi-objective optimization tool that provides the ability to understand impacts to reliability and weather-based resilience as the fuel mix changes

Literature Review Key Findings - Summary

Literature was reviewed to compile existing grid resilience studies providing insight to the following questions:

1) What is the impact to grid resilience as baseload is decreased in the fuel mix?
2) How do different baseload energy sources perform under various stressing events?
3) What is the impact to resilience for a high percentage renewables system?
4) What is the impact to resilience for a high percentage natural gas system?

Question	**Findings**
Impact to Resilience as Baseload is Decreased	No studies quantifying the minimum and optimum baseload required for resilience were identified. Several studies identified technical issues to investigate as well as the need to better define characteristics, metrics and benefits of resilience
Performance of Energy Sources under Stressing Events	There are a very limited number of studies quantifying or projecting performance of various energy generation technologies under stressing events; however, several provided a retrospective analysis of specific events and others stated the need for a detailed understanding of interdependence of fuel delivery infrastructures
High Percentage Renewables Systems	No analyses were identified that specifically addressed resilience for a high variable renewable generation system; however, several studies did evaluate reliability issues
High Percentage Natural Gas Systems	Limited analyses evaluating resilience for systems with high penetration of natural gas were found. A few studies identified the need to understand implications of greater natural gas dependency.

Literature Review Key Findings - Detailed

- No studies quantifying the minimum and optimum baseload required for resilience (frequency response) were identified
  - The following issue was identified multiple times: as non-synchronous generation technologies[1] increase (e.g., renewables), and synchronous generation technologies[1] decrease (e.g., coal, nuclear), system inertia could decrease and likely will lead to a degradation of ERS frequency regulation
  - Several studies[1-6] referenced the need to research capabilities and limits of rotating mass-based inertia[1], inverter-based synthetic inertia[2], demand-side response system frequency control[3] (e.g., industrial motors), storage-base inertia (e.g., flywheel energy storage systems)[4]
  - Characteristics, metrics, benefits and compensation for resilience are not fully understood; proposed metrics, potential evaluation frameworks, economic analysis of resilience investments, and event modeling frameworks for extreme events are needed[7-12]
  - There is a lack of literature on fuel security, fuel assurance, and fuel supply chain issues; the majority available focused on qualitative observations about natural gas and electric infrastructures, given the growing reliance on natural gas.
  - No studies were identified that quantified current grid complexity, projected future grid complexity as a function of fuel mix and approaches to provide frequency response, or defined the relationship between increasing system complexity and grid resilience.
- There are a very limited number of studies quantifying or projecting performance of various energy generation technologies under stressing events
  - Most studies focused on a retrospective analysis of specific events (e.g., Polar Vortex, Hurricane Sandy) or reliability portfolio analysis for specific markets (e.g., PJM, a regional transmission organization) with some extreme weather use cases[10, 13-20]
  - Several studies stated the need for detailed analysis of natural gas infrastructure and delivery, particularly under extreme weather events.[21-24]
- No analyses were identified that specifically addressed resilience for a high variable renewable generation system; however, several studies did evaluate reliability issues
  - Most studies identified a multitude of technical issues that emerge as renewable generation penetration increases and need substantial further study; a primary concern is frequency response[2, 25-29]
  - As renewables increase, system complexity increases; no studies quantifying system complexity impacts on resilience degradation were identified
  - Grid codes and standards need to be evaluated and implemented based on system needs [6, 30]
  - Further quantitative studies evaluating cost of variable renewables to provide ERS need to be performed
- Limited analyses evaluating resilience for systems with high penetration of natural gas were found
  - Several recent studies focused on understanding implications of the increasing interdependence of the U.S. electric power and natural gas infrastructures[31-33]
  - Several analyses identified the need for additional, detailed analysis to quantify regional reliability implications of greater natural gas dependence (e.g., supply chain, storage, transport, price spikes).[23, 24, 31, 32, 34-36]

Report: Study of Grid Reliability and Resilience – Executive Summary

The power sector is critical to the modern economy and high quality of life. Every economic sector depends on electricity. Electricity is necessary for life-critical purposes such as food preservation and water treatment. As a result, failures in the electric system have rippling effects through every aspect of society.

At the same time, the grid is changing quickly due to the rapid rise of variable forms of renewable energy like solar and wind power. In parallel, the power sector has endured recent high-profile failures due to extreme weather. Hurricanes Sandy (2012) and Maria (2017) knocked out power for millions of people for extended periods of time in the Northeast and Puerto Rico, respectively. By contrast, Hurricane Harvey (2017) had limited impact on the grid in Texas, and Hurricane Irma (2017) knocked out power for millions, but that power was restored relatively quickly. Because of the changing fuel and technology mix and the range of experiences in response to severe weather events, it is worthwhile to understand the key factors for grid reliability.

This report takes a holistic look at grid reliability and resilience by assessing a range of technical parameters for different fuels and technologies throughout the power sector's supply chain.

This report has several conclusions and findings:

- Vulnerability of the transmission and distribution system is a more important cause of outages than power plant performance or fuel supply reliability, but power plants are worth looking at nevertheless.
- While the ability to store fuel on site has been in the news (e.g., with solid fuels such as nuclear, coal and biomass), power plant reliability is determined by more than a dozen different factors.
- Every fuel and technology option has upsides and downsides from a reliability, vulnerability or resilience perspective.
- Nuclear energy makes an important contribution to grid reliability. Importantly, of the zero-carbon power options, nuclear is the most reliable and available generator except in areas that have reliable hydropower.
- Because each fuel and technology combination has strengths and weaknesses, a diverse fuel mix is important.

[1] Inertia plays an important role in maintaining the stability of the electric grid. It can absorb excess energy when a sudden load drop occurs, and can release energy it stored when needed. Sources of inertia in the interconnected power grid include the rotating mass in power plant turbo-machinery, i.e. turbine blades, turbines and generators shafts, and their mechanical couplings.

[2] Fast frequency control is so-called synthetic or emulated inertial response. Converters can provide short-term frequency regulation to limit frequency deviation. A main difference between synthetic and real inertia is the need to measure the frequency (Ackermann, 2017)

[3] Demand side response system frequency control is a method of decreasing or increasing overall system inertia by using demand-side sources, such as industrial motors or temperature-controlled devices

[4] Flywheel energy storage systems are composed of a rotating mass that can provide some inertial frequency control when there are imbalances between electricity supply and demand

Overall, the U.S. grid is a high performer. However, much can be done to improve its overall reliability. As an outcome of the analysis in this report, there are several recommendations to be made:

1. Harden the transmission and distribution (T&D) system via undergrounding, tree trimming, or pole replacement.
2. Improve nuclear power plants' responsiveness (through decoupled, integrated processes such as water treatment or hydrogen production) and resilience (through improved supply chains for specialized parts).
3. Improve rotational inertia contributions from wind and solar.
4. Develop fast-acting carbon capture systems to keep the responsiveness of coal or natural gas systems without the emissions.
5. Invest in electricity and thermal storage research and development to help nuclear and renewables by absorbing excess supply or for providing missing supply.

The conclusions and findings support this topic is of national importance and worthy of ongoing study.

Report: Study of Grid Reliability and Resilience – Conclusions and Recommendations

Transmission and distribution operations dominate the resilience discussion since they affect the entire bulk power system. However, power plant resilience and reliability still play important roles in recovery after disruption. The cumulative resilience contributed by any given power plant is determined by a wide array of factors. The ability to store fuel onsite has been under a lot of attention recently, but it is just one of many factors and perhaps is less relevant than ramping, rotational inertia, and other attributes. All power plant fuel–technology combinations have resilience tradeoffs. Of the low-carbon power plants, nuclear plants make important contributions to rotational inertia for frequency stability and ramping to meet load in a firm/dispatchable way, although this is rarely done in the U.S. today. Because each power plant type exhibits positive and negative characteristics (which can vary based on the event), maintaining a diverse fuel mix offers valuable flexibility for the bulk power system to withstand and recover from disruptions.

Overall, the U.S. grid is a high performer. However, much can be done to improve its overall reliability and resilience after disruptions. As an outcome of the analysis in this report, there are several recommendations to be made:

(1) **Harden the T&D system**: Because the T&D system is such a critical vulnerability for the networked power sector, and the leading cause of outages, improving its reliability and resiliency characteristics is worthwhile. Improving the system can be done in a variety of ways, including undergrounding (costs more up front, but has lower operating costs, smaller rights-of-way, and less vulnerability to wind events), replacing brittle wooden poles with metal poles, tree trimming, predictive analysis based on sensor data, and expanded network connections to facilitate power wheeling.

(2) **Improve nuclear power plants' responsiveness and resilience**: Nuclear is a good contributor to grid reliability, but more can be done to reduce its vulnerability and improve its resilience. It would be valuable to develop faster-ramping nuclear reactor designs or integrated schemes for decoupled processes (e.g., with heat storage, water treatment, hydrogen manufacturing, and so forth), to

reduce its cooling water dependencies (via dry cooling or other approaches), and to enhance its supply chain of parts to reduce down-time in the event of a failure.

(3) **Improve rotational inertia contributions from wind and solar**: While wind and solar have many benefits (i.e., geographic dispersion, low environmental impact, insensitivity to water availability, etc.), their contributions to frequency regulation via rotational inertia are practically nonexistent. Investing in R&D on the topic of synthetic inertia or fast-switching frequency regulation with wind and solar technologies would benefit the overall system.

(4) **Rapid Carbon Capture**: Invest in R&D for fast-acting carbon capture to retain the fast-response benefits of natural gas (or coal), but without the emissions.

(5) **Electricity and Thermal Storage**: Invest in storage R&D to help nuclear (by absorbing excess supply) and renewables (for providing missing supply).

1. REPORT: QUANTIFY THE VALUE OF INERTIA FROM NUCLEAR PLANTS – EXECUTIVE SUMMARY

Inertia is a critical factor for ensuring the stability of the electric grid. Frequency of electric supply is considered as one of the key indicator of stability and should be studied under both normal and abnormal conditions. In this report, a representative electric power system is modeled and studied using high fidelity digital real-time simulations for accurate assessment of rotational and thermal inertia. The need for a systematic assessment and theoretical quantification of both rotational and thermal inertia imparted by nuclear and thermal power plants is identified as a key area of future research. Electromagnetic transient models are used to represent power systems and its components, and mechanical mass representations for rotating mass from turbines and generators are interfaced in digital real-time simulations. The effect of inertia is examined through real-time simulations of typical disturbances in a wide area electric grid with a representative power plant. Comparison of inertial response from a representative nuclear generator is compared at varying inertia levels for quantifying the effect of rotational inertia on grid stability. Inertia from rotational masses and corresponding effect in electric grid is observed for practical events that occur in the grids. Varying degree of total inertia are modeled in the system to provide insights into the transient stability aspects. Two sample cases of modeling thermal aspects of nuclear plant are considered for this phase of the investigation and results are presented.
The main contributions of this work are summarized below:

- Thermal effects are included for the regenerative steam cycle to represent the effect of thermal inertia in the electric grid;
- A systematic mathematical approach utilizing a combination of existing power system analysis methods and new techniques is developed for quantifying thermal and rotational inertia from nuclear power plants in electric grid.
- A representative set of power systems events that demonstrate the importance of inertia provided by rotating synchronous machines that are directly connected to the grid.
- A perspective of the role of thermal inertia in maintaining the stability and hence the reliability and resilience of the grids.
- As a future direction an exegertic analysis for thermal inputs to the steam turbine for a more accurate representation and quantification of thermal inertia is highly recommended based on the results shown here.

2. REPORT: QUANTIFY THE VALUE OF INERTIA FROM NUCLEAR PLANTS – CONCLUSIONS AND RECOMMENDATIONS

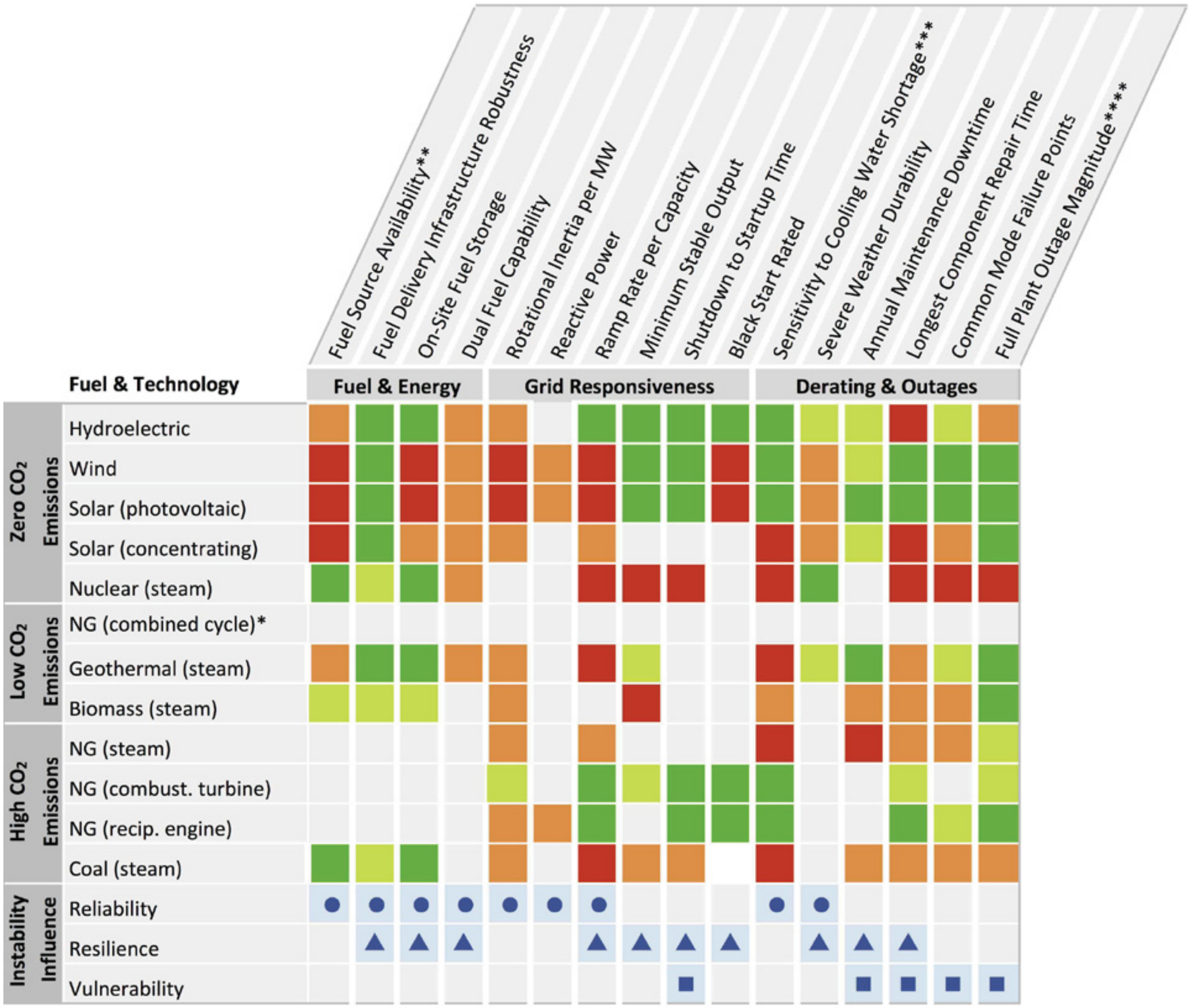
Following is the summary of the observations and proposed future work based on the summary for consideration:

- A theoretical plus simulation-based treatment of rotational inertia and its variations are discussed in this report. Systematic reduction of rotational inertia and its impacts on a test power system is assessed in real-time environment is also presented. A general observation that higher the rotational inertia better is the power system stability gauged against typical events.
- Ideal representation of thermal impacts associated with nuclear and thermal power plants for determining power system stability and margins is has limited accuracy. Results indicating the significant difference in the response of synchronous generators are observed when basic thermal models are included.
- Theoretical and modeling approaches that accurately represent thermal inertia of nuclear and thermal power plants must be rigorously established and validated. The value of rotational and thermal inertia must be quantified and validated using practical and theoretical work. Real-time co-simulation of thermal and electrical systems are recommended for the evaluation of thermal and rotational inertia of nuclear and thermal power plants.
- The role of thermal and rotational inertia imparted by nuclear power plants in power grids is significant to the stability and resilience of grids. Reduction in the inertia of systems will lead to equipment as well as grid-wide issues as discussed earlier. One of the significant challenges with such events is cascading failures that lead to brownouts and blackouts through the power grids. The theoretical assessment along with the validation of inertial value to the grid is hence very significant to a stable, reliable, and resilient power grid.

3. TOOL: MULTI-OBJECTIVE OPTIMIZATION TOOL TO PROVIDE INSIGHTS ON WEATHER-BASED RESILIENCE AS FUEL MIX CHANGES

The report on grid reliability and resilience provide a quantitative set of factors that affect reliability, resilience, and vulnerability for a large set of energy sources. The data was used to build a multi-objective optimization tool in R with user-friendly controls to allow the user to yield insights on weather-based resilience as the fuel mix changes.

Table 1. Consolidated range of factors that affect reliability, resilience, and vulnerability.



Legend			
Much better than NGCC	Better than NGCC	Worse than NGCC	Much worse than NGCC

Notes	
*	This chart considers NGCC generators to be the benchmark technology for power generation in the U.S. The chart rates other generators by comparing them against the NGCC benchmark.
**	i.e., "Availability factor"
***	Each generator type can use a variety of cooling technologies and water sources of varying robustness. For simplicity, this column considers cooling water consumption magnitude.
****	Typical plant size has more to do with financing and economies of scale, but it does also influence grid vulnerability.

Figure 1: Screenshot of Optimization Tool for Weather-Based Resilience

The tool provides the user the ability to change the fuel mix across all energy sources, change the input weighting factors per attribute (data set currently used is derived from Table 1), select specific attributes for optimization (this gives the user the ability to interactively explore various definitions of resilience), and understand the impact to each attribute under weather-based conditions as the fuel mix changes.

4. PROPOSED PATH FORWARD SUBJECT TO DOE REVIEW AND APPROVAL

1) Expand the regional study to include a larger set of attributes, including transmission and distribution based, synthetic inertia, demand-side inertia, price stability and fluctuations.

2) Extend the regional attribute study to a national level for weather-based resilience. Each region has unique fuel mix challenges, policies, weather, etc.; it is critical to leverage and further develop strong relationships in industry (e.g., RTO/ISOs, owner / operators) to validate and refine our resilience grid models.

3) Study impacts of interdependence of fuel supply infrastructures. In particular, evaluate fuel availability and price stability under high impact, low frequency weather events and how it changes the fuel mix with respect to percentage nuclear.

4) Work with stakeholders to expand the definition of resilience to include cyber and physical as well as weather-based events.

5) Real-time co-simulation of thermal and electrical systems are recommended for the evaluation of thermal and rotational inertia of nuclear and thermal power plants.

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