Meeting Notes

U.S. Department of Energy
Quadrennial Energy Review
Technical Workshop on
Resilience Metrics for Energy Transmission and Distribution Infrastructure

April, 29th, 2014

777 North Capitol St NE Ste 300, Washington, DC

Purpose

The purpose of this technical workshop, "Resilience Metrics for Energy Transmission and Distribution Infrastructure," is to explore existing technical research and modeling on resilience metrics, discuss the applicability of existing metrics to energy infrastructure, and identify areas for further research and development of new metrics. The information shared at the technical workshop will feed into the analysis conducted by the U.S. Department of Energy (DOE) and other federal agencies for the purpose of preparing the Year One Quadrennial Energy Review (QER) Report.

Workshop Timeline and Meeting Notes

8:30 – 9:00 Registration

9:00 – 9:15 Introductions and Purpose, EPSA

Rima Oueid (EPSA) provided a welcome and invited attendees to introduce themselves. Karen Wayland (EPSA) provided an introduction to the speakers for the workshop and introduced the workshop's purpose. Namely, she mentioned that the workshop is meant to garner feedback and input from sector experts on the topic of energy resilience metrics related to transmission, storage, and distribution. This is in preparation for a later workshop with a larger list of attendees and slightly broader scope. Karen also thanked Rima Oueid, Dan Ton, Steve Walsh, and Jeffery King for organizing, hosting, and helping to make this meeting a reality.

9:15 – 10:15 Energy System Resilience Metrics – Overview and Data Assessment, RAND

Henry Willis (RAND) provided a synthesis of the current state of energy system resilience metric knowledge. Namely, he sought to introduce the groups that are thinking about resilience, and how they are approaching it. Dr. Willis introduced a word cloud with the purpose of highlighting the large number of terms often associated with resilience. He argued that it is more important for this workshop to understand the properties which are to be captured when measuring resilience than to argue over its precise definition. He provided two primary guidelines:

1. Resilience describes the state of service from a system in response to a disruption

2. Metrics should be selected based on the purposes of individuals measuring resilience or responding to disruption

Dr. Willis introduced graphs that describe a system's performance through time, highlighting that they represent a generic system in response to disruption. He posited the response depends on the type of service (e.g., line workers to a response or power to a community), the type and extent of disruption (e.g., one hazard or multi-hazard), the timeframe of consideration, the scope of assessment, and finally the system's design, operation, and human response (e.g., redundancy, maintenance, response). He offered several examples using graphs of a hypothetical system with various modes of response to disruptions over multiple scales. One important behavior mode mentioned was the ability of a system to capitalize on the chance that the aftermath of disruption provides to learn or improve in anticipation of the next event. Dr. Willis also noted that different systems will have different levels of resilience to the same disruption.

Rich Lorden (EPRI) commented that some of the disruptive events under consideration may have no precedent, and asked how to measure or credit resilience to these types of events.

Dr. Willis responded that the short answer is modeling, and that his later points about validity, practicality, and reliability of metrics may answer the question.

He continued by introducing categories or levels for various purposes of resilience metrics:

1. Inputs: What is available? E.g. infrastructure investments
2. Capacities: How are inputs organized? E.g. response teams, plans
3. Capabilities: What tasks can be performed? E.g. line repair, backup delivery
4. Performance: What is produced/delivered? E.g. energy delivery, efficiency, robustness, sustainability
5. Outcomes – what is achieved? Effect of resilience on the things we care about. E.g. economic activity, costs and damage, human welfare

He summarized the difference between capability and capacity as: "If you have a bike, can you ride it?" Two perspectives were offered, one being a bottom-up perspective from 1-5 often taken by engineers, and another being top-down from 5-1 often used by system planners and policy professionals. Dr. Willis stressed that there may not be one set of metrics which captures resilience for all parties, so the challenge is in framing this discussion about what parts of resilience we measure for certain decisions and why. Therefore, he stressed a balance between simplicity and comprehensiveness using three guiding principles: validity, reliability, and practicality.

Dr. Willis discussed that metrics support both strategic and operational decision making.

A question from the group arose on the topic of exposure; whether Dr. Willis believes there is a clear set of threats or exposures. Dr. Willis claimed that we often think we know the set of exposures, which causes a failure to assess the full set. Another commenter from the electric power industry claimed that it starts with assessing the whole spectrum of known threats. Craig Miller (NRECA) commented that for the unknown threats, non-threat-based analysis is important, mentioning a concentration on agility and

graceful degradation. He used the concept of a straight stake versus a screw for securing utility poles, claiming that some designs are inherently better. Dr. Willis claimed that this is true only if the options are equal in cost, and if they are not an analysis balancing expected performance versus cost is warranted.

Dr. Willis concluded by summarizing the properties of metrics that will end up defining them, returning to the transect that defined his five categories of metrics. He left the group with a question: which of these properties is the industry most concerned about? Rima Oueid invited comments from the audience.

Judi Greenwald (DOE) asked for clarification on more concrete examples of resilience metrics. Dr. Willis commented that groups often revert to checklists, auditing, and accounting when things are difficult to measure, and that these can be metrics but they translate poorly to the actual system performance. He described the difference between capability and capacity again, as capability reflecting proficiency at utilizing capacity. The translation from capacity to capability could be a real measurement, or it could be an expert assessment/translation based on the capacity accounting.

A commenter mentioned that the definition of metrics at this point was very broad. For example, if financial performance is desired, could that be a performance-based metric? Often desired outcomes in one dimension of performance interfere with another. Dr. Willis responded by opening this discussion as an ongoing question for the workshop: How big should the scope be? Where are the boundaries of interest for the industry? What are the outcomes that DOE is trying to achieve by creating resilience metrics?

A commenter from the utility industry mentioned they use three aspects when planning for resilience: preparedness (i.e., typically measured in hindsight, fix things that are broken, measures of how long to get back online), hardening (i.e., how much loss can be avoided if built differently, but may not show the interrelatedness between customers/stakeholders), and stakeholder/community outreach. He offered an example of multiple hurricanes: the first of which inspired them to invest in hardening, only to find during the second hurricane that their major loads were offline because the load owners hadn't invested in hardening themselves. Now both the load and transmission/distribution system are hardened.

Dr. Willis asked this commenter whether there were specific contracts in place for level of service during such a high-consequence event. The commenter responded that there are individual customer arrangements, but nothing specific. Another commenter from the electric utility industry mentioned that the utility thinks more micro than macro, in that they try to minimize down time for each piece of equipment following an event.

Commenter (insurance) provided an insurance perspective, stating that there currently isn't a full communication of expectations in terms of resilience, giving the example of building codes, standards for roads, and risk management plans within existing institutions. She claimed that there isn't currently

a method to communicate how outcomes of high-consequence events will impact the things people care about. Dr. Willis commented that it will be important to check whether the indicators/metrics proposed here help define risk more fully from an insurance perspective. The commenter ended this discussion by agreeing that the externalities are clearly not monetized, such as jobs returning to an area or people being able to maintain a quality of life after an event.

Chen-Ching Liu (Washington State University) contrasted contingency-based planning for reliability with a different method for planning for resilience in the electricity sector. His view is that there is no commonly adopted performance metric that summarizes response to extreme events. He suggested this metric include the ability of a system to minimize disruption, recover, restore, and absorb, and cited the lack of clear definitions as a hindrance for the industry. Dr. Willis asked whether there is this distinction between reliability and resilience in the oil or gas sectors. An attendee representing the natural gas sector highlighted the difference between firm and interruptible contracts for natural gas. Ehsan Khan (DOE) offered that reliability is a much more established performance measure in the electric power industry and the distinction between it and resilience will be important to get right. Another attendee representing the electric power industry commented that resilience is on the fringes of reliability, in that long-term or extreme scenarios are not specifically planned for because there is no regulatory/policy framework that necessitates this planning. One aspect of this is that every extreme event is different, and therefore in contrast to common events, learning from one extreme event does not always help plan for the next.

The conversation turned to how the government might define resilience and more specifically which aspects of performance they could be interested in. The example came up of a utility working with a Public Utilities Commission and balancing multiple aspects of performance, such as service reliability, environmental impact, price, etc. In essence, multiple agencies might govern different aspects of resilience that could be in competition. The question was asked whether we are covering all of these aspects, or only whether the service was delivered. Dr. Willis commented that this is a good scoping question for the workshop.

Dr. Willis attempted to connect the two questions: how do you plan for resilience and what kinds of benefits are we trying to capture with resilience metrics? Rich Lorden (EPRI) claimed that predicting performance given events that do not occur often is extremely difficult, and cautioned the group to not think about things only in terms of a cost-benefit analysis. He later expanded this notion by claiming that estimating performance in the macro sense is not as difficult as performing a high-fidelity simulation. The commenter from the insurance industry also claimed to be uncomfortable with the variances under discussion, and offered up the alternative of trying to minimize the extreme negatives. She challenged the group to think of different types of information than classically used, specifically related to different types of events, demographic change, human decisions, and the human-nature interface. Eric Vugrin (Sandia) offered ideas such as green buildings that may have payoff even when the extreme events don't happen, and suggested the group think about these side benefits.

Tony Thomas (NRECA) asked whether the consumer has a role in survivability, and how to reflect that role, mentioning the responsibility of some consumers to have backup generators. Rima Oueid mentioned that during Hurricane Sandy many backup generators failed. Tony agreed, mentioning that exercising the backups from time to time is important, but often it is against regulations. Rima and others highlighted that these services should be understood and monetized. This will inform industry as to when it makes sense to have locally-sited backups, and when it makes sense to invest in a more resilient supply infrastructure.

10:30 – 12:30 Energy Infrastructure Resilience & the QER, Sandia National Laboratories

Rima Oueid mentioned the upcoming June workshop in Brookhaven, which will be focused on sharing the outcomes of the work being shared today. She then introduced the team presenting from Sandia National Laboratories: Ross Guttromson, Jean-Paul Watson, Eric Vugrin, and Tom Corbet.

Ross Guttromson (Sandia) introduced the purpose of the presentation as a discussion of resilience metrics, what they need to be and provide. He outlined that he will propose a common framework that outlines resilience metrics across sectors. The definition of resilience that Sandia is using comes from Presidential Policy Directive 21 and NAS report, *Disaster Resilience: A National Imperative*, which Ross mentioned is not a restrictive definition. In response to a question from the audience, he and JP Watson asserted that resilience metrics could be defined for explicit or implicit sets/characterizations of threats. Ross also stressed that R&D will be needed once metrics are developed, to enable use and application.

Eric Vugrin took the podium to introduce an illustrative scenario that contrasted system performance without threat, under threat, and under threat with resilience improvements. He complemented Dr. Willis on outlining what a resilience framework should include. Eric presented a notional power system under threat by hurricane, showing load not served and recovery effort through time as two measures of performance. He contrasted this with a second system that improves resilience through technical design, action plans, preparation, coordinated execution, adaptation, and other means. The second system improved in both performance measures by lessening impact and recovering faster. Dr. Vugrin then outlined what performance measures need to do: reliably measure whether the system is serving its intended purpose. He presented the translation of multiple performance measures into a smaller set of consequence measures. He described the difference between performance and consequence as the difference between load served and dollars lost, and stated that consequence units will depend on the entity who is measuring. Dr. Vugrin explained that often we will have multiple sources of uncertainty when projecting consequence to a rare event, including characterization of the threat, what is damaged, how the response plays out, etc. If this range of uncertainty is explored, the outcome is a probability distribution of consequence given uncertainty. It would be preferable to have higher probabilities more to the left of this distribution, meaning higher chance of low consequence. Dr. Vugrin suggested multiple ways of comparing two distributions, e.g. the mean or the probability above some unwanted consequence (the tail).

Ross Guttromson gave insight into the concepts that this illustrative scenario is based on. First, a metric is a means of measuring, not a value judgment or a prescription on how to measure. Second, resilience complements reliability by focusing on low probability scenarios with potentially high consequence. He proposed that resilience metrics must inform decision making, be valid, repeatable, feasible, usable for the decision maker and usable for the analyst, scalable, and allow for quantification of uncertainty and description of confidence. Dr. Guttromson concluded this section by mentioning that this current work is directed toward a national strategy for energy resilience, which ultimately means the metrics need to be useful for national policy, but that doesn't preclude them being useful elsewhere.

Stephanie Hamilton (Brookhaven) added that the metrics should not make managing resilience overly complicated by adding a host of new things to calculate and track.

Rich Lorden (EPRI) and Jean Paul Watson (Sandia) discussed whether an optimization approach is appropriate or even possible in this space, given the difficulty in quantifying much of the uncertainty. Dr. Watson suggested that the fidelity of models and the scale of questions could be posed in such a way to make it possible and useful. Dr. Lorden commented that the presence of microgrids may warrant transient analysis which makes the large-scale optimization intractable. The group settled on this being a highlight of the need for R&D in this space, and the importance of including the human decision maker in the loop for these types of studies.

Jean Paul Watson (Sandia) followed this discussion by presenting some of the mathematics behind the proposed resilience metric framework. He delved more deeply into the process behind the scenario which Eric Vugrin presented. He discussed the transformation between real-world measurement and performance indicators, such as from voltage and current to transfer capability for power systems. Dr. Watson then explained how uncertainty from multiple sources could be quantified and incorporated into weighted or probabilistic projections for these performance indicators using models and/or algorithms. He then explained how these weighted or probabilistic performance indicators could be translated to consequence using another complementary set of models and/or algorithms, and finally how the range of possible consequences could be summarized by a probability distribution. Dr. Watson made clear that the choice of how to summarize the distribution(s) (e.g. mean vs. tail) and the units/levels of distribution(s) would ultimately be up to the decision maker.

A commenter from the insurance industry questioned whether these distributions could cover what people actually value, and whether that could help drive consensus around ratepayer approvals to do what's necessary to improve resilience. Dr. Watson agreed that resilience as a concept isn't enough; it must be posed in units that matter to what people value.

Dr. Watson then presented an example derivation of metrics based on the IEEE 14-bus power system. He added the caveat that there is no information in the IEEE system about the notional humans that the system serves – and that this information would likely be necessary for most measures of consequence. He then went on to show that multiple realities of performance could be calculated using a range of uncertain parameters, actions, etc., and that these multiple realities translate into a distribution of

consequence. A question was raised about difficulty in assessing probabilities of consequence. Dr. Watson responded that likelihood could be used as a softer version of probability when understanding of probabilities was lacking, and that this does not affect the framework or the mathematics.

The discussion moved to how this would be used to inform a rate case to a Public Utilities Commission. Dr. Watson commented that the consequence distributions would have to be framed or translated to metrics that the PUC cares about (e.g. price), and that the existence of resilience metrics enables this kind of analysis. Another commenter mentioned that this enables more fact-based and transparent decision making. Dr. Vugrin highlighted that the current framework for these types of decisions does not quantify the effects of low-probability, high-consequence events.

Tom Corbet (Sandia) next addressed the group with two examples of how to derive and use resilience metrics under the proposed framework. The first example was an oil system under an earthquake disruption. He used the National Transportation Fuels Model to simulate impact to performance given this threat. He highlighted that simulating the dynamic response in addition to the initial effects is crucial to understanding the resilience of this system. Dr. Corbet presented dynamic curves that showed shortfalls in supply at certain nodes during the event. He claimed that a translation to consequence could be performed using different models, or that the supply of oil could be the consequence itself to some decision makers.

Stephanie Hamilton (Brookhaven) asked whether there needed to be consistency between models to develop adequate metrics. Dr. Corbet highlighted the differences (e.g. storage) between the oil system and the power system. Dr. Watson suggested that the models should include restoration and recovery actions, and that these models represent a large gap in R&D.

Jeff Dagle (PNNL) reinforced that the consequences of an extreme event are not linearly extrapolated from regularly experienced events, so we shouldn't expect the standard models to work for this type of analysis. He asked how such a model of extreme events could be validated. Dr. Corbet suggested that one could start with real events, but use other confidence-building exercises such as exposure to subject matter experts to validate. Dr. Guttromson suggested that discussion of modeling needs should be saved for the roadmap exercise to be presented at the next workshop in June.

An economist suggested that many different types of rare events occur that disrupt the oil industry, and while they are uniquely rare by themselves, the aggregated response of the system follows patterns that can be summarized by analyzing price dynamics. Other commenters mentioned that this type of analysis may not be appropriate for the power grid.

Many commenters mentioned that the discussion should turn to who will use the metrics, and how they will be populated based on who will use them. There may be tradeoffs between stakeholders and sectors, and tough decisions about who pays for resilience. A commenter from the insurance industry suggested that more research and focus be applied to the social science side in order to assess the human aspect of resilience. She gave the example of the lack of a consistent risk tolerance between

industries, largely from a misunderstanding of the impact and response of the human system or bias toward the response of the engineered system.

Chen-Ching Liu (WSU) added that there will be regional differences in risk tolerance for different types of threats. He suggested that what has been presented here is a very concrete basis for determining what should survive under which events. Dr. Liu highlighted that the hard part will be modeling and understanding the response of this natural-engineered-human coupled system. Finally, this analysis would lead into a risk-based cost-benefit that must be stakeholder-inclusive. This will help us choose as a society what we can accept at what cost.

Tom Corbet next presented a use case for the natural gas sector, driven by a San Andreas earthquake threat. This exampled used the commercial model called GPCM. This system had capacity and capability to adapt and recover, but policies and plans were lacking to utilize that capability. In this case, the question to be informed by the resilience metric was: who pays for upkeep of a natural gas line that spans borders and is nominally utilized in emergency? Dr. Corbet claimed that if the proposed resilience metric framework were in place and populated by adequate models, we could assess the added resilience to multiple stakeholders in this case.

A discussion was initiated by Jeff Dagle (PNNL) about whether it matters that customers may not be able to take the service – e.g. perhaps supply shortages don't matter when customers aren't there.

Ross Guttromson ended the discussion with an outline of the challenges, namely strategy and stakeholder engagement, interdependencies between systems, common knowledge and common models, consequence estimation, and decision support. He asserted that resilience metrics are critical to set goals at a national level, and that they should allow for depth of application but be able to be simplified. He also stressed that R&D will be needed to advance decision support and that success will depend on a multi-disciplinary approach.

1:30 – 3:30 Sector-specific metrics, working session

Presentation 1:
Emmanuel Bernabeu (Dominion Electric) presented an electric power systems perspective on resilience, claiming that resilience is an operating paradigm for Dominion. He used the terms anticipate, adapt, absorb, and recover. He highlighted the importance of including events that can be anticipated, while thinking about events that cannot be anticipated. Dr. Bernabeu presented a systematic procedure to prioritize implementation and guide investment in regard to physical security. He introduced the n-k1-k2 criterion for extreme contingencies, which gives Dominion the ability to immediately dispatch resources to what they expect are the worst consequence locations. Dominion uses a static index and dynamic index to summarize response to extreme contingencies. The static index is based on counting limit violations from a static load flow under the impact of contingency. The dynamic index is an aggregate of the dynamic response of all generators in the system, and summarizes the spread of generator angles, the delta across critical paths, etc. He contrasted these metrics with what may be needed to fully

encompass resilience – e.g. his presented metric only looks at a small subset of threats (physical security) and is concerned with the initial system response (the absorb part of resilience). Resilience metrics will incorporate many more types of scenarios and behaviors. Dr. Bernabeu opined that even if you come up with the metric, it will be difficult to set the regulation or "make the speed limit."

A commenter suggested that this is the most useful and implementable index that he has seen in the space so far. Kwok Cheung cautioned that these metrics don't begin to address the system's ability to restore itself to a healthy state after the disturbance. Dr. Bernabeu agreed that, while useful, the metric he presented doesn't fully encapsulate resilience, but instead highlights the challenges and a starting point.

Dr. Bernabeu concluded that resilience is a holistic concept (non-trivial metric) and that resilience requirements of an organization are a function of system characteristics, critical loads, and the operating environment.

Presentation 2:
J Mark Drexel (ConEdison) presented Con Edison's approach to risk assessment for storm hardening. He introduced the aspects that make ConEd unique, namely its density, service area (New York City), and customer expectations. Mr. Drexel outlined many of the takeaways from superstorm Sandy, specifically that it was unprecedented in impact, and that some equipment failures didn't matter if the SCADA equipment was flooded. He claimed that ConEd's hardening principles are summarized as: protect infrastructure, harden components, mitigate impact, and facilitate restoration. ConEd treats these as approaches, and determines a set of solutions using spreadsheets for each threat. The goal of these sets of solutions is to return the community to some sense of normalcy. A mantra that hints at ConEd's approach to redundancy was offered: "if you need one, put in three." To inform planning for storm hardening, modeling is used to suggest the likelihood of significant storms, the likelihood of surge level, estimates of damage across a range of wind speeds, etc. Combining these with expected outcomes from other models gives ConEd an estimate of risk exposure to storms. The modeling goals for ConEd include risk reduction, link funding to reduction in the risk, rank from highest to lowest, and design for the event not predicted (such as for flooding risk, design to the FEMA +3ft approach) modified by climate change as needed.

Mr. Drexel's summarized his personal perspective on resilience as it complements this type of planning. He highlighted that there are currently twenty-eight metrics that their Public Services Commission (similar to a PUC?) holds them to for storms, involving a report card of performance metrics and system attributes such as crews, municipal calls, life sustaining equipment customers, etc. His suggestion was to make the resilience metrics realistic and linked to funding, in turn linked to real reduction in risk. Mr. Drexel further suggested that economic measures should be incorporated so that investments can be prioritized, offering an exponential graph with critical assets on the x-axis and asset risk reduction on the y-axis. He split this graph into thirds, which showed that the majority of risk reduction could be accomplished with about a quarter of the overall cost of all investments considered. The group commented that this looks like a classic 80/20 model (20% of activities bring 80% of overall impact).

Henry Willis asked whether the actual risk changed after Sandy, and why they didn't perform this analysis before Sandy. Mr. Drexel responded that the risk had not changed after Sandy until these investments were put in place, but the event mobilized people to the point that there was enough attention to consider the benefit of these investments.

Presentation 3:
Anders Johnson (Kinder Morgan) presented a viewpoint on natural gas pipeline resilience. Kinder Morgan is one of the major natural gas pipeline owners and operators in the United States. Mr. Johnson started the presentation with a background of Kinder Morgan, leading into how Kinder Morgan views resilience. His main comment was that they don't use resilience metrics because they've lived it so often; it's engrained in their thinking. He offered an example of cyber issues, in which they lose communications due to different types of events every year, and the strategy is to understand how to function without basic communications. He sees the value of having resilience metrics as providing a standard to compare performance during extreme events both across industries and within industries. He contrasted cyber with physical threats, explaining that they also experience a number of physical disruptions every year such as people shooting exposed pipeline. In general, older pipelines tend to be more in parallel and therefore offer less vulnerability to these types of threats. Newer mega-pipelines have higher vulnerability.

A major discussion point during this presentation was the interdependence between the natural gas sector and the electric power sector. Mr. Johnson highlighted that electric utilities are often reluctant to purchase firm contracts for capacity with pipeline owners. The peaks in demand, especially in winter, are growing, while the troughs are staying the same, and the shoulder months offer fewer chances to perform maintenance. The northeast is particularly vulnerable in that less than 25% of northeast power plants purchase firm natural gas capacity. He suggested that one function of resilience metrics would be to provide the appropriate incentive for power asset owners to purchase firm capacity. A second vulnerability due to interdependency is an increasing trend toward electric compressor stations on the natural gas system. One activity taken to prevent a death spiral between loss of natural gas compression and loss of electricity generation is an understanding between Kinder Morgan and the electric utilities to not shed the compressor stations.

Mr. Johnson suggested that the need for a new natural gas line to the Northeast would be augmented with a clear view of the value of resilience to both the natural gas and electric sectors. He claimed that the industry knows the "right size" for this line but that the market currently doesn't support it. The regulatory/policy help based on resilience metrics could provide this market signal.

An attendee asked if there is any problem with the system itself aside from the lack of a market signal for the electric industry to buy firm capacity, and another signal to help them build new pipelines. Mr. Johnson claimed that the lack of market signals combined with the highly regulated nature of the natural gas industry limits the upside of resilience-enhancing investments, while the floor of their rate of return is essentially capped. This creates an investment-averse environment.

Presentation 4:
Christina Sames (American Gas Association) presented a viewpoint from AGA, which is an advocacy group for the natural gas industry. She started the presentation with a number of figures that speak to the high reliability of the natural gas system, such as a $19B annual expenditure to maintain safety and reliability. She asserted that most disruptions to the system are local and due to third parties, and that the system has a large capacity to reroute, absorb, and adapt, such as the ability to ramp from 70 Bcf to 139 Bcf in one day. She presented the four biggest vulnerabilities in her view to the natural gas system: natural disasters, lack of supply or supply-demand mismatch, physical/cyber attack, and disruption due to natural gas-electricity interdependencies. She opined that this natural gas-electricity interdependency could lead to disruption based on price volatility magnification alone, and suggested the need for a new line to the Northeast for these reasons. She offered multiple methods to increase resilience: system additions, storage expansion, storage closer to supply, review of electric markets and their support of gas infrastructure investment, and distributed generation (in the form of combined heat and power). Ms. Sames also offered ideas for resilience metrics, namely customer outages per customers served, duration of customer outages per customers served, variance in regional gas and electric prices, and security metrics. She requested that new resilience metrics do not recreate or replace the security metrics already in place.

An attendee asked whether the industry is concerned more with safety than reliability or resilience, and if there were any case where they would run overpressure. Ms. Sames replied that the control system is hardwired to prevent them from overpressuring, but there is an effective overpack (line packing) for short-term storage.

Another commenter asked about the storage options in addition to line pack. Ms. Sames responded that there are some geological formations that are candidates, but not close enough to the critical loads. Liquefied natural gas is an option, but not one that people have invested in heavily to date.

Presentation 5:
Bernie Vaughan (retired BP) presented his view of oil supply chain resilience, starting off with the good news that the system is highly distributed. The oil supply chain, in contrast to natural gas, is inherently global. Most oil fields represent less than 1% of the world's supply, and it is a global community, so loss of a single field or political motivations of a single country do not represent a large disruption by themselves. Oil is fairly fungible in that many systems can effectively accept different types of crude, although he claimed that many industry representatives would suggest otherwise. One negative is that the industry is fairly efficient and therefore has low surge capacity. Storage is often present for only one day beyond the nominal resupply interval. However, the distribution system is also redundant enough such that the loss of one or two terminals does not have a large impact.

Instead of individual refineries being the issue for resilience, then, Mr. Vaughan opined that choke points are the primary vulnerability. He gave the example of a New Madrid earthquake or a Houston shipping channel, which would cut off or deny large chunks of supply from the demand. He suggested that one metric could be the comparison of the resupply interval to the cost of disruption. He also

contrasted the repair time of a pipeline with that of a refinery. The latter have much longer and more expensive repair needs. On the finished product side, there is very little storage of gasoline across the USA, approximately 5-7 days, and perhaps 25 days of crude storage, much of it being located far from refineries. Mr. Vaughan suggested the need for a strategic stockpile to buffer the fast response of price to disruption.

Presentation 6:
Julia Philips (ANL) presented Argonne National Laboratory's approach to integrated resilience analysis. Argonne has focused on all 16 infrastructure sectors for the Department of Homeland Security, developing a review of concepts and ideas on what it means to be resilient in the critical infrastructure arena. She offered a definition of resilience, including four major themes: preparedness, mitigation measures, response capabilities, and recovery mechanisms. Under the Enhanced Critical Infrastructure Protection Initiative (ECIP), Argonne focuses on the assets more closely than the overall system response. The components to their metrics are attributes of the system. Ms. Philips presented how the attribute-based metrics are connected to improving performance by surveying the asset owners for their assessments. These surveys are combined with the metrics in a dashboard that is presented to the asset owners, so that they may compare themselves to others. Under the Regional Resilience Assessment Program (RRAP), Argonne is working to address the more complex problem of measuring resilience beyond a single asset perspective, to address dependencies, interdependencies, cascading effects, regional resilience capabilities, and security gaps. A suite of products, including surveys, dashboards, and dependency curves will follow. Ms. Philips concluded with a guiding approach: elicit experts, find common themes for all infrastructures, place value on resilience properties, build surveys to understand regional/community resilience, and include interdependencies.

An attendee commented that paradigms change over time, so the impact of an attribute of the system (e.g. storage) will change how it contributes to resilience in the future. The problem of disclosure of information was also mentioned as a continuous choke point for comparison of resilience between firms. Ms. Philips claimed that as firms understand how bad the consequence of poor resilience can be, they tend to open up and become less reluctant to share information.

Conclusion

Rima Oueid thanked the attendees and outlined the next steps. She invited written questions and comments, and especially studies or seminal literature in the area of energy resilience metrics.