UNITED STATES OF AMERICA

BEFORE THE

FEDERAL ENERGY REGULATORY COMMISSION

	)	
Grid Resilience in Regional Transmission	)	**Docket No. AD18-7-000**
Organizations and Independent System	)	
Operators	)	

REPLY COMMENTS OF MICHAEL MILLIGAN, Ph.D.

Introduction

On March 9, 2018, PJM and other RTOs/ISOs provided comments to FERC in response to the Notice of Proposed Rulemaking on Grid Resilience in Regional Transmission Organizations and Independent System Operators Pricing (NOPR)**.** I hereby provide comments on the RTO/ISO responses. My comments address two main issues: (1) the relationship between reliability (and much of existing operational practice) and resilience, and (2) providing a summary of the reliability (grid) services that can be provided by key technologies today.

For more than 30 years I have developed a deep expertise on the topic of maintaining a reliable and resilient North American power system in light of the changes in the generation mix and the electricity power markets. Until my recent retirement, I was Principal Researcher for Transmission and Grid Integration at the Department of Energy's (DOE) National Renewable

Energy Laboratory (NREL). During my 25 years of service at NREL I led and participated in numerous task forces for the NERC (including most recently the NERC Essential Reliability Services Task Force, ERSTF, which is now the Essential Reliability Services Working Group, ERSWG), the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society, and the Western Electricity Coordinating Council (WECC). I have authored or coauthored more than 225 journal articles, conference papers, technical reports, and book chapters related to the power system.[1] Prior to my work at NREL I was a utility planner for seven years.

I am providing these comments to provide some context for the relationship between bulk electric system (BES) reliability and resilience. *My comments apply exclusively to the BES*.[2] The utility industry, working closely with FERC and the North American Electric Reliability Corporation (NERC) have developed a body of market and reliability rules that have served the electricity consumers very well. Although reliability is highly valued, it is also expensive; therefore the existing power system, and indeed any power system, will never be perfectly reliable. Different regions of the U.S. have therefore established similar, yet different, assessments of the cost-effective reliability target. On the BES this can be seen primarily in the difference between planning reserve margins, but it is also apparent by comparing operational reliability that may require that the system can respond to an N-1 outage, N-2 outage, or possibly some other level of operational reliability.

---

[1] My professional profile can be found on LinkedIn at www.linkedin.com/in/michael-milligan-11999234, and most publications are available at http://tinyurl.com/y8kollw9.

[2] We note that electrical outages are most often caused by issues on the distribution system, and that BES outages are relatively infrequent.

The concept of resilience has received increasing attention in recent years, in part because of several reliability events that include large weather anomalies such as the 2014 Polar Vortex. Recently the U.S. Department of Energy proposed a rule-making process (RM18-1-000) to compensate generators that could maintain a stock of fuel, hypothesizing that this would increase BES resilience. As the RM18-1-000 process played out, it became increasingly clear that (a) there is a desire by the industry, and associated public benefit, to obtain a better understanding of BES resilience, particularly in the face of large weather events or other high-impact/low frequency (HILF) events. FERC discontinued RM18-1-000 and launched the current Docket AD18-7-000, asking the industry to describe what is now being done to assess resilience and what steps are now underway to maintain a BES that is hardened against potential threats. Many of the RTO/ISO responses to FERC's initial query pointed out the relationship between reliability and resilience, noting that there is some overlap between the two concepts.

My comments are in substantial agreement with the RTO/ISO comments that point out a strong relationship between reliability and resilience. Market design and reliability rules are most flexible and adaptive to new, innovative technologies if they are performance-based and technological neutral. Rules that specify *how* a resilient system and are tied to specific technologies (such as those that use fuel) are not consistent with long-standing reliability rules such as the NERC Control Performance Standards (CPS) and Balancing Authority Area Limits (BAAL). Both of these are agnostic to *how* system balance is achieved, and instead specify *what* level of balancing is required.

I argue that resilience must be defined in such a way that it is consistent with the broad and deep state of knowledge of BES reliability, including the existing NERC Transmission Planning standards (TPLs). As the FERC works with the industry to develop a working definition of resilience, the objective should not be confused with the means. Because of the relatively rare nature of HILF events, it is difficult to quantify their likelihood, and also therefore difficult to include these events in a probabilistic risk framework. I show a simple approach and graphic that allows for a collaborative description of HILF events that FERC, NERC, and the industry could use as a framework, complemented by reliability calculations to show how the system can perform in the face of various HILF events.

Finally, because there is some significant overlap between the concepts of reliability and resilience, and because there is a high level of interest in both of these, I also include a summary of the reliability services that can be obtained from several types of resources. Upon reviewing the technical capabilities of key technologies, it is apparent that no single technology can provide all of the services that are needed for BES reliability.

1. Highlights of RTO Responses: Reliability and Resilience Today

The RTO comments showed that there is a strong relationship between reliability and resilience, and it may in fact be difficult to cleanly separate them. For example, the NYISO response states that

> "Reliability and resilience are not necessarily separate and distinct concepts in relation to the electric system. Rather, these two concepts are highly intertwined and often indistinguishable. The NYISO shares Commissioner LaFleur's position that resilience is an element of the existing requirements related to maintaining the reliable operation of the bulk power system."[3]

Recent interest in grid resilience appears often to be focused on HILF events such as unusual weather events like the 2014 Polar Vortex. To a limited degree, existing reliability metrics that capture loss of load events can capture a system's response to HILF events. For example, a system that cannot successfully survive such weather events (and other HILF events) would exhibit a reliability shortfall such as loss of load, but the traditional reliability framework may not suitably capture the likelihood of such events, nor the system's response to them. Reliable systems must, by their definition, be reliable across a wide range of potential disruptions. Depending on how "resilience" is defined, one could say that reliable systems are resilient to "everything," whereas one system may be resilient to fuel supply disruptions while another system is not. The latter, if it were to experience shortages resulting in service disruption, would also not be reliable.

Grid operators and planners factor many types of risks into their normal activities. To guard against potential grid outages, there are various types of reserves that are provisioned over many different time steps; the key objective to maintaining a reserve is to ensure that the system can continue to operate reliably under various disturbance conditions. Planning reserve is capacity that is built (or otherwise acquired) that is above and beyond anticipated peak demand. This reserve helps guard against the potential of undersupply that might occur as a result of multiple resource (or transmission) forced outages during periods of high demand. Holding all else constant, a higher planning reserve would provide a higher overall level of reliability in the long-term; however, costs increase with reserves, thus some type of cost-benefit analysis could help determine the best level of planning reserve. Thus, higher reliability levels would provide diminishing returns, and should therefore be carefully evaluated for cost-effectiveness. If multiple resources fail unexpectedly during periods of high demand, capacity that is part of planning reserve may be able to eliminate, or at least reduce, load-shedding. The system operates reliably and is resilient to (at least some of) these outages. This line of argument is proposed by SPP. The NYISO response to FERC describes the role of operating reserves and ancillary service markets in helping with reliability and resilience. The SPP comments expand on this notion, noting that to adhere to NERC's BAL reliability standards, SPP ensures sufficient grid services that include energy, frequency regulation, spinning reserve, and supplemental reserve. These services are provided via the market mechanism, although voltage support, while required, does not lend itself to competitive markets and is thus provided by some form of market-based contracting. Systems are operated to "absorb the impact from the loss of multiple facilities" and operating the system so that single contingency events "will not disrupt the continued operation of the system."[4] Various grid services are necessary to ensure this reliable operation, including

---

[4] Response of the New York Independent System Operator, Inc. Docket No. AD18-7-000, page 4.

voltage support, frequency regulation and response, contingency reserves. In RTO/ISO areas most of these services can be obtained via the wholesale market. SPP is examining a market construct for a ramp product, noting that "ramping is part of reliability and also helps during recovery from contingency."[5]

The PJM response to FERC recognizes that resilience is not simply about HILF events, but also includes other potential threats to the safe and reliable operation of the BES that have changed over time. Many of these threats may not be a part of the regular planning and operational processes that are currently in place; therefore, it is important to systematically review and update these potential risks on a regular basis. PJM also points out that many HILF events may be difficult to analyze in a quantitative, probabilistic way because they do not occur often enough to allow for a sufficient risk-based characterization of the phenomenon.[6]

2. Reliability and Resilience

As several RTO/ISO submissions to this FERC docket have pointed out, power system resilience has not been rigorously defined in a well-accepted way. Likewise, there is widespread recognition that there are strong links between reliability and resilience, and yet these links also are not well-defined.

---

[5] FERC Docket No. AD18-7-000. Comments of Southwest Power Pool, Inc. on Grid Resilience Issues.

[6] NERC (2014) Integrating Variable Generation Task Force 1.6, Probabilistic Methods, discusses both probabilistic and scenario-based approaches to assessing system performance under uncertainty. Available at https://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20I1/IVGTF%20Task%201-6_09182014.pdf).

Good market design should be technology-neutral and performance-based. This means that any resource that is capable of providing a given service should be allowed to participate in the market. Resources that agree to sell a service that it cannot ultimately provide should have its compensation adjusted accordingly, and under some conditions may be disqualified from further market participation. At the same time, a good market design will not specify "how" a service is provided, but instead should specify the parameters regarding the delivery of the product itself. This opens the possibility for technical progress, and ensures that FERC and the market design do not need to be concerned with what happens behind the meter, as long as the product is provided as specified. FERC has appeared to strive for this type of market design, although there remain technology-specific market rules.

Similarly, for many years the control performance standards (CPS) required by NERC were/are technology-neutral.[7] Under the CPS2 rules, for example, the balancing area authority is required to keep imbalances within prescribed limits at least 90% of the time on a monthly basis. This standard was agnostic to which resources that would be used to achieve balance.

Defining attributes such as cold-weather, fuel storage, goes behind the scenes to specify "how" a service is provided and is removing the RTO/BAA's authority for cost-effectively providing needed services during times of HILF events, and moving that authority to FERC or NERC. This would be analogous to NERC requiring that a certain technology must be used to bring the RTO/ISO/BAA CPS or BAAL obligation into compliance; this type of requirement

---

[7] As is the BAAL standard; CPS is discussed herein because it was successfully used for many years. See NERC (2018), "Reliability Standards for the Bulk Electric Systems of North America," available at https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

does not exist, and furthermore, would eliminate potentially valuable resources that could help provide the needed response. Specifying "how" a system complies with a balancing obligation, reliability obligation, or resilience obligation is generally an over-specification. Barring other social goals, such over-specification will generally increase cost and discriminate against resources that are physically able to provide the service, but that are prevented because of market or reliability rules.

Most markets respond to shortages with high prices…and/or have capacity markets. What is important is the delivery of electrons and grid services, and a good market design will be agnostic to how this is done. Resilience is a desirable outcome, but *the outcome should not be confused with methods to achieve it.* In collaboration with the RTOs/ISOs *FERC should pursue technology-neutral, performance-based frameworks for achieving a resilient bulk power system.*

How are Reliability and Resilience Related?

The NERC has developed several transmission planning standards, known as TPLs.[8] Of the four types of categories, A, B, C, D, the latter specifies the characteristics and requirements of TPL-004—System Performance Following Extreme BES Events.[9] A Category D event

- "May involve substantial loss of customer Demand and generation in a widespread area or areas

---

[8] NERC Standard TPL-001-1 – System Performance Under Normal Conditions, available at https://www.nerc.com/files/TPL-001-1.pdf for a general description.

[9] NERC TPL-004—System Performance Following Extreme BES Events, available at https://www.nerc.com/files/tpl-004-0.pdf

- Portions of all reconnected systems may or may not achieve a new, stable operating point
- Evaluation of these events may require joint studies with neighboring systems"

The NERC requirements for this type of event are as follows:[10]

> **"B. Requirements**
>
> **R1.** The Planning Authority and Transmission Planner shall each demonstrate through a valid assessment that its portion of the interconnected transmission system is evaluated for the risks and consequences of a number of each of the extreme contingencies that are listed under Category D of Table I. To be valid, the Planning Authority's and Transmission Planner's assessment shall:
>
> **R1.1.** Be made annually.
>
> **R1.2.** Be conducted for near-term (years one through five).
>
> **R1.3.** Be supported by a current or past study and/or system simulation testing that addresses each of the following categories, showing system performance following Category D contingencies of Table I. The specific elements selected (from within each of the following categories) for inclusion in these studies and simulations shall be acceptable to the associated Regional Reliability Organization(s).
>
> **R1.3.1.** Be performed and evaluated only for those Category D contingencies that would produce the more severe system results or impacts. The rationale for the contingencies selected for evaluation shall be available as supporting information. An explanation of why the remaining simulations would produce less severe system results shall be available as supporting information.
>
> **R1.3.2.** Cover critical system conditions and study years as deemed appropriate by the responsible entity.
>
> **R1.3.3.** Be conducted annually unless changes to system conditions do not warrant such analyses.
>
> **R1.3.4.** Have all projected firm transfers modeled.
>
> **R1.3.5.** Include existing and planned facilities.

---

[10] NERC TPL-004—System Performance Following Extreme BES Events, pp-2. Available at https://www.nerc.com/files/tpl-004-0.pdf.

> **R1.3.6.** IncludeReactivePowerresourcestoensurethatadequatereactiveresources are available to meet system performance.
>
> **R1.3.7.** Include the effects of existing and planned protection systems,including any backup or redundant systems.
>
> **R1.3.8.** Include the effects of existing and planned control devices.
>
> **R1.3.9.** Include the planned (including maintenance) outage of any bulk electric equipment (including protection systems or their components) at those demand levels for which planned (including maintenance) outages are performed."

FERC, working with NERC and the power system industry, should carefully evaluate this NERC TPL-004 standard to see if it already embodies the principles of resilience, and if it doesn't do so, address any gaps that exist.

Probabilistic methods to assess power system reliability have been in existence starting at least in 1947,[11] and today there is a large body of literature and best-practices for ensuring power system reliability. Power system operation requires that the system can sustain the loss of any single resource, referred to as N-1. In some systems there is an additional level of security of (N-1)-1 which is meant to allow for reliable operation after the loss of two resources. (The choice of reliability target is a policy decision.) In the long-term, reliability can be assessed using a family of metrics based on loss of load probability (LOLP): loss of load expectation (LOLE), loss of load hours (LOLH), or expected unserved energy (EUE). Many other metrics exist, but these serve as useful examples for the present discussion.[12]

---

[11] Calabrese (1947) Generating Reserve Capacity Determined by the Probability Method. AIEE (American Institute of Electrical Engineers) Transactions on Power Systems. Vol 66, 1439-1450.

[12] Billinton and Allan (1996) Reliability Evaluation of Power Systems. Springer.

A reliable system has few, if any, disruptions that happen in the time period of interest. All else equal, a short disruption duration is less unreliable than a long duration. The family of metrics from reliability analysis can identify number of disruptions, length of disruptions, lost energy consumption during a disruption, and many other characteristics of an outage. These metrics can be calculated and applied proactively (in studies of the future) and also retroactively over any desired historical period. For example, BES reliability of experiencing an outage of 1 day in 10 years LOLE is a commonly used target.[13] LOLE counts occurrences but ignores the depth of the shortage; EUE would quantify the unserved energy, either of a single event or of multiple events within a time period under study.

Although there is a long tradition of using well-defined, rigorous reliability metrics, resilience has no such broadly-acceptable and rigorously defined metrics, or objectives. In FERC's Jan 8, 2018 Order, resilience is said to be

> The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.[14]

---

[13] One subtlety of LOLE-related metric is whether they count a loss of load event as a reserve shortage or as unserved demand. A second subtlety is whether LOLE is accounting for emergency imports from neighboring systems. For this discussion we focus on loss of load/inability to serve demand. See also: Ibanez and Milligan (2014), Comparing Resource Adequacy Metrics and Their Influence on Capacity Value, 13th International Conference on Probabilistic Methods Applied to Power Systems Durham, United Kingdom
July 7–10, 2014 available at https://www.nrel.gov/docs/fy14osti/61017.pdf and NERC (2011) Integrating Variable Generation Task Force 1-2: Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning. Available at https://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20IVGT/Sub%20Teams/Probabilistic%20Techniques/IVGTF1-2.pdf

[14] P4.

For a resilient power system in this sense, the disruptive event must either be anticipated per se (for example with a weather forecast predicting a storm), or more generally by the provisioning of an appropriate type and quantity of reserves (anticipate), arrest frequency decline and/or increase supply quickly enough to prevent system collapse (absorb), and ensure the imbalance caused by the disruptive event is then corrected so that the system can return to its nominal operating state. Some HILF events may be successfully managed with existing grid infrastructure. In this case, anticipation of the potential event occurs in the operational time frame. However, given that HILF events do not happen often, it is more likely that these events must be anticipated in the investment time frame so that sufficient grid infrastructure can be developed in time to ensure grid resilience in the long run.

The FERC description of resilience is consistent with the typical categories of response to a reliability event such as the sudden loss of a resource that causes frequency drop. The possibility of a reliability event is anticipated by ensuring sufficient contingency reserves at all times, even though the timing of the event cannot be known in advance. The system then absorbs the event when frequency falls, and then begins adapting when inertial and frequency response help to arrest the frequency decline. The recovery is the combination of AGC and dispatch that bring the system back to nominal frequency. When interpreted this way, it is difficult to cleanly separate reliability from resilience.

To begin to explore some of the conceptual links between reliability and resilience, we consider two hypothetical systems, for which a five-year retrospective reliability study is performed. During a severe winter storm, System A is able prevent loss of service throughout the storm, and barring any other reliability events, would have a high reliability score that would include low-or-zero EUE, LOLE and LOLH. Conversely, suppose that System B is not able to serve demand throughout the storm, and therefore institutes a series of rolling blackouts (or worse). The five-year retrospective reliability analysis would show higher EUE, LOLE, LOLH for System B as compared to System A. We would also say that while System A was resilient to (at least) this winter storm, System B was not. The reliability metrics pick this up, thus in this case the lack of resilience can be found in reliability assessments.

Reliability Metrics and Resilience

The following discussion provides an example as to how these existing reliability metrics could be used to help assess the impact of systems' resilience against HILF events. *This discussion is intended only to motivate further explorations by FERC and the industry to establish a useful framework that is consistent with the overlap between reliability and resilience; other approaches may prove to be superior. However, FERC is encouraged to continue collaboration with the power system industry to further explore how this, and other, reliability metrics may be utilized in the context of bulk system resilience.*

Case 1, No outage: then the system performed reliably and there is no reliability penalty. LOLE would be zero. EUE = 0 (note that all "expectations" could be replaced by "actual;" expectations can be calculated by standard LOLE reliability models).

Case 2, Single, shallow outage (SSO): Small LOLE with small EUE. If the frequency of these SSO events were to increase, then LOLE and EUE would both increase, not necessarily proportionately.

Case 3, Single, deep outage (SDO): Small LOLE with large relative EUE.

Case 4, Multiple, shallow outages (MSO): High LOLE, relatively small EUE.

Case 5, Multiple, deep outages (MDO): High LOLE, high EUE.

One resilience metric could be calculated as EUE/LOLE, which would have the units of energy/occurrences (or divided by hours, days if desired; maybe a family of metrics). This is an imperfect measure, and in cases of multiple bulk outages various statistical measures applied to EUE and LOLE could also be used. Because this is a new conceptual approach, it is not clear what the precise relationship between LOLE and EUE would be, nor is it clear what target metrics would be considered "good." However, this framework may be a useful starting point.

As PJM points out, it is often not possible to evaluate HILF events' risk because they are rare, and therefore can't be characterized accurately in a statistical or probabilistic framework. For such events, discrete scenarios can be developed that characterize events that threaten resilience, then grid modeling can be used to assess the likelihood of riding through the event.[15]

Not all regions will experience the same risk profile from the same events. For example, the well-known 2014 Polar Vortex may, in some sense, typify weather-related risks in ISONE, whereas tropical storms or tornados would be expected to occur in regions like SPP. It may be appropriate to develop resilience metrics that allow for differing risks in different locations that can show how a given region can respond under specific conditions. Given a sufficiently precise definition of a 100-year storm, for example, one could estimate resilience by simulating the storm's impact on fuel, transmission, and resources and quantify as described above, or with other relevant metrics.

As pointed out in some of the RTO/ISO responses to FERC, it is not possible, nor even desirable, to ensure the power system can withstand all threats. In some cases, the cost of resilience could far exceed the cost of damage. This suggests that it would be useful to undertake

---

[15] NERC (2014) (ibid) IVGTF 1.6 has some discussion of this.

cost-benefit analyses of which risks to cover. It is also likely that both the costs and benefits of hardening the system to some threats to resilience will vary from system to system.

There are different HILF events that are significant for each RTO/ISO. A pragmatic approach to analyzing resilience would be to identify the top HILF threats for each RTO/ISO, and conduct analyses of the likely response/resilience of the system. As an example, one RTO might find that key threats are likely from cyberattack, fuel supply disruptions, flooding, severe heat, and polar vortex-type cold weather storms. A limited number of profiles for each of these potential events could be developed, and the system simulated for each one. Some type of scoring, perhaps based on EUE or other metric, could be normalized into simple scores of 0-10, a high number reflecting more resilience. A graphical snapshot of this RTO's resilience could be represented in a radar chart such as Figure 1.

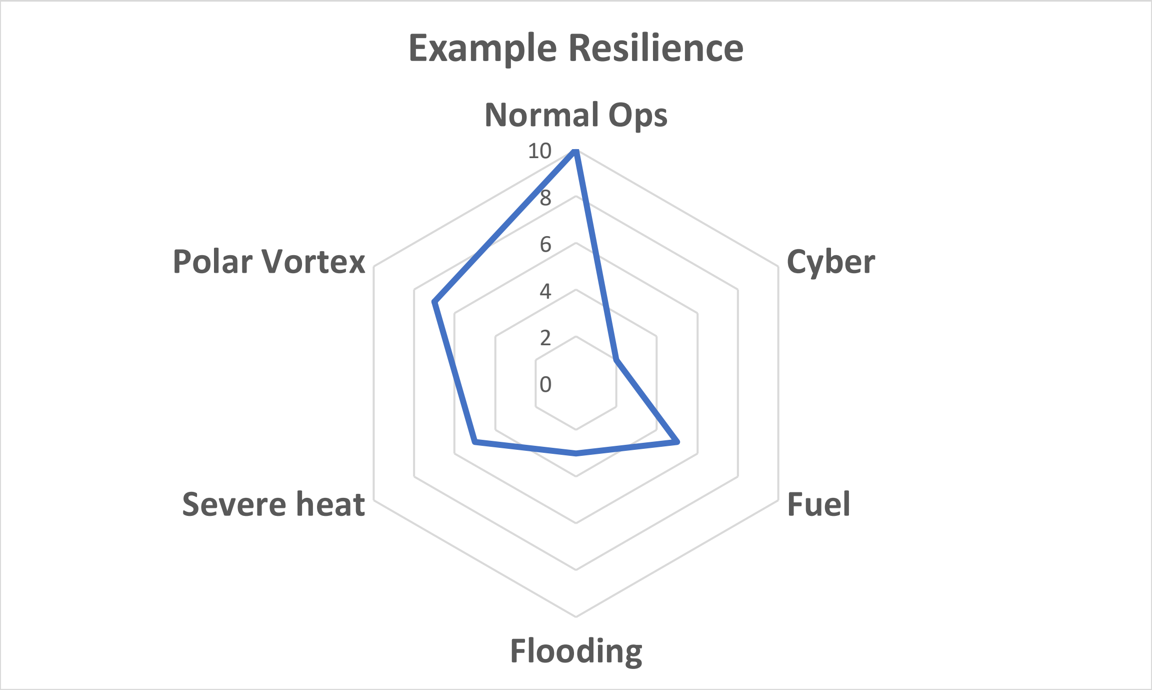


Figure 1. Example Resilience Graphic

The figure shows the system response to five threats in addition to “normal operations.” The response is measured on a scale from 0-10, where 10 represents a fully reliable system in the face of the given threat, which in the example could be (a) cyberattack, (b) fuel disruption, (c) flooding, (d) severe heat, or (e) polar vortex storm.[16] The threats here are examples, and they can be changed as appropriate. Specific indices such as LOLE, EUE, or others could be used to develop both a target level to ride through the threat, and the actual grid performance using appropriate models that can accurately capture the impact of the associated event.

Because each of the threats illustrated in Figure 1 cannot be anticipated in detail, alternative scenarios around each threat would need to be developed. For example, the RTO may wish to analyze alternative polar vortex storms—all storms are different—to better understand impacts. Extending this hypothetical case to account for six storm scenarios Figure 2 illustrates another hypothetical graphic. Similar scenarios and graphics would be developed for the other identified threats.

No doubt these simple examples can be significantly improved; however, the point is that it is possible to develop one or more useful graphics that can illustrate the system’s resilience in the face of HILF events. However, because these events are relatively rare, it is not possible to precisely characterize their risks and therefore may miss other more critical and more likely events.

These simple examples were introduced by the notion one could map one or more reliability metrics to the normalized 0-10 score, which would be a relatively simple process. Additional metrics such as recovery cost, temporary energy replacement cost, time to full recovery, and

---

[16] The area within the boundary is meaningless.

others could also be used so that a suite of indicators could be used to begin showing some of the multiple dimensions of resilience.

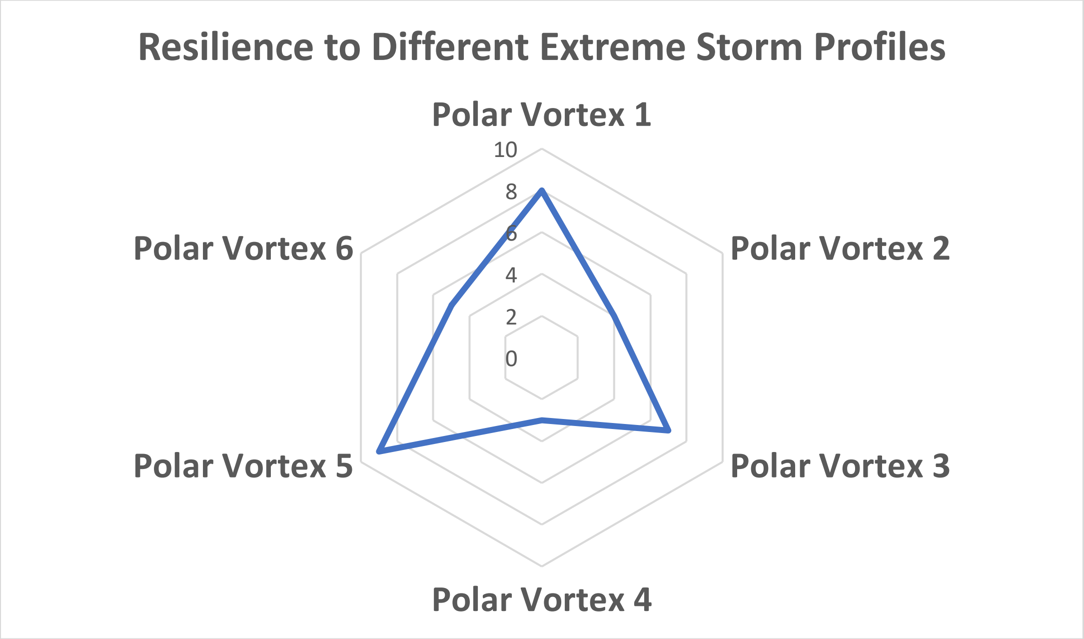


Figure 2. Example storm resilience graphic

Recommendations for FERC

- FERC, in collaboration with the power system industry, should undertake an in-depth evaluation of the NERC TPL-004 to determine its applicability to BES resilience.
    - If it is found the TPL has gaps, then an evaluation of these gaps and remedies could be undertaken in the context of the TPL. Because NERC's purview is limited to reliability, any new rules regarding resilience should be mindful of PJM's comment cited earlier, that the cost-effectiveness of solutions and response should be a critical component of resilience.

    - There is currently no TPL-004 requirement that all such events can be successfully managed by the BES. FERC and the industry should collaborate to ensure that successful management of HILF events is consistent with the many cost-benefit tradeoffs involved.

- FERC should work to endeavor that approaches to manage the power system during HILF events are not over-specified.
- FERC, in collaboration with the power system industry, should to develop a suite of scenarios that comprise HILF threats. A subset of those threats can be identified as those most relevant to resilience performance rules or guidelines. Although there may be some commonality of these threats to many RTOs/ISOs, there should be recognition that threats will differ among the RTOs/ISOs and rules/guidelines should account for these differences.
- FERC, in collaboration with the power system industry, should examine the existing suite of reliability metrics and determine whether they can adequately capture system performance during the identified HILF events. Simple metrics should be developed that can provide indicators of how well the BES can survive the identified HILF events so that comparisons of readiness, performance, and alternative threat levels can be made.
- Resilience may include more than just reliability, and FERC may want to consider aspects such as recovery time, infrastructure replacement, and cost of replacement energy during the rebuilding period.

3. **Rules That Prevent Response Will Inhibit Reliability and Resilience**.

Disruptive grid events have impacts that can range from milliseconds to weeks, or even months (Puerto Rico example). Resilient systems have the ability to respond to these events, eliminating (or at least reducing) outages as compared to less resilient systems. The system response must also span these time frames, according to the type of event and its impact. Resilience therefore encompasses many time frames and many different system responses that can come from inertial and automatic responses, power system operators and market actions, and infrastructure repair. *High-impact events are likely to require a deep system response that is best met by broad capabilities across many resource types.*

From a regulatory perspective, this means that artificial limits that prevent some resources from responding will be counter-productive, and to allow for maximum possible response from a deep resource pool, rules should be based on performance, not on type. This means that reliability, resilience, and market rules should be technology-neutral and performance-based. FERC has begun moving in that direction:

- Order 827, which eliminated the exemption for wind energy to provide reactive power. Instead, the pro forma LGIA and SGIA have been revised so that all newly-connected non-synchronous generators will be required to provide reactive power on the high side of the substation
- Order 828, which extends the same voltage and ride through requirements for LGIA resources so that is also applies to transmission-connected SGIA resources. Now, newly-connected SGIA facilities must ride thru abnormal frequency and voltage events without disconnecting. Specific settings are subject to the Transmission Provider and must be consistent with good practice and with TP practice relative to other resource types.

- Order 842, requiring all newly interconnecting LGIA and SGIA resources to provide primary frequency response.

These recent rules have the impact of broadening helpful response from a variety of resources that otherwise would have been prevented from helping during a system emergency. Achieving a BES that is reliable and resilient thus depends in part on rules or restrictions that should allow for broad response by diverse resources in such a way that public goals can be achieved. This allows for new technology to emerge, or existing technology to adapt, so that it can provide grid services that can help reliability/resilience. Currently there are some RTO/ISO rules that prevent variable energy resources (VER) from providing some reserve products.

Recommendations for FERC

- To pave the way for more resilience and reliability, market rules should be revisited, and revised in such a way that reserve products—in fact, all market products—are technology-neutral and performance-based.[17] FERC should examine market rules, and NERC should examine reliability rules, that may compromise reliability and resilience because they do not allow for some types of technologies to respond.
- Resource performance should not be over-specified. Rules should focus on "what," not "how."

---

[17] Ela et. al (2011) Operating Reserves and Variable Generation, NREL. Available at https://www.nrel.gov/docs/fy11osti/51978.pdf.

4. What Services are important, and how can they be provided?[18]

There are several prerequisites for a resource to provide a grid service: (1) physical capability of providing the service, (2) be in an appropriate operating state to provide services when called upon, (3) have an economic incentive, and/or no economic dis-incentive, to provide the service.

Reliable grid operation depends on ensuring that the aggregate demand and supply are matched at all times. To accomplish this balance, grid operations have various processes that operate on multiple time scales so that the needed equipment can be in place and available when needed. Some of these grid services operate in very fast time scales, such as primary frequency response, helping to ensure that system frequency is held at nominal values (within small allowable differences). Other grid services operate more slowly, such as frequency regulation and ramping, but are also used to maintain system balance. The aim of these comments is to provide a short, yet comprehensive, summary of the essential reliability services (a.k.a. grid services) that can be provided from key resource types. These services are not provided uniformly; a resource may respond quickly or slowly, be capable of providing the given service for long or short time periods, be able to provide a limited quantity of a given service, or be able to provide services only if the resource is in certain state(s).

The discussion below focuses on selected key resources, including coal-fired, gas-fired, nuclear, hydro, wind, and solar generation. Additionally, we provide information about generic battery storage, and some discussion of emerging demand-response.

---

[18] NERC Essential Reliability Services Concept Paper. Available at https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Concept%20Paper.pdf#search=erstf

Demand response is not a single technology; rather it is a combination of technologies that allow the customer to alter consumption patterns, with the possibility of selling services to the grid operator via established electricity markets. In principle, DR can deliver several services to the grid: (1) energy efficiency, which reduces electricity consumption and often reduces peak demand, (2) price responsive load, which can shift usage from high-value time period to low-value time periods, (3) peak shaving, which does not reduce total energy consumed but shifts some demand to off-peak periods, (4) reliability response that includes a fast frequency response that can respond quickly to system contingency, (5) frequency regulation service.[19] Although there is a very large technical and economic potential for DR, it has generally been slow to develop in the U.S. With recent improvements in electricity market design, communication, instrumentation, and control technology, DR appears to be emerging and may in the future capture a significant market presence.

Currently there is interest in developing new DR products that illustrate its forward potential. PJM has undertaken a pilot program to help develop and adopt a regulation signal that could be used to help integrate grid-scale batteries, flywheels, and water heaters.[20] Mosaic Power utilizes a fleet of hot water heaters to supply frequency regulation into the PJM market.[21] There are

---

[19] For a more complete discussion see Milligan and Kirby (2010) Utilizing Load Response for Wind and Solar Integration and Power System Reliability. Presented at WindPower 2010. National Renewable Energy Laboratory. Available at https://www.nrel.gov/docs/fy10osti/48247.pdf.

[20] PJM: Advanced Technology Pilot Program at http://pjm.com/markets-and-operations/advanced-tech-pilots.aspx

[21] Mosaic Power Water Heater Efficiency Network at https://mosaicpower.com/how-it-works/

recent grid interconnected water heating (GIWG) pilots at Portland General Electric (PGE), Arizona Public Service (APS), and Green Mountain Power (GMP).[22] In ERCOT, DR provides up to 50% of the required contingency reserve. [23] Programs like this depend on the diversity of demand coupled with the thermal storage capability residing in the hot water heater so that a response fast enough to provide frequency regulation can be obtained.

Demand response market development and technology are poised to change rapidly, and it is not clear how much of this capability will be developed. DR can provide frequency regulation, may be able to shift loads from peak to off-peak, and may be able to function in a short-term dispatch market. For the discussion that follows, we include DR capabilities as they appear to be effective today; however, this is a rapidly changing technology/market.

The ability of different resources to provide grid services is being driven by a "digital revolution" that is occurring in the electric power sector.[24] Wind, solar, and battery storage are electronically coupled to the power system. Because the power electronics devices that couple DC to AC power offer very fast response, it is now possible to use software to control how the resource interacts with the power system, subject to physical constraints. This has profound implications on how current and future wind, solar, and battery resources will provide grid

---

[22] Utility Dive, June 20, 2017, "Utilities in hot water: Realizing the benefits of grid-integrated water heaters. Available at https://www.utilitydive.com/news/utilities-in-hot-water-realizing-the-benefits-of-grid-integrated-water-hea/445241/.

[23] Ela, E; Milligan, M.; Kirby, B. (2011) Operating Reserves and Variable Generation. Available at https://www.nrel.gov/docs/fy11osti/51978.pdf page 46.

[24] Ahlstrom, (2018) "Digital Transformation of Power Systems: Implications on Reliability, Operations, and Markets." IEEE Transmission and Distribution Conference and Exposition. April 17-19. Denver, CO.

services, and may also have a significant impact on the way that some grid services are defined, offered, and procured.

Reactive power and voltage control

Description: The supply of reactive power provides the ability to regulate voltage, which in turn prevents equipment damage from voltage that is outside of nominal design limits. As with real power, maintaining an active reserve for reactive power helps promote system reliability and resilience.

Resources that can provide reactive and voltage control: Large thermal plants—coal, nuclear, and natural gas—can provide this service if they are generating real power, as can hydro power. Wind and solar plants can provide reactive and voltage control though power electronics-based controls, and can therefore supply the service even if they are not generating.[25] Battery with power electronics can provide this service similarly to wind/solar because the connection characteristic is the same.[26]

Voltage/voltage ride-through

Description: Devices that are interconnected into the BES are designed to operate at nominal voltages within a range of design limits. A grid disturbance, which may be caused by a transmission line or generator tripping offline or other faults, may cause the voltage to vary so that other resources may go offline. In many cases, the original fault does not in itself threaten

---

[25] NERC (2009) Special Report: Accommodating High Levels of Variable Generation. Available at https://www.nerc.com/files/ivgtf_report_041609.pdf.

[26] Tan, J., Zhang, Y. "Coordinated Control Strategy of a Battery Energy Storage System to Support a Wind Power Plant Providing Multi-Timescale Frequency Ancillary Services." IEEE Transactions on Sustainable Energy, Vol 8, No. 3, July 2017.

grid stability; however, if other resources or loads trip offline, the cascading disconnections may cause a blackout. To prevent this type of cascading outage, generators can be designed to ride through voltage fluctuations within a given limit.

Resources that can provide voltage ride-through: Wind generators are required to ride through voltage faults[27] and can ride through these events better than most other generators. Solar plants are physically capable of riding thru voltage disturbances, but until the recent FERC Order 828, did not always do so. Order 828 requires that newly-connected solar facilities subject to the SGIA must ride thru abnormal frequency and voltage events without disconnecting.

For many years distributed solar resources were required to remain offline after a voltage event. Recent changes in the IEEE 1547 requirement will now require new DER resources to ride through the event. Because batteries are connected to the grid via a converter like wind and solar, they can, with proper controls, ride through a voltage excursion.[28] Presumably, they would also be subject to the same ride-through requirements as solar plants.

Not all resources can provide this service.[29] Gas-fired generation is often taken offline by grid disturbances, and therefore have limited, if any, voltage ride-through potential.[30] Similarly,

---

[27] FERC Order 661 https://www.ferc.gov/CalendarFiles/20051212171744-RM05-4-001.pdf

[28] P1547/D7.3, Dec 2017 - IEEE Approved Draft Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. Available at https://ieeexplore.ieee.org/document/8233447/.

[29] I describe voltage ride-through as a service, but I note that this is not a NERC requirement. Instead, NERC's PRC-024 refers to the setting of voltage protection relays.

[30] TRC Solutions (2015) Revisions to NERC PRC Standards Have Significant Implications for Utility Compliance Programs. Available at https://www.trcsolutions.com/writable/images/Regulatory-Update-NERC-PRC-Standards-Changes-Nov-2015-FINAL.pdf.

coal plants often go offline during voltage faults because some combination of the generator or critical plant equipment such as pumps and conveyor belts cannot ride through the disturbance.[31]

Nuclear plants can go offline for similar reasons.[32] The inability of some large generators to ride through a disturbance contributed to recent blackouts in Washington, D.C. and Florida.[33]

Inertial and fast frequency response

Description: This reserve is always online and responding to small frequency changes even if there is no sudden system disturbance. This response is a combination of inertial response from large, rotating machines (generators) and fast frequency response (FFR).[34]

Resources that can provide this service: Inertial response is provided by large rotating generators, such as coal, nuclear, or gas. FFR can be supplied by coal and gas plants, and it is not provided by nuclear plants because governor response has been disabled in the U.S. FFR can be supplied by VER and batteries that have sufficient controls and incentives to do so. In many cases this FFR is much faster than that provided by thermal generation and can have a beneficial impact on the initial rate of frequency decline immediately after a disturbance. PFR can be

---

[31] NERC (2015) Standard PRC-024-2 – Generator Frequency and Voltage Protective Relay Settings. Available at https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf.

[32] Electric Light and Power (2015) Both Calvert Cliffs nuclear units go offline due to D.C. area disruption. Available at https://www.elp.com/articles/2015/04/both-calvert-cliffs-nuclear-units-go-offline-due-to-d-c-area-disruption.html

[33] Reuters (2008) FPL cites human error as cause of Florida blackout. Available at https://www.reuters.com/article/us-florida-blackout/fpl-cites-human-error-as-cause-of-florida-blackout-idUSWNAS318320080229.

[34] Traditionally, the fastest form of frequency response is the inertial response of large, rotating machines. In the past few years, power electronics have made it possible for wind and solar power to provide an extremely fast frequency response that operates in a similar time scale as inertial response. We distinguish these as inertial response and fast frequency response, FFR, respectively.

provided by natural gas, coal, and nuclear plants although in practice approximately 10% of these plants actually provide this response.[35] Wind, solar, and batteries can provide upward response during the recovery period after a disturbance if they are operating in a partially-curtailed state.[36,37] As noted earlier, in ERCOT DR provides up to one half of the contingency response obligation for the market.

Frequency regulation:

Description: Generation that responds to computer signals (automatic generation control, AGC), commonly at intervals of one to four seconds, to ensure frequency is in nominal range. AGC service is utilized at all times, but it is also useful during the recovery period after a contingency event (see above). Resources that provide AGC must operate below maximum output so that they have sufficient response room both up and down. In RTO markets AGC is obtained via wholesale markets, and suppliers' opportunity cost for energy sales is compensated.

Resources that can provide frequency regulation: Although the system needs to have access to up-regulation and down-regulation, individual resources can provide either, or both of

---

[35] Comments of the North American Electric Reliability Corporation Following September 23 Frequency Response Technical Conference. Docket Nos. RM06-16-010 and RM06-16-011 available at https://www.nerc.com/files/FinalFile_Comments_Resp_to_Sept_Freq_Resp_Tech_Conf.pdf. Also see Miller et al (2013) "Eastern Frequency Response Study" shows the impact of alternative levels of participation in frequency response by large thermal plants. Available at https://www.nrel.gov/docs/fy13osti/58077.pdf.

[36] Gevorgian and Zhang (2016) "Wind Generation Participation in Power System Frequency Response," 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, Austria. Available at https://www.nrel.gov/docs/fy17osti/67287.pdf.

[37] Milligan et al (2015) Alternatives No More. IEEE Power and Energy Magazine, October. Available at http://iiesi.org/assets/pdfs/ieee-power-energy-mag-2015.pdf

these responses. A resource can provide down-regulation when it is operating at maximum output, and it can provide up-regulation and down regulation when it is operating below maximum power. Wind and solar resources are no different: they can provide upward frequency regulation only if (a) they are "pre-curtailed," running at less than maximum output for the given wind/solar fuel input, and (b) only if there is sufficient wind/sun for the resource to respond.[38] They can provide downward regulation even when at maximum power (subject to the wind and solar resource). Obtaining this service from variable energy resources (VER), such as wind and solar power, may be costly because a more expensive resource from the dispatch stack must be called upon to make up for the energy lost by the VER providing frequency regulation. Batteries can supply frequency regulation if the state of charge is sufficient, or if charging is in process during the time the services is called upon.[39] Gas generators can generally provide this service efficiently and accurately. Nuclear plants in the U.S. do not provide this service, whereas coal plants can do so, but often do not have the capability for accurate response.[40] [41] Hydro generation and DR can also provide this service.

---

[38] ERCOT: Demonstration of PFR Improvement September 2017. ERCOT Operations Planning. https://www.pjm.com/-/media/committees-groups/task-forces/pfrstf/20171009/20171009-item-04-ercot-frequency-response-improvements.ashx

[39] Battery-supplied regulation does not require up-down charging, but can also be provided by variable/intermittent charging or discharging, separately.

[40] Chen, Leonard, Keyser, Gardner, "Development of Performance-Based Two-Part Regulating Reserve Compensation on MISO Energy and Ancillary Service Market. IEEE Transactions on Power Systems, Vol 30, 1, Jan 2015.

[41] Examples can be found in Milligan M, et al. Integration of Variable Generation, Cost-Causation, and Integration Costs Electr. J. (2011), doi:10.1016/j .tej.2011.10.011, and in Milligan et al. (2011) Cost-Causation and Integration Cost Analysis for Variable Generation, NREL. Available at https://www.nrel.gov/docs/fy11osti/51860.pdf.

Flexibility/Dispatch

Description: Although several definitions of flexibility have emerged, they generally describe the ability of the resource—or portfolio of resources—to have the ability to react to changes in the power system, both anticipated and unanticipated.[42] Flexibility that is inherent in a particular resource depends on its design objectives and operational modes, along with the type of fuel it uses. Controllable hydro plants, some combined cycle gas, aero-derivative gas turbines, and reciprocating engines are very flexible. Some plants that are somewhat inflexible can be made more flexible by "strategic modifications, proactive inspections and training programs, among other operational changes to accommodate cycling, can minimize the extent of damage and optimize the cost of maintenance."[43]

Ramping/ramping reserve:

Description - Ramping—changing the output of a generator or other resource in a given time period—has been identified as an essential reliability service by NERC[44] and is receiving renewed attention following CAISO's adoption of it as a market-based product, and MISO's ramp capability product development.[45] Ramping is an inherent part of power system operation

---

[42] Examples include Cochran et al.(2014) Flexibility in 21st Century Power Systems. Clean Energy Ministerial and National Renewable Energy Laboratory. Available at https://www.nrel.gov/docs/fy14osti/61721.pdf, and Milligan et al.(2015) Advancing System Flexibility for High Penetration Renewable Integration. NREL. Available at https://www.nrel.gov/docs/fy16osti/64864.pdf,

[43] Cochran et al. (2014) Flexible Coal: Evolution from Baseload to Peaking Plant. NREL. Available at https://www.nrel.gov/docs/fy14osti/60575.pdf.

[44] NERC ERSTF ibid

[45] MISO (2016) Ramp Capability Modeling in MISO Dispatch and Pricing. Presented at FERC Technical Conference on Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software, June 27-29. Available at

because resources must change their output to match fluctuating demand. As the BES evolves to higher levels of variable generation (VER) such as wind/solar, additional ramping will be needed to maintain system balance. Although some RTOs/ISOs have developed ramping products, others are able to utilize the fast, 5-minute economic dispatch to find sufficient flexibility in the operational time frame. Without ramping products, inflexible resources may be rewarded for their inflexibility if they are paid the market-clearing energy price during ramp-constrained periods when combustion turbines (or other costly resources) are on the margin.[46] Ramp products can separate the ramping service from the energy product, providing incentive to flexible resources that can ramp. There is some evidence that a look-ahead dispatch that locks in advisory prices may result in the same dispatch and revenue as an energy market with ramp product.[47]

Resources that can provide ramping/ramping reserve: Wind and solar plants can both provide very fast and accurate dispatch/ramping response. However, this may be costly to the system because these plants typically have the lowest marginal cost for producing energy and therefore incur the largest lost opportunity cost if they are backed down to retain headroom for ramping, so may not be utilized often. Most natural gas generators have the potential to ramp and are often the resource of choice to do this because they have reasonably good flexibility and are often marginal units in the dispatch stack. Many coal plants have limited ramping capability

---

https://www.ferc.gov/CalendarFiles/20160629114652-1%20-%2020160621%20FERC%20Technical%20Conference_MISO%20Ramp%20Product.pdf

[46] Milligan, M., Kirby, B. (2010) Market Characteristics for Efficient Integration of Variable Generation in the Western Interconnection. NREL Technical Report. P 17. https://www.nrel.gov/docs/fy10osti/48192.pdf

[47] Ela, E.; O'Malley, M. (2016) Scheduling and Pricing for Expected Ramp Capability in Real-Time Power Markets. IEEE Transactions on Power Systems, Volume: 31, Issue: 3, May.

because of a combination of thermal inertia, operating practice, and design, and therefore may have difficulty ramping as quickly as needed in some situations. Nuclear plants do not provide ramping service in the U.S. because of a combination of regulations, economics, and technical challenges, but can be more flexible in other countries.[48] Batteries can ramp up or down very quickly, depending on the state of charge. Controllable hydro power can normally ramp quickly, but they may be subject to water flow constraints or other regulations that may inhibit this response[49]. DR can potentially provide this service, but it may be limited in the energy component that it can provide.

Recommendations for FERC

- As new flexibility products are defined and evaluated, FERC should collaborate with the industry to better-understand the need for these products, how their provision may interact with other BES products and market dispatch, and whether changes in business practices or product definitions may have an impact on the need for the service. New products should be developed in a technology-neutral way, and may specify speed and depth of response, along with other attributes of the product in question.

Other facets of flexibility

---

[48] Utility Dive (2016), "How market forces are pushing utilities to operate nuclear plants more flexibly." Oct. Available at https://www.utilitydive.com/news/how-market-forces-are-pushing-utilities-to-operate-nuclear-plants-more-flex/427496/

[49] U.S. Department of Energy Hydropower Vision: A New Vision for United States Hydropower. https://www.energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source.

Description: Although resource flexibility is often thought of as fast ramping, there are additional flexibility components:

(a) Fast startup time: ability to move from non-operational state to operational state.

(b) Fast shutdown time: ability to go off-line; may be to a cold state or warm state

(c) short min up/down times: Minimum length of time that the plant must stay in an operational state before being taken offline, or minimum length of time that a plant must be in a non-operational state before it can be started again.

(d) Minimum stable generation level: The minimum output level that the plant can sustain, often expressed as a percentage of rated power. This is also an indicator of the plant's operating range: the difference between rated capacity and minimum stable generation.

Resources that can provide other facets of flexibility:

Coal, nuclear, and some gas plants generally have slow startup and shutdown times, and relatively long minimum uptimes and downtimes. Nuclear plants in the U.S. do not cycle or ramp, and therefore have undemonstrated minimum generation levels that are significantly below rated power.

Coal plants' minimum generation levels are dependent in part on plant design, but they are often in the 65-75% of rated capacity range. The high minimum generation constraints limit flexibility and limit the ability to efficiently utilize wind and solar energy.[50] This inflexibility

---

[50] Lew et. al (2013) The Western Wind and Solar Integration Study Phase 2. National Renewable Energy Laboratory. Available at https://www.nrel.gov/docs/fy13osti/55588.pdf . See also Cochran et. al (2017) Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I—National Study. National Renewable Energy Laboratory. Available at https://www.nrel.gov/docs/fy17osti/68530.pdf.

causes more wind and solar energy to be curtailed. Thermal plant startup and shutdown times are generally long, as are minimum uptime and downtime.

Some gas plants have similar flexibility attributes as some coal plants. However, newer combined cycle gas plants can be quite flexible, and some can be operated either in combined cycle mode or single cycle mode, providing additional flexibility compared to only combined-cycle mode operation. Peaking plants that use aero-derivative gas turbines or reciprocating engines can be very flexible, with minimum generation levels that may approach as little as 1% of rated capacity, short up/down minimums, fast starting and shutdown, and fast ramp rates.[51]

Hydro plants can be very flexible from a technical point of view. Their main constraints, if any, relate to a combination of water supply and water regulations, including water delivery schedules and minimum/maximum flow constraints to mitigate environmental damage. Thus, there is no one-size-fits-all characterization; however, this resource has the potential to be very flexible.[52]

Wind and solar plants can ramp very quickly in both directions, depending on the generators' current state, and can both achieve a very low minimum generation level even when the wind is blowing or the sun is shining.

Batteries have similar characteristics as wind and solar, but subject to the battery's state of charge.

---

[51] Milligan and Kirby (2010) Utilizing Load Response for Wind and Solar Integration and Power System Reliability. Presented at WindPower 2010. National Renewable Energy Laboratory. Available at https://www.nrel.gov/docs/fy10osti/48247.pdf.

[52] See Chapter 2 of the U.S. D.O.E Hydro Vision report https://www.energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-Chapter-2-10212016.pdf

DR does not have specific minimum up/down times in the same sense as conventional generators. However, there are limits as to how much/how often a DR resource may be called upon, and this may provide a similar constraint. However, the quick potential response of DR makes it a valuable contributor to ramping capability over short time frames.

Recommendation for FERC

- As DR technology and its understanding mature, FERC should consider ways in which speed of response and depth of response can be compensated. This should not be a DR-only investigation but should be developed in a technologically neutral way so that alternative technologies can compete.

Reliability Services Summary

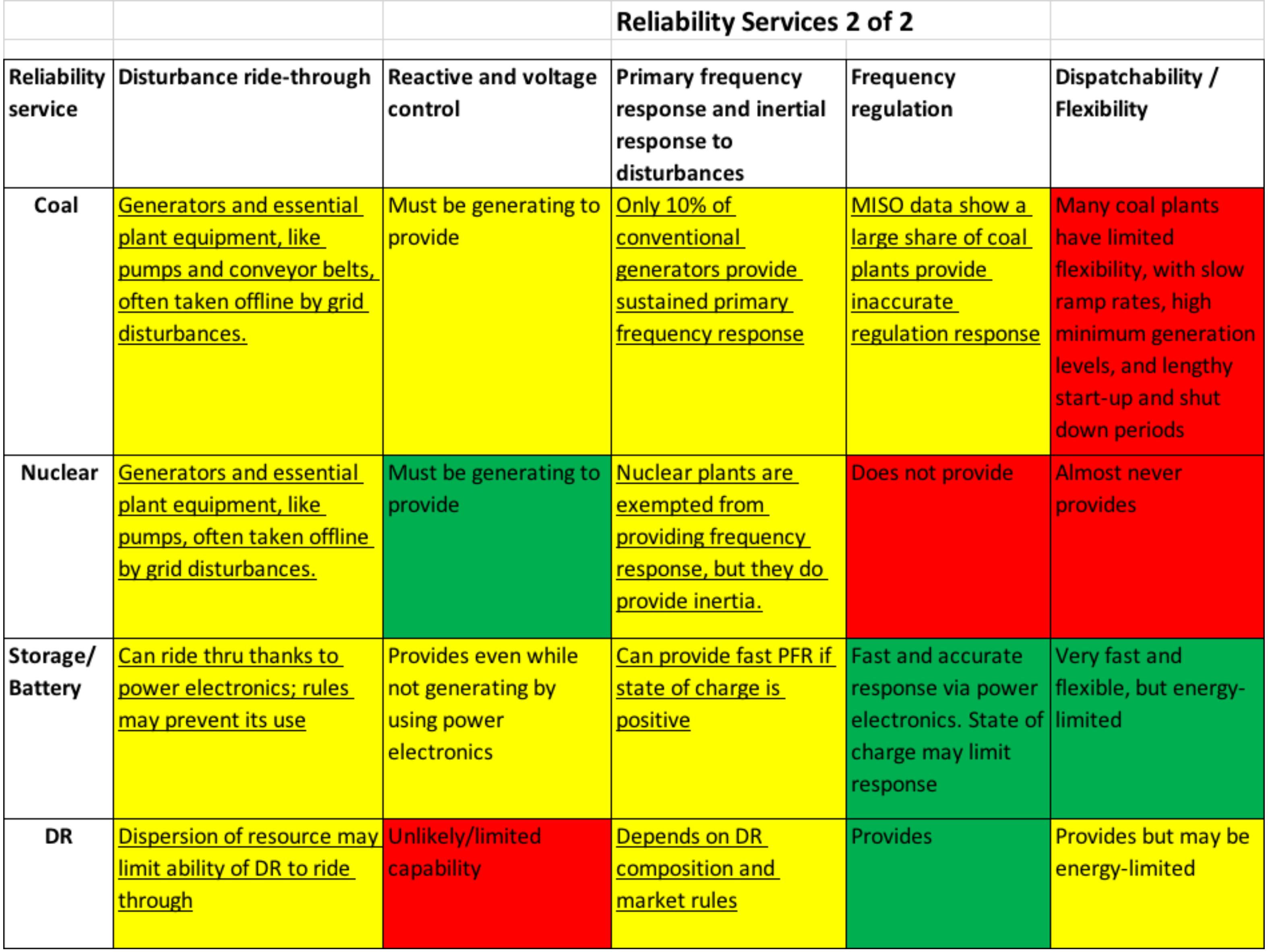
All resources discussed in these comments can provide at least some reliability services. The speed of provision, depth of provision, and machine type and state will all play a role in determining the physical capability of each resource type. Market and reliability rules may limit response in some cases; however, rules should be revised if that is the case. Table 1 and Table 2 summarize the discussion of the reliability service capabilities from different resources.

Table 1. Reliability Service Capabilities, 1 of 2

Reliability Services 1 of 2

Reliability service	Disturbance ride-through	Reactive and voltage control	Primary frequency response and inertial response to disturbances	Frequency regulation	Dispatchability / Flexibility
Wind	Excellent voltage and frequency ride-through due to power electronics isolating generator from grid disturbances. Wind meets more rigorous ride-through requirement (FERC Order 661A) than other generators.	Provides, and can provide while not generating by using power electronics.	Wind regularly provides fast and accurate PFR in ERCOT today. Can be economic to provide upward response if curtailed.	Fast and accurate response. Can provide but often costly, particularly for upward response. Provides on Xcel's system.	Fast and accurate response. Can but often costly, particularly for upward response. Provides on Xcel's system.
Solar PV	Can thanks to power electronics, but standards have prevented use of capability	Provides, and can provide while not generating by using power electronics.	Can provide downward frequency response today, can provide upward frequency response and fast power injection if curtailed.	Fast and accurate response. Can provide but often costly, particularly for upward response.	Fast and accurate response. Can provide but often costly, particularly for upward response.
Hydro	Can often stay online through the disturbance	Must be generating to provide	Only 10% of conventional generators provide sustained primary frequency response	Provides	Run-of-river is not flexible, but contollable hydro can be very flexible
Gas	Generators often taken offline by grid disturbances.	Must be generating to provide	Only 10% of conventional generators provide sustained primary frequency response	Provides	Most gas generators are operated flexibly

Table 2. Reliability Service Capabilities, 2 of 2



Reliability Services 2 of 2

Reliability service	Disturbance ride-through	Reactive and voltage control	Primary frequency response and inertial response to disturbances	Frequency regulation	Dispatchability / Flexibility
Coal	Generators and essential plant equipment, like pumps and conveyor belts, often taken offline by grid disturbances.	Must be generating to provide	Only 10% of conventional generators provide sustained primary frequency response	MISO data show a large share of coal plants provide inaccurate regulation response	Many coal plants have limited flexibility, with slow ramp rates, high minimum generation levels, and lengthy start-up and shut down periods
Nuclear	Generators and essential plant equipment, like pumps, often taken offline by grid disturbances.	Must be generating to provide	Nuclear plants are exempted from providing frequency response, but they do provide inertia.	Does not provide	Almost never provides
Storage/ Battery	Can ride thru thanks to power electronics; rules may prevent its use	Provides even while not generating by using power electronics	Can provide fast PFR if state of charge is positive	Fast and accurate response via power electronics. State of charge may limit response	Very fast and flexible, but energy-limited
DR	Dispersion of resource may limit ability of DR to ride through	Unlikely/limited capability	Depends on DR composition and market rules	Provides	Provides but may be energy-limited

Resilience

In the absence of precise definitions and metrics surrounding the term "resilience" it is difficult to embark on an objective discussion. However, based on well-known work on power system reliability, it is important to distinguish between resilience of a single resource vs. resilience of the power system. The economics and reliability—and resilience—of the BES benefit significantly from the principle of diversity. For example, to achieve a 1d/10y loss of load expectation, it is not necessary for each individual resource to be able to achieve a forced outage rate of 0.027% (which roughly equates to 1 day per 3,650 days outage). Instead, the portfolio of plants, all of which have forced outage rates that exceed 0.027% must achieve the 1d/10y resource adequacy target. This can be done by overbuilding capacity so that the installed capacity exceeds peak demand by some margin, commonly called the planning reserve margin (PRM)[53]. The relationship between plant forced outage rates, installed capacity, and resource adequacy is discussed in more detail in Milligan and Porter.[54]

In the same way, we would expect a combination of plants with different resilience characteristics—which are not currently well-known—to provide for a resilient system. As stated

---

[53] PRM is discussed in NERC (2011) Integrating Variable Generation Task Force 1-2: Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning. Available at https://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20IVGT/Sub%20Teams/Probabilistic%20Techniques/IVGTF1-2.pdf

[54] Milligan, M., Porter, K. (2006) The Capacity Value of Wind in the United States: Methods and Implementation. Electricity Journal, Vol. 19, Issue 2. March. Available at https://www.nerc.com/docs/pc/ivgtf/elec-journal-capacity-value-published-feb-2006.pdf.

elsewhere in this document, there are currently no measures for resilience, nor are there any specific targets or criteria for how much resilience is socially desirable or achievable.

It is appropriate to return to the earlier discussion herein regarding over-specification of rules. FERC's Jan 8 Order provides one definition of resilience: "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."[55] It is important to note that this definition does not specify or prescribe how resilience should be achieved. Instead, it suggests the potential for a framework to develop systems that are resilient.

FERC Docket RM18-1-000 hypothesized several features of a resilient power system. Some of these features were shown to be uncorrelated with the ability of the system to successfully survive Polar Vortex storms.[56] The current docket aims to gather information regarding resilience from the RTOs/ISOs with the aim to help develop a resilience framework.

Drawing another example from reliability, I show that reliability rules have been successful in achieving high BES reliability *without* prescribing how to achieve it.

There are many ways one could improve the reliability of a power plant. Some of these include:

- continuous monitoring of vibration to predict bearing and seal problems
- need sufficient instrumentation on cooling towers to improve control and monitoring, which can reduce the probability of failures
- maintaining sufficient water level in boiler drum can reduce maintenance
- regular plant inspections
- timely acquisition and storage of fuel[57]

---

[55] Ibid.

[56] Milligan comments to RM18-1-000

[57] PowerMag http://www.powermag.com/how-to-increase-power-plant-asset-reliability-using-modern-digital-technology/?printmode=1

Capacity market rules, energy market rules, and BES reliability rules are largely silent on these measures. However, plant operators will undertake these measures so that their resource(s) may participate in capacity markets and/or periods during which prices are high, subject to cost-benefit trade-offs and other constraints. We do not have, nor do we need, a market for (a) vibration monitoring, (b) cooling tower instrumentation and monitoring, (c) boiler drum water level requirements, etc. Each of these items represents a *means* to attain the objective of participating in the market and providing a service for the grid operator. This is an important point: ***Whatever resilience framework FERC decides to implement, it should focus on how much resilience is needed, and how to incentivize this resilience. FERC should not over-specify resilience by requiring how resilience is produced.*** Instead, FERC should ensure sufficient incentives to achieve the intended level of resilience.

Recommendation for FERC

- FERC should refrain from over-specifying resilience requirements. In specifying contributing factors to resilience and establishing requirements or markets around these factors, FERC would be opening the door to a flood of new products that would introduce unnecessary complication and potential unintended consequences, be difficult to track, and difficult to ensure that the ultimate target of resilience would be achieved. This means that if plants are compensated for onsite fuel storage, for example, then the principle of comparability would require them to also be compensated for the installation and operation of continuous vibration monitoring, cooling tower instrumentation, and other contributors to reliability (and resilience). If the FERC intends to go down the road of market development for resilience, it must carefully define, describe, and measure resilience, and ensure that market products do

> not (a) introduce unintended consequences, which are more difficult to avoid when market complexity increases, and (b) achieve the target resilience level in an economically inefficient manner. These considerations imply that, *if* a resilience market of some type is established, it should focus on the acquisition of resilience only, as measured by grid performance.

Resilience objectives, if suitably defined and deemed to be cost-effective, can also be achieved by some form of regulatory requirement. As described in an early section of this document, specific resilience targets could be developed and electricity production simulations/reliability models can be used to assess system performance under these scenarios.

With this discussion in mind, I provide an overview of key resource-types' performance under key stress conditions, most of which have been raised by both the U.S. DOE NOPR RM19-1-000 and the current FERC proceeding AD18-7-000.

Cold Weather Performance

Description: Cold weather can have impacts on non-fuel related issues that are specific to the technology. Examples include the 2014 Polar Vortex that affected all or part of the Midwest, South Central, and East Coast regions of the United States (and part of Canada). The Polar Vortex Report[58] from NERC states that in SERC, "The extended time below freezing is extremely rare for the southern United States, with the temperatures outside most winter

---

[58] NERC Polar Vortex Review 2014. https://www.nerc.com/pa/rrm/January%202014%20Polar%20Vortex%20Review/Polar_Vortex_Review_29_Sept_2014_Final.pdf.

generation design characteristics." Resource adequacy studies are often done with limited annual data; including multiple-year datasets and scenario(s) that can capture cold weather events can influence resource adequacy and can help inform system planners about potential cold-weather impacts on plant investment. Capacity value calculations[59] provide information about individual resources, or groups of resources, on ensuring capacity during peak periods, and cold weather performance inputs will contribute to more accurate analysis and solutions. Therefore, cold weather performance is already taken into account by capacity value calculations.

Key Resources and their Cold Weather Performance Characteristics: Wind plants have produced high output during cold weather spells in ERCOT[60] and in PJM wind power produced above its capacity value during most of the cold weather.[61] Solar plants generally produce less output during the winter because of a combination of shorter days and lower sun angles.

During the 2011 ERCOT event natural gas processing plants experienced mechanical failures, and the increase in customer demand coupled with reduced gas volume resulted in falling pressure in the gas lines, and consequently fuel shortages for some plants. In PJM during

---

[59] NERC (2011) Integrating Variable Generation Task Force 1-2: Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning. Available at https://www.nerc.com/comm/PC/Integration%20of%20Variable%20Generation%20Task%20Force%20IVGT/Sub%20Teams/Probabilistic%20Techniques/IVGTF1-2.pdf

[60] FERC/NERC Staff Report on the 2011 Southwest Cold Weather Event, available at https://www.ferc.gov/legal/staff-reports/08-16-11-report.pdf. During Feb 1-2 wind power output in ERCOT ranged from 40-75% of available capacity.

[61] PJM Interconnection: Analysis of Operational Events and Market Impacts During the January 2014 Cold Weather Events. May 8, 2014. Available at https://learn.pjm.com/Media/library/reports-notices/weather-related/20140509-analysis-of-operational-events-and-market-impacts-during-the-jan-2014-cold-weather-events.pdf.

the 2014 event, natural gas scheduling difficulties caused high gas prices, but also caused some units which needed gas for only a few hours to take, and burn, gas deliveries for the full day even though not all the gas was needed. Gas plants accounted for 47% of outages in PJM, and 55% of the outages in all regions affected by the Polar Vortex.

Coal plants accounted for 34% of forced outages in PJM, some of which were partial outages. More broadly, coal accounted for 26% of outages during the storm, and these were caused by a variety of problems including frozen coal piles and equipment malfunction resulting from the extremely cold weather.[62]

Some nuclear capacity was out of service during the 2014 Polar Vortex, but the impact was less than it was for coal and natural gas.

Battery storage can experience a reduction in power and energy during cold weather, and its ability to produce energy depends on its state of charge, which would not be able to provide a consistent supply energy during a multi-day weather event.

The development of a suite of modeling scenarios can help inform system planners about the impact of events that can put cold-weather-induced stress on the system and help in identifying solutions. FERC could engage with the various RTOs/ISOs to develop key sensitivities to incorporate into long-term planning models.

---

[62] NERC Polar Vortex Review 2014. https://www.nerc.com/pa/rrm/January%202014%20Polar%20Vortex%20Review/Polar_Vortex_Review_29_Sept_2014_Final.pdf.

Hot Weather Performance and Cooling Water Impacts

Description: High temperatures can result in generator de-rating because of a combination in combustion inefficiency or cooling water temperature increases. Weather-dependent resources may experience higher or lower outputs than during other times of the year.

Key Resources and their Hot Weather Performance Characteristics: Large steam plants such as coal and nuclear require significant amounts of cooling water. As temperature rise, cooling water sources will become warmer. This in turn causes a reduction in efficiency of the plant, and therefore a de-rating of plant output.[63] Natural gas plants will also experience a degradation in efficiency in hot weather because of lower combustion efficiency.[64] Wind plants will often produce less power during hot weather, and solar plants will generally produce high levels of output during hot weather. Neither wind nor solar plants need cooling water. Batteries may experience an efficiency loss at very high temperatures, but their resilience characteristic in hot weather is more likely driven by its energy-limited constraint along with its state of charge.

All of these impacts can be quantified using a combination of production simulation models and resource adequacy models, and they are a part of the capacity value and resource adequacy calculations.

---

[63] Colman (2013) The Effect of Ambient Air and Water Temperature on Power Plant Efficiency. https://pdfs.semanticscholar.org/51ec/37cdcba5d9ff462112c14e92b1c36ff72870.pdf. And International Energy Agency https://www.iea.org/ciab/papers/power_generation_from_coal.pdf and NREL https://www.nrel.gov/docs/fy17osti/67084.pdf

[64] Wartsila: Combustion Engine vs. Gas Turbine: Ambient Temperature. Available at https://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-derating-due-to-ambient-temperature

Fuel Delivery Impacts

Description: Fuel supply disruptions can cause partial or full outages of some power plants. These disruptions can be caused by extreme weather events, but also by compromised fuel transport issues that may not be weather related.

Key Resources and their Fuel Delivery Impact Characteristics: Wind and solar depend only on wind speed and solar insolation to produce power and energy.

Natural gas plants rely upon distribution pipelines which provide fuel close to real-time. Fuel supply disruptions can result from cold weather (as described above), supply shortages, or pipeline failures that can include fractured pipes, malfunctioning compressors, or other mechanical problems. Some regions have natural gas storage facilities, but this is relatively uncommon so storage can only partially mitigate supply shortages.

Some coal plants are located far from fuel supplies, and therefore rely on railroad coal deliveries. These can be disrupted by labor strikes, frozen or snowbound railroad tracks, or other transport issues. Mine-mouth plants are generally immune from these issues.

All of these impacts can be quantified using a combination of production simulation models and resource adequacy models.

Summary

The concept of resilience is not new, and NERCs' TPL-004 provides one possible framework that can be used to assess it. Reliability and resilience are closely linked, as can be seen by the existence of TPL-004, although it is apparent that a more rigorous and widely-accepted definition of resilience, along with associated metrics for assessing resilience, is needed. As FERC engages with the power system industry to further develop the concepts and metrics surrounding resilience, a common framework that has consistent links between the two topics will be critical.

To ensure that the grid can respond efficiently to resilience challenges, market rules or regulations that restrict or limit the types of resources that can participate will result in some combination of unnecessary cost or unnecessary outages. Although it is clear that all resources do not provide the same combination or level of reliability and resilience, allowing all resources to respond if/when they are needed implies that the market rules and other regulations should strive to be technology independent, and markets should be designed based on performance. During periods of stress on the power system, restricting desired response from resources is not helpful.

New resources such as wind and solar generation can provide most grid services, although provision of some of those services may not always be economic because of their low marginal cost, making it most economic to use them for energy. Advances in power electronics controls makes it possible for virtually any asynchronous resource connected to the grid via a power electronics converter to provide very fast frequency response, frequency regulation, and voltage ride-through.

No individual resource can provide all of the required grid services to maintain reliability. Successful operation of the power system requires that the portfolio of resources can collectively make it possible to operate the system economically and reliably. As new technologies are developed and as old ones evolve, rules and regulations should be agnostic to the resource type, and instead specify the service that is needed. This encourages the development or improvement of resources so that they can help make the grid better.

The following section consolidates all of the recommendations to FERC herein.

Recommendations for FERC

- FERC and the industry should continue taking account of the large body of work, and operating practice, to build on best-practices to develop a framework to measure, analyze, and evaluate BES resilience in a meaningful way.
    - Detailed analysis of all RTO/ISO efforts, which has begun with this docket, and should continue
    - Include relevant information, standards from NERC
- FERC, in collaboration with the power system industry, should undertake an in-depth evaluation of the NERC TPL-004 to determine its applicability to BES resilience.
    - If it is found the TPL has gaps, then an evaluation of these gaps and remedies could be undertaken in the context of the TPL. Because NERC's purview is limited to reliability, any new rules regarding resilience should be mindful of PJM's comment cited earlier, that the cost-effectiveness of solutions and response should be a critical component of resilience.
    - There is currently no requirement that all such events can be successfully managed by the BES. FERC and the industry should collaborate to ensure that successful management of HILF events is consistent with the many cost-benefit tradeoffs involved.
- FERC, in collaboration with the power system industry, should examine the existing suite of reliability metrics and determine whether they can adequately capture system performance during the identified HILF events. Simple metrics should be developed that can provide indicators of how well the BES can survive the identified HILF

events so that comparisons of readiness, performance, and alternative threat levels can be made.

- Resilience may include more than just reliability, and FERC may want to consider aspects such as recovery time, infrastructure replacement, and cost of replacement energy during the rebuilding period.
- Develop specific RTO/ISO objective: what type of resilience, response, ride-through, is required? This may differ based on RTO/ISO
    - Short-term can be addressed with current plant, transmission system, infrastructure
    - Long-term may require investment to ensure resilience
- FERC should work to endeavor that approaches to manage the power system during HILF events are not over-specified.
- FERC, in collaboration with the power system industry, should to develop a suite of scenarios that comprise HILF threats. A subset of those threats can be identified as those most relevant to resilience performance rules or guidelines. Although there may be some commonality of these threats to many RTOs/ISOs, there should be recognition that threats will differ among the RTOs/ISOs and rules/guidelines should account for these differences.
- FERC, with the industry, should develop trade-off curves for cost, reliability, and resilience
    - These will be somewhat different for each RTO/ISO
- To pave the way for more resilience and reliability, market rules should be revisited, and revised in such a way that reserve products—in fact, all market products—are

technology-neutral and performance-based.[65] FERC should examine market rules and NERC should examine reliability rules that may compromise reliability and resilience because they do not allow for all types of technologies to respond.

- Resource performance rules should not be over-specified. Rules should focus on "what," not "how." In specifying contributing factors to resilience and establishing requirements or markets around these factors, FERC would be opening the door to a flood of new products that would introduce unnecessary complication and potential unintended consequences, be difficult to track, and difficult to ensure that the ultimate target of resilience would be achieved.
- As new flexibility products are defined and evaluated, FERC should collaborate with the industry to better-understand the need for these products, how their provision may interact with other BES products and market dispatch, and whether changes in business practices or product definitions may have an impact on the need for the service. New products should be developed in a technology-neutral way, and may specify speed and depth of response, along with other attributes of the product in question.
- As DR technology and its understanding mature, FERC should consider ways in which speed of response and depth of response can be compensated. This should not be a DR-only investigation but should be developed in a technologically neutral way so that alternative technologies can compete.

---

[65] Ela et. al (2011) Operating Reserves and Variable Generation, NREL. Available at https://www.nrel.gov/docs/fy11osti/51978.pdf.

Document Content(s)