ENERGY STORAGE IN PJM

EXPLORING FREQUENCY REGULATION MARKET TRANSFORMATION

July 27, 2017

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EXECUTIVE SUMMARY

TO MAINTAIN RELIABILITY, THE ELECTRIC POWER GRID NEEDS TO ALWAYS BALANCE ELECTRICAL SUPPLY WITH DEMAND. While grid operators pay close attention to forecasting load (i.e. demand) and scheduling generation (i.e. planning for dispatch of generation supply) ahead of time, there will be short-term errors in load forecasts or unexpected fluctuations of power plant output. Because demand and supply need to be balanced almost immediately, these sudden changes necessitate instantaneous adjustments within the timeframe of seconds to minutes. So grid operators rely upon “frequency regulation” resources to correct for these small mismatches between supply and demand. Frequency regulation resources are paid to automatically adjust output according to the operator’s signal in order to respond to these short-term fluctuations.

Traditionally, centralized power plants (like hydropower, steam generators, or combustion turbines) have provided frequency regulation services. Following recent technological and cost improvements, energy storage technologies (including batteries and flywheels) have begun to provide frequency regulation to grid systems as well. In 2012, the PJM Interconnection (PJM)—the regional transmission organization that operates the electricity grid across 13 mid-Atlantic states and D.C.—divided its frequency regulation market into slow and fast components. Fast response resources included energy storage that could absorb or release power very quickly, and more traditional resources like natural gas-fired power plants that could ramp power up and down with a slight delay.

The fast frequency regulation product was initially designed to require resources to provide zero energy on net when averaged over 15 minute periods. This concept, where the cumulative energy input equals the cumulative energy output, is called “energy neutrality.” This design enhanced the ability of energy storage resources to respond to the grid operator’s frequency regulation signals by ensuring the storage resource had available capacity to offer. As a result of this design, a lot of energy storage investment occurred in the PJM region. As of August 2016, PJM accounted for 46 percent of the rated power (MW) of grid-connected battery projects operational in the United States (DOE Office of Electricity Delivery & Energy Reliability 2016). Recently, other regions such as California have seen substantial energy storage deployment.

Frequency regulation has played a large role in energy storage commercialization, and will continue to play a role. But how large a role depends on changes to the design of PJM’s frequency regulation market. PJM embarked on these changes in an effort to correct observed problems in the market. Specifically, some energy storage resources at some instances would be pulling power from the grid in an effort to achieve energy neutrality at the precise time the grid operator needed resources to be injecting power, and vice versa.

Starting in 2015, PJM embarked on a series of changes to its frequency regulation market to correct for observed issues, and more changes are being proposed. Changes implemented to date have resulted in reduced growth rates of energy storage resources in the PJM footprint. The energy storage industry perceives these market changes to be unduly unfair, and is challenging PJM through two complaints before the Federal Energy Regulatory Commission (FERC).

The underlying technological issue facing PJM's frequency regulation system is that advanced energy storage units can provide quick and accurate responses in a short timescale, but cannot sustain this output for a long time. Consequently, PJM, the energy storage industry, and the Federal Energy Regulatory Commission (FERC) need to resolve a significant market design challenge: How should the market place different technologies on a competitive playing field when their technical characteristics differ fundamentally, all while protecting system reliability?

This report will focus on the technological and economic aspects of PJM's frequency regulation market design, while avoiding commenting on the legal nuances of the ongoing complaints. This report first discusses the importance of frequency regulation in relation to compliance with reliability standards. Then it provides an overview of how two central market design dimensions of the PJM frequency regulation system were created: the signal construction and the valuation system for these two different signal types. This article looks at the recent market design changes and seeks to examine their impacts on system reliability as well as energy storage providers. Finally, the article considers the future direction of how energy storage interacts with frequency regulation needs.

CONTENTS

The cover image depicts overlaid monthly plots of 10-minute historical area control error (ACE) published on http://www.pjm.com/markets-and-operations/etools/oasis/system-information/historical-area-control-error-data

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WHY IS FREQUENCY REGULATION NEEDED?

IN NORTH AMERICA, LOCAL ELECTRICITY GRID SYSTEMS ARE CONNECTED TOGETHER IN THREE LARGE AREAS KNOWN AS INTERCONNECTIONS, IN ORDER TO IMPROVE RELIABILITY REDUNDANCIES AND ACHIEVE ECONOMIES OF SCALE.[1] Each interconnection acts as "a large machine" where the grid-connected synchronous generators all rotate at the same frequency (NERC Resources Subcommittee 2011). Keeping a constant frequency of 60 Hertz (Hz) throughout the system is critical to maintaining electric system reliability. Within an interconnection, any supply and demand mismatch causes the electrical frequency to deviate from the target 60 Hz. For example, excess demand will slow down the spinning of the system's synchronous generators, thereby reducing the alternating current's frequency according to the "swing equation"; the reverse happens when supply exceeds load (Basler and Schaefer 2005).

An interconnection consists of individual balancing authorities. Each balancing authority has the responsibility to manage its short-term mismatches of supply and demand, also known as area control error (ACE).[2] As one balancing authority within the larger Eastern Interconnection, PJM must comply with the reliability standards set by the North American Electric Reliability Corporation, or NERC (NERC 2015).[3] In order to manage its ACE and maintain the power grid frequency close to 60 Hz, a grid operator needs to be able to continuously increase or reduce (i.e. regulate) supply or demand. So frequency regulation is a tool to smooth out these real-time imbalances, or ACE. This is accomplished when energy resources (power plants, energy storage, or demand response) automatically follow the grid operator's frequency regulation signal to inject or cut back power, also known as automatic generation control.

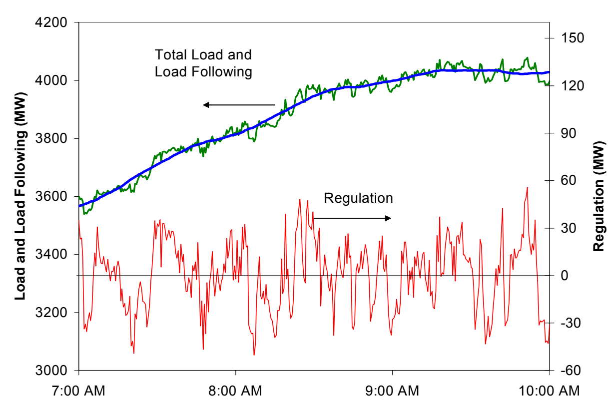


Figure 1: *Illustration of Frequency Regulation (Kirby 2004, Fig. 4)*

[1] The three interconnections are known as the Eastern, Western, and ERCOT interconnections.

[2] More precisely, the ACE is a sum of interchange error (unintended electricity flows with neighbors due to supply-demand mismatches) and frequency bias (which accounts for some additional responsibility to help stabilize the overall interconnection's system frequency).

[3] The "Real Power Balancing Control Performance" standard (BAL-001-2) requires each balancing authority to control its ACE within specified limits in terms of yearly averages (measured by the Control Performance Standard 1 or CPS1) and on a minute-by-minute basis (measured by the Balancing Authority ACE Limit, or BAAL).

Figure 1 illustrates how frequency regulation works. The green line represents demand load (or load net of intermittent renewables that cannot be dispatched). The smooth blue line represents *load following*, where power plants ramp up during the day to match the load, on the scale of hours. The red line represents *frequency regulation*, which can be viewed as the error difference between the green supply and blue load lines. Note that the right axis (corresponding to the red line) is at a smaller scale than the left axis (corresponding to the blue and green lines). In other words, compared to load following resources, frequency regulation resources provide smaller-magnitude responses, but these responses must occur on a much quicker timeframe.

SIGNAL CONSTRUCTION: TRADEOFF BETWEEN PRECISION AND DURATION

Energy storage resources have the advantage of being able to quickly and precisely respond to frequency regulation signals, but are challenged by long duration requirements.

Precision Advantage

Conventional resources that generate power by spinning turbines have ramp rates. These ramp rates are driven by mechanics and translate into a lag times to respond to frequency regulation signals. In other words, it takes time to either increase or decrease the plant's level of output. This is analogous to the time it takes for a racecar to accelerate or brake to a certain speed. In contrast, energy storage resources like batteries or flywheels have nearly instantaneous ramp rates, i.e. effectively changing 100 percent of power capacity per minute. Due to the faster ramp rate, a 2008 Pacific Northwest National Laboratory study suggests that one megawatt (MW) of a fast-responding resource can provide the same regulation service as 1.7 MW of an average hydropower plant, 2.7 MW of an average combustion turbine, or 29 MW of an average steam turbine (Makarov, et al. 2008).

Duration Challenge

On the other hand, energy storage devices are energy limited, meaning they have finite ability to absorb or inject power. In comparison, conventional power plants can perpetually adjust their output either above or below a benchmark, as long as there is fuel. As ***Table 1*** shows, if fast regulation resources cannot sustain output for a long time, their performance advantage decreases.

In 2011, FERC's Order 755 required grid operators to compensate frequency regulation providers, including new fast ramp-rate resources, according to their actual performance and technical ability to support the grid system. On October 1, 2012, with the purpose of incorporating accurate but energy-limited storage resources, PJM split the frequency regulation signal into two signals: slow-responding Regulation A (RegA) and fast-responding Regulation D (RegD, where the D is for "dynamic").[4] In the initial construction of this split-signal system, RegA was designed for resources "with the ability to sustain energy output for long periods of time, but with limited ramp rates," while RegD was designed for resources "with the ability to quickly adjust energy output, but with limited ability to sustain energy output for long periods of time" (Monitoring Analytics 2014).[5]

Conventional Resource	**Average Ramp Rate** (% of Total Capacity Per Minute)	**Replacement by 1 MW Fast Response Regulation** (Unlimited Duration)	**Replacement by 1 MW Fast Response Regulation** (Duration Limited to 15 Minutes)
Hydropower	32.0%	1.72	1.43
Combustion Turbine	20.4%	2.70	2.24
Combined-Cycle	2.0%	27.50	22.84
Steam Turbine	1.9%	28.94	24.04

Table 1: *How Many MW of Conventional Regulation Resource Could 1 MW of Fast Regulation Replace? (Makarov, et al. 2008, Table 6-1, 6-2)*

[4] A more detailed history of the PJM frequency regulation market's evolution can be found at: http://www.pjm.com/%7E/media/committees-groups/committees/oc/20150701-rpi/20150701-item-02-history-of-regulation-d

[5] Another description is that RegA represents a low-pass filtered signal, i.e. the slow-moving component, and RegD represents the high-pass filtered signal, i.e. the fast-moving component (Xu, et al. 2016)..

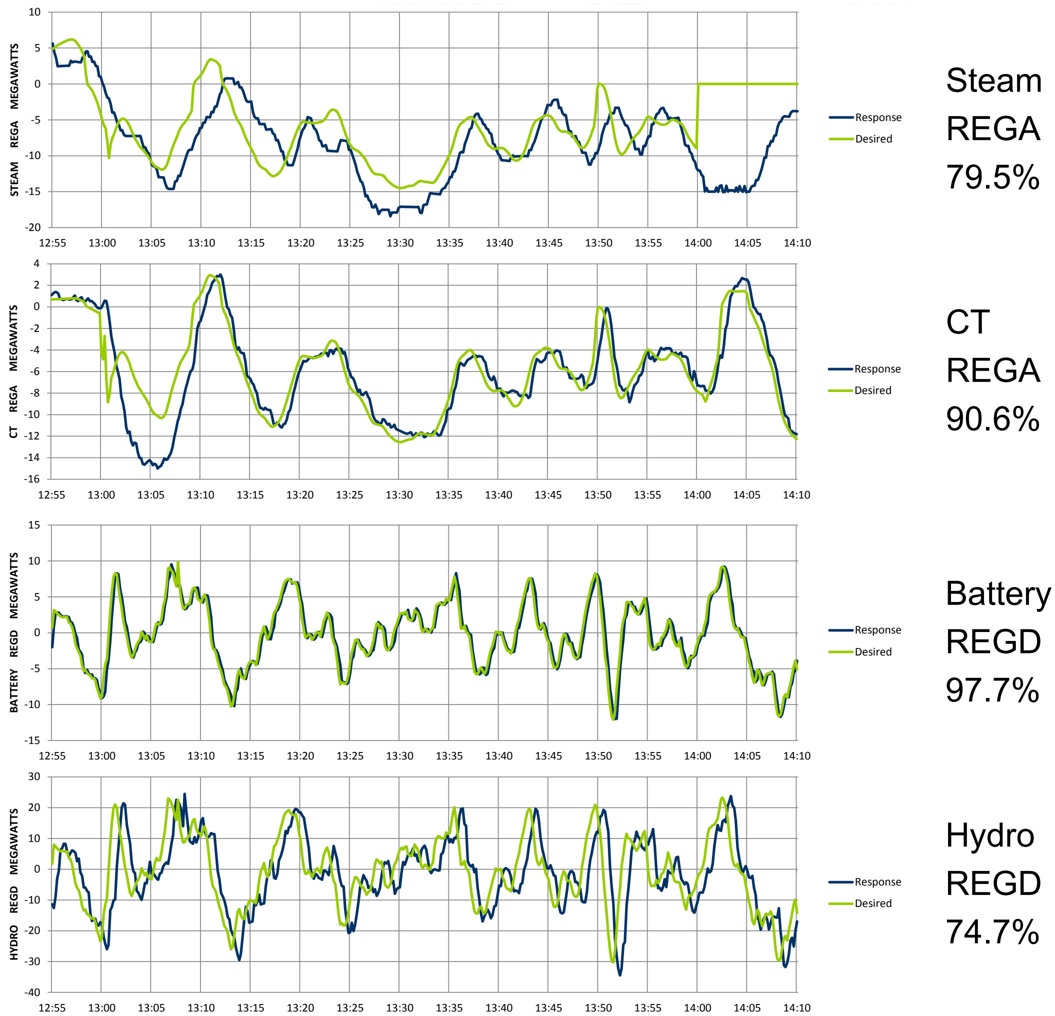


Figure 2: *Example Plots Comparing Responses to RegA and RegD Signals. The plots show RegD having a faster-moving signal than RegA, and an overall mean closer to zero. (Benner, Performance, Mileage and the Mileage Ratio 2015)*

Figure 2 provides a graphic representation of RegA (on the top) and RegD (on the bottom) signals, with the RegA signals moving more slowly compared to the RegD signals. An important part of the initial market design was that the RegD signal was "energy neutral." This meant on average, over a 15-minute period, the amount of energy provided by RegD resources equaled the amount of energy absorbed. An energy neutral signal ensured that the energy storage resource would never become over-charged or over-discharged, which is important to the operating integrity of the asset. Also, if energy neutrality helps energy-limited resources stay within operational bounds, the grid operator could better predict ahead of time how the resources will respond to any given signal.

VALUATION SYSTEM: COMPARING DIFFERENT TECHNOLOGIES

PJM's goal is to ensure power system reliability at minimal cost; and any system costs are ultimately passed through to electricity consumers. In general terms, when choosing between two products, the preference is to get a "bigger bang for the buck," i.e. more benefit at lower cost. Specifically, economics teaches that the least-cost way to obtain a desired level of output requires that each input resource's ratio of cost to marginal benefit is equal, i.e. $P_A / MB_A = P_D / MB_D$ (Haas 2015, 28). By ensuring that the ratio of the two resources' prices are related by $P_D / P_A = MB_D / MB_A$, PJM can achieve this least-cost optimality condition.

[6] Otherwise, if the price per marginal benefit of A is more expensive than that of D, then the last marginal unit of benefit could be more cheaply obtained by switching from A to D, while maintaining the same total level of reliability. A standard argument is as follows. The objective function is to minimize $P_A A + P_D D$ subject to f(A,D) = K, where K is the desired level of frequency regulation benefits. This gives the Lagrangian: $P_A A + P_D D + \lambda[K - f(A,D)]$. Differentiating with respect to A and D gives: $0 = P_A - \lambda MB_A = P_D - \lambda MB_D$. Thus $\lambda = P_A / MB_A = P_D / MB_D$.

Given these economic principles, PJM developed a valuation system to determine the optimal mix of RegA and RegD resources. In order to design its original valuation system, PJM utilized a study that simulated different hypothetical combinations of RegA and RegD amounts; this study was conducted by the U.S. branch of KEMA, a Dutch technical consulting company (KEMA 2011). In this study, KEMA varied the total amount of regulation used (measured as a percentage of historical peak load), and for each level of total regulation varied the percentage coming from RegD. At each combination point, KEMA calculated a reliability score (NERC's CPS1 metric), capturing how well the area control error is being managed. By connecting combination points with the same reliability outcome, KEMA produced contour plots revealing the relationship between RegA, RegD, and the resulting system reliability.

Starting at its original status quo mix (i.e. total regulation amount equal to 1 percent of peak load, with zero RegD), PJM could maintain the original level of reliability control by increasing the share of RegD while using less regulation overall. So by introducing RegD resources, PJM could reduce the overall amount of regulation needed while keeping reliability the same; equivalently, PJM could improve system reliability without incurring more requirements for regulation.

At a certain point, continuing to increase the share of RegD, KEMA discovered, led to diminishing returns from using more RegD. KEMA explained the diminishing returns by noting that RegD was "designed as a complement to the RegA signal and was not designed to carry all system regulation." According to PJM, the specific reason that an excessive percentage of RegD resources can worsen reliability control is that the RegD control signal, in order to maintain average energy neutrality, sometimes moves "in the opposite control direction than desired by dispatch" (Martini 2015). In those instances, the grid operator effectively would be paying different types of resources to cancel out each others' services. In other words, the fact that RegD sometimes moved against system needs was recognized by and incorporated into the valuation system, because the system could otherwise utilize increasing shares of RegD without detriment to reliability.

These concepts of optimal mix and relative benefits are captured by the marginal benefits factor (MBF), which measures how well a RegD resource can substitute for RegA, while still satisfying the same regulation requirement. The original marginal benefits curve is seen in ***Figure 3***, which shows the MBF dropping to zero at a RegD percentage of 62 percent (Benner, Benefits Factor and the "Effective" MW 2015).

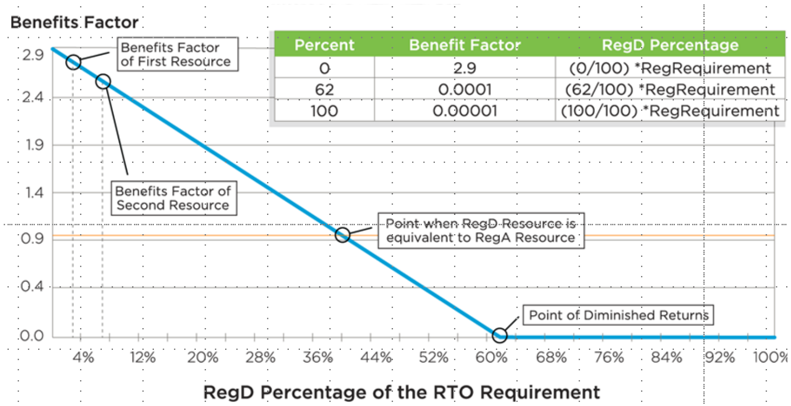


Figure 3*: Original marginal benefits factor curve – as of August 11, 2015. Source: (Olaleye, Regulation Clearing and Benefits Factor Calculation 2015)*

MARKET DESIGN CHANGES: REVISING THE SIGNAL AND VALUATION SYSTEM

Starting around 2015, PJM operators noticed high levels of RegD resources that raised concerns about operations and compliance (PJM Operating Committee 2015). This was worrisome to PJM because the energy neutrality requirement sometimes forced the RegD signal to move in the opposite direction of the ideal ACE control. Essentially, the storage resources' needs from the grid to achieve energy neutrality sometimes worked against the grid's frequency regulation needs.

To preserve reliability at each moment, PJM dispatchers sometimes had to manually intervene to correct the fast regulation signal moving in the wrong direction. The independent market monitor organization for PJM, Monitoring Analytics, identified some main issues: the benefits factor curve incorrectly overvalued RegD, and the settlement process did not consistently utilize the benefits factor curve (Haas 2015). Resulting from these flaws, the frequency regulation system often over-procured as well as over-compensated fast-responding resources from a system efficiency standpoint.

In response to the observed issues, PJM started a Regulation Performance Impacts stakeholder group (under the Operating Committee) on May 26, 2015 to focus on a "short term solution that can be implemented quickly" (PJM OC 2015). Subsequently, PJM started a Regulation Market Issues Senior Task Force (under the Markets and Reliability Committee) on September 26, 2015 to resolve broader and interrelated issues with the regulation market (PJM RMISTF 2015). These two stakeholder processes for operational and market design reforms proceeded in parallel.

1. **December 14, 2015:** The Operating Committee implemented a short-term solution by decreasing the benefits factor curve, effectively decreasing the value placed on RegD in recognition of its sometimes counterproductive movements (Olaleye, Proposed Revision to the Adjusted Total Cost Formulation and the Benefits Factor Curve 2015). This reduced the amount of RegD resources to be procured from the original horizontal MBF intercept, i.e. the point where no additional RegD units should be procured, from 62 percent to a lower 40 percent. The revision also set a hard 26.2 percent RegD cap during hours of the day when the grid dispatcher frequently moved the regulation signal manually. This curve revision functioned as a new cap on the total amount of RegD resources that could be committed (Clean Energy States Alliance 2015). The revised marginal benefits factor curve is shown in *Figure 4*.

From a theoretical perspective, this benefits factor revision fixed PJM's original interpretation of the KEMA study. The KEMA study showed that at about 42 percent of RegD share, system "reliability is the same as no RegD at all"; however, as of July 2015, PJM interpreted this conclusion to mean that the "benefit is 1.0" at 42 percent of RegD share (Benner, Benefits Factor and the "Effective" MW 2015). Under a correct interpretation, KEMA's study showed that further increases of RegD past 42 percent would worsen reliability, meaning no additional RegD should be utilized and thus the marginal benefit value should be zero. The updated MBF curve in *Figure 4* better captures this conclusion.

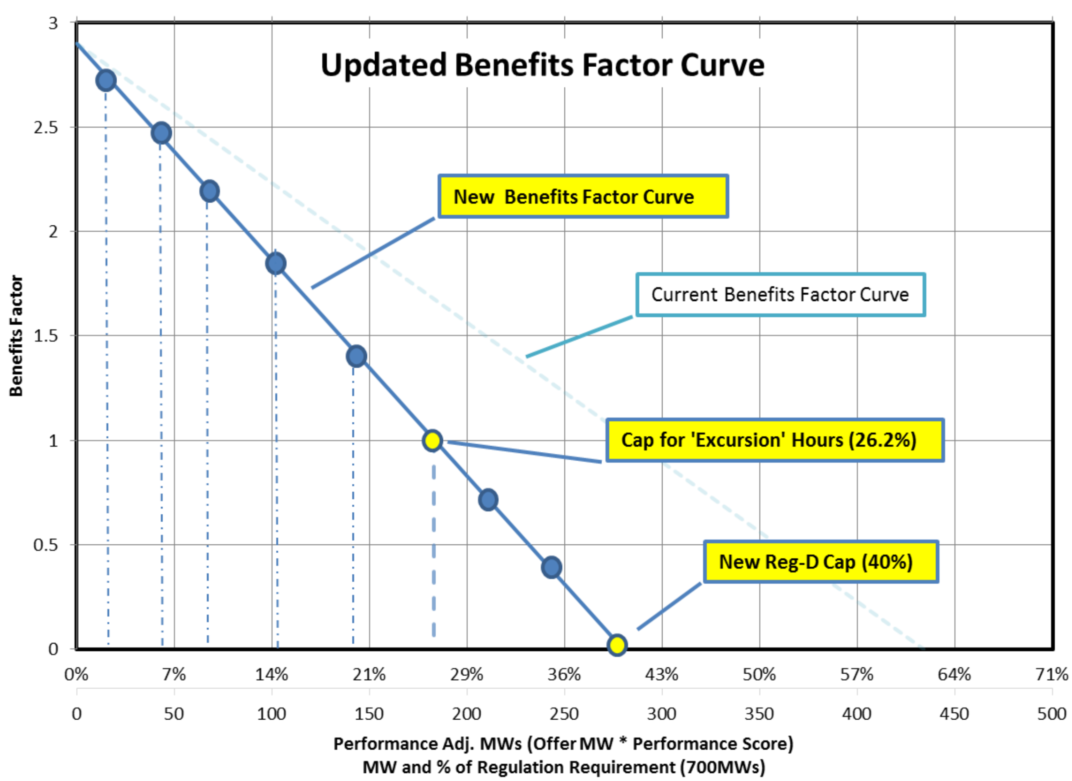


Figure 4*: Marginal Benefits Curve After Revision by the Operating Committee—proposed August 17, 2015, and implemented November 4, 2015. (Velasco 2015)*

2. **January 9, 2017**: As part of the Senior Task Force stakeholder process, PJM re-engineered the frequency regulation signals to achieve "conditional neutrality" for RegD resources, meaning the signal no longer guarantees that RegD resources are returned to energy neutrality (PJM Staff 2017). Concretely, the new RegA and RegD signals now work together such that energy neutrality is only supported for RegD resources when there are freely available RegA resources with extra capacity.

   The rationale of this new signal design is to avoid the aforementioned problem of RegD resources sometimes moving in the opposite direction of ideal control. PJM maintained that since the signal construction rules did not require a change to PJM Manuals or the Tariff (i.e. one of PJM's main governing documents), PJM can implement the signal change immediately.

3. **Pending**: On February 27, 2017, the Regulation Market Issues Senior Task Force voted to endorse a package of longer term holistic reforms to the frequency regulation market (PJM RMISTF 2017). In the revised system, a new marginal rate of technical substitution (MRTS) is based on the same concept as the benefits factor to measure the relative value of RegD versus RegA resources; the rate of technical substitution is calculated by PJM based on system conditions (using a method similar to KEMA's) and is consistently applied throughout the clearing and settlement stages.

   Unlike the old marginal benefits curve, which is static across all times, the new MRTS proposal defines eight separate MRTS curves, i.e. one for each season, differentiating between ramp and non-ramp hours. Compared to the Operating Committee's current short-term solution implemented in November 2015, the new proposal makes the initial segment of the curve even steeper; then, after roughly 50MW of RegD service, the proposal would value RegD resources even less than under the current curve (where the old curve intersects a new curve). *Figure 5* provides a visual comparison of the three sets of valuation systems.

On June 22, the Markets and Reliability Committee voted in favor of the Senior Task Force's proposal (PJM 2017). Since the proposal passed, the PJM Member Committee will then review it. As the changes involve changes to the Tariff, the PJM Board has ultimate authority on the changes, and the Board will decide whether to file these adjustments with FERC.

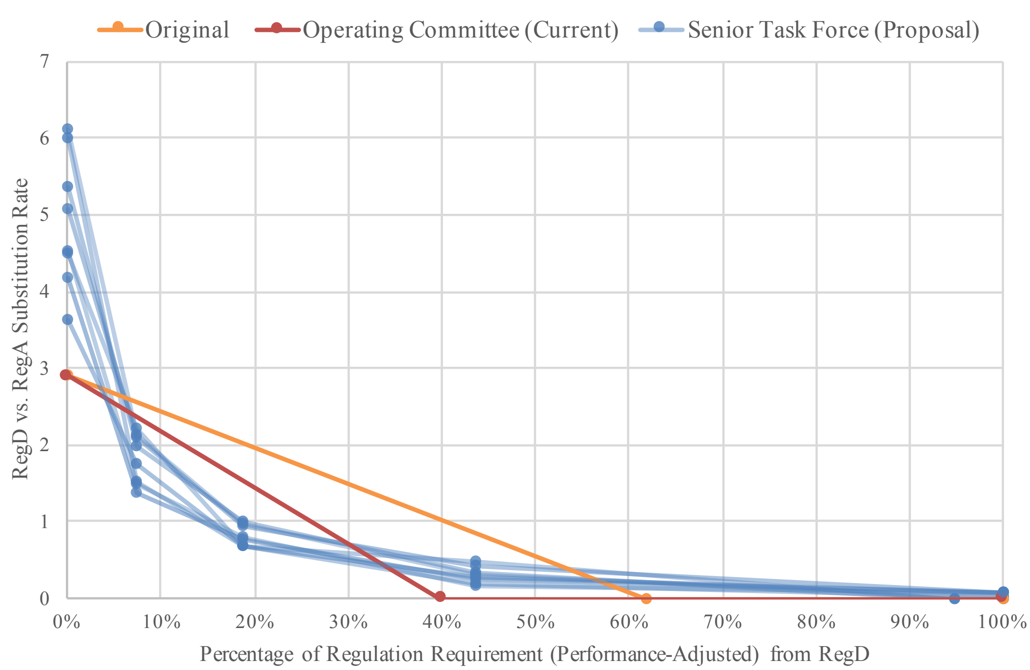


Figure 5*: Comparison Between Different Substitution Rate Curves. The blue (Senior Task Force proposal) curves are constructed from the MRTS curve points data file (PJM 2016)*

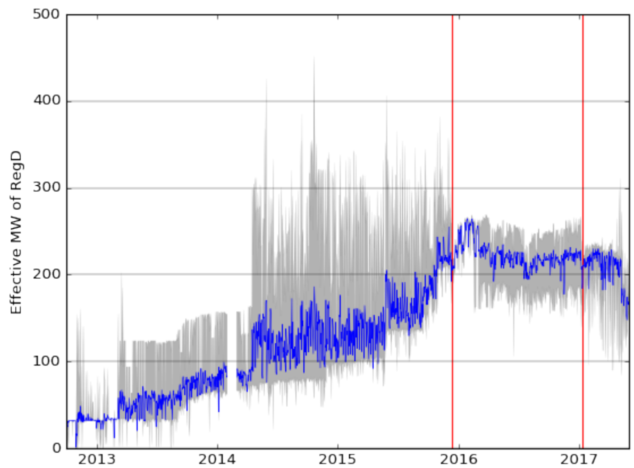


Figure 6*: Amount of RegD Effective MW Out of Total MW of Regulation (showing daily averages of individual hourly percentages in blue, along with ranges of daily minimum and daily maximum in gray). The first red line denotes the 2015 benefit factor change, and the second red line is the introduction of the new signal. Constructed from PJM's "Ancillary Service Market Results" files (http://www.pjm.com/markets-and-operations/ancillary-services).*

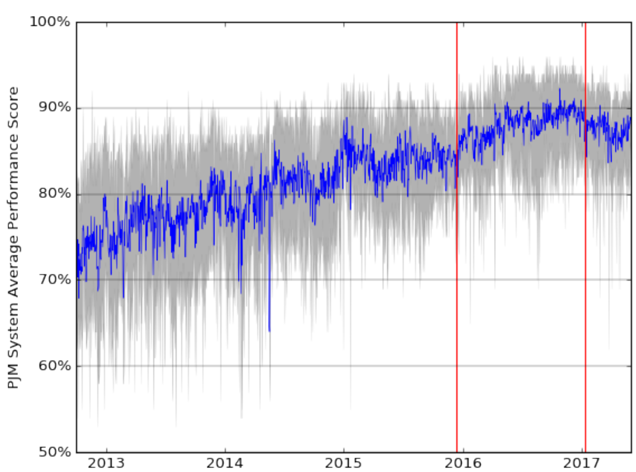


Figure 7*: System Average Performance Score (showing daily averages of individual hourly scores in blue, with ranges of daily minimum and maximum in gray). Constructed from PJM's "Historical Market Data" files (http://www.pjm.com/markets-and-operations/ancillary-services).*

IMPACT OF MARKET DESIGN CHANGES

The market design changes implemented thus far have decreased the effective megawatt participation of RegD resources in the regulation market. ***Figure 6*** shows the evolution of RegD participation, measured in MW adjusted for the benefits factor. Empirically, RegD resource participation steadily grew—from the signal's introduction up until the end of 2015. After a lag caused by some batteries already under construction,[7] the December 2015 short-term market adjustment stopped this continued growth in RegD services. Furthermore, the adjustment also constrained the daily maximum of hourly RegD levels. Finally, the January 2017 signal revision resulted in a declining amount of RegD.

Figure 7 shows the evolution of the PJM system's average performance score. Each resource's performance score calculation is an average of three scores: accuracy, delay, and precision (PJM "Performance Scoring"). Accuracy captures how closely a resource follows the control signal's movements, delay measures the lag time for the resource to start moving as intended, and precision represents the instantaneous error between signal and response.[8]

While the system performance score is not necessarily the ultimate objective for grid reliability, a higher performance score indicates that grid operators are better able to anticipate how exactly resources will respond (i.e. reducing "unintentional" flaws in how resources respond). Yet following a signal perfectly is not necessarily beneficial for the overall system if the signal itself acts in the opposite direction of ideal control at certain instances (i.e. an "intentional" flaw in how RegD resources behave). Empirically, the steady rise in RegD coincided with a period of steadily increasing system average performance, which continued even after the 2015 devaluation and cap—this may have resulted from poorer performing RegD resources dropping out first. In comparison, the 2017 signal revision was followed by a dip in the system average performance score.

[7] The ESA complaint's footnote 86 notes "The increase in the weeks after the December Cap reflects that at least 38MW of storage was already under construction when the cap was put in place and entered service in December 2015."

[8] The performance score is an equal-weight average of accuracy, delay, and precision scores. Accuracy is the highest statistical correlation (Pearson r) found by comparing PJM's signal to the resource's response over a 5-minute window (shifted in increments of 10 seconds). Delay is based on the time shift at which this highest correlation occurs, e.g. if the time shift occurs at 0 or 10 seconds then the delay score is a perfect 100%. Finally, the precision score is the average absolute difference between signal and response (allowing for a 10 second delay) scaled by the hourly average signal; this is also known as the mean absolute error (PJM 2017, 54).

This reduced system performance score primarily resulted from decreased performance of energy storage (i.e. unable to perform because not in an energy neutral state, or due to heat rate concerns related to duration of operation) and demand-side response (i.e. related to issues with sustained output), while other resource types' performance has remained the same as seen in ***Table 2***.

Regulation Type	MW	Steam	Hydro	CT	Energy Storage	DSR
Reg A	Avg. Performance Score (Jan.1)	75%	86%	84%	NA	85%
	Avg. Performance Score (Jan. 20)	75%	87%	84%	NA	85%
Reg D	Avg. Performance Score (Jan. 1)	NA	77%	90%	96%	85%
	Avg. Performance Score (Jan. 20)	NA	77%	90%	93%	82%

Table 2*: Frequency Regulation Performance Before and After Introduction of New Controller Signal (Endress 2017)*

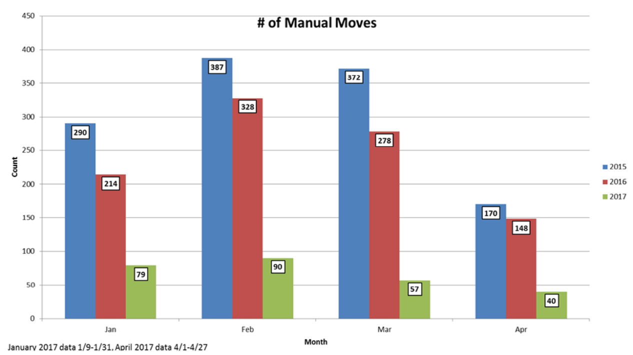


Figure 8*: Effect of RegD Devaluation and Signal Redesign on Reducing the Need for Manual Intervention by Dispatchers. (PJM Interconnection 2017)*

Signal Type	Date	Avg. Median Daily ACE	Avg. Daily Stdv
New Signal	Jan 2017(1/9-1/31)	34	244
	Feb 2017	32	236
	Mar 2017	38	269
Old Signal	Jan 2017(1/1 - 1/8)	68	285
	2016	56	274
	2015	52	284

Table 3*: Effect of Signal Redesign on Improving the Control of PJM's Area Control Error (PJM Interconnection 2017).*

PERSPECTIVES ON MARKET DESIGN CHANGES

From PJM's perspective of protecting system reliability in a cost-effective manner, these market revisions have improved overall stability ("Answer and Motion to Consolidate of PJM Interconnection, L.L.C."). First, the December 2015 devaluation and cap on RegD helped to decrease the number of manual moves required to keep ACE in check—managing ACE is the ultimate purpose of frequency regulation. This can be seen by the data in ***Figure 8***. The 2017 signal revision very significantly reduced the necessity of manual moves (comparing to the same months of prior years), because the new signal no longer has a built-in tendency to sometimes worsen ACE.

Second, PJM has directly demonstrated superior ability to control ACE following the introduction of the new signal. ***Table 3*** presents same-month comparisons showing the median daily ACE dropping closer to zero, along with a reduction in the variability of ACE. This improvement in ACE management strongly suggests that the reduction in how predictable RegD resources respond (seen in the performance score drop in ***Table 2***) is offset by the signal's improved overall contribution to reduce ACE.

On the other hand, these market changed have harmed energy storage providers, who responded by filing two complaints against PJM that are currently under review by the Federal Energy Regulatory Commission (FERC). The Energy Storage Association (ESA), an industry trade group, filed a FERC complaint against PJM on April 13, 2017, and the next day Renewable Energy Systems Americas and Invenergy Storage Development filed a similar complaint.[9] The short-term benefit factor reduction has negatively impacted energy storage operators in PJM. These operators have experienced decreased market share and reduced revenues, while investment in new storage resources in PJM has declined.

Lowering the RegD benefit factor at the end of 2015 raised the effective prices of RegD resources during the market optimization process, leading PJM to obtain fewer megawatts of regulation service from energy storage. ***Figure 7*** shows the share of regulation provided by RegD dropping in 2016, with an ensuing plateau.

[9] The ESA complaint alleges that "PJM has unilaterally implemented a series of arbitrary, capricious and discriminatory changes to its Regulation market" (Burwen and Kaplan 2017).

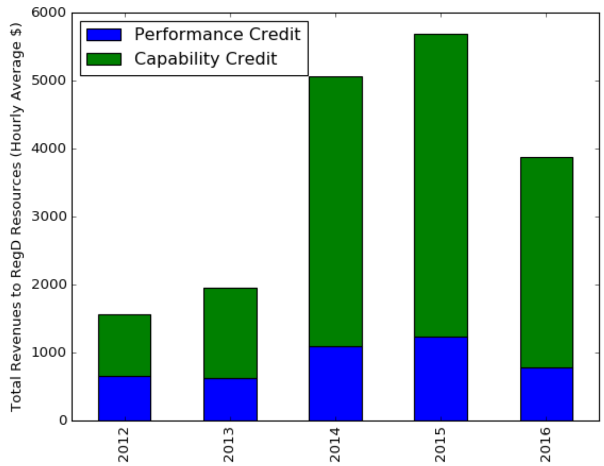
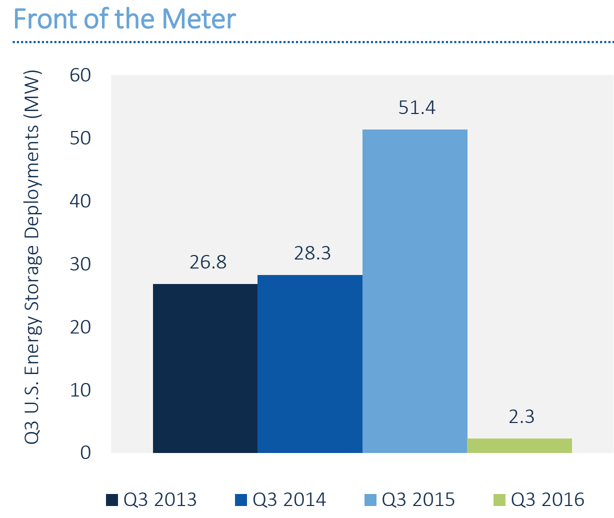


__Figure 10__: Effect On existing Resources - Total Revenues to RegD Resources in PJM, calculated using PJM's "Ancillary Service Market Results" and "Historical Market Data" files. (http://www.pjm.com/markets-and-operations/ancillary-services). The data files include effective MW levels of RegD, which incorporate the performance scores at each hour. Regulation resources are paid a sum of a performance credit and a capability credit (Byrne, Concepcion and Silva-Monroy 2016).

Figure 10 shows a 2016 decrease in the total revenues paid out to RegD resources, about a 32 percent reduction spread across all existing RegD resources.

In addition, the reduction in revenues of battery resources in PJM has translated to reduced investment in new installations, leading to a drop in front-of-the-meter energy storage deployment in 2016 Q3 compared to 2015 Q3, seen in ***Figure 11***.

PJM itself notes that the original RegD signal targeted convergence to neutrality within 5 minutes, and that across 95 percent of the time the signal converged in less than 15 minutes (Benner, A Brief History of Regulation Signals at PJM 2015). Storage operators argue that utilizing this guidance from the grid operator, companies have designed, invested in, and developed energy storage resources to provide enough capacity to cover 15 minutes of continued regulation service. However, the ESA complaint notes that under the new signal, PJM "is dispatching limited-energy regulation resources in a single, sustained direction for up to an hour at a time, on an almost daily basis" (Burwen and Kaplan 2017).



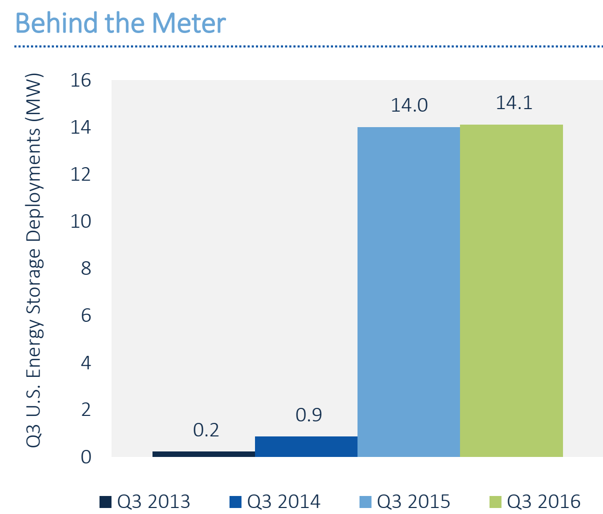


__Figure 11__: Effect on New Resource Deployment - Comparing Quarter 3 of 2015 versus 2016. Front of the meter battery installations declined in the U.S. (GTM Research 2016)

After energy neutrality was replaced by conditional neutrality, sustained periods of the frequency regulation signal have increased the amount of energy flowing through battery systems. In response, battery operators can either accept the higher system temperatures (known as heat rate), or lower the capacity for bidding into the market. Excessive heat rates damage the expected lifetime of batteries, as well as potentially void manufacturer warranties that call for reasonable operating conditions. In its affidavit contained in the ESA complaint, Invenergy calculated that its battery systems increased their operating temperatures by 43percent, potentially degrading service life up to 50 percent. The affidavit from EDF Renewable Energy, contained in the ESA complaint, explains how a battery project chose to lower its bidding capacity by 25 percent, leading to net revenues decreasing by 26.75 percent on average.

From its perspective, the ESA finds fault in the apparent incongruity between the present signal and valuation methodology (Energy Storage Association 2016). Specifically, the benefits factor curve was revised to place less value in RegD, because at times it moved against system needs; at the same time, the revised signal design no longer moves against system needs. In other words, ESA argues PJM reduced its valuation for a flawed product; and later PJM fixed the flaws of this product but retained the lowered valuation.

From their perspective, PJM and the market monitor would like to move towards a system that combines both the improved signal as well as the more accurate technical substitution curve in the proposal. It appears that one reason why PJM chose to implement the signal first then gradually revise the technical substitution valuation in the future is to obtain real-life data on the new signal's performance. Following the implementation of the new signal, PJM states that it "has committed to updating the RTS curves to reflect real-world performance of regulation resources" (PJM Staff 2017). In this way, PJM will be able to use empirical data to inform its future valuations of RegA versus RegD, as opposed to continuing to rely on simulations and heuristics.

POSSIBLE OPPORTUNITIES TO IMPROVE EFFICIENCY

Recognizing both PJM's responsibility for reliability and the disadvantage of energy storage under sustained signals, unbundling regulation directions (up versus down) may offer additional efficiency. This is because PJM derives different benefits from regulation up versus down. In its response to ESA's question why PJM's operations called on sustained periods of full regulation power mostly in the "lower" direction, PJM explains its actual reliability requirements: The dispatcher knowingly tends to bias regulation signals in the "lower" direction, because the ACE being below zero "poses larger reliability risks to the system" than the ACE being above zero (PJM Interconnection 2017). Due to this asymmetry, "signals are pegged more often in the lower direction than in the raise direction." Operationally, PJM has very distinct methods to deal with negative versus positive ACE: PJM uses "synchronized reserves to help manage" low ACE during a system disturbance, while PJM calls on frequency regulation as "the first line of defense" for high ACE.

So separating the directions, as is done by the California Independent System Operator (CAISO), may be beneficial. For PJM, dispatchers would have more granularity of control, and prices would better reflect actual system conditions. Frequency regulation prices in CAISO, for example, differ significantly between up and down directions. For energy storage operators, separating regulation directions would enable each resource to dynamically opt out of either regulation up or down, depending on their individual states of charge. This could thereby eliminate the need altogether for energy neutrality (conditional or not) to be baked into the signal design. Of course, the main disadvantage of even more market design adjustments is the time and uncertainty involved. One upside is that transitioning to such a system would not disrupt incumbents that wish to continue bidding into both regulation directions.

Ultimately, continuing the process of implementing the task force's proposal can maximize system efficiency (i.e. greatest reliability for least cost) because the proposed technical substitution rate can properly capture the full value of the improved RegD signal.

CONCLUSION

When providing frequency regulation, energy storage resources have good precision but limited duration. The recent evolution of PJM's frequency regulation rules can be seen as market signals that reflect the grid system's needs along this precision-duration tradeoff. Changing market conditions can incentivize development and investment into energy storage resources with more energy capacity (i.e. megawatt-hours) rather than more power (i.e. megawatts). An energy storage project with the ability to provide or absorb power for longer durations can achieve higher performance scores under the new conditional neutrality RegD signal. Eric Hsia, Manager of Performance Compliance at PJM, explained back in 2016: "The future of batteries in PJM is up to the advances in the technology. If they can discharge longer than one hour, it is up to them what they want to do in PJM" (Maloney 2016). However, for these market incentives to work well, PJM would need to move towards a valuation system that fully captures the value of the new signal design.

At the same time, the ongoing FERC complaint process combined with the ongoing approval of PJM's long-term proposal introduce uncertainty about the participation of energy storage on the PJM frequency regulation market. Furthermore, developments on the federal level at FERC, including the Notice of Public Rulemaking (NOPR) on "Energy Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators" could expand opportunities for energy storage projects that participate in the wholesale market (FERC 2016). The NOPR would help to streamline market rules to maximize the technical potential of energy storage, including better integration of wholesale revenues with other revenue streams (FERC 2017). How these FERC rulings evolve, as well as how they interact with the ongoing PJM market changes, introduces both regulatory uncertainty and market expansion potential for the deployment of energy storage in the PJM region.

Regardless of the future outcome of these FERC processes, developers have already begun diversifying beyond providing frequency regulation towards other revenue streams, such as distribution-sited or customer-sited energy storage systems that also provide services to the host. For example, the Southeastern Pennsylvania Transit Authority (SEPTA) had piloted a Wayside Energy Storage Project, which uses a lithium-ion battery system to store energy from regenerative braking from SEPTA trains while also participating in PJM's frequency regulation and demand response markets (ABB 2014). Similarly, vehicle-to-grid systems where cars sell electricity back to the grid can generate frequency regulation market revenues in order to supplement the inherent transportation benefits of using a car or the revenues of a car fleet operator (Kempton, et al. 2008).

In the longer term, energy storage might play a greater role as frequency regulation requirements adjust in the presence of higher levels of renewables. Long-term renewable energy integration studies conducted by the National Renewable Energy Laboratory (NREL) and PJM show that various renewable expansion scenarios could call for increased levels of frequency regulation.[10] According to NREL's *Eastern Renewable Generation Integration Study*, achieving a scenario of 30 percent variable generation from wind and solar photovoltaics in PJM involves increasing the frequency regulation requirement by 107 percent (Bloom, et al. 2016).[11] Similarly, according to the most recent renewable energy integration study commissioned by PJM itself, the 30 percent variable generation scenarios would also necessitate between an 80 and 127 percent increase in the regulation requirement, depending on the renewable resource mix (GE Energy Consulting 2014). In this sense, streamlining the frequency regulation market design—even if it negatively affects energy storage providers today—helps make the electricity system more efficient and able to incorporate more renewable energy resources in the future.

Despite the uncertain prospects of frequency regulation for energy storage in PJM, frequency regulation remains an important opportunity for energy storage technologies uniquely capable of rapid and accurate response. Along with other timescales of grid balancing, frequency regulation has an important role in the modernization of grid flexibility in the transition towards larger shares of intermittent renewables. Energy storage will play an increasingly important role to make power grids more reliable and help keep the lights on.

[10] These studies' baseline levels are higher than current reality, because they assume a regulation requirement of at least 1 percent of peak load; however, PJM was able to improve efficiency via performance-based regulation and achieved regulation requirements lower than 1 percent. The PJM market monitor describes this historical requirements reduction: "The use of a performance score to measure the accuracy of a regulating resource is the primary reason that the required regulation has been lowered from 1.0 percent to 0.7 percent" (Monitoring Analytics 2013). Still, the relative increases in regulation requirements are likely valid.

[11] This scenario includes moderate expansion of regional electric transmission. The percentage increase is between the 2013 average of 753 MW and the 30% scenario's midpoint of 1560 MW (982 to 2,137 MW reported).

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The author wishes to acknowledge helpful comments from a reviewer of an earlier draft. Any remaining errors are the responsibility of the author alone.